NovaTorque Brushless Permanent Magnet Motor Bench Test Report

Submitted to:

Sacramento Municipal Utility District

SMUD™

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https://www.smud.org/en/business/save-energy/rebates-incentives-financing/customer-advanced-technologies.htm

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1. Executive Summary

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 the second generation of brushless permanent magnet motor (conventionally known as an *Electronically Commutated Motor*), developed by NovaTorque.

NovaTorque claims that the new motors save energy when compared against National Electrical Manufacturers Association (NEMA) Premium Efficiency induction motors in variable speed applications. As stated by NovaTorque, the reason for this energy reduction is that the motor's efficiency does not degrade as quickly as a 'typical' induction motor as it is unloaded or as the speed is reduced.

ADM visited NovaTorque's facility in Fremont, CA to witness motor performance bench testing and then completed the potential energy savings analysis contained in this report. Two sizes of motors were tested (3 and 5 HP) and compared against standard and premium efficiency control motors of the same size.

The NovaTorque motors provided a higher efficiency than the control motors over all of the tested operating parameters, see Figure 1. Annual energy savings estimates ranged from 7% to 22% as discussed in section 5.

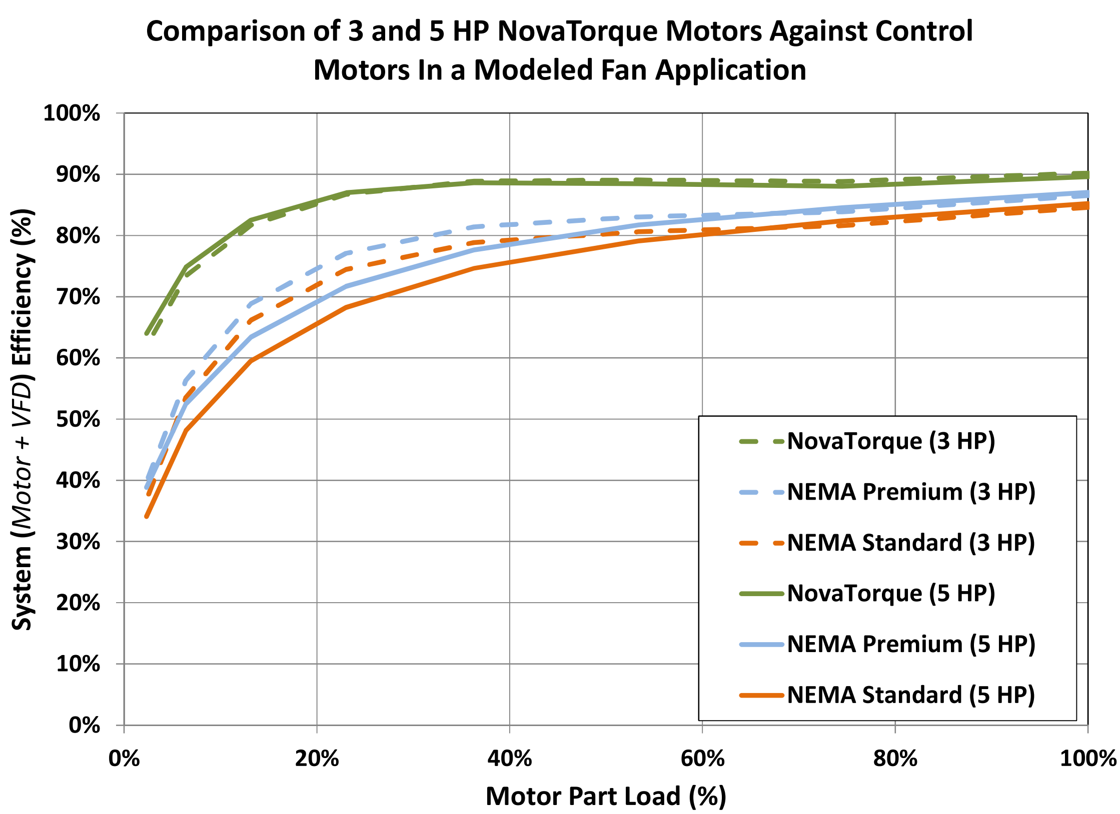


Figure 1: Motor and VFD System Efficiency Summary

2. Introduction

2.1 Background

ADM Associates, Inc., under a contract with the Sacramento Municipal Utility District, conducted an evaluation of new high efficiency motors. SMUD provided funding under its Customer Advanced Technologies (CAT) program to evaluate the second generation of brushless permanent magnet motor (conventionally known as an Electronically Commutated Motor), developed by NovaTorque (see Figure 1). The NovaTorque PremiumPlus+™ Motor must be paired with a qualified variable frequency drive (VFD) to optimize savings. The NovaTorque PremiumPlus+™ motor's performance as an energy efficiency technology was evaluated using laboratory testing. This testing was conducted in order to quickly provide SMUD with an initial technology assessment of this second generation of NovaTorque motors which now also includes a 5hp size motor.

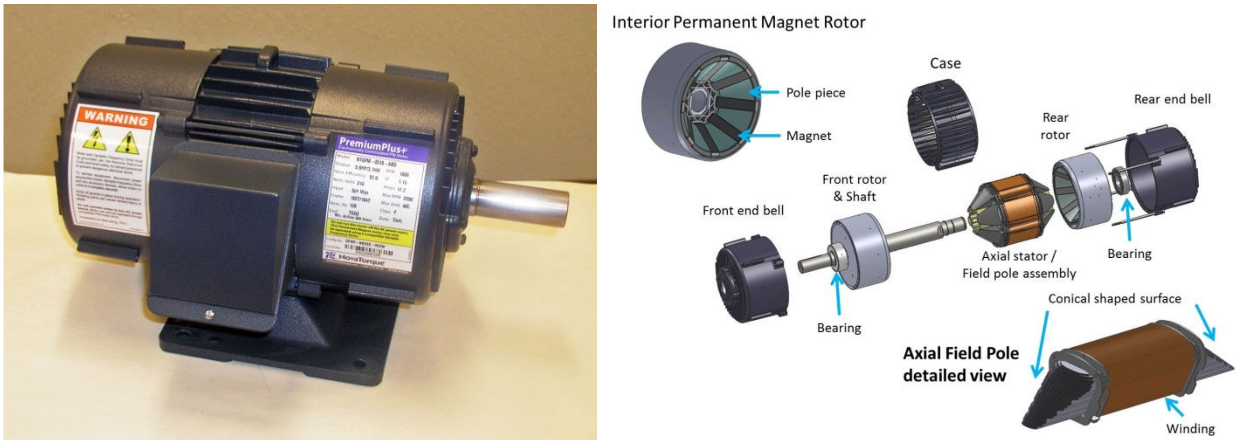
NovaTorque claims that the new motors save energy when compared against NEMA Premium Efficiency induction motors in variable speed applications. As stated by NovaTorque, the reason for this energy reduction is that the motor's efficiency does not degrade as quickly as a typical induction motor as it is unloaded or as the speed is reduced. Figure 2 illustrates the motor and its various components, and NovaTorque supplied ADM with the following description of their motor technology.[1]

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.

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

Figure 2: The NovaTorque PremiumPlus+™ Brushless Permanent Magnet Motor and Exploded View



2.2 Assessment Objectives

The goal of this study was to determine motor efficiency over a full range of operating conditions for both 3hp and 5hp motors. These findings are presented as a tool that can be used to shape future energy efficiency programs through understanding efficiency differences between the performance behavior of both ECM motors and common induction motors.

2.3 Methodology

ADM visited NovaTorque's facility in Fremont, California in order to evaluate their motor's performance using a dynamometer test stand. The NovaTorque PremiumPlus+™ motor was tested alongside two "typical" control induction motors to compare its efficiency at various torque and speed settings. The control induction motors were standard commercial off-the-shelf (COTS) motors. Tests were performed for 3 HP and 5 HP motor sizes for a total of six (6) motors tested. The NovaTorque motors tested are the newest second generation motors. The control induction motors were new units, and were selected and purchased by ADM. NovaTorque provided the variable frequency drive (VFD) by which all six motors were driven during the testing. The following tables illustrate all test points at which data was collected (Table 1 and Table 2), as well as the list of parameters recorded at each data point (Table 3):

Table 1: List of Motor Loading Points at Which Performance Data was Collected (3 HP)

3HP Motor Test Protocol

Cells give Horsepower output

% Load	Load (Nm)	15% 270	25% 450	40% 720	50% 900	60% 1080	75% 1350	100% 1800	No Drive* 100% Actual	% Speed RPM
15%	1.78	0.07	0.11	0.18	0.22	0.27	0.34	0.45	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	

Table 2: List of Motor Loading Points at Which Performance Data was Collected (5 HP)

5HP Motor Test Protocol

Cells give Horsepower output

% Load	Load (Nm)	15% 270	25% 450	40% 720	50% 900	60% 1080	75% 1350	100% 1800	No Drive* 100% Actual	% Speed RPM
15%	2.97	0.11	0.19	0.30	0.37	0.45	0.56	0.75	Actual	
25%	4.95	0.19	0.31	0.50	0.62	0.75	0.94	1.25	Actual	
40%	7.91	0.30	0.50	0.80	1.00	1.20	1.50	2.00	Actual	
50%	9.89	0.37	0.62	1.00	1.25	1.50	1.87	2.50	Actual	
60%	11.87	0.45	0.75	1.20	1.50	1.80	2.25	3.00	Actual	
75%	14.84	0.56	0.94	1.50	1.87	2.25	2.81	3.75	Actual	
100%	19.78	0.75	1.25	2.00	2.50	3.00	3.75	5.00	Actual	

Table 3: List of Motor Performance Parameters Recorded at Each Loading Data Point

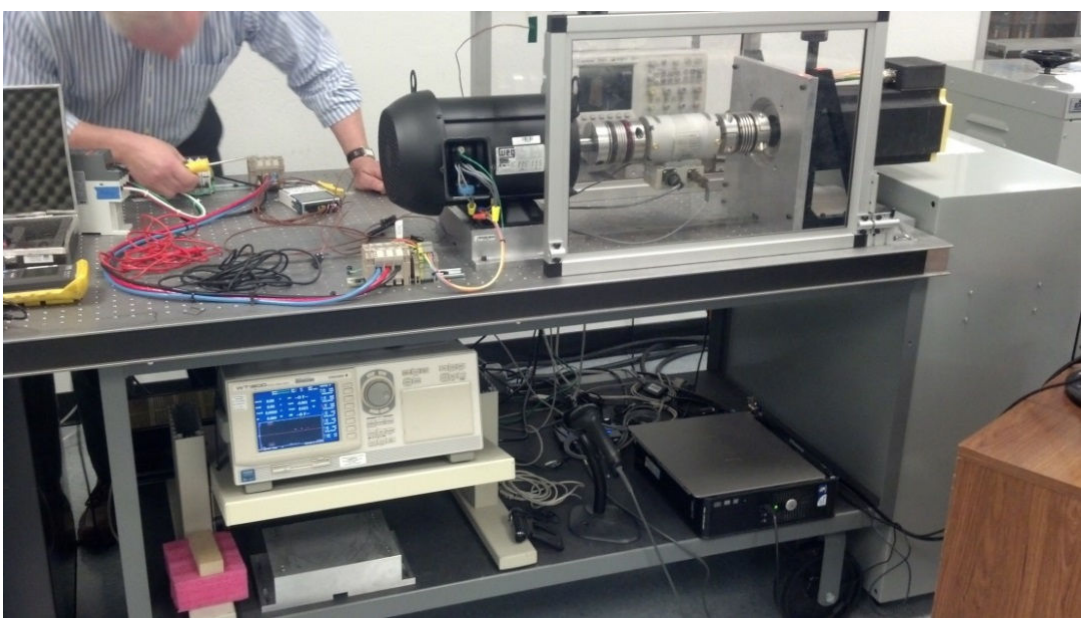
#	Description Of Parameter
1	Speed (RPM)
2	Motor Output (Brake) Power (W)
3	Torque (Nm)
4	Volts (phase to phase for each combination of phases)
5	Amps (Read for each phase)
6	System Input Power (W)
7	Motor Input Power (W)
8	System Efficiency (%)
9	Motor Efficiency (%)

Measurement Equipment

The dynamometer 5 HP automated test system stand setup has a torque range of 0 to 22.5 N-m, a speed range of 0 to 4000 RPM, and power limit of 3.7 kW. The setup contains the following equipment and is shown in Figure 3.

- Himmelstein MCRT torque transducer – 22.5 Nm
- ABB-Baldor servo motor
- Yokogawa WT1600 power meter
- Dell Latitude E6400 notebook computer
- Tests that can be performed:
    - Motor and system efficiency

Figure 3: Dynamometer Test Bench Used to Test Motors



Verification of Primary Instrumentation

While onsite, ADM made several independent measurements of System Input Power in order to validate the primary instrumentation. System Input Power was measured using a handheld AEMC 3910 true RMS power meter. ADM found no discrepancies between the independent measurements and those of the primary instrumentation.

3. Products Evaluated

ADM purchased four new induction motors that were used as controls against the NovaTorque motors. The control motors were purchased from a single manufacturer, and were rated at two different efficiencies (89.5% and 87.5%). The control motors were commercial off-the-shelf (COTS) motors and rated at 3 hp and 5 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. Table 4 provides the size and efficiency categories of motors evaluated.

Table 4: List of Motor Products Evaluated

	3 HP Motor	5 HP Motor
Control	Standard	Standard
Control	Premium	Premium
NovaTorque	PremiumPlus+™	PremiumPlus+™

4. Results

Before discussing the results of this study, it should first be noted that a similar study was performed by ADM in December of 2010 on the 1st generation version of the 3 HP NovaTorque PremiumPlus+™ motor and the estimated energy savings presented in that report cannot be directly compared to those presented here. The reason for this is that all energy savings are calculated using a "system efficiency" curve. This curve incorporates both motor efficiency and VFD drive efficiency to estimate final electric power. In the course of this study it was found that the VFD drives used when collecting motor performance data were different than those used in the previous study. The VFD used in the 2nd generation testing better represents the typical VFD used by NovaTorque customers than the VFD used in the 1st generation tests. Figure 4 below illustrates the differences in the drive efficiencies between the two tests.

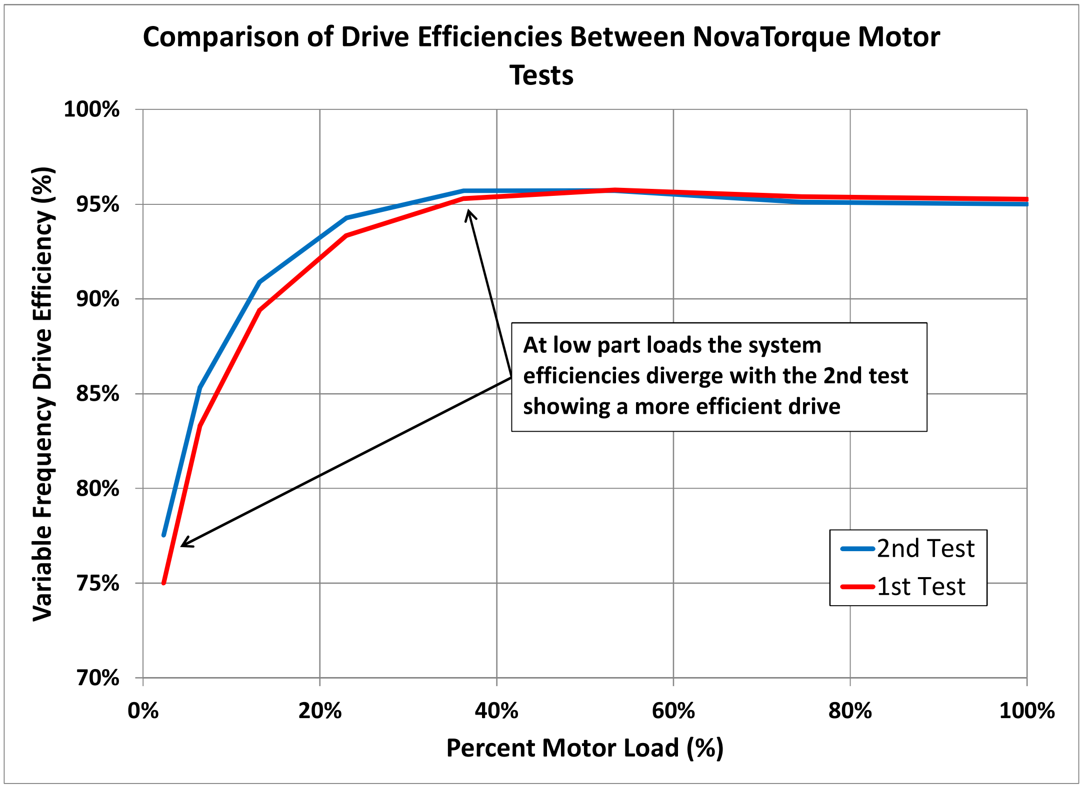


Figure 4 Comparison of VFD Efficiencies Between Current Motor Test and Previous 1st Generation Motor Test

Ultimately, the energy savings potential for any motor technology will be dependent on both the application (e.g. HVAC fan vs. process pump) and the VFD hardware used to drive it. The energy savings presented here assume both a motor load profile and drive efficiencies. The energy impacts for real world implementations of this motor will vary.

Figure 1 in the Executive Summary illustrates the measured performance for all six motors. As 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. As expected, the measured efficiencies for equivalent brake powers at lower speeds were slightly lower. Overall the NovaTorque motors were more efficient than the typical induction motor.

4.1 3 Horsepower Motors

Figure 5 compares each of the 3 HP motors' measured efficiencies versus its speed (RPM), holding torque constant. The solid lines in Figure 5 represent the motors measured performance at 100% of the rated torque output at 1800 RPM (~12 Nm), while the dotted lines represent measured 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 quickly declined as speeds were decreased in a similar fashion for all three motors. The second generation 3 HP NovaTorque motor shows a higher sustained efficiency with much less efficiency degradation at lower speeds than do the control motors. The slopes for all three motors are relatively parallel down to approximately 900 RPM, after which the standard and premium motor efficiency begins to decline more quickly. This is observed in the gap between the lines at various speeds. The change in efficiency degradation among all three motors is similar above 900 RPM, but below this point the gap widens substantially. This trend indicates that the NovaTorque system is able to better maintain its operating efficiency at reduced speeds. 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, for variable speed applications, the NovaTorque motor would save more energy than typical induction motors in applications in which the motor spends considerable time at lower loads.

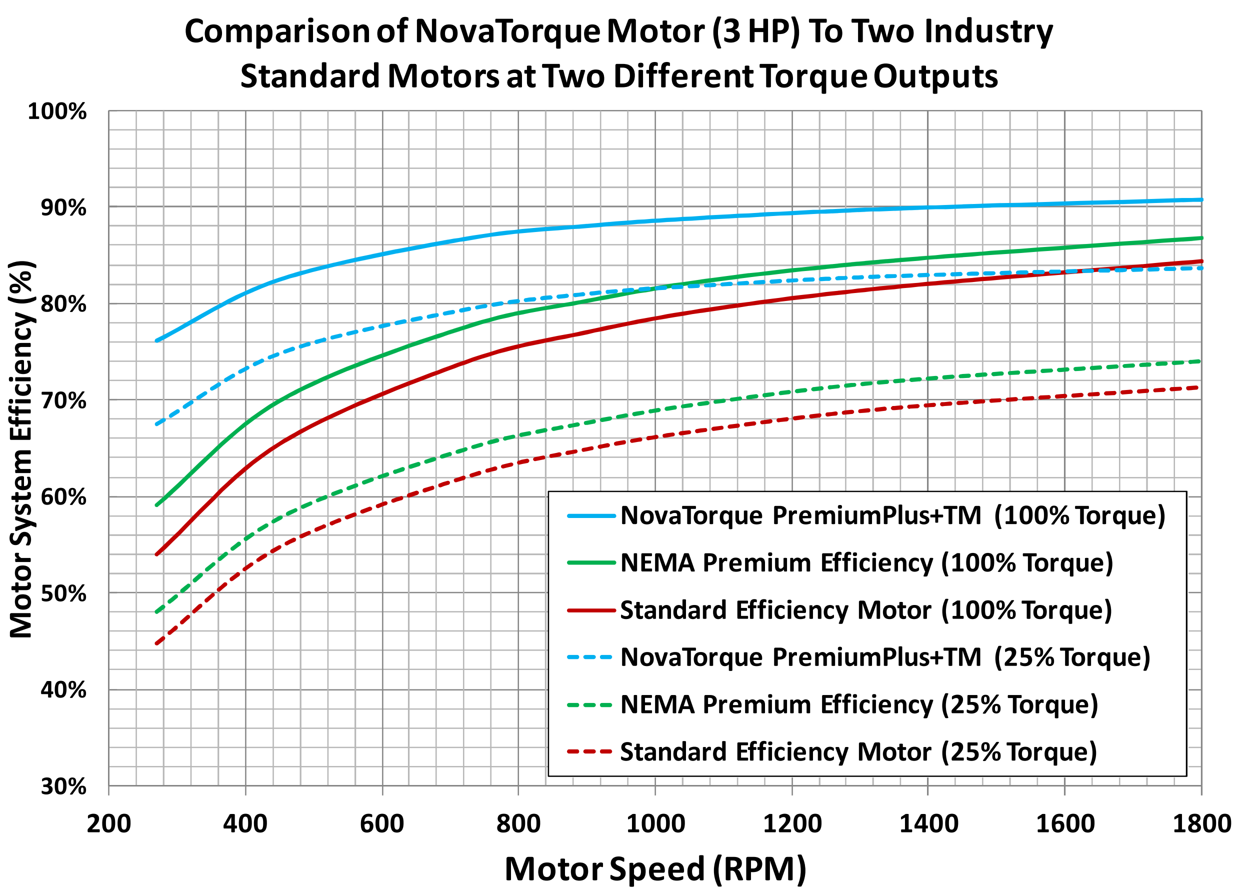
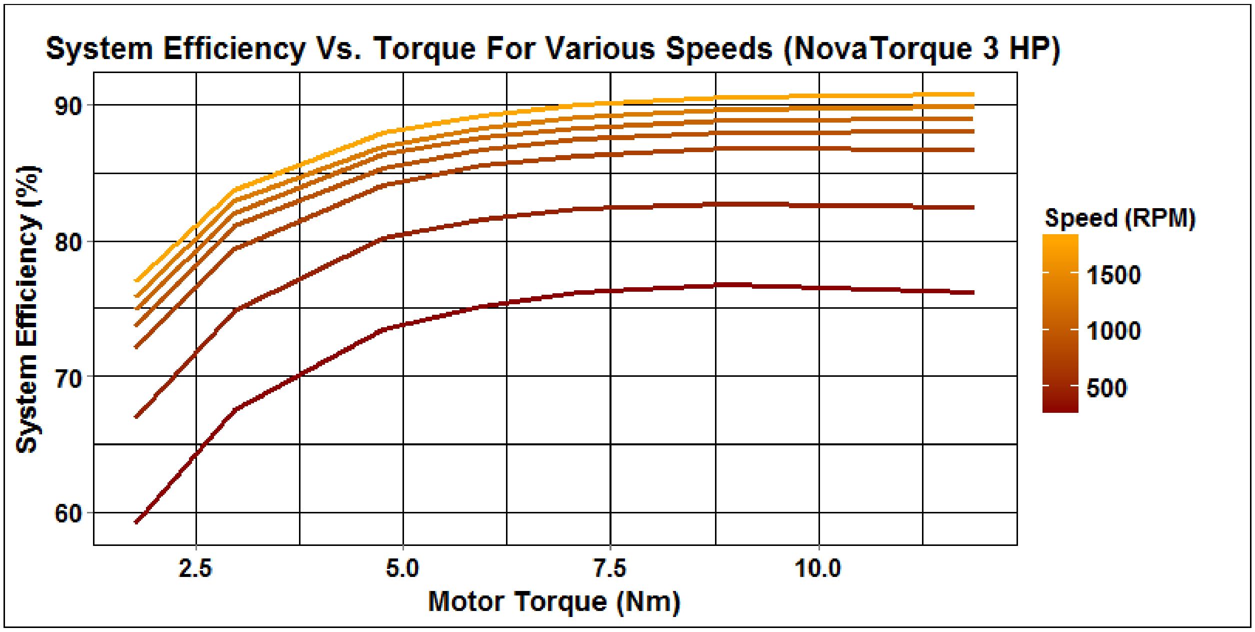


Figure 5: 3 HP Motor System Efficiency at 25% and 100% of Rated Torque

Figure 6 shows two charts for the 3 HP NovaTorque premium plus motor and VFD system. One chart shows system efficiency versus torque where each line plotted represents a fixed speed and the other chart shows system efficiency versus speed where each line plotted represents a fixed torque.



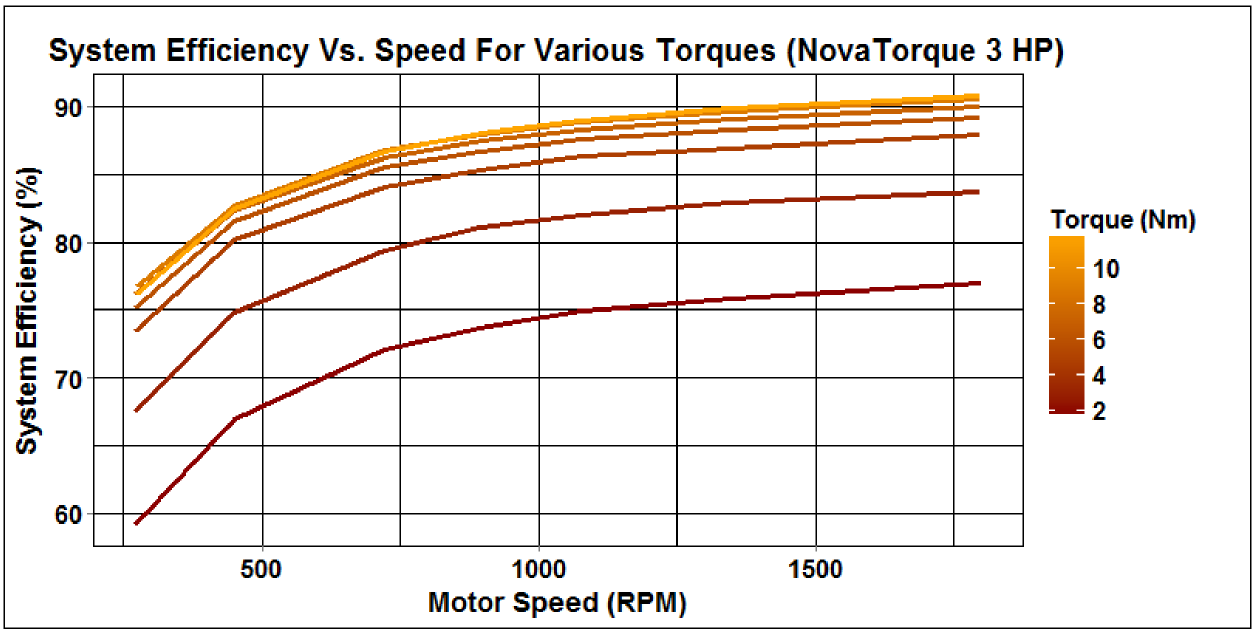
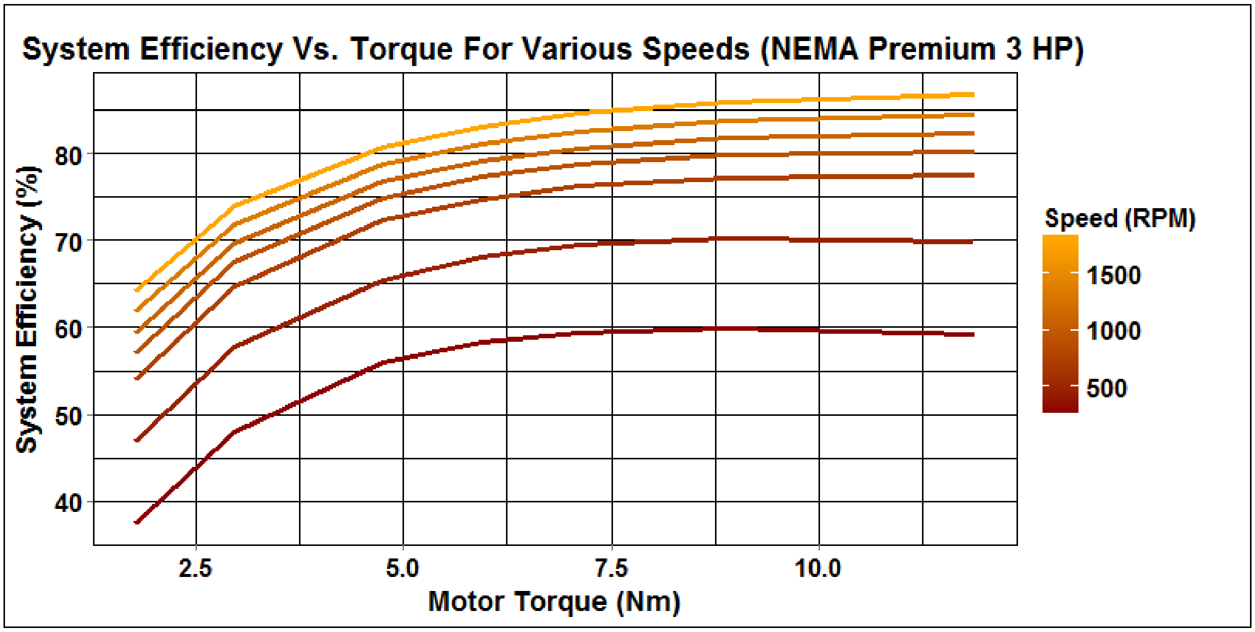


Figure 6: 3 HP NovaTorque PremiumPlus+™ Efficiency with Varied Speed (RPM) and Torque

Figure 7 shows two charts for the 3 HP NEMA premium efficiency motor and VFD system. One chart shows system efficiency versus torque where each line plotted represents a fixed speed and the other chart shows system efficiency versus speed where each line plotted represents a fixed torque.

Figure 8 shows two charts for the 3 HP standard efficiency motor and VFD system. One chart shows system efficiency versus torque where each line plotted represents a fixed speed and the other chart shows system efficiency versus speed where each line plotted represents a fixed torque.

A comparison of Figures 6, 7, and 8 shows that the NovaTorque motor not only have a higher initial efficiency, but it is able to maintain a higher efficiency over the control motors throughout the tested operating range.



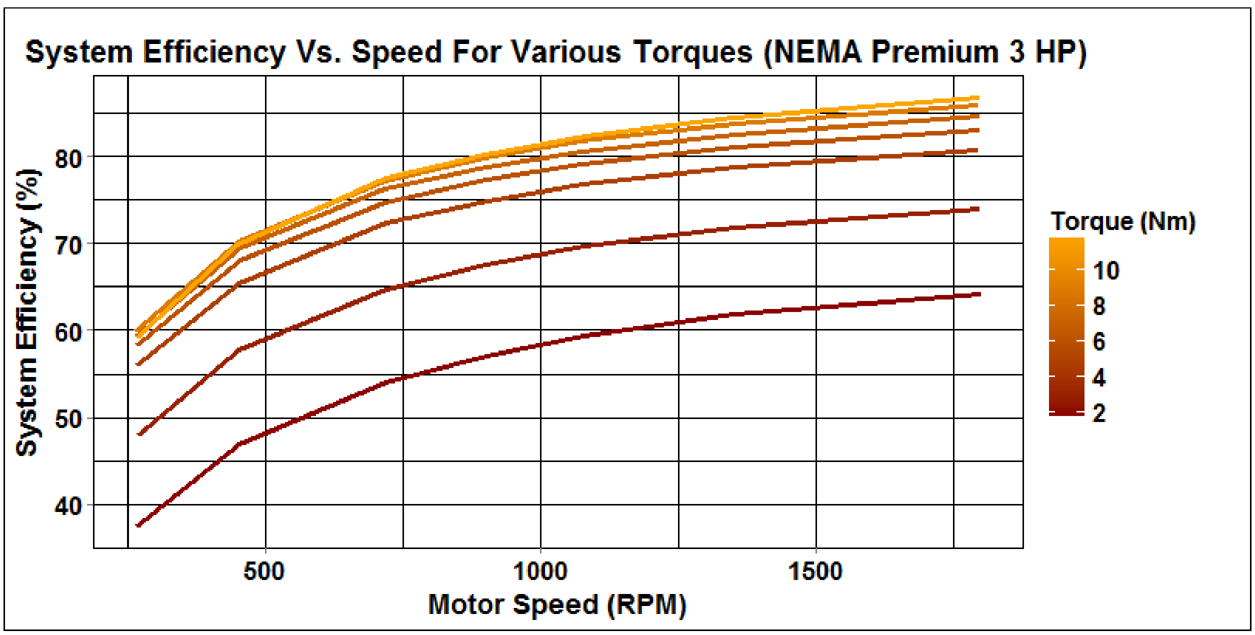
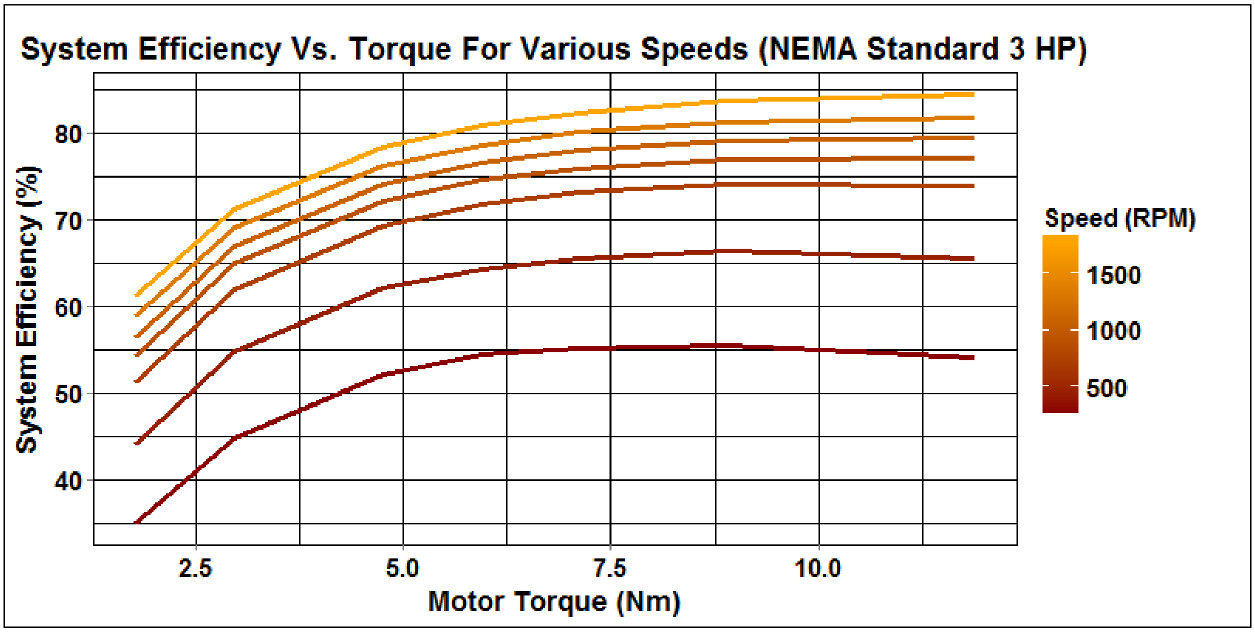


Figure 7: 3 HP NEMA Premium Efficiency with Varied Speed (RPM) and Load



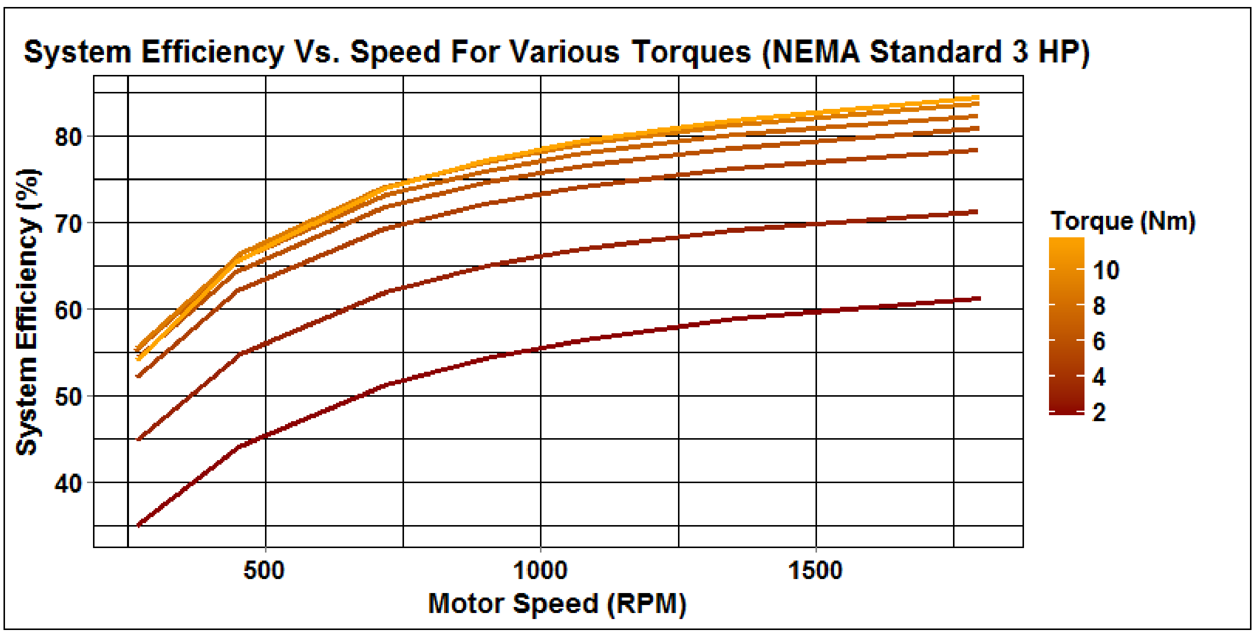


Figure 8: 3 HP Standard Efficiency with Varied Speed (RPM) and Load

4.2 Five Horsepower

Figure 9 compares each of the 5 HP motors' measured efficiencies with its speed (RPM), holding torque constant. The solid lines in Figure 9 represent the motors' measured performance at 100% of the rated torque output at 1800 RPM (~20 Nm), while the dotted lines represent measured performance at 25% of the rated torque at 1800 RPM (~ 5 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 5 HP NovaTorque motor shows a higher sustained efficiency with much less efficiency degradation at lower speeds than the control motors. The slopes for all three motors are relatively parallel down to approximately 900 RPM, after which the standard and premium motors begin to fall off a bit faster. This is observed in the gap between the lines at various speeds. The change in efficiency degradation among all three motors is similar above 900 RPM, but below there the gap widens substantially. This trend indicates that the NovaTorque system is able to better maintain its operating efficiency at reduced speeds. 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, for variable speed applications, the NovaTorque motor would save more energy than typical induction motors in applications in which the motor spends considerable time at lower loads.

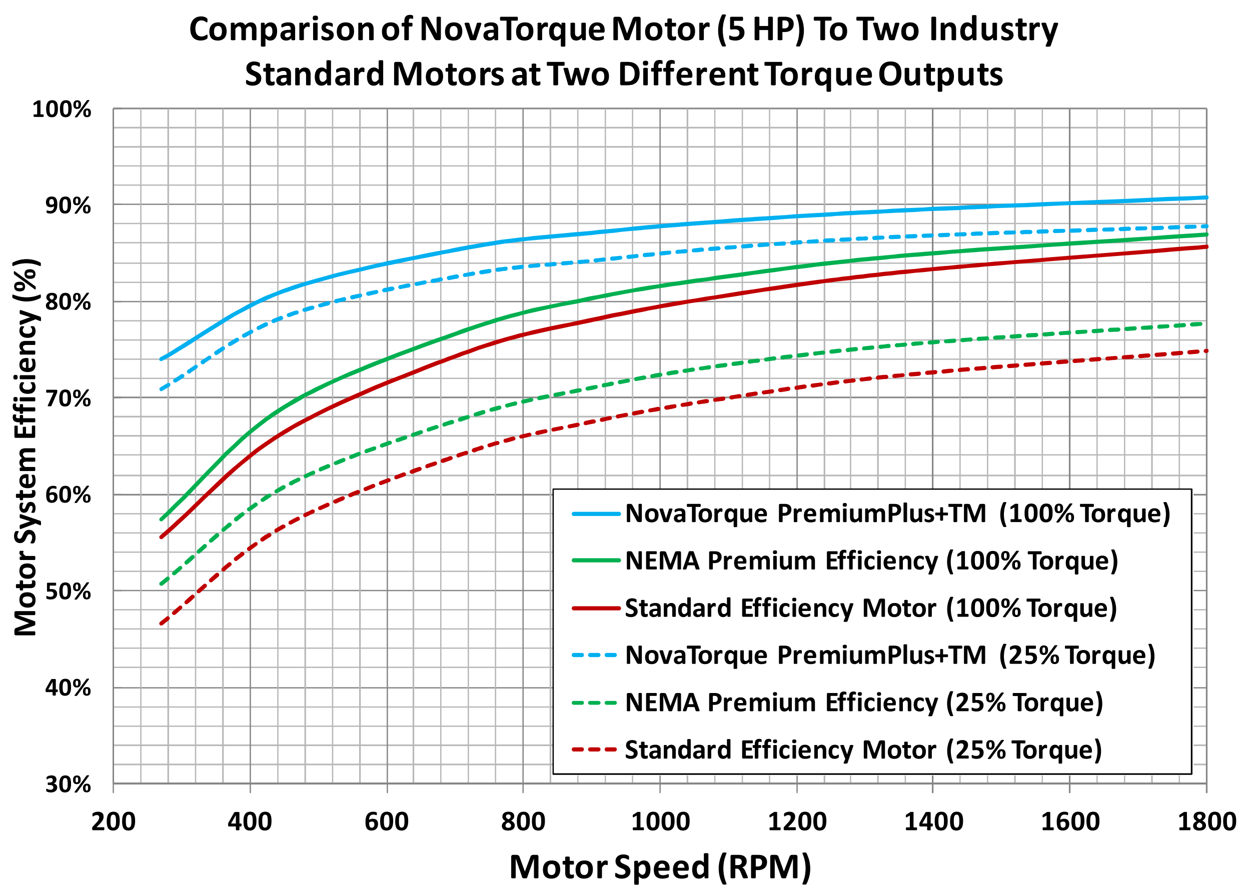
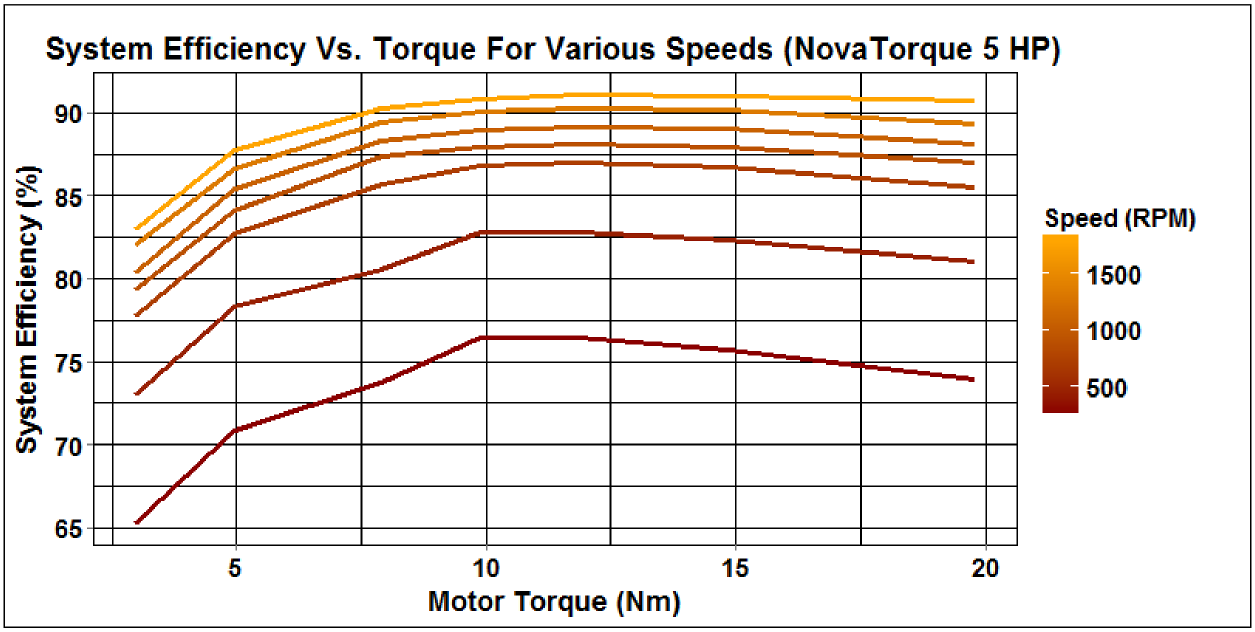


Figure 9: 5 HP Motor Efficiency at 25% and 100% of Rated Torque

Figure 10 shows two charts for the 5 HP NovaTorque PremiumPlus+™ motor and VFD system. One chart shows system efficiency versus torque where each line plotted represents a fixed speed and the other chart shows system efficiency versus speed where each line plotted represents a fixed torque.



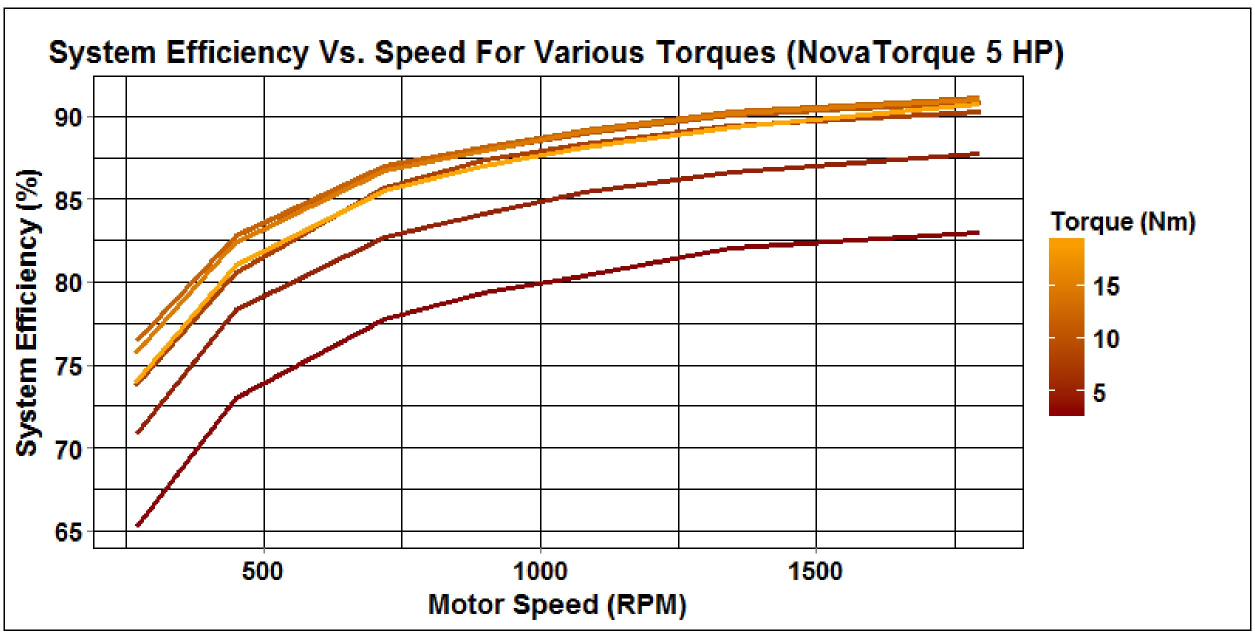


Figure 10: 5 HP NovaTorque PremiumPlus+™ Efficiency with Varied Speed (RPM) and Load

Figure 11 shows two charts for the 5 HP NEMA premium efficiency motor and VFD system. One chart shows system efficiency versus torque where each line plotted represents a fixed speed and the other chart shows system efficiency versus speed where each line plotted represents a fixed torque.

Figure 12 shows two charts for the 5 HP NEMA premium efficiency motor and VFD system. One chart shows system efficiency versus torque where each line plotted represents a fixed speed and the other chart shows system efficiency versus speed where each line plotted represents a fixed torque.

A comparison of Figures 10, 11, 12 shows that the NovaTorque motor does not have a higher initial efficiency, but it is able to maintain a higher efficiency over the control motors throughout the tested operating range.

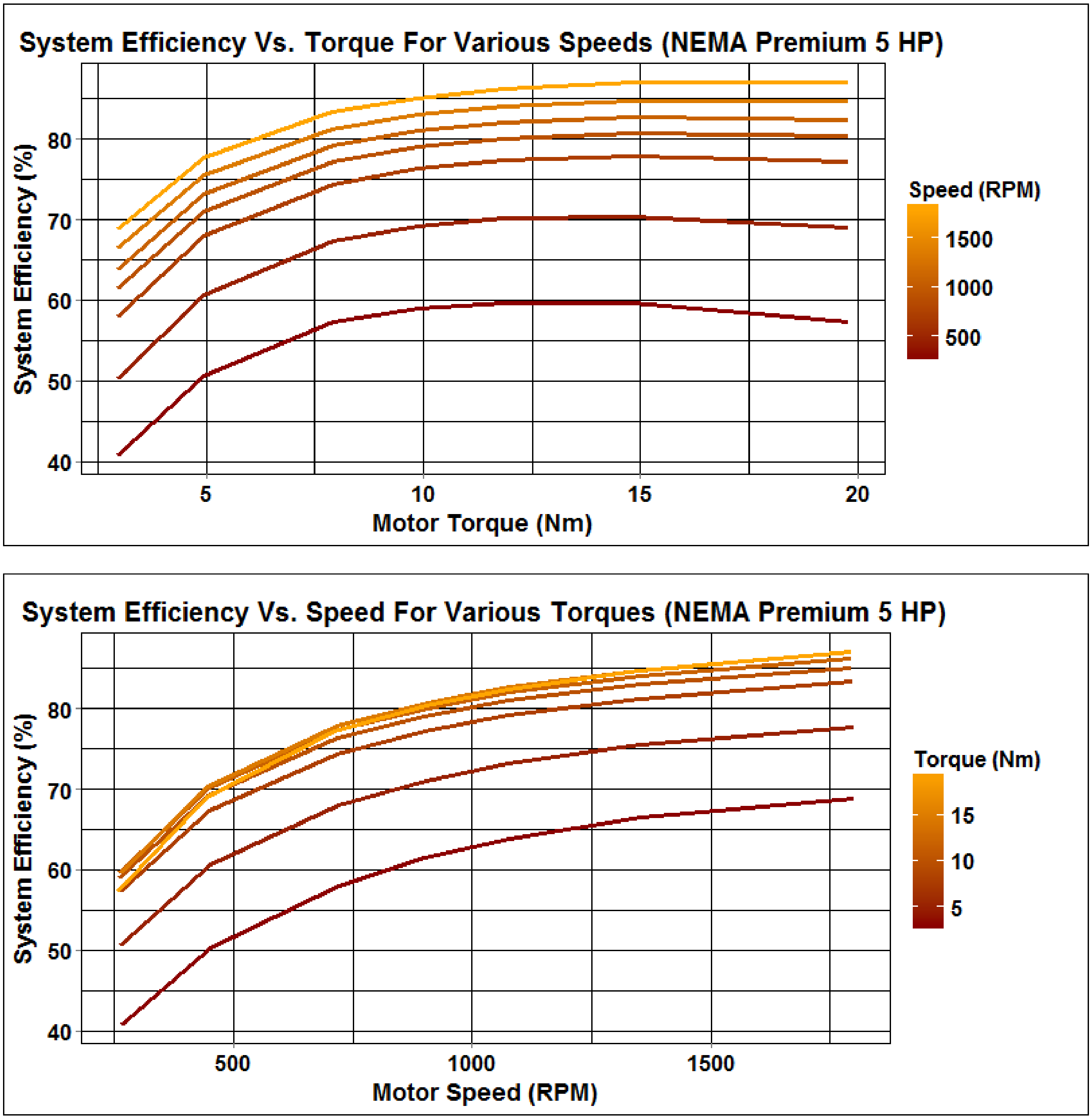
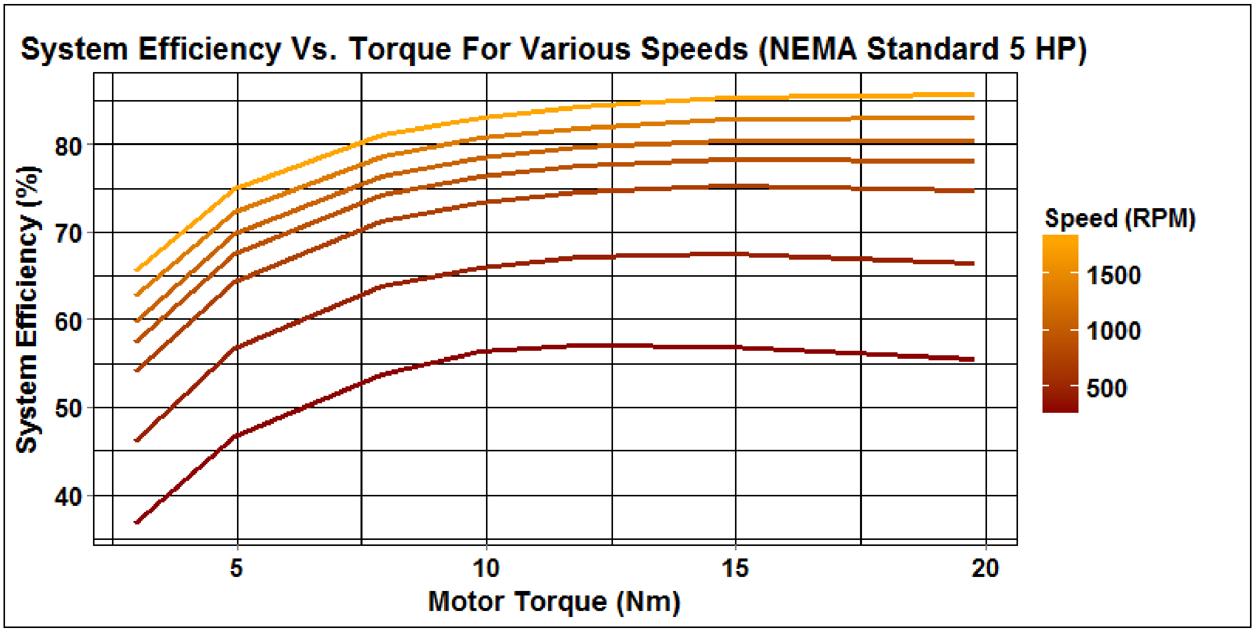


Figure 11: 5 HP NEMA Premium Efficiency with Varied Speed (RPM) and Load



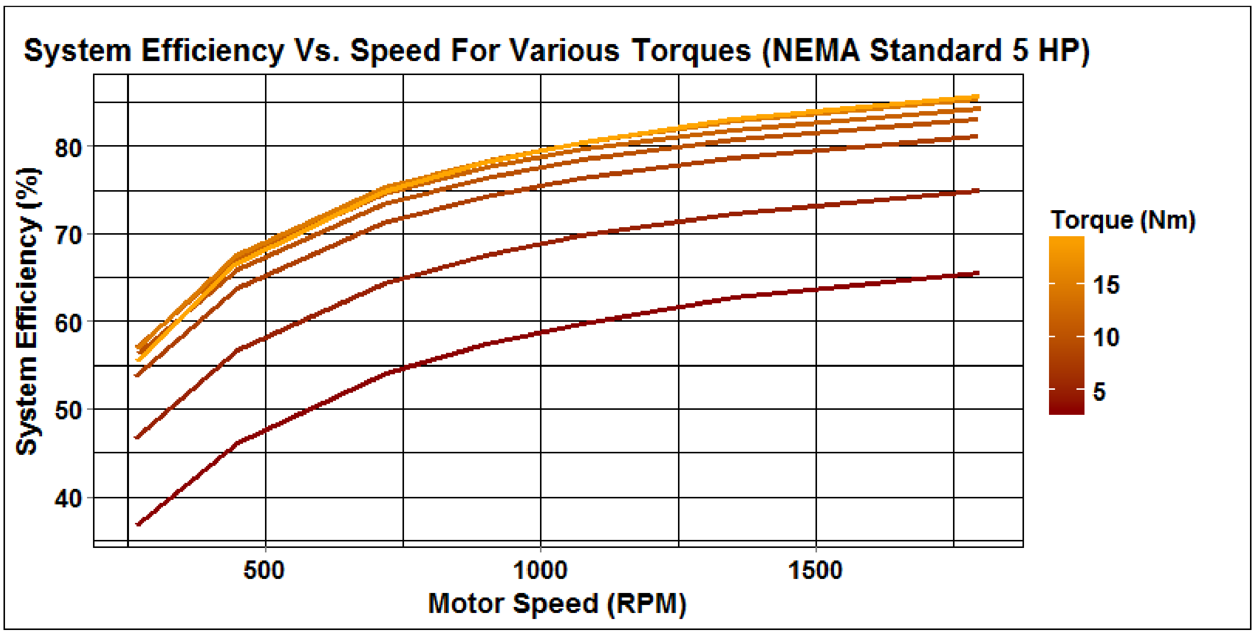


Figure 12: 5 HP Standard Efficiency with Varied Speed (RPM) and Load

Summary

The laboratory bench testing data collected and used to produce the performance curves for both the 3 and 5 horsepower motors show that the NovaTorque motors have a superior capability to sustain their efficiency at varied speeds and loads compared to the control induction motors. The substantial increase in efficiency at typical motor operating parameters suggests that energy savings can be realized.

5. Energy Savings

Based on the measured 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 these energy savings by applying the measured motor data to a simulated annual load profile for a typical HVAC supply fan variable speed motor application.

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

$$\eta = a + bx + cx^2 + dx^3 + ey + fy^2 + gy^3 + hxy$$

Where:

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

By fitting a curve to the measured data, its equation can then be used to predict the performance of the motor at any conceivable operating point within its range - even points that are not directly measured. 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 to identify potential energy savings.

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 13 and Figure 14. This paper examines potential NovaTorque savings in supply fan and chilled water pump applications.[2]

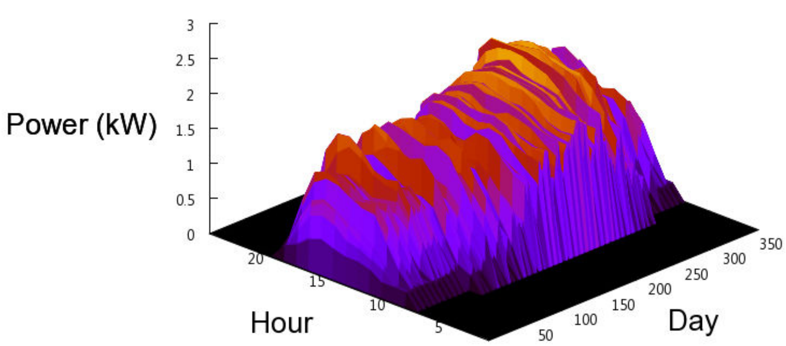


Figure 13: Annual Load Profile Used to Predict Motor Savings for the Variable Speed Supply Fan Application

[2] Note that the graphs shown are for the 3 HP motor. The load profile used to model energy savings for the 5 HP was identical except for scale.

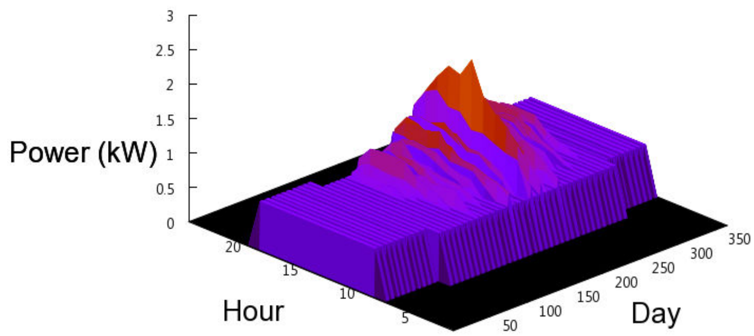


Figure 14: Annual Load Profile Used to Predict Motor Savings for the Variable Speed Chilled Water Pump Application

Potential energy savings were estimated using the following formula:

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

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]

Savings are presented as annual estimates and normalized to rated motor horsepower. The estimated savings for the 3 and 5 HP supply fan motors and chilled water pump are listed in Table 5 and Table 6 respectively. Energy cost savings estimates are based on an annual average energy cost of $0.10 per kWh.

Table 5: Estimated Annual Savings of NovaTorque PremiumPlus+™ When Compared Against Control Motors in Supply Fan Application

	Supply Fan (3 HP)		Supply Fan (5 HP)	
	NEMA Premium Motor	Standard Motor	NEMA 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 6: Estimated Annual Savings of NovaTorque PremiumPlus+™ When Compared Against Control Motors in CHW Pump Application

	CHW Pump (3 HP)		CHW Pump (5 HP)	
	NEMA Premium Motor	Standard Motor	NEMA 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%

As expected, NovaTorque motor shows more savings compared to the standard induction motor than does the premium motor, but both savings percentages are still significant (7%-22% compared to only a 3%-11% savings by using a premium motor over a standard motor). Both 3 and 5 horsepower motors have the opportunity to realize energy savings in typical HVAC fan motor and chilled water pump applications. Energy savings for a NovaTorque motor replacing an oversized motor would be higher. Figure 15 and Figure 16 are time series plots showing each motor's simulated demand (kW) profile over an average summer day.[3]

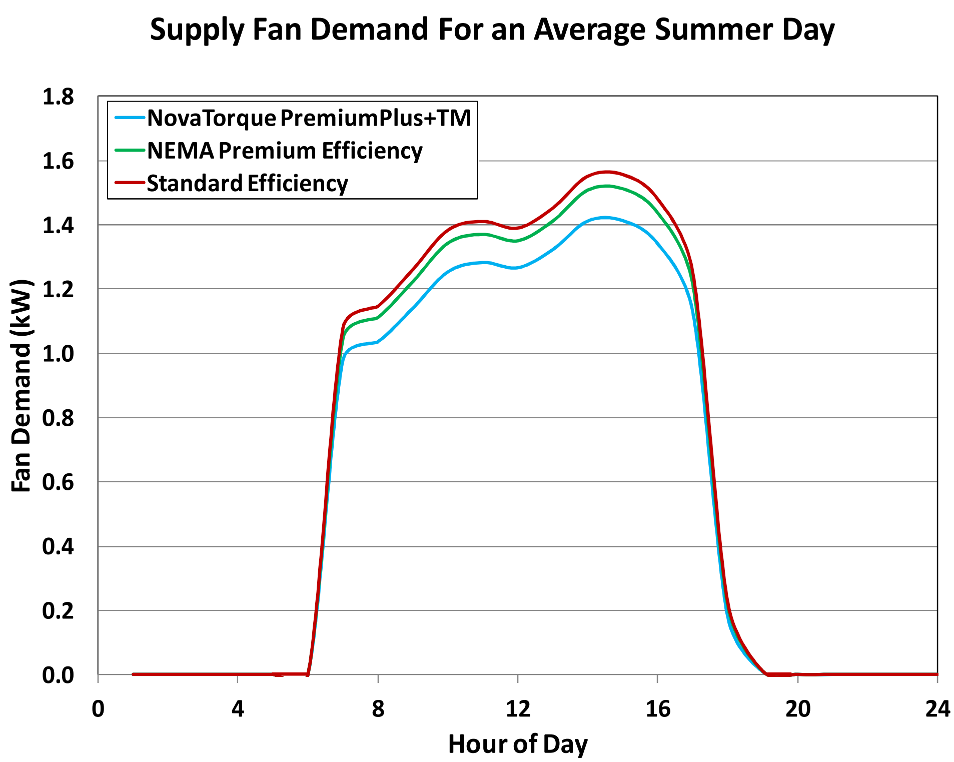


Figure 15: Simulated Demand for a Modeled 3 HP Supply Fan for an Average Summer Day

[3] Average summer day is defined here as the average of all days from June through September. Also, it should be noted that since the same load profile was used to model the energy impacts for both the 3 and 5 HP motors, the hourly demand profile for the 5 HP motor will look identical except for scale.

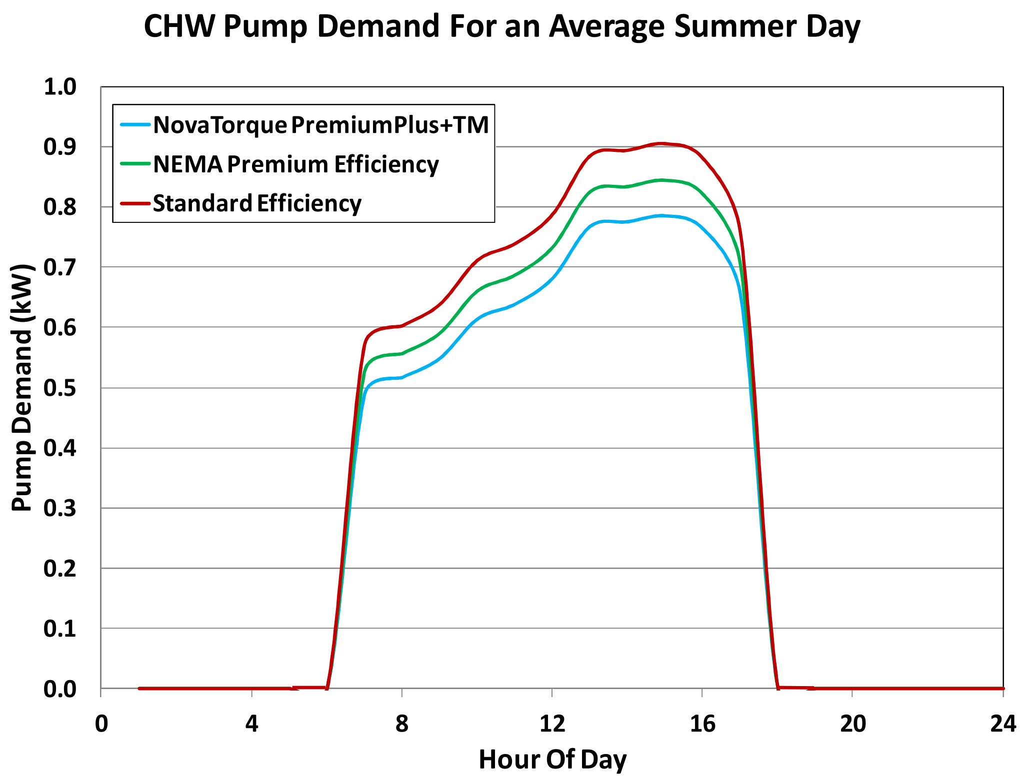


Figure 16: Simulated Demand for a Modeled 3 HP *CHW Pump* for an Average Summer Day

6. Conclusion

The findings presented in this report indicate that the NovaTorque PremiumPlus+™ 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 does a NEMA Premium Induction motor. Savings are dependent on motor sizing of existing motors and speed distribution of the motors' operation 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 resulting from the two motors and two applications presented in this report ranged from 7% to 22% as compared to the control motors. Comparison with an existing in-situ motor would likely show more savings if the existing motor has a lower rated efficiency and if the performance has degraded over time. As 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 motors' performance is evaluated in an actual variable speed application.