Advanced Energy
909 Capability Drive, Suite 2100
Raleigh, NC 27606-3870
919-857-9000 | www.advancedenergy.org

Performance Testing Results
For FlexMod™ Controller

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RECIPIENT ORGANIZATION

Advanced Energy

PARTNERS

Raser Technologies, Inc.

Washington State University Energy Program

TECHNICAL CONTACT

Ken Dulaney, P.E.

Advanced Energy

909 Capability Drive, Suite 2100 | Raleigh, NC 27606

919-857-9055 | Fax: 919-832-2696

kdulaney@advancedenergy.org

BUSINESS CONTACT

Maggy Inman

Advanced Energy

909 Capability Drive, Suite 2100 | Raleigh, NC 27606

919-857-9004 | Fax: 919-832-2696

minman@advancedenergy.org

AUTHORS

Advanced Energy

Ken Dulaney

Emanuel Agamloh

Raser Technologies, Inc.

Tim Fehr

CONTRIBUTORS

Advanced Energy

David Berkowitz

Matt Wagenhauser

Raser Technologies, Inc.

George Holling

Sergei Kolomeitsev

Doug Sward

Ned Warner

Washington State University and EERE Information Center

Johnny Douglass

Gil McCoy

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Executive Summary

Most of the electricity generated in the United States is used in an electric motor. In U.S. industry, there are more than 13 million motors. Many of these are operating inefficiently because of changing loads or less than optimum control schemes. The U.S. Department of Energy estimates that improved system controls including variable speed drives could save nearly 15,000 gigawatt-hours per year and potentially $900 million per year in energy savings in pump, fan and compressed air systems alone.

Therefore, there is a market need for an efficient, modular motor controller capable of operating with a range of motor sizes and types. The wide applicability and low cost could result in substantial energy savings in industry, residential and hybrid vehicle markets. The overall objective of this project was to develop and evaluate such a controller.

Under this project, Raser Technologies developed the FlexMod™ controller using Symetron™ technology. This motor controller design uses adaptive tuning to optimize performance based upon unique motor characteristics. The prototype drive can use various power modules and different IGBT designs. The modular construction methods should reduce manufactured costs.

Advanced Energy tested the FlexMod™ controller and a comparable, commercially available controller on a 5 hp and a 20 hp AC induction motor. The tests produced a system efficiency map over 300 to 1800 rpm and 25% to 125% rated torque. The tests demonstrated that the FlexMod™ design was 2 to 10% more energy efficient on average.

The results of this project should be provided to major motor manufacturers and the utility industry in order to reduce energy costs in the industrial, residential and hybrid vehicle markets. A full copy of this report may be downloaded from these websites:

- www.motorresourcecenter.org/docs/ Performance Testing Results for FlexMod Controller.pdf
- www.rasertech.com

Abstract

There is a market need for an efficient, modular motor controller capable of operating with a range of motor sizes and types. The wide applicability and low cost could result in substantial energy savings in industry, residential and hybrid vehicle markets. Under this project, Raser Technologies developed the FlexMod™ controller using Symetron™ technology. This motor controller design uses adaptive tuning to optimize performance based upon unique motor characteristics. The prototype drive can use various power modules and different IGBT designs. Advanced Energy tested the FlexMod™ controller and a comparable, commercially available controller on a 5 hp and a 20 hp AC induction motor. The tests produced a system efficiency map over 300 to 1800 rpm and 25% to 125% rated torque. The tests demonstrated that the FlexMod™ design was 2 to 10% more energy efficient on average.

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Introduction

Electric Motor Energy Use

In 2005, the United States consumed more than four million Gigawatt hours of electricity. Generating this energy required millions of tons of coal and thousands of pounds of processed nuclear fuel, and released more than two billion tons of carbon dioxide (CO_2) into the atmosphere[1]. There is great awareness that there are consequences to this level of energy use and pollution. The U.S. Department of Energy (DOE) and a myriad of other organizations promote energy efficient products and behaviors to help reduce the negative environmental and economic impacts of our energy use. This project evaluated one technology that could have a substantial impact on the single largest consumer of electric energy: the electric motor.

Government studies find that electric motor driven systems consume nearly 70% of all industrial electricity in the United States. According to the Energy Efficiency and Renewable Energy Office of the DOE, there are more than 13.5 million AC electric motors greater than 1 horsepower (hp) operating in U.S. industry[2]. Most of these motors are powered directly from the 60 Hertz line voltage and operate at a constant speed. If the load is constant and at least 50% of the rated load, then these motors can be very efficient. For example, 20 hp motors meeting the National Electrical Manufacturers Association (NEMA) Premium standards are at least 93% efficient, and 100 hp NEMA Premium motors are over 95% efficient[3].

However, many motor loads are not constant, and many motors drive equipment that does not operate continuously. One common motor control scheme is the “on / off” method. Examples of motor driven systems using this control method include residential and industrial heating and air conditioning fans, water pumps tied to float level controls and many types of blowers. In these systems, the control variable (i.e., temperature set point, water level, etc.) deviates from an allowed range and causes the motor driven fan or pump to come fully on until the control variable returns to an acceptable value. Then the system powers off. A good example of this control scheme is found in most residential heating, ventilation and air conditioning (HVAC) systems. On / off control for motor driven systems results in high startup currents and additional losses due to fluid turbulence and overshoot of the control variable. Such control schemes are simple and inexpensive, but they can be inefficient.

Another method of controlling a motor driven system is with a variable speed drive. A common type of variable speed drive is known as a voltage / frequency (V/F) controller. V/F controllers vary the supplied voltage to match the speed and load requirements, while attempting to maximize efficiency over the full range of power. Some V/F drives allow the user to program the exact relationship between voltage and frequency. V/F controllers are typically sized for moderate power ranges like 5 to 10 hp, 10 to 20 hp and 20 to 50 hp.

For applications where dynamic performance is an important consideration, "vector drive" motor controllers may be used. These controllers are more expensive than V/F controllers because of more sophisticated electronics that allows control of both frequency and current. Therefore, V/F drives only adjust motor speed while vector drives adjust motor speed and torque. Vector drives are usually found in specialty applications where torque control is important. For example, certain winding applications have growing rotational inertias as material is added to the roll. Examples include thread in textiles, paper and printing, and electrical wire winding on transformers. A vector drive can replace inaccurate and inefficient brake systems when torque control is required.

A relatively new application where electric motors are subject to variable loads at variable speeds is in hybrid electric vehicles. A hybrid electric vehicle couples an internal combustion engine with an electric motor in order to increase fuel economy. The average increase in fuel economy of the hybrid vehicle over its conventional equivalent is about 30%. The electric motor system in these vehicles requires a sophisticated motor controller. Currently, hybrid electric vehicles use relatively expensive motors and controllers to achieve the performance and efficiency expected by the market. The initial cost of a hybrid vehicle is about $2,500 to $3,000 more than the traditional model.

Hybrid vehicles represented only 1.2 percent of the total vehicles sold in 2005. However, hybrid vehicle sales are projected to grow rapidly. Since the introduction of the Toyota Prius in 2000, hybrid vehicle sales have generally doubled each year. The ABI Research & Automotive Technology Research Group predicts that 5% to 6% of all vehicles sold in the United States will be hybrids by 2013, assuming fuel costs continue to increase following historic trends[4]. Therefore, consumers should expect electric motors used in more vehicle types in the future.

The purpose of this background information is to clarify that electric motors are ubiquitous in modern society. They are in our homes, our businesses, our factories and our vehicles. Many of these motor driven systems are operating at less than maximum efficiency and could benefit from a variable speed drive. Therefore, there is a clear market need for a low cost, energy efficient controller.

Potential Impact

As stated above, motor driven systems consume an enormous amount of energy. Yet many of these systems could be more efficient if they used a variable speed drive. The U.S. Department of Energy estimates that improved system controls including variable speed drives could save more than 20% of manufacturing motor system energy use in pump, fan and compressed air systems[5]. This represents nearly 15,000 GWh per year and potentially $900 million per year in energy savings.

In common fan applications like those in residential HVAC systems, adding a variable speed drive can reduce energy use in several ways. The power required to turn a centrifugal fan is theoretically proportional to the cube of the fan speed. So half speed requires only one eighth the input power. In reality, this is closer to a squared relationship, i.e., half speed equals one fourth power. With an on / off control method, the motor operates at full power for a brief period of time to move a certain volume of air to adjust the temperature at the thermostat. Therefore, the amount of heating or cooling provided to the conditioned space is proportional to the volume of air delivered to that space. And volume is directly proportional to fan speed. So if a house requires a certain volume of air throughout the day then delivering that volume at lower speeds consumes less power but still meets the heating or cooling need of that space. Continuously operating a fan at half speed uses one quarter of the energy required to cycle the fan on and off for the same airflow. This translates into reduced operating costs for the same heating or cooling load. Depending upon utility rates and airflow requirements, adding a variable speed drive to a home HVAC system could save several hundred dollars each year in operating costs.

In addition to increased energy efficiency, a modular motor drive platform can result in substantial non-energy savings for industrial facilities. Most manufacturing plants have multiple brands and models of variable speed drives throughout the facility. This increases their spare parts inventory and increases their maintenance training requirements (i.e., personnel need to learn multiple systems). However, a modular drive platform that used a common interface and only required different power modules for different motor sizes could decrease overall maintenance costs assuming comparable maintenance requirements between the modular system and other variable speed drives.

A low cost, modular drive system could clearly have a very large impact on energy use and industrial maintenance costs.

Project Approach

To meet the project objectives required design, fabrication and testing of the motor controllers. Publication of test results is the final phase.

PHASE I — DESIGN

This was the longest phase of the project and consisted of several tasks, including defining the objectives and goals, electrical design, mechanical design, and system simulation and analysis. Raser Technologies performed all of these tasks.

PHASE II — FABRICATION

Based upon the objectives and detailed designs developed in Phase I, Raser Technologies fabricated several FlexMod™ controllers for verification testing.

PHASE III — TESTING

Advanced Energy and Raser Technologies tested the FlexMod™ controller to measure system efficiencies with the various motor types.

PHASE IV —RESULTS PUBLICATION

All parties intend to present the testing results at various industry venues and on their websites. Dissemination plans include posting this report and a summary document on the website for Washington State University's Energy Program.

More detail on each phase is provided in later sections.

Project Outcomes

Results of this study show:

1. Phase I design and simulation efforts demonstrated that an improved motor controller could substantially improve system efficiencies while meeting cost goals and performance targets.
2. Phase II fabrication of the controller provided data to support a cost-effective approach to manufacturing.
3. Phase III performance verification testing conducted at Advanced Energy's lab showed that the FlexMod™ controller used on the 5 and 20 hp motors demonstrated substantial improvements in system efficiency over the ABB controller. Testing at Raser's lab showed that comparable improvements in efficiency could be expected for 50 hp motors.
4. Phase IV results dissemination will include conference presentations, press releases and report publication on multiple websites.

PHASE I — DESIGN

Performance Targets

The first phase of this project involved design and simulation of the controller performance. However, establishing performance targets is the first step of any design effort. Raser reviewed industry publications and discussed performance needs with Department of Energy and Department of Defense personnel to establish targets that would be appropriate for an advanced motor and drive system. Some of the targets are absolute values and some are relative values when compared to existing, commercially available technologies. Based upon this information, Raser established the performance targets listed in Table 1.

Table 1: FlexMod™ Performance Targets

Parameter	Target
Maximum Drive Power	100 kW
Range of Drive Power	5 kW to 100 kW
Motor Efficiency at Rated Load	95% for 50 kW continuous load
Motor Efficiency Improvement	2% over 50% to 150% full load
System Energy Efficiency Improvement	2% over 25% to 125% load for variable speed systems
Controller Efficiency	>95% for 100 kW Maximum Power
$/kW at Maximum Power	<$20/kW for 100 kW Maximum Power
Power to Weight Ratio	> 5 kW/kg for 100 kW Maximum Power
Power to Volume Ratio	> 5 kW/liter for 100 kW Maximum Power

In addition to the above performance targets, Raser intends for the FlexMod™ controller system to accommodate a variety of different motor types and power ranges while using common hardware components. Therefore, a similar controller design could be used on three phase AC induction motors as well as three phase brushless AC motors, three phase brushless DC motors and brush type DC motors. All of these would be accommodated with the same basic hardware but with software specific to that motor type. Future versions of the controller may also accommodate switched reluctance and permanent magnet motors. Currently, the FlexMod™ controller has only been tested with three phase AC induction motors.

For three phase AC induction motors, the FlexMod™ controller has four control strategies:

- Standard Voltage/Frequency (V/F) control
- V/F control with low speed voltage boost
- Symetron™ torque control with feedback
- Symetron™ velocity control with feedback

Symetron™ is Raser Technologies' control strategy that senses motor characteristics and adjusts control parameters accordingly to maximize performance. The FlexMod™ control strategy is selected through software changes and does not require any hardware modifications.

Electrical and Mechanical Design

After establishing performance targets, Raser engineers proceeded with electrical and mechanical designs of the controller hardware. The design goal was to design a controller with software based algorithms to provide the flexibility to control multiple motor types. The prototype FlexMod™ controller developed for this project used a microprocessor computing core. Production versions will likely use a lower cost digital signal processing core. Beyond the main computing functions, there is minimal external circuitry. Selective feedback signals allow continuous monitoring of the power modules and provide warning of possible overload situations.

The performance that can be achieved is dependent on the software utilized to implement the variable speed drive. In most variable speed drives, a V/F control algorithm is employed. In some cases, a vector control algorithm is used, especially for precise torque control. The FlexMod™ controller can employ any of these control algorithms. However, to get the best system performance, Raser has developed special algorithms and other software to maximize the system efficiency for the motor and application. This is part of the Symetron™ technology.

To keep costs low, designers selected generic control boards and power modules to cover the power ranges for 2.5 to 5 hp, 5 to 20 hp, and 20 to 100 hp. The power modules can be commercially available (such as those made by Semikron) or custom designed by a high performance power system manufacturer. For the prototype FlexMod™ controllers developed for this testing, Raser used custom power modules for the 5 to 20 hp controller and a commercial available module for the 50 hp drive. Both FlexMod™ prototype controllers used a low cost, fully isolated, floating, bipolar gate drive.

The proprietary FlexMod™ power modules feature conventional inverter topology using six IGBTs. Many controller designs try to limit the switching speed of the main power switches to reduce or eliminate the problems commonly associated with fast switching electronics, i.e., current spikes, electromagnetic interference, etc. However, limiting the switching speed and increasing the switching time, increases the power losses during switching. Raser designers chose to operate at a high switching frequency to maximize drive and system efficiency. This higher than typical switching frequency results in near sinusoidal waveforms that also increase overall drive system performance.

Modern generation III and IV IGBTs can operate safely at 18 kHz. Operating at higher frequencies can cause circuit inductance reactions that can generate voltage spikes and damage power devices. Also, the minimum “turn-on” and “turn-off” times published by the manufacturer must be maintained to avoid device failures due to the inductance of the bonded leads inside the power module package. Within these constraints, design of a fast switching, efficient power module focused on the design of the gates and mechanical layout for minimum circuit inductances.

Analysis and Simulation

Raser used both commercially available software and internally developed simulation programs to analyze multiple controller designs. Simulations included not only the power module performance but also the motor and overall drive performance. Primary design iterations focused on switching speed and power module selection. Simulation indicated substantial efficiency gains were possible.

One difficulty encountered during simulation involved the nature of the Symetron algorithms. These algorithms seek to continuously improve the performance at a particular speed and load. Therefore, each operating point requires a separate simulation to determine performance. Raser elected to perform simulations at selected load points to predict overall performance.

PHASE II – FABRICATION

Based on designs developed in Phase I, Raser fabricated several FlexMod™ controllers for testing. These prototypes were assembled at the Raser design center in Utah. Development tests were conducted at Raser and other laboratories. Using knowledge gained from these tests, Raser modified the design and verified the controller performance with both custom and general purpose power modules. These prototypes were briefly tested with some representative motors in the 5 hp to 100 hp range.

To optimize FlexMod™ performance, Raser also performed characterization testing on the motors. Data from this characterization is used by the adaptive optimization algorithms that form the basis of Symetron™.

The particular controller delivered to Advanced Energy for performance verification testing used custom power modules to match the power stage characteristics of the 20 hp ABB drive. The FlexMod™ controller used the same IGBTs as the ABB drive in order to get an "apples to apples" comparison of the Symetron™-based controller to the ABB V/F-based drive. Figure 1 shows the FlexMod™ controller.

Figure 1: FlexMod™ Controller

Based on the prototype design, Raser engineers developed package dimensions that would be appropriate at manufacturing volumes. Raser also estimated the controller weight and calculated other performance parameters as shown in Table 2.

Table 2: FlexMod™ Dimensions

Parameter	Value
Height	17.5 inches
Width	7.5 inches
Length	8.0 inches
Volume	1,050 cubic inches (16.8 liters)
Weight	8.64 kg
Power to Weight Ratio	12 kW/kg for 100 kW Maximum Power
Estimated Weight (Mass Production)	7.0 kg
Power to Weight Ratio (Mass Production)	14 kW/kg for 100 kW Maximum Power
Power to Volume Ratio	5.95 kW/liter

An exterior design drawing for the FlexMod™ controller is included in Appendix I.

The Raser engineering team estimated the mass production costs of the controller assuming more than 10,000 units per year. There are two methods for estimating this cost. One is a bottom-up approach that begins with a bill of materials, estimated prototype costs and a mass production cost reduction factor, and generates a per unit cost. The other method is a top-down approach that begins with an existing, comparable product cost and subtracts margins at each step in the sales process. Values in the table below were estimated by the Raser engineering team.

Table 3: FlexMod™ Estimated Costs: Bottom Up and Top Down

Bottom Up Estimate	Value	Top Down Estimate	Value
Materials	$354	Retail Price	$1,250
Materials Margin	+$177	Distributor Margin	-$290
Labor	+$85	Manufacturer Margin	-$160
Labor Margin	+$85	Volume Discount	-$185
Total	**$702**	**Total**	**$615**

These estimates yield a cost to power ratio of approximately $6 to $7 per kW for a 100kW controller.

PHASE III — TESTING

Introduction

The verification testing phase of the project ran from June 5 through June 15, 2006, at Advanced Energy's motor test lab in Raleigh, N.C. Advanced Energy operates the first motor testing lab in the world to receive accreditation by the National Voluntary Laboratory Accreditation Program (NVLAP) for motor efficiency testing of motors from 1-200 horsepower and above. Since 1991, the lab has conducted more than 2,000 IEEE 112B motor efficiency tests and has provided testing to 20 motor manufacturers to comply with EPACT efficiency testing requirements. The lab is also the only independent motor lab in the nation to be evaluated and accepted under Underwriters Laboratory's Energy Verification Services Laboratory Program.

Table 4: Test Schedule

Date	Motor	Drives
June 5	20 hp	Line Voltage
June 6	20 hp	ABB
June 7	20 hp	ABB
June 8	20 hp	ABB, FlexMod™
June 9	20 hp	ABB, FlexMod™
June 12	20 hp	ABB, FlexMod™
June 13	20 hp	ABB, FlexMod™
June 14	5 hp	Line Voltage, ABB, FlexMod™
June 15	5 hp	ABB, FlexMod™

Equipment Configurations

The diagrams below show the equipment configuration during the testing for both motors. Specifications for the eddy current dynamometer and other test equipment are presented in Appendix II.

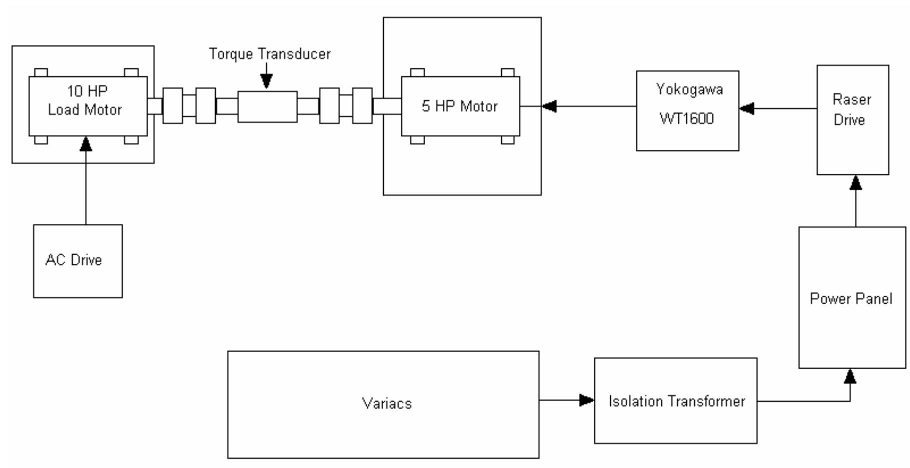


Figure 2: 5 hp Motor Test Configuration

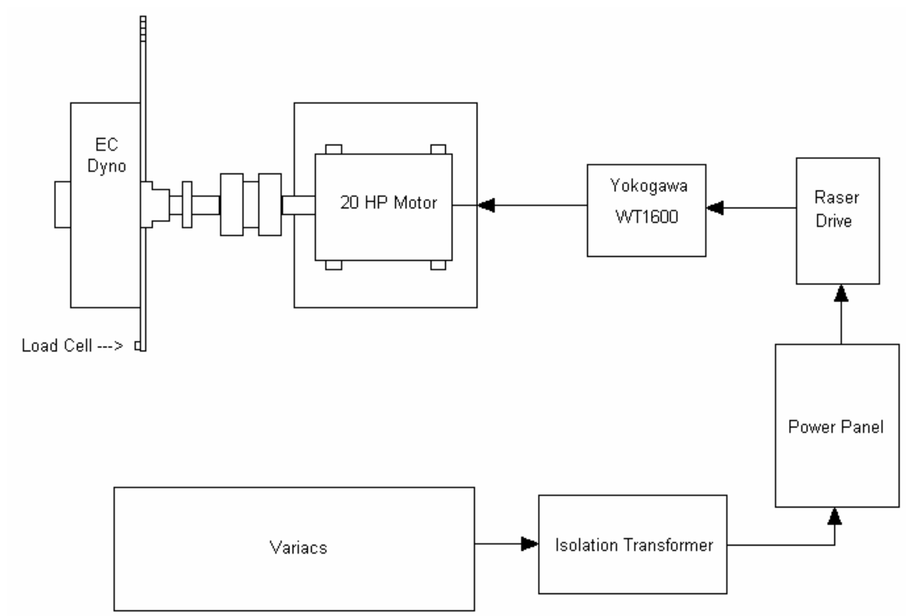


Figure 3: 20 hp Motor Test Configuration

The Yokogawa WT 1600 was used to measure input power to the motor in order to determine motor efficiency. However, these results are not relevant to this project because the emphasis is on system efficiency improvements. This meter had no impact on system efficiency measurements.

Figures 4 through 7 show some of the lab equipment during the testing.

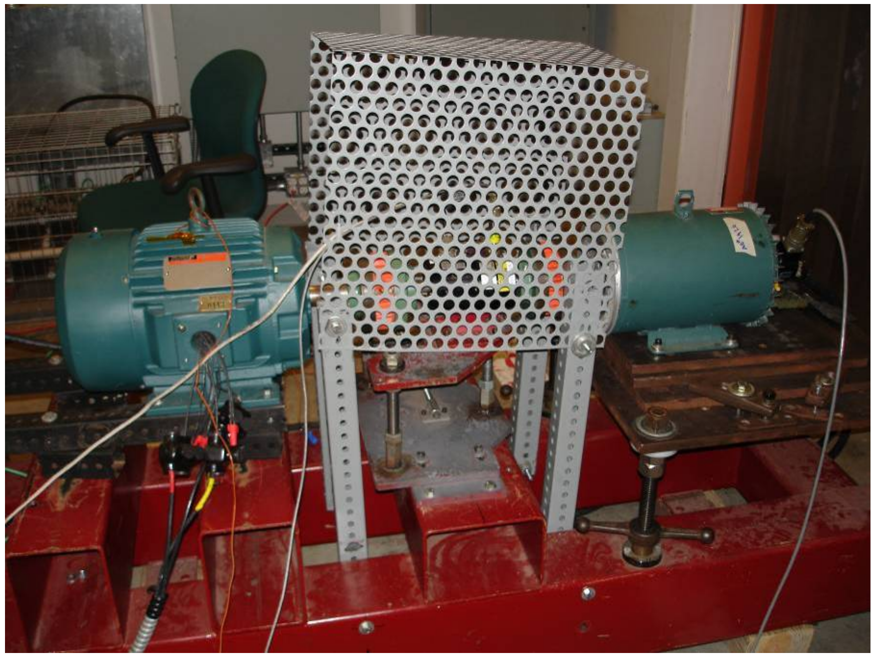


Figure 4: 5 hp Motor on Test Stand

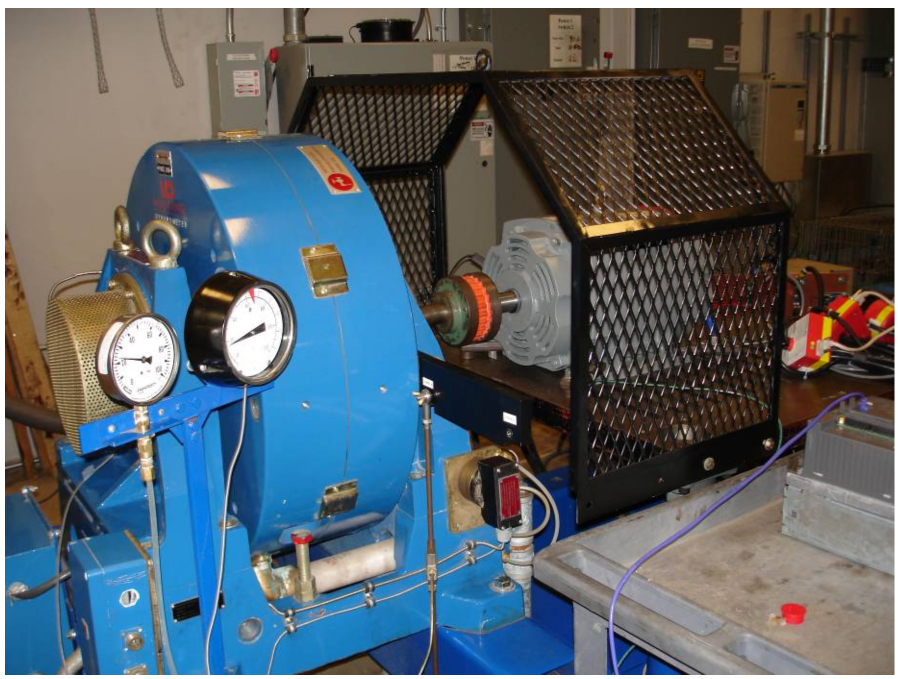


Figure 5: EC Dynamometer with 20 hp Motor

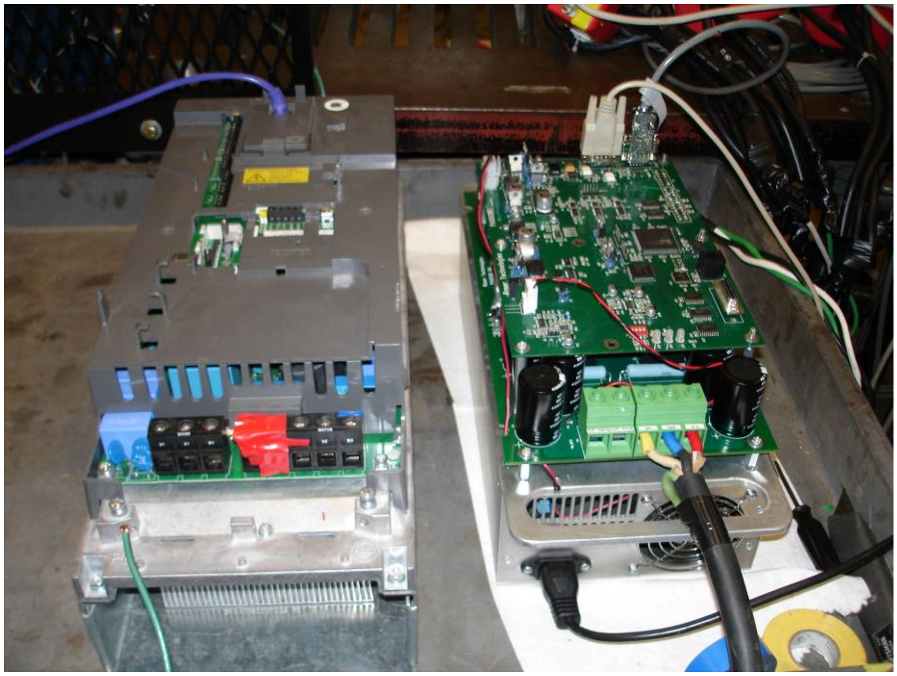


Figure 6: ABB (left) and FlexMod™ Controllers

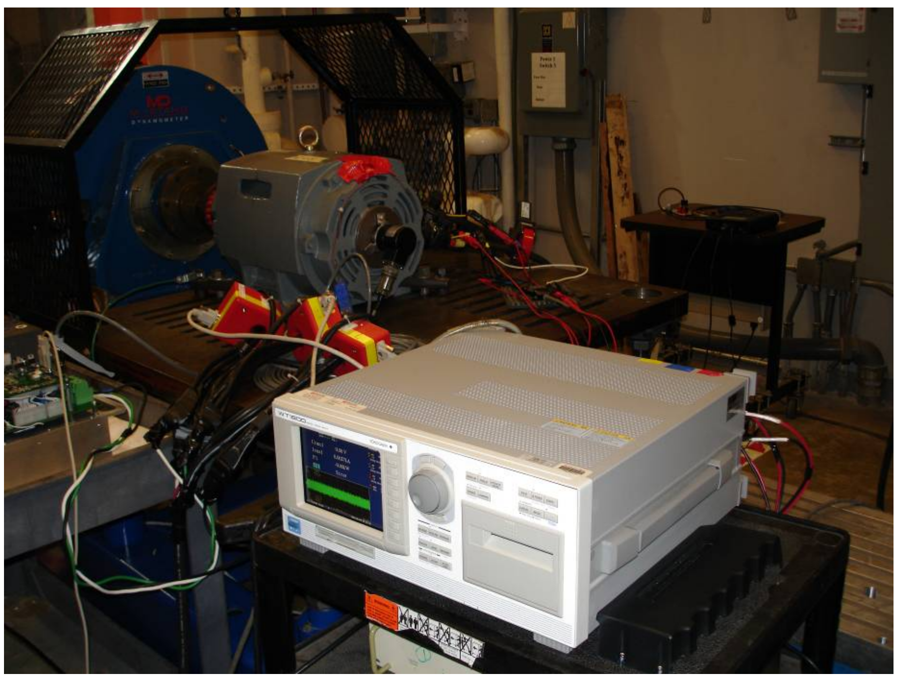


Figure 7: Yokogawa Power Meter

It should be noted that the prototype FlexMod™ controller had cooling fans that were externally powered. According to Raser personnel, these fans only consume 3 watts of power. On the production units, fan operation would be based on the drive temperature. Advanced Energy did not measure this power during the testing, but the impact is considered negligible. The ABB controller cooling fan was powered by the three phase input power to the controller.

Testing Protocol

Raser and Advanced Energy personnel developed the test protocol to collect efficiency data at multiple loads and speeds. The basic protocol consisted of a few simple steps. During the testing there were several deviations in order to allow adjustments to the FlexMod™ software. The basic protocol steps included:

- Monitor winding temperature at fixed speed of 300 rpm to verify thermal stability
- Set motor speed to appropriate value
- Adjust torque level to appropriate value
    - Leeson 5 hp rated torque is 20 Nm
    - GE 20 hp rated torque is 80 Nm
- For the FlexMod™ controller, allow Raser personnel to set software parameters as needed
- Record data including speed, temperatures, torque, input and output power, motor efficiency and system efficiency
- Repeat test for 25%, 50%, 75%, 100% and 125% of rated torque and 300, 600, 900, 1200, 1500 or 1800 rpm

It is important to note that Raser personnel modified software parameters during the testing. The Symetron™ technology involves adaptive tuning to continuously optimize motor and system efficiency for the speed and torque operating point. During the testing at Advanced Energy, the adaptive algorithm or table “calculations” were performed offline and then input to the controller. The algorithm and table data were still being optimized by Raser at the time of the test at Advanced Energy.

Therefore, once Raser personnel were satisfied with the variable settings for a specific load and speed, Advanced Energy would collect the data for that load point. This procedure was followed for all the testing with the FlexMod™ controller. After the testing at Advanced Energy was completed, Raser implemented this adaptive algorithm as an automated process into the FlexMod™ software. However, Advanced Energy did not test any FlexMod™ controllers with the adaptive tuning algorithm incorporated directly, and Advanced Energy did not collect data to confirm the Raser controller performance with that algorithm activated.

Results

Each motor was tested at line voltage, with the ABB controller, and with the FlexMod™ controller. At each load point (i.e., a torque and speed combination), Advanced Energy measured system efficiency. This enabled comparison of the two controllers across a full range of operation. Appendix III contains the summary data sheets for all the tests. Plots of relevant data are shown below.

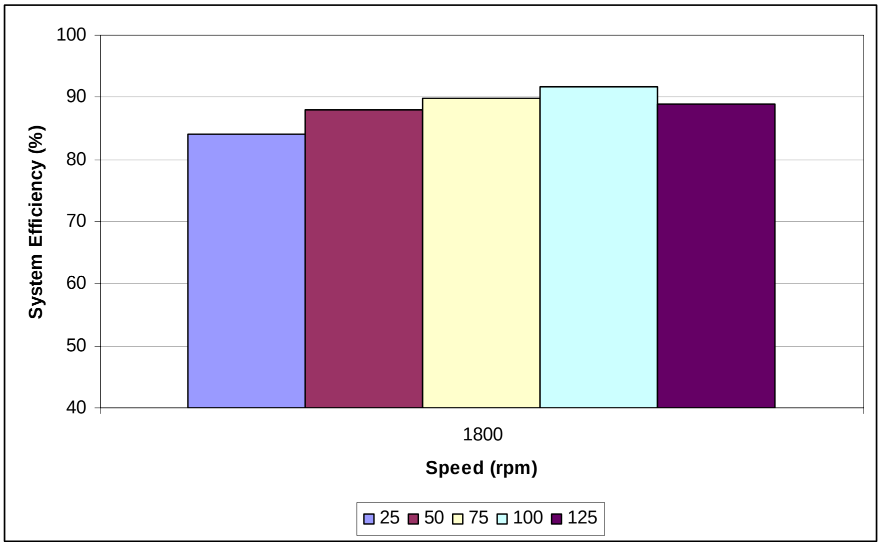


Figure 8: 5 hp Line Voltage Performance

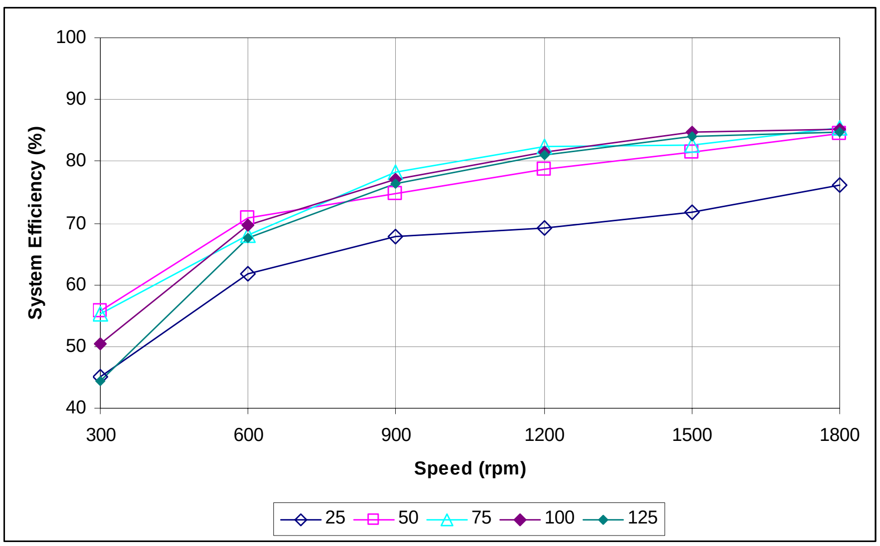


Figure 9: 5 hp ABB Drive Performance

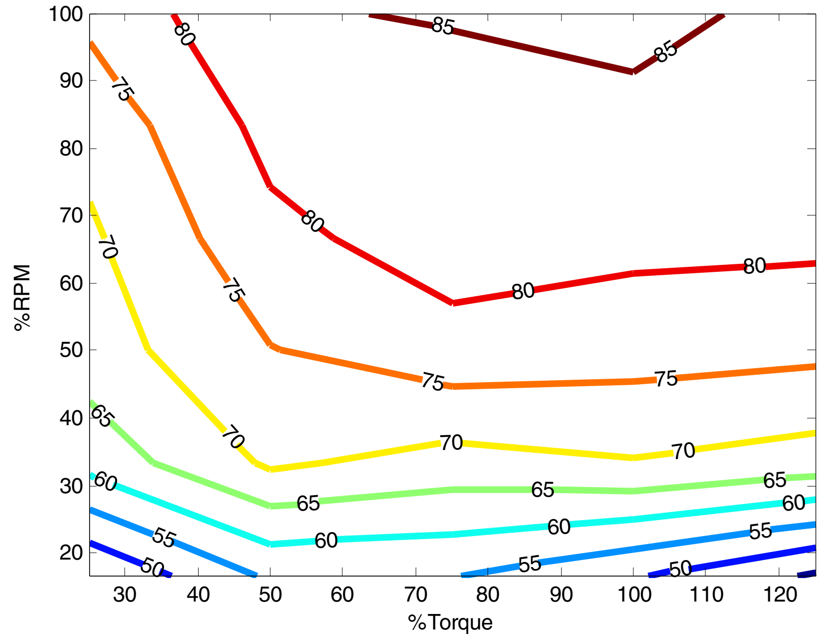


Figure 10: 5 hp ABB Drive Performance (Efficiency Isopleth)

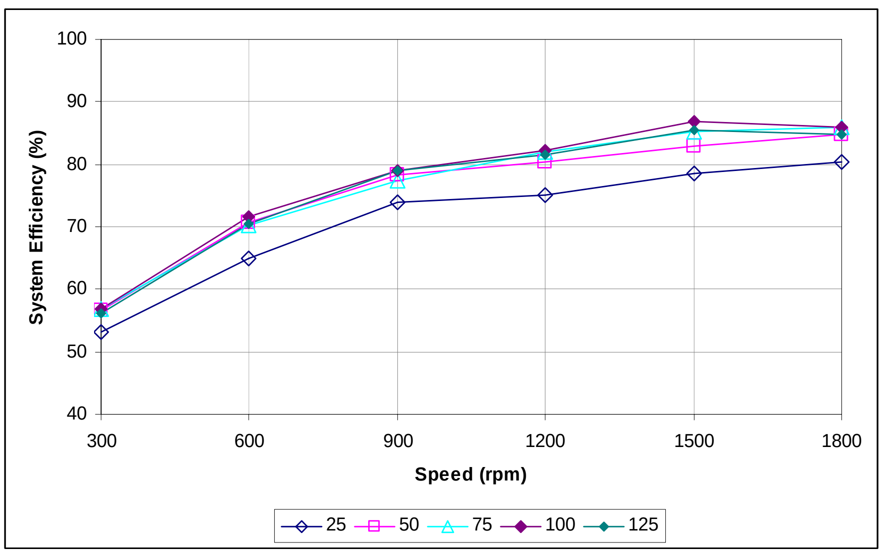


Figure 11: 5 hp FlexMod™ Drive Performance

Figure 15 below compares the ABB drive performance with the FlexMod™ drive performance. For most of the load points, the FlexMod™ drive had a higher system efficiency.

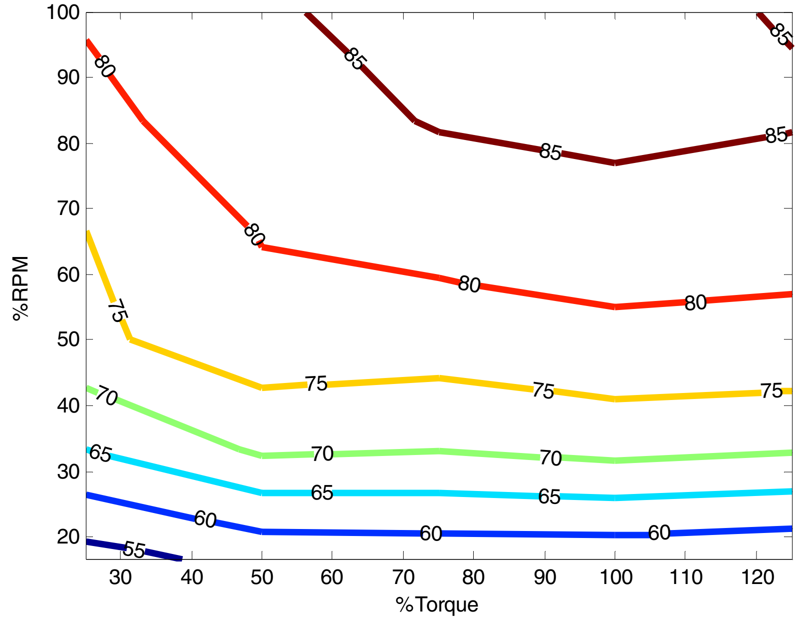


Figure 12: 5 hp FlexMod™ Drive Performance (Efficiency Isopleth)

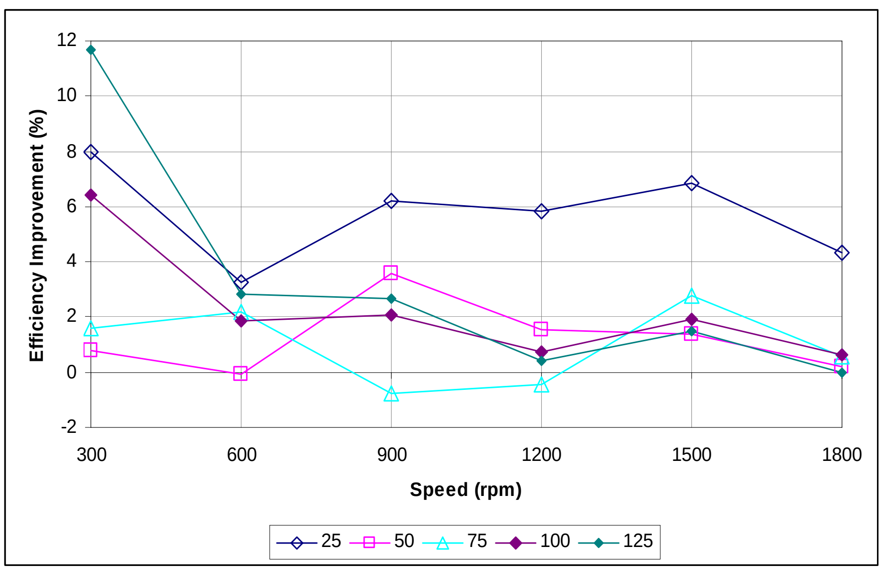


Figure 13: 5 hp FlexMod™ Improvement

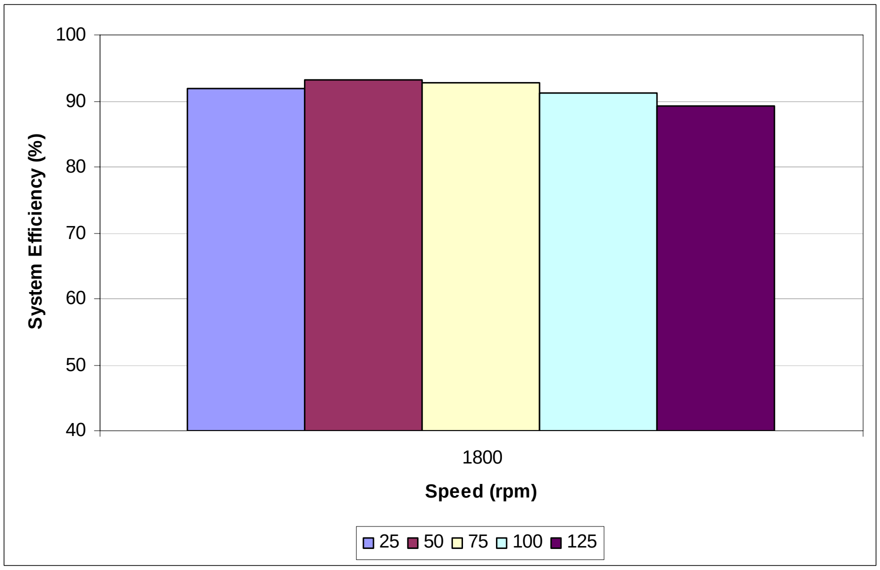


Figure 14: 20 hp Line Voltage Performance

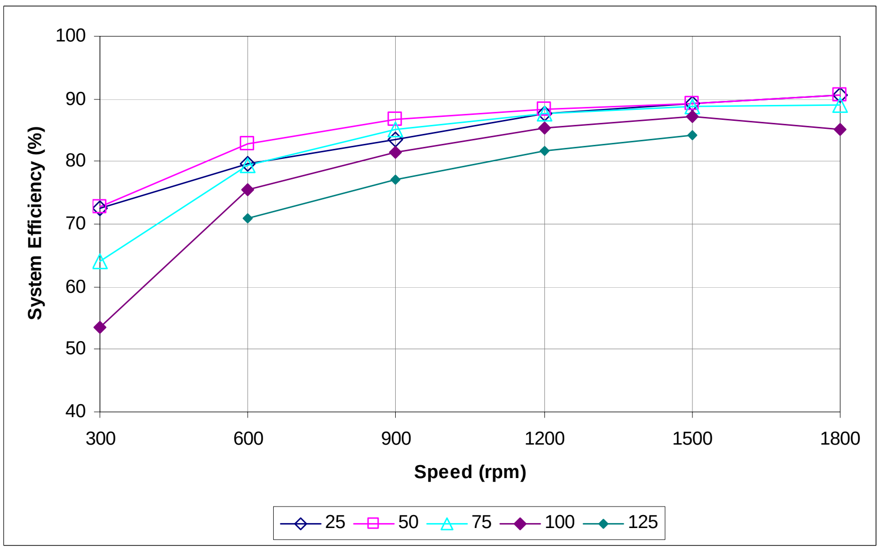


Figure 15: 20 hp ABB Drive Performance

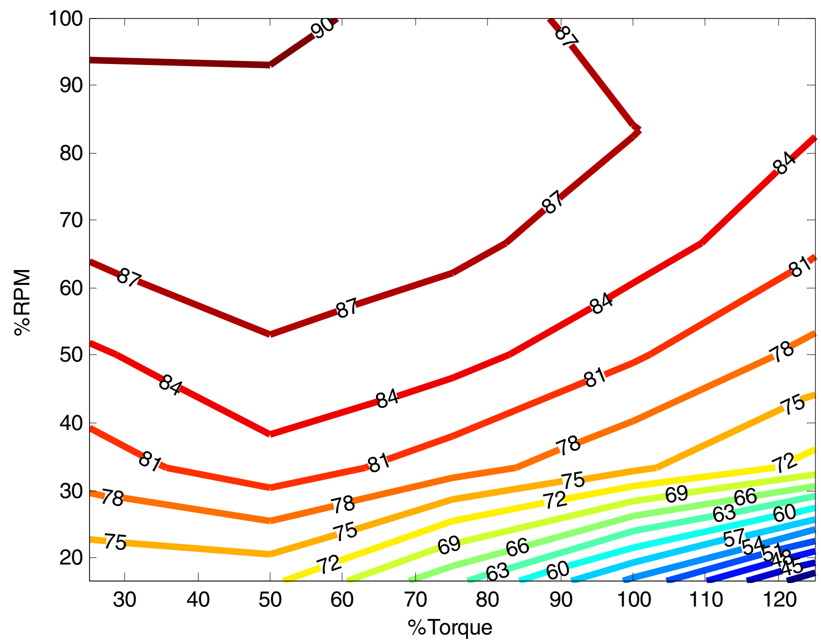


Figure 16: 20 hp ABB Drive Performance (Efficiency Isopleth)

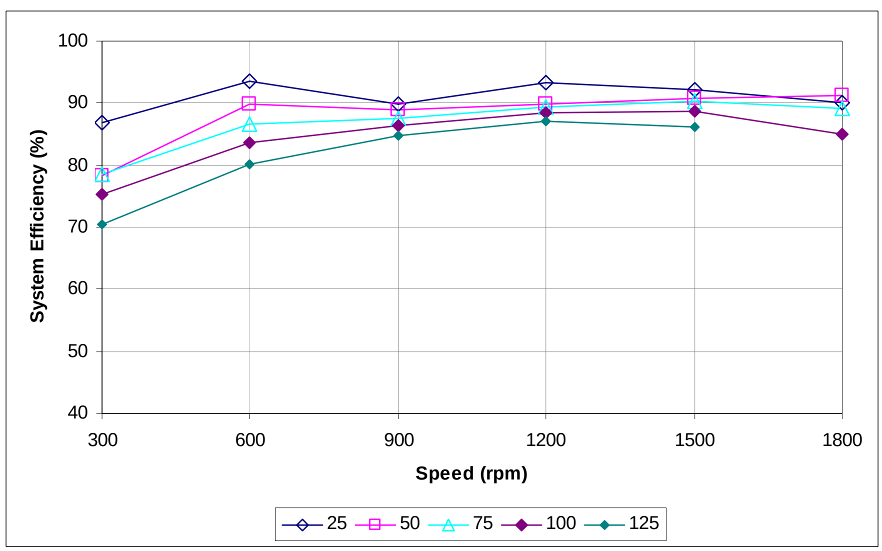


Figure 17: 20 hp FlexMod™ Drive Performance

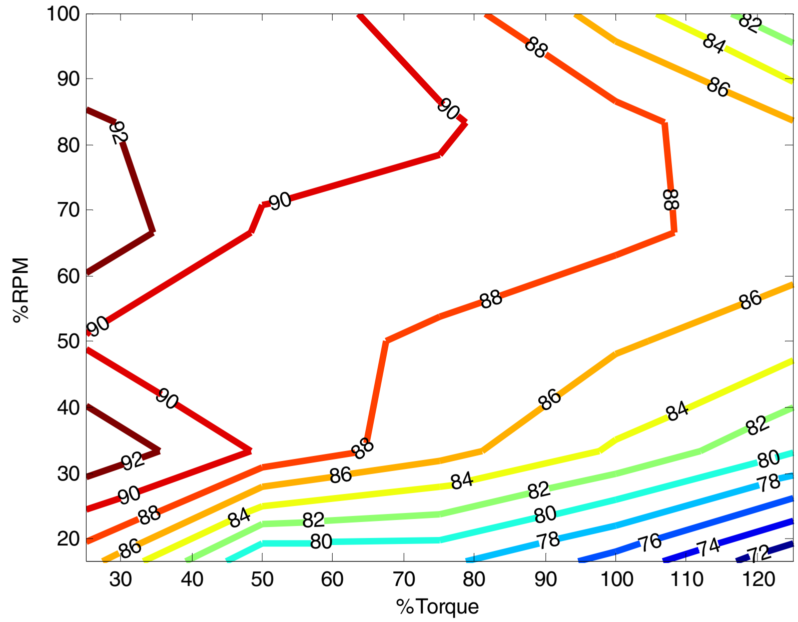


Figure 18: 20 hp FlexMod™ Drive Performance (Efficiency Isopleth)

Note that the charts in figures 15 through 18 do not show data for the 125% load at 1800 rpm for either the ABB drive or the FlexMod™ drive. During the testing, input voltage was held constant at 215 volts AC. At the highest speed and load, the power requirements exceeded the maximum available power to the controllers and neither system could produce the required torque. Therefore, this data is not reported.

Figure 20 below compares the ABB drive performance with the FlexMod™ drive performance for the 20 hp motor. As in the 5 hp data, the FlexMod™ drive had a higher system efficiency for most of the load points.

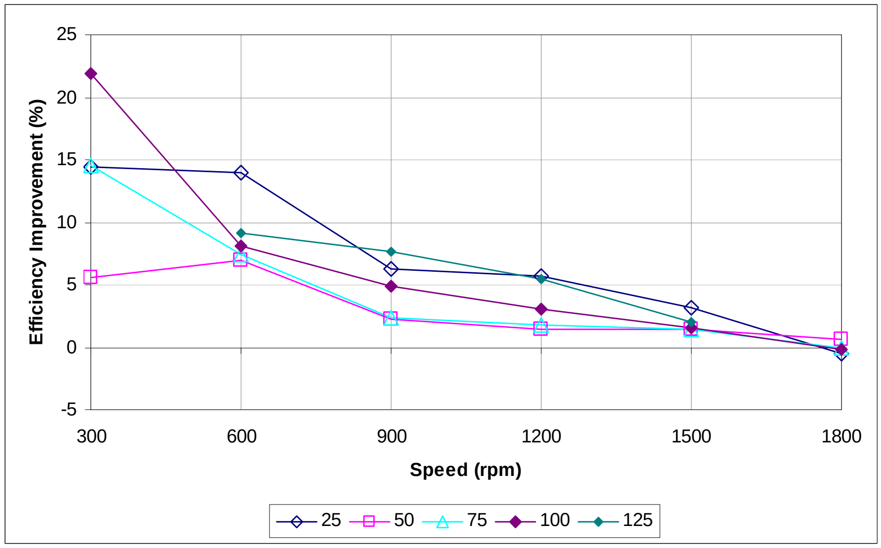


Figure 19: 20 hp FlexMod™ Improvement

Additional Testing

Raser conducted additional testing on a 50 hp motor at their facility. Advanced Energy personnel were not present for this testing. The data is presented here at Raser's request and indicates that the performance improvements seen at the 5 and 20 hp levels continue in the higher power motor. Raser personnel followed a similar testing protocol as was performed at Advanced Energy's lab. The FlexMod™ controller utilized larger power modules for this testing and Raser used a larger ABB drive as the comparable drive.

Plots of relevant data are shown below. Note that 125% load data was not collected for the FlexMod™ controller. Tables of the data are in Appendix IV.

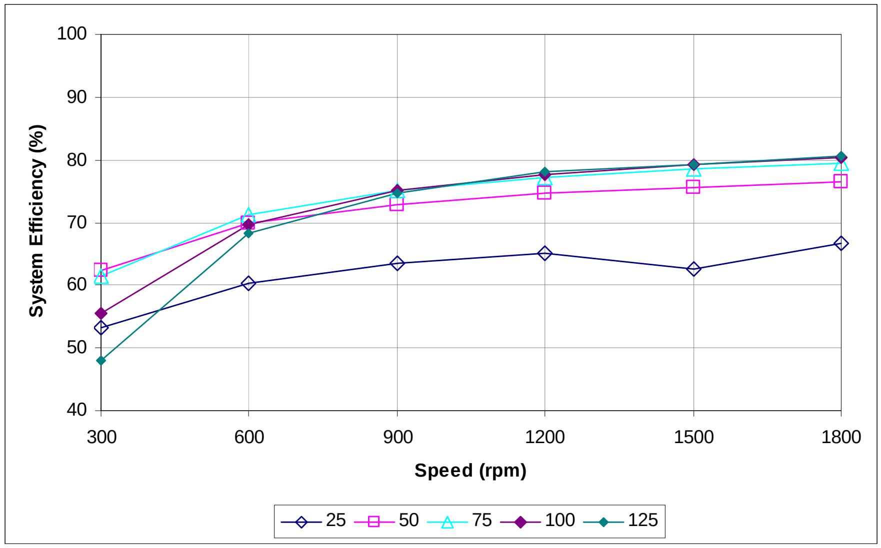


Figure 20: 50 hp ABB Drive Performance

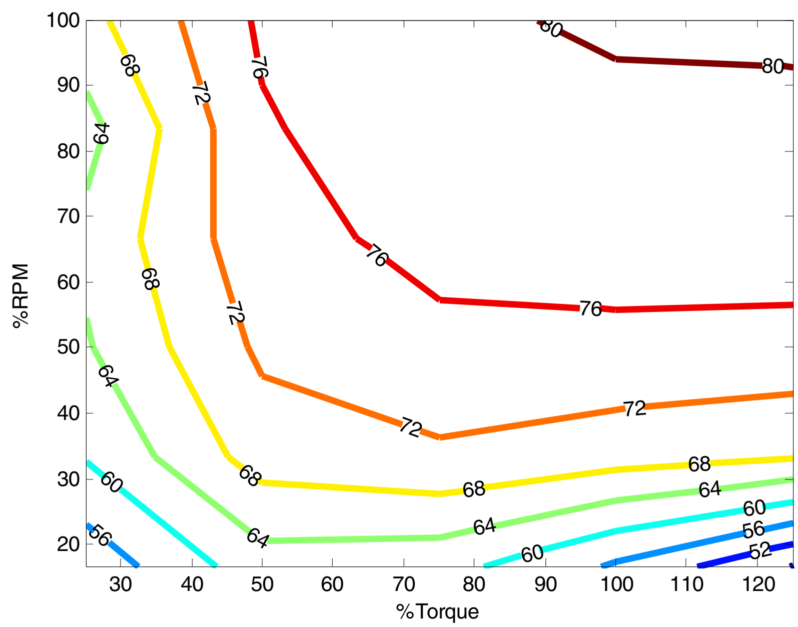


Figure 21: 50 hp ABB Drive Performance (Efficiency Isopleth)

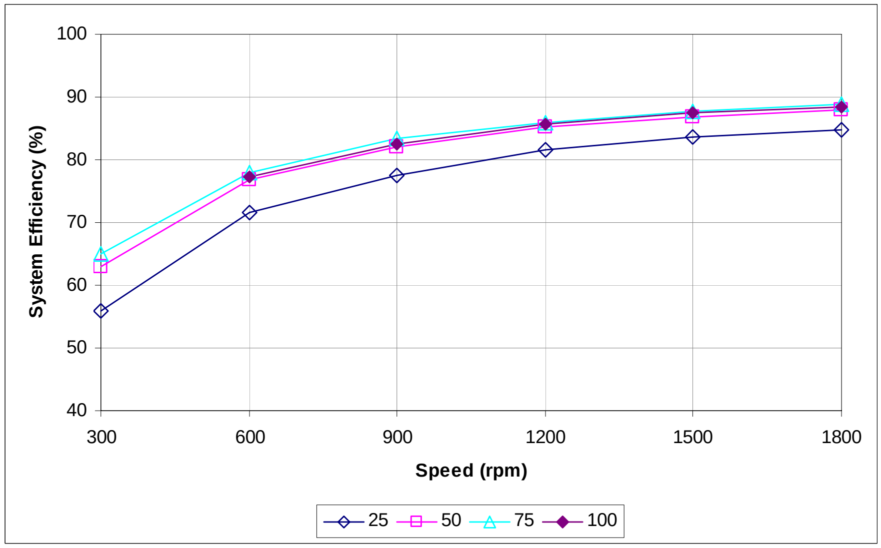


Figure 22: 50 hp FlexMod™ Drive Performance

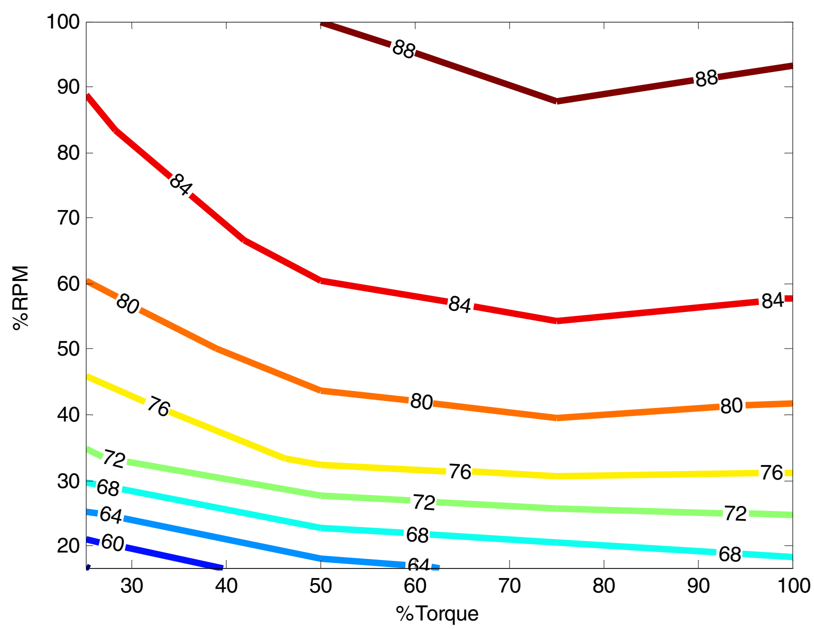


Figure 23: 50 hp FlexMod™ Drive Performance (Efficiency Isopleth)

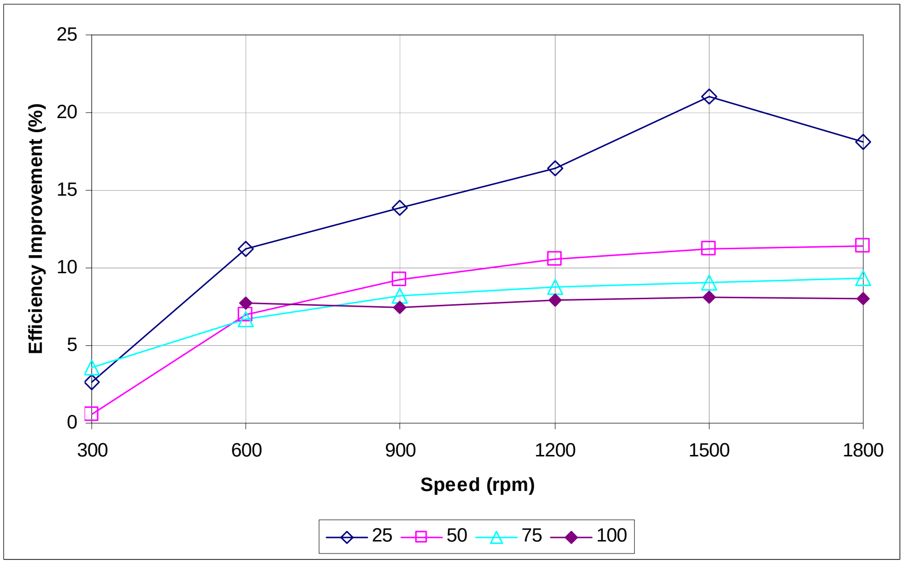


Figure 24: 50 hp FlexMod™ Improvement

PHASE IV —RESULTS AND PUBLICATION

The FlexMod™ controller met the performance targets set in Phase I. Those targets and actual values are shown in Table 5.

Table 5: FlexMod™ Performance

Parameter	Target	Value	Method
Maximum Drive Power	100 kW	37.3 kW	Testing
Range of Drive Power	5 kW to 100 kW	3.7 kW to 37.3 kW	Testing
Motor Efficiency at Rated Load	95% for 50 kW continuous load	Not Measured	
Motor Efficiency Improvement	2% over 50% to 150% full load	Not Measured	
System Energy Efficiency Improvement	2% over 25% to 125% load for variable speed systems	2 to 10% over 25% to 125% load	Testing
Controller Efficiency	>95% for 100 kW Maximum Power	96% to 98%	Testing
$/kW at Maximum Power	<$20/kW for 100 kW Maximum Power	<$7/kW	Simulation
Power to Weight Ratio	> 5 kW/kg for 100 kW Maximum Power	12 kW/kg	Testing
Power to Volume Ratio	> 5 kW/liter for 100 kW Maximum Power	5.95 kW/liter	Testing

This final report documenting the project results will be available through several websites including:

- www.advancedenergy.org/ motors_and_drives
- www.rasertech.com

In addition to being available from the web, the results will be disseminated through conference presentations and table top displays. Currently, there are plans to promote the results at the 2006 Electric Drive Transportation Association Conference and the 2007 Motor and Drive Systems Conference.

Conclusions and Recommendations

1. Electric motors are the dominant consumers of electric energy in the United States. Previous studies have shown that applying variable speed drives can result in significant energy savings for many motor driven systems. However, existing variable speed drives have high initial costs relative to other motor system components.

2. There is a market need for low cost, efficient and modular motor controllers. Such a product could substantially reduce energy consumption in many areas, including industrial motor systems, residential HVAC systems and hybrid vehicles. In addition, a modular platform could reduce industrial motor maintenance costs by providing an inexpensive and standard platform for motor controllers.

3. This project documented the performance and characteristics of the FlexMod™ motor controller. Advanced Energy measured motor system efficiencies for multiple motor sizes at a range of loads and speeds for a FlexMod™ controller and a comparable, commercially available ABB controller. Other estimates indicate that a mass produced version of the controller would meet the stated performance targets of cost and power density.

4. The FlexMod™ controller using Symetron™ technology involves adaptive tuning to continuously optimize motor and system efficiency for the speed and torque operating point. During the testing, the adaptive algorithm or table "calculations" were performed offline and then input to the controller. The algorithm and table data were still being optimized by Raser at the time of the test at Advanced Energy. Future testing should include controllers that have the adaptive tuning algorithm activated.

5. The FlexMod™ controller showed substantial (2% to 10%) increases in system efficiency at various load points when compared to the ABB drive, considered a popular, high end controller in widespread use.

6. A recommended follow-on activity is to provide the results of this study to the electric utility industry and major equipment manufacturers that use electric motors. Such dissemination should encourage these industries to include more efficient motor controllers as part of any energy efficiency programs.

References

1. Energy Information Agency. “Basic Electricity Statistics for 2005.” http://www.eia.doe.gov/neic/quickfacts/quickelectric.html
2. U.S. Department of Energy, Industrial Technologies Program Best Practices. “United States Industrial Motor-Driven Systems Market Assessment” http://www1.eere.energy.gov/industry/bestpractices/us_industrial_motor_assessment.html
3. NEMA Standards Publication MG 1-2003. http://www.nema.org/premiummotors
4. ABI Research. “Consumer Hybrid Vehicles.” http://www.abiresearch.com. Press release dated October 30, 2006.
5. U.S. Department of Energy, Industrial Technologies Program Best Practices. “United States Industrial Motor-Driven Systems Market Assessment” http://www1.eere.energy.gov/industry/bestpractices/us_industrial_motor_assessment.html

Appendices

Appendix I — FlexMod™ Design Drawing

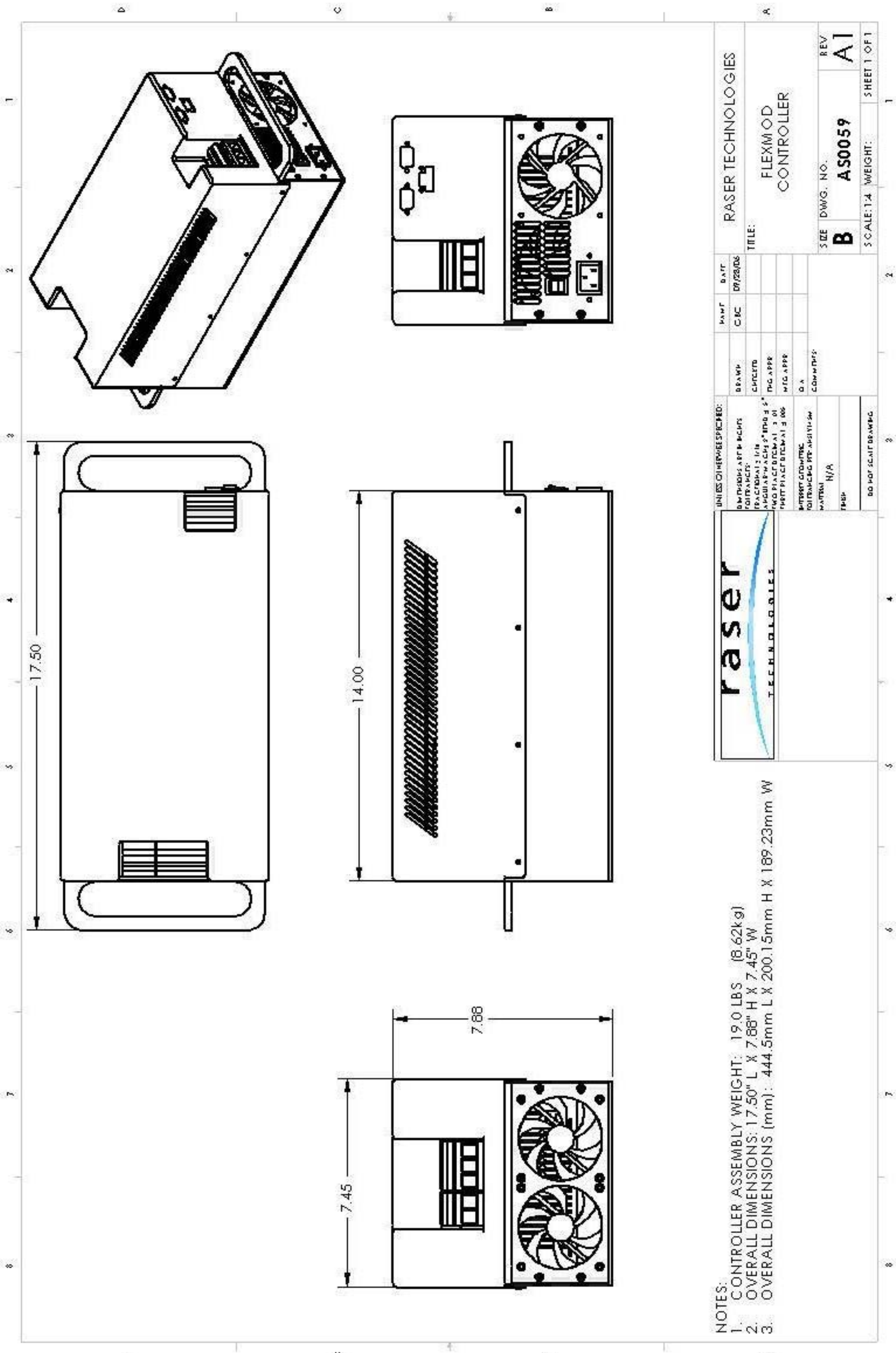
Appendix II — Lab Equipment Specifications

Appendix III — Test Data

- 5 hp Test Data
- 20 hp Test Data

Appendix IV — Raser Test Data

Appendix I — FlexMod™ Design Drawing



Appendix II — Lab Equipment Specifications

- Accredited for motor efficiency testing by the National Voluntary Laboratory Accreditation Program (NVLAP) of the National Institute of Standards and Technology, (Sept. 1996). (NVLAP Code 200081)
- Only independent motor lab in the nation that has been evaluated and accepted under Underwriters Laboratory's Energy Verification Services Laboratory Program

- Single or three-phase closed-loop voltage control, 0-700 VAC, 490 amps continuous at 60 Hz, 200 amps continuous at 50 Hz
- AC Variable Frequency PWM Drives: 1 to 500 hp, 230 to 460 volts

- DC drive: four-quadrant, 125 hp. Armature voltage from 265 to 530 volts at 205 amps. Field voltage from 216 to 432 at 10 amps.
- 36 volt DC battery with 6 hour ratings of 935 Amp-hr or 32 kWh.
- 8 to 248 volt DC battery in 8 volt increments (31 modules)
  - Up to 770 amps, 200 kW peak (1 minute)
  - 10 kW continuous for 8 hours
  - Configurable to provide 100 kW continuous at 240-500 VDC

- Simultaneous acquisition of volts, amps, watts, torque, rpm, temperature and other device outputs on up to 32 single ended (16 differential) analog input channels with 16 bit resolution (±0.0015 percent of full scale) at up to 1 MHz scan rate.
- Additional simultaneous acquisition on 12 channels of voltage (up to 2kv) and / or current (up to 500 A, 0-150 kHz) with true 12 bit resolution (±0.024 percent of full scale) at up to 1 MHz scan rate for accurate capture of waveforms distorted by power semiconductor devices and other short duration transients.
- Digital input/output up to 32 Bits and 10 MHz on 48 channels.
- 4 analog output channels with 16 bit resolution at 1.25 MHz.
-
- True RMS AC or DC Volts (0-700v) and AC Amps (5, 10, 25, 50, 125, 250 and 500 amp ranges) on individual phases to accuracy of ±0.25% of full scale, 0-150 kHz.
- True RMS single or 3 phase power to accuracy of ±0.2% of reading, for 3 or 4 wire delta or wye configuration. Watt ranges available from 300 W to 300 kW.
- DC amperage measurement (10, 300, 600, 900 and 1200A ranges), ±0.3% of full scale
- Dynamometer capabilities
  - Mustang Dry Gap Water Cooled Eddy Current Dynamometer
    - Model MD-DGEC-250
    - 250 kW max power, 8000 rpm max speed
    - Inertia: 0.464 kgm^2
    - Constant torque, high load inertia: 1200 Nm, 330 hp maximum.
  - Variable torque, low load inertia: 0-8000 rpm, 1320 Nm (880 lb-ft), 250 hp maximum (8000-9000 rpm @ 125 hp maximum).
- Shaft power measurement
  - Torque measurement available covering the range 0.5-1100 Nm (0.4-800 lb-ft). Torque measurement accuracy is ±0.2% of full scale. Torque measurement at speeds up to 9000 rpm is available for the range 0.5-560 Nm (0.4-410 lb-ft)
  - Shaft speed measurement, 0-15000 rpm, with accuracy ±0.1 rpm

- ABB controller
  - 20 hp, 59.4 amp continuous, 240/3/60 VFD, NEMA 1, wall-mounted
  - Model No. ACH550-UH-059A

- 5 hp Leeson motor
  - New Leeson Model No: C184T17FK15D
  - Horizontal, 4-pole, TEFC, 1760 rpm, 208-230/460V, 184TC frame
  - 1.15SF, 50/60 Hz, NEMA Premium, Efficiency 89.5, FLA 12.8
  - Serial: CC005A
- 20 hp GE motor
  - New GE model no: 5KE256AC205C
  - Horizontal, 4-pole, ODP, 1750 rpm, 230/460V, 256T frame, inverter-duty
  - 1.15SF, 50/60 Hz, energy efficient, efficiency 91.0, FLA 46.2/23.1
  - Serial: DPH144452043
- 50 hp Baldor motor
  - New Baldor model no: M4115TS
  - Horizontal, 4-pole, TEFC, 1770 rpm, 230/460V, 326TS frame, inverter-duty
  - 1.15SF, 60 Hz, energy efficient, efficiency 93.0, FLA 118/59
  - Serial: C0010060189

Appendix III — Test Data

5hp Test Data

Target Speed	Target Load	Torque		Actual Speed		Av. Line Volts		Av. Line Current		Pin		Amb Temp		Stator Temp		Sync Speed		System eff.	
		Nm		RPM		V		A		W		°C		°C		RPM		%	
RPM	%	ABB	Raser	ABB	Raser	ABB	Raser	ABB	Raser	ABB	Raser	ABB	Raser	ABB	Raser	ABB	Raser	ABB	Raser
300	25	5.13	5.49	301.39	300.83	215.58	215.25	1.61	1.87	359.26	326.06	23.72	23.09	81.59	75.37	312.03	322.13	45.11	53.07
	50	10.09	10.01	297.57	301.13	215.12	215.00	2.36	2.78	563.47	558.09	23.73	23.18	83.15	80.00	324.05	325.75	55.80	56.57
	75	15.19	15.62	298.24	301.04	215.21	215.25	3.33	3.96	858.32	866.67	23.75	23.23	76.05	89.02	344.95	327.08	55.26	56.84
	100	20.61	20.05	301.47	301.04	215.28	215.26	4.76	4.91	1288.17	1110.23	23.73	23.64	91.32	84.52	375.02	329.49	50.52	56.94
	125	24.97	25.13	300.74	300.99	215.32	215.20	6.33	6.03	1771.14	1413.11	23.88	23.77	95.18	91.96	411.33	331.07	44.41	56.06
600	25	5.11	5.28	598.32	601.35	215.22	215.52	2.35	2.48	518.31	510.99	23.52	22.51	80.59	71.05	609.01	620.27	61.78	65.02
	50	10.04	9.82	599.18	597.45	215.35	215.29	3.62	4.07	890.30	869.12	23.82	22.46	81.09	80.18	621.01	618.80	70.77	70.72
	75	15.11	15.21	598.33	601.56	215.60	215.23	4.92	5.79	1390.55	1363.95	23.74	22.73	83.29	86.10	633.01	625.70	68.07	70.27
	100	19.95	19.88	598.12	601.44	215.22	215.54	6.38	7.29	1793.48	1750.61	23.79	22.89	88.49	81.45	648.01	628.15	69.69	71.54
	125	24.96	24.99	598.40	601.54	215.57	215.50	7.97	8.88	2311.81	2233.45	23.74	23.04	94.80	86.40	669.02	631.02	67.67	70.50
900	25	5.33	5.38	899.61	899.87	215.29	215.68	3.10	3.24	741.44	685.83	23.46	22.06	64.14	54.51	909.02	920.89	67.69	73.88
	50	10.09	10.13	898.77	897.99	215.47	215.55	4.73	5.31	1270.09	1216.35	23.53	22.18	66.09	57.74	918.02	922.68	74.80	78.36
	75	15.20	15.32	898.80	902.20	215.60	215.72	6.51	7.46	1828.42	1868.94	23.65	22.36	69.10	63.43	930.01	930.56	78.24	77.47
	100	19.99	20.01	898.64	901.12	215.67	215.52	8.19	9.38	2443.01	2387.66	23.66	22.62	73.84	72.88	942.01	936.37	77.01	79.09
	125	24.96	24.86	898.70	899.49	215.50	215.40	9.86	11.32	3080.38	2968.08	23.77	22.73	84.10	83.89	957.02	940.37	76.26	78.91
1200	25	5.01	5.18	1199.85	1199.15	215.62	215.28	3.61	3.87	911.02	867.93	24.01	24.31	79.92	79.05	1209.02	1221.19	69.17	75.01
	50	10.09	10.07	1198.79	1198.42	215.46	215.14	5.86	6.60	1609.90	1573.86	24.02	24.45	80.05	81.06	1218.03	1222.58	78.72	80.29
	75	15.01	15.03	1199.09	1198.54	215.57	214.00	7.99	9.12	2287.41	2300.85	24.16	24.99	82.47	77.29	1230.03	1229.75	82.42	81.99
	100	20.87	20.73	1201.71	1198.67	215.50	215.57	10.23	11.96	3228.31	3167.93	24.03	25.06	85.17	72.51	1247.37	1236.20	81.38	82.14
	125	24.93	24.89	1197.10	1198.69	215.47	215.19	11.97	14.08	3853.21	3832.97	23.71	24.80	92.90	77.56	1254.02	1250.54	81.11	81.53
1500	25	5.09	4.95	1500.96	1500.27	215.52	215.47	4.23	4.45	1114.81	989.77	24.07	24.58	81.10	79.20	1509.03	1515.72	71.74	78.58
	50	10.20	10.32	1499.41	1500.63	215.15	215.44	6.98	8.05	1964.13	1956.94	24.06	24.78	80.61	77.27	1518.03	1518.62	81.54	82.90
	75	15.18	15.12	1499.18	1501.08	215.51	215.77	9.35	10.78	2887.56	2786.89	24.27	24.67	82.27	81.58	1530.03	1523.70	82.53	85.32
	100	20.34	20.03	1498.12	1500.19	215.56	215.53	11.76	13.60	3762.92	3627.50	24.15	24.56	86.59	85.98	1540.83	1531.17	84.82	86.75
	125	25.37	25.24	1499.35	1501.36	215.52	215.68	14.30	16.61	4746.18	4646.80	23.90	24.60	92.99	88.89	1556.68	1542.58	83.93	85.40
1800	25	5.13	5.06	1799.92	1795.68	215.20	215.54	4.77	5.12	1271.08	1181.89	23.81	24.38	59.62	68.82	1806.07	1812.76	76.15	80.48
	50	10.03	10.22	1799.95	1799.73	215.58	215.57	7.81	9.01	2237.99	2274.74	23.80	24.30	61.74	70.74	1818.04	1818.80	84.48	84.66
	75	15.02	15.09	1799.96	1799.55	215.28	215.78	10.53	12.29	3314.99	3305.90	23.88	24.46	65.19	75.72	1833.04	1828.49	85.43	86.01
	100	20.46	20.05	1799.94	1799.72	215.22	215.52	13.60	15.81	4527.14	4401.68	23.80	24.55	72.55	80.57	1848.04	1844.91	85.20	85.84
	125	25.33	24.94	1797.74	1800.60	215.23	215.33	16.72	19.33	5623.54	5547.34	24.03	24.58	86.03	84.08	1867.68	1861.83	84.80	84.80

Baseline 5hp Test (Line Voltage)

Target Load	Torque		Speed	Power Out	Volts R-B	Volts B-Y	Volts Y-R	Current R	Current B	Current Y	Power In	Amb Temp	Stator Temp	Sync rpm	Motor eff.
%	Nm	ft-lb	RPM	Hp	V	V	V	A	A	A	W	^0C	^0C		
25	5.26	3.88	1794.12	1.33	230.27	230.51	230.56	11.45	11.46	10.87	1177.22	23.84	42.45	1800.26	84.01
50	10.11	7.46	1783.41	2.53	230.73	230.36	230.10	12.26	12.33	11.84	2147.64	23.94	45.12	1799.87	87.94
75	15.09	11.13	1775.32	3.76	230.61	230.20	230.21	13.79	13.83	13.20	3120.10	24.00	48.90	1800.29	89.94
100	19.99	14.74	1767.37	4.96	230.45	230.58	230.95	15.56	15.47	15.19	4038.59	24.06	55.58	1800.23	91.62
125	25.21	18.59	1755.30	6.21	230.20	230.28	230.64	17.76	17.78	17.42	5215.58	24.00	63.32	1799.99	88.85

20hp Test Data

Target Speed	Target Load	Torque		Actual Speed		Av. Line Volts		Av. Line Current		Pin		Amb Temp		Stator Temp		Sync Speed		System eff.	
		Nm		RPM		V		A		W		^0C		^0C		RPM		%	
RPM	%	ABB	Raser	ABB	Raser	ABB	Raser	ABB	Raser	ABB	Raser	ABB	Raser	ABB	Raser	ABB	Raser	ABB	Raser
300	25	19.95	20.04	300.72	300.40	215.60	215.48	3.30	3.91	867.88	725.65	23.28	24.26	44.41	56.35	311.99	**	72.41	86.87
	50	40.10	40.81	300.69	300.91	215.11	215.28	6.25	7.12	1738.35	1644.36	23.31	24.26	44.82	56.30	327.02	320.79	72.65	78.21
	75	60.11	60.01	300.64	299.14	215.77	215.50	9.52	10.27	2959.32	2395.46	23.31	24.16	49.01	59.52	348.08	320.27	63.96	78.49
	100	80.01	80.26	300.54	299.73	214.85	215.57	14.08	13.50	4712.64	3344.77	23.38	24.10	61.26	62.40	380.92	327.61	53.44	75.32
	125	-	100.61	-	300.30	-	215.35	-	17.11	-	4491.92	-	23.99	-	68.58	-	335.75	-	70.45
600	25	20.82	20.82	600.99	601.01	215.19	215.35	5.84	6.54	1646.08	1443.33	22.16	21.98	26.83	44.13	612.02	641.70	79.61	93.59
	50	40.39	40.25	600.97	601.09	215.18	215.59	9.97	11.53	3067.55	2806.00	22.24	21.99	28.31	44.09	621.00	618.25	82.86	89.77
	75	60.73	60.02	597.79	600.72	215.39	215.47	14.28	16.46	4793.71	4225.00	22.40	22.08	32.39	45.23	633.01	625.83	79.32	86.72
	100	80.85	80.17	600.83	600.08	215.16	215.19	19.70	21.53	6731.42	5736.33	22.61	22.19	39.55	48.71	653.26	629.00	75.58	83.73
	125	91.92	100.13	601.82	600.25	215.22	215.20	23.40	26.63	8166.11	7298.00	23.04	22.30	58.37	53.45	672.58	635.35	70.95	80.11
900	25	20.64	20.43	901.54	899.05	215.51	215.69	7.92	8.83	2333.08	2072.83	23.13	23.34	48.07	43.25	912.01	917.33	83.53	89.76
	50	39.87	40.22	900.70	902.70	215.34	215.11	13.15	15.97	4337.92	4135.00	23.23	23.48	46.42	42.73	921.03	919.81	86.70	88.95
	75	60.24	60.69	901.51	897.77	215.42	215.50	19.64	22.77	6673.88	6217.17	23.32	23.57	47.60	44.29	936.01	919.03	85.23	87.59
	100	80.87	80.92	901.67	900.72	215.28	215.26	26.76	29.37	9379.98	8397.33	23.36	23.64	50.65	47.39	951.01	925.25	81.41	86.27
	125	100.11	100.07	900.50	901.59	215.78	215.31	34.79	35.38	12244.92	10521.00	23.47	23.74	59.49	52.07	972.62	931.77	77.11	84.81
1200	25	20.51	20.73	1202.22	1200.52	215.50	215.25	9.60	11.33	2944.01	2790.81	23.70	23.81	46.10	40.52	1212.03	1218.57	87.73	93.38
	50	40.50	40.23	1197.96	1199.73	215.55	215.06	17.01	19.95	5750.78	5631.49	23.76	23.93	44.22	39.88	1218.02	1218.00	88.35	89.76
	75	60.70	59.60	1200.63	1198.75	215.27	215.24	25.03	28.02	8708.45	8366.77	23.89	23.98	45.02	40.73	1233.01	1220.73	87.65	89.44
	100	80.09	80.01	1197.55	1201.56	215.52	215.53	33.69	36.00	11754.94	11380.55	23.99	24.10	48.12	44.22	1245.04	1227.02	85.45	88.47
	125	99.97	100.65	1198.18	1199.97	215.65	215.53	43.47	44.37	15379.99	14530.12	24.07	24.23	54.65	48.96	1263.03	1229.65	81.57	87.06
1500	25	20.94	20.60	1501.94	1501.86	215.08	215.59	11.43	13.65	3696.12	3512.15	23.49	22.20	37.56	34.21	1512.05	1519.00	89.12	92.26
	50	40.81	39.95	1502.19	1498.36	215.67	215.24	20.59	24.22	7192.05	6908.31	23.60	22.26	36.20	34.03	1521.03	1519.86	89.28	90.75
	75	60.73	59.90	1502.62	1498.67	215.51	215.57	30.69	33.85	10768.17	10419.47	23.69	22.37	37.56	35.60	1533.03	1524.25	88.76	90.23
	100	80.60	79.98	1501.21	1501.15	215.64	215.54	40.98	43.30	14548.01	14175.86	23.84	22.56	41.68	40.38	1545.04	1537.24	87.10	88.71
	125	100.73	99.83	1500.87	1496.11	215.82	215.06	53.15	54.16	18820.65	18158.39	24.03	22.81	49.35	48.34	1563.03	1547.19	84.13	86.14
1800	25	20.79	20.46	1802.08	1799.43	215.68	215.39	13.13	15.73	4335.74	4283.28	23.98	22.97	39.61	34.75	1812.04	1819.27	90.52	90.01
	50	40.72	40.61	1802.85	1800.70	215.29	215.57	24.35	28.18	8492.16	8402.71	24.05	23.18	38.56	35.13	1826.94	1827.31	90.53	91.15
	75	60.00	60.41	1799.86	1800.81	215.75	215.59	35.92	39.73	12694.19	12793.80	24.20	23.33	40.38	37.93	1839.01	1839.08	89.10	89.05
	100	80.89	80.45	1799.13	1802.12	215.42	215.69	50.62	53.55	17886.49	17850.46	24.38	23.39	44.63	45.46	1863.03	1870.36	85.22	85.07
	125	82.09	91.81	1801.81	1798.48	215.73	215.66	51.63	63.55	18234.38	21504.76	24.56	23.64	52.00	60.66	1871.24	1899.37	84.95	80.41

Baseline 20hp Test (Line Voltage)

Target Load	Torque		Speed	Power Out	Volts R-B	Volts B-Y	Volts Y-R	Current R	Current B	Current Y	Power In	Amb Temp	Stator Temp	Sync rpm	Motor eff.
%	Nm	ft-lb	RPM	Hp	V	V	V	A	A	A	W	^0C	^0C		
25	20.93	15.44	1790.73	5.26	214.97	215.07	214.75	16.95	17.84	16.84	4276.43	23.05	28.49	1800.01	91.79
50	40.89	30.16	1778.94	10.22	215.01	215.00	215.20	26.70	27.17	26.34	8177.55	23.22	29.93	1800.02	93.15
75	59.93	44.21	1768.99	14.89	215.40	215.09	215.00	36.99	38.15	36.77	11985.59	23.36	32.84	1800.38	92.65
100	80.60	59.45	1752.87	19.84	215.09	215.13	215.05	49.71	50.51	49.67	16229.70	23.56	38.98	1799.88	91.17
125	99.95	73.72	1731.27	24.30	215.02	215.16	215.19	62.74	63.26	62.70	20302.00	23.75	49.69	1799.80	89.27

Appendix IV — Raser Test Data

System Efficiency at Speed and Load Points

ABB Data		% Full Load				
		25	**50**	**75**	**100**	**125**
Speed	**300**	53.30	62.30	61.50	55.50	47.90
	600	60.30	69.80	71.30	69.60	68.30
	900	63.60	72.80	75.10	75.10	74.70
	1200	65.10	74.60	77.20	77.70	78.00
	1500	62.60	75.60	78.60	79.30	79.20
	1800	66.70	76.60	79.50	80.40	80.60

Raser Data		% Full Load				
		25	**50**	**75**	**100**	**125**
Speed	**300**	55.90	62.90	65.10		
	600	71.50	76.80	78.00	77.30	
	900	77.50	82.00	83.30	82.60	
	1200	81.50	85.20	86.00	85.60	
	1500	83.60	86.80	87.70	87.40	
	1800	84.80	88.00	88.80	88.40	