Bi-directional dc-dc Converter

Including Vehicle System Study to determine Optimum Battery and DC Link Voltages

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This presentation does not contain any proprietary or confidential information

The Challenge

- PHEV requires high power density battery/energy storage for hybrid operation and high energy density battery for EV mode range.
- Battery Technologies to maximize power density and energy density simultaneously, are not commercially feasible.
- The use of bi-directional dc-dc converter allow use of multiple energy storage, and the flexible dc-link voltages can enhance the system efficiency and reduce component sizing.
- Design a bi-directional dc-dc converter and fabricate a 5kW POC unit to demonstrate the following;
  - **High inlet and ambient temperatures (> 105 °C)**
  - **High efficiency (> 90 %)**
  - **High power density (20 – 50 W/in3)**
  - **Low cost (≤ $75 /kW)**

Purpose of Work for FY08

1. Vehicle modeling, simulation, and operation voltages optimization.
2. DC-DC Power converter and control modeling.
3. Silicon Carbide device specifications.
4. Silicon Carbide and MOSFET comparative performance evaluation.

Key Technical Challenges

- High inlet and ambient temperatures (> 105 °C)
- High efficiency (Target > 90 %), Estimated 95% (@ rated power)
- High power density (20 – 50 W/in3), Estimated > 16 W/in3
- Cost**:** ≤ $ 75 /kW for 75,000 quantities

DC Link Voltage Optimization

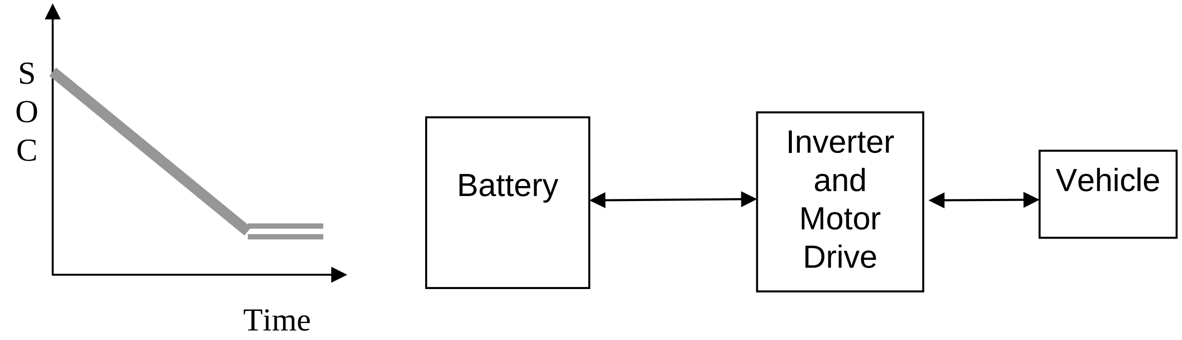


Fig 1. Base Line PHEV, charge depletion Operation Mode.

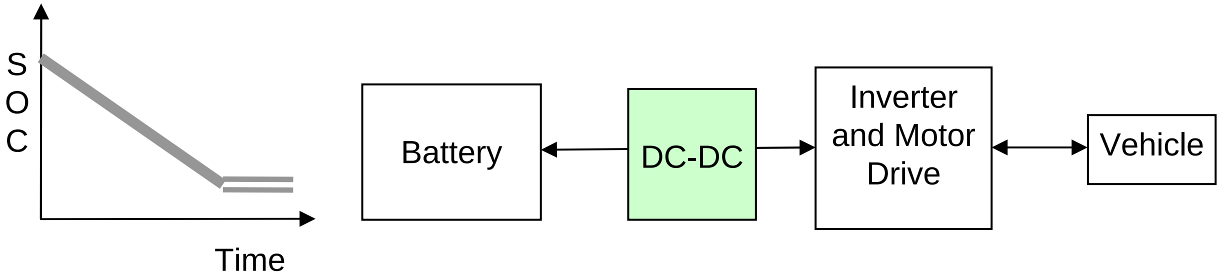
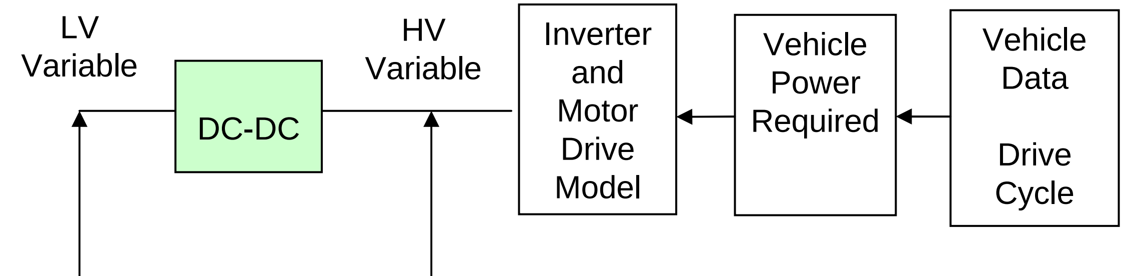


Fig 2. Single Battery with DC-DC converter and DC link Voltage Regulation

DC Link Voltage Optimization Cont.



LV Variable

DC-DC

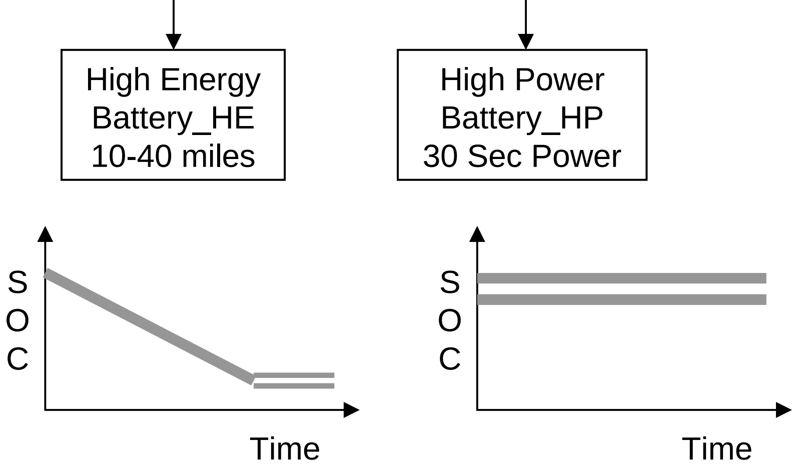
HV Variable

Inverter and Motor Drive Model

Vehicle Power Required

Vehicle Data

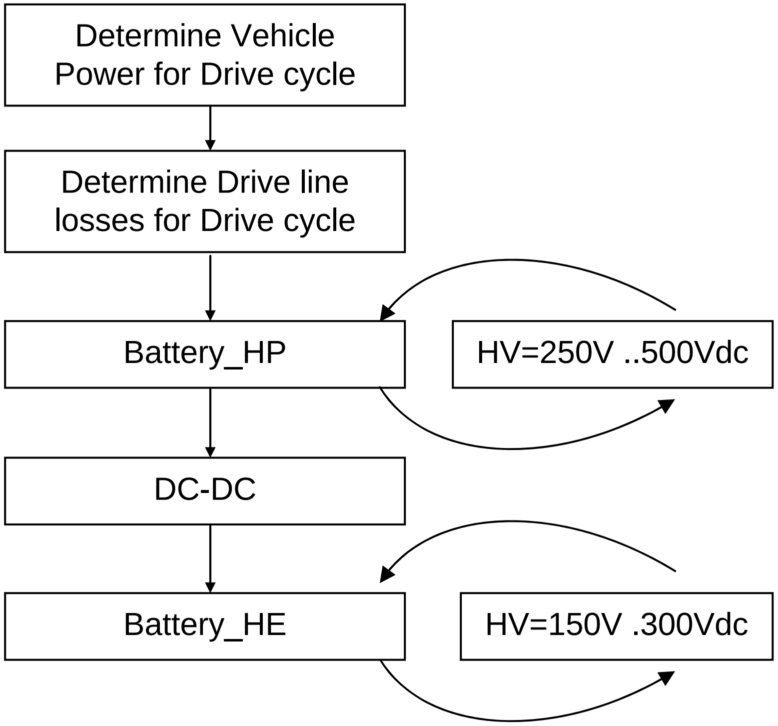
Drive Cycle



High Energy Battery_HE 10-40 miles

High Power Battery_HP 30 Sec Power

Fig 3. Dual Energy Storage System (one optimized for power density and one optimized for energy density) with DC-DC converter and DC link Voltage Regulation



Determine Vehicle Power for Drive cycle

Determine Drive line losses for Drive cycle

Battery_HP

HV=250V ..500Vdc

DC-DC

Battery_HE

HV=150V .300Vdc

Fig 4. Vehicle System Modeling Diagram

DC Link Voltage Optimization Cont.

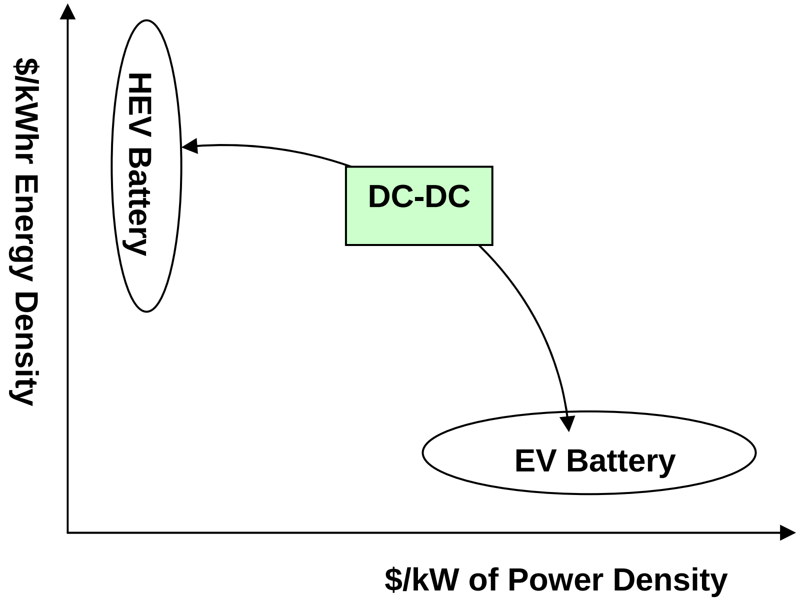


Fig 5. Typical Battery cost $/kWhr vs. $/kW.

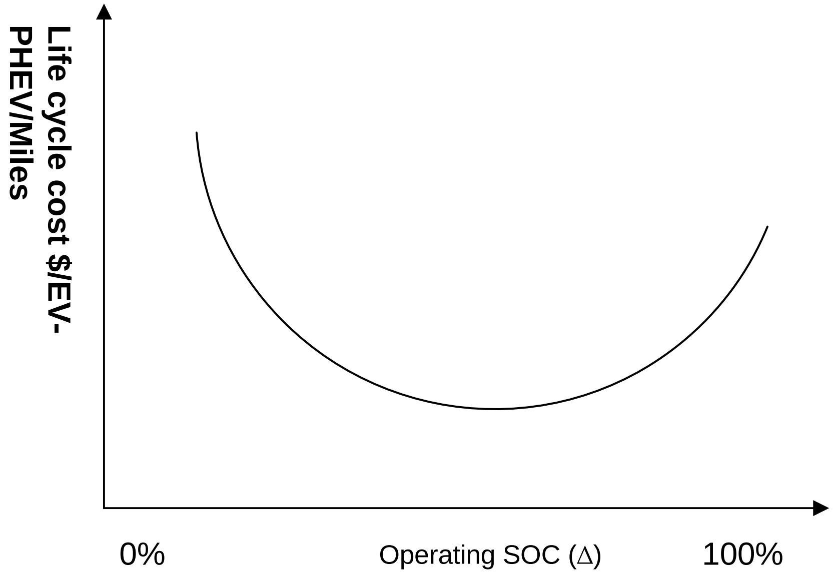


Fig 6. Battery cycle life cost $/ EV-PHEV/mile.

All-SiC Dc-Dc Bidirectional Converter

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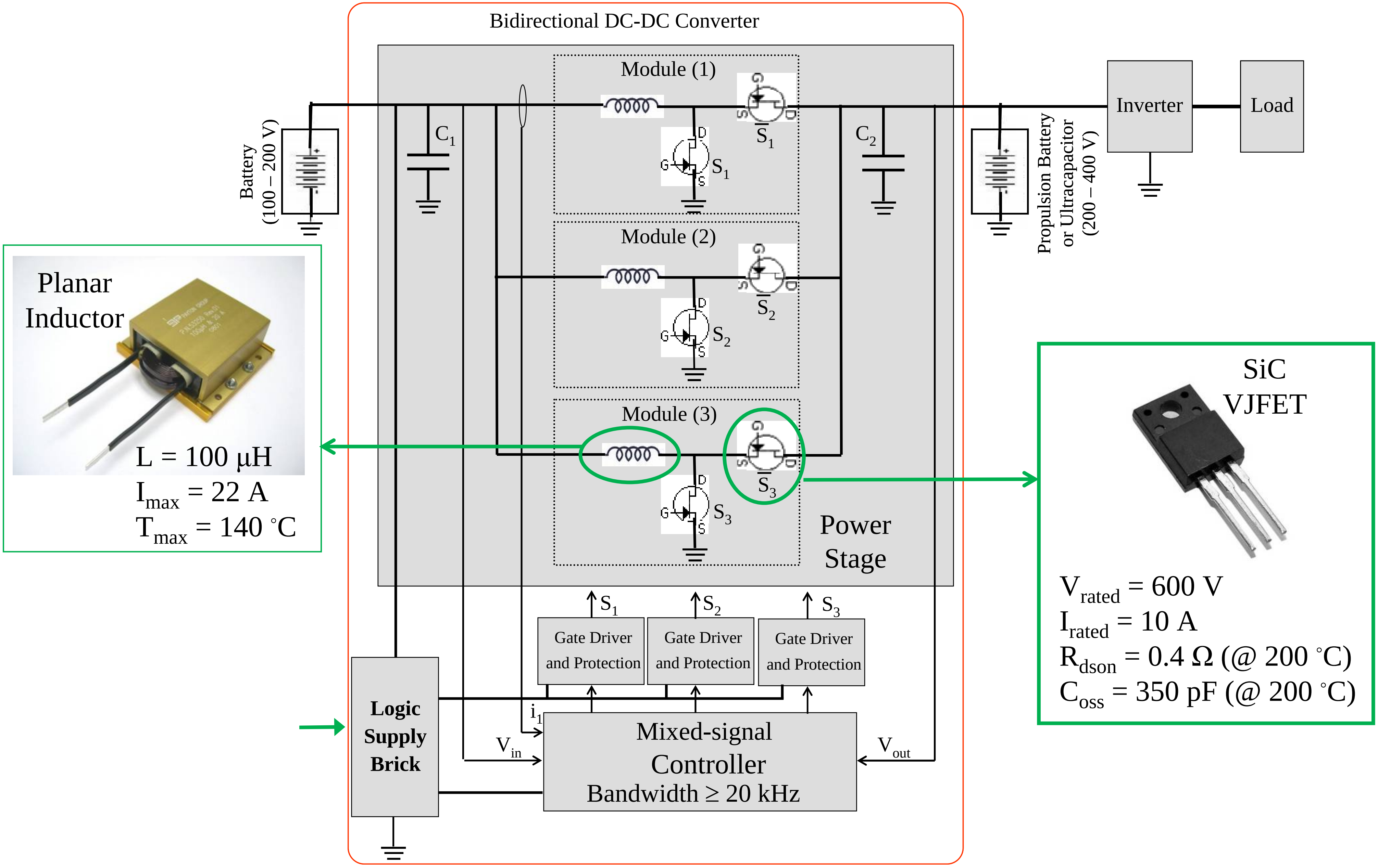


Planar Inductor

$L = 100\ \mu H$

$I_{max} = 22$ A

$T_{max} = 140\ ^{\circ}C$

SiC VJFET

$V_{rated} = 600$ V

$I_{rated} = 10$ A

$R_{dson} = 0.4\ \Omega$ (@ 200 °C)

$C_{oss} = 350$ pF (@ 200 °C)

SiC VJFET Advantages

Comparison of the on resistances and output capacitances of SiC VJFET with state-of-the-art MOSFETs.

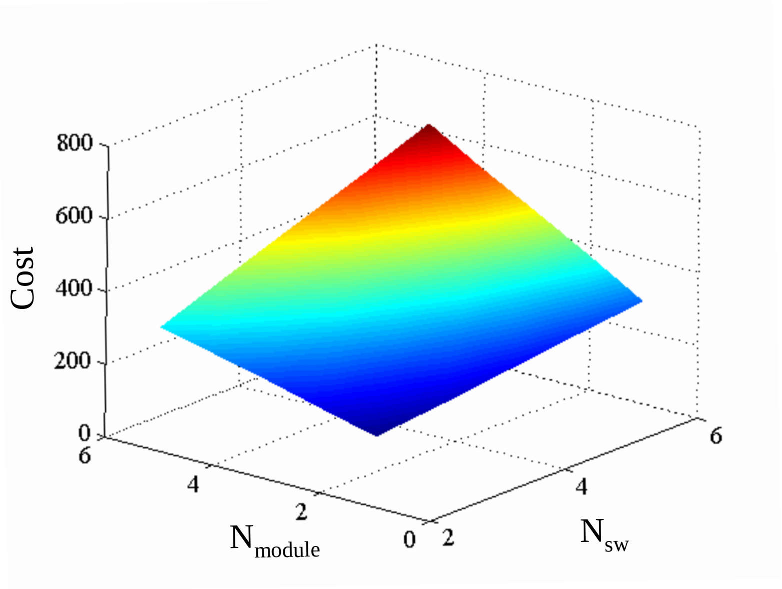
Device Type	Ratings	On resistance (ohm)			Output Capacitance (pF)		
		25 ^{o}C	150 ^{o}C	200 ^{o}C	25 ^{o}C	150 ^{o}C	200 ^{o}C
SiC VJFET (SiCED)	600 V, 10 A	0.42	0.74	0.8	~ 350	~ 350	~ 350
SuperFET FCPF11N60	600 V, 11 A	0.38	0.83	N/A	~ 700	~ 700	N/A
CoolMOS SPB11N60C3	600 V, 11 A	0.38	0.95	N/A	~ 550	~ 550	N/A
CoolMOS 20N60S5	600 V, 20 A	0.2	0.49	N/A	~ 900	~ 900	N/A

- For the same device rating, SiC VJFET provides superior on resistance and output capacitance as compared to the Si field-effect devices. That implies lower conduction as well as switching losses.

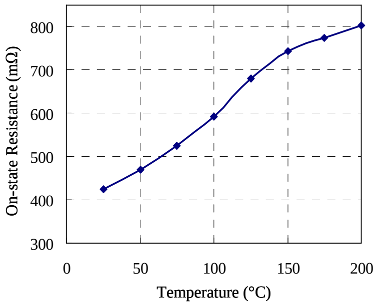
- For a Si device with higher current rating, lower on resistance comes at the price of higher output capacitance. This implies, lower conduction loss, but higher switching losses. The latter can limit maximum switching frequency and power density.

Optimal Number of Converter Modules and Switches per Module

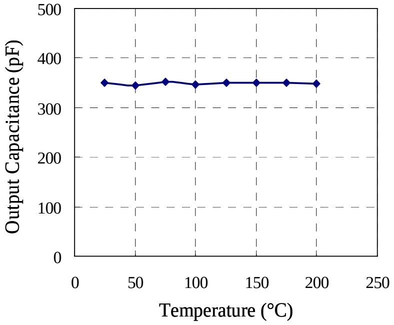
- Selection based on estimated efficiency and cost
  - SiC VJFET operating at 175 °C
  - Planar magnetics operating at 140 °C
- Optimized values
  - Number of converter modules: 3
  - Number of switches per module: 2 x 4

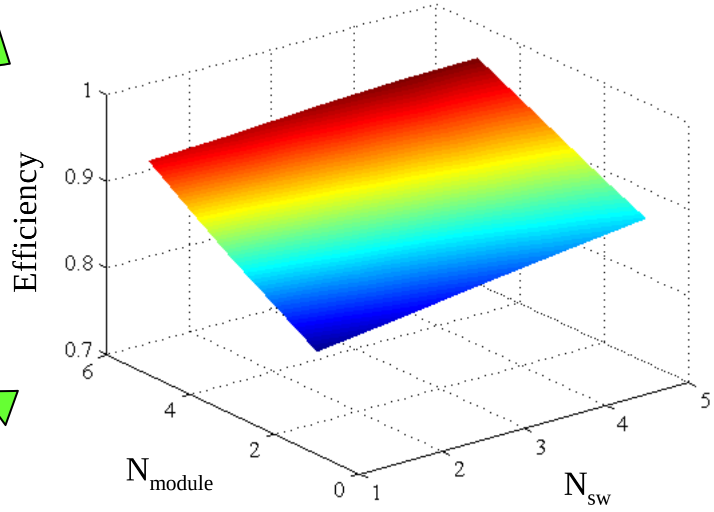


Variations of SiC VJFET On-resistance with Temperature



Variations of SiC VJFET Device Capacitance with Temperature





Gate Driver and Protection

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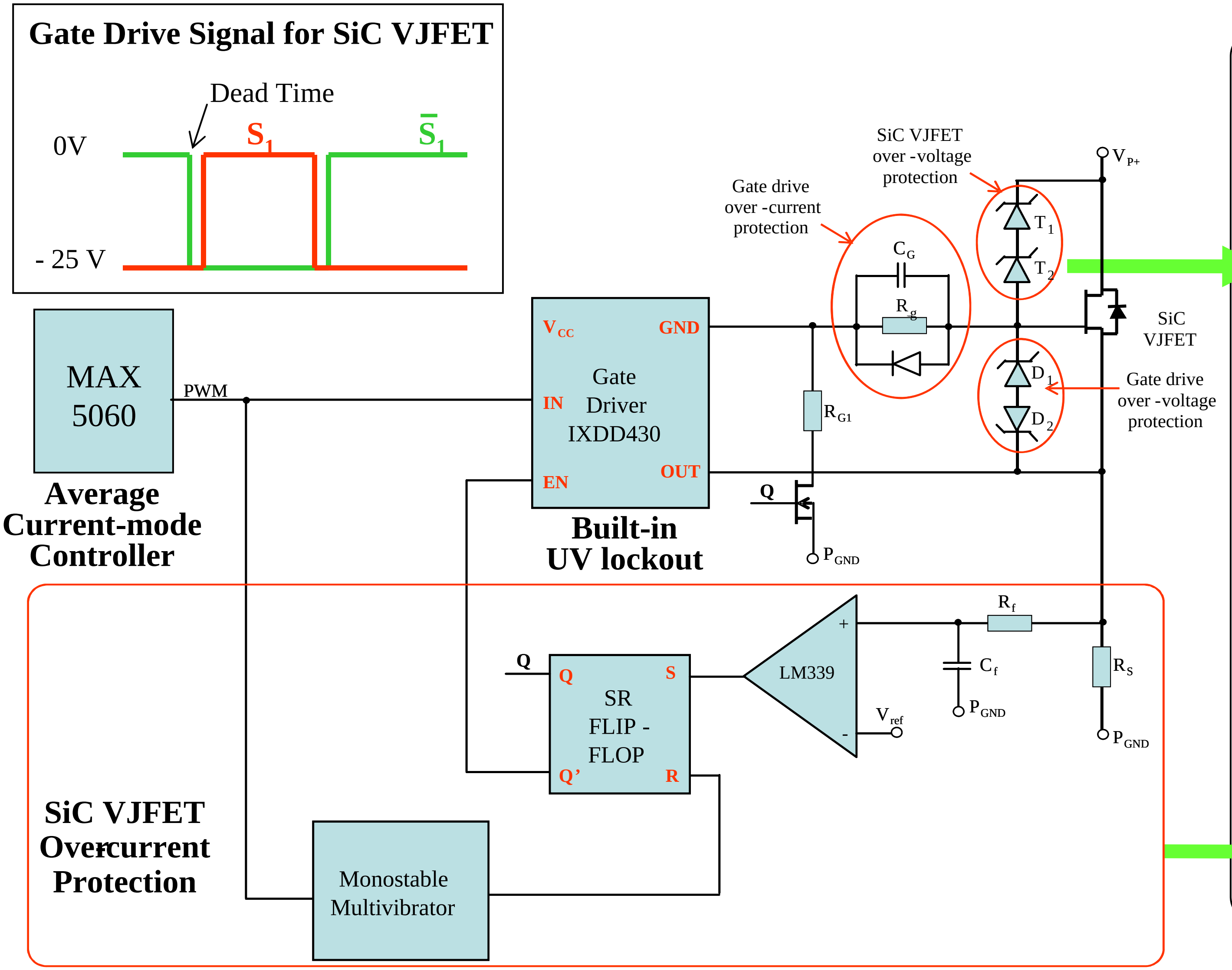
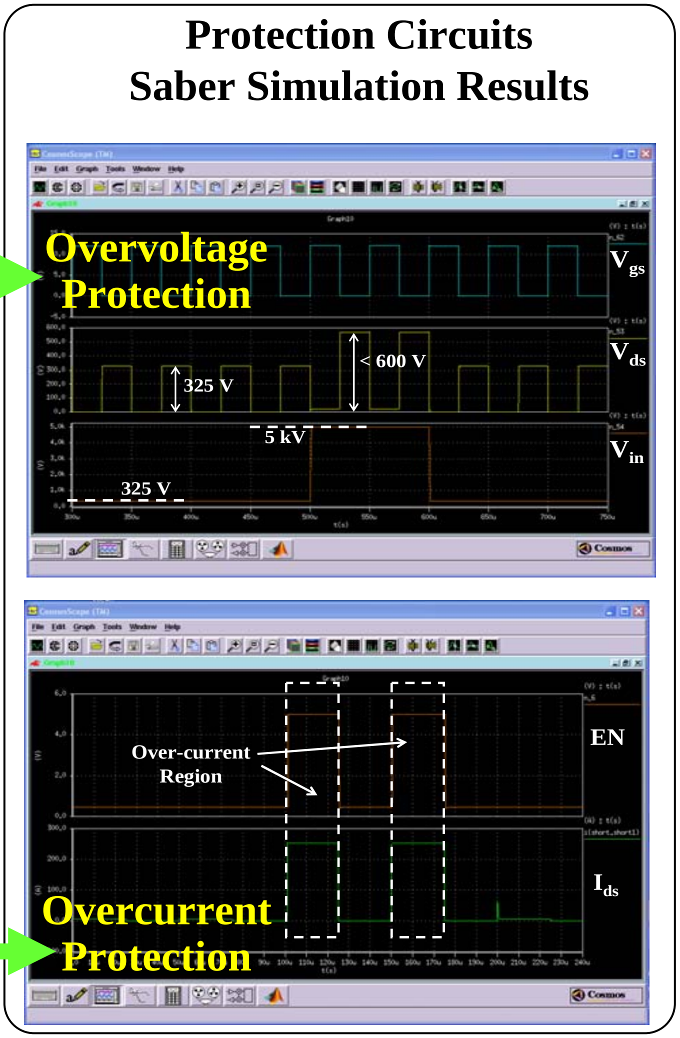
Issues:

- SiC are normally-on devices and require ≤ - 25 V to turn off
- Self-contained ASICs are not available leading to discrete design of protection circuits



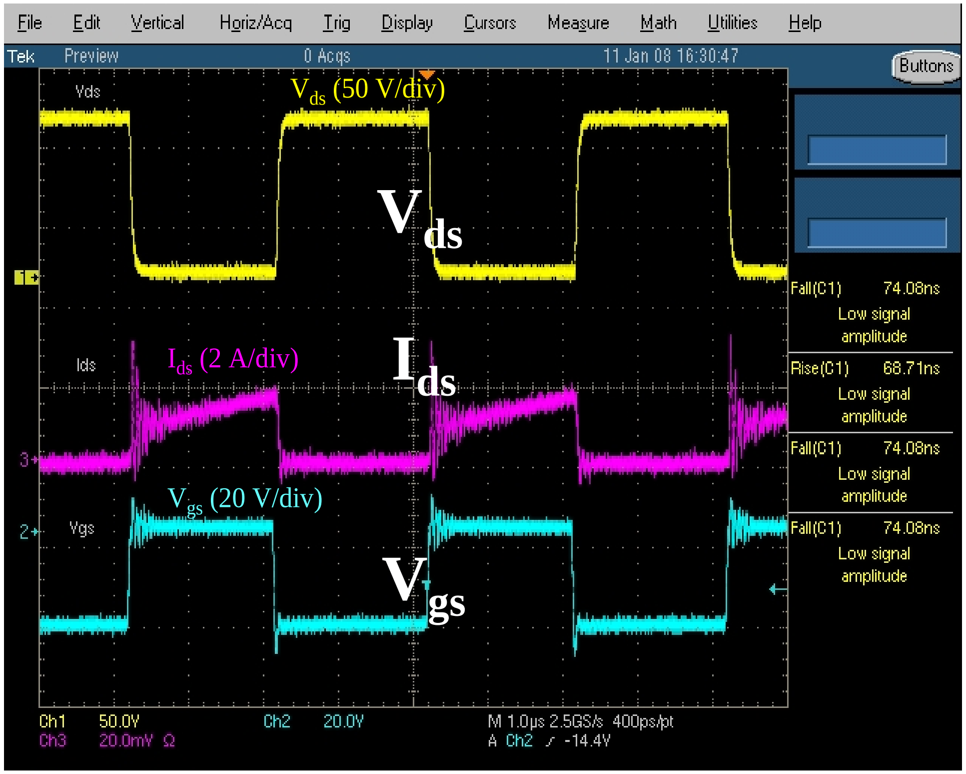
Gate Drive Signal for SiC VJFET



Protection Circuits
Saber Simulation Results

Preliminary, Experimental Gate-drive Results

Time Domain



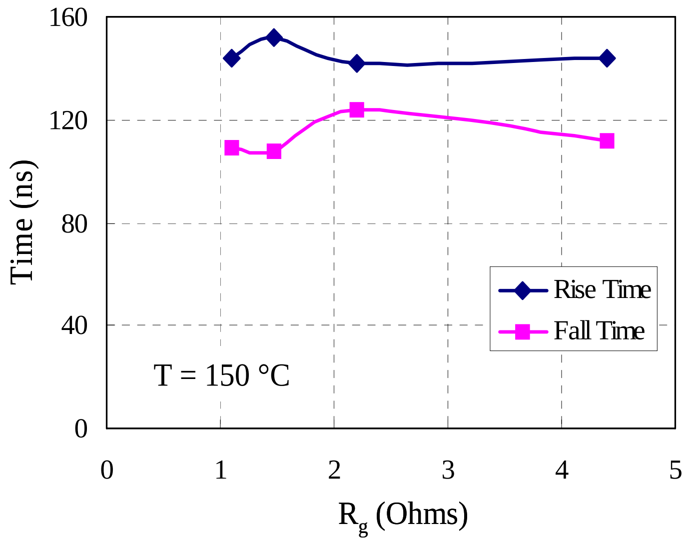
Fall(C1) 74.08ns
Low signal amplitude

Rise(C1) 68.71ns
Low signal amplitude

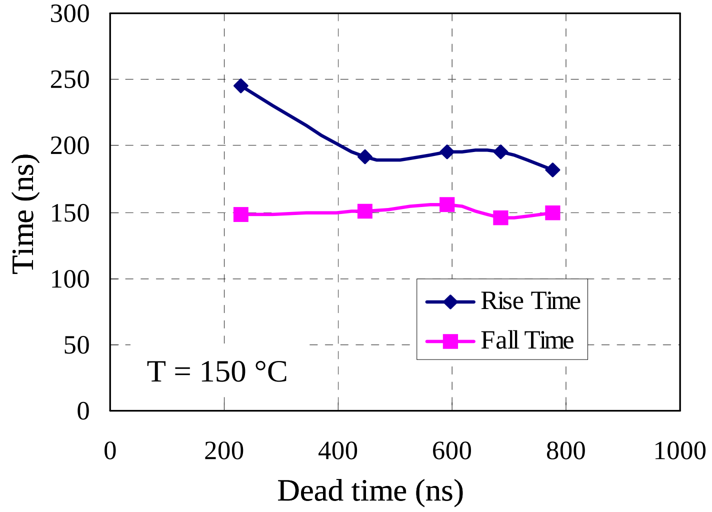
Fall(C1) 74.08ns
Low signal amplitude

Fall(C1) 74.08ns
Low signal amplitude

Parametric: Rise and Fall times with variations in Gate Resistance

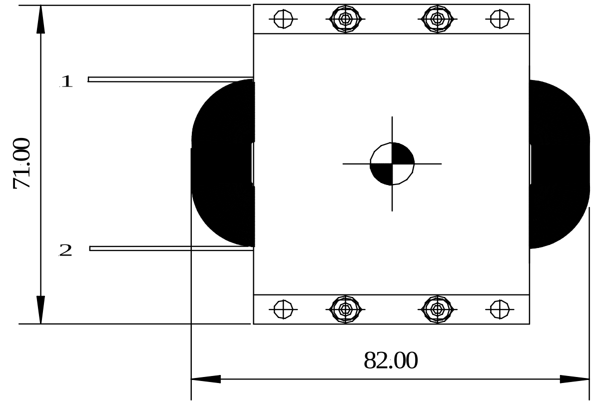


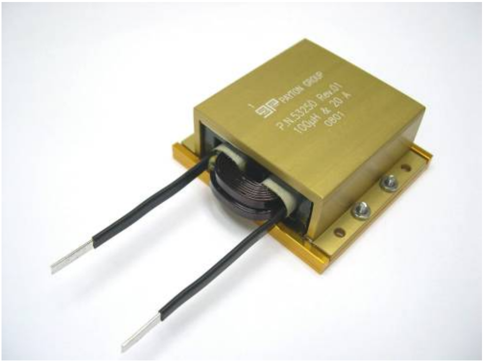
Parametric: Rise and Fall times with variations in Dead Time



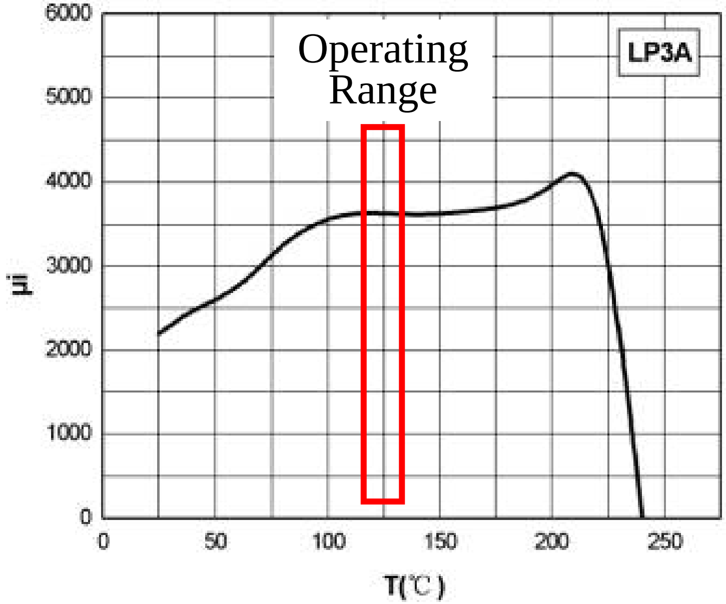
Planar Inductors Design

- Core: Ferrite LP3A
- Number of turns: 18
- Loss increases by 1.2 W/°C

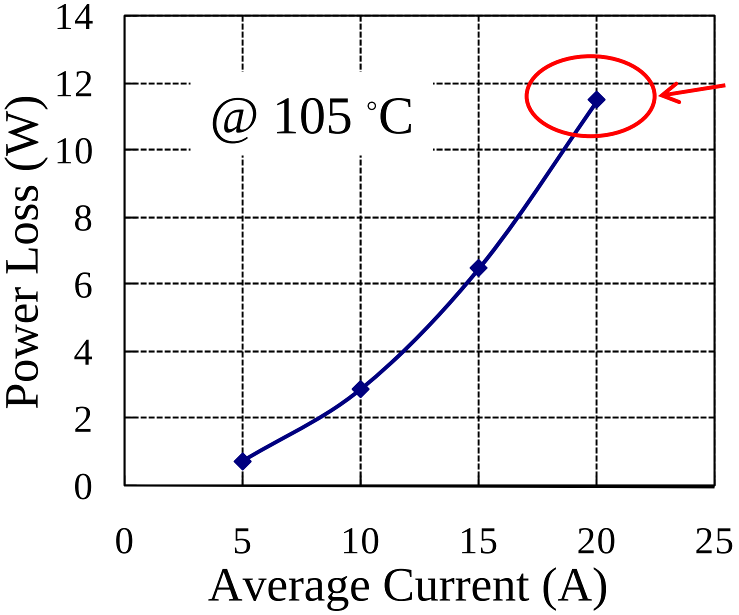




Variation of Flux Density with Temperature

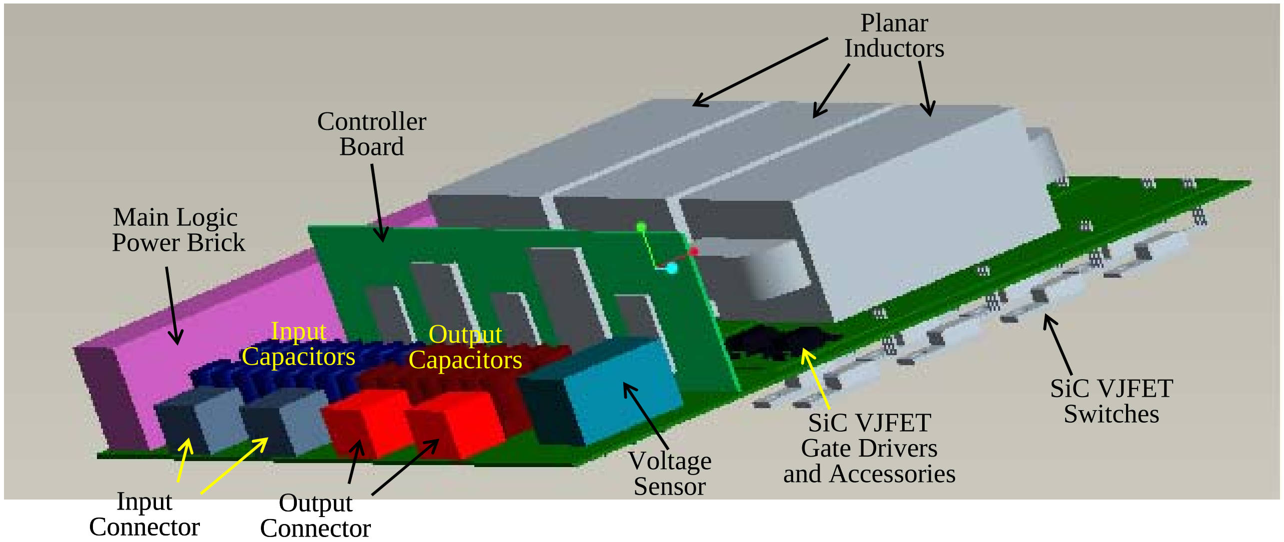


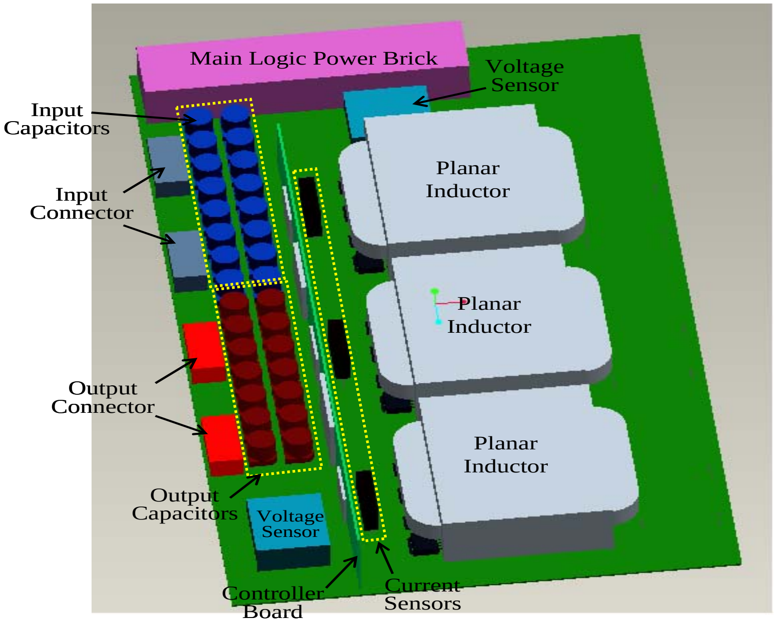
Variation of Power Loss with Load



Rated operating point

CAD Layout Design





Control System

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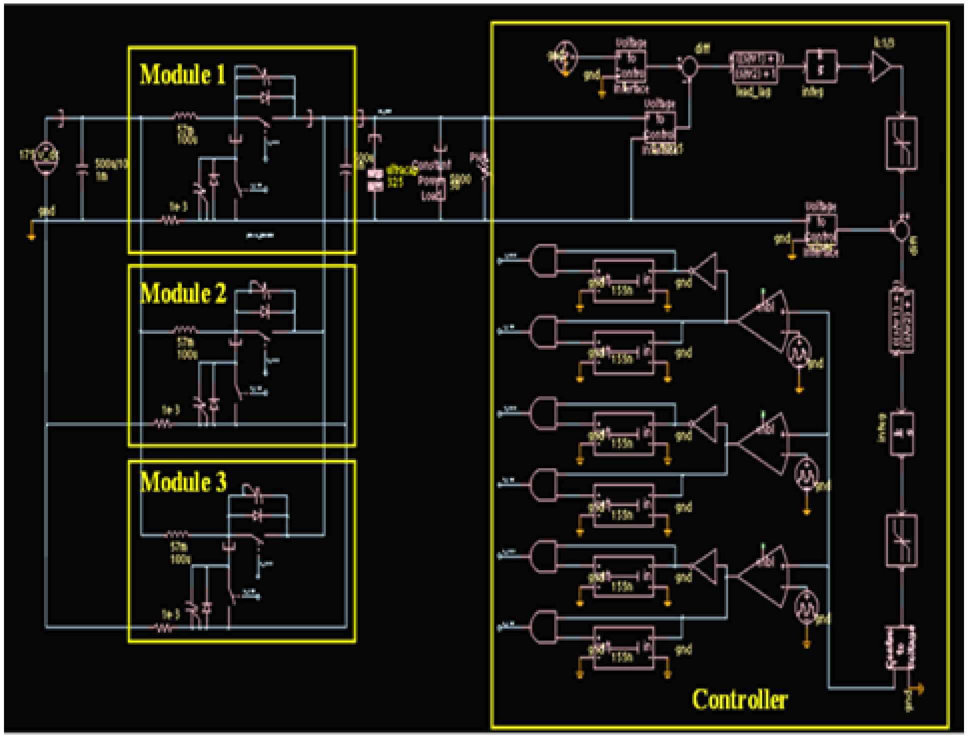
Operating Modes

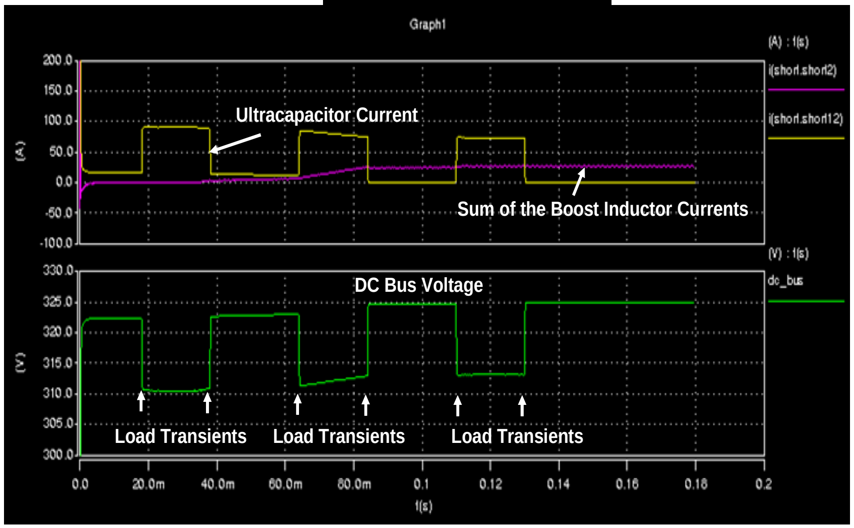
- Motoring mode, where the power flows from the 100 – 180 V energy-source battery to the dc bus
- Generating mode, where the power transfer is in the opposite direction
- Charging mode, where the plug-in energy is transferred most likely from the dc bus to the 100 – 180 V battery energy source.

SABER Schematic

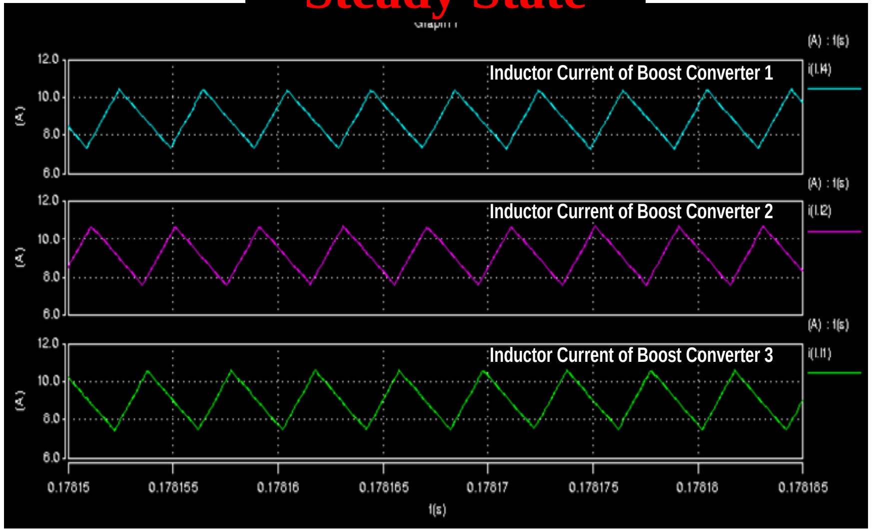


Simulation Waveforms

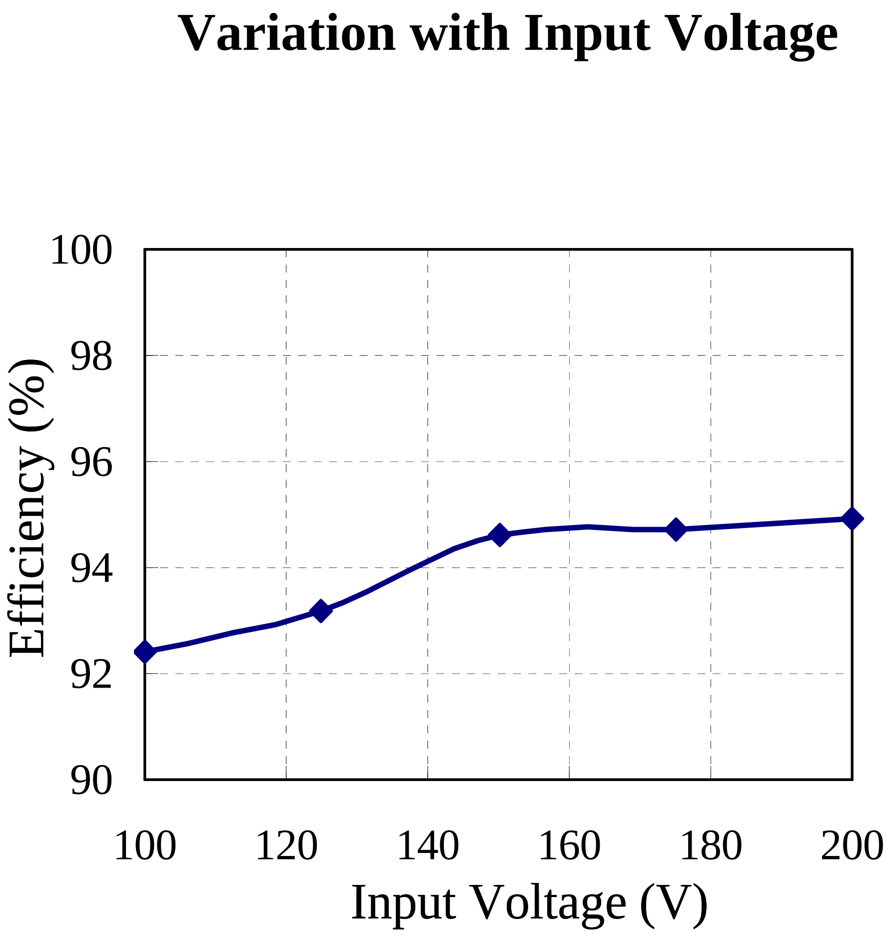
Transient

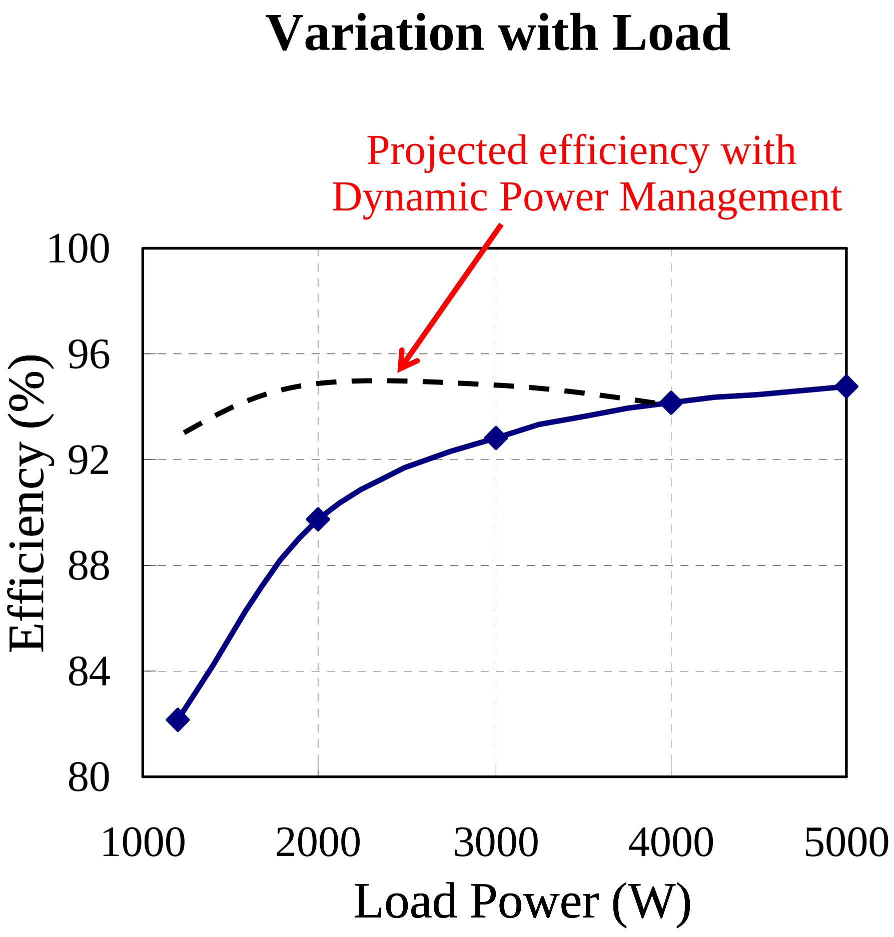


Steady State



Efficiency Variations (Design Estimations)





Phase I Activities for 2008

- Collect data from battery and other sub-system supplier
- Complete the dc voltage optimization modeling
- Characterize the power devices and magnetic components.
- Fabricate and Characterize the Sic converter
- Fabricate and characterize the Si converter
- Design the integrated magnetic, sensor and Power Silicon.

Summary

DC voltage optimizations.

- Vehicle Configurations defined
- Motor and inverter Supplier Cost and loss model data is needed.
- Battery Supplier Cost and loss model data is needed.
- Drive Cycle for the study is US06

Sic Converter.

- Magnetic and power stage designed
- Gate Driver designed and molded.
- Converter System modeling.

Si Converter.

- Magnetic and power stage design on-going.
- Integrated Magnetic, Silicon and Sensors design ongoing.