Report Type:

Final Scientific/Technical Report

DOE Award Number:

DE - FC26 - 07NT43124

Program/Project Title:

Bi-Directional DC-DC Converter for PHEV Applications

Date of Report:

02/09/2011

Period covered by the report:

From: 10/01/2007 To: 01/31/2011

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Executive Summary

Plug-In Hybrid Electric Vehicles (PHEV) require high power density energy storage system (ESS) for hybrid operation and high energy density ESS for Electric Vehicle (EV) mode range. However, ESS technologies to maximize power density and energy density simultaneously are not commercially feasible. The use of bi-directional DC-DC converter allows use of multiple energy storage, and the flexible DC-link voltages can enhance the system efficiency and reduce component sizing. This will improve fuel consumption, increase the EV mode range, reduce the total weight, reduce battery initial and life cycle cost, and provide flexibility in system design.

A comparison of the actual accomplishments with the goals

Task 1: Provide vehicle level specifications and interface and functional requirements for the POC dc-dc power converter. Provide vehicle system level study and determine the top level (module) Failure Mode and Effect analysis.

Subtasks Objectives;

- 1.1. Determination vehicle and control system interface
- 1.2 Vehicle System and module level FMEA analysis
- 1.3. Reliability modeling to determine MTBF

Task 2: Provide design and fabrication for the magnetic, switching components, input and output ripples and filter determinations. The power devices are high speed IGBT with SiC diodes. This configuration offers the most cost effective and commercially viable solution for the midterm, due to the cost and availability of SiC devices.

Subtasks Objectives;

- 2.1. Bi-directional dc-dc converter fabrication
- 2.2. SiC power module and driver design and fabrication
- 2.3. Silicon customization
- 2.4. Control loop modeling
- 2.5. System Design Review

Task 3: Provide FEA modeling for the magnetic circuit, design and fabricate the component sizing and also determine the losses due to high switching frequency and high current. Measure the temperature rise and cooling system performance.

Subtasks Objectives;

- 3.1 Design and fabricate the integrated magnetic, windings, power silicon, sensors and cooling system
- 3.2. Magnetic FEA modeling and analysis test set-up
- 3.3. Design validation and testing

Task 4 and Task 5 have been combined.

Design and fabricate the multi phase SiC power converter and provide the interface, control and communications for the unit. Develop the custom components specifications and procure the components and fabricate for POC testing.

Task 5: Design and fabricate the multi phase MOSFET power converter and provide the interface, control and communications for the unit. Develop the custom components specifications and procure the components and fabricate for POC testing.

Subtasks Objectives;

- 5.1. Design and fabricate a Silicon based, multi phase power converter to meet the project
- 5.2. Performance validation testing Completed for 10kW, upgrading to 20kW.
- 5.3. Fabricate the magnetic and validate the performance
- 5.4. Power loss measurement
- 5.5. Thermal performance validation

Task 6: Provide a performance design validation on the POC units and a comparative measured performance and cost study for the SiC and MOSFET design including the magnetic, packaging and cooling system cost and performance.

Subtasks Objectives;

- 6.1. Project Critical Design Review
- 6.2. Critical Design Review for dc-dc Converter design. Completed with No customer input. We are applying this to commercial vehicle application. 20kW-30kW.

Task 7: Provide a production readiness review for the design based on the final Bill of Material and fabrication method. Perform manufacturing feasibility DFMA and production testing and tooling requirement.

Subtasks Objectives;

- 7.1. Production Readiness Review

Summary: Despite many interface with passenger vehicle OEM, there is no on-going project for the dual battery system. We will apply this to the commercial vehicle with 20kW-30kW rating.

Task 8: Provide the project management, planning and reporting for the project. Participate on the DOE reviews and interface with other sub-system and vehicle system providers.

Subtasks Objectives;

- 8.1. Project Management and Reporting, Phase II Tasks 1 through Task 3.
- 8.2. Project Management and Reporting, Phase II Tasks 5 through Task 8

Project Activities

The primary objective of this project was to design and develop the bi-directional dc-dc converter and also to complete the vehicle system modeling to include some dynamic to determine the overall vehicle energy and power management strategy.

Energy Storage Systems Resistive Loss Modeling

The battery losses are analytically determined from a case of using more modules to increase the battery pack voltage, however the pack will have higher energy storage, or we can use smaller modules and more of them in series so we increase the total pack voltage, but the total energy is the same or we use same number of modules but each module has a higher voltage resulting a higher pack voltage. Basically for a give energy capacity battery we can show that the losses are the same assuming that the battery characteristics are identical and scalable.

Case 1: General Case

More modules in series to get higher voltage, each module having a voltage of V_m and internal resistance R (dynamic as a function of SOC and rate of discharge, etc). The total voltage of the battery pack is V_p .

Figure 1: Electric circuit of n modules (batteries) in series

$$P = V_p \cdot I \quad (1)$$

$$V_p = V_m \cdot n \quad (2)$$

$$I = \frac{P}{V_p} \quad (3)$$

$$P = T \cdot \omega \quad (4)$$

$$P_{Loss} = (I^2 R)n = \left(\frac{P}{nV_m} \right)^2 Rn = \left(\frac{P}{V_m} \right)^2 \frac{R}{n} \quad (5)$$

$$P_{Loss} \propto \frac{1}{n} \quad (6)$$

For the same power draw for different number of identical module in series, the power loss is proportional to the reciprocal of number of modules. As the number of modules in series increases we have a bigger battery pack, higher energy storage, and lower discharge current.

Case 2: Scale module impedance and use more modules

We use smaller Ahr module which has higher internal resistance in battery pack 2 ($R_2 > R_1$) but with the same module voltage ($V_{m2} = V_{m1}$). The number of modules in battery pack 2 is higher than that of battery pack 1 ($n_2 > n_1$) therefore the battery pack 2 voltage is higher than battery pack 1 voltage ($V_{p2} > V_{p1}$), identical total energy storage.

Figure 2: Electric circuit of n_2 modules (batteries) with R_2 internal resistance in series compared with n_1 modules with R_1 internal resistance in series

$$R_2 = R_1 \frac{n_2}{n_1} \quad (7)$$

$$P_{Loss,1} = \left(\frac{P}{V}\right)^2 \frac{R_1}{n_1} \quad (8)$$

$$P_{Loss,2} = \left(\frac{P}{V}\right)^2 \frac{R_2}{n_2} = \left(\frac{P}{V}\right)^2 \frac{R_1 \frac{n_2}{n_1}}{n_2} = \left(\frac{P}{V}\right)^2 \frac{R_1}{n_1} \quad (9)$$

$$P_{Loss,2} = P_{Loss,1} \quad (10)$$

If smaller battery and more modules in series are used, losses are the same. Same power loss regardless of number of modules in series as long as the total capacity is the same. We assume that as the battery size is scaled down the internal impedance scales up linearly.

Case 3: Scale module impedance and use the same number of modules

Comparison of two sets of battery packs with the same number of modules ($n_1 = n_2$), however modules used in battery pack 2 have higher module voltage than the modules used in battery pack 1 ($V_{m2} > V_{m1}$), hence the battery pack 2 has a higher pack voltage than battery pack 1 ($V_{p2} > V_{p1}$) and the internal resistance of each module is scaled accordingly. The battery pack 1 and pack 2 have identical energy storage rating.

Figure 3: Electric circuit of n modules (batteries) with R_1 internal resistance in series compared with n modules (batteries) with R_2 internal resistance in series

$$R_2 = R_1 \left(\frac{V_{m2}}{V_{m1}} \right)^2 \quad (11)$$

$$P_{Loss,1} = \left(\frac{P}{V_{m1}} \right)^2 \frac{R_1}{n} \quad (12)$$

$$P_{Loss,2} = \left(\frac{P}{V_{m2}} \right)^2 \frac{R_2}{n} = \left(\frac{P}{V_{m2}} \right)^2 \frac{R_1 \left(\frac{V_{m2}}{V_{m1}} \right)^2}{n} = \left(\frac{P}{V_{m1}} \right)^2 \frac{R_1}{n} \quad (13)$$

$$P_{Loss,2} = P_{Loss,1} \quad (14)$$

This shows same power loss for both cases. However, if we use same number of battery modules with one pack using modules with higher voltage and lower Ahr rating. Same power loss regardless of voltage rating of battery modules in series as long as the total capacity is the same. We assume that as the battery size is scaled, the internal impedance also scales linearly.

Inverter Loss Modeling

The Advisor model for inverter and motor loss is based on the motor speed (rpm) and torque (Nm). Therefore, the data does not reflect the loss dependency on voltage and current variations. The inverter switches were modeled with manufacturer's published E-on and E-off switching losses. The IGBT conduction loss V_{ce} and diode conduction loss of V_f were modeled for a sine-wave motor current excitations using three different switching frequencies of 10kHz, 16kHz and 20kHz. The PHEV motor max power is 50kW. The losses were tabulated for 100%, 50%, 30% and 20% of load current. All calculations are done at junction temperature of 120°C. We used 600V and 1200V IGBT modules data from Powerex. There was limited data on Infineon IGBT modules to be considered for this analysis. As the DC voltage is increased the corresponding AC voltage and AC rms currents are calculated for modeling purposes.

The polynomial fit curves are used for power losses versus current equations for analysis and data point interpolation. The average power loss and corresponding total energy loss versus voltage for different frequencies for one driving cycle (US06) is presented in the following figures.

Figure 4: Average power loss (W) versus voltage for one driving cycle

Figure 5: Total energy loss (Whr) versus voltage for one driving cycle

The inverter power loss variation with the DC bus voltage for power modules of 600V and 1200V IGBT modules varies with the manufacturer silicon switching characteristics, E_{on} , E_{off} and V_{ce} . For the standard 600V and 1200V power modules a DC bus voltage of 400 Vdc nominal (300V min, 550Vmax) shows the lowest power loss. A drive system model was developed and the result of such simulation may be of no surprise since the 600V IGBT modules have been designed for a typical 400Vdc bus operation and the switching frequency used is high for the typical 1200V modules and we had to use a larger module due to thermal

characteristics. Also if we use MOSFET at 250V, the inverter losses will be lower. However, we need to use larger silicon size and hence cost.

The nominal 400V battery voltage allows utilization of most existing 600V power devices and critical components. Also the 400V battery voltage selection will simplify the charging circuit for the PHEV when operating from 110 Vrms to 220 Vrms AC line. The charging circuit sizing and selection is not a part of this study.

Figure 6: Power loss over one driving cycle for V=700 volts and three different frequencies

Figure 7: Power loss over one driving cycle for different voltages at 10 Hz frequency

Battery Power Requirement

Based on aerodynamic drag coefficient (CD) and gross vehicle weight rating (GVWR), four typical vehicles are investigated: aerodynamic car, sedan passenger, midsize SUV, SUV type 1 and SUV type 2. These vehicle types are shown in Table 1.

CD	0.4		Midsize SUV (A=2.8 m ²)	SUV1 (A=3.0 m ²)	SUV2 (A=3.0 m ²)
	0.3		Sedan Passenger (A=2.2 m ²)		
	0.2	Aerodynamic car (A=2.0 m ²)			
		3000	4000	5000	6000
GVWR (lb)					

Table 1: Vehicle types investigated (CD is aerodynamic drag coefficient, GVWR is gross vehicle weight rating, and A is vehicle frontal area)

The battery power requirements of the vehicles in Table 1 are investigated for three different drive cycles: constant speed (steady state), USSD and US06 drive cycles.

Case 1: Steady State (constant speed of 55 mph)

Figure 8: Battery power requirement for 55 mph constant speed

Case 2: Urban Dynamometer Driving Schedule (UDDS)

A modified version of Advisor is used for modeling and simulation purposes. An electric vehicle (EV) is investigated and its specifications are shown in Figure 9. One drive cycle of

UDDS is applied (Figure 10 and Table 2). The simulation results are shown in Figure 4 to Figure 6.

Figure 9: ADVISOR model for electric vehicle (EV)

Figure 10: Urban Dynamometer Driving Schedule (UDDS)

Parameter	Value
Average speed	19.58 mph
Max speed	56.7 mph
Distance	7.45 miles
Time	1369 s
Idle time	259 s
Number of stops	17

Table 2: UDDS drive cycle statistics (one cycle)

Figure 11: Battery power requirement for electric vehicle (UDDS drive cycle)

Figure 12: Energy requirement per mile for electric vehicle (UDDS drive cycle)

Figure 13: Electric vehicle range (UDDS drive cycle)

Case 3: US06 Drive Cycle

In this case, one drive cycle of UD06 is applied (Figure 14). The simulation results are shown in figures 8-10. To perform sensitivity analysis of battery power with respect to CD and GVWR parameters, the vehicle frontal area assumed to be constant (2.0 m^2) in this case, whereas for cases 1 and 2 the vehicle frontal area (A) varied based on the numbers in Table 1.

Figure 14: US06 Drive Cycle

Parameter	Value
Average speed	47.97 mph
Max speed	80.3 mph
Distance	8.01 miles
Time	600 s
Idle time	45 s
Number of stops	5

Table 3: US06 drive cycle statistics (one cycle)

Figure 15: Battery power requirement for electric vehicle (US06 drive cycle)

Figure 16: Energy requirement per mile for electric vehicle (US06 drive cycle)

Figure 17: Electric vehicle range (UD06 drive cycle)

These simulation results are used to select the appropriate battery pack for each type of vehicle based on the running drive cycle.

Dual Battery System Modeling

Figure 18 depicts the PHEV utilizing dual battery system. One battery is designed and optimized for power density and will operate at some given SOC (50%-70%), with small SOC variation. While the other battery chemistry and packaging is selected and optimized for energy density and will operate a wide range of SOC, it will typically start with 100% SOC, then it is discharged down to 5% SOC. The power battery can also be replaced with Ultra capacitor as well with similar system advantages. The system benefit associated with the dual battery overcomes the deficiencies of the bidirectional dc-dc converter.

While the power battery is delivery high rms power to the PHEV system the energy battery will be providing the average power to the vehicle almost acting as a range extender. The energy battery will be design to operate up to a couple of hours, therefore the discharge rate will be C/2 or lower. The energy battery technology can be selected to enhanced energy density to reduce cost and weight, knowing that it will only discharge at C/2 or lower. The energy battery cooling system can also be designed with such a low discharge rate.

Figure 18: PHEV with dual battery system

Vehicle Control Strategy and Energy Management

For a PHEV operation, the battery is charged via the grid, then the vehicle operates in a charge depletion mode and uses the stored battery energy and when the battery reaches a pre-determined SOC level, then it is operated in charge sustaining mode. Depending on the battery technology and packaging, the battery should be able to deliver the required power at the charge sustaining SOC. Therefore some portion of the battery energy cannot be utilized, due to power limitations. Typical charge sustaining operation is 20%-30% SOC level. During such

mode of operation the battery is subjected to EV discharge cycles (typically 80% DOD) and the power cycles of the hybrid operation especially at lower charge sustaining SOC. The battery cycle life is reduced and the battery design, chemistry, and packaging cost is increased.

Dual Battery System Simulation

Modified (customized) version of Advanced Vehicle Simulator (ADVISOR) is used for modeling and simulation purposes (Figure 19). Parallel hybrid power-train control strategy has been employed. Urban Dynamometer Driving Schedule (UDDS) drive cycle has been considered for simulation (Figure 10 and Table 2). In order to run the simulation for approximately 100 miles distance, fourteen UDDS cycles have been used which results in total distance of 104.3 miles (167.9 km). A SUV class vehicle has been investigated in this study. The vehicle specifications are presented in Table 4.

Figure 19: ADVISOR simulation model

Parameter	Value
Gross Vehicle Weight Rating	GVWR=3800 lb (1724 kg)
Rolling Resistance	RR=0.008
Drag Coefficient	CD=0.28
Frontal Area	FA=2.0 m ²

Table 4: Vehicle specifications

One set of battery pack consisting of seventeen U-Charge® XP UEV-18XP batteries is used for PHEV model and two sets of GAIA 60 Ah HE-602040 and 7.5 Ah UHP-341450 Lithium Ion

cell battery packs consisting of 93 batteries each along with an 8 kW DC-DC converter are used for modeling an EV/HEV with dual battery pack system (Figure 20). The specifications of these batteries are presented in Table 5 and Table 6. The single battery pack with 17 modules provides 22.5 kWh energy.

The 60 Ah HE-602040 battery pack with high energy density is used for EV mode with charge depleting strategy (EV battery). The 7.5 Ah UHP-341450 battery pack with high power density is used for HEV mode with charge sustaining strategy (HEV battery). The EV and HEV battery packs in the dual battery system provide 20 and 2.5 kWh energy respectively with 93 batteries in each battery pack. Thus the dual battery system is sized to provide the same amount of energy as the single battery system (22.5kWh).

For the HEV battery, the highest and lowest desired State of Charge (SOC) are set to 0.7 and 0.6 respectively. For the EV battery, the highest and lowest desired SOC are set to 1.0 and 0.1 respectively. The initial SOC is set to be 1.0 for both EV and HEV batteries.

Figure 20: (a) PHEV single battery system (b) EV/HEV dual battery system with DC-DC converter

Parameter	Value
Nominal Voltage	3.6 V
Nominal Capacity	60 Ah
Weight	1500 g
Specific Energy	144 Wh/kg
Energy Density	374 Wh/l
Specific Power	1800 W/kg
Power Density	4680 W/l
Max. Discharge Current	120 A

Table 5: GAIA 60 Ah HE-602040 (high energy)

Parameter	Value
Nominal Voltage	3.6 V
Nominal Capacity	7.5 Ah
Weight	320 g
Specific Energy	84 Wh/kg
Energy Density	211 Wh/l
Specific Power	9370 W/kg
Power Density	23470 W/l
Max. Discharge Current	75 A

Table 6: GAIA 7.5 Ah UHP-341450 (ultra high power)

The single and dual battery systems are simulated separately. The load demands for single and dual battery configurations are presented in Figure 21. The EV battery is providing the average power while the HEV battery provides the extra required power.

Fast Fourier Transform (FFT) of load demand of these two cases are shown in Figure 22. It is observed that EV battery provides lower frequency load demand and HEV battery provides higher frequency load demand.

Figure 21: Load/Power demand; (a) Single battery system (b) Dual battery system

When utilizing the dual battery the power battery is only subjected to the hybrid power cycles and the energy battery is subjected to the EV cycles only. Figure 23 shows the charge and discharge characteristic of the dual battery system, with and without slew rate control. Ideally we want the energy battery to supply the average power and the power battery to deliver the rms with zero average power.

Figure 22: FFT of power; (a) Single battery system (b) Dual battery system

Figure 23: PHEV with dual battery control strategy; (a) No slew rate control, (b) With slew rate control

Fundamentally since we operate the energy battery at higher DOD, then we use the 10%-20% more of the stored battery energy. Meanwhile due to lower discharge requirements, the energy density can be optimized and can be increase by 20%-30%, as such reducing the weight of the battery and the cost of battery. The energy battery production cost is propositional to the material uses and if we have higher energy density (Whr/kg), then the cost will reduce proportionally. The dual system range increase, weight reduction and cost reduction is much higher compared to the deficiencies and the cost of the bi-directional dc-dc converter used.

Figure 24: Battery rms and average power with optimum control strategy; (a) Single battery (b) Dual battery

Figure 24 shows the rms and average power for the power and energy battery when a proper vehicle energy management is used. The EV battery is in charge depleting operation mode and HEV battery is charge sustaining. The SOC of the single battery PHEV system and EV/HEV with dual battery systems are presented in Figure 25. It is observed that the EV range has been increased in the dual battery system.

Figure 25: Dual Battery and bi-directional dc-dc converter range improvement over single battery; (a) State of Charge (SOC), (b) Total energy used

The weight and cost reduction and the range increase for the dual battery system is shown in Figure 26.

The dual battery system cost, weight and range analysis is presented in Table 7. For production of large capacity batteries such as the one used for PHEV, the cost is proportional to the material used and if the chemistry can provide higher energy density (Whr/kg), then the weight and cost is reduced almost inversely rotational to the battery energy density.

Figure 26: The cost and weight reduction and range extension of the dual battery system.

	Total battery Ahr	Pack Voltage	Total Capacity KwHr	%SOC used	dc-dc Eff.	Total usable capacity	Energy Density Whr/kg	Total Weight Kg	Cost (1) \$/Kwhr (\$/kg)	Total cost
Single pack	69	370	25.53	80%		20.4	85	300	\$ 750	\$ 19,148
Dual (EV Energy pack)	60	370	22.2	95%	97%	20.5	110	202	\$ 580	\$ 12,866
Dual (HEV Power pack)	6	370	2.22	35%		0.8	65	34	\$ 981	\$ 2,177
	66	370	24.42			21.2		236		\$ 15,043
						Capacity Ratio		Weight Ratio		Cost Ratio
						104%		79%		79%
								Total Battery Saving \$		\$ 4,104
								Added additional BMS cost		\$ 275
								Added dc-dc cost(8kW rated)		\$ 552
								Total Vehicle System Saving \$		\$ 3,277
			EV range increase:			12%		Cost Saving:		17%
	Total battery Ahr	Pack Voltage	Total Capacity KwHr	DOD	dc-dc Eff.	Total usable capacity	Energy Density Whr/kg	Total Weight Kg	Cost (1) \$/Kwhr (\$/kg)	Total cost
Single pack	33	370	12.21	80%		9.8	85	144	\$ 750	\$ 9,158
Dual (EV Energy pack)	27	370	9.99	95%	97%	9.2	110	91	\$ 580	\$ 5,790
Dual (HEV Power pack)	6	370	2.22	35%		0.8	65	34	\$ 981	\$ 2,177
	33	370	12.21			10.0		125		\$ 7,967
						Capacity Ratio		Weight Ratio		Cost Ratio
						102%		87%		87%
Additional Benefits:										
Lower cycle life cost.										
The energy battery is subjected to EV cycles (~1000), not EV+HEV										
PHEV and HEV can use common platforms with plug-n-play plug-in option.										
(1) The battery production cost is mainly proportional to material/weight cost.										
								Total Battery Saving \$		\$ 1,191
								Added additional BMS cost		\$ 275
								Added dc-dc cost(6kW rated)		\$ 414
								Total Vehicle System Saving \$		\$ 502
			EV range increase:			14%		Cost Saving:		5%

Table 7: PHEV cost and performance with dual battery and bidirectional dc-dc converter

Bidirectional dc-dc converter performance

The bidirectional dc-dc converter efficiency and the dynamic performance of the converter are shown in Figure 27.

(a)

(b)

Figure 27: Bidirectional dc-dc converter, (a) Efficiency (b) Response

Bidirectional dc-dc Converter Packaging

The bidirectional dc-dc converter package is shown in Figure 28. The dc-dc converter performance exceeds the program targets.

Figure 28: Bidirectional dc-dc converter packaging

FEA modeling for the magnetic circuit

The following figures show the results for FEA modeling for the magnetic circuit, including flux density in core (Figure 29), input current and copper/core loss (Figure 30).

Figure 29: Flux Density in Core

Figure 30: (a) Input Current, (b) Copper loss, and (c) core loss

CFD Modeling of dc-dc Converter

Computational Fluid Dynamics (CFD) modeling for thermal and flow simulation has been carried out for the DC-DC converter. With 8kW power and 95% efficiency, the total power loss would be 400W. The coolant inlet temperature is 35°C at 2 GPM. This will result in maximum temperature of 37°C on the cold plate. The simulation results for fluid temperature and pressure as well as cold plate temperature are presented in Figure 31 and Figure 32. A sensitivity analysis with respect to the inlet flow rate and temperature has been performed and the simulation results for the junctions' maximum temperature are in an acceptable safety margin range for all the cases.

Figure 31: Flow simulation results, (a) Temperature, °C, (b) Pressure, psi

Figure 32: Contour of cold plate temperature (°C)

Major Accomplishments

- Developed a vehicle level simulation modeling, based on Simulink with dual battery system and the dc-dc converter for characterizing vehicle drive cycles for various vehicle system configuration and drive cycles as well as different vehicle platforms (Economy, Compact, Sedan and SUV)
- Developed an FEA parametric model and analysis techniques to characterize the magnetic and thermal behavior of the dc-dc converter critical components.
- Developed a vehicle level power and energy management. Based on such analysis the converter dynamics had to be coordinated with the vehicle and implement a power and current slew rate control.
- Developed converter level modeling to determine the operation trade off and control system.
- The dynamic and static behavior of the Si and SiC converters were validated with fabricating a test unit and validating the losses and transient responses, including the converter system control. The modeling methodology enables optimization and switching frequency operation sensitivity studies.
- Established OEM customer and industry supplier relationships to study the potential of utilizing the dual battery system for PHEV application with the bi-directional dc-dc converter.
- Demonstrated High efficiency (meeting and exceeding the target > 95 %).
- Custom Silicon packaging with 1200V NPT fast IGBT and 1200V SiC diode with high inlet and ambient temp of 105 °C.
- Has been able to demonstrate high power density of 62.5 W/in³, exceeding the program target of (20 – 50 W/in³).
- Demonstrated the low cost ($\leq$ \$62.5 /kW) for quantities of 10k/year.
- The dual battery system provides 14% increase in range, while
- Reducing the weight by 13% and
- Reducing the cost by 5%

Conclusions

The dual battery system for PHEV has proven to increase the range by 14%, reduce the weight by 13%, and the cost by 5%. When using dual battery system the HEV and PHEV vehicle platforms can use more common parts and same vehicle platform and the customer has the option to choose the EV range desired and the EV battery can be sized optimally for application requirement to reduce cost and enable the commercialization of PHEV.

The bidirectional dc-dc convert technology has met and exceeded the program requirements, following are a summary;

- Demonstrated High efficiency (meeting and exceeding the target > 95 %).
- Custom Silicon packaging with 1200V NPT fast IGBT and 1200V SIC diode with high inlet and ambient temp of 105 °C.
- Demonstrates high power density of 54 W/in³, (target 20 – 50 W/in³).
- Demonstrated the low cost ($\leq$ \$62.5 /kW) for quantities of 10k/year (target \$75/kW).

Products developed under the award

a. Publications:

Farzad Ahmadkhanlou, Abas Goodarzi, and Don Kang, "Plug-In Hybrid Electric Vehicle with Dual Battery System", Proceedings of the 25th World Battery, Hybrid and Fuel Cell Electric Vehicle Symposium & Exhibition (EVS-25), Shenzhen, China, Nov. 5-9, 2010

A copy of the paper is submitted.

b. Web site: <http://www.evs25.org>

c. Networks:

Research and Development group from Maxwell Technologies Inc. from San Diego, CA are very interested in our Dual Battery concept and results and have initialed a potential collaboration.

d. Technologies/Techniques:

- Dual battery system concept
- Demonstrates high power density and low cost
- Battery sizing and optimization
- Compact dc-dc converter design and packaging
- Demonstrated high efficiency

e. Inventions/Patent Applications:

Patent Disclosure Pending

f. Other products:

MATLAB code, SIMULINK model, Solid Works Flow Simulation (FloWorks) model, COSMOS model, MATHCAD code, MS Excel files, and MS Access database.

Computer Modeling

a. Model description

The 60 Ah HE-602040 battery pack with high energy density is used for EV mode with charge depleting strategy (EV battery). The 7.5 Ah UHP-341450 battery pack with high power density is used for HEV mode with charge sustaining strategy (HEV battery). The EV and HEV battery packs in the dual battery system provide 20 and 2.5 kWh energy respectively with 93 batteries in each battery pack. Thus the dual battery system is sized to provide the same amount of energy as the single battery system (22.5kWh).

For the HEV battery, the highest and lowest desired State of Charge (SOC) are set to 0.7 and 0.6 respectively. For the EV battery, the highest and lowest desired SOC are set to 1.0 and 0.1 respectively. The initial SOC is set to be 1.0 for both EV and HEV batteries.

Figure 33: SIMULINK model of dual battery system

Dual battery system has been modeled in MATLAB version 7.9 (R2009b) and SIMULINK version 7.4 (R2009b).

b. Performance criteria

The performance of vehicle for different drive cycles has been investigated. The step size considered for the simulation of the model is 0.1 seconds. Therefore, the simulation cannot capture very high frequency transient signals from the electronic components. It is meant for the steady state case. The overall performance was to meet the following criteria:

1. To provide a vehicle system level study (in close collaboration with the drive system, charging system, energy system and vehicle mission and drive cycle requirements) to determine the optimum operating battery and dc-link voltage levels that maximize efficiency and minimize cost;
2. Design and develop a bi-directional dc/dc power-conversion system in support of PHEV program to meet the commercialization cost, weight, and volume;
3. To design, develop, and complete performance validations of the production-intent prototype high power density power 8 kW multi-phase bidirectional dc/dc boost converter.
4. To meet the following product-design targets:

- $\geq 95\%$ power-conversion efficiency at junction temperatures of 130-150°C for Si and $\geq 180^\circ\text{C}$ for SiC for inlet coolant temperature of 105°C;
- Current-loop bandwidth of ≥ 20 kHz via implementation of a novel load-sharing nonlinear hybrid controller that has demonstrated the fastest control performance for parallel dc/dc converters.

c. Test results

In vehicle performance modeling, sensitivity analysis has been performed with respect to the total energy of the battery. The results confirm the superiority of dual battery system over regular single battery system for all the cases.

For the cooling system of dc-dc converter, sensitivity analysis with respect to inlet temperature and flow rate of coolant has been conducted. The junction maximum temperature is in an appropriate safety margin range for all the cases.

d. Theory

Battery sizing is done such that the EV battery has adequate energy for the required average energy of the drive cycle in the specified range, and the HEV battery has enough power for the transient load picks during the drive cycle. The high frequency load will be on HEV battery and the average load on EV battery. By this methodology not only the EV range of the vehicle but also the life of the EV battery increases.

Peukert's law relates the capacity of a lead-acid battery in terms of the rate at which it is discharged and is expressed by the following equation:

$$t = H \left(\frac{C}{IH} \right)^k$$

where:

H is the rated discharge time,

C is rated capacity at discharge rate of H ,

t is actual time to discharge the battery,

k is Peukert constant and increases with the age of the battery,

t is the actual time to discharge the battery.

Figure 34: Peukert's law (www.mpoweruk.com)

Therefore, the effective capacity of the cell is reduced if the cell is discharged at very high rates. The life of a battery decreases with higher loads. Dual Battery system decreases the rate of discharge of the battery which results in longer battery life

The journal paper is being prepared and has not been submitted yet.

e. Hardware requirements

DC-DC converter sizing has been modeled and determined. We recommend an 8kW bi-directional DC-DC converter with high efficiency (greater than 95%), high power density (20–50 W/in³), and low cost (\$75 /kW) to meet up to the SUV class vehicles driving at UDDS, which is most typical of urban driving for PHEV application.

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