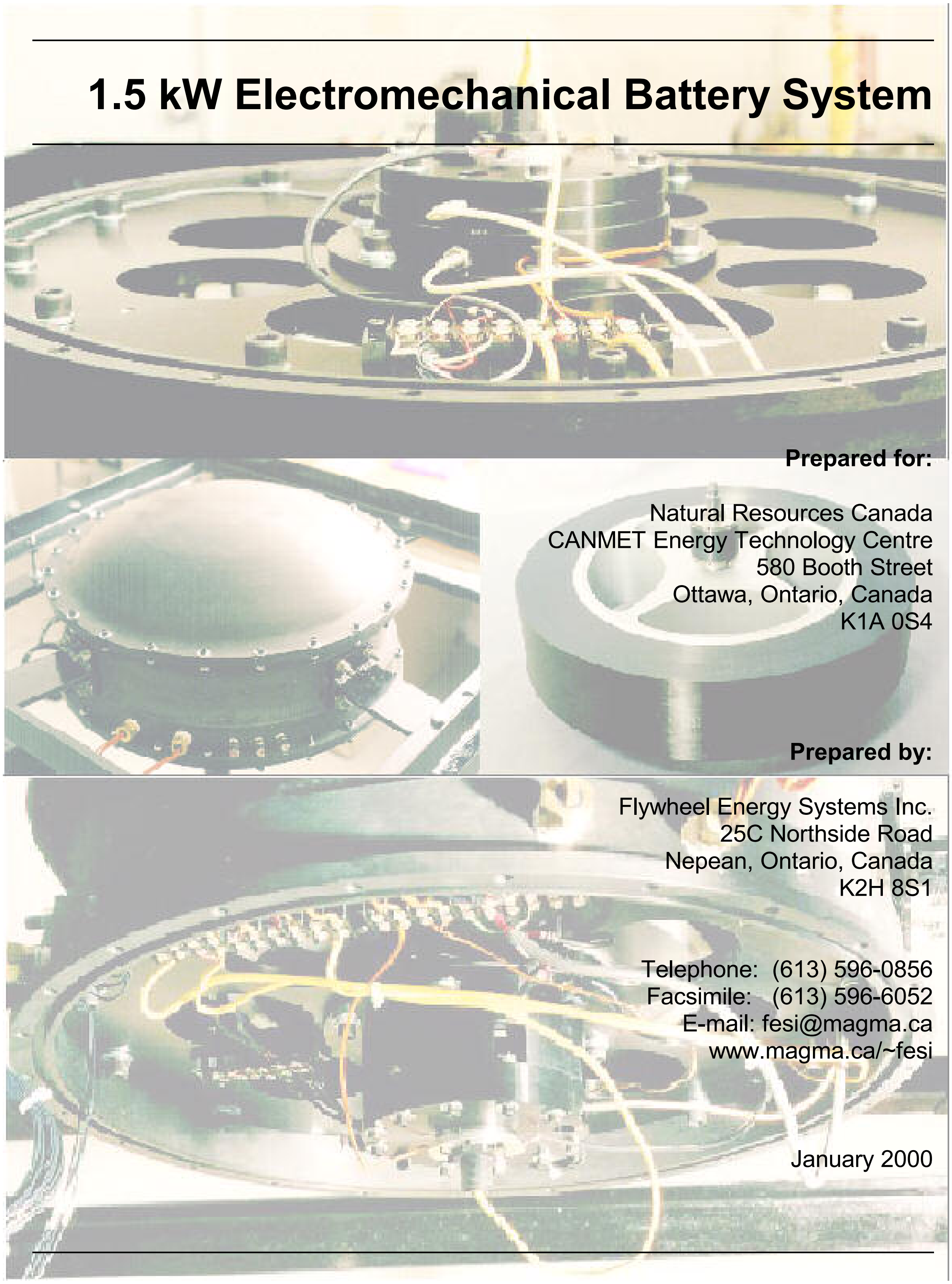
CETC-0100-01 Rev.2

1.5 kW Electromechanical Battery System



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Terms and Acronyms

Specific Parameters	Specific parameters is a generic term that collectively refers to a set of parameters that are commonly used to compare energy/power equipment. However, these terms are often reversed in the literature. In this report:
Specific Energy	Energy per unit mass (Wh/kg, Wh/lb)
Specific Power	Power per unit mass (W/kg, W/lb)
Energy Density	Energy per unit volume (Wh/L, Wh/ft^3)
Power Density	Power per unit volume (W/L, W/ft^3)

ACES	Attitude Control Energy Storage
CANMET	Canada Centre for Mineral and Energy Technology
CETC	CANMET Energy Technology Centre
Draper or CSDL	The Charles Stark Draper Laboratory, Inc., Cambridge, Massachusetts
EMB	Electromechanical Battery
EMF	Electromotive Force
FEA	Finite Element Analysis
FESI	Flywheel Energy Systems Inc., Nepean, Ontario
FFT	Fast Fourier Transform
FRH	Flex-Rim Hub
NRCan	Natural Resources Canada
PWGSC	Public Works and Government Services Canada
PWM	Pulse Width Modulation
SL-MTI	SL-Montevideo Technology, Inc., Montevideo, Minnesota
TDC	Transportation Development Centre, Transport Canada
UPS	Uninterruptible Power Supply

Summary Report

Introduction

Future vehicle propulsion systems will likely be a hybrid combination of an efficient primary energy supply coupled with an energy management device. A hybrid propulsion system has recognized advantages regarding increased fuel efficiency and reduced carbon dioxide emissions. Other benefits include reduced hydrocarbon, nitrogen oxide, carbon monoxide, particulate, and acoustic emissions. These advantages are most effectively realized in the stop-and-go duty cycles endured by urban transit vehicles, taxis, and delivery vans. Figure 1 shows the power requirements for a light delivery van operating on the Federal Urban Drive Schedule. The primary energy supply addresses the vehicle's average power requirement (red line) while the energy management device addresses the driver's instantaneous power demand (blue line).

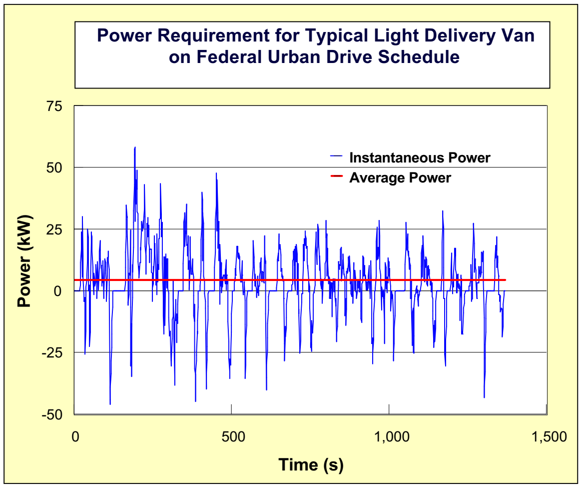

Figure 1 *Power Requirement for Typical Light Delivery Van Operating on Federal Urban Drive Schedule*

The energy management device must store enough energy to satisfy the deepest draw cycle the vehicle will experience and be able to provide the peak power demanded while minimizing overall vehicle weight. Chemical batteries, ultracapacitors, and flywheels may be used as the energy management device, however flywheels have a higher specific power value than chemical batteries and a higher specific energy value than ultracapacitors. Flywheels therefore offer the most attractive balance of power, energy storage, and weight for vehicular applications. Figure 2 shows the specific energy versus specific power diagram for flywheels, chemical batteries, and ultracapacitors (source: U.S. Department of Energy).

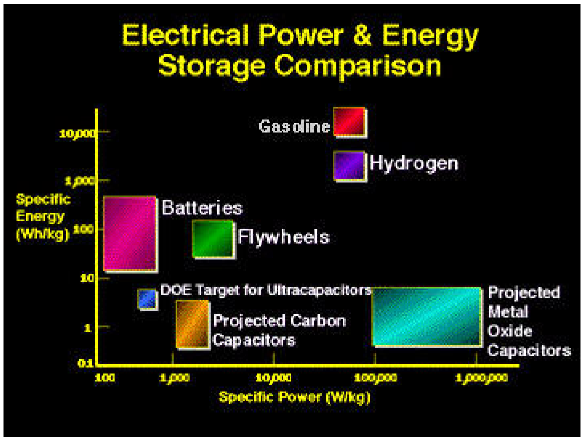

Figure 2 *Electrical Power & Energy Storage Comparison (source: US DOE)*

A flywheel or electromechanical battery (EMB) is a device that stores energy for later use. Like a conventional battery, the energy transfer is electrical; however, unlike conventional batteries, the energy is stored as kinetic energy in the form of a spinning disc—the flywheel rotor. The motor/generator transfers energy by charging (speeding up) and discharging (slowing down) the flywheel rotor. The bearings support these rotating components. The controller/converter directs the flow (power) and form (output waveform or DC voltage) of the electrical energy. The evacuated housing reduces aerodynamic drag on the rotating elements, thereby increasing efficiency. Figure 3 is a schematic of an electromechanical battery showing these components.[1]

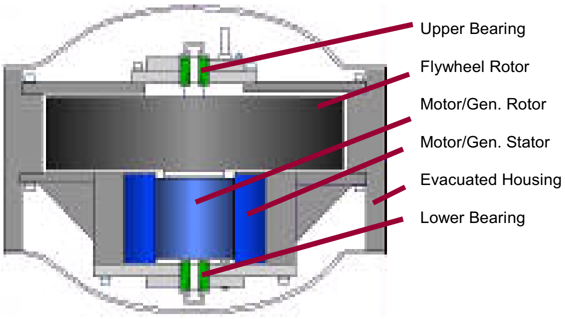

Figure 3 *EMB Schematic*

Program Summary

Prior to deploying a viable EMB system for hybrid vehicles, a number of technical challenges (such as dynamic, thermal, and electrical stability, vacuum preservation, life, safety, weight, and cost) need to be resolved. These challenges are being tackled according to a phased development plan. Figure 4 shows the program steps and technology milestones envisioned for a hybrid urban bus demonstration/deployment program. This report summarizes the work undertaken to manufacture, model, and test the 1.5 kW – 1kWh EMB.

Three pre-program activities served as the basis for this work. Initially, Flywheel Energy Systems Inc. (FESI) developed a series of high performance flywheels under contract with Natural Resources Canada (PWGSC contract #23440-4-1191/01-SQ).[2]

These flywheel rotors provide between 75 Wh/kg and 97 Wh/kg specific energy at a life of 100,000 deep discharge cycles. Table 1 shows the dimensions and performance parameters for the Series 45 fly-

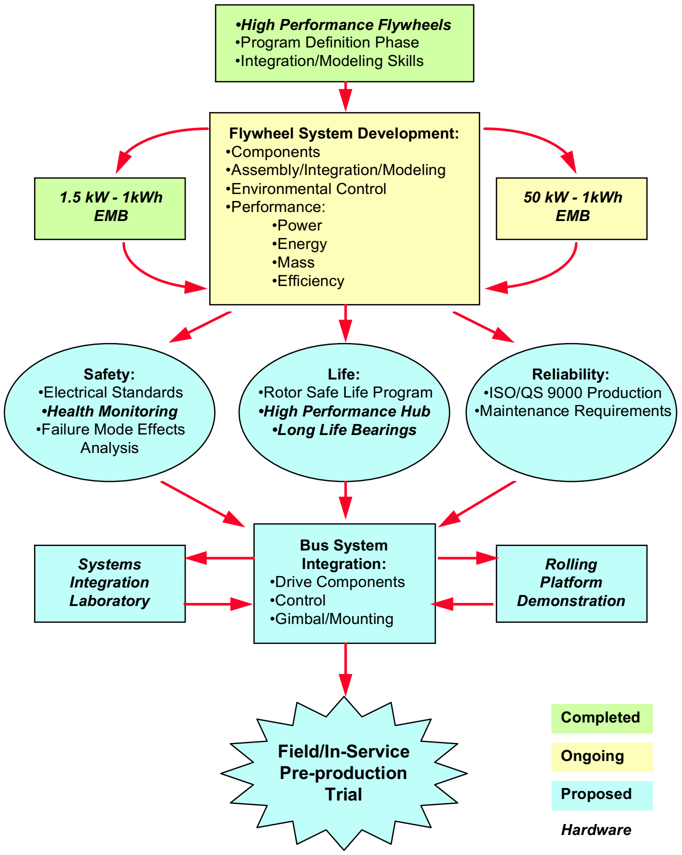

Figure 4 *Program Steps and Hardware Required for Hybrid Bus Demonstration*

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[1] Figure 3 is a schematic based on FESIs 50 kW EMB; this high power EMB retains a high specific energy flywheel rotor similar to that used in the 1.5 kW EMB. The 1.5 kW EMB retains (essentially)the motor designed for the ACES units. The selected topology segregates technical risks and challenges associated with EMB development by component and permits them to be tackled in a risk-mitigated, phased development plan. The versatility of this arrangement also minimizes the engineering effort required to address the unique power and energy requirements for vehicular, power quality, and space applications of the technology.

[2] Flywheel Energy Systems Inc., *Development of High Performance Flywheels for Electromechanical Batteries*, Contract No. 23440-4-1191/01-SQ Final Report, March 1997.

Table 1 *Dimensions and Performance Parameters for the Series 45 Family of Flywheels*

Model	Design Speed	Tip Speed		Inside Diameter		Outside Diameter		Specific Energy		Energy Density	
	(rpm)	(ft/s)	(m/s)	(inches)	(mm)	(inches)	(mm)	(Wh/lb)	(Wh/kg)	(Wh/in^3)	(Wh/l)
Mark 1	42,500	2,790	849	10.8	274	15.0	382	34	75	0.98	60
Mark 2	45,000	2,980	907	10.8	274	14.4	385	39	85	1.11	68
Mark 3	45,000	3,180	970	10.8	274	16.2	412	42	93	1.37	83
Mark 4	45,000	3,270	996	10.8	274	16.7	423	44	97	1.46	91

wheels. All flywheels exhibited excellent dynamic stability (typically less than 0.0003 inches of runout) under dynamic testing. Figure 5 shows the Series 45 family of flywheels: Mark 1, Mark 2, Mark 3, and Mark 4 (from right to left).

Figure 5 *Series 45 Family of Flywheels*

As part of the high performance flywheel development contract, FESI conducted a detailed decision analysis of EMB configurations (and hence flywheel rotor configurations). The conclusions reached during this process identified an axially integrated flywheel and motor/generator topology as the best candidate for future EMB development. This arrangement places the flywheel rotor (composite rim and flex-rim-hub) and the motor/generator adjacent to one another on a common support shaft—the power rating (motor) and energy stored (flywheel) thus become essentially independent, allowing component development to proceed independently and still be readily integrated (see Footnote 1).

The axial length and series number (indicating maximum operating speed) of an FESI flywheel can be readily scaled to fit virtually any energy storage application while maintaining the characteristic high specific energy and energy density levels shown in Table 1.

Secondly, rotor dynamic and thermal models were developed as part of the hybrid urban bus demonstration program definition phase, co-funded by FESI and Transport Canada's Transportation Development Centre (PWGSC contract #T8200-6-6516/001-XSD).[3]

Thirdly, FESI developed and tested two EMB systems for the Charles Stark Draper Laboratory's (CSDL) Attitude Control and Energy Storage (ACES) program. The testing of the first ACES unit (shown in Figure 6) coincided with the rotor dynamic and thermal model development, thereby providing the opportunity to correlate the modeling efforts undertaken for TDC with data measured from ACES. The data from 126 test runs covering 129 hours of running time were captured, analyzed, and used to correlate the models. The rotor dynamics model was subsequently used to fine-tune the response of the second ACES unit while the thermal model was instrumental in identifying and isolating motor rotor heating in the first ACES unit; modifications were made to correct the problem.

All of these pre-program activities were complete by November, 1997.

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[3] Flywheel Energy Systems Inc., *Canadian Electromechanical Battery Development Program: Definition Phase*, Contract No. T8200-6-6516/001-XSD Final Report, June 1997.

Figure 6 *Attitude Control Energy Storage (ACES) System*

Program Support

Given the technology potential and resident Canadian experience/expertise in EMB system integration and modeling, Flywheel Energy Systems Inc. and the CANMET Energy Technology Centre of Natural Resources Canada agreed to co-fund the design, modeling, assembly, and testing of a low power (1.5 kW) EMB incorporating a high performance flywheel. The motor/ generator and motor controller/converter were supplied by SL-Montevideo Technology, Inc. (SL-MTI).

Achievements

The set objectives of this project have been met, with the exception of full speed testing. The motor controller used in the test program had an upper speed limit of 34,000 rpm. Rotor dynamic and thermal models have been developed and correlated with measured data. The suspension system part count, complexity, and cost have been greatly reduced while maintaining excellent control over system stability. The 1.5 kW EMB has demonstrated the ability to level a DC bus subjected to cyclic loading. The next major step in follow-on work to a hybrid bus demonstration (the high performance 50 kW EMB) has been initiated and benefits greatly from the work carried out in this program.

Design

The EMB consists of a high performance fibre-reinforced composite rim, patented flex-rim-hub, shaft, motor rotor and stator, bearings, support structure, evacuated housing, and instrumentation. A Series 45 Mk 3 flywheel rotor was selected and sized based on several parameters. Most importantly, the rotor was sized to store and deliver 1 kWh of net energy (15,000 rpm – 45,000 rpm). This energy level is considered representative of hybrid light delivery van and full size urban bus requirements.

One of the primary objectives of the design effort was to move the design closer to a production machine with lower manufacturing costs, reduced parts count and complexity, and higher specific energy and energy density. Relative to the ACES units, this machine has 40% fewer parts, one quarter the number of high precision parts (with tolerances <0.0005 inches), eight times the specific energy (Wh/kg), and four times the energy density (Wh/l).

FEA stress analysis was performed for numerous proprietary components, including the patented flex-rim-hub and the motor/ generator composite sleeve. The motor composite sleeve FEA model is shown in Figure 7; the four separate sets of gap elements necessary to model shaft, lamination, magnet, and sleeve interfaces require dense meshing and increased computational power, while boundary conditions have been used to capture the symmetry of the design and minimize runtimes. Using a carbon fibre composite sleeve increased the end of life factor of safety (S.F. = 100,000 cycle strength/operating stress) from 1.3 (for Inconel 718) to 3.2.

FEA of the flex-rim-hub was used to determine equivalent hub stiffness inputs to the rotor dynamic model—this model incorporates dynamic stiffening effects, rotating structural damping (from the shaft, hub, and composite rim), rotating viscous damping (representing Coulomb damping effects

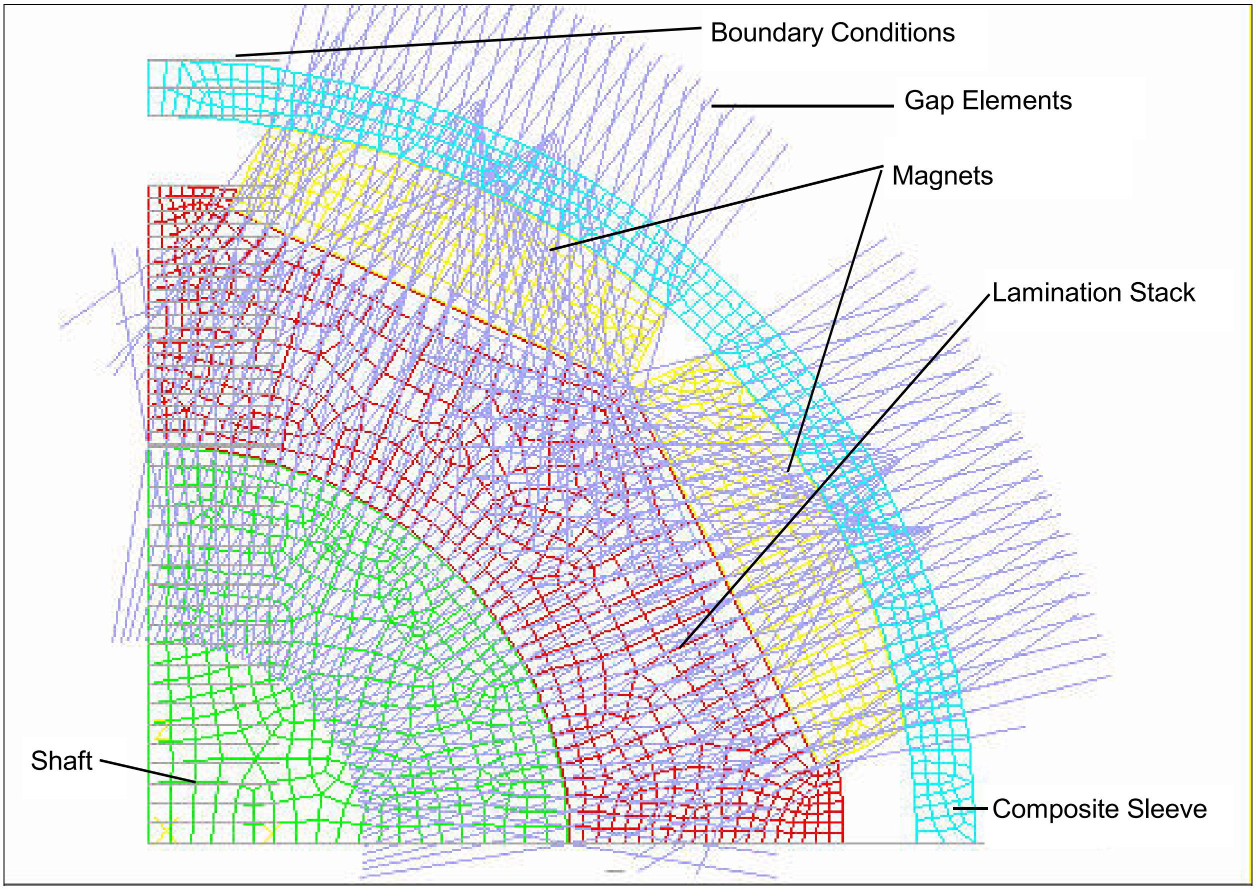

Figure 7 *Motor Rotor FEA Model*

between the hub and rim), bearing stiffnesses, bearing mount stiffnesses and damping, and housing and flexible-mount stiffnesses and damping. The rotor dynamic model provided input values to the bearing mount system (suspension) design. Dynamic requirements for the suspension system include the following qualitative conditions:

- critical-free operation between 15,000 and 45,000 rpm at all operating temperatures,
- sufficient damping to prevent instability (whirl) of the rotating components, and
- stable and repeatable response to unbalance excitation.

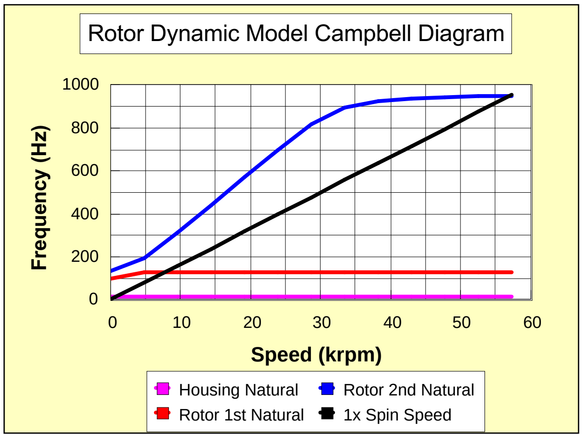

Figure 8 *Rotor Dynamic Model Campbell Diagram*

Figure 8 shows the Campbell diagram generated by the rotor dynamic model FEA package.

Equilibrium thermal analysis was conducted using a highly detailed finite element model. With over 35 separate parts, 10 separate radiation and convection surfaces, and 16 heat sources, this model drew on industry and government published data, internal experimental data, and correlations developed during FESI's previous integration and testing projects. This FEA model was used to develop a thermal map of the EMB; the model drew upon existing aerodynamic drag and bearing loss models (developed under the TDC contract and correlated with measurements taken during the ACES program) and incorporated revised motor loss estimations. Correlation with test results was less accurate for the motor loss model than for the other models.[4]

Structural natural frequency analysis was extended to include higher order natural frequencies when bending modes in the main support plates of the EMB were being excited (unexpectedly) during initial testing. This investigation resulted in the redesign of both (upper and lower) structural support plates—modal testing of the plates in both original and redesigned configurations confirmed the accuracy and importance of this analysis in the design process.

Figure 9 shows the two modes studied (axial and out-of-plane torsional), along with the natural frequencies for the top support plate in final (reinforced) and original configurations. Figures 10 and 11 show the FFT spectrum of the 1.5 kW EMB with the original and modified plates, respectively.

Build

The housing was cast, then the plates, bearing mounts, stator mount, slip ring, housing, and various retaining rings were machined to final dimensions. SL-MTI provided the stator, rotor laminations, and samarium cobalt (SmCo) magnets. The aluminum flex-rim-hub was fabricated by wire-EDM. The vacuum domes were formed by "spinning"—this minimized the amount of precision machining required. All the aluminum structural components were anodized black to resist corrosion and improve radia-

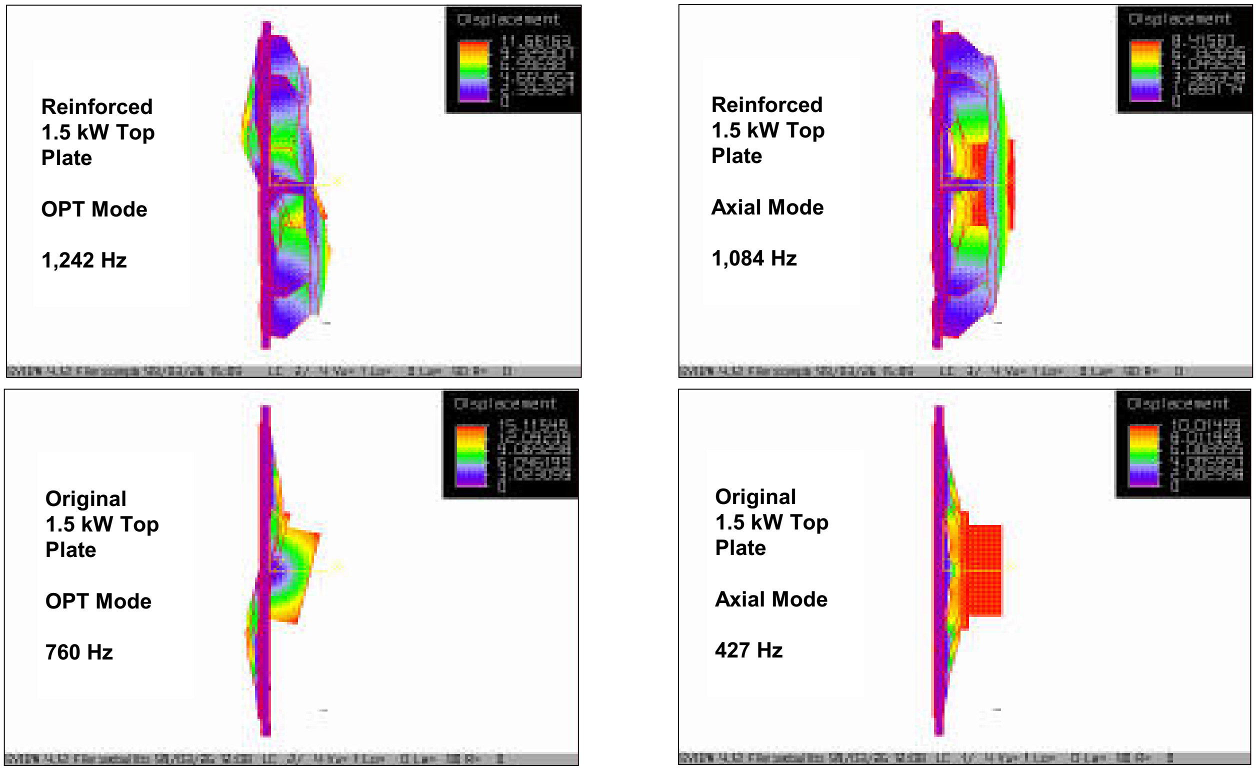

Figure 9 *1.5 kW EMB Top Plate Natural Frequency Modes — Axial and Out of Plane Torsional (OPT) Modes*

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[4] Little public information is available concerning motor loss distribution models—particularly motor rotor losses. Due to limited heat rejection paths, and the vacuum environment, understanding this issue remains critical to successful EMB integration.

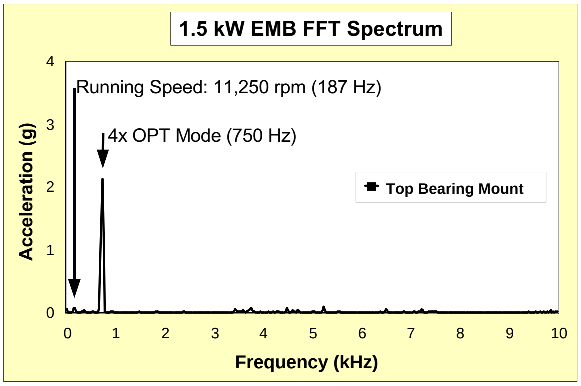

Figure 10 *1.5 kW EMB FFT Spectrum–Original*

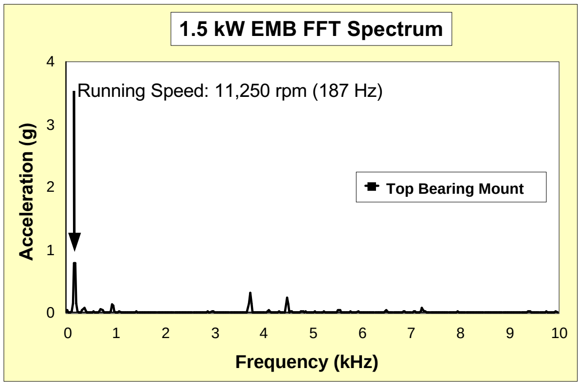

Figure 11 *1.5 kW EMB FFT Spectrum–Reinforced*

tion emissivity. FESI fabricated and machined the composite rim and motor composite sleeve to final dimensions. Figure 12 shows all the components of the EMB—despite the apparent complexity, there are fewer than 100 parts in this machine (excluding fasteners).

Since they are essential to the success of the EMB, considerable time and attention was devoted to bearing design and selection. After consulting with bearing manufacturers and drawing on experience with the bearings used in the Draper ACES program, precision high-speed angular contact ball bearings were selected. Hybrid (ceramic ball, steel raceway) bearings were chosen to increase life and reduce losses.

Drawing upon previous experience, a porous polyimide retainer was matched and impregnated with a low viscosity, low vapour pressure bearing oil to form a finite-life continuous lubrication system. The retainer selected also allows re-impregnation without disassembling the bearing. The bearings are custom assembled and impregnated Barden 101H precision high-speed angular contact ball bearings: 52100 bearing steel raceways, matched silicon nitride (SiN) ceramic balls, Meldin 9000 polyimide porous retainer, and Nye 177A low viscosity/low vapour pressure synthetic oil.

Figure 12 *1.5 kW EMB Compoments*

The shaft, motor rotor laminations, magnets, composite sleeve, and balance disks were assembled and precision balanced

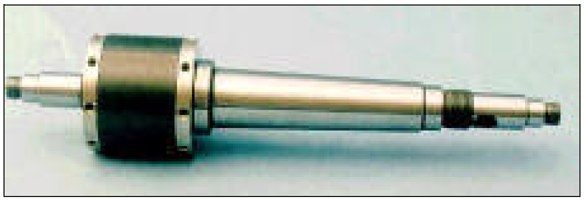

Figure 13 *1.5 kW EMB Motor Rotor and Shaft*

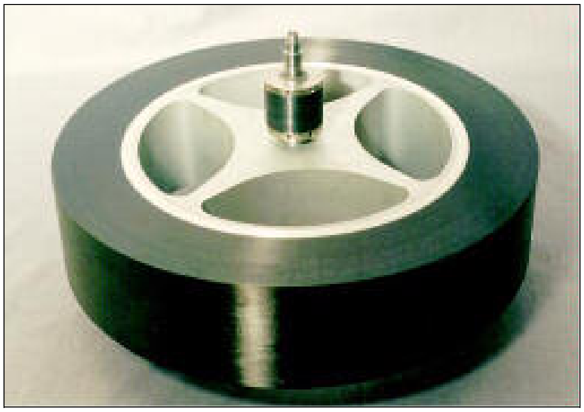

Figure 14 *1.5 kW EMB Rotating Assembly*

(Figure 13), then the hub and composite rim were assembled to the shaft (Figure 14).

The EMB housing was mounted in an assembly frame and the lower structural components attached. The rotating assembly was then centered and the upper structural components attached. The bearings and bearing mounts were installed and aligned, followed by instrumentation and preliminary data acquisition checks.

The following instrumentation was installed on the EMB:

- 9 thermocouples
- one proximity probe (used as a tachometer and phase trigger)
- two proximity probes (used to monitor displacements at each bearing)
- three accelerometers (one monitoring radial or axial vibration at each bearing and one monitoring housing vibration)

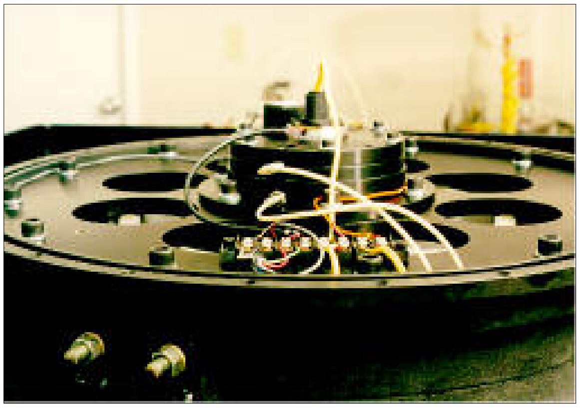

Figure 15 *1.5 kW EMB Upper Instrumentation*

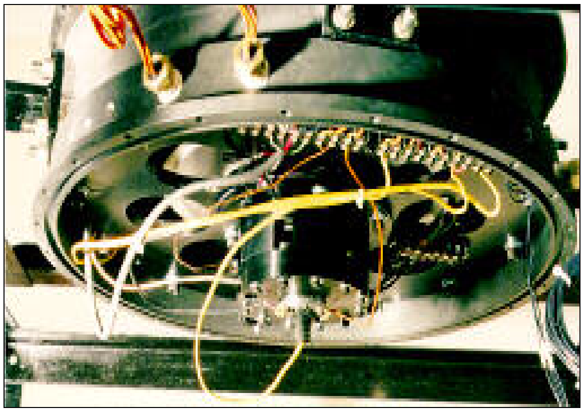

Figure 16 *1.5 kW EMB Lower Instrumentation*

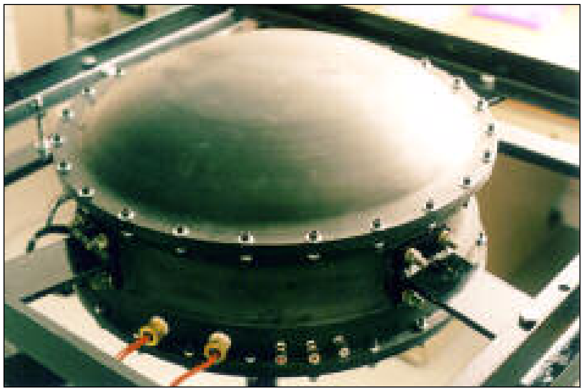

Figure 17 *1.5 kW EMB Complete Assembly*

Figures 15 and 16 show the upper and lower surfaces of the instrumented EMB, while Figure 17 shows the complete EMB in its assembly frame, ready for installation in the test chamber.

Test

The 1.5 kW EMB motor/generator controller uses pulse width modulation (PWM) and a sensorless drive. At low speeds the back electromotive force (EMF) produced is too low for the controller to read, so the controller runs ‘blind’ (at greatly reduced current and power levels) from 0 to 3,000 rpm. Above 3,000 rpm, the controller can supply maximum current/power levels to accelerate (charge and discharge) the flywheel.

During the test program, the 1.5 kW EMB logged over 110 cycles and 155 hours of run-time. The data acquisition equipment room is shown in Figure 18. Figure 19 is a

Figure 18 *FESI Data Acquisition Equipment Room*

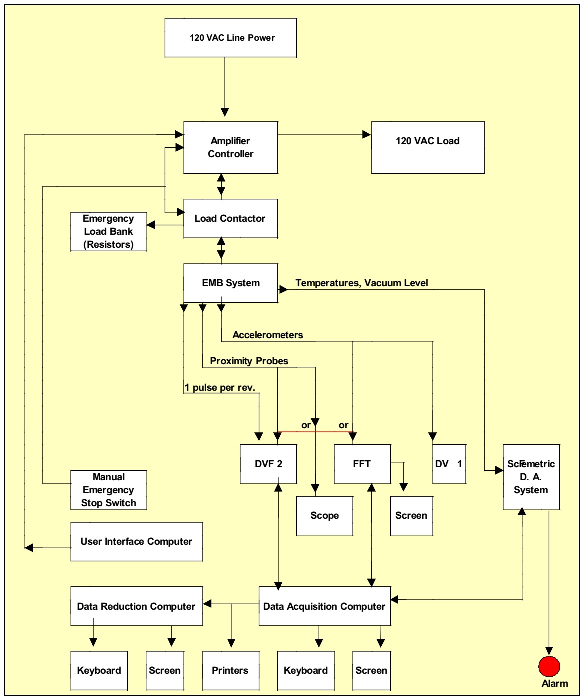

Figure 19 *1.5 kW EMB Test Schematic*

schematic of the 1.5 kW EMB test setup.

Dynamic

Low speed (static) balancing was performed below first critical speed (~7,000 rpm), then the system was balanced at successively higher speeds throughout the testing program. Synchronous displacements of the rotating assembly (as measured at the bearing seats) were tuned to remain below 0.00025 inches (<0.007 mm) for speeds above 10,000 rpm. Below 10,000 rpm displacement amplitudes climbed to about 0.0003 inches (~0.01 mm) as the rotor traversed a suspension natural frequency. The housing vibration levels remained below 0.3 g over this entire speed range (Figure 20 shows the flywheel rotor synchronous dynamic response and housing synchronous vibration for near-final balance trim).

Thermal

Thermal loading mechanisms in the 1.5 kW EMB include motor rotor heating (due to hysteresis), aerodynamic drag, bearing losses, and motor stator heating (due to both speed-dependent back iron heating and power-dependent coil heating—I^2R losses). Since heat conduction paths from the rotating assembly are extremely limited (bearing contact areas are very small), the majority of heat transfer occurs by radiation. Thermal equilibrium is achieved when heat dissipation matches heat generation in the rotating components—this condition results in the highest component temperatures. Achieving thermal equilibrium in the EMB vacuum environment requires considerable runtime; since rotating component losses are predominantly speed dependent, FESI elected to conduct a constant speed thermal equilibrium test at a representative speed of 31,000 rpm.

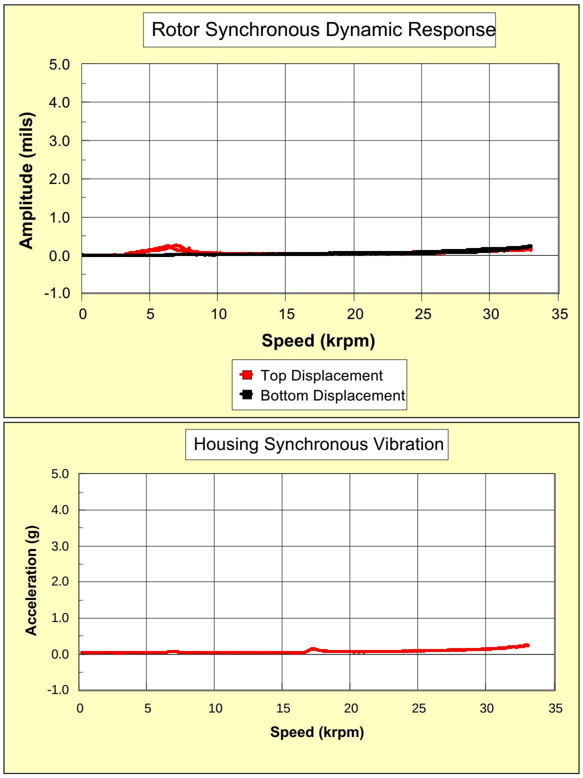

Figure 20 *1.5 kW EMB Dynamic Response*

The 1.5 kW EMB was accelerated to 31,000 rpm and held there for over eight hours at a vacuum level of 2-3 millitorr. Throughout the eighth hour of running, monitored temperature values increased by at most 1 °C—this was within the accuracy of the thermocouples and therefore considered to be thermal equilibrium. Figure 21 shows the monitored temperatures during the test and the FEA thermal profile. Table 2 shows the correlation obtained.

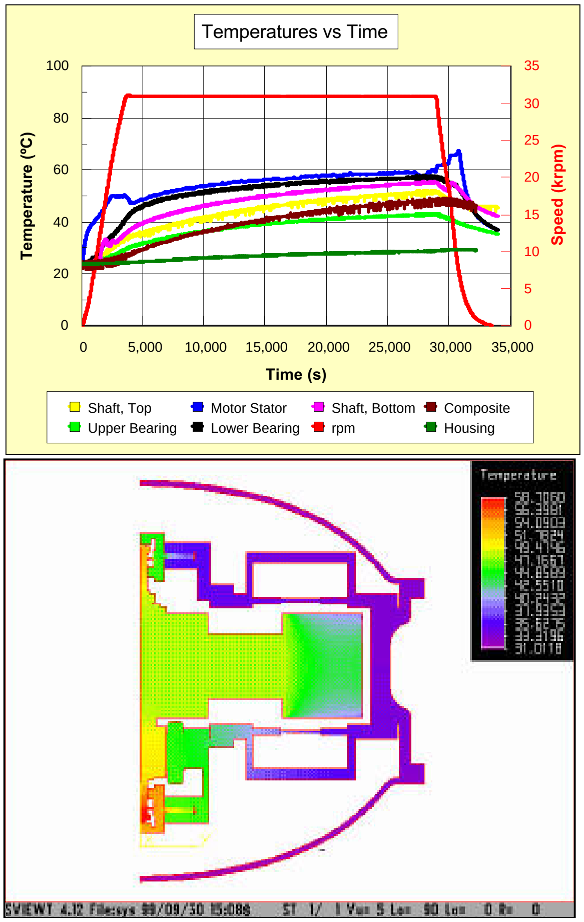

Figure 21 *Thermal Equilibrium Test and FEA Model*

Table 2 *FEA Thermal Model Correlation*

Thermocouple Location	Modelled (°C)	Measured (°C)	Difference(°C)
Shaft, Top	52	51	-1
Upper Bearing	45	43	-2
Shaft, Bottom	58	55	-3
Lower Bearing	55	57	2
Motor Stator	48	57	9
Composite Rotor	47	48	1
Housing	31	29	-2

Power

Figure 22 shows the flywheel power, speed, and monitored temperatures during constant power cycle testing. This demonstration is the simplest load levelling demand schedule: constant power drawn from the EMB, then constant power delivered to the EMB. Since the test was conducted at a vacuum level of 10 millitorr, the component temperatures are slightly higher than those measured during constant-speed thermal equilibrium testing. This test proved that the EMB could be operated at reasonably high power levels without adverse dynamic or thermal consequences.

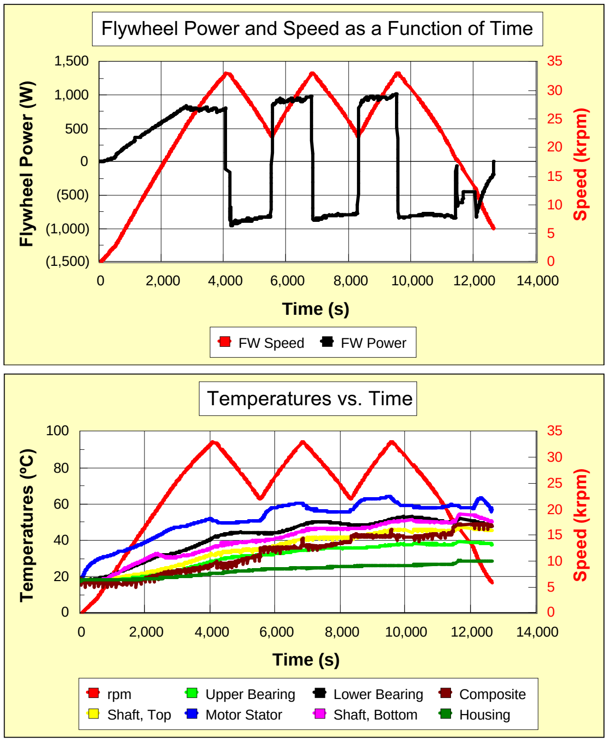

Figure 22 *1.5 kW EMB Cyclic Power Test*

UPS Demonstration

Electromechanical batteries are energy management devices; since this 1.5 kW EMB is a building block in the hybrid vehicle demonstration program, it was designed to demonstrate a DC bus load-leveling capability. The simplest demonstration configuration conceived was an uninterruptible power supply (UPS). To facilitate this test, SL-MTI designed a voltage regulation control strategy into the motor controller/power electronics package.

In UPS configuration, the EMB protects a power quality sensitive load from voltage surges or sags in the grid-supplied power. To demonstrate this feature, a simple test procedure was devised, as follows:

- The machine is accelerated to test speed. This process requires approximately one hour.
- A load is connected to the output plug of the controller—for this demonstration the load is a PC running a simple program. If power stops flowing to the load, the program will shut down.
- The motor contoller is switched to voltage regulation mode via a software interface.
- The controller is disconnected from the line power. The flywheel speed decreases as the motor/generator maintains power to the load via the controller/converter and UPS circuit; the PC continues to operate uninterrupted.
- The controller is reconnected to the line power and the flywheel is recharged.

The machine can be disconnected and reconnected to the line power as many times as desired for the demonstration. A simulation of a severe UPS demand schedule, multiple power outages, is shown in Figure 23. Each interruption continues for a 1,000 rpm drop followed by a 300 rpm climb.

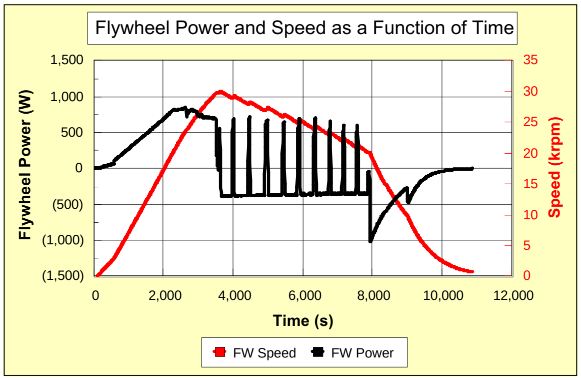

Figure 23 *UPS Demonstration*

Conclusion

The 1.5 kW EMB developed under the "High-Performance Electromechanical Battery Program" has demonstrated stable and consistent dynamic, thermal, and load control response. The software tools and skills base developed in earlier phases of the work have been employed to produce accurate and reliable thermal and dynamic models of the EMB.

Long life bearings and health monitoring require further development (as part of the Safety, Life, and Reliability engineering shown in Figure 4) for commercial EMB system deployment. The experience gained during the 1.5 kW EMB development program has been applied to the next step on the path to demonstrating a hybrid urban transit bus—the 50 kW EMB.

Follow-on Work

The next hardware development in the hybrid bus demonstration program (see Figure 4), the 50 kW - 1kWh EMB (co-funded by FESI and CANMET's Energy Technology Centre), is underway. This EMB is sized to meet the energy and power requirements of a light delivery van and two such systems operated in parallel would meet the peak power demands of a hybrid urban transit bus. Figure 24 shows an elevation view of the assembled 50 kW EMB.

Figure 24 *Assembled 50 kW EMB*