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► Chapter 5 Electric Machine Design and Analysis
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  – Copper cage induction machine for EV applications
  – Other electric machine and control
Chapter 1
Passive Components
SuperCap Research highlights

Desired parameters

- High energy density
- High power density
- High cycling stability
- Low cost

Contact: Dr. Wu Lu (lu.173@osu.edu)
Asymmetrical SuperCap Research Highlights

► Hybrid electrodes combine the advantage of high power density, long cycling stability of carbon electrodes and the high energy density of metal oxides

► Asymmetrical structure extends the potential window of existing electrolytes leading to high energy density

---

**Graphene**

**MWCNT**

**MoO$_3$**

**WO$_3$**

**V$_2$O$_5$**

**RuO$_2$**

**Co$_3$O$_4$**

**MoO$_2$**

**Fe$_3$O$_4$**

**CuO**

**TiO$_2$**

**In$_2$O$_3$**

**Cu$_2$O**

**SnO$_2$**

**CoO**

**MnO$_2$**

**Work Function /eV**

<table>
<thead>
<tr>
<th>Cation</th>
<th>Total potential window</th>
</tr>
</thead>
<tbody>
<tr>
<td>MnO$_2$</td>
<td>7.5</td>
</tr>
<tr>
<td>MoO$_3$</td>
<td>7.0</td>
</tr>
<tr>
<td>WO$_3$</td>
<td>6.5</td>
</tr>
<tr>
<td>V$_2$O$_5$</td>
<td>6.0</td>
</tr>
<tr>
<td>RuO$_2$</td>
<td>5.5</td>
</tr>
<tr>
<td>Co$_3$O$_4$</td>
<td>5.0</td>
</tr>
<tr>
<td>MoO$_2$</td>
<td>4.5</td>
</tr>
<tr>
<td>Fe$_3$O$_4$</td>
<td>4.0</td>
</tr>
</tbody>
</table>

**Electrochemical Potential /eV**

- The chemisorption of H$^+ +$ OH$^-$ leads to a potential change $\Delta E_1$
- The total potential window is $E_0 + \Delta E_1 + \Delta E_2$

---

**Contact:** Dr. Wu Lu (lu.173@osu.edu)
Ultra-Wide Gap AlGaN Channel Transistors

- Ultra-wide bandgap AlGaN – $E_{G\text{, AlN}}$ (6.2 eV) > $E_{G\text{, GaN}}$ (3.4 eV)
- Breakdown field: $F_{BR\text{, AlN}}$ (15 MV/cm) > $F_{BR\text{, GaN}}$ (3 MV/cm)
- Could enable high power / high threshold normally-off transistors

Sanyam Bajaj, Faith Akyol, Sriram Krishnamoorthy and Yuewei Zhang

Heterostructure engineered graded ohmic contacts

$\rho_C$ ($\Omega \cdot \text{cm}^2$)

$\rho_C$ ($\Omega \cdot \text{cm}^2$) vs. Al composition in AlGaN channel

$I_{DS\text{, MAX}}$ of 60 mA/mm; 3T breakdown of 200 V/$\mu$m

Contact: Dr. Siddharth Rajan (rajan.21@osu.edu)
Dielectric/III-Nitride Based MOSFETs

- Interface control enables high-performance MOSFETs
- Low hysteresis, subthreshold slope
- High mobility and on-off ratio

- Normally-off MOSFET
- $V_{th} = +1.08\ \text{V}$ (at $I_D = 10^{-3}\ \text{mA/mm}$)
- $\Delta V = 100\ \text{mV}$
- Saturation $I_{ds} \sim 320\ \text{mA/mm}$
- Maximum $g_m = 90\ \text{mS/mm}$
- Subthreshold swing = 67 mV/dec.
- Mobility = 225 cm$^2$/V-s

Contact: Dr. Siddharth Rajan(rajan.21@osu.edu)

Sadia K. Monika, Sanyam Bajaj
Chapter 2
Applications of Power Electronics Circuits
Dynamic, On-Chip Power Supply Grids

Summary:

► Goal  → Large number of dynamic and highly-efficient on-chip power supplies
► Purpose  → Adaptive, real-time powering of highly integrated systems
► Approach  → Multi-frequency SIMO and MIMO power converters with fully-integrated outputs in nanometer CMOS
► Applications  → System-on-Chip and multi-core processors
Low-Noise, Low-EMI Switching Power Converters

Summary:
► Goal → Switching schemes to eliminate spurious noise and reduce EMI
► Purpose → Enable using switching power converters within noise-sensitive devices to achieve much higher power efficiency
► Approach → Spur-free spread-spectrum switching techniques
► Applications → Wireless communication devices

Hysteretic Implementation in 0.35-µm CMOS

Low and high frequency spectral behavior

Contact: Dr. Ayman Fayed (Fayed.1@osu.edu)
Energy Harvesting Platforms

Summary:
► Goal → Energy harvesting platforms with regulated battery management
► Purpose → Significant improvement in system running time with a much less number of batteries and less device weight
► Approach → Single-step, multi-input multi-output power converters using a single inductor to harvest solar, mechanical, thermal, and wireless energy
► Applications → Portable soldier, biomedical implants, sensor grids, and IoT devices

Contact: Dr. Ayman Fayed (Fayed.1@osu.edu)
Ahmed Abdelmoaty and Sita Asar to continue future work

MPPT operation with 3-point sampling

Battery charging and discharging phases
Si-WBG HyS (Hybrid Switch)

Motivation:
High Power Density and High Efficiency for High Power Converters
► Recommended maximum switching frequency for IGBTs < 20 kHz

Challenges to replace Si IGBT with WBG device
► WBG power devices are available in small die sizes only
► Need to parallel multiple devices for high current
► Emerging technology/Reliability is under evaluation
► Expensive

A Mixed Technology Switch
Applications: Electric Propulsion Aircrafts/EVs

Research Outcomes:
► >75 kHz switching frequency for High Power Converters
► >50% savings in switching loss
► Die Size Optimization Algorithm/ 6:1 (Si:SiC) Die Current Ratio
► Relaxed Thermal Management System
► 79% Cost Reduction compared to a single WBG Switch
► Influence of parasitics in the interconnections

Dynamic Current Sharing: Influence of Interconnect Parasitic Inductance

Switching Frequency Limits

Proposed Concept

Proposed Gate Control

Switching Energy Comparison
Three Level T-Type Power Electronics Building Block

Motivation:
► Specific Power Density: 25 kW/kg
► Low Profile/Footprint & Good Form Factor
► Minimum Loop inductance
► Low Switching and Conduction Losses

Approach and Research Outcomes:
Si-SiC HyS (Hybrid Switch) for low losses
Multi-Layer (5) Busbar Concept

1. DC+
2. DC Neutral
3. DC-
4. AC
5. Common Source

Minimum Loop inductance
► < 25 nH excluding Modules
► < 40 nH including Modules

Low Weight using Aluminum Bars

Specific Power Density: 25 kW/kg!
Effects of RWP and Filters on WBG Device Switching

**Highlights of Work:**

- Effects of RWP (Reflected Wave Phenomenon) Currents & Voltages on device switching is studied
- Cable and motor load reduce the device \( \frac{dv}{dt} \) and increase switching losses
- Output inductor increases losses but increases damping time for reflected wave and does not reduce \( \frac{dv}{dt} \) at motor terminals
- RC filter reduce \( \frac{dv}{dt} \) at load but increase switching losses
- A combination of \( L_{aux} \) and RC terminal network identified for reduced losses
- Simulation and experimental verification using Double Pulse Test of CREE C2M0080120D & C4D20120D

### Impedance comparison (as seen by top device)

### Increased Damping Time of RW (comparison w/ and w/o \( L_{aux} \))

<table>
<thead>
<tr>
<th>Condition</th>
<th>( E_{on} (\mu J) )</th>
<th>( E_{off} (\mu J) )</th>
<th>( E_{total} (\mu J) )</th>
<th>( V_{load} (V) )</th>
<th>( \frac{dv}{dt} ) at load (V/ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4m + Motor</td>
<td>24.7</td>
<td>266.2</td>
<td>290.9</td>
<td>759</td>
<td>8.3</td>
</tr>
<tr>
<td>4m + Cable + ( L_{aux} )</td>
<td>25.2</td>
<td>242.7</td>
<td>267.8</td>
<td>818</td>
<td>3.6</td>
</tr>
<tr>
<td>4m + Cable + RC</td>
<td>24.7</td>
<td>265.9</td>
<td>290.6</td>
<td>610</td>
<td>4.3</td>
</tr>
<tr>
<td>4m + Cable + RC + ( L_{aux} )</td>
<td>25.3</td>
<td>252.2</td>
<td>277.4</td>
<td>574</td>
<td>2.6</td>
</tr>
</tbody>
</table>

Contact: Dr. Fang Luo  (luo.571@osu.edu)
Evaluation of a Interleaved Zero Current Switching Inverter against Interleaved Hard Switching Inverters

Motivation:
► interleaved technique
► Zero Current Transition without complex circuit
► Reducing passive components with same active switches

Conclusion:
1. Both topologies achieve evenly distributed loss on phases within switching cycle, thus requiring the same current rating device
2. Device output capacitance resonates with small interphase inductor, thus generating additional conduction and switching loss
3. Turn-on loss reduction is related to switching frequency and inductance value indirectly
4. Inductor loss in IZCTI is higher than its in IHSI in high switching frequency
5. DM noise from 4 MHz to 40 MHz is effectively attenuated in IZCTI compared to IHSI
Power Loss Model for MHz Critical Conduction Mode

Power Factor Correction Circuits

MHz CrM Mode PFC Difference:
► Larger negative inductor peak current.
► Longer duration of non-energy transfer stage.

Model Improvement:
► Switching frequency estimation error improved from over 50% to less than 10%.
► Accurate power loss and efficiency estimation.

Inductor Current Model

Switching Frequency Estimation (Compared w/ Traditional Model)

Efficiency and Power Loss Estimation

Contact: Dr. Jin Wang (wang.1248@osu.edu)
Adaptive Constant Power Control and Power Loss Analysis of a MHz GaN based High Power Density AC/DC Converter for Low Power Applications

**Motivation:** at MHz fs, dc-link cap size -> bottleneck of further power density improvement

**Achievements:**
- Power loss model of constant power operation with MHz switching frequency
- Improved light load efficiency with adaptive constant power control

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**Digital control diagram**

**A 70 W prototype**

**Experimental waveform at 60 W**

**Higher Eff but still meets the voltage ripple requirement**

---

Chengcheng Yao, Yue Zhang, Xuan Zhang, He Li and Huanyu Chen

Contact: Dr. Jin Wang (wang.1248@osu.edu)
Touch Current Suppression for Semiconductor-Based Galvanic Isolation

Semiconductor-based Galvanic Isolation:
► The switches deliver DM load power during the ON states.
► The switches sustain the CM isolation voltage and block the CM leakage current during the OFF states.

Enabling Technology – WBG Power Devices:
► High isolation voltage rating → High breakdown voltage.
► Low CM leakage current → Low output capacitance $C_{oss}$
► High efficiency → Low on-resistance $R_{ds\_on}$

CM Leakage Current ($I_{CM}$) Analysis:
► A pulse CM leakage current is generated at every turn-on event, charging up the switch $C_{oss}$, and it repeats at $f_{sw}$.
► $I_{CM}$ ↓ needs $C_{oss}$ ↓, and also $f_{sw}$ ↓.

CM Leakage Current ($I_{CM}$) Reduction:

20 dB reduction of leakage current achieved
Electromagnetic Noise Mitigation for Ultra-fast On-die Temperature Sensing in High Power Modules

On-die Temperature Sensing Diode
- **Strong noises** coupled to the sensor during switching
- Temperature sensing time constant around **several milliseconds**

**Noise Compensation and Sensing methods**

- Contact: Dr. Jin Wang (wang.1248@osu.edu)

**Achievement:** With the proposed noise compensation methods, temperature sensing with a 0.8 us time constant is achieved.
10 kW High Power Density GaN-based Three Phase Inverter

Motivations

► To improve three phase inverter’s power density by utilizing high voltage high current GaN HEMTs;
► To investigate existing issues of implementing GaN HEMTs into high power application.

Enhanced System Reliability

Phase-leg Design

► Low stray inductance, low dc resistance and low thermal resistance design insures the high efficiency operation of the inverter.

Experiment Results

50 kHz, 10 kW Operation

Efficiency Curve
SiC based Modular Multilevel Converter

Motivations

To improve medium voltage variable frequency motor drive system power density and efficiency by utilizing high voltage high current SiC power modules;

System specifications:

<table>
<thead>
<tr>
<th></th>
<th></th>
<th>Output Frequency</th>
<th>0-1 kHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Voltage</td>
<td>7 kV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Input Power</td>
<td>1 MVA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Output Voltage</td>
<td>4.16 kV</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Submodule Performance

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_{DS} )</td>
<td>20 V</td>
</tr>
<tr>
<td>( I_D )</td>
<td>300 A</td>
</tr>
<tr>
<td>( V_{DS} )</td>
<td>1,160 V</td>
</tr>
</tbody>
</table>

MMCs SMs Design

1.7 kV/300 A SiC MOSFET Power Modules Evaluation

Optical Fiber Communication Based SM Gate Drive Board

Design of MMC Single Arm

Submodule Performance

Turn-off Transient

Turn-on Transient

Contact: Dr. Jin Wang (wang.1248@osu.edu)
1.7 kV SiC Power Module Gate Drive Design for MMC

Design Target and Challenges

Driving capability
- Strong gate current
- +20/-5 V gate voltage

Reliability
- Comprehensive protection functions
- Topology with excellent EMI immunity capability

Insulation
- 3 kV working insulation within gate drive board
- 10 kV gated drive board external insulation to house keeping power supply

Gate Drive Board Design

Size: 103 mm * 77 mm
Optical Fiber Communication Based SM Gate Drive Board

Overcurrent Protection
- Vgs: 20 V
- Vds: 1,160 V
- Id: 600 A
- 1,160V/600A Overcurrent protection in 1.5 μs

Gate Drive System Delay
- Driving system delay from DSP to MOSFET: 400-450 ns
Medium Voltage SiC Power Module Evaluation and Gate Drive Design

Research outcomes:
► Device static, dynamic, and package evaluation
► Gate driving circuit design
  - High insulation voltage
  - High common mode transient immunity (CMTI)
  - Comprehensive protection functions

Device tested:

<table>
<thead>
<tr>
<th>Voltage rating</th>
<th>Current rating @ 25 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiC Module1</td>
<td>15 kV</td>
</tr>
<tr>
<td>SiC Module2</td>
<td>4.5 kV</td>
</tr>
</tbody>
</table>

Double pulse test results for 15 kV SiC MOSFET

High voltage lab at The Ohio State University
Comparison on GaN Device Based LLC, Phase-Shift Bridge and Phase-shift QSC Circuits

Research Targets:
► Theoretically compare the efficiency, power density and cost of three DC/DC circuits
► Compare circuits performance when currently available GaN devices employed
► Evaluate circuits potential and predict the influence of future generations of GaN devices on the circuit selection

1 kW phase shift QSC prototype:
► GaN devices employed for all the switches.
► Reduced voltage stress on primary side components: $2/3 V_{dc}$ (switches) and $1/3 V_{dc}$ (transformer).
► Peak efficiency (preliminary): 94.4%.
► Zero voltage switching in a wide range.

Contact: Dr. Jin Wang (wang.1248@osu.edu)
## Power Module Packaging and High Power Density Three-Phase Inverter Design

### Double-End Sourced Layout Design

![Double-End Sourced Layout Diagram]

- **DC<sub>1</sub>**
- **DC<sub>2</sub>**
- **C<sub>d1</sub>**
- **C<sub>d2</sub>**
- **M<sub>1</sub>-M<sub>4</sub>**
- **D<sub>1</sub>-D<sub>4</sub>**
- **S<sub>1</sub>-S<sub>4</sub>**
- **G<sub>1</sub>-G<sub>4</sub>**
- **M<sub>5</sub>-M<sub>8</sub>**
- **D<sub>5</sub>-D<sub>8</sub>**
- **S<sub>5</sub>-S<sub>8</sub>**
- **G<sub>5</sub>-G<sub>8</sub>**
- **56.83 mm**

### Improved Dynamic Performance

**V<sub>DS_peak</sub>:**
- 505V, 499V, 487V

**V<sub>DS_peak</sub>:**
- 461V, 464V, 461V

**I<sub>DS_peak</sub>:**
- 24A, 22A, 24A

**I<sub>DS_peak</sub>:**
- 33A, 23A, 18A

**Drain-Source Voltage (V):**
- 0 to 600V
- 10 m/div
- 0 to 80 ns

**Drain Current (A):**
- 0 to 35A
- 50 m/div
- 0 to 300 ns

### Improved Thermal Performance

#### Baseline Layout vs. DES Layout

- **DC Bus**
- **Numbers in Celsius**
- **M1, M2, M3, M4, M5, M6**
- **100.5, 101.3, 100.7**
- **84.0, 84.6, 83.6**

### Three-Phase Inverter Adopting DES Layout

- **Power – Efficiency Curve**
- **Efficiency vs. Output Power (Percentage)**
- **Baseline**
- **DES**

---

Miao Wang, Dr. Fang Luo, Dr. Longya Xu

Contact: Dr. Longya Xu (longyaxu@gamil.com)
Comparison of A Novel 4-Level Hybrid Clamped Converter and A 4-Level MMC for Motor Drive Application

Topography of one phase hybrid clamped converter (HCC)

4L- HCC @ 5 Hz

4L- MMC @ 5 Hz

System cost comparison

Performance comparison between HCC and MMC

almost identical performance at 60Hz

Improved performance at 5Hz:
- 2 times larger available phase voltage
- 2 times smaller \( V_{cap} \) ripple and smaller THD % and losses

Jianyu Pan, Dr. risha Na, and Dr. Longya Xu

Contact: Dr. Longya Xu (longyaxu@gamil.com)
Design of 30kVA Inverter Using SiC MOSFET for 180°C Ambient Temperature Operation

Motivation
- Develop a 30kVA inverter for a wide temperature range from -10°C to 180°C
- Demonstrate the performance of a high temperature (HT) and low cost gate driver circuit
- Challenge: Optimize the system configuration and thermal management

Experimental Result
- Recorded Temperature profile of HT inverter
- Room temperature at 25°C
- High temperature at 180°C

Contact: Dr. Longya Xu (longyaxu@gamil.com)
Chapter 3
High Voltage
Low Pressure Partial Discharge

Summary

► In aircraft, PD occurs at a lower voltage level due to lower pressure at higher altitudes
► Existing standards do not adequately cover testing procedures suitable for low pressure conditions
► The goal of this project is to provide a testing procedure for future PD test standards
► This project includes 60 Hz AC testing and pulse voltage testing on various aircraft application components
► The pressure levels for this project range from 87 Torr (50,000 feet) to 760 Torr (sea level)

Twisted pair testing sample and the low pressure chamber

Sample result illustrating PD pulses on current waveform

Blue: Voltage, Green: Current
Efficiency and Electromagnetic Interference Analysis of Wireless Power Transfer for High Voltage Gate Driver Application

Motivation

- Isolated gate driver is required to operate high-voltage voltage source controlled switches.
- Isolation requirement can be as high as several kVs.
- Develop a coreless power supply for gate driver with strong insolation, high efficiency, and low parasitic capacitance.

System Design

- Maximum Efficiency: 90%
- Maximum Transfer power: 9W
- Parasitic capacitance: 1.7 pF

Transfer efficiency and power test

Radiated EMI Analysis

Time variation of electromagnetic field
Chapter 4
Operation and Protection of Microgrids and Vehicle Power Systems
Study of DC Arc Fault in Power Distribution System on Mild Hybrid Electric Vehicles

Research contents:
► Study possible DC arc failure modes and their impacts on the power distribution system of mild HEVs
► Study the relationship of DC arc characteristics with parameters e.g. voltage, current, gap length, temperature
► Develop a DC arc detection and protection system features in fast, accurate detection/ protection with cost effective MCUs.

Simulation model for a power distribution system

Preliminary DC arc test waveform

DC arc test setup

Contact: Dr. Jin Wang (wang.1248@osu.edu)
Intelligence Relay for Islanded Microgrid

1. Enable plug-and-play of DER
2. Detect high impedance
3. Avoid unnecessary loss of DERs
4. Economical, reliable and fast bus protection

V_{abc} \quad \Delta V \quad \Delta I

\text{Sign (SGN) calculator}

\text{Tripping element}

\text{CB trip}

E_{op} \quad E_{HIF} \quad \text{Trip}

\text{Central controller INFO}

\text{Data processing}

\text{RS}_1 \quad \text{RS}_2

\text{Relay INFO}

Kexing Lai, Dr. Mahesh Illindala

Contact: Dr. Mahesh Illindala (Illindala.1@osu.edu)
Control Method to Prevent Microgrid Collapse

Contact: Dr. Mahesh Illindala

Mariana Pulcherio, Ajit Renjit and Dr. Mahesh Illindala
Viterbi Algorithm Based Distribution System Restoration

Beginning Stage
Zero switching pair operation (1 state)

Stage One
One switching pair operation ($c_n^2$ states)

Stage Two
Two switching pair operation ($c_n^3$ states)

Stage $m-1$
$m-1$ switching pair operation ($c_n^{m-1}$ states)

Stage $m$
m switching pair operation ($c_n^m$ state)
Smart Loads to Prevent Stalling of Microgrid

**Critical Loads**
- Natural gas Genset 1: 208kW, 480V
- Utility Grid: 4.16kV/480V
- Natural gas Genset 2: 208kW, 480V
- Jaw Crusher: 55kW, 480V
- Vibrating Screen: 22kW, 480V
- Impact Crusher: 75kW, 480V
- Vibrating Feeder: 11kW, 480V
- Conveyor System: 60kW, 480V

**Adjustable/Schedulable Loads**
- Dust Collection System
- Sump Pumps
- Compressors

**Control Algorithm**
- Start
- Read $f$, $P$
- Calculate $\Sigma MP_{req}$ ($T_{on1} + T_{on2} + (2Hf)$)
- Close BRK
- Put back the shed loads
- Wait for $T_d$ seconds
- Open BRK
- Calculate $D = 2\times(\Sigma MP_{req} - P)$
- $D \leq 0$?
  - Yes
  - No
- Shed load equal to the resolution just higher than $D$

---

**Diagram**

- Diagram showing power and speed relationships for different load conditions.

---

**Contact:** Dr. Mahesh Illindala (Illindala.1@osu.edu)
Chapter 5
Electric Machine Design and Analysis
PMSM with High Power Density and Efficiency

PMSM Designed and Analyzed:

Research outcomes:
- High power density: 13-14kw/kg at 350kw
- High efficiency: 97.2-99.3% over a wide operating range
- Thermal analysis verifies the package
- Structure analysis verifies speed ~21,000rpm
- Potential application for next-generation of electrified airplane

Parameter | Value | Unit
--- | --- | ---
Stator OD | 230 | mm
Stator ID | 211 | mm
Stack Length | 93 | mm
Br (NdFeB 38EH) | 1.23 | T @ (20-200)C
Lamination Material | VAC48, M19
Lamination Thickness | 0.3 | mm

FEM Analysis of EM Design

Predicted power and efficiency map

Thermal and stress analysis

Sleeve Thickness = 1mm, deformation = 80 microns with stress ~ 30MPa at 21,000 rpm

Air Gap Thermal Conductivity 5 x 0.026 W/m/K with forced Liquid cooling jacket

Contact: L. Xu, email at xu.12@osu.edu
Copper cage induction machine for EV traction

Design Targets:
► Compact size: 5-6kw/kg
► Efficiency: >95%
► Wide speed range: 0-15,000rpm

Solutions: Copper rotor IM for small slip losses and high torque production:

The performance of the designed IM:
200 kw at the speed of 10,000 rpm
with the total losses = 5.4kw for
Efficiency = 97.3%
300 kw at the speed of 15,240 rpm
with the total losses = 6kw and
Efficiency = 98%

High torque for EV application:
Taking 2017 Toyota Camry hybrid for example:
With an optimized two-stage gearbox, 0-60 mph of 4.9 s (faster than any conventional production car other than a Tesla), a top speed of 98 mph, and otherwise excellent performance. If a three-speed gearbox is used, the top speed becomes 176 mph.
CHPPE Sponsors

Existing Members at Different Levels
Thank you!

Please Contact CHPPE Faculties for Further Information.