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**Modular Energy Storage System for
Alternative Energy Vehicles**

FINAL SCIENTIFIC / TECHNICAL REPORT

Magna Electronics, Inc.
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Executive Summary

An electrical vehicle environment was established to promote research and technology development in the area of high power energy management. The project incorporates a topology that permits parallel development of an alternative energy delivery system and an energy storage system. The objective of the project is to develop technologies, specifically power electronics, energy storage electronics and controls that provide efficient and effective energy management between electrically powered devices in alternative energy vehicles – plug-in electric vehicles, hybrid vehicles, range extended vehicles, and hydrogen-based fuel cell vehicles. In order to meet the project objectives, the Vehicle Energy Management System (VEMS) was defined and subsystem requirements were obtained. Afterwards, power electronics, energy storage electronics and controls were designed. Finally, these subsystems were built, tested individually, and integrated into an electric vehicle system to evaluate and optimize the subsystems' performance.

Phase 1 of the program established the fundamental test bed to support development of an electrical environment ideal for fuel cell application and the mitigation of many shortcomings of current fuel cell technology.

Phase 2, continued development from Phase 1, focusing on implementing subsystem requirements, design and construction of the energy management subsystem, and the integration of this subsystem into the surrogate electric vehicle. Phase 2 also required the development of an Alternative Energy System (AES) capable of emulating electrical characteristics of fuel cells, battery, gen set, etc. Under the scope of the project, a boost converter that couples the alternate energy delivery system to the energy storage system was developed, constructed and tested.

Modeling tools were utilized during the design process to optimize both component and system design. This model driven design process enabled an iterative process to track and evaluate the impact of design alternatives and the impact of changes. Refinement of models was accomplished through correlation studies to measured data obtained from functioning hardware. Specifically, correlation and characterization of the boost converter resulted in a model that was effectively used to determine overall VEMS performance.

The successful development of the boost converter can be attributed to utilization of previously proven technologies and adapting to meet the VEMS requirements. This program provided significant improvement in development time of various generations of boost converters. The software strategies and testing results support the development of current energy management systems and directly contribute to the future of similar, commercial products at Magna E-Car Systems. Because of this development project, Magna E-Car Systems is able to offer automotive customers a boost converter system with reduced time to market and decreased product cost, thus transferring the cost and timing benefits to the end use consumer.

Table of Contents

1	Introduction	4
2	Final Summary of Phase II Tasks.....	5
2.1	Build and Assemble the Boost Converter	5
2.2	Mid-Range and High-Range Voltage Electronics Behavior Study.....	7
2.3	Integration of the Boost Converter into the Vehicle	8
2.4	Key Inefficiency Drivers and Interfaces.....	15
2.5	Thermal Management Study.....	16
2.6	Implementation of Energy Management Controls.....	17
2.7	Vehicle Energy Performance and Efficiency.....	18
2.8	Project Management and Planning	19
3	Additional Tasks Performed	20
4	References	25
5	Appendix A: Vehicle Energy Management System Model.....	25
4.1	Energy Storage System (ESS) Model.....	26
4.2	Alternative Energy Source (AES) Model.....	29
4.3	Vehicle Power Load Model	31
4.4	DC/DC Converter Model	33
4.5	VCU Model	35
4.6	ESS Battery Management Unit (BMU).....	39
4.7	AES Battery Management Unit (BMU).....	41
6	Appendix B: DC/DC Boost Converter Specifications	43
7	Appendix C: Acronyms	44

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1 Introduction

The overall objective of this project is the establishment of an electrical vehicle environment to promote research and technology development in the area of high power energy management. In effort to meet this objective, the project was first divided into two phases. During Phase I:

- A Vehicle Energy Management System (VEMS) was defined and subsystem requirements were obtained as shown in Figure 1.
- Power electronics, energy storage electronics and controls were designed.
- These subsystems were built and integrated into a surrogate electric vehicle to evaluate and optimize the subsystem's performance.
- A DC/DC boost converter that couples the Alternative Energy System (AES) and the Energy Storage System (ESS) was developed.
- The hardware of the main power stage of the converter was built and testing began.

The goal of Phase II was to finish the design and testing of the boost converter and the AES. In addition to this, integrate the converter and AES into the surrogate vehicle and optimize the complete VEMS design. Phase II was completed and the overall project status is provided in this final report by summarizing each of the eight tasks as defined in the Phase II Statement of Project Objectives (SOPO). These eight tasks are:

1. Build and Assemble the Boost Converter
2. Mid-Range and High-Range Voltage Electronics Behavior Study
3. Integration of the Boost Converter into the Vehicle
4. Identify Key Inefficiency Drivers and Interfaces
5. Thermal Management Study
6. Implementation of Energy Management Controls
7. Vehicle Level Energy Performance and Efficiency
8. Project Management and Planning

Figure 1. Vehicle Energy Management System - ESS, AES and DC/DC Boost Converter

2 Final Summary of Phase II Tasks

All tasks will include the following topics:

- Project summary of the full program activities, including products developed and approaches used
- Problems encountered, including departure from planned methodology and the impact on the project results

2.1 Build and Assemble the Boost Converter

Project Summary

Two complete boost converters were built. Module 1 is used for initial debug, high power testing and vehicle integration. Module 2 was built as a backup or surrogate unit for spare parts. See Figure 2 for boost converter block diagram and Figures 3 and 4 for top side and bottom side converter.

Figure 2. DC/DC Boost Converter Block Diagram

Module 1 was connected to the cooling loop and underwent full verification testing at low and high power levels.

- Verified temperature sensor response at higher temperatures
- Verified current sensors under higher current loads
- Verified that fault detection adequately protects from high voltage or high current conditions
- Collected power in/power out data over expected operating range. Voltage in from 110 voltage direct current (VDC) to 165 VDC. Voltage out from 290 VDC to 330 VDC.

Power from 1.7 kW to 33 kW. Data collected will be used to update VEMS DC/DC boost converter model which will be discussed in Task 2.2

- Module 1 is ready for VEMS integration and then vehicle integration which will be discussed in Task 2.3

Figure 3. Boost Converter Case with Electrical Connectors and Power Inductors

Figure 4. Control Board Mounted on Top of Gate Drive Board

Thermal management studies showed that the boost converter will generate approximately 1500W of heat (nearly 80% due to the IGBT module) during peak operation and will require a

coolant flow rate of 10 liters per minutes. Three sets of radiators, pumps and fans were purchased during Phase I. Radiator sizing was determined, and the appropriate combination was chosen.

Problems Encountered

The majority of the problems that were encountered throughout 2010 were delays in the ordering and requisition of boards and other components. These delays were a result of internal ordering processes, as well as the high demand of these components throughout the industry. Components that were not readily available had to be built either in-house or at external prototype shops. An example of this delay was the unique power inductor used for this project. The new core material advantage of the power inductor was the lower cost and smaller package size due to the elimination of the air gap. This new inductor was intended to be used in other internal development programs; therefore, causing a delay in specifying an inductor to meet the needs of multiple applications.

Computer-aided design (CAD) and software resources were a continuing problem throughout the program. Due to the quick expansion of customer programs within Magna E-Car Systems and the difficulty in acquiring capable and experienced engineers at the necessary rate of utilization, resources were often pulled off of the boost converter development program to support other, more demanding programs. Continually getting new engineers assigned to the program resulted in the repeat of the “learning curve” and time necessary to get up to speed on the program before being able to effectively assist in the next activity or task.

2.2 Mid-Range and High-Range Voltage Electronics Behavior Study

This task consists of a study which covers the following:

- Estimation of Efficiency of the System: Includes a study of the interaction between the converter, energy storage system and the motor controller
- Further Efficiency Gains: Focus study on optimization of the mid-range and high-range power systems.
- Cost and Performance Evaluation: Specific cost and performance drivers will be investigated.

Project Summary

The study was completed and submitted in early 2012. The VEMS DC/DC boost converter model was update with actual efficiency data collected from Module 1. The complete VEMS MATLAB™ model which includes the DC/DC boost converter is shown in Appendix A. Figure 5 shows the Module 1 measured vs. simulated efficiency. Figure 6 shows the simulated power in vs. power out. Both plots are taken from a US06 drive cycle. What can be noticed is that during low power modes, the efficiency of the measured data is better. The opposite is true for high power modes.

Problems Encountered

Systems engineering support to complete the study was an issue late in the program until the study was finally completed. A combination of internal and external resources was used to solve this issue.

Figure 5. Simulated vs. Measured Efficiency

Figure 6. Power In vs. Power Out

2.3 Integration of the Boost Converter into the Vehicle

Project Summary

Figure 7 shows the complete VEMS installed in the battery tray including all high and low voltage wiring. Figure 8 shows the battery tray with the cover on. Figure 9 shows the boost converter radiator installed in front of the main radiator, and associated cooling lines. Figure 10 shows the boost converter coolant lines and pump. Also shown is the wiring for charging the batteries. Figure 11 shows the battery tray installed in the vehicle. Figure 12 shows the boost converter under test.

To date, the system level testing that has been done is:

- The VEMS without the boost converter on the test bench. This testing was to validate the Vehicle Control Unit software and Set Point Algorithm. The AV900 battery cycler was used to simulate the converter; it was not yet completed.
- The boost converter in stand-alone without the VEMS on the test bench

The Set Point Algorithm resides in the vehicle control unit (VCU). Its function is to monitor the State of Charge (SOC) of the high voltage ESS battery. Under all conditions, it attempts to keep the SOC at a calibrated set point (usually 70%). When there is a demand from the vehicle, the algorithm commands the boost converter to supply current so the SOC will not drop significantly. The algorithm will always try to keep the SOC at the set point and adjust the converter current appropriately.

The AV-900 battery cycler was used to validate system operation between the VCU and Battery Control Units (BMU). It was also used to validate the set point algorithm. The VCU has the software to communicate to the boost converter.

The AV-900 is an ideal development test environment due to its equipment being Controller Area Network (CAN) enabled, as well as having the capability to be programmed in a C-based language to control the various peripheral equipment and automate power delivery to attached test devices. The CAN capability allowed the battery cycler to interface with the two battery controllers (BMU-A and BMU-K), as well as the VCU to replicate the behavior of the boost converter in addition to providing high voltage power delivery. Channel A of the battery cycler was configured to simulate a boost converter, and Channel B was configured to simulate the electric energy created and dissipated by a vehicle electric drive motor.

Once the system was powered, Channel A of the battery cycler would communicate over the CAN BUS (using a Magna E-Car Systems' internal communication protocol) with the battery controllers and the system controller to bring the entire system online and connect to the high voltage system. With the system initialized the battery cycler Channel A would supply the high voltage bus with the current requested by the vehicle controller to keep the state of charge of the A123 pack at the predetermined level. Figure 13 shows a block diagram of the bench test set up that utilizes the AV-900 acting as both a vehicle load and a boost converter while being controlled with the C-based command script mentioned above.

Following the start-up procedure, the battery cycler Channel B was enabled to run an artificial drive cycle profile consisting of 20A charge and discharge cycles shown below in Figure 14. Given the efficiency of the system, the drive profile is charge depleting and would bring the state of charge of A123 to a lower level if it is to be run without the energy contribution of the boost converter. Testing conducted on the system verified the proper control functionality of the set point algorithm. The A123 battery was placed at a higher state of charge than the set point level and after running the charge depleting profile, the SOC was brought to a lower level requiring contribution from the boost converter. The voltage graph in Figure 15 shows how the voltage level of the battery decreases until it reaches SOC set point and remains stable due to the added contribution of the boost converter. This also verifies the communication between controllers is functioning properly.

The boost converter was tested independently connected to the AV-900 to exercise the input (mid-voltage) and output (high voltage). The input voltage input current, and output voltage was commanded. The input voltage and current as well as the output voltage and current were measured. The efficiency was calculated from the measured data. Figure 16 shows a small subset of the test matrix used. This is how Module 1 was validated as mentioned in Section 2.1.

Problems Encountered

Due to Magna E-Car Systems' extensive vehicle integration experience, no major issues occurred in the integration of the energy management system. All components were successfully integrated into the battery tray assembly. The auxiliary cooling system was successfully integrated into vehicle and utilized for cooling of the DC boost module. The primary problem that occurred was a system failure that caused all of the high speed CAN communication busses to fail in 2010. The CAN busses were located between the VCU and BMU, as well as between the BMU and vehicle traction inverter module (VTIM). An extensive failure analysis study was done and showed that the root cause of this failure was a high voltage application in excess of 5V to the BMU signal powering the VTIM units. The corrective action was to harden this 5V supply signal.

Figure 7. Complete VEMS within Battery Tray Including Wiring

Figure 8. Battery Tray w/ Cover On

Figure 9. DC/DC Radiator w/ Coolant Lines

Figure 10. DC/DC Coolant Lines, Pump and Wiring

Figure 11. Battery Tray Installed in Vehicle

Figure 12. DC/DC Boost Converter Under Test

Figure 15. Set Point Algorithm Results, Controlling the High Voltage ESS Battery SOC

Commanded				Measured				<i>Efficiency</i>
<i><u>Pin</u></i>	<i><u>Vin</u></i>	<i><u>Iin</u></i>	<i><u>Vout</u></i>	<i><u>Vin</u></i>	<i><u>Iin</u></i>	<i><u>Vout</u></i>	<i><u>Iout</u></i>	
								Vout*Iout/Vin*Iin
1.7	165	10.3	290	164.91	10.423	289.80	5.586	0.9423
5.0	165	30.3	290	164.81	30.18	289.77	16.54	0.963
8.3	165	50.3	290	164.75	50.28	289.75	27.68	0.969
11.6	165	70.3	290	164.70	70.51	289.80	38.99	0.973
14.9	165	90.3	290	164.62	90.02	289.73	49.88	0.975
18.2	165	110.3	290	164.61	110.48	289.78	61.28	0.976
21.5	165	130.3	290	164.54	130.36	289.77	72.32	0.977
24.8	165	150.3	288	164.45	150.27	289.71	83.30	0.976
28.1	165	170.3	289	164.46	170.34	289.72	94.40	0.976
29.7	165	180.0	290	164.43	179.89	289.74	99.68	0.977
31.4	165	190.3	290	164.40	190.22	289.75	105.41	0.977
33.0	165	200.0	290	164.39	199.63	289.77	110.58	0.976

Figure 16. Boost Converter Test Matrix

2.4 Key Inefficiency Drivers and Interfaces

Key inefficiency drivers were identified in the Mid-Range and High-Range Voltage Electronics Behavior Study and the Thermal Management Study. The drivers are as follows:

- The power limiting within the VCU must be optimized. The VCU will limit the power of the vehicle inverter/traction motor when the SOC of either battery gets too high or low. If the power limit calibrations are too aggressive, the vehicle will undergo unnecessary limiting which causes drivability/performance issues. These calibrations must take into account

worse case drive cycles and the amount of regeneration. System bench testing, dynamometer and road testing are needed to properly tune these limits.

- The gain of the Set Point Algorithm can be optimized to minimize the time the boost converter spend and maximum power (>26kW). This optimum calibratable gain minimizes the energy utilized by the DCDC converter output. When the output energy is minimized, the power dissipation across the converter is also minimized which aids in the efficiency of the system.
- The Set Point Algorithm gain, set point and deviation from the set point calibrations can be optimized to minimize the output energy from the boost converter. If the calibrations can be optimized to draw more current from the battery (which is very efficient), then the boost converter operation is minimized. This causes less power dissipation and higher efficiency. For future design considerations, an adaptive gain algorithm could be developed to further improve efficiency.
- The boost converter is most efficient above 12.5kW. The efficiency drops from 96% at above 12.5kW, and drops to 90% when operating below 12.5kW. If the converter can be turned off below 12.5kW, an efficiency gain is achieved. There would be a price to pay with regards to the ending SOC of the ESS battery at the end of the drive cycle. If this can be tolerated, efficiency is achieved. The converter does not need to be totally turned off. It could go into a low power mode below 12.5kW by using the following methods:
 - phase reduction – turning off phases of the three phase converter during low power modes
 - rotating pulse reduction – dropping pulses during low power applications
- The current boost converter design implements a pin-fin cold plate design for use with the IGBT module. The cold plate is separate from the IGBT module and an interface exists when marrying the two together. A layer of thermal grease is used for conduction purposes. A new IGBT module has recently been developed that is constructed with an integrated pin-fin cold plate with the module, thus eliminating this interface. This construction reduces the thermal resistance, thus increasing the efficiency of the module and ultimately the converter itself.
- Studies have shown that optimizing the application of the thermal grease between baseplate type modules (current design), and the cold plate can reduce the thermal resistance. Using a stencil instead of rolling or painting on the grease provides for a more even distribution. If an even amount of grease is applied across the baseplate, it spreads out around the screw locations in good form. However, the spreading of the thermal grease in the center is poor. An optimized stencil would be designed to minimize grease around the attachment screws and maximize the grease in the center. The clamping pressure is greater around the screws than in the center of the baseplate⁽¹⁾.

Problems Encountered

No major issues, specific to the inefficiency occurred during this project. Voltage and thermal study specific issues are described in more detail within their respective sections.

2.5 Thermal Management Study

The study has four main objectives:

1. Thermally model the IGBT module using Finite Element Analysis (FEA), and predict the IGBT and anti-parallel diode junction temperatures during a system level transient simulation

2. Compare the FEA simulation data to the data extracted from laboratory bench test equipment, refine the system level model, and discuss the differences
3. Explore enhanced cooling strategies to lower the junction temperatures of the IGBT and anti-parallel diodes
4. Discuss equivalent air cooled configuration

Project Summary

This study was completed in mid-2012. A comparison was made between measured temperature from the Analysis Tech™ thermal characterization test equipment and the Finite Element Analysis model:

- The measured IGBT temperature showed a 4C reduction in temperature as compared to the FEA model
- The measured diode temperature showed a 0.27C reduction in temperature as compared to the FEA model

The air cooled heat sink approach to cooling the IGBT module is not feasible versus the liquid cooled cold plate mainly due to:

- It will be much larger than the cold plate which in turn forces a bigger boost converter case.
- The weight will increase which typically is never a good alternative
- The fan size will be substantial and will need to be packaged and supplied with power.
- Overall, suitable packaging and performance is unacceptable for vehicle application.

Problems Encountered

The design of the 3D layout of the boost converter and case encountered some delays due to the original layout of the cooling channel. The space originally intended for the channel was slightly smaller than required and could not be expanded due to interference with the capacitors on the completed gate drive board. This layout issue resulted in re-design and was ultimately solved at the end of 2010.

Other delays occurred in the requisition of the thermal characterization equipment. Due to its overall expense and very specific equipment options, additional time was utilized by the procurement team to compare and research the various suppliers and equipment available, as well as compare the potential use for future designs. After finally acquiring the equipment, it was discovered that the calibrated test times in the default settings were not long enough for the device to be thoroughly heated. It was determined that the IGBT module needed more time to reach the thermal set points because of the large thermal mass of the cold plate that it was attached to. The settings were adjusted accordingly. This did not deviate from the original scope, but delays caused a deviation from the original project timing. This resulted in the need for project extensions.

2.6 Implementation of Energy Management Controls

Project Summary

There are four controllers within the Vehicle Energy Management System: VCU, BMU (2), and DC/DC converter.

- Battery Management Unit - The main algorithms within the BMU are the SOC algorithm and the state machine (start up, normal, shut down and charging). The SOC algorithm was carry over from another previous project, which lends history and experience. . All

that had to be done is calibrate it with the appropriate battery cells (A123 & Kokam). Both have very different polarization curves. The state machine was implemented early in Phase I. The software for the BMU's was completed early in Phase I.

- Vehicle Control Unit - The main algorithms within the VCU are the Set Point Algorithm, state machine (start up, normal, shut down and charging), communication with the vehicle through the gateway, and communication to the DC/DC converter. The gateway is a controller that passes Ford's Standard Corporate Protocol (SCP) network messages to the VEMS CAN 2.0 network, and vice versa. The VCU software was broken up into four releases which spanned over Phase I and II. The state machine for controlling the BMU's, and the communication to the vehicle via the gateway was completed in Phase I (software versions 1 and 2). The Set Point Algorithm was modeled in Simulink™ and C-code was generated utilizing MathWorks Real Time Workshop Embedded Coder™. This modeling allows changes to be made to the model, simulated to verify the intent and code and then can be automatically generated, instead of lengthy hand-coding and the potential for software errors. This algorithm was completed in Phase II, software release 3. Communication to the DC/DC converter was completed in Phase II, software 4. The VCU software is considered complete with the version 4 release. This software will allow the complete VEMS to properly enter into start up, normal, shut down and charging modes and communicate with the vehicle.
- DC/DC converter - The main algorithms within the DC/DC converter are the 120 degree phase shift, and the state machine (start up, normal, shut down and charging). Both functions were implemented and debugged by the 1st Quarter 2012. The converter was fully tested over the full power range (see Task 2.3 above). The DC/DC converter software is considered complete.
- The developed VEMS control system was bench tested for performance capacity (reference Section 2.3 for details).

Problems Encountered

Ordering and requisition of capital equipment and components resulted in early timing delay issues due to internal process changes and difficulty in specification alignment. After appropriate processes were developed, minimal delays occurred throughout 2011. Software resources required continued management and alignment due to the frequent turn around and re-assignment to other projects. However, this prevented further delays. This did not deviate from the original scope, but delays caused a deviation from the original project timing. This resulted in the need for project extensions.

2.7 Vehicle Energy Performance and Efficiency

Project Summary

The vehicle level information regarding energy performance and efficiency is from simulation. Table 1 shows energy used, range, efficiency and specific energy for both the 1998 Ford Ranger EV with lead acid batteries (actual), and equipped with VEMS (simulated). Refer to Task 2.4 above for additional efficiency discussions.

What is interesting is that the efficiency is relatively the same, but the specific energy for the VEMS system is about 35% on average better than that of the lead acid configuration. This makes sense due to the density of lead vs. lithium ion. The VEMS configuration was actually weighed within the existing battery tray used on the 1998 Ranger and was compared to the

weight of the lead acid configuration within the tray. The VEMS is 870 pounds lighter than the lead acid battery configuration (1916lbs/870kg vs. 1046lbs/475kg). The take away here is that much more lithium ion batteries can be added to extend the range. Packaging of the AES battery pack was not optimized. Another 15 KWh could easily be added to the existing battery tray of the Ranger if packaged properly. This would roughly double the range. The specific energy would also go up due to the fact that if all the AES cells were properly packaged, the weight would only go up a few hundred pounds (e.g. 1250lbs/568kg); this would give a specific energy of 57 Wh/kg.

Table 1. Energy, Range, Efficiency and Specific Energy vs. Vehicle Configuration

	1998 Ranger EV Original Performance Statistics from 1997 per Idaho National Laboratory (Lead Acid)	1998 Ranger EV equipped with VEMS - simulated
Constant 45 mph		
Energy Used (KWh)	20.63	17.98
Range (miles)	86.9	77.3
Efficiency (Wh/mile)	237	232
Specific Energy (Wh/kg)	23.7	37.9
Constant 60 mph		
Energy Used (KWh)	20.60	17.68
Range (miles)	57.9	52.1
Efficiency (Wh/mile)	356	339
Specific Energy (Wh/kg)	23.7	37.2
Driving Cycle Range per SAE J1634		
Energy Used (KWh)	21.96	N/A
Range (miles)	65.1	
Efficiency (Wh/mile)	337	
Specific Energy (Wh/kg)	25.2	
UDDS		
Energy Used (KWh)	N/A	17.53
Range (miles)		52.3
Efficiency (Wh/mile)		335
Specific Energy (Wh/kg)		36.9

Problems Encountered

Comparative data did not include UDDS for Phase 1 (test was not run), and comparative data was not available for Phase II SAE J1634 because of insufficient detail on the drive cycle to integrate into simulation model. The simulated numbers at constant 45 mph and 60 mph demonstrate key performance capabilities of Phase I vs. Phase II designs. The simulated results aligned with expectations.

2.8 Project Management and Planning

Project Summary

Program management efforts focused continually on resource management and task timing. As previously mentioned, resources were constrained on this program and new engineers to the program had to be trained and “brought up to speed” on the program. This type of management required a full time program manager and technical lead to ensure continued momentum. Progress of the tasks was managed through regular red issue meetings and periodic escalation to management, as needed.

During the third quarter of 2010, Magna E-Car Systems was established as a joint venture between Magna International and the Stronach Trust. As a result, Magna E-Car Systems absorbed part of Magna Electronics, including the team and project of the DE-EE0002442 award. This change in structure created significant delays in the program, including invoicing and reporting. No cost extensions and novation in awardee name were requested. Changes in the DOE program management contributed to some delays and the novation was retracted with the expectation of Magna Electronics and Magna E-Car Systems performing internal financial transfers as received.

A technical program review and status update was provided to the management team at the U.S. DOE National Energy Technology Laboratory on January 24, 2011. Quarterly progress and milestone reports were submitted each quarter to the DOE by the established due dates throughout the life of the project.

Problems Encountered

The problems encountered throughout the life of the program were primarily due to lack of resources and the resulting timing delays.

With this program being one of the first government awards for the organization, many processes had to be established to ensure compliance and consistency. These processes, along with the change in processes that occurred when the new legal entity was established in the third quarter of 2010, inadvertently resulted in numerous delays in purchasing, invoicing, task management, document sharing and other highly intranet-based processes.

The delay and uncertainty in receiving an extension approval and ultimately being able to invoice the DOE lowered the priority of the program within Magna E-Car Systems. This lowered priority resulted in a reluctance to dedicate employees full-time to the DOE program over competitive, confirmed and profitable customer programs. Employees were assigned to the DOE program on a part time basis and usually were replaced with new employees that struggled with the “learning curve” of the previous accomplishments and lessons learned of the program. Program managers, lead scientists, engineers and technicians were all replaced at some point (and some multiple times) throughout the life of the program.

3 Additional Tasks Performed

Advanced Control Algorithms on High Efficiency Isolated Full Bridge Converter

This activity was added to the original project objectives as a result of the information and knowledge of the DC/DC converter efficiencies by Magna E-Car Systems throughout the term of the overall project. This further study of the efficiencies and control algorithms was necessary to fully understand and build a next generation DC/DC converter. Due to the compressed timeline and lack of internal resources to complete this study, Kettering University in Flint, Michigan was contracted to assist in the activities. Besides offering Magna E-Car Systems the assistance in completing the study, this project provided additional hands-on experience and knowledge for the numerous graduate and undergraduate students that worked on the project. The goal of this project was to develop a high efficiency DC/DC converter capable of a 400 volts direct current (VDC) input to a variable 250-450VDC output with efficiencies contained in Table 2 below. In addition, control algorithms for the phase-shift full bridge converter needed to be developed with a focus on high efficiency, low electrical stress and fast response time.

Table 2. DC/DC converter output efficiencies

Output Voltage	Power	Efficiency
250 – 400VDC	100%	>97%
200 – 250VDC	80%	94%
400 – 450VDC	80%	92%
	75W minimum power	<90%

In order to develop and prove-out the DC/DC converter, a thorough design analysis and modeling needed to precede the prototype build and test. The steps and milestones of this project were organized accordingly:

- Design analysis
 - Block diagram
 - Topology selection
 - Thermal analysis
 - Electromagnetic Compatibility (EMC) – sources of concern
 - Worse case circuit analysis
- Modeling and simulation
- Prototype part build
- Prototype test plan / results

Full Bridge Block Diagram

The block diagrams illustrating the main power-flow components and the major input/output (I/O) connections between the Texas Instruments (TI) DSP and peripheral circuits are shown in Figures 17 and 18 respectively.

Figure 177. Full bridge power flow block diagram

Figure 18. Major I/O connections with DSP

Topology Selection

A thorough and comprehensive study was completed of the various DC/DC topologies designed. The pros and cons were weighed for each topology along with the operational theory. A total of nine topologies were examined. The attractive features of each converter topology are identified in Table 3. The types of DC/DC topologies included:

- 4.1 – Forward converter
- 4.2 – Flyback converter
- 4.3 – Half-bridge converter
- 4.4 – Full-bridge inductor, inductor, capacitor (LLC) resonant converter

After studying these comparisons, the full-bridge LLC resonant converter (4.4) topology was selected due to its high efficiency (wide soft-switching range), as well as its simple control and high-power capability.

Table 3. Comparison of DC/DC topologies

Converter Type	4.1	4.2	4.3	4.4
Low Cost	X	X		
High Efficiency			X	X
Simplicity of Control	X	X	X	X
Reliability			X	X
Low electrical stress		X		X
High-Power capability			X	X

Thermal Analysis

The system is operated at the target efficiency (97%) and at the full rated power (10kW); therefore the calculated total loss shall be 300W. Assuming that this power is evenly distributed, using the equipped air-cooled heatsink manufacturer's specified thermal resistance of 0.028 °C/W, the temperature rise of the heatsink should approximately be 8.4 °C above ambient. In practice, this heating will not be evenly distributed, resulting in localized "hot-spots"

within the heatsink. For safe operation, the junction temperature of each device does not approach the rated maximum value, while operating at this "hot-spot".

For this full bridge, another issue reported is the loss distribution at different output voltage is different. At low out voltage, the conduction loss of secondary-side diodes is higher than the high output voltage case because of the high current. At high out voltage, the turn-off loss of the primary-side metal-oxide semiconductor field-effect transistor (MOSFET) will increase due to the high turn-off current. The simulated power device losses are shown in Table 4. Here P_{sw} is the MOSFET switching loss and P_d is the secondary-side diode loss. So the highest $P_{sw}+P_d$ happens roughly at $V_o=400V$.

Table 4. Phase shifted full-bridge (PSFB) loss distribution per device

$V_o(V)$	200	250	400	450
$P_{sw}(W)$	16.9	11.5	21.5	21.2
$P_d(W)$	8.1	13.7	13.0	5.6

The copper loss of the transformer and inductor is very small due to the small internal resistance (1.46m Ω , 1.49m Ω , 0.59m Ω for resonant inductor, transformer primary side and secondary side, respectively). Therefore, this part of the loss could be ignored. The iron loss is difficult to estimate since the present transformer was not underdesigned. Theoretically, it could be assumed 100W iron loss for the transformer (1% loss for the optimal transformer) and 20W for the resonant inductor. It can also be assumed that approximately 10W will be dissipated within the two relays. Based on Table 3, the maximum power dissipation in each MOSFET and its body diode is roughly 21.5 W. If a heatsink temperature of 78.4°C and a thermal resistance between heatsink and TO-247 package of ~0.2 °C/W (due to Kapton film isolation) is assumed, it can be verified that the junction temperatures will not exceed their rated maximum value.

$$T_J = T_S + P_d * (\theta_{JC} + \theta_{CS}) \rightarrow (78.4 \text{ } ^\circ\text{C}) + (21.5W) * (0.9 \text{ } ^\circ\text{C/W} + 0.2 \text{ } ^\circ\text{C/W}) = 102.05 \text{ } ^\circ\text{C}$$

Below in Table 5 is a list of all the major semiconductor / high-current carrying components used in the DC/DC prototype, along with their rated maximum junction temperature; the highest measured case temperature and calculated junction temperatures while operating at 10kW in 25°C ambient. Values listed are for a single component of the type specified.

Table 5. The measured temperature of different components

Device	Rated $T_{J,max}$	Meas. T_C	Calc loss (W)	Rated θ_{JC}	Calc'd T_J
MOSFET	175°C	55°C	21.5	0.26	60.59
Diode	175°C	55°C	13.0	0.9	66.7
Transformer	(155°C)	70°C	100	0.3	100
Inductor	(155°C)	54°C	20	0.6	66

Note: All measured / calculated values are based on DC/DC converter running at 10kW at 25°C ambient temperature.

Electro-Magnetic Compatibility Sources of Concern

All of the diodes of this system are softly turned off without any reverse recovery loss. The MOSFET is softly turned on zero voltage shifting (ZVS); therefore, there is no noise at the turn-on moment. So the only major EMI comes from the half turn-off moment of the MOSFET. Since the MOSFET turn-off current is also low (<20A per piece), the EMI issue of this system is extremely low compared to other topologies. This is also regarded as the advantage of LLC resonant topology.

Worst-Case Circuit Analysis

- Shoot-through or bridge-bridge short circuit: Assume the stray inductance between the DC bus and bridge is ~20nH. When phase-phase short circuit happens (or shoot through) at the bridge side, the maximum allowed protection time is:

$$\Delta t = \frac{L_{stray} \Delta I}{V_{DC}} = \frac{20nH \times (225 \times 2 - 50)A}{400V} = 20(ns)$$

The PCB designed has the desaturation functionality. The gate-drive chip HCPL-316J will monitor the voltage across of the MOSFET, VDS. When shoot-through happens, VDS will go up, which will be detected by HCPL-316J shutting down all the PWM signals and launching the fault display. In the development stage, shoot through did happen several times due to the inappropriate gate-drive parameter settings; however, no semiconductor switches were burned due to the instantaneous shutting down by the HCPL-316J.

- Output short-circuits: When the output of the system gets directly short circuit at the maximum output voltage 450V and with the assumption that the short-circuit load have an inductance 200nH (filtering inductance) and 200mΩ (battery resistance), the output current peak (simulated) is 1900A. This current will blow the output fuse, relay and wire since it will discharge the output capacitors, C101 and C102. If the fuse fails to be burned within 2.7us, then the transformer current will increase to 1260A after 10us theoretically. However, in the present system, the hardware over-current protection will be triggered when MOSFETs current is above 100A, which will shut down the entire switch and the output relay. Therefore, the system will be resistive to the fault of output short circuit.

Modular DC/DC Converter

The overall goal of this project was to develop an analog controlled 800W DC/DC converter with high operating efficiency which can be paralleled to be combined to make converters up to 3.2kW or greater. The topology utilized is full bridge buck only from HV to LV with primary ZVS and secondary synchronous rectification and is shown in Figure 19. Each DC/DC is 800W output rated with up to four units planned for parallel operation to achieve 3.2kW. Parallel operation is accomplished by syncing each unit with the microcontroller on unit #1 that provides a timing signal shifted by 180 degrees for two units in parallel and 90 degrees for four units. Efficiency measured on an 800W unit was between 93% and 96% when load is >50% and the input voltage is <350Vdc. The block diagram of this system is shown in Figure 20.

Figure 19. 1600W DC/DC converter

Figure 20. DC/DC block diagram

Upon completion of the hardware prototype build, both the 800W and 1600W modules were tested. The tests and results are:

- Power level: 800 W – 3.2 kW
- Input voltage range: 150 – 450V
- Output: 10-16 V and 0 – 250 Ampere
- Paralleling concept of current sharing met requirements
- Efficiency:
 - Peak efficiency: 95.94%: at 60°C 3.2 kW cooling plate temperature
 - Peak efficiency: 93.6%, at 87°C, 1.6kW, 100% load
 - Peak efficiency: 94.25%, at 87°C , 1.6kW, 70% load (3 hours)
- Average efficiency: > 91.5%: 3.2 kW (50% load) for full input voltage range
- Temperature: Continuous operation up to 87°C (normal OEM-req. 65°C)
- Output ripple: Test result: 0.2 voltage peak to peak (V-pp). (Requirement 0.1 V-pp.)
- EMC Testing: Evaluation conducted only. Improvement would be required. Circuit board layout changes are required to meet customer EMC requirements.

4 References

- [1] Nishimura, Y., Oonota, M., and Momose, F., Thermal Management Technology for IGBT Modules, Fuji Electric Review, Vol. 56, No. 2

5 Appendix A: Vehicle Energy Management System Model

Figure 18. Vehicle Energy Management System Simulation Model

This top level system model of Figure 21 includes the following models which are explained in detail below:

- ESS Battery – This is a Lithium Ion characterized battery model for the A-123 Systems cells used for the Energy Storage System
- AES Battery – This is a Lithium Ion characterized battery model for the Kokam cells used for the Alternative Energy Source
- Vehicle Power Load Model – This models the electrical power load of the surrogate vehicle (1998 Ford Ranger EV) over a US06 drive cycle
- DC/DC Converter – This is an average model of the DC/DC converter
- VCU – This is high level model of the SOC set point algorithm
- ESS Battery Management Unit – This is the controller that monitors and controls the ESS battery and communicates status over the VEMS CAN bus
- AES Battery Management Unit – This is the controller that monitors and controls the AES battery and communicates status over the VEMS CAN bus

4.1 Energy Storage System (ESS) Model

Figure 22. Energy Storage System (ESS) Model Details

Model Description:

The ESS Model is a characterized dynamic Lithium Ion battery model as shown in Figure 22. The input parameters to the model are tuned to the data sheet specifications in order to match the discharge characteristics of the cell. It contains a Breaker model that simulates the contactors to the DC bus. The Breaker is controlled by the ESS Battery Management Unit (BMU).

Theory of Operation:

Figure 23 shows the internal operation of the Lithium Ion battery model along with the definition of the equations used for the nonlinear battery voltage E_{batt} . There are three operating regions for the model: exponential, nominal and end-of-charge. Referring to Figure 24, the exponential zone is where the voltage drops exponentially from a fully charged condition shown in yellow. Depending on the battery characteristics, this area is more or less wide. The nominal zone represents the charge that can be extracted from the battery until the voltage drops below the battery nominal voltage E_0 . The end-of-charge zone represents the total discharge of the battery where the voltage drops rapidly. E_0 is related to the battery's open circuit at-rest voltage and is found from the polarization curve at the end of the nominal zone. As can be seen in the Lithium-Ion E_{batt} charge and discharge equations below, the three zones are modeled by making the specific components of the equations more or less active: $\hat{i}$ component for the nominal region, it component for the end-of-charge region, Exp component for the exponential region. The internal resistance iR voltage drop is either added or subtracted (charged or discharged respectively) to the nonlinear battery voltage E_{batt} and is applied to the electrical terminals of the model. The polarization curve for the ESS battery pack is generated from the manufacturer data sheet for an individual cell.

The input parameters given below are entered into the model and 'tuned' to match the polarization characteristics from the data sheets.

Figure 2319. Block Diagram of Lithium Ion Dynamic Battery Model

Lithium-Ion Model

Discharge Model ($i^* > 0$)

$$u = E_0 - K \cdot \frac{Q}{Q - it} \cdot i^* - K \cdot \frac{Q}{Q - it} \cdot it + A \cdot \exp(-B \cdot it)$$

Charge Model ($i^* < 0$)

$$u = E_0 - K \cdot \frac{Q}{it + 0.1 \cdot Q} \cdot i^* - K \cdot \frac{Q}{Q - it} \cdot it + A \cdot \exp(-B \cdot it)$$

where,

E_{batt} = Nonlinear voltage (V)

E_0 = Nominal constant voltage (V). This voltage represents the end of the linear zone of discharge characteristics.

$Exp(t)$ = Exponential zone dynamics (V)

Sel = Represents the battery mode. $Sel = 0$ during battery discharge ($i^* > 0$), $Sel = 1$ during battery charge ($i^* < 0$)

K = Polarization constant (Ah)⁻¹ found from the polarization curve

i^* = low frequency current dynamics (A)

it = Extracted capacity (Ah)

Q = Maximum battery capacity (Ah)

A = Exponential voltage (V) found from the polarization curve

B = Exponential capacity (Ah)⁻¹ found from the polarization curve

Ri = Internal resistance found from manufacturer data sheet

Figure 24. Lithium Ion Polarization Curve of the ESS Battery Pack

Input Parameters:

The following parameters are found from manufacturer's data sheet for the ESS Li-Ion battery:

- Nominal voltage (V) – this is E_0 above
- Rated Capacitance (Ah)
- Initial State-Of-Charge (%) – This is the initial state of charge of the battery before simulation
- Maximum Capacity (Ah) – this can be different from rated for some manufacturers
- Fully Charged Voltage (V) – voltage when battery is fully charged
- Nominal Discharge Current (A) – several curves can be used for discharge and are chosen with this parameter
- Internal resistance (Ohms)
- Capacity (Ah) @ Nominal Voltage
- Exponential zone [Voltage (V), Capacity (Ah)]

Available Signals:

The following signals are available for plotting:

- ESS_Status – bus with 3 signals
 - SOC – battery State-Of-Charge (%)
 - Current – Output current
 - Voltage – Output voltage
- In1 – Command signal to turn on the contactors from the ESS Battery Management Unit (BMU)
- V bat+, Vbat- - Electrical ESS high voltage DC bus (voltage, current)

4.2 Alternative Energy Source (AES) Model

Figure 20. Alternative Energy Source (AES) Model Details

Model Description:

The AES Model is a characterized dynamic Lithium Ion battery model as shown in Figure 25. The input parameters to the model are tuned to the data sheet specifications in order to match the discharge characteristics of the cell. It contains a Breaker model that simulates the contactors to the DC bus. The Breaker is controlled by the AES Battery Management Unit (BMU).

Theory of Operation:

Refer to theory of operation for the ESS Lithium-Ion battery model above. The AES battery has a different (lower voltage) polarization curve shown in Figure 26.

Figure 21. Lithium Ion Polarization Curve of the AES Battery Pack

Input Parameters:

The input parameters are the same as the parameters for the ESS Li-Ion battery above.

The following signals are available for plotting:

- ### 4.3 Vehicle Power Load Model

Model Description:

Theory of Operation:

The purpose of this model is to provide an accurate dynamic electrical vehicle load for the ESS, AES and DC/DC converter of the VEMS. Magna Electronics uses an electric propulsion load simulator to generate the power versus time profile for an inverter/traction motor combination. The power profile is divided by the DC high voltage bus value. The resultant current is applied to the ESS, AES and DC/DC converter as a load.

The model also has a CAN input from the VCU (described below) that limits power. When the VCU determines that the power limit is exceeded of the VEMS, a signal is sent to the Vehicle Power Load Model to limit the power demand from the vehicle. This is to dynamically simulate the power limiting that the VCU commands to the vehicle Traction Inverter Module (TIM) to limit power in either discharge or regeneration.

Input Parameters:

- Drive cycle
- Electric traction motor type
- Inverter type
- Final drive ratio
- Gear box efficiency
- Gear box inertia
- Maximum motor RPM
- Vehicle CD or dynamometer coefficients (A, B, C)
- Vehicle mass
- Regeneration included (yes/no)
- Tire size

Available Signals:

The following signals are available for plotting:

- Load_Cur: Output load current from vehicle (propulsion system)
- Load_Pwr: Power versus Time waveform which is represented as source model (Power vs. Time Drive Cycle block above). Positive power is represented as a load and negative power is regeneration back to the ESS battery – see Figure 28.

Figure 23. Power ($\times 10^4$ KW) versus Time (seconds) for US06 Drive Cycle

- Vehicle_Speed: US06 Vehicle Speed vs. Time profile that was used to generate the power profile is also given by the model for plotting reference comparisons – See Figure 29.

- Command_Pwr: Raw output power demand for various drive cycles (power vs. time)
- Command_Load_Energy: Raw output energy (Wh)
- Actual_Load_Energy: The output energy after power limiting (Wh)
- From_VCU_CAN: bus signal containing <Power_Limit> calculation from VCU
- DC_V+, DC_V-: Electrical high voltage DC bus (voltage, current)

4.4 DC/DC Converter Model

Model Description:

The DC/DC Converter Model is an average, non-switching model of a DC/DC converter as shown in Figure 30. It contains an efficiency map to give actual switching and conduction losses across the converter. It also contains an adjustable power limiting feature to limit the maximum output power.

Theory of Operation:

The theory behind this model is that the power output on the right is equal to the power input on the left times the efficiency ($P_{out} = \text{efficiency} \cdot P_{in}$). The input voltage from the AES is typically 142 – 172V. The output voltage to the ESS is typically 290 – 330V. The VCU commands current out of the DCDC converter to control the state-of-charge (SOC) of the ESS battery via the Set Point algorithm (described below). The efficiency mapping is a 3D lookup table consisting of $\text{Efficiency} = f(\text{Input Power, Output Voltage})$ as shown in Figure 31.

Figure 31. DCDC Converter Efficiency Lookup Table Model

Input Parameters:

- Power Limit Set Point: Limit that sets the maximum allowable power output (W)

Available Signals:

The following signals are available for plotting:

- DCC_CurCom: Input current command from VCU
- DCIN_Pwr: Input Power from AES(W)
- DCOUT_Pwr: Output Power to ESS (W)
- DCOUT_Current: Output current resulting from commanded input current from VCU
- DCIN_Current: Input current from AES
- DCOUT_Eff_Energy: Output energy (Wh)
- DCIN_Eff_Energy: Input energy (Wh)
- AES +, AES -: Electrical mid-range voltage DC bus (voltage, current)
- ESS +, ESS -: Electrical high voltage DC bus (voltage, current)

4.5 VCU Model

Figure 32. VCU Model Details

Model Description:

The VCU Model of Figure 32 controls the current delivered by the DCDC converter to the ESS and propulsion subsystems. The State-Of-Charge (SOC) of the ESS battery is the main input to the model and the DCDC converter current control output DCDC_CurCom is varied to maintain a desired SOC set point. There is power limiting functions to limit power due to the ESS battery becoming too high (over regeneration) or too low, AES battery becoming too low and the DCDC

converter being at a maximum output power state for too long. The VCU also controls the contactors for the AES and ESS batteries (ESS_Init&AES_Init).

Theory of Operation:

The VCU model has two main features: Set Point algorithm and Power limiting.

- **Set Point Algorithm** – Figure 33 shows what is underneath the VCU->Set Point Algorithm block of Figure 28. This algorithm was developed so that code can be auto generated from Simulink using MathWorks Real Time Workshop™. The algorithm reads in the ESS SOC and outputs the DCDC converter current magnitude whose value depends upon how far the SOC is from the calibration CalCurrSetPointMax (default = 70%). This algorithm also adjusts this set point to the calibration CalCurrSetPointMin when the AES SOC becomes 10% (AES battery empty). This feature allows the set point to be moved down so that the ESS battery can be emptied when the VEMS system reaches the full empty state. C++ code was generated from this model and linked into the VCU main embedded code.

Figure 33. VCU Set Point Algorithm Block

- **Power Limiting** – There are three power limiting blocks

1. ESS Power Limiting – Figure 34 shows the ESS_Power_Limit block. The output of this block provides power limiting depending on ESS SOC and the Power Demand from the <Command_Pwr> signal of the Vehicle Power Load Model. If the ESS SOC is greater than VCU_ESS_PL_HighSP, then power limiting is requested to stop regeneration. If the ESS SOC is less than VCU_ESS_PL_LowSP, then power limiting is requested to reduce the power demand. If the ESS SOC is less than VCU_ESS_PL_LowOff, then power limiting is requested to stop power demand completely. Otherwise the power limiting is set to zero.

Figure 25. ESS Power Limit Block

2. AES Power Limiting – Figure 35 shows the AES_Power_Limit block. The output of this block provides power limiting depending on AES SOC and the Power Demand from the <Command_Pwr> signal of the Vehicle Power Load Model. If the AES SOC is less than VCU_AES_PL_LowSP, then power limiting is requested to reduce the power demand. If the AES SOC is less than VCU_AES_PL_LowOff, then power limiting is requested to stop power demand completely. Otherwise the power limiting is set to zero. Note: since the AES battery does accept regeneration, no high AES SOC limiting is needed.

The Output will provide AES Power Limiting Depending on AES SOC and the Power Demand. If the AES SOC is less than VCU_AES_PL_LowSP, then the Power Demand * VCU_AES_PL_Gain is directed to the output to impose a large power limit. If the AES SOC is less than VCU_AES_PL_LowOff, then the Power Demand is directed to the output to remove discharge power from the AES battery. Otherwise the power limiting is set to zero.

Figure 26. AES Power Limit Block

3. DCDC Power Limiting – Figure 36 shows the DCDC_Power_Limit block. The output of this block will provide a pulse after upper DCDC input power threshold (VCU_DCDC_PL_HighSP) has been exceeded for 30 seconds. This pulse will remain active until the lower threshold (VCU_DCDC_PL_LowSP) is crossed. The 30 second timer will reset once the lower threshold is crossed. Power limiting only occurs when <Command_Pwr> signal of the Vehicle Power Load Model is above the VCU_DCDC_PL_Off.

Output will provide a pulse after upper DCDC input power threshold (VCU_DCDC_PL_HighSP) has been exceeded for X seconds. This pulse will remain active until the lower threshold (VCU_DCDC_PL_LowSP) is crossed. The X second timer will reset once the lower threshold is crossed. Power Limiting only occurs when the Commanded Power is above the VCU_DCDC_PL_Off at a gain of VCU_DCDC_PL_Gain

Figure 27. DCDC Power Limit Block

Input Parameters:

- VCU Main block:
 - PL_Select: This selects which power limit block is active for power limit control (ESS, AES, DCDC, none)

- Set Point Algorithm block:
 - CalDCDCGain: Gain of Set Point algorithm – the higher the gain, the more current delivered to the DCDC converter per deviation from CalCurrSetPointMax (A/%)
 - CalCurrSetPointMax: High ESS SOC Set Point that the algorithm tries to achieve (%)
 - CalCurrSetPointMax: Low limit when AES battery is low (%)
 - CalSlewRate: The Amps/sec rate that the DCDC current output current can change (A/s)
- ESS_Power_Limit block:
 - VCU_ESS_PL_HighSP: The ESS SOC high limit where power limiting starts to limit regen (%)
 - VCU_ESS_PL_LowSP: The ESS SOC low limit where power limiting starts to limit VEMS discharge current (%)
 - VCU_ESS_PL_Gain: The gain for power limiting (W/%)
 - VCU_ESS_PL_LowOff: The ESS SOC absolute low limit where power limiting is full on and discharge current is set zero (%)
- AES_Power_Limit block:
 - VCU_AES_PL_LowSP: The AES SOC low limit where power limiting starts to limit AES discharge current (%)
 - VCU_AES_PL_Gain: The gain for power limiting (W/%)
 - VCU_AES_PL_LowOff: The AES SOC absolute low limit where power limiting is full on and discharge current is set zero (%)
- DCDC_Power_Limit block:
 - VCU_DCDC_PL_HighSP: The power high threshold where the limit timer starts (W)
 - VCU_DCDC_PL_LowSP: The low power limit threshold where the power limit is stopped
 - VCU_DCDC_PL_Time: Duration before power limit starts (sec)
 - VCU_DCDC_PL_OFF: Overall enable limit for power limiting (W)
 - VCU_DCDC_PL_Gain: Gain of the power limit (W/s)

Available Signals:

The following signals are available for plotting:

- CAN_In bus:
 - ESS <SOC>: SOC of ESS battery (%)
 - AES <SOC>: SOC of AES battery (%)
 - <Command_Pwr>: Power from Vehicle Power Load Model
 - <DCIN_Pwr>: Input power from DCDC converter
- CAN_Out bus:
 - DCDC_CurCom: Set Point algorithm DCDC converter current command from VCU
 - Power_Limit: The power limit commanded by the VCU
 - ESS_Init: Control signal to turn on the ESS battery contactor
 - AES_Init: Control signal to turn on the AES battery contactor

4.6 ESS Battery Management Unit (BMU)

Figure 28. ESS Battery Management Unit (BMU) Model Details

Model Description:

The ESS BMU Model of Figure 37 controls model reads the state of the ESS battery and broadcasts the information to the VCU. It also receives the ESS battery contactor command and passes that signal to the ESS battery model. As a safety precaution, the simulation will stop when the ESS battery ever reaches 30% SOC. This is to simulate a low limit safety contactor open scenario.

Theory of Operation:

This is a simplified model of the actual BMU. It doesn't control cell balancing. It passes the ESS battery state to the VCU and calculates the energy of the ESS battery. It also simulates the command signal for contactor control to model turning off the contactors when commanded by the VCU.

Input Parameters:

Absolute ESS Low SOC Limit: When the ESS SOC hits this low limit SOC set point, the simulation stops

Available Signals:

The following signals are available for plotting:

- ESS_SOC: SOC state of the ESS battery (%)
- ESS_Current: ESS current
- ESS_Voltage: ESS high voltage
- ESS_Power: ESS battery power (W)

- ESS_Eff_Energy: ESS battery energy (Wh)
- To_ESS_Battery_Hardwire: Control signal to the ESS battery contactor

4.7 AES Battery Management Unit (BMU)

Figure 29. ESS Battery Management Unit (BMU) Model Details

Model Description:

The AES BMU Model of Figure 38 controls model reads the state of the AES battery and broadcasts the information to the VCU. It also receives the AES battery contactor command and passes that signal to the AES battery model.

Theory of Operation:

This is a simplified model of the actual BMU. It does not control cell balancing. It passes the AES battery state to the VCU and calculates the energy of the AES battery. It also simulates the command signal for contactor control to model turning off the contactors when commanded by the VCU.

Input Parameters:

None

Available Signals:

The following signals are available for plotting:

- AES_SOC: SOC state of the AES battery (%)
- AES_Current: AES current
- AES_Voltage: AES high voltage
- AES_Power: AES battery power (W)
- AES_Eff_Energy: AES battery energy (Wh)
- To_AES_Battery_Hardwire: Control signal to the AES battery contactor

6 Appendix B: DC/DC Boost Converter Specifications

The Magna E-Car Systems 30 kW DC/DC Converter (shown to the right) is equipped with a CAN interface for complete external control and status monitoring. Both Current and Voltage Mode switching designs offer increased power and reliability in a compact low-profile package. Extra input and output filtering reduce EMI to extremely low levels. Reliability features include thermal shutdown and current limiting.

The liquid cooled Three-Phase interleaved design is completely controlled via a CAN interface that allows preset voltage and current limits, fault detection and converter status messaging. In addition to individual input phase current sensing, each phase's current and slew rate can be controlled in order to implement various controls or low power modes.

Electrical Specifications:

INPUT

- Input Operating Voltage Range: 80 – 160 VDC (extendible to OUTPUT Voltage)
- Input Voltage Ripple: 250 mV peak-peak
- Input Operating Current Range: 0 – 350 A
- Input Current Ripple: 5% of operating current, est. impedance 0.12Ω

OUTPUT

- Output Operating Voltage Range: 190 – 365 VDC
- Output Voltage Ripple: 2.5% of operating voltage
- Output Operating Current Range: 0 – 130 A

7 Appendix C: Acronyms

Acronyms

A	Amp
AES	Alternative Energy System
BMU	Battery Management Unit
CAD	Computer Aided Design
CAN	Controller Area Network
DC	Direct Current
DC/DC	Direct Current to Direct Current
DOE	Department of Energy
EMI	Electromagnetic interference
ESS	Energy Storage System
FEA	Finite Element Analysis
HV	High Voltage
IGBT	Insulated Gate Bipolar Transistor
kg	Kilogram
kW	Kilowatt
kWh	Kilowatt-Hour
PCB	Printed Circuit Board
RPM	Rotations (or Revolutions) Per Minute
SCP	Standard Corporate Protocol
SOC	State of Charge
SOPO	Statement of Project Objectives
UDDS	Urban Dynamometer Driving Cycle
V	Volts (or Voltage)
VCU	Vehicle Control Unit
VDC	Volts Direct Current
VEMS	Vehicle Energy Management System
VTIM	Vehicle Traction Inverter Module
W	Watt
Wh	Watt-Hour