U.S. Department of Energy
FreedomCAR and Vehicle Technologies, EE-2G
1000 Independence Avenue, S.W.
Washington, D.C. 20585-0121

FY 2005

TESTING OF THE SEMIKRON VALIDATION AIPM UNIT AT THE OAK RIDGE NATIONAL LABORATORY — JANUARY 2005

Prepared by:

Oak Ridge National Laboratory

Mitch Olszewski, Program Manager

Submitted to:

Energy Efficiency and Renewable Energy
FreedomCAR and Vehicle Technologies
Vehicle Systems Team

Susan A. Rogers, Technology Development Manager

March 2005

OAK RIDGE NATIONAL LABORATORY

MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

ORNL/TM-2005/44

Engineering Science & Technology Division

TESTING OF THE SEMIKRON VALIDATION AIPM UNIT AT THE OAK RIDGE NATIONAL LABORATORY JANUARY 2005

S. C. Nelson
C. W. Ayers

Publication Date: March 2005

Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831
managed by
UT-BATTELLE, LLC
for the
U.S. DEPARTMENT OF ENERGY
Under contract DE-AC05-00OR22725

UT-BATTELLE

ORNL-27 (4-00)

TABLE CONTENTS

LIST OF FIGURES

LIST OF TABLES

PURPOSE

This report documents the electrical tests performed on the Semikron high-voltage automotive integrated power module (AIPM) at the Oak Ridge National Laboratory (ORNL). Testing was performed with an inductive/resistive load and with a motor load at the National Transportation Research Center (NTRC) during the second quarter of FY 2005.

DESCRIPTION OF THE AIPM UNIT

The Semikron inverter (Serial Number 0430 129-AD) is a validation unit developed for hybrid electric vehicle (HEV) traction drive applications. The AIPM was designed to operate with a nominal dc link voltage of 325 Vdc with a minimum and maximum dc link voltage of 200 and 450 Vdc, respectively. The inverter has been constructed with 600-V, 400-A insulated gate bipolar transistors (IGBTs). The unit utilizes a CAN interface for communications and has integrated current sensors. The unit has over-current, over-voltage, and over-temperature protection. The inverter is liquid cooled with coolant flow rate of 10 L/min.

The unit weighs approximately 17 lbs (7.7 kg). The unit is roughly rectangular in shape, but has irregular dimensions. The maximum length, including mounting flanges and hose connections, is 17.6 in. (449 mm). Excluding the mounting flanges and hose connections, the unit measures 16.1 in. (410 mm). The maximum width of the unit is 8.2 in. (210 mm) and the minimal width is 7.2 in. (185 mm). The maximum height of the unit is about 4 in. (100 mm). The volume of the unit is approximately 6.9 liters.

DESCRIPTION OF TESTS

The AIPM unit was visually inspected, measured, and weighed after the unit arrived at ORNL (January 2005). The isolation between the input and output terminals (i.e., dc link and phase voltage terminals) was checked with a digital volt meter prior to the testing. The minimal isolation was greater than 1 Mohm.

The unit was tested per the AIPM test plan (see Appendix A). The AIPM specification is contained in Appendix B. The equipment used in the testing is listed in Appendix C.

Inductive Load Testing

The initial testing of the inverter was performed in the Power Electronics' laboratory, room L101, of the NTRC building with an inductive/resistive load. The load was connected in a Y-arrangement with an inductor and a resistor connected in series for each leg. Figure 1 shows a top view of the Semikron AIPM unit being load tested. Figure 2 shows the notebook computer used to run the control software, the Yokogawa power meter, and the power supply for the Semikron controller. The Semikron inverter is in the background in Fig. 2. Figure 3 shows a more detailed view of the CAN bus display (graphical user interface). Figures 4 and 5 show the inductive and resistive load banks. Figure 6 shows the coolant temperature controller, and Fig. 7 shows the dc power supply.

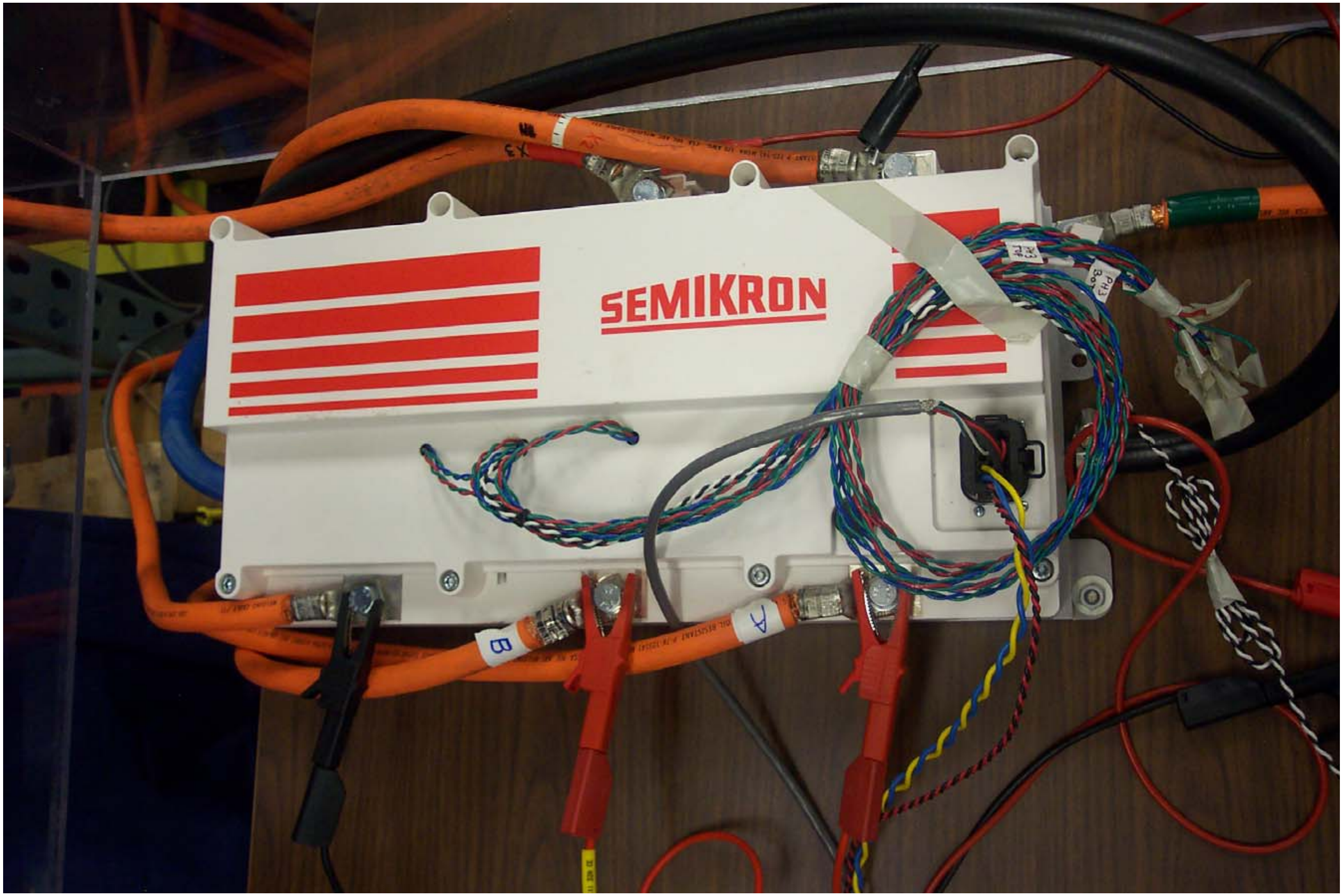


Fig. 1. Top view of Semikron AIPM unit.

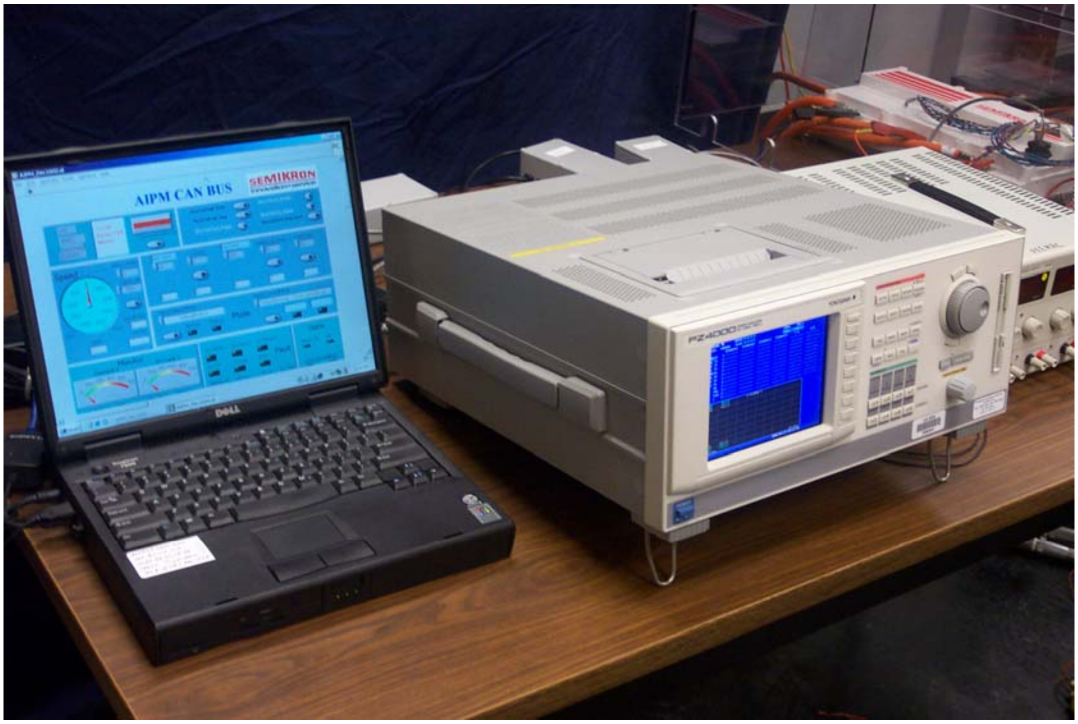


Fig. 2. Control computer, power meter, power supply, and Semikron unit.

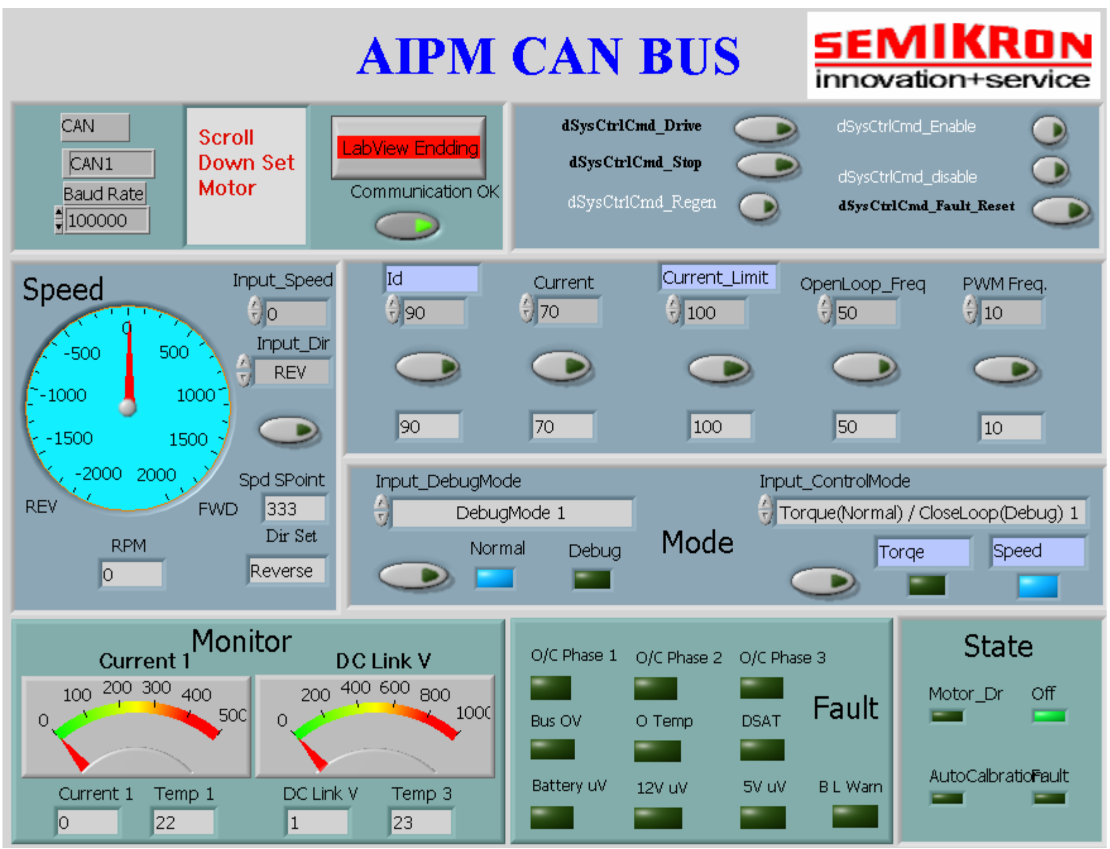


Fig. 3. CAN bus display.

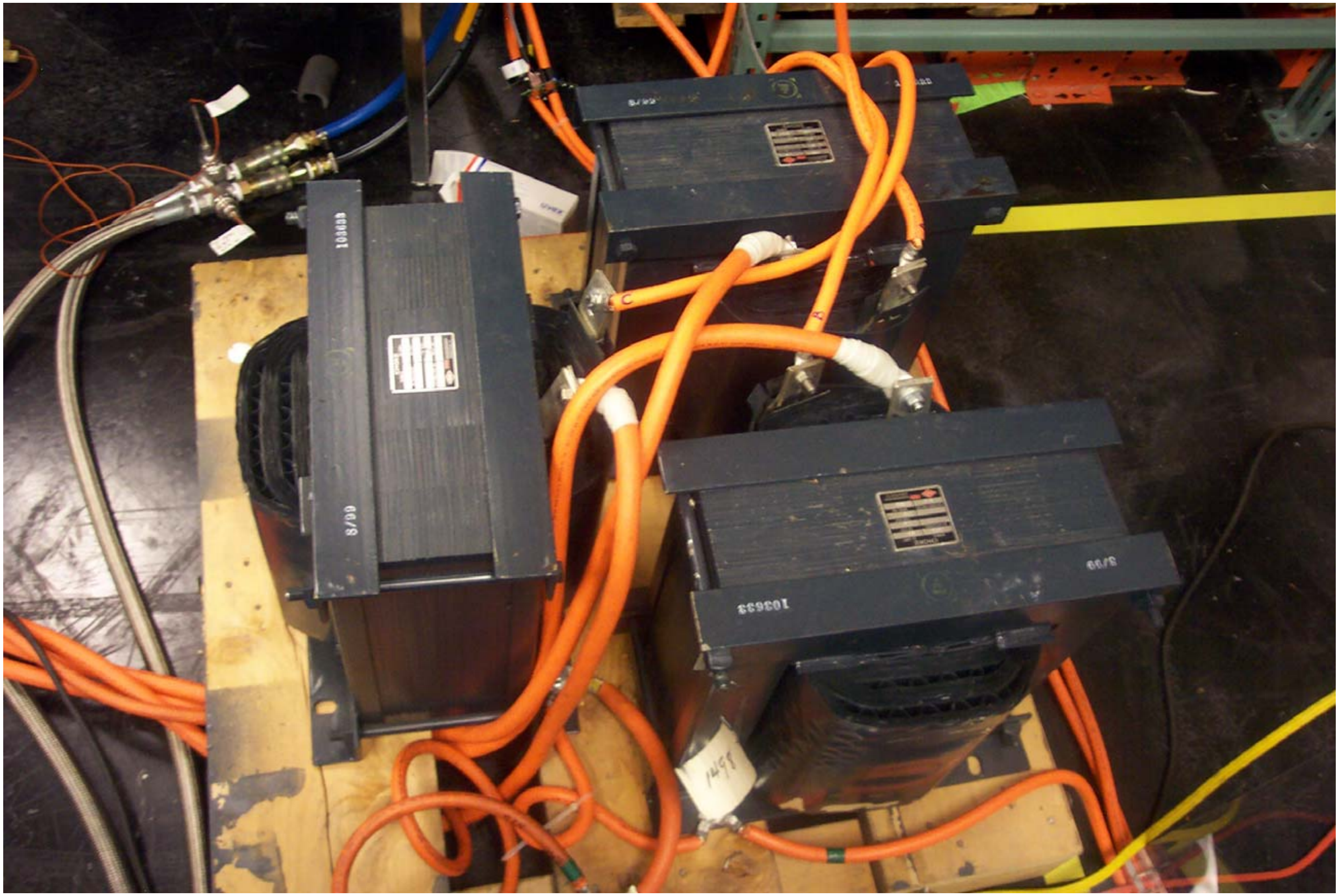


Fig. 4. Inductor load bank.

Fig. 5. Resistor load bank.

Fig. 6. Coolant temperature controller.

Fig. 7. DC power supply.

Table 1 lists the test results when the inverter was operated at 50 Hz at six different power levels with a 200 Vdc link for short duration testing. The unit was operated at each test point for about one minute with 20ºC coolant at a flow rate of 2.5 gpm. The average efficiency for the six data points is 0.966, and the efficiency increased with increased power levels.

Table 1. Short duration testing of Semikron inverter with 200 Vdc link

dc link (Vdc)	Freq (Hz)	Idc (A)	Vac (V_{LL})	Iac (A_{rms})	Pin (kW)	Pout (kW)	Effic.	Cool. (°C)	Flow (gpm)
200	50	7.5	87.5	24.9	1.51	1.43	0.947	20	2.5
200	50	16.5	106.3	34.0	3.3	3.15	0.955	20	2.5
200	50	28.1	123.1	43.3	5.71	5.54	0.970	20	2.5
200	50	43.3	137.0	53.6	8.79	8.56	0.974	20	2.5
200	50	61.5	149.4	64.5	12.46	12.14	0.974	20	2.5
200	50	74.9	156.8	70.8	15.13	14.8	0.978	20	2.5

Table 2 displays the test results when the inverter was operated with a 250 Vdc link for short duration testing with 20ºC coolant with a 2.5 gpm flow. The unit had an average efficiency of 0.962 when operated with an output frequency of 10 Hz at seven different power levels. The inverter had an average efficiency of 0.976 when operated at five different output frequencies (i.e., 10, 20, 30, 50, and 60 Hz) with a requested dc link current of 80 A. The average efficiency during the load testing with a 250 Vdc link was 0.968.

Table 2. Short duration testing of Semikron inverter with 250 Vdc link

dc link (Vdc)	Freq (Hz)	Idc (A)	Vac (V_{LL})	Iac (A_{rms})	Pin (kW)	Pout (kW)	Effic.	Cool. (°C)	Flow (gpm)
250	10	6.09	94.18	22.7	1.53	1.44	0.941	20	2.5
250	10	13.19	114	33.7	3.3	3.13	0.948	20	2.5
250	10	22.99	131.3	44.4	5.75	5.54	0.963	20	2.5
250	10	35.19	146	54.2	8.79	8.5	0.967	20	2.5
250	10	50.32	159.4	64.0	12.56	12.21	0.972	20	2.5
250	10	67.62	171.7	74.0	16.88	16.45	0.975	20	2.5
250	10	89.51	183.6	84.8	22.35	21.61	0.967	20	2.5
250	20	89.99	184.9	85.5	22.47	21.84	0.972	20	2.5
250	30	90.7	107.5	86.4	22.66	22.28	0.983	20	2.5
250	50	87.08	190.4	84.7	21.71	21.21	0.977	20	2.5
250	60	86.56	194.6	84.7	21.67	21.26	0.981	20	2.5

Table 3 shows the test results when the unit was operated with a 400 and 450 Vdc link for short duration testing. With a 400 Vdc link, the unit was operated with an output frequency of 10 and 50 Hz with the same requested output current. The unit had a higher efficiency (0.986) when operated at 50 Hz. The unit was tested with a 450 Vdc link with an output frequency of 10, 50, and 70 Hz and the same requested output current. The inverter's efficiency exceeded the efficiency goal (i.e., 0.97) at 50 and 70 Hz, but was below specification at 10 Hz (0.939).

Table 3. Short duration testing of Semikron inverter with 400 and 450 Vdc link

dc link (Vdc)	Freq (Hz)	Idc (A)	Vac (V_{LL})	Iac (A_{rms})	Pin (kW)	Pout (kW)	Effic.	Cool. (°C)	Flow (gpm)
400	10	35.6	294.7	37.7	14.22	13.95	0.981	20	2.5
400	50	35.8	295.9	36.7	14.3	14.1	0.986	20	2.5
450	10	40.5	331.6	40.5	18.34	17.22	0.939	20	2.5
450	50	40.9	335.4	41.4	18.53	18.09	0.976	20	2.5
450	70	45.5	337.1	42.5	18.66	18.36	0.984	20	2.5

Table 4 displays the results when the unit was operated with a 325 Vdc link for short duration testing with 70ºC coolant and a flow rate of 2.5 gpm. The unit was operated at output frequencies of 10, 20, 50, 75, and 100 Hz with the same requested dc link current of 20, 40, 60, 80, and 100 A during the test. The Semikron inverter demonstrated efficiencies near or above the target efficiency (i.e., 0.97) when operated at a reasonable load. In general, the higher efficiencies were demonstrated when the unit was operated with an output frequency of 20 Hz. Figure 10 plots efficiency vs. output power for the inverter based on the test results in Table 4.

The inverter was tested at continuous output power levels (i.e, 30 kW) for 60 minutes with 70ºC coolant with a flow rate of 2.5 gpm. Table 5 displays test data from the continuous power test. Figure 8 shows the test data from the power meter and the current waveforms for the inverter. The inverter operated with an efficiency of 0.972 at the end of the 60 minute test. Phase A, phase B, and the dc link currents are displayed in the plot of Fig. 8. Note that the two-wattmeter method was used to measure the inverter's output per Blondel's theorem. Element 1 is measuring the input, and elements 2 and 3 are measuring the output of phases A and B. Element 4 is not being used in the test. Sum A and B are the summation of the dc input and the output of the inverter, respectively.

The inverter was operated at power levels greater than the continuous power level for short durations with 70ºC coolant. The inverter demonstrated a peak power capability of 57.7 kW with an efficiency of 0.976 when operated with a dc link of 400 V. The inverter produced 38.6 and 41.2 kW of output power when operated with a 325 and 335 Vdc link. Table 6 summarizes the test results for short duration testing at power levels greater than 30 kW. Figure 9 shows the test data from the power meter and the current waveforms at peak power. The inverter's input and output power was 59.17 and 57.74 kW for an efficiency of 0.976.

Table 4. Short duration testing of Semikron inverter with 325 Vdc link

dc link (Vdc)	Freq (Hz)	Idc (A)	Vac (V_{LL})	Iac (A_{rms})	Pin (kW)	Pout (kW)	Effic.	Cool. (°C)	Flow (gpm)
325	10	5.4	108.2	27.0	1.8	1.6	0.892	70	2.5
325	10	18.6	150.3	45.5	6.0	5.7	0.944	70	2.5
325	10	40.1	182.4	65.2	13.0	12.4	0.957	70	2.5
325	10	69.4	209.6	85.3	22.5	21.8	0.971	70	2.5
325	10	104.4	232.6	104.0	33.7	32.8	0.973	70	2.5
325	20	5.5	107.9	27.7	1.8	1.6	0.898	70	2.5
325	20	18.7	150.3	45.9	6.0	5.8	0.957	70	2.5
325	20	39.37	183.8	65.1	12.81	12.4	0.968	70	2.5
325	20	69.7	210.1	85.7	22.4	22.0	0.983	70	2.5
325	20	104.7	232.9	104.1	33.7	32.9	0.976	70	2.5
325	50	5.1	110.9	26.9	1.6	1.5	0.909	70	2.5
325	50	18.2	155.6	45.4	5.9	5.6	0.956	70	2.5
325	50	39.8	188.9	65.3	12.8	12.3	0.964	70	2.5
325	50	69.3	217.6	85.3	22.3	21.6	0.969	70	2.5
325	50	105.9	242.2	105.5	34.0	33.2	0.976	70	2.5
325	75	5.2	110.8	27.2	1.7	1.5	0.873	70	2.5
325	75	18.3	163.3	45.5	5.9	5.6	0.959	70	2.5
325	75	39.6	198.1	65.3	12.7	12.3	0.972	70	2.5
325	75	68.9	228.5	85.4	22.1	21.4	0.970	70	2.5
325	75	105.1	253.5	104.7	33.7	32.8	0.973	70	2.5
325	100	5.0	122.5	26.4	1.6	1.4	0.894	70	2.5
325	100	18.3	172.2	45.1	5.9	5.6	0.949	70	2.5
325	100	39.4	209.8	64.8	12.6	12.3	0.969	70	2.5
325	100	68.3	241.0	84.5	21.9	21.3	0.974	70	2.5
325	100	84.2	257.2	94.0	27.4	26.7	0.974	70	2.5

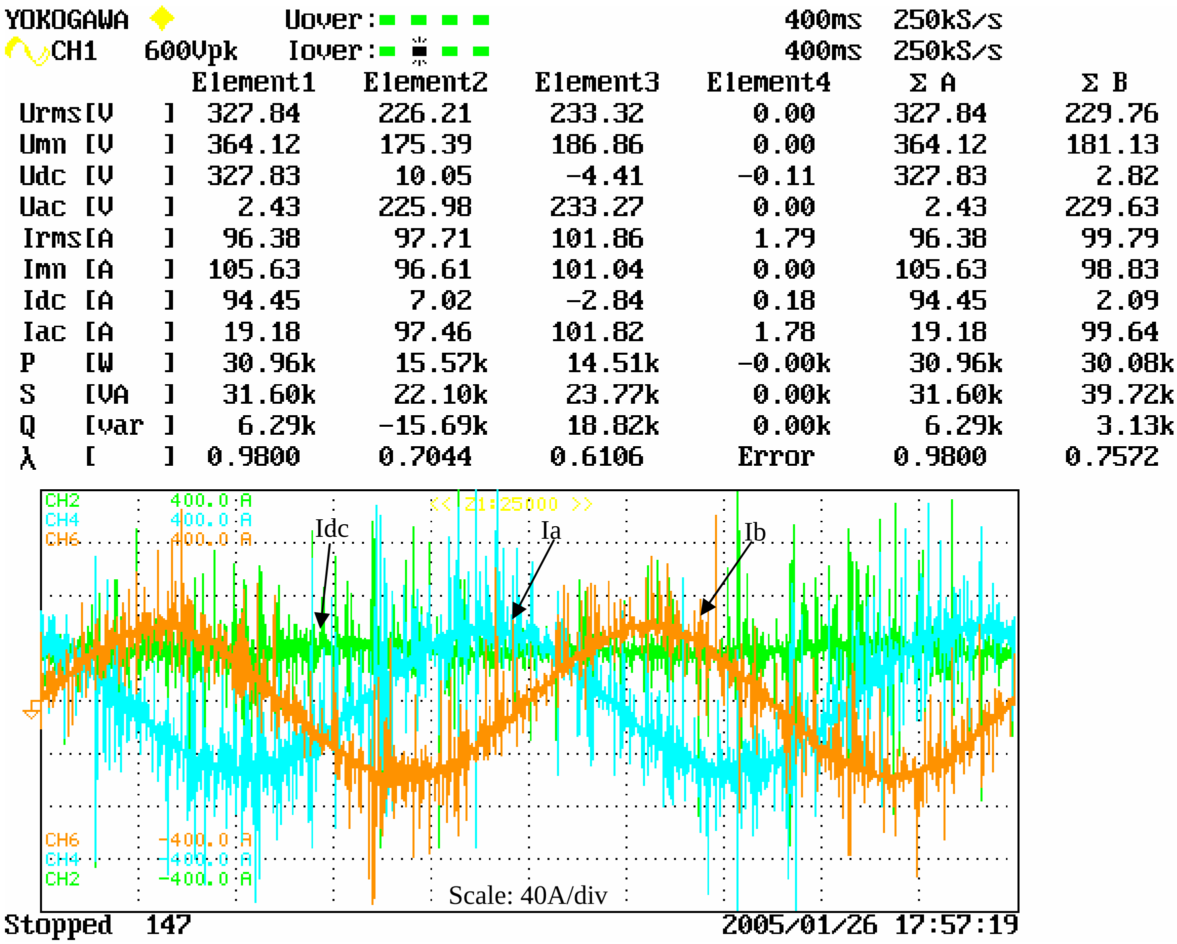


Fig. 8. Power meter readings and current waveforms at end on continuous power test.

Table 5. Continuous power testing of Semikron inverter with 325 Vdc link

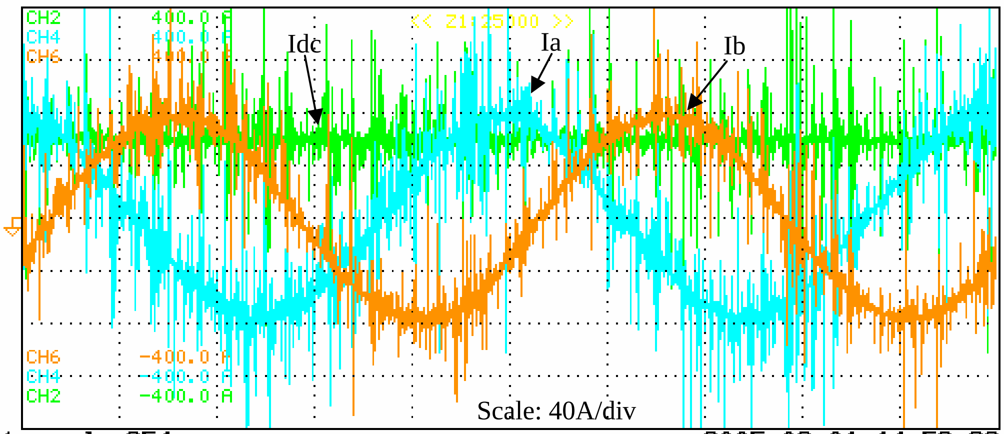
dc link (Vdc)	Freq (Hz)	Idc (A)	Vac (V_{LL})	Iac (A_{rms})	Pin (kW)	Pout (kW)	Effic.	Cool. (°C)	Flow (gpm)	Time (m)
325	20	94.99	229.6	99.4	30.9	30.1	0.975	70	2.5	5
325	20	95.79	228.8	99.9	31.0	30.2	0.976	70	2.5	30
325	20	94.47	229.8	99.5	31.0	30.0	0.967	70	2.5	45
325	20	94.45	229.8	99.8	31.0	30.1	0.972	70	2.5	60

Table 6. Testing of Semikron inverter at greater than continuous power levels

dc link (Vdc)	Freq (Hz)	Idc (A)	Vac (V_{LL})	Iac (A_{rms})	Pin (kW)	Pout (kW)	Effic.	Cool. (°C)	Flow (gpm)
325	20	118.7	242.1	111.2	38.6	37.7	0.977	70	2.5
335	30	122.5	122.7	114.9	41.2	40.0	0.970	70	2.5
400	20	147.1	299.6	137.5	59.2	57.7	0.976	70	2.5

YOKOGAWA Uover: 400ms 250kS/s
CH1 600Vpk Iover: 400ms 250kS/s

	Element1	Element2	Element3	Element4	Σ A	Σ B
Urms[V]	402.09	296.62	302.63	0.00	402.09	299.62
Umn [V]	446.60	245.61	255.80	0.00	446.60	250.70
Udc [V]	402.08	11.87	-11.21	-0.03	402.08	0.33
Uac [V]	2.38	296.38	302.42	0.00	2.38	299.40
Irms[A]	148.38	136.33	138.63	1.83	148.38	137.48
Imn [A]	163.81	134.49	138.51	0.00	163.81	136.50
Idc [A]	147.13	7.29	-7.33	0.16	147.13	-0.02
Iac [A]	19.22	136.13	138.43	1.82	19.22	137.28
P [W]	59.17k	31.08k	26.66k	-0.00k	59.17k	57.74k
S [VA]	59.66k	40.44k	41.95k	0.00k	59.66k	71.35k
Q [var]	7.68k	-25.87k	32.39k	0.00k	7.68k	6.51k
λ [ ]	0.9917	0.7685	0.6356	Error	0.9917	0.8092



Stopped 354 2005/02/01 14:52:22

Fig. 9. Power meter readings and current waveforms at end on peak power test.

Dynamometer Testing

The inverter was tested driving a Solectria motor in the 100-hp dynamometer test cell at ORNL's NTRC. The Solectria motor is a four-pole induction motor with a base speed of 2500 rpm. Dynamometer testing was performed with a dc link voltage of 325 V with the inverter being supplied with 70ºC coolant with a flow rate of 2.5 gpm. The inverter supplied electrical energy to drive the induction motor from 750 to 2500 rpm with a torque load of 100, 150, and 200 Nm.

Figure 11 plots the inverter efficiency vs. motor speed during the test. The highest efficiency (0.97) was obtained at 2500 rpm with a load of 150 Nm. Table 7 presents the test data for the 100, 150, and 200 Nm tests. The higher inverter efficiency was obtained near the base speed on the motor at the higher torque loads. The inverter meets the efficiency goal at a speed of 2500 rpm. Figure 12 plots torque vs. phase current with a family of curves at each speed.

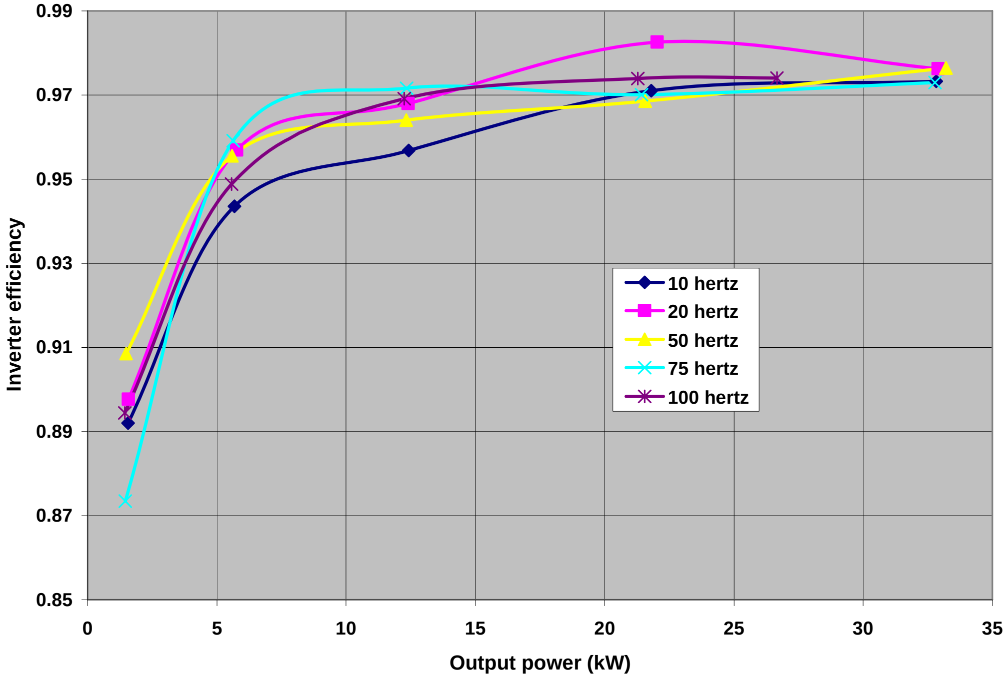


Fig. 10. Inverter efficiency vs. output power.

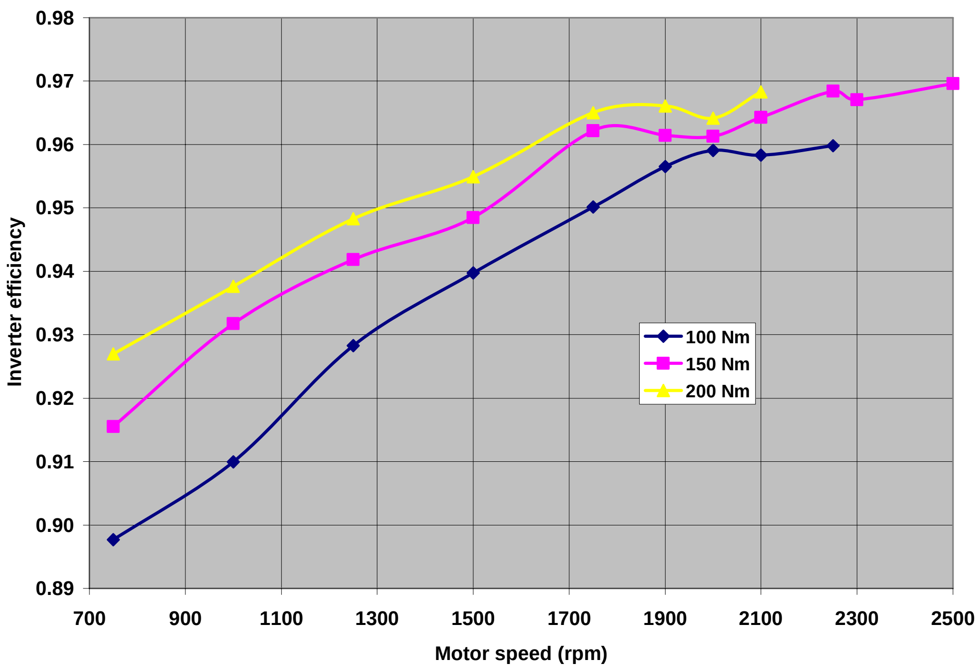


Fig. 11. Inverter efficiency vs. motor speed.

Table 7. Dynamometer testing of Semikron inverter—speed vs. inverter efficiency

dc link (Vdc)	Speed (rpm)	Torq (NM)	Idc (A)	Vac (V_{LL})	Iac (A_{rms})	Pin (kW)	Pout (kW)	Mech (kW)	AIPM Effic.
325	750	100	34.3	145.7	155.0	11.2	10.1	7.8	0.898
325	1000	100	43.7	167.9	166.6	14.3	13.0	10.4	0.910
325	1250	100	49.5	184.4	157.2	16.3	15.1	13.1	0.928
325	1500	100	58.4	202.4	162.2	19.3	18.1	15.6	0.940
325	1750	100	65.2	211.7	134.5	21.5	20.4	18.3	0.950
325	1900	100	70.6	222.5	140.5	23.2	22.2	19.9	0.957
325	2000	100	72.7	222.6	130.0	23.9	23.0	20.9	0.959
325	2100	100	78.0	235.3	144.3	25.7	24.6	21.9	0.958
325	2250	100	82.5	241.3	142.7	27.1	26.0	23.5	0.960
325	750	150	49.5	147.5	178.0	16.2	14.9	11.8	0.916
325	1000	150	62.0	169.8	189.1	20.7	19.2	15.7	0.932
325	1250	150	72.1	184.9	180.5	23.7	22.4	19.6	0.942
325	1500	150	85.5	203.0	184.4	28.2	26.7	23.5	0.948
325	1750	150	97.2	208.7	161.3	32.0	30.8	27.4	0.962
325	1900	150	105.7	223.7	169.6	34.7	33.4	31.4	0.961
325	2000	150	109.2	211.1	165.6	35.9	34.5	31.4	0.961
325	2100	150	115.9	234.3	170.1	38.1	36.7	33.0	0.964
325	2250	150	121.5	233.7	162.4	39.9	38.6	35.2	0.968
325	2300	150	127.2	251.2	190.3	41.9	40.5	36.1	0.967
325	2500	150	140.5	232.1	178.1	46.1	44.7	40.0	0.970
325	750	200	19.2	149.3	206.5	21.8	20.2	15.7	0.927
325	1000	200	83.7	170.8	215.8	27.4	25.7	20.9	0.938
325	1250	200	96.5	185.8	209.9	31.7	30.1	26.1	0.948
325	1500	200	114.0	204.0	215.6	37.5	35.8	31.4	0.955
325	1750	200	132.2	212.9	204.1	43.4	41.9	36.7	0.965
325	1900	200	141.9	221.9	205.0	46.6	45.0	39.8	0.966
325	2000	200	147.8	217.2	210.2	48.5	46.8	42.0	0.964
325	2100	200	155.9	234.0	206.0	51.1	49.5	43.9	0.968

The inverter was tested at continuous power (30 kW) by driving the motor from 1000 to 2400 rpm. Figure 13 shows the tests results at seven different motor speeds with the inverter supplying 30 kW of electrical power. The inverter had an efficiency that ranged from 0.94 to 0.97 with an output power of 30 kW.

Figure 14 shows the power meter readings and current waveforms during the continuous power test on the dynamometer. The inverter was operating with an efficiency of 0.943 based on an input power of 32.17 kW and an output power of 30.35 kW. Figures 15 and 16 shows a view of the dynamometer test cell from the control room with load motor and dynamometer.

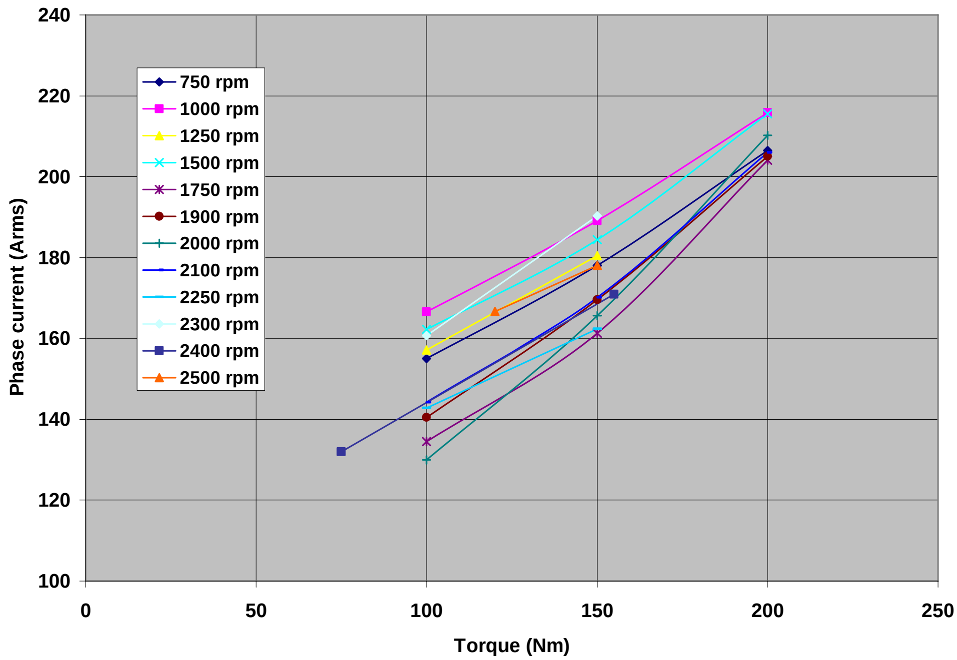


Fig. 12. Semikron inverter phase current vs. torque.

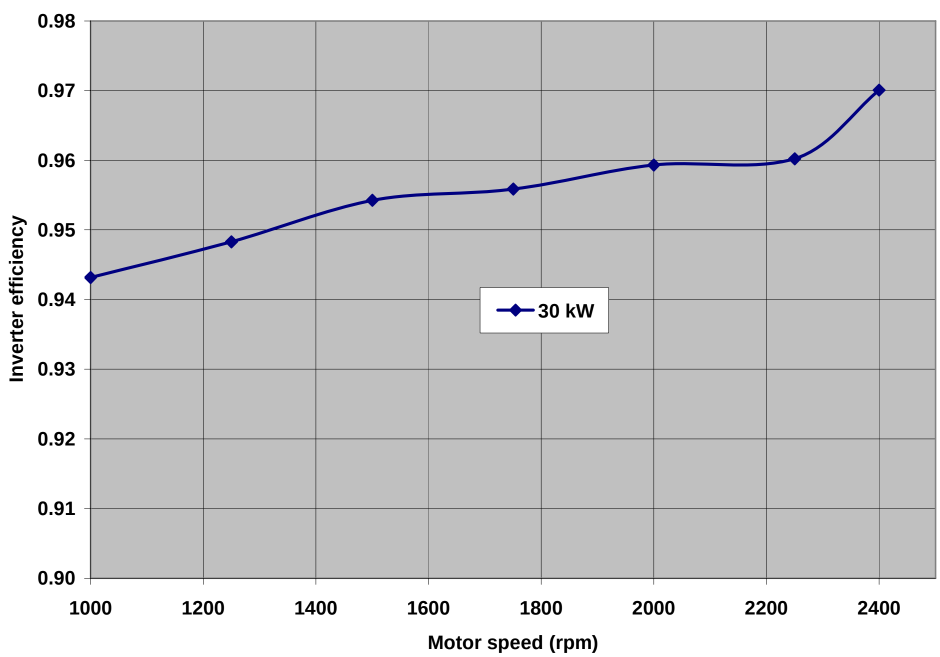
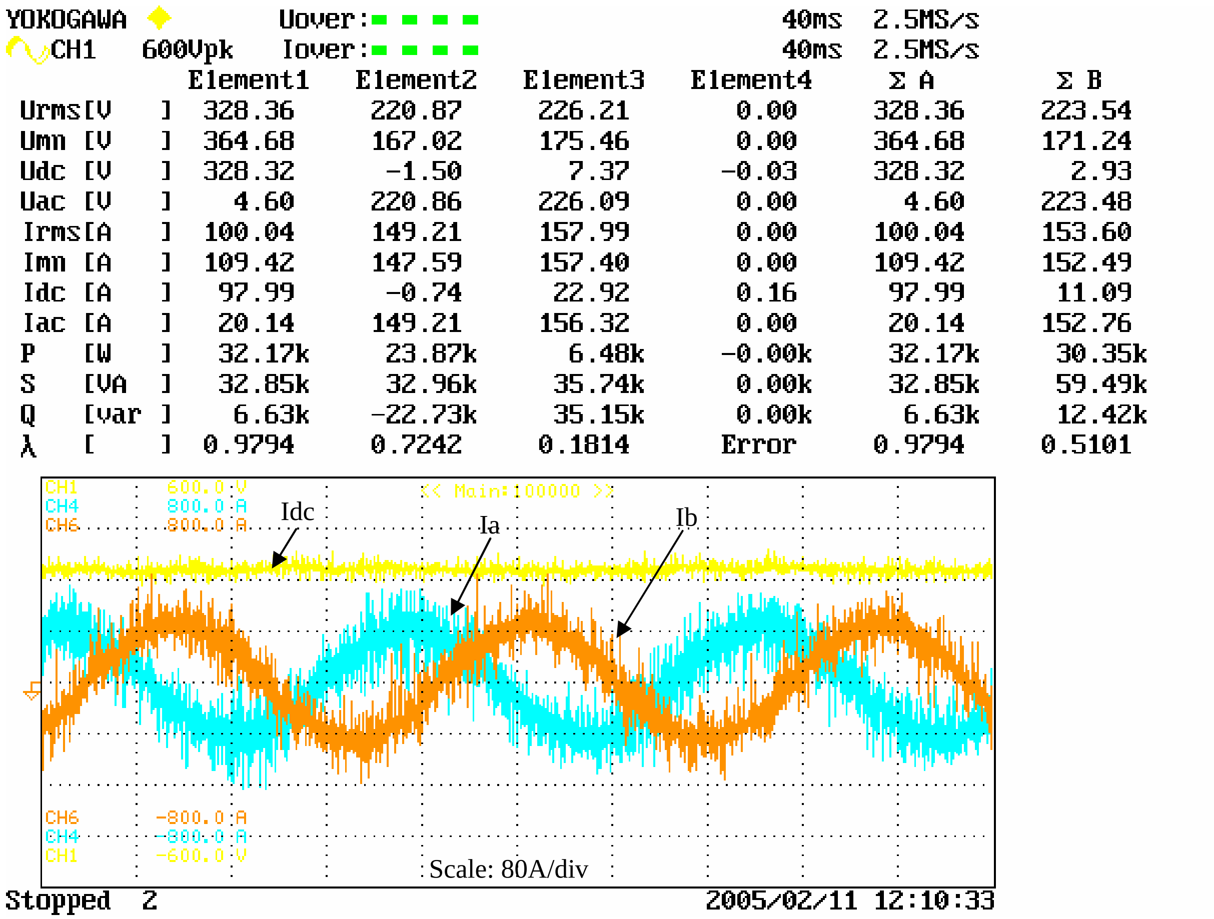


Fig. 13. Semikron inverter efficiency vs. speed at continuous power.



	Element1	Element2	Element3	Element4	Σ A	Σ B
Urms [V]	328.36	220.87	226.21	0.00	328.36	223.54
Umn [V]	364.68	167.02	175.46	0.00	364.68	171.24
Udc [V]	328.32	-1.50	7.37	-0.03	328.32	2.93
Uac [V]	4.60	220.86	226.09	0.00	4.60	223.48
Irms [A]	100.04	149.21	157.99	0.00	100.04	153.60
Imn [A]	109.42	147.59	157.40	0.00	109.42	152.49
Idc [A]	97.99	-0.74	22.92	0.16	97.99	11.09
Iac [A]	20.14	149.21	156.32	0.00	20.14	152.76
P [W]	32.17k	23.87k	6.48k	-0.00k	32.17k	30.35k
S [VA]	32.85k	32.96k	35.74k	0.00k	32.85k	59.49k
Q [var]	6.63k	-22.73k	35.15k	0.00k	6.63k	12.42k
λ [ ]	0.9794	0.7242	0.1814	Error	0.9794	0.5101

Fig. 14. Power meter readings and current waveforms during continuous power test on dyne.

CONCLUSIONS

The Semikron AIPM inverter demonstrated the ability to operate at the continuous and peak power levels when supplied with 70ºC coolant at 2.5 gpm for induction load tests. The inverter operated at continuous power levels for 60 minutes during the induction load tests with an average efficiency of 0.972.

During dynamometer testing the inverter had efficiencies that ranged from 0.94 to 0.97 when operated at continuous power levels. The controller for the inverter had a maximum speed setting of 2500 rpm that prevented driving the motor to higher speeds. The unit as delivered had a peak specific power density of 7.1 peak kW/kg exceeding the goal of 5 kW/kg. The unit had a volumetric peak power density of 8 peak kW/l failing to meet the goal of 12 kW/l. Table 8 summarizes the details used in this calculation.

Table 8. Specific power density summary

Characteristic	Semikron measurement	FreedomCAR goal
Weight (kg)	7.7	NA
Volume (l)	6.9	NA
Peak power (kW)	55	55
Peak specific power density (Peak kW/kg)	7.1	5
Peak volumetric power density (Peak kW/l)	8	12

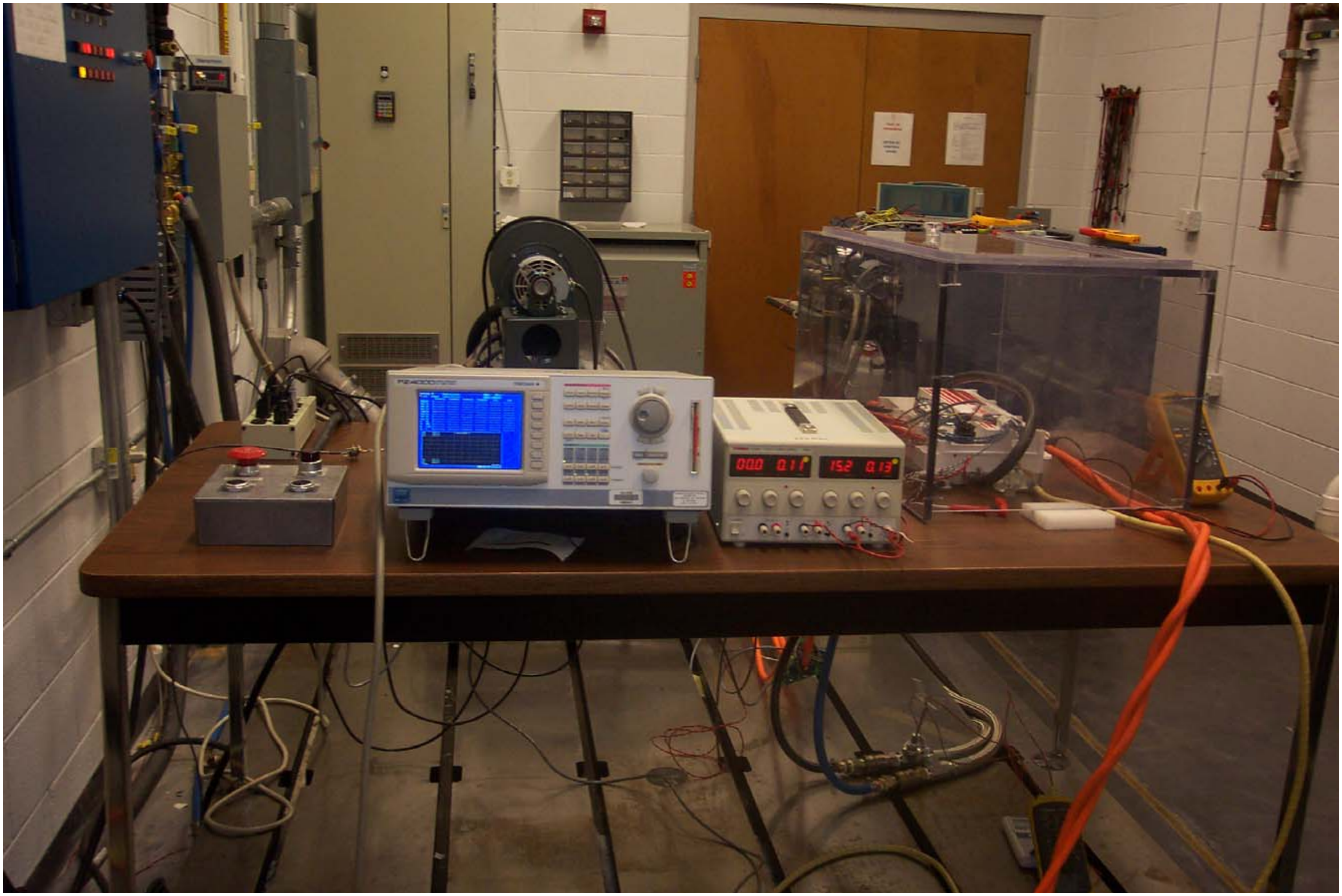


Fig. 15. View of dynamometer test cell from control room.

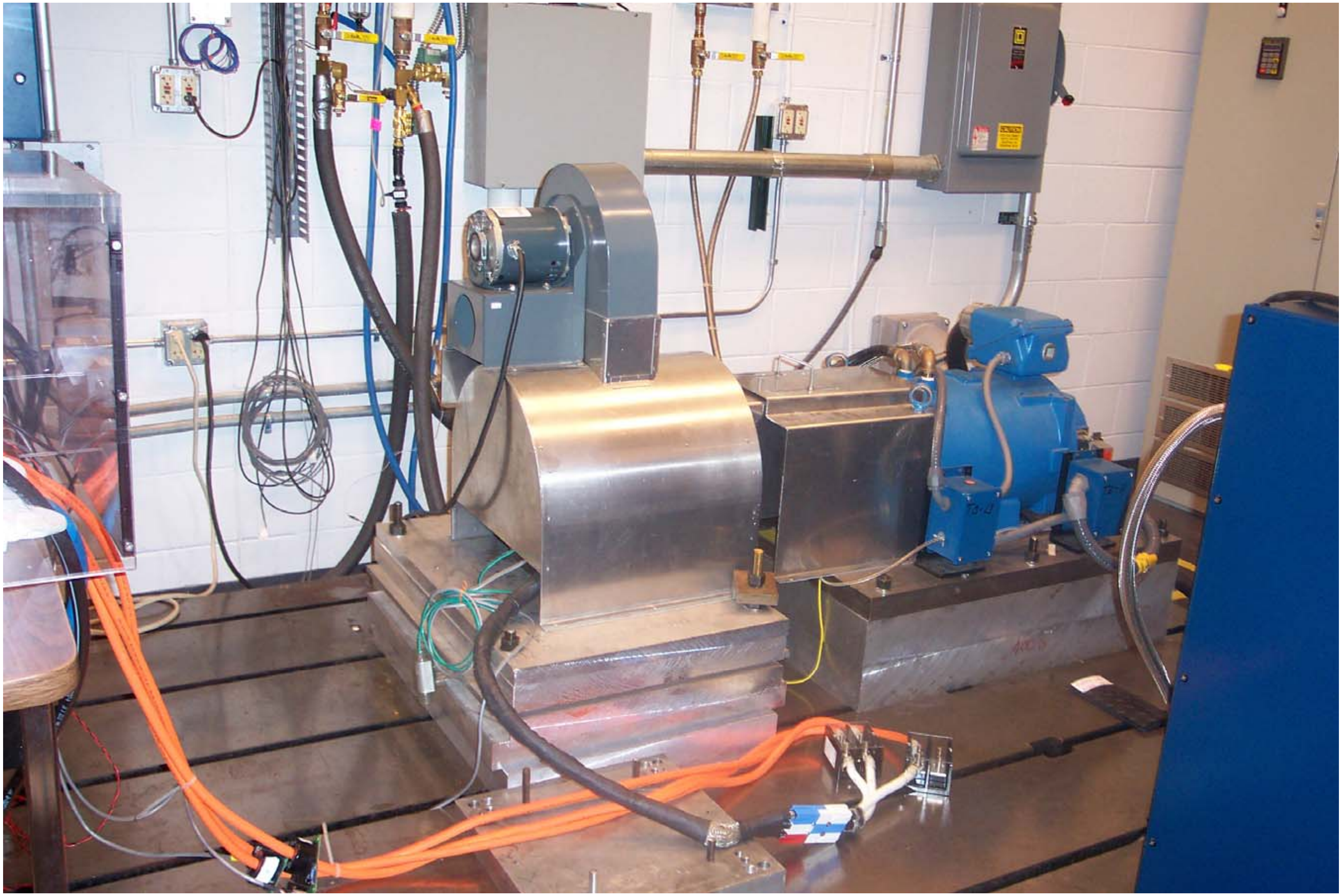


Fig. 16. Load motor and 100-hp dynamometer.

APPENDIX A:

AUTOMOTIVE INTEGRATED POWER MODULE (AIPM)
TEST PLAN

Revision 0

January 2005

A.1 INTRODUCTION

This document describes the tests to be performed as part of the overall evaluation of the Automotive Integrated Power Module (AIPM) hardware to be delivered by the contractors to the Oak Ridge National Laboratory (ORNL). These evaluations are to be done on behalf of the Department of Energy (DOE) to ascertain whether the units meet the target specifications referenced in the contracts and to determine their overall performance capabilities. The tests described herein may or may not be fully implemented, depending on several parameters such as funding, whether the prototype is deemed capable of surviving the tests, etc. Additionally, tests beyond those described herein may be performed at the discretion of ORNL or DOE. It is important to recognize that AIPMs should be designed to the referenced specifications and not to simply pass the evaluation tests. AIPMs that are determined to be designed to pass the test parameters rather than to meet the intent of the specification are not acceptable.

The intent of this test plan is to acquire the required data to characterize the device under test (DUT). In many cases, it is planned to utilize data acquisition systems to acquire and store data so that key parameters, such as efficiency, voltage regulation, etc., can be determined for the DUT at various operational conditions.

Two basic test setups are used in this test plan, an inductive load and a dynamometer system setup. For inductive load testing, the ac (alternating current) output of the DUT is connected to a three-phase inductive load and the dc (direct current) input is connected to a voltage source capable of supplying the appropriate voltage and current levels for the DUT. Some inductive load tests are performed prior to dynamometer tests to detect problems early in the test sequence.

There are two primary modes of operation for the DUT when the dynamometer is used in the test plan. During motoring tests, the DUT is supplying power to the motor and a family of inverter efficiency curves can be determined at various speeds and torques. Section 3 contains a summary of what test-setup is utilized for each test.

The DUT will require cooling when it is operated during inductive load or dynamometer tests. Typically, nominal cooling parameters are required for the tests being performed (see AIPM specification). The inlet coolant temperature should be controlled to the upper limit (70°C) when the performance of the unit is being compared to the AIPM specification.

A.2 INITIAL ELECTRICAL TEST (CHARACTERIZATION)

A.2.1 Receipt of DUT

The DUT shall be examined to determine that damage has not occurred during shipping or handling, and that the configuration of the DUT agrees with the information supplied by the vendor. Measure and record the following information: weight and dimensions.

A.2.2 Electrical Tests on Bench

A.2.2.1 Isolation impedance

Perform the following safety check, prior to the start of electrical testing, to verify the unit was not damaged during shipping. Measure with a multi-meter the isolation impedance between terminals and case of DUT to verify no fault conditions. The isolation impedance terminal to case of the DUT should be ≥ 1 MΩ.

A.2.2.2 Inductive load test

During the inductive load test, the ac outputs (of each phase) of the DUT will be connected to an inductive load in series with a matched resistor to provide a ≥ 80% power factor for the output frequency of the DUT. The dc inputs for the DUT are connected to a voltage source capable of supplying the maximum rated operating voltage and current levels for the DUT. The inductor and resistor should be rated for the current and power required for the test. Record the power rating of the DUT and do not exceed the rating during the inductive load test.

A.2.2.2.1 *Minimal dc link voltage test with inductive load*

Apply minimal dc link voltage to the DUT and establish current flow at approximately 10 A. Check to confirm the current phases and dead times are correct prior to increasing the current. Increase dc link current in steps of 10 to 20 A without exceeding the power rating for the DUT; record the dc link voltage, dc link current, input power, output power, output frequency, and output currents and voltages. Operate the DUT at each current level for approximately one minute. Repeat step in third sentence of this paragraph (i.e., increase dc link current).

A.2.2.2.2 *Maximum dc link voltage test with inductive load*

Repeat step A.2.2.2.1 with maximum dc link voltage.

A.2.2.2.3 *Nominal voltage test with inductive load*

Operate the DUT at 10 Hz and repeat step A.2.2.2.1 with nominal dc link voltage. Increase the output frequency of the unit by 10 to 30 Hz and repeat step A.2.2.2.1. Operate the DUT at a total of three to six different output frequencies at nominal dc link voltage.

A.2.2.2.4 *Continuous power test*

Confirm ability of unit to operate at continuous power levels for one hour with nominal rated dc link voltage. Record current waveforms and test data at the end of one hour of operation.

A.2.2.2.5 *Peak power test*

Confirm ability of unit to operate at peak power levels for 24 seconds with nominal rated dc link voltage. Record current waveforms and test data at the end of the peak power test.

A.2.3 Electrical Test on Dynamometer System

Connect the DUT to the drive motor on the dynamometer system. Verify the test setup and that the data acquisition system is operational. Record the model, serial number, and parameters of the motor utilized in the test. The motor parameters should include horse-power or kW, maximum rated speed and torque. Record the ambient temperature of the laboratory (dynamometer test cell) at the beginning and end of each dynamometer run. Do not exceed any parameter for the DUT or the test motor (i.e. maximum rated speed).

A.2.3.1 Nominal battery voltage

Verify the nominal battery voltage and the rated and maximum output currents (at the nominal voltage) for the DUT. Set the dc voltage input to the DUT at the nominal battery operating voltage and do not exceed the maximum limit of the output currents from the inverter. Drive the load motor from rest to the rated speed in increments of approximately 10% of the rated motor speed and apply increasing torque loads to the motor. Increase speed by 10% and repeat previous step until the target motor speed is obtained. Drive the motor to rest. Operate the coolant system for the DUT at nominal conditions during this test.

Record the following information at each speed increment: motor shaft speed (rpm), motor's torque load and mechanical power, input voltage and current to the inverter, and output voltages and currents from the inverter.

A.3 TEST SETUP SUMMARY

This test plan utilizes two basic test setups, testing with an inductive load and testing with the dynamometer system. The table below summarizes what setup is used for each test and in some tests the DUT is inactive.

Test No.	Test description	Inductive Load	Dynamometer Test	Inactive
A.2.2.1	Isolation impedance			x
A.2.2.2	Inductive load	x		
A.2.3.1	Nominal battery voltage		x	

APPENDIX B:

RECOMMENDED AIPM AND AEMD SPECIFICATION

Requirement	AIPM series	AEMD series		AIPM parallel	AEMD parallel
Continuous power (kW)	**30 output**	30 input		**15 output**	15 input
Peak power (kW)	**55 output**	**55 input**		**30 output**	30 input
Battery operating voltage (Vdc)	**325(200-450)**	**325(200-450)**		**325(200-450)**	**325(200-450)**
Power factor	>0.8			>0.8	
Maximum current (A)	**300**	**300**		**200**	**200**
Precharge time--0 to 200Vdc (sec)	2	NA		2	NA
Eff (10-100% speed, 20% rated T curve) (%)	> 97	>93		> 97	>93
Torque ripple (%)	NA	5		NA	5
Output current ripple –peak to peak (%)	<= 5			<= 5	
Input voltage & current ripple (%)	<= 5	NA		<= 5	NA
Current loop bandwidth (kHz)	2	NA		2	NA
Max fundamental electrical freq. (Hz)	1000	1000		1000	1000
Ambient operating temperature (°C)	-40 to **+105**	-40 to +105		-40 to **+105**	-40 to +105
Storage temperature (°C)	-50 to +125	**-50 to +125**		-50 to +125	**-50 to +125**
Cooling system flow rate, max (gpm)	2.5	2.5		2.5	2.5
Maximum coolant inlet temp. (°C)	70	70		70	70
Maximum inlet pressure (psi)	25	25		25	25
Maximum Inlet pressure drop (psi)	2	2		2	2
Useful life (years/miles)	15/150,000	15/150,000		15/150,000	15/150,000
Minimum isolation impedance-terminal to grd (M ohm)	**1**	**NA**		**1**	**NA**
Minimum insulation impedance-terminal to grd (M ohm)	NA	20		NA	20
Maximum weight *	5 kW/kg	35 kg		5 kW/kg	22 kg
Maximum volume*	12 kW/liter	11 liters		12 kW/liter	7 liters

Note: Changes are identified by bold type.

APPENDIX C

EQUIPMENT USED IN TESTING AIPM

Equipment item	Model	Calibration information
Avtron Resistor Load Bank	K595D14442	NA
Bay Voltex Coolant Conditioner	MCHT-4050-E1	NA
DyneSystems 100-HP Dynamometer	EAC100-04836-01	Calibrated 2/7/05
EMHP Power Supply	EMHP 300-200-42211	NA
NWL Transformer Inductive Choke	103533	NA
Solectria Motor	AC55	NA
TFNMA Power Supply	EX354T	NA
Yokogawa PZ4000 Power Meter	253710	Due 8/27/05

NA-not applicable.

DISTRIBUTION

Internal

1. D. J. Adams
2. C. W. Ayers
3. E. C. Fox
4. K. P. Gambrell
8. L. D. Marlino
9. S. C. Nelson
10. M. Olszewski

11–12. Laboratory Records

External

13. T. Q. Duong, U.S. Department of Energy, EE-2G/Forrestal Building, 1000 Independence Avenue, S.W., Washington, D.C. 20585.
14. G. L. Hagey, 501 Randolf Street, Williamsburg, Virginia 23185.
15. M. W. Lloyd, Energetics, Inc., 7164 Columbia Gateway Drive, Columbia, Maryland 21046.
16. S. A. Rogers, U.S. Department of Energy, EE-2G/Forrestal Building, 1000 Independence Avenue, S.W., Washington, D.C. 20585.
17. E. J. Wall, U.S. Department of Energy, EE-2G/Forrestal Building, 1000 Independence Avenue, S.W., Washington, D.C. 20585.
18. P. G. Yoshida, U.S. Department of Energy, EE-2G/Forrestal Building, 1000 Independence Avenue, S.W., Washington, D.C. 20585.