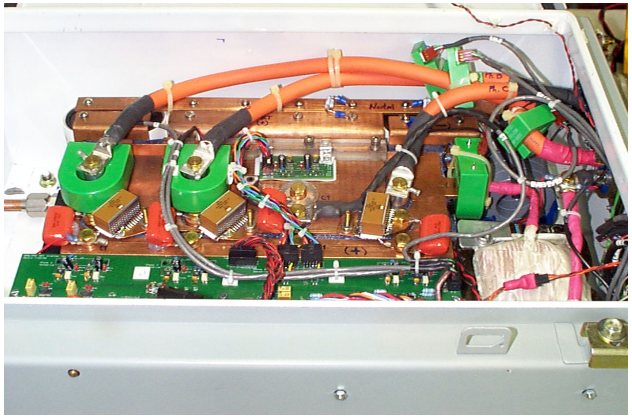
Power Electronics & Electric Machinery Innovations at Oak Ridge National Laboratory

Don Adams
SECA Core Technology Program Review
June 19, 2002

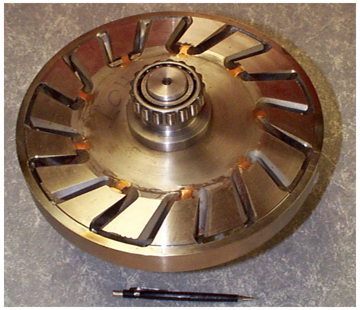
Unique: Power Electronics & Electric Machinery Research Center

- A staff of 20 researchers
- 700 m^2 laboratories
- Only DOE national laboratory with an all-encompassing PEEM program.
- The Center's world-wide reputation is supported by awards, patents, publications, and recognition by professional societies, academia, industry and DOE.

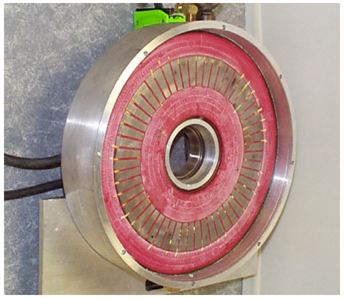


100 kW, installed on vehicle 1999
Soft switching and sensorless

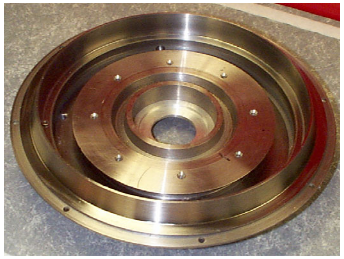
- The Center is actively involved in partnerships with several universities, private and public companies, other federal agencies, and consortiums.
- Projects supported by various offices of DOE, DOD, and industry.
- Plurality of funding is for hybrid-electric vehicles, and other areas include heavy hybrid vehicles, fuel cells, distributed energy, power quality and transmission, and motors and drives for special applications.
- Projects directly funded by industrial partners allow proprietary work.



Rotor of a HSUB motor



Stator armature of a HSUB motor



Stator DC field end bracket

Government R&D Programs

- Power Electronics & Motors Pervade Almost All Government R&D Programs
- Developments Are Synergistic and Useful to All
- Each Application Has Specific Requirements

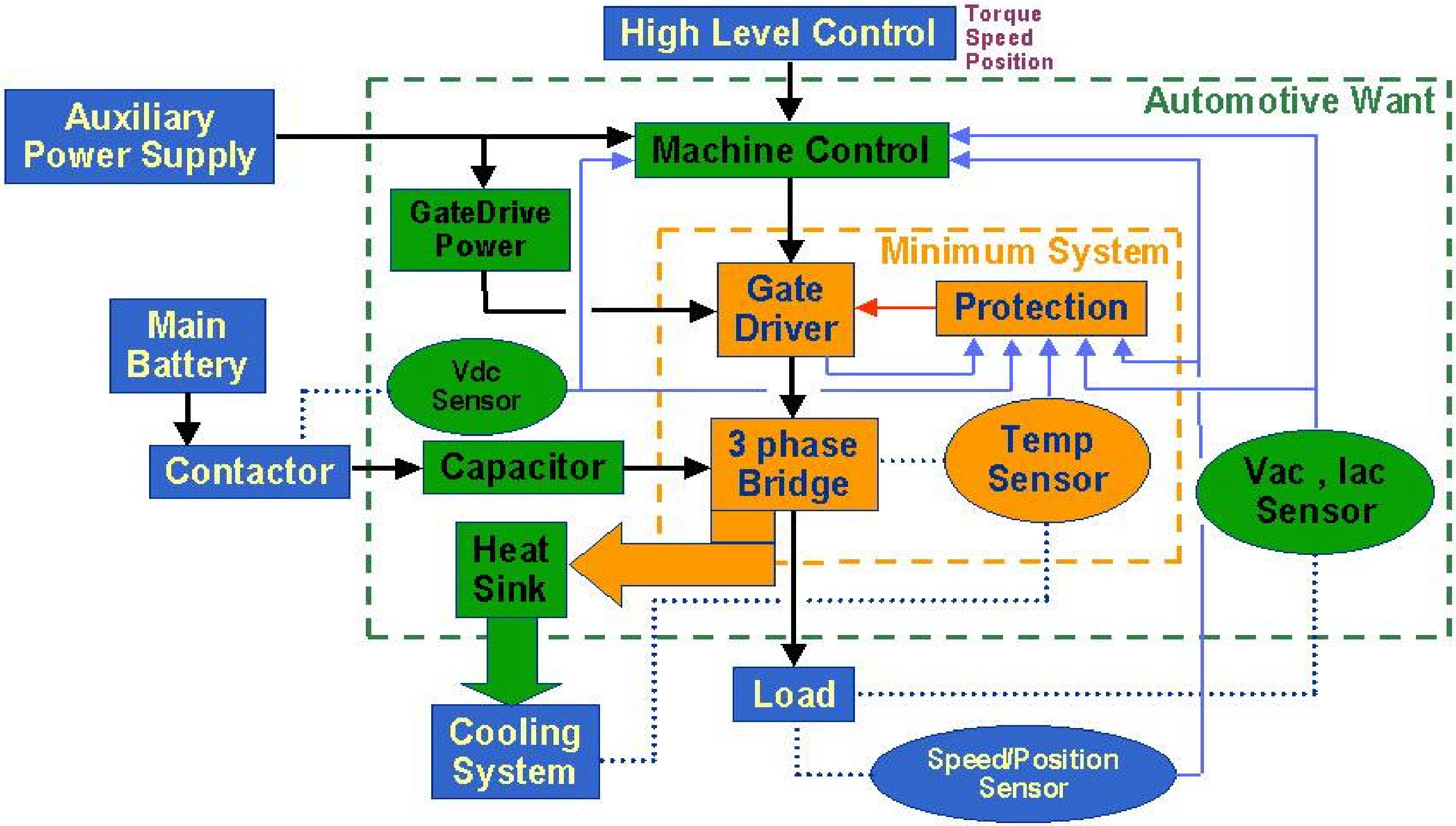
PNGV Technical Performance Objectives

Parameter	1997	1999	2000	2004
Electric Motor / Generator:				
Specific Power at Peak Load (kW/kg)	1.2	1.5	1.5	1.6
Volumetric Power Density (kW/l)	3.5	4	4	5
Cost ($/kW)	10	10	6	**4**
Efficiency (10% to 100% speed, 20% rated torque)	90	88	92	96
Power Electronics (Inverter/Controller):				
Specific Power at Peak Load (kW/kg)	2	5	4	5
Volumetric Power Density (kW/l)	8	9	10	12
Cost ($/kW)	25	15	10	**7**
Efficiency (10% to 100% speed, FTP drive cycle)	93	95	95	97-98

DOE/FreedomCAR AIPM Project

- Integrate commonly used power electronics into single inverter package
- Increase automotive energy efficiency
- Reduce component costs

AIPM


High Level Control
Torque
Speed
Position
Automotive Want
Auxiliary Power Supply
Machine Control
GateDrive Power
Minimum System
Gate Driver
Protection
Main Battery
Vdc Sensor
Contactor
Capacitor
3 phase Bridge
Temp Sensor
Vac , Iac Sensor
Heat Sink
Cooling System
Load
Speed/Position Sensor

Electrical Testing

- Inductive load testing
- Noise
- Constant speed, torque sweeps
  - Nominal battery voltage
  - Minimum battery voltage
  - Maximum battery voltage
- Acceleration/deceleration
- Regeneration

Environmental Testing

Temperature cycling

Humidity

EMI/EMC

Altitude

Splash

Salt spray

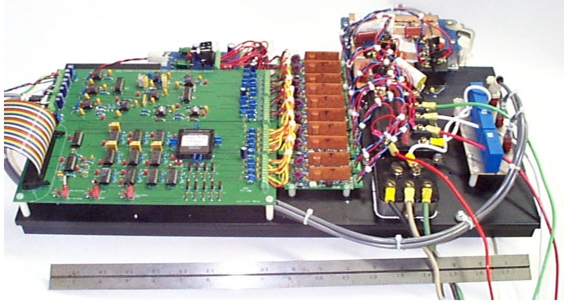
Vibration

Drop

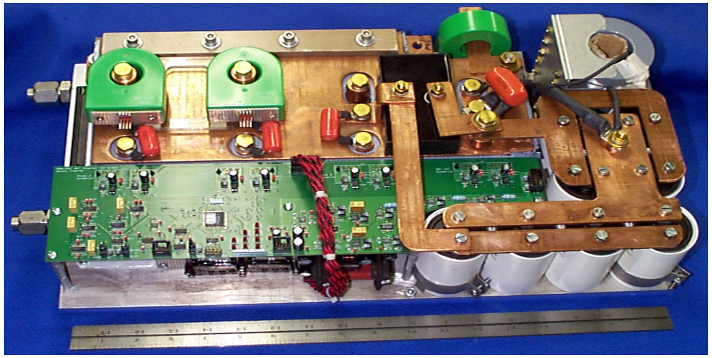
Shock

Thermal cycling

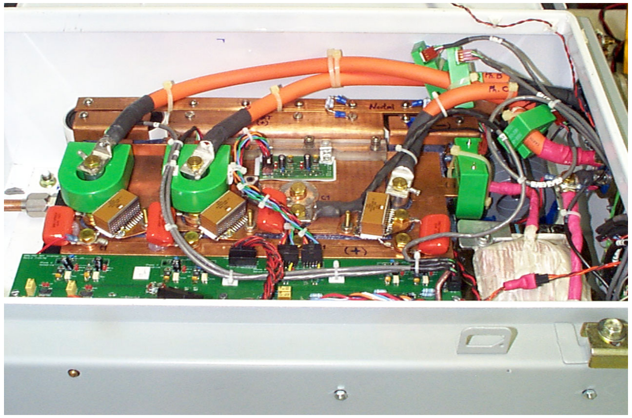
Auxiliary Resonant Tank Soft Switching Inverter



1st unit - proof-of-principle
10 kW output, invented 1997

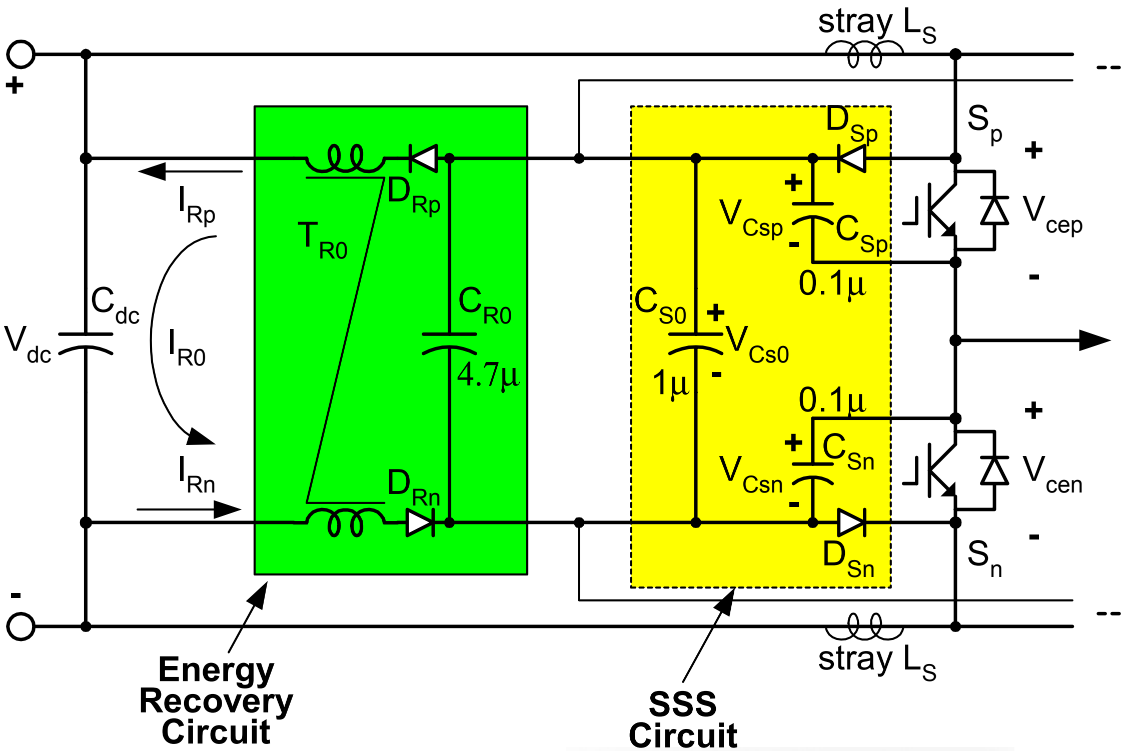


2nd unit - laboratory prototype
100 kW, built mid 1998



3rd unit - vehicle ready
100 kW, installed on vehicle 1999

Soft Switching Snubber Inverter



SSSI Features:

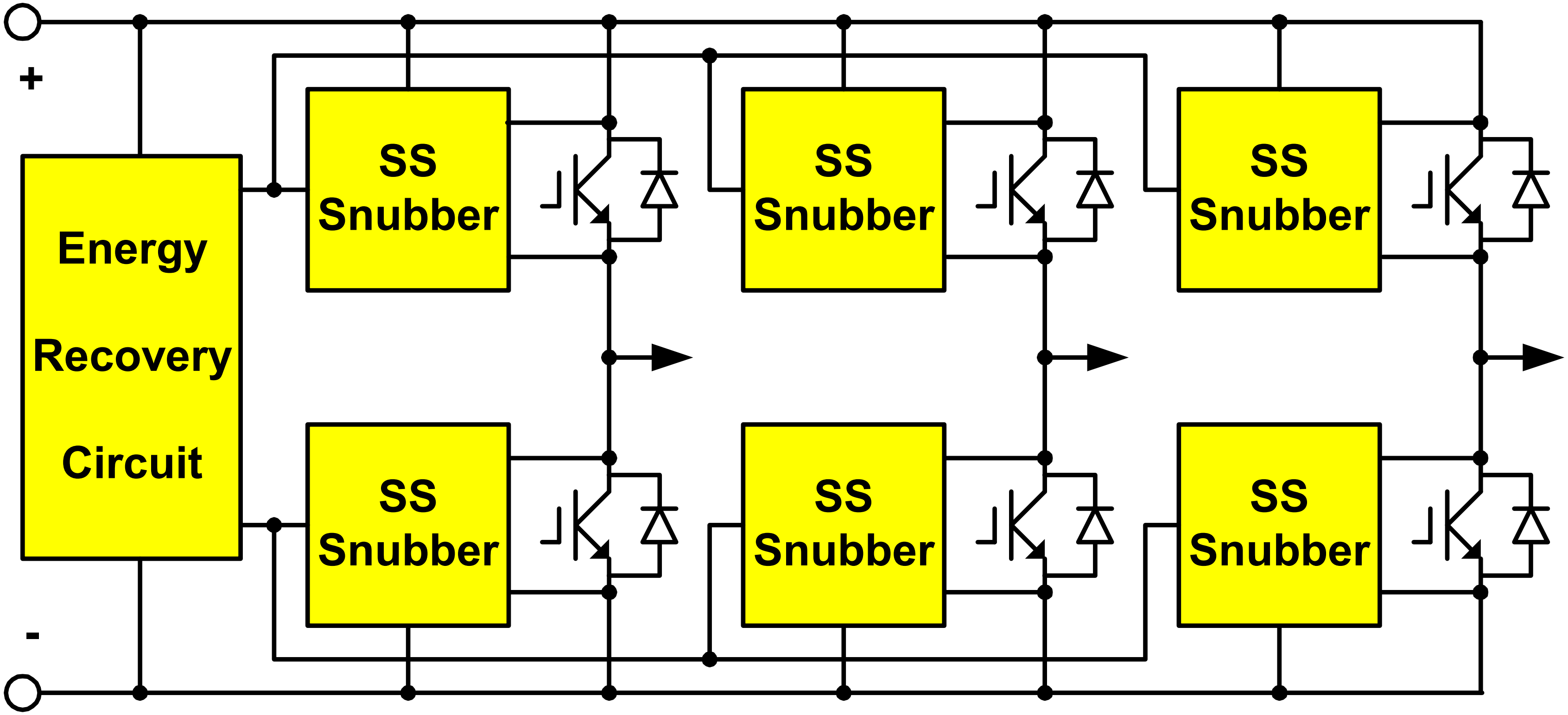
- Only passive components
- No additional control
- Any PWM possible
- Use of stray inductance
- No need for dc bus plane

SSSI Benefits:

- Reduced dV/dt and di/dt
- Lower cost
- Greater reliability

Per-Phase Configuration

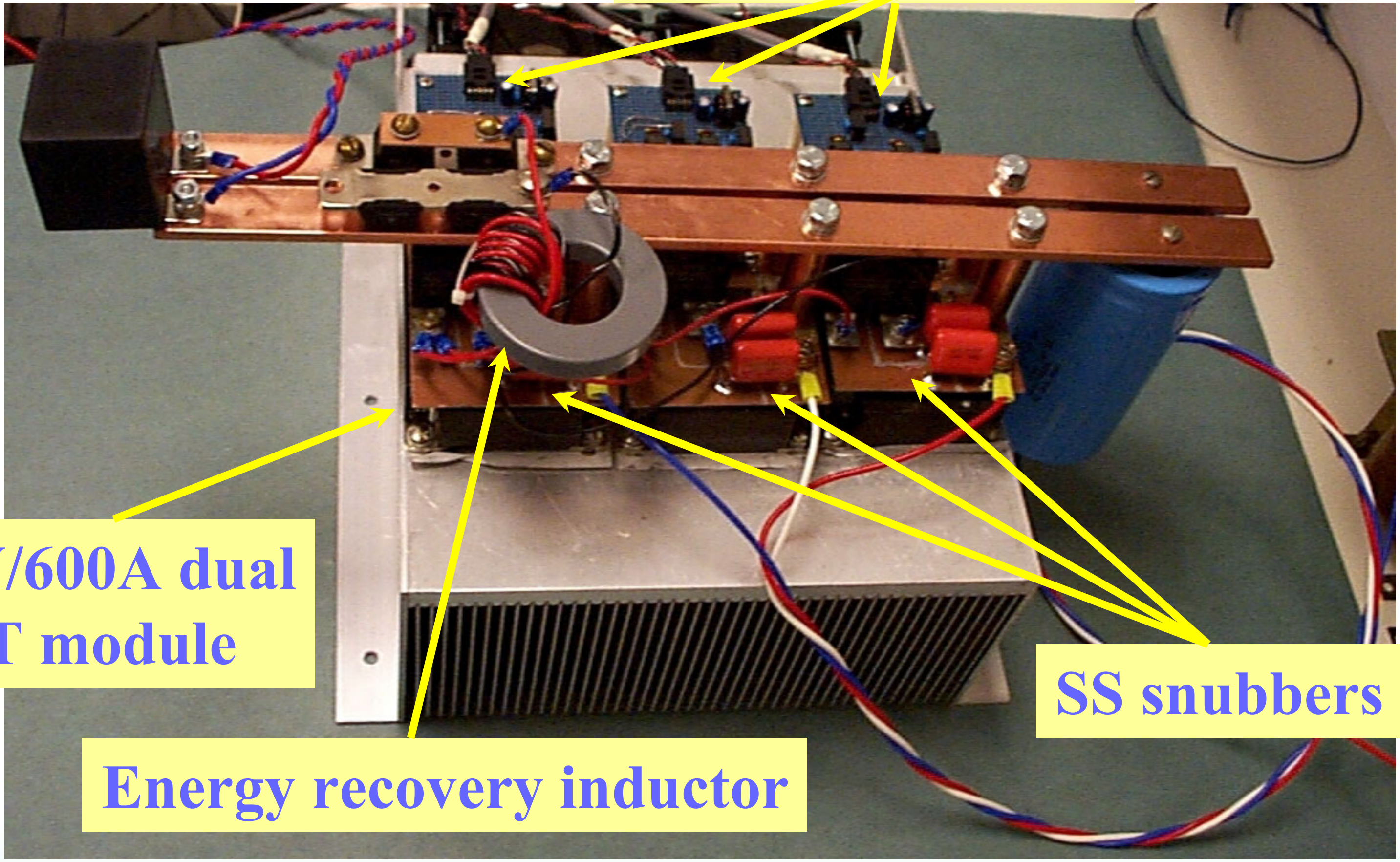
Soft Switching Snubber Inverter



Three-phase configuration

Soft Switching Snubber Inverter

Proof-Of-Concept Test Setup



Gate drive boards

600V/600A dual IGBT module

SS snubbers

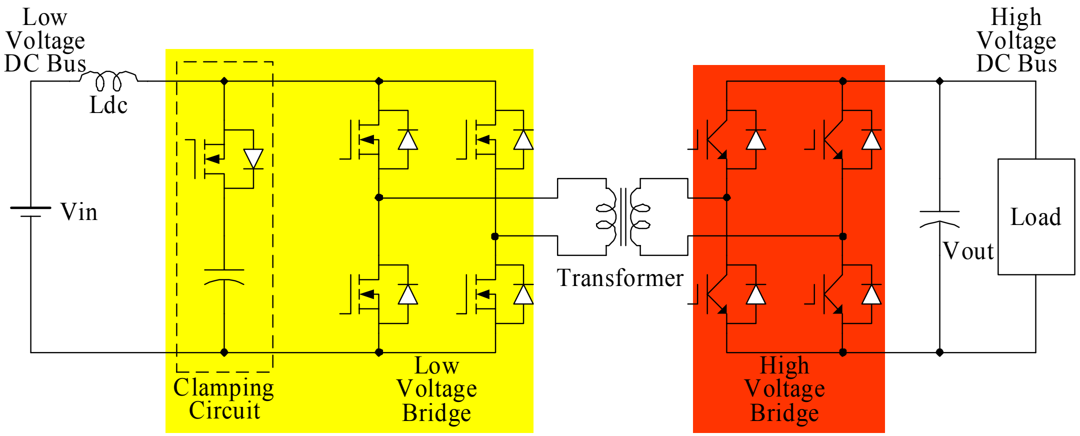
Energy recovery inductor

Bi-directional DC/DC Converter

- Background Review -

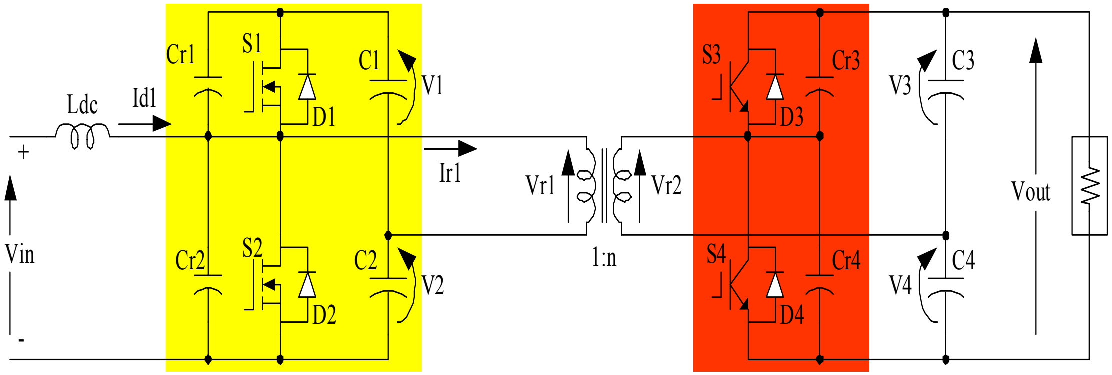
- **Challenges in DC/DC Converters for Fuel Cell Vehicles**
  - **High power and high current – 5 kW peak/1.6 kW cont.**
  - **High voltage ratio – 12 V vs 300 V**
  - **Bi-directional**
  - **Low cost and reliability**
  - **Very few topologies/products available**
    - **High cost, excessive number of components**
    - **High EMI emission**
- **DC/DC Converter Development at ORNL**
  - **First generation (1997~1999, developed at Virginia Tech through subcontract)**
  - **Second generation (1999~)**

Bi-directional DC/DC Converter



First Generation

- Dual full bridges
- Soft switching with the help of the clamping circuit

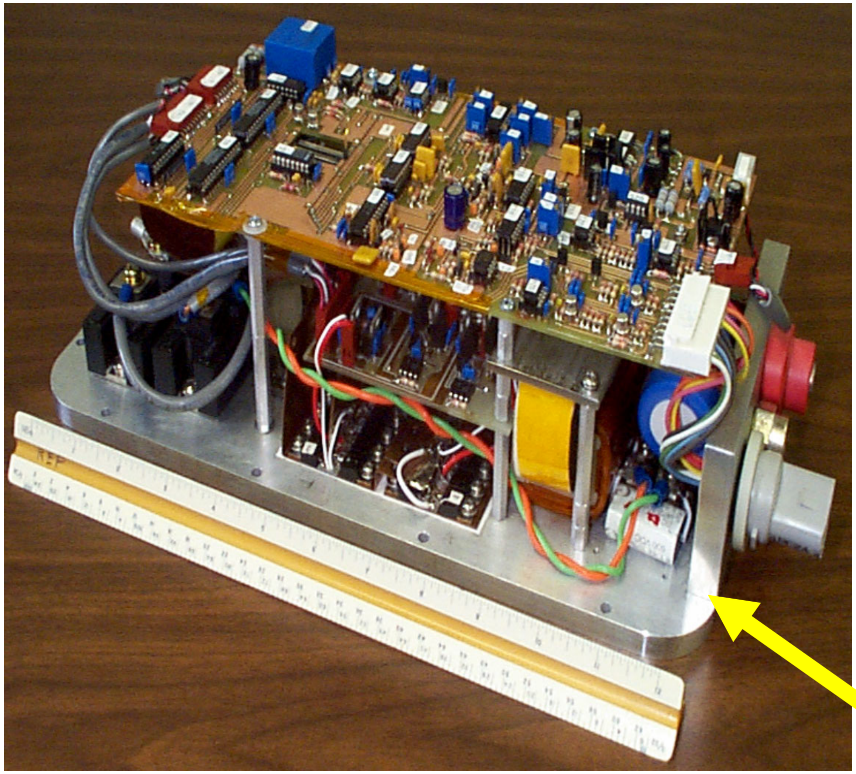


Second Generation

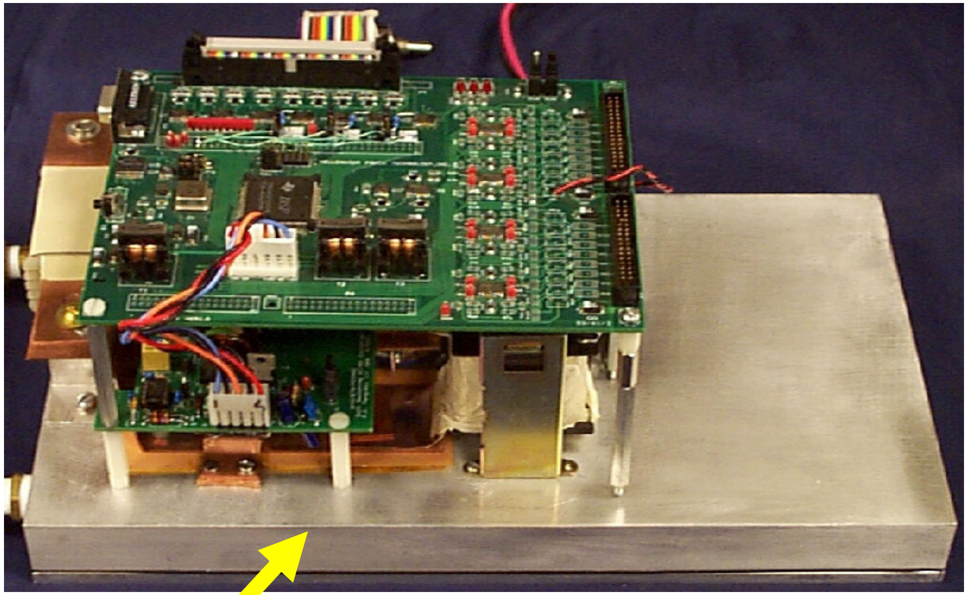
- Half the component count
- Soft switching w/o additional components
- Less control and accessories (power supplies, gate drivers)
- More compact, light, and reliable
- Low cost

Bi-directional DC/DC Converter

First Generation (1997~1999)

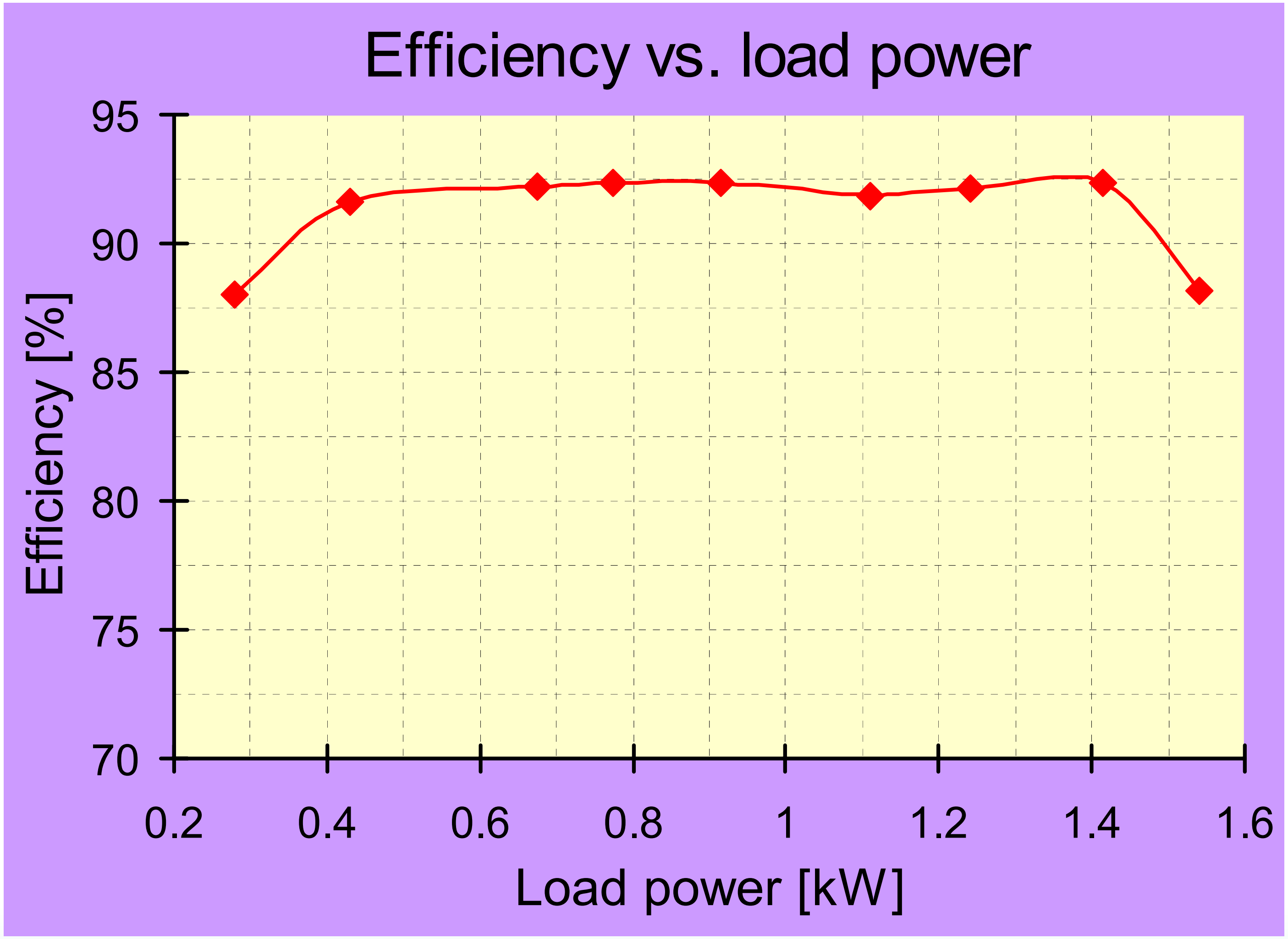


Second Generation (1999~)



Same footprint (7.5” X 13.5”)

Bi-directional DC/DC Converter
Efficiency Chart

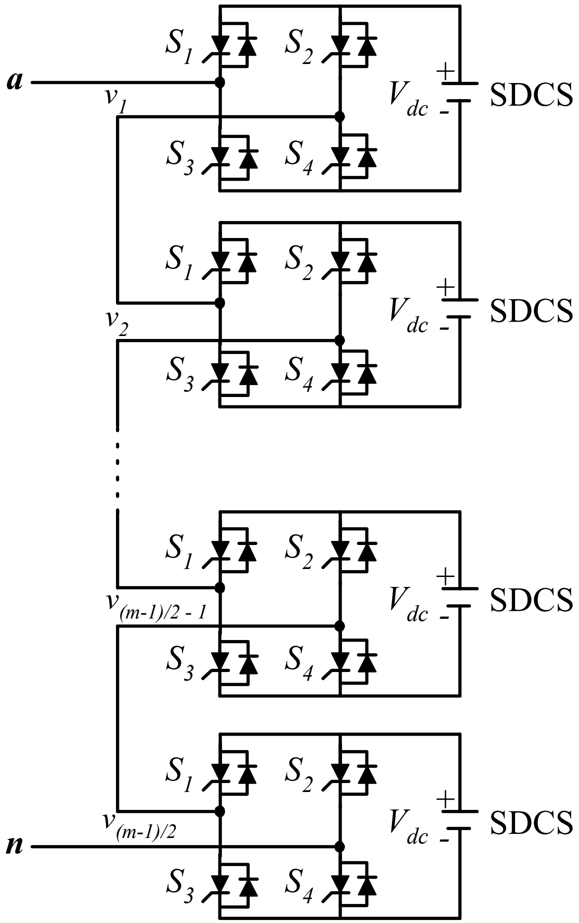


Multilevel Converters

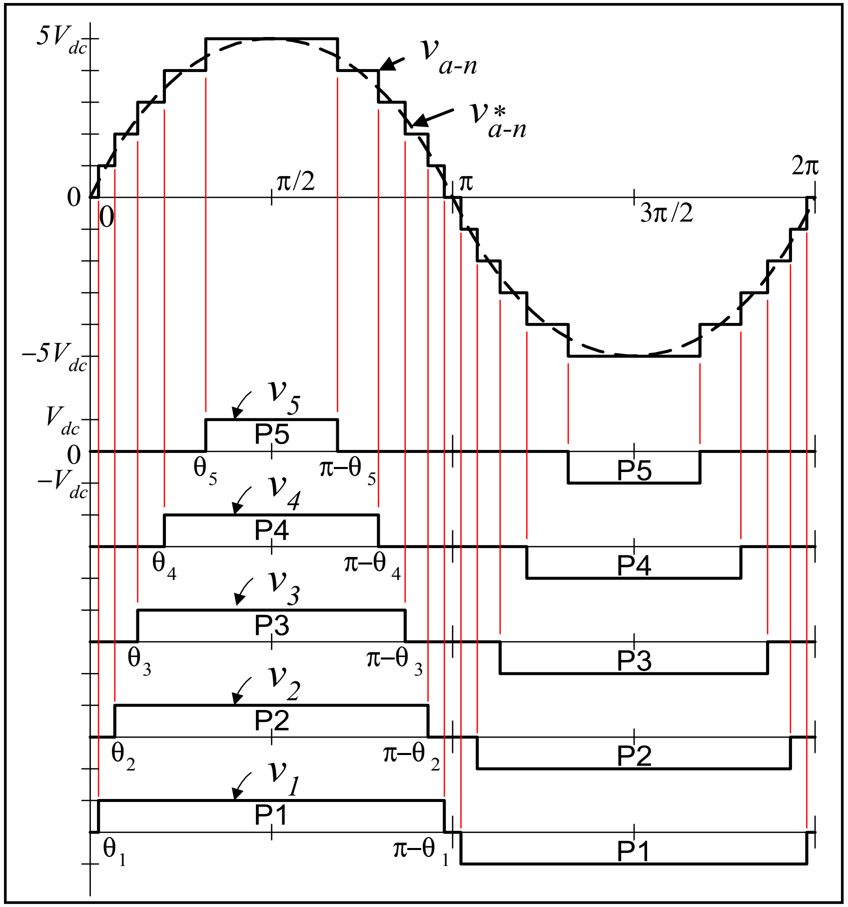
- ## General Structure
  - Synthesize a sinusoidal voltage from several levels of dc voltages
  - More levels produce a staircase waveform that approaches a sinusoid
  - Harmonic distortion of output waveform decreases with more levels
  - No voltage sharing problems with series connected devices
  - Low dV/dt reduces switching losses, EMI, and damage to motor insulation and bearings

- ## Control Scheme
  - Fundamental frequency switching of devices
  - Elimination of lower frequency harmonics

Multilevel Cascaded Inverter with Separate DC Sources

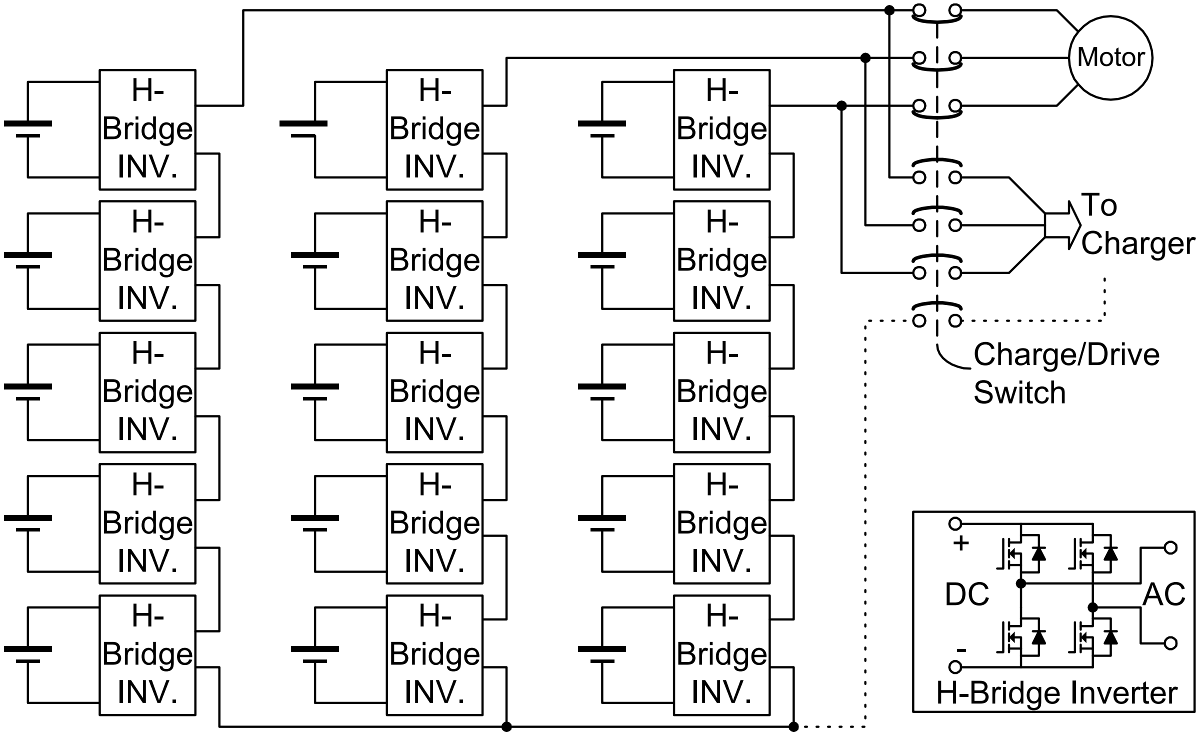


Single phase cascade structure



Output Voltage Waveform

Three Phase Multilevel Cascaded Inverter Motor Drive and Battery Charging Circuit



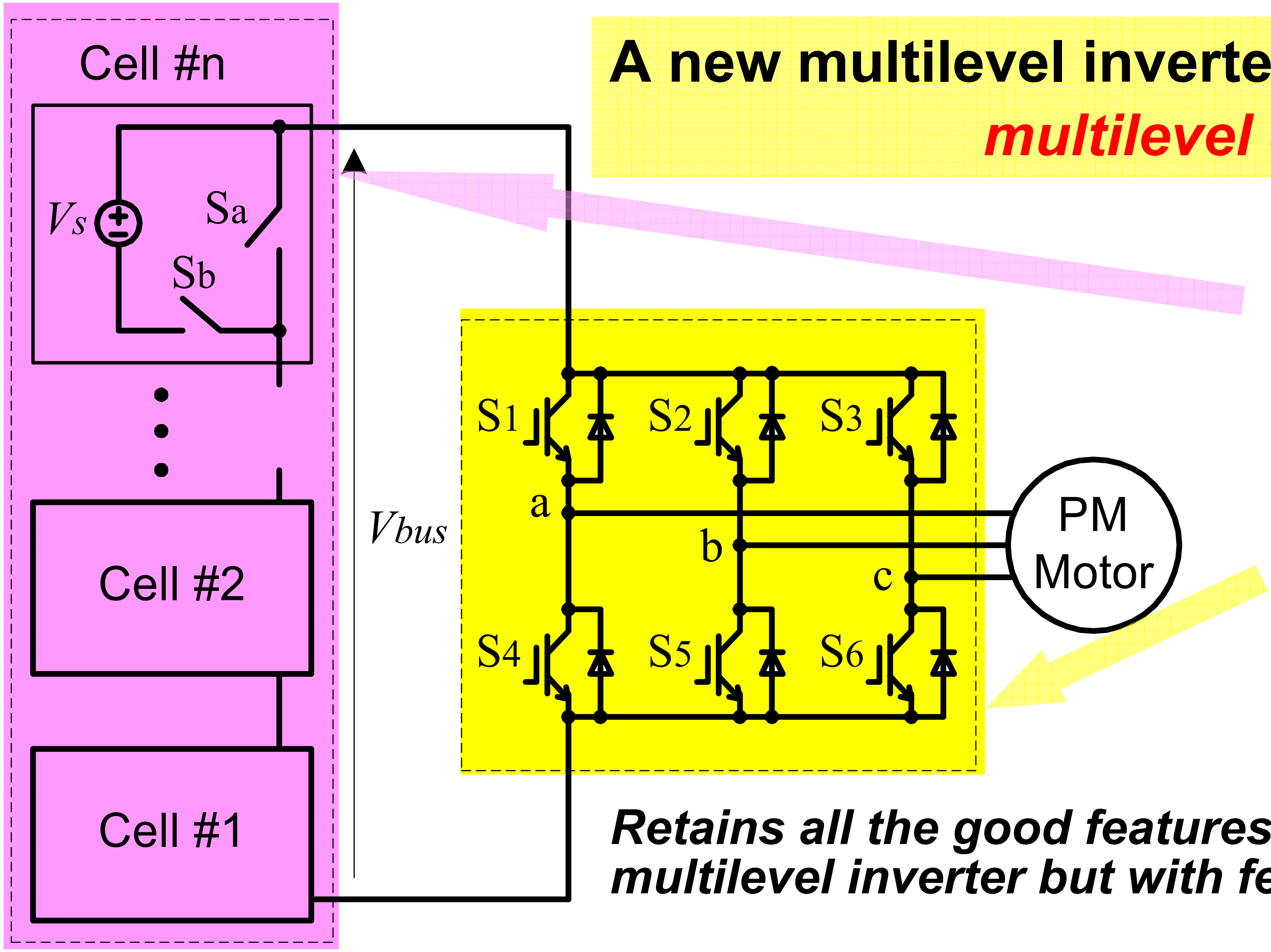
Three phase wye connection

Multilevel Inverters for Motor Drives

- Background
  - ORNL proposed for motor drive and utility applications (1994~)
  - Diode-clamped, multilevel-inverter-based back-to-back system for large HEVs (1996~)
  - H-bridge multilevel inverter for HEVs (1997~)

- Features of H-Bridge Multilevel Inverter
  - Extremely high efficiency: ≥ 99% over 10–100% load
  - Extremely low THD, both voltage and current
  - Almost no EMI: 3-order (60 dB) < 10-kHz PWM inverter
  - Low dc voltage (<50 V): open wiring and safety
  - High reliability because of redundancy
  - A large number of switches

A new multilevel inverter – *multilevel dc link inverter*



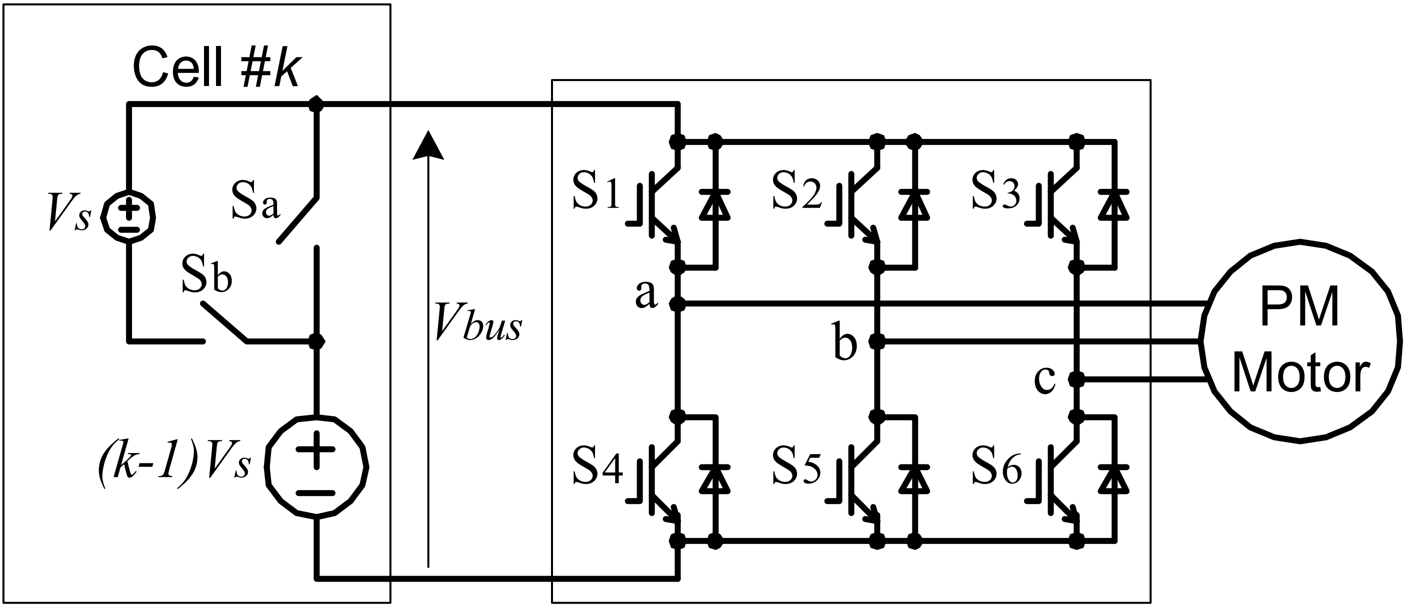
- **A multilevel dc source**

+

- **A bridge inverter**

Retains all the good features of the H-bridge multilevel inverter but with fewer switches

MLDCL inverter for PM motors with very low inductance



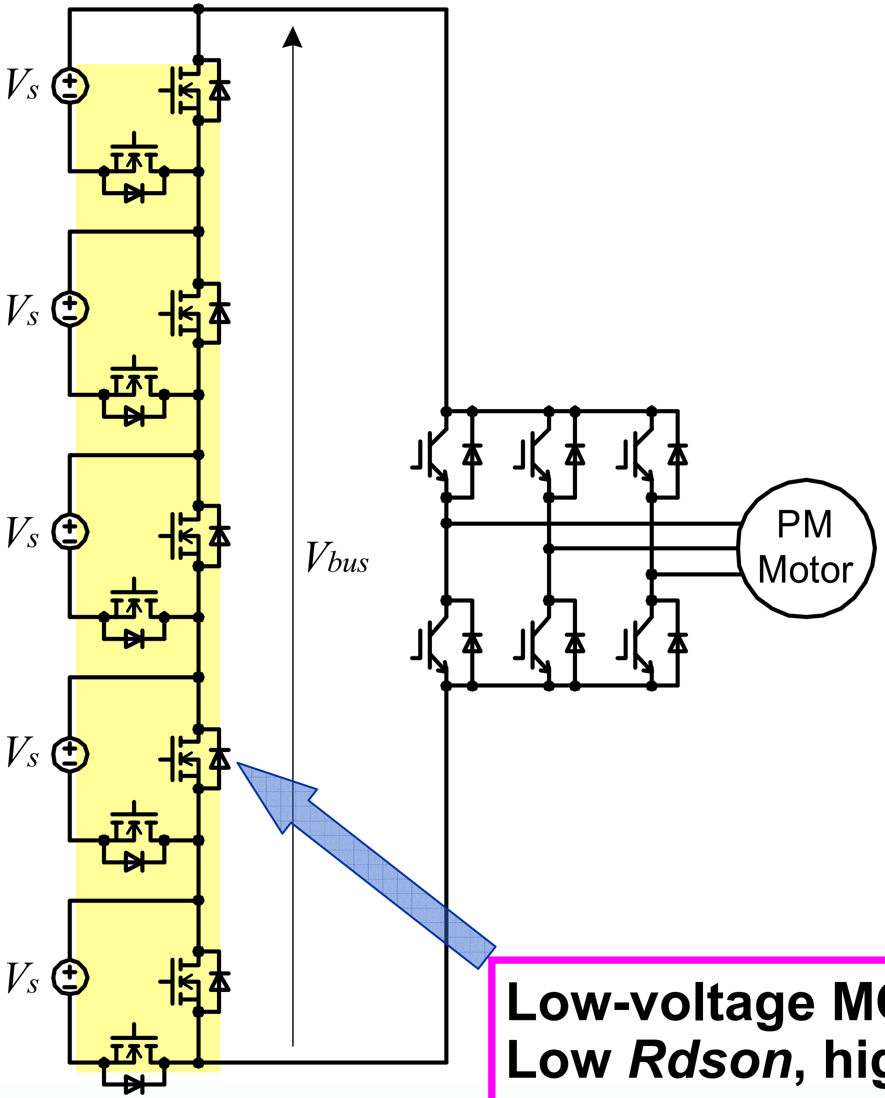
***L*<<100μH**

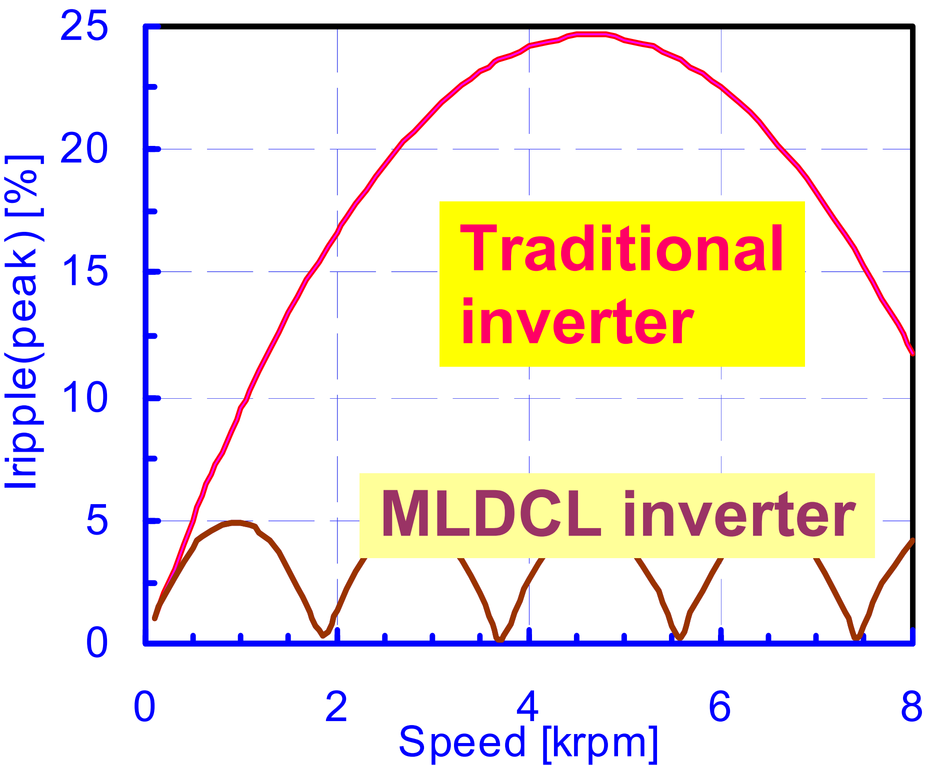
- ***k* cells are active, but only one of the cells performs PWM.**
- **The bridge inverter works in the six-step manner without doing PWM.**

- **The number of active cells, *k*, is determined by the speed, *N*.**

$$\frac{(k-1)V_s}{K_{bemf}} < N < \frac{kV_s}{K_{bemf}}$$

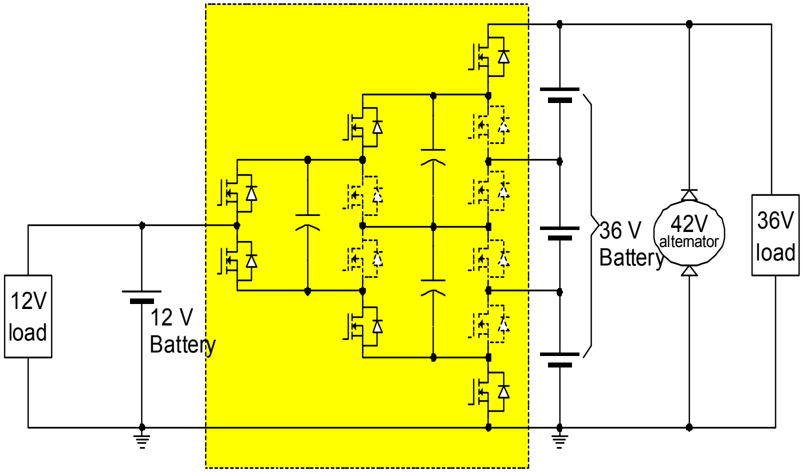
A 5-Level MLDCL for HEVs

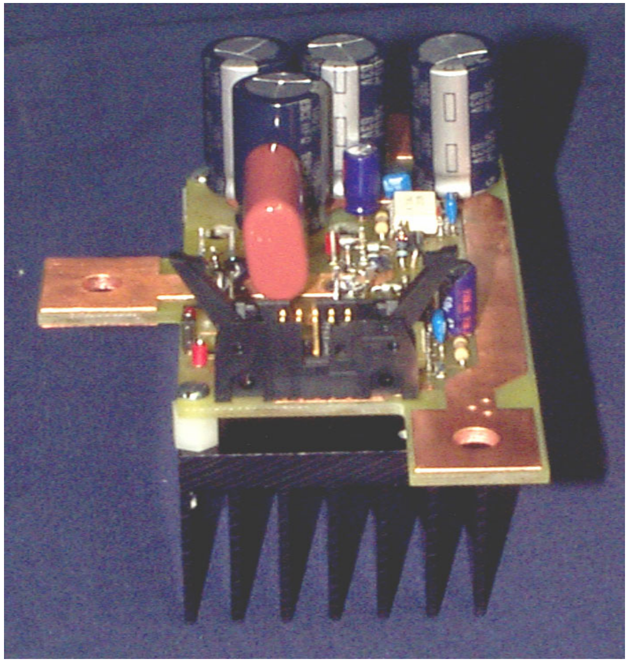




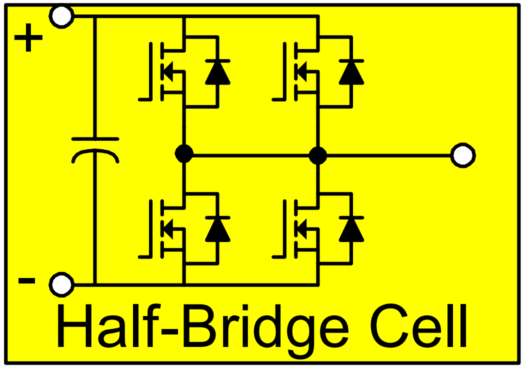
L_m=37.5μH, V_s=65V, *fsw*=20kHz

Low-voltage MOSFETs:
Low *Rdson*, higher switching frequency





Utilize the 2-kW (140 A/60 V) half-bridge multilevel cell modules for dual voltage systems



Future Power Electronics *Will Be* SiC

Today's Technology	Advantages of Silicon Carbide	Payoff
Large energy losses	Reduce loss by 10x	Large improvement in efficiency
Limited voltage and power level	Increase power 10^3x	Simplify use (no need to series/parallel devices)
Low operating temperature (<150ºC)	Increase range to 350ºC or higher	New applications; eliminate massive heat sinks
Large heat sinks & filters	Reduce size/weight by 3x	Lightweight, compact systems

SiC Background

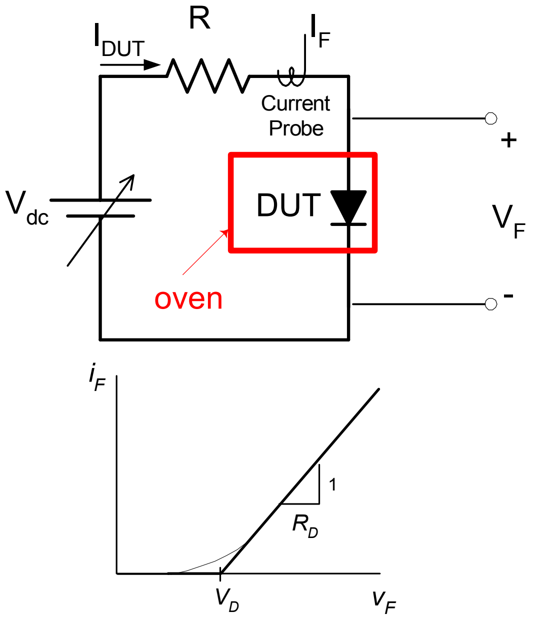
- SiC device properties superior to present Si devices
  - They can operate at high temperatures (up to 350°C).
  - They have low thermal resistivity.
  - They have higher breakdown (blocking) voltages.
  - They have low on-resistance (low conduction losses).
  - They have excellent reverse recovery characteristics.
  - They can operate at high switching frequencies.
- Challenges in applications of SiC
  - SiC material is more expensive than Si.
  - Yield is low because manufacturing processes are not mature.
  - New circuits, gate drivers are needed to take advantage of SiC properties.

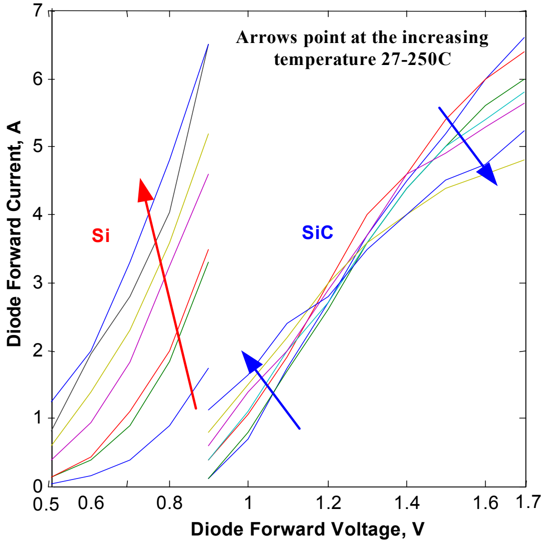
Update on the State of the Art in SiC Devices

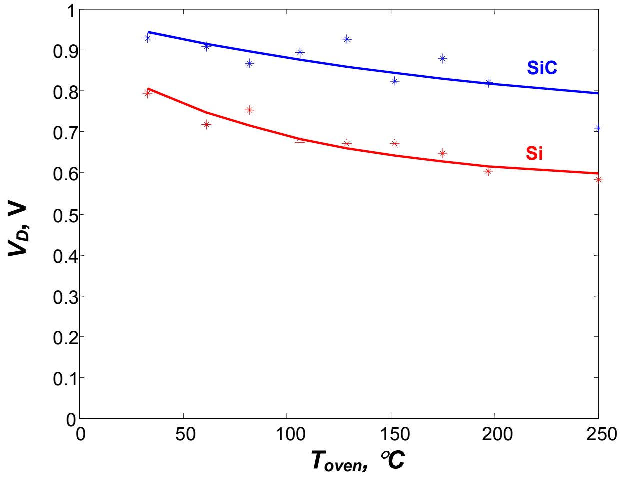
- As of May 2002, only three companies have advertised the commercial availability of SiC power devices:
  - Infineon (Schottky diodes, 600 V up to 12 A or 300 V up to 10 A).
  - Microsemi (Schottky diodes, 200/400/600 V, 1 A/4 A).
  - Cree (Schottky diodes, 600 V up to 10 A; MOSFETs, 18–28 V and <1 A).
- Some prototype SiC power devices not commercially available yet are advertised by SiCed and IXYS.
- Several other companies are doing research with SiC devices but have not gone into commercial production.

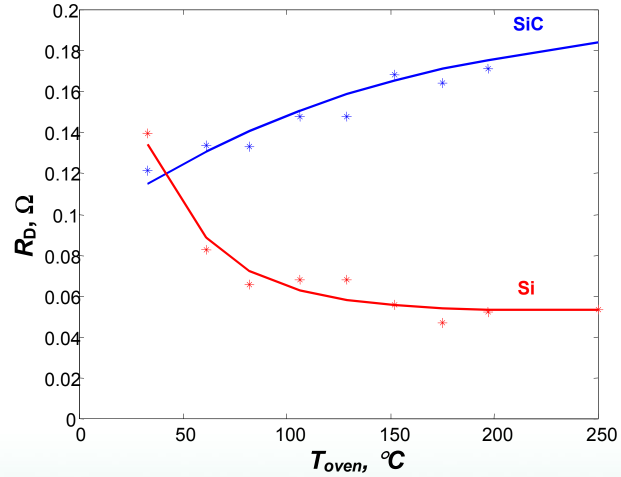
Large quantities of highly optimized SiC devices are still a few years away.

Device Modeling – Diode Conduction Losses



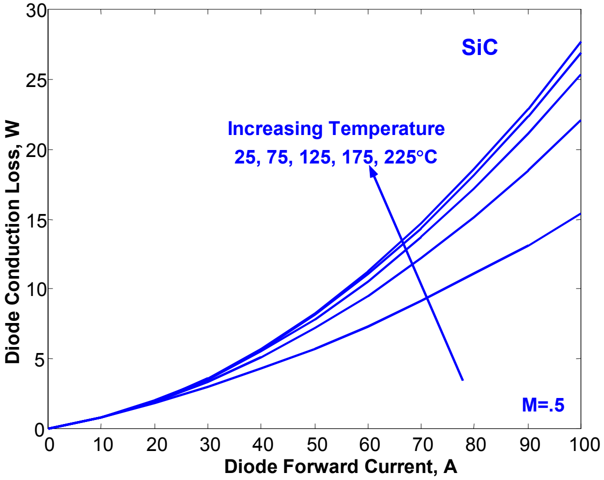




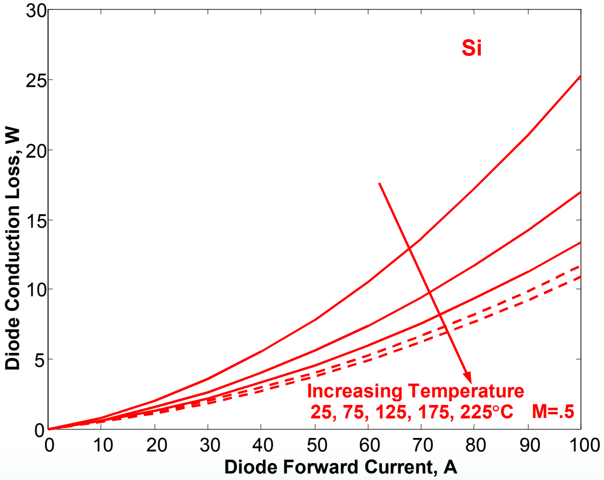


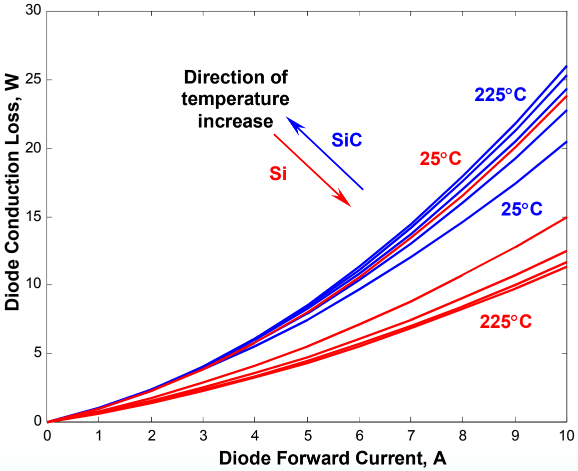
- **Forward voltage drop of Si diode is smaller than that of the SiC diode at the same forward current.**
- **I-V characteristics of the SiC diodes do not vary much with temperature.**
- **Si: both R_D and V_D decrease with temperature**
- **SiC: R_D increases with temperature**
  V_D decreases with temperature

Device Modeling – Diode Conduction Losses (cont'd)

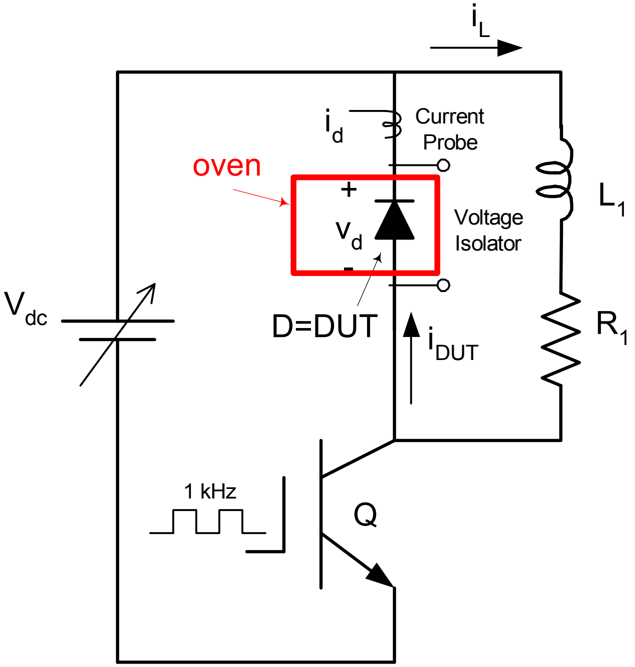


- Si: Conduction loss decreases with temperature
  SiC: Conduction loss increases with temperature
- The conduction loss of the SiC diode is less than that of the Si diode at low temperatures, and vice versa at higher temperatures.
  - Note that the Si diode cannot withstand $T_j > 150$°C

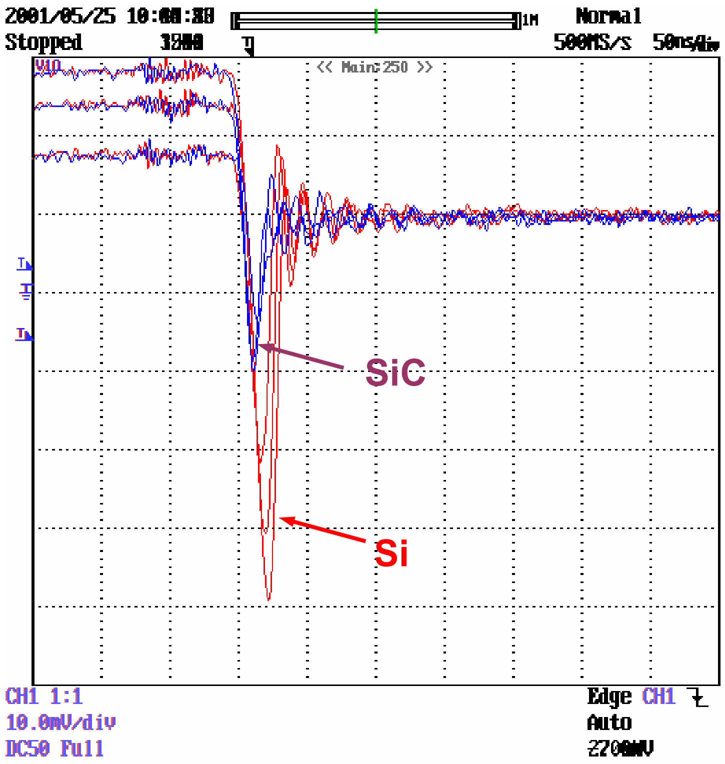




Device Modeling – Diode Switching Losses



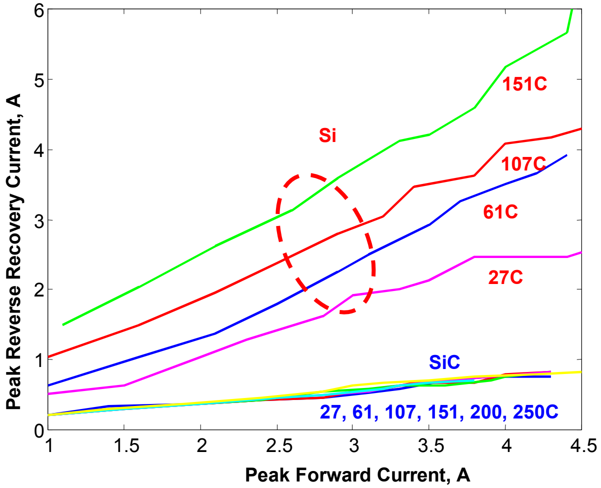
Reverse recovery loss measurement circuit



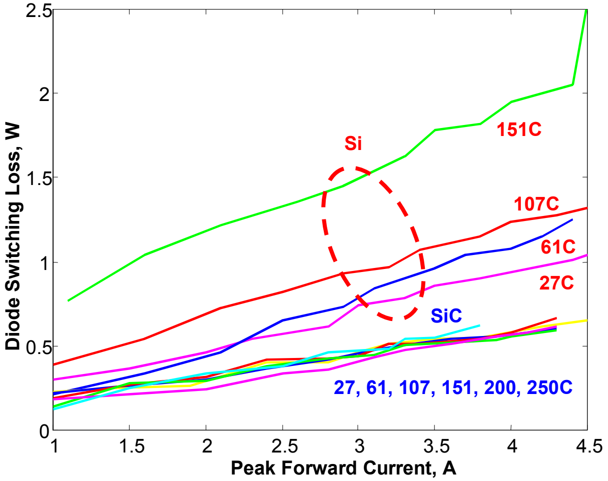
Typical reverse recovery waveforms of the Si pn and SiC Schottky diodes

Device Modeling - Diode Switching Losses (cont’d)

Peak Reverse Recovery Current



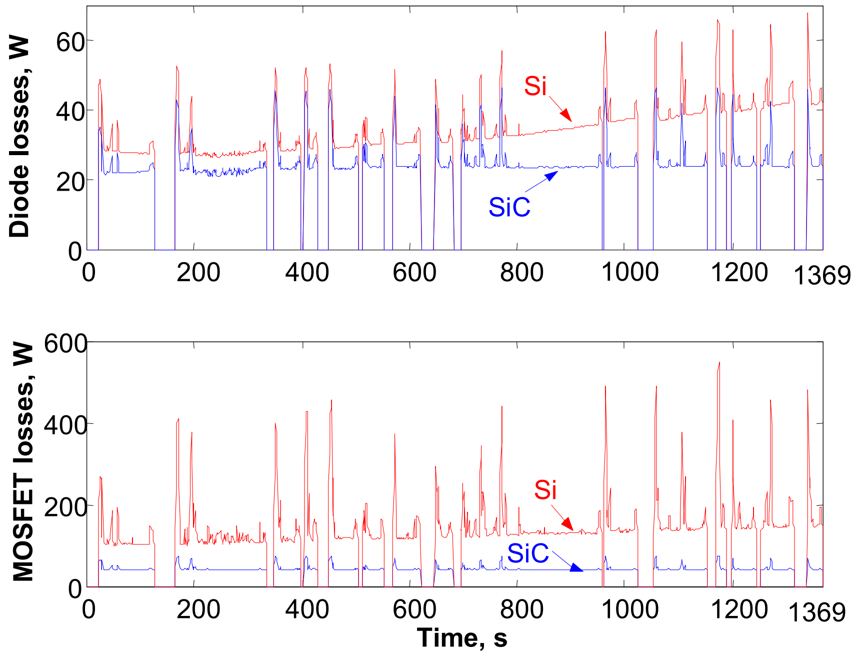
Experimental Switching Losses



- **SiC Schottky diode peak reverse recovery current and loss do not change with temperature.**
- **Si pn diode peak reverse recovery current and loss increase severely with temperature.**
- **SiC diode reverse recovery loss is less than that of the Si diode at any operating temperature (≤250°C)**

∴SiC diode is more reliable and more efficient

Simulated Performance in an HEV Application

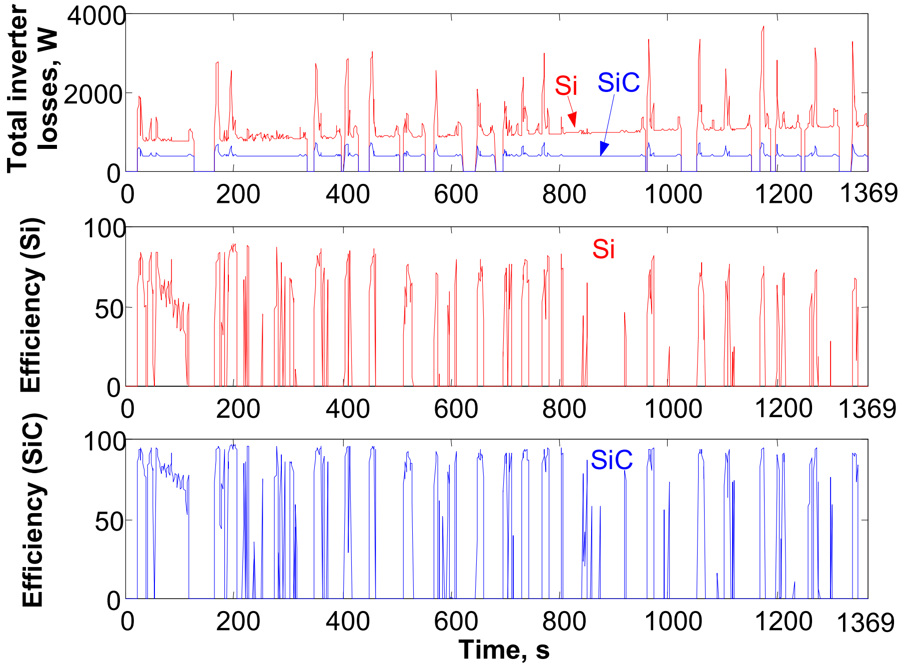


- **SiC diode losses are lower** primarily because SiC has lower reverse recovery losses
- **SiC MOSFET losses are lower** because
  - switching losses are similar
  - SiC MOSFET conduction losses are lower

$(R_{on,sp\,(Si)} = 180\times10^{-3}\ \Omega\text{-cm}^2$

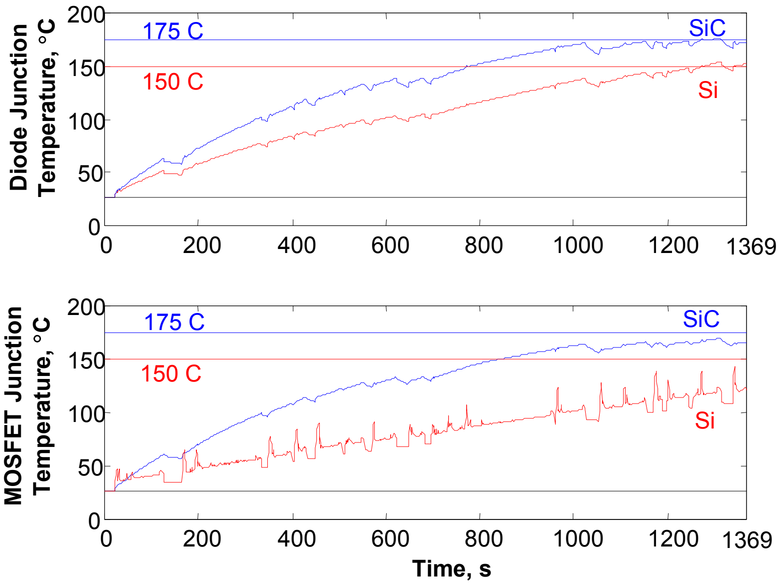
$R_{on,sp\,(SiC)} = 0.3\times10^{-3}\ \Omega\text{-cm}^2)$

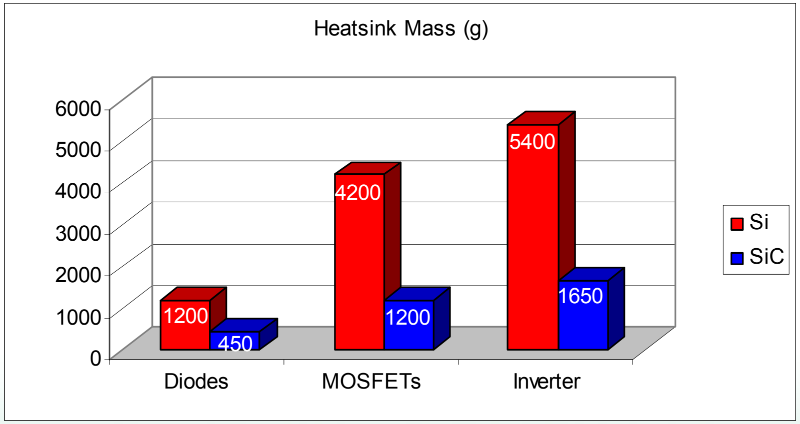
Simulated Performance in an HEV Application (cont’d)



- **Energy loss in inverter for FUDS cycle:**
  - **Si: 925 W·sec**
  - **SiC: 338 W·sec**
- **Peak efficiency (inverter not at rated load for most of FUDS cycle):**
  - **Si: 80 – 85%**
  - **SiC: 90 – 95%**

Simulated Performance in an HEV Application (cont'd)





- If natural-air-cooled, finned, aluminum heatsinks are used, then
  - Si inverter needs a heatsink with a volume of 1998 cm^3 and a weight of 5.4 kg
  - Si inverter needs a heatsink with a volume of only 606 cm^3 and a weight of 1.65 kg

Parametric Device Study

Some suggestions are as follows:

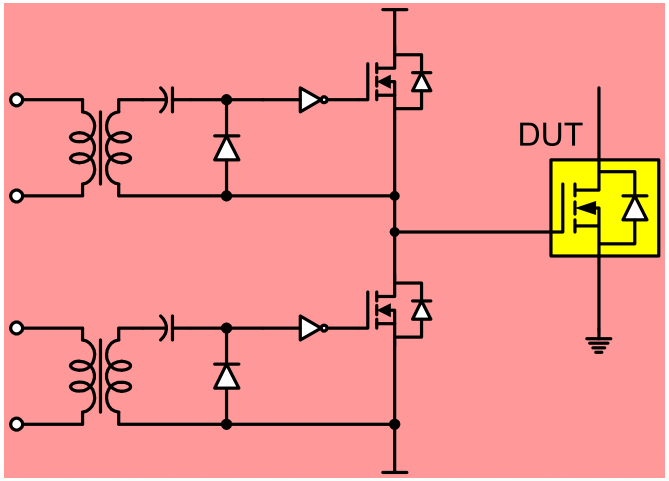
- **To decrease MOSFET switching losses, increase the transconductance (g_m) by increasing the channel width (w) and the device area (A).**
- **Decrease the channel and contact resistances to decrease the MOSFET conduction losses.**
- **Modify the diode carrier density distribution or increase the device area to decrease the diode switching losses.**
- **For the traction drive, to decrease the diode conduction losses,**
  - **If** $29.3A > \frac{V_D}{R_D}$ **, then keep the doping density and R_D constant;**
  - **If** $55.9A < \frac{V_D}{R_D}$ **, then decrease the doping density so that V_D will be smaller.**

New Gate Drives for SiC MOSFETs/IGBTs

- Problems and Limitations of existing gate drives
  - They are operable only at up to *20 kHz* switching at high power.
  - They have a long *(1-2μs)* propagation delay.
  - They do not take advantage of SiC's <u>high-speed</u> and <u>high-temperature</u> operation.

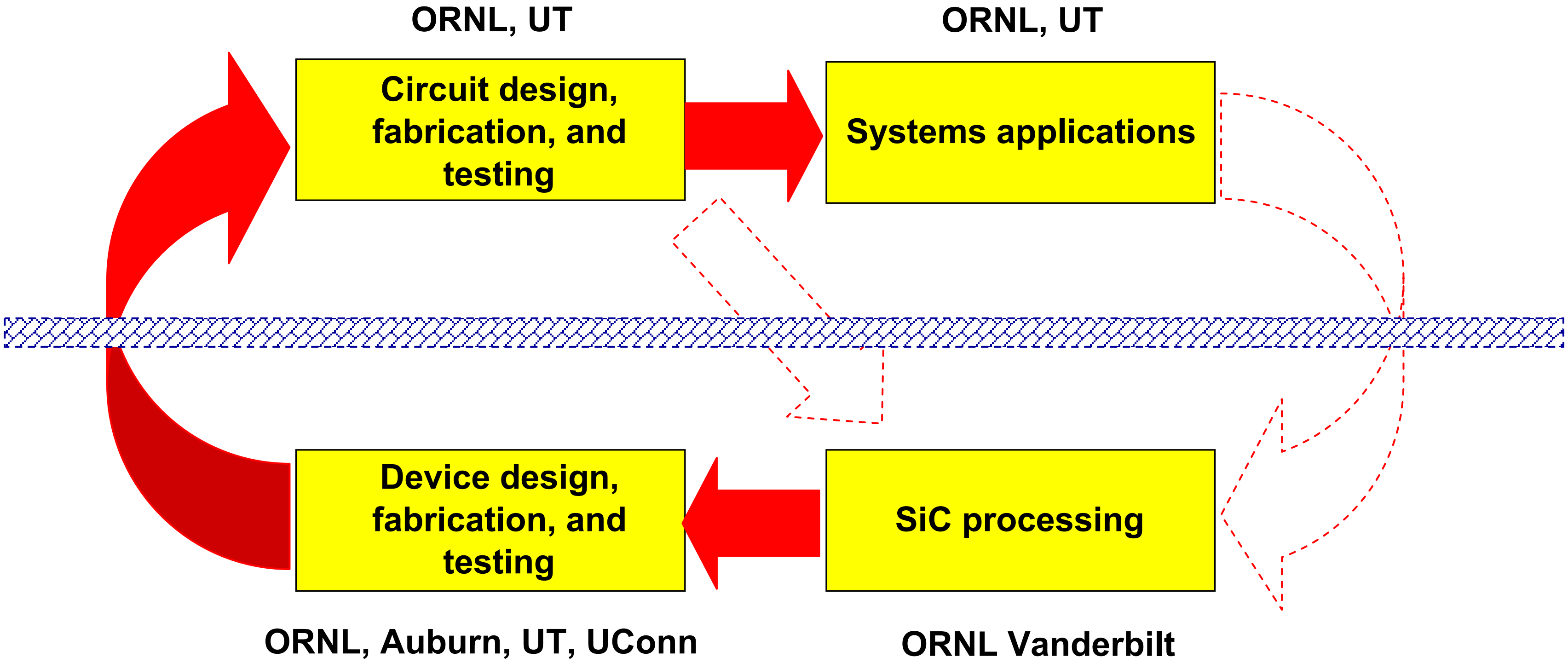
Innovative new circuit designs required to exploit advantages of SiC

- Design and build new gate drive
  - A new gate drive circuit developed for SiC MOSFETs operated at up to *500 kHz* at high temperatures (*250°C*).
  - Test gate drive on SiC MOSFETs developed by ORNL and/or others.



Closing the Loop - LDRD

For application-specific power devices with optimum performance



ORNL, UT

Circuit design, fabrication, and testing

ORNL, UT

Systems applications

Device design, fabrication, and testing

ORNL, Auburn, UT, UConn

SiC processing

ORNL Vanderbilt

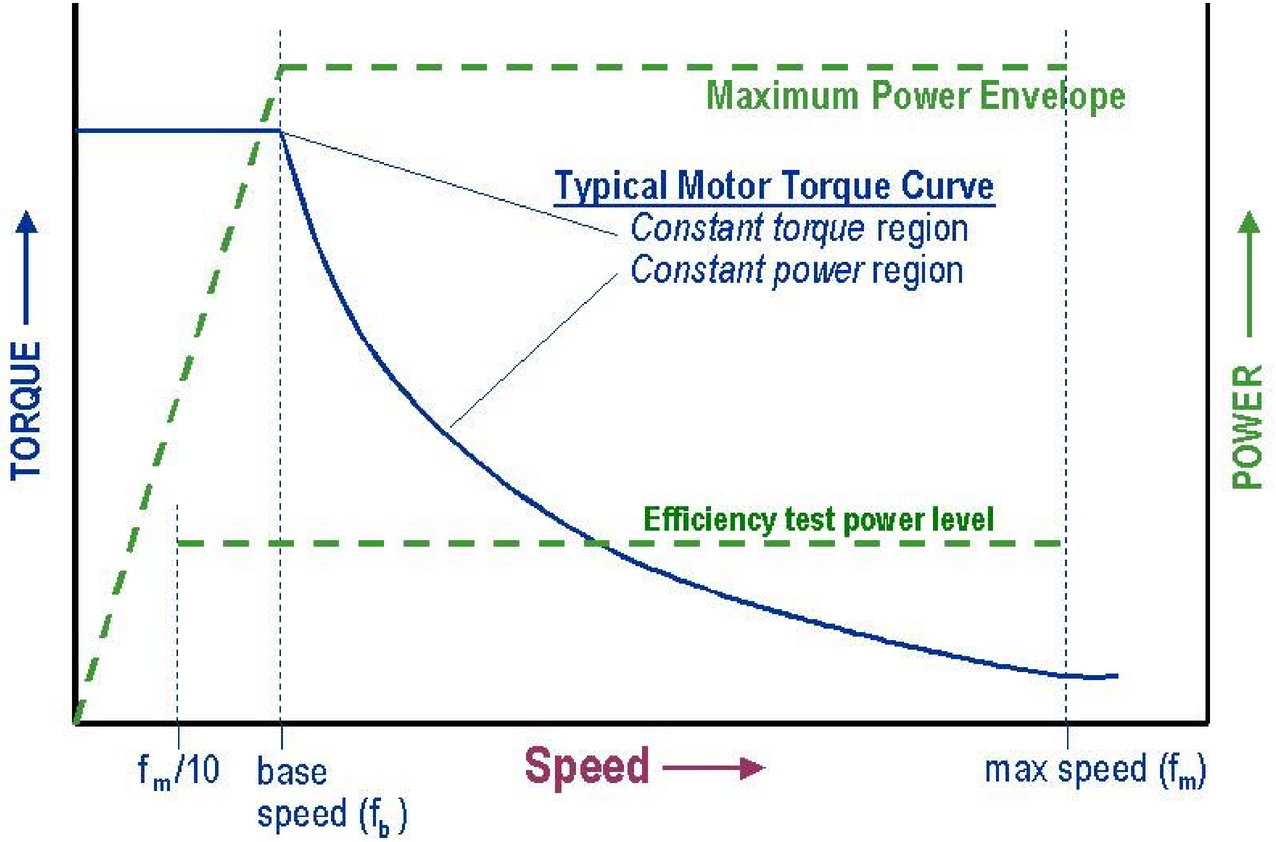
Publications

- “Effects of Silicon Carbide (SiC) Power Devices on PWM Inverter Losses,” *The 27th Annual Conference of the IEEE Industrial Electronics Society (IECON'01)*, Denver, Colorado, November 29–December 2, 2001, pp. 1187–1192.
- “Impact of SiC Power Electronics for Hybrid Electric Vehicles,” *SAE Future Car Congress Proceedings*, Arlington, Virginia, June 3 – 5, 2002.
- “Testing, Characterization, and Modeling of SiC Diodes for Transportation Applications,” *IEEE Power Electronics Specialists Conference (PESC'02)*, Cairns, Australia, June 23–27, 2002.

Related National Laboratory Power Module Developments

- Fiber Optic Voltage & Current Sensors
- DC Buss Capacitors
- Snubber Capacitors
- Carbon Foam for Thermal Management
- Motor Controller Development

Torque - Speed Curves for AEMD testing

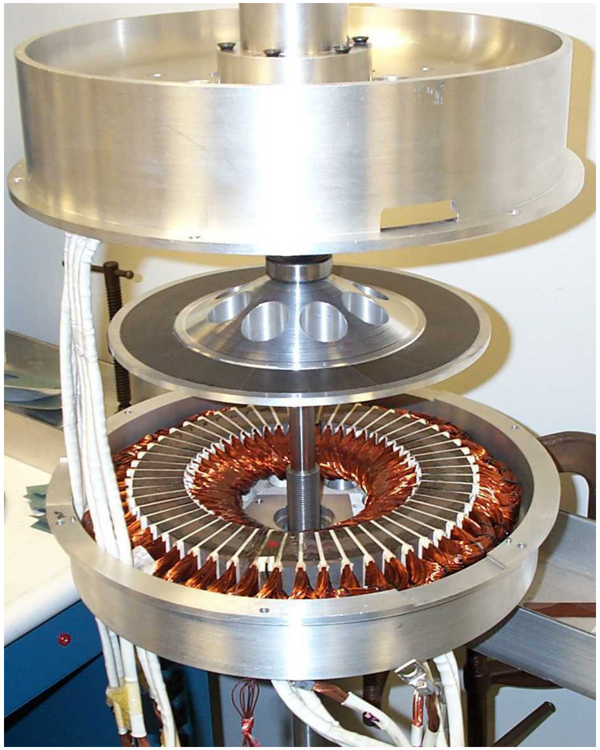


Permanent Magnet Motor Field Weakening

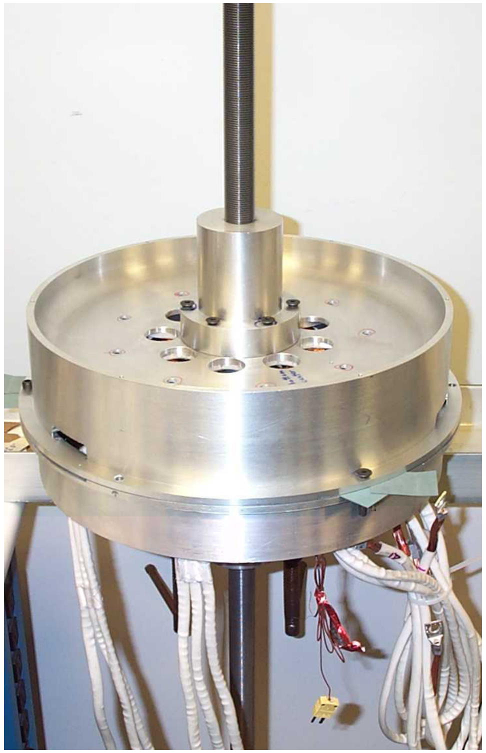
- Analyze known field-weakening methods for electronically switched permanent magnet (PM) type motors.
- Identify deficiencies that may limit their use as an HEV drive systems.
- Identify ways to mitigate the consequences of these deficiencies.
- Compare attributes of all PM motor/drive systems that are FreedomCAR HEV candidates and recommend one as the PM drive system of choice.

Rotor Assembly

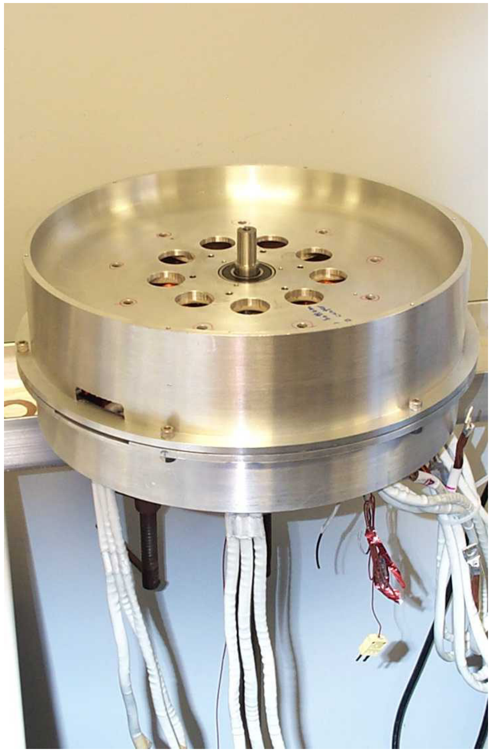
(20-kW axial-gap PM motor)



Pre-closure

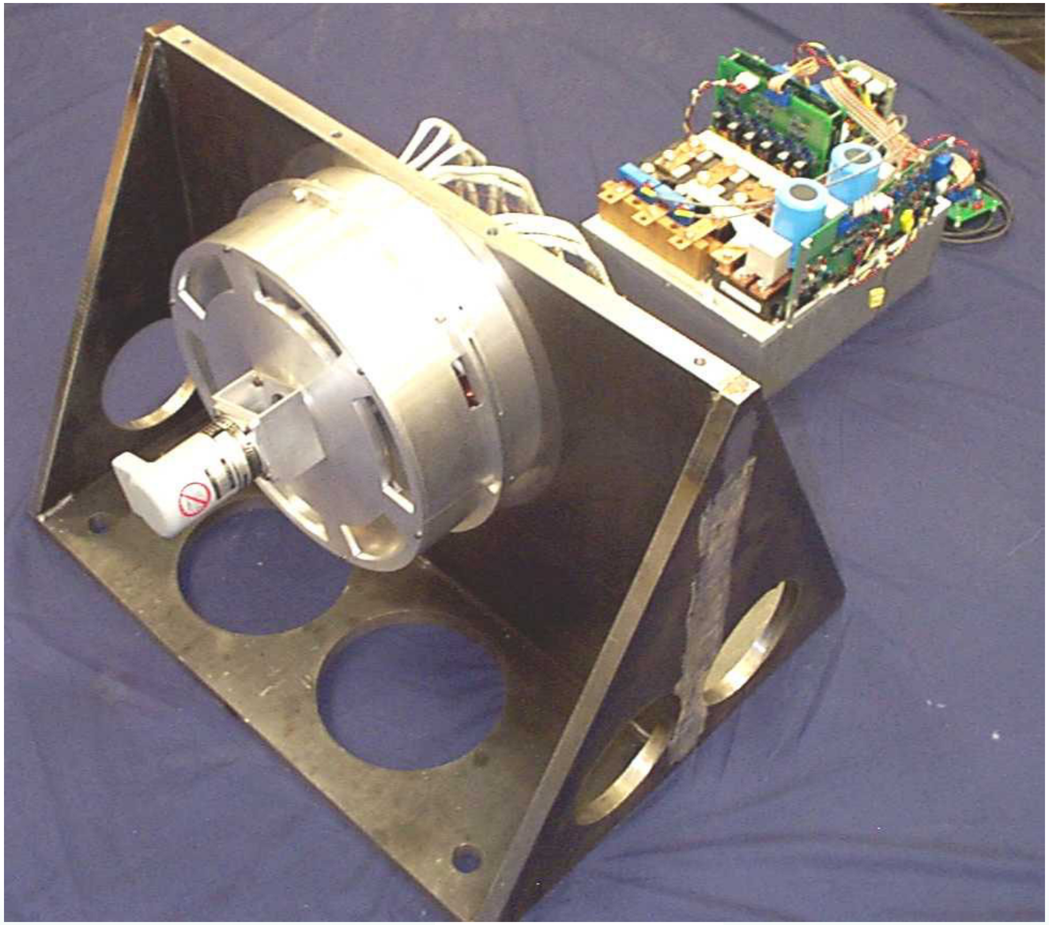


Post-closure

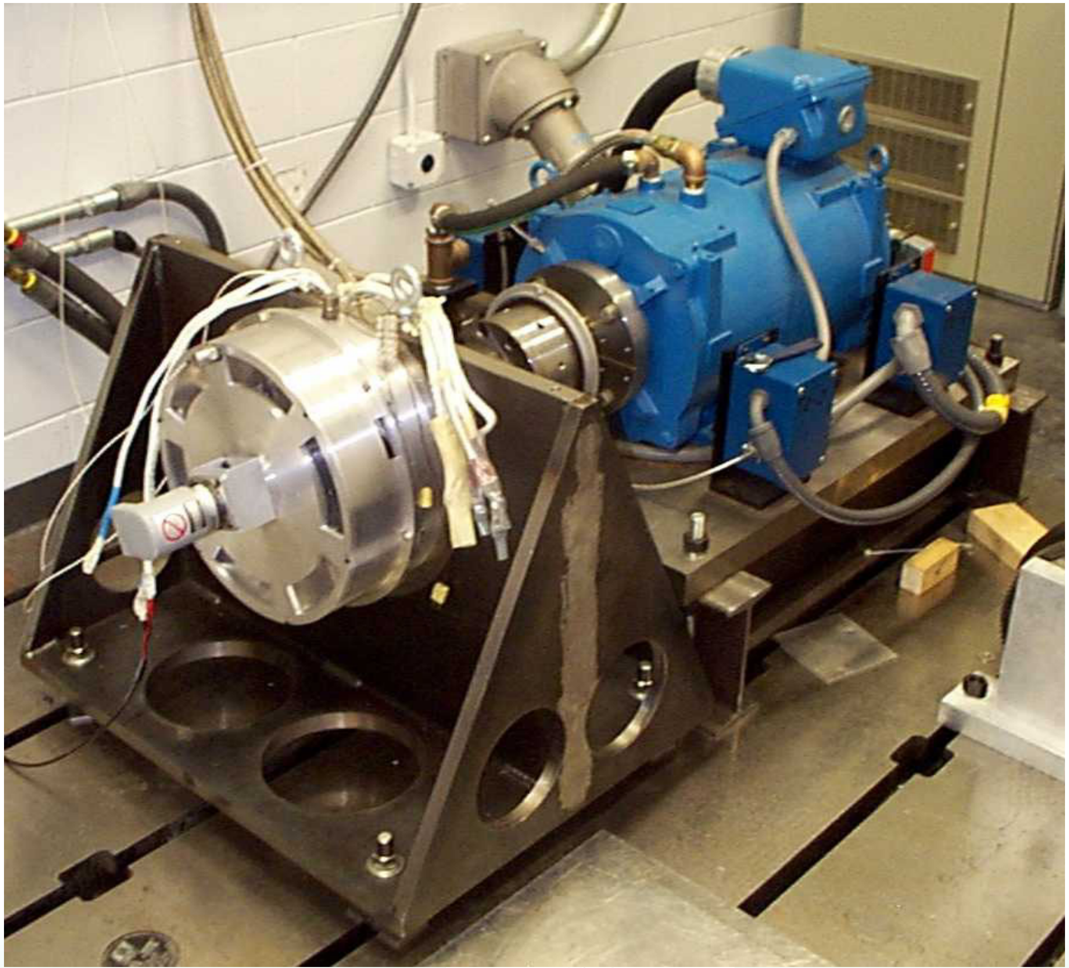


Jig removed

Motor Mounted to Test Frame
(20-kW axial-gap PM motor)

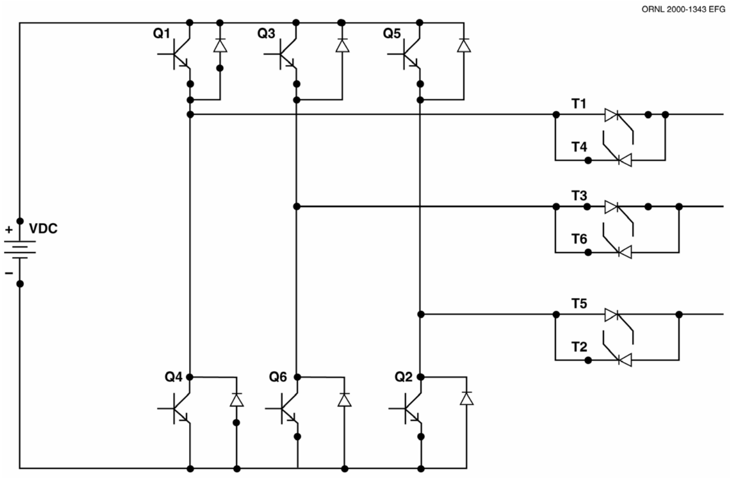


DMIC Inverter and Motor in Test Cell 1 Ready for Prequalification



Dual Mode Inverter Control Inverter Topology

- Thyristors prevent the detrimental mixture of motoring and regeneration during high-speed operation in motoring mode.
- Loss of semiconductor firing signals extinguishes motor current within one-half electrical cycle.



- Motor cannot enter regeneration when firing signals are lost, and thyristors isolate motor from faults in the transistor inverter and dc voltage supply system.
- During coasting, the motor current can be cut off, eliminating stator copper losses.
- Transistors need to be rated only to block the dc supply voltage. Motor emf is blocked by thyristors.

Features of the DMIC

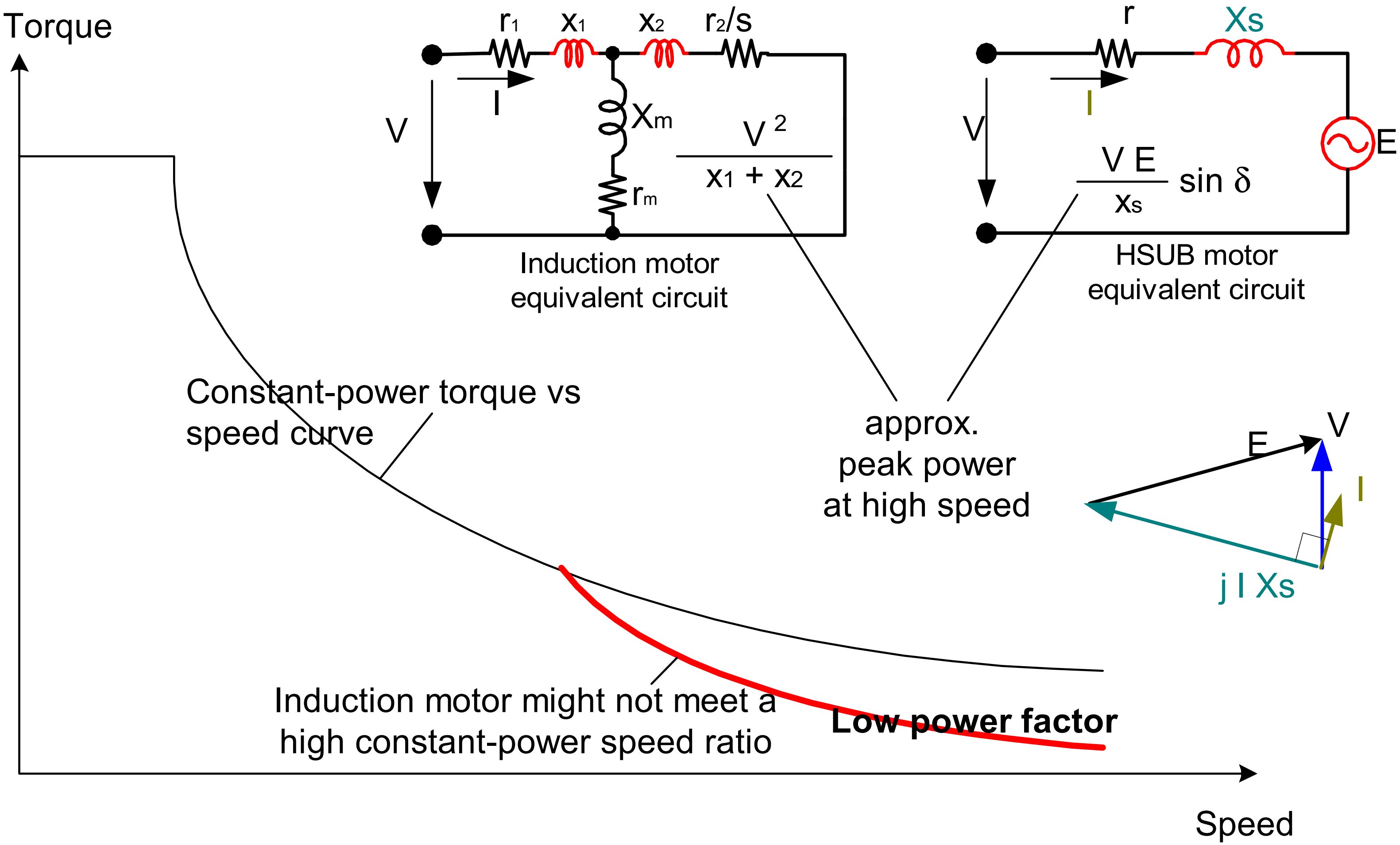
- Can drive “low” inductance BDCM over a wide CPSR without exceeding the rated (base speed) rms motor current.
- Can drive “high” inductance BDCM over a wide CPSR without exceeding the rated rms current. Can expect up to 50% more power at high speed.
- Can tolerate large changes in the dc supply voltage. As the dc supply voltage decreases, motor power is reduced, but the rated rms motor current can be maintained.
- Can control both motoring and regenerative braking over the entire speed range.
- Achieves functional equivalent of field weakening without supplementary field windings or exotic rotor/magnet configuration.

Features of the DMIC (continued)

- Each phase "idles" twice during one electrical cycle, allowing position estimation schemes developed for conventional operation below base speed to be extended to operation above base speed. May eliminate the need for an encoder.
- Motor current can be extinguished within half an electrical cycle if the transistor inverter or dc supply system short-circuits.
- Loss of semiconductor firing signals while motoring at high speed results in rapid extinction of motor current rather than deep regenerative braking.
- "Coasting" at high speed does not involve any stator copper losses since the motor current is cut off.

Conclusions

- The DMIC can tolerate very large inductance and voltage variations.
  - Allows motor designer to optimize design based on machine concerns likely to lead to low inductance.
  - Lower inductance decreases dc supply voltage requirements and increases peak power capability.
  - Unnecessary to oversize the dc supply, the electric motor, the electronics, and the cooling system when using this technology.
- Coasting losses with the DMIC are solely the hysteresis and eddy current losses of the motor. When CPA is used coasting losses may be an order of magnitude greater.
- The thyristors in the DMIC inverter protect against
  - shorting the dc bus
  - loss of the dc bus
  - loss of firing signals



Induction motor equivalent circuit

$$\frac{V^2}{x_1 + x_2}$$

HSUB motor equivalent circuit

$$\frac{V\,E}{x_s}\sin\delta$$

approx. peak power at high speed

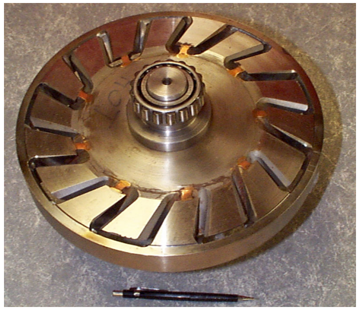
Constant-power torque vs speed curve

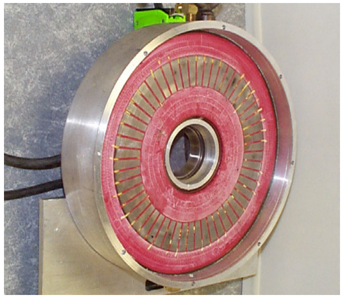
Induction motor might not meet a high constant-power speed ratio

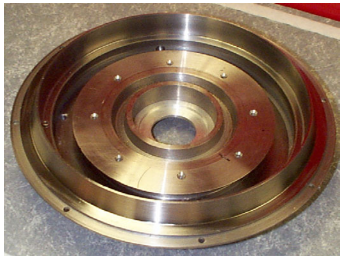
Low power factor

Unique Properties of HSUB Motor

- No rotor copper loss
- Easy field weakening
- High power factor and high CPSR
- No vibration and noise problems
- Simple inverter, no sensor
- Higher air gap flux density
- Good cooling for high current density
- Robust – can be axial-gap or radial-gap







Operation of HSUB Motor

- The DC flux produced by an excitation coil is delivered to the rotor through the air gap without any brush.

- The DC flux in the rotor is guided to the north and south poles that interact with the armature.

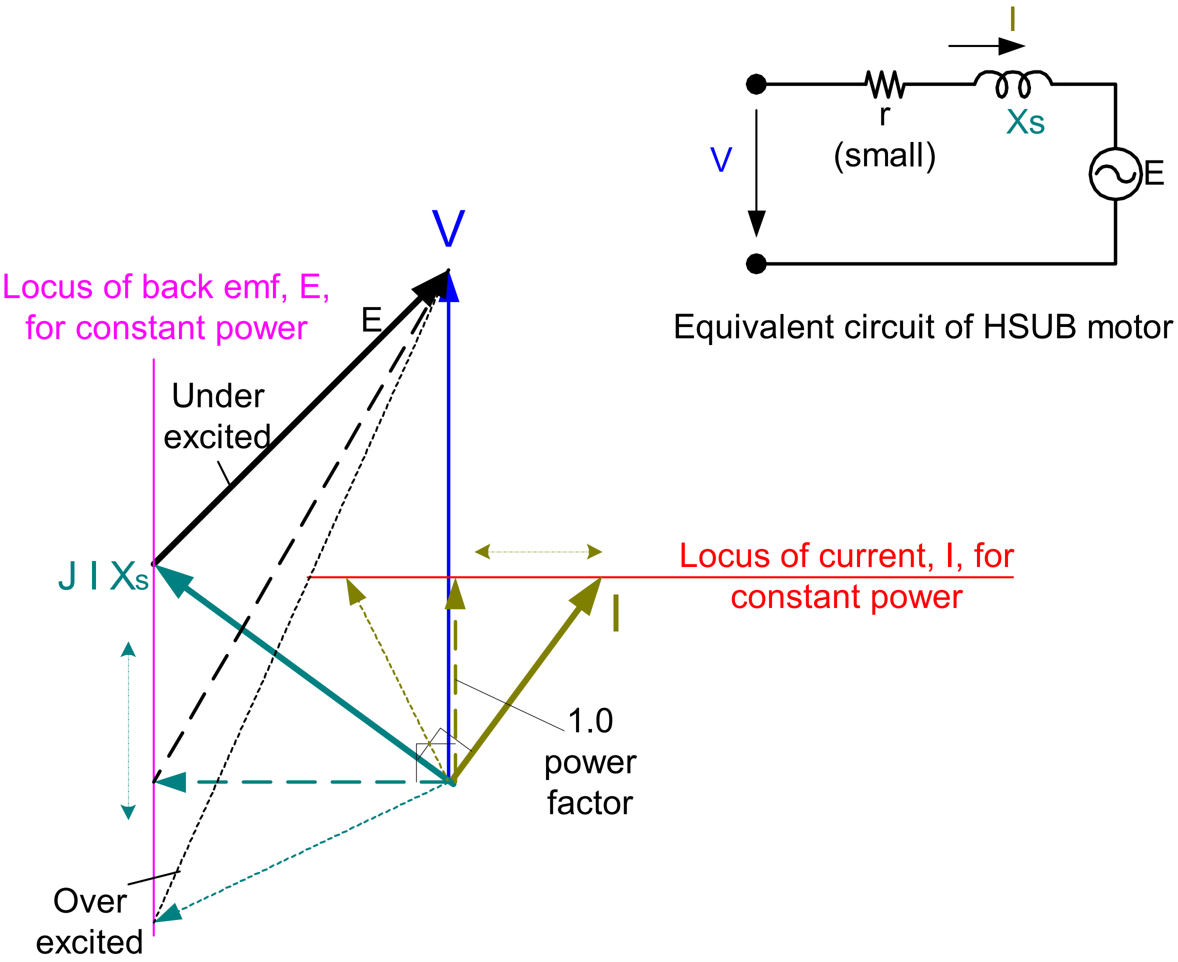
- The undiffused arrangement provided by PMs guides the flux to the main air gap that faces the armature.

- Both the PMs and the excitation coil can enhance the air-gap flux density. Consequently, a high air-gap torque under a given armature current can be obtained.

- Controlling the current of the excitation coil can weaken the main air-gap flux. A simple power electronics drive required by the HSU-B machine may lower the motor drive system cost.

- Direct cooling of the stationary armature and excitation windings allows high current density.

High Power Factor from HSUB Motor



Equivalent circuit of HSUB motor

42-V or 380-V System?

- Consumer safety (below 50v)
- Low power factor has stronger impact on a 42-V motor – larger actual silicon area and copper lead size required

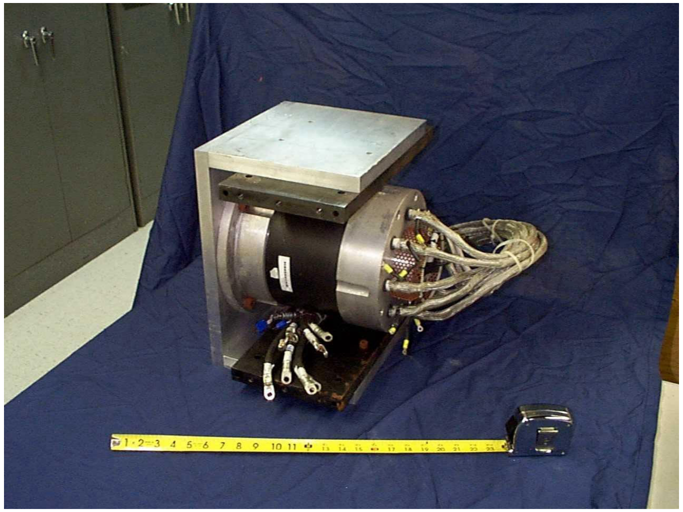
Example: 0.7 PF, 30% area increase

For 380 V: 1 sq.in --> 1.3 sq.in

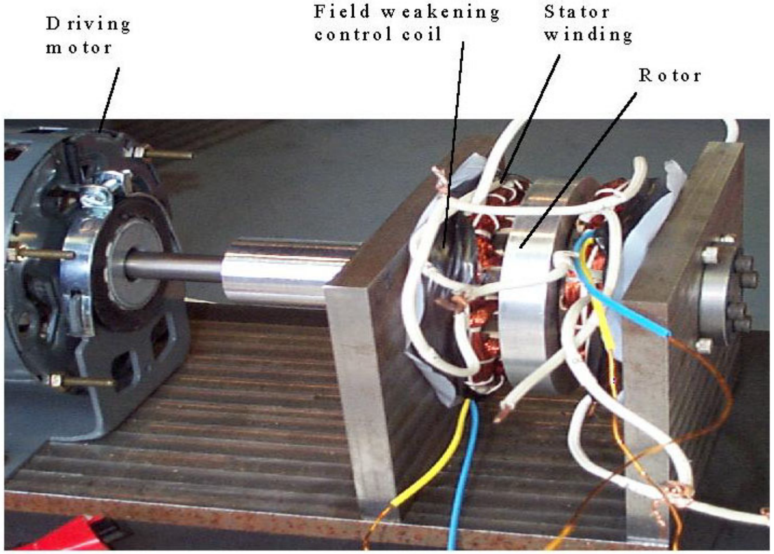
For 42 V: 9 sq.in -->12.7 sq.in

3.7 sq.in compared with 0.3 sq.in

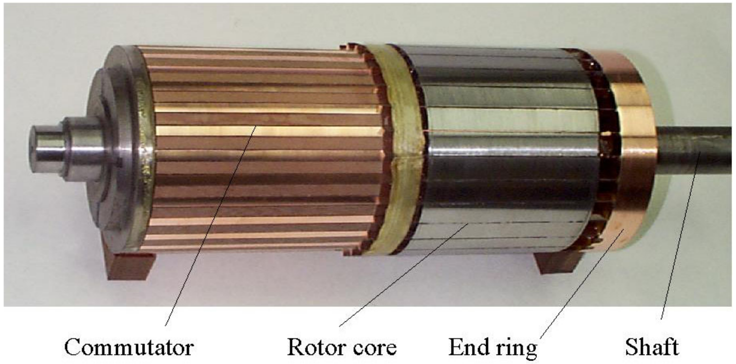
- HSUB motor offers high power factor



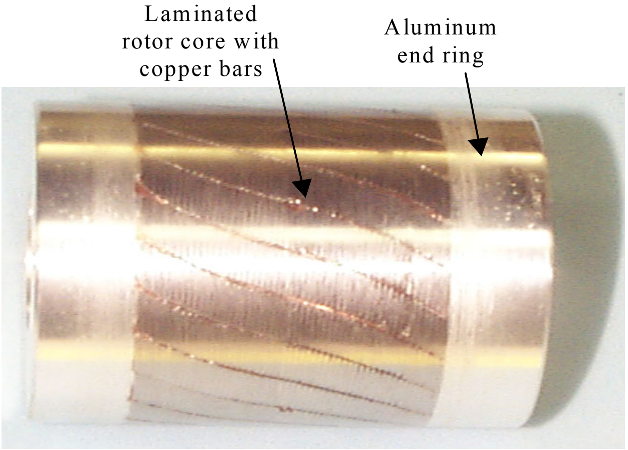
Switched Reluctance Motor



Field-Weakened PM Motor



Soft Commutated dc Motor



Copper-Aluminum Joining

Don Adams
Oak Ridge National Laboratory
Office: 865-946-1321
adamsdj@ornl.gov

Project Objectives

- **Project Goals**

  The purpose of this project is to develop simulation tools for SiC devices in relevant transportation applications. Once developed, these tools can be used to assess the impact of expected performance gains with SiC devices and determine areas of greatest impact.

- **Project Objectives (Tasks) for FY 2002**
  - Updated the state of the art in SiC devices.
  - Developed models of SiC devices (diodes and MOSFETs).
  - Simulated performance of an HEV traction drive using these device models.
  - Performed a parametric analysis to determine device parameters that need to be modified to improve the system performance of this drive.

Soft Switching Snubber Inverter

Regenerative Circuit Design Issues (cont'd)

Total recovered power for prototype at I_{lrms} = 250 A can be calculated by

$$P_R = (6\times 0.1\mu\text{F}\times(400\text{V})^2 + 4.31\times 1\mu\text{H}\times 250^2)\times 10\text{kHz}$$
$$= 3654\text{W}$$

The average recovery current is

$$I_{R\_avg} = \frac{P_R}{V_{dc}} = \frac{3654\text{W}}{330\text{V}} = 11\text{A}$$

Soft Switching Snubber Inverter

Regenerative Circuit Design Issues (cont’d)

Assuming the diode forward voltage drop is V_D and the winding resistance is R_t, the power loss and energy recovery efficiency of the circuit can be approximately expressed as follows:

$$P_{loss} \approx 2I_{R\_avg}^2 R_t + 2V_D I_{R\_avg}$$

$$\eta = 1 - \frac{P_{loss}}{P_R}$$

For the prototype, the recovery efficiency is around 97% assuming $R_t = 0.25\Omega$ and $V_D = 1.5$ V.

Task 2: Bi-directional DC/DC Converter

- **Summary of Progress**
  - Analysis, simulation, and preliminary testing with control circuits on breadboards (1999~1901)
  - Design refinement, new control schemes, PCB design and assembly, and comprehensive testing (2001~2002)

- **Plans for Project Continuation**
  - Improvement of transformer efficiency
  - Testing under peak load conditions
  - Testing of start-up operation
  - Possibility for dual-voltage 14-V/42-V systems

Soft Switching Snubber Inverter

Regenerative Circuit Design Issues

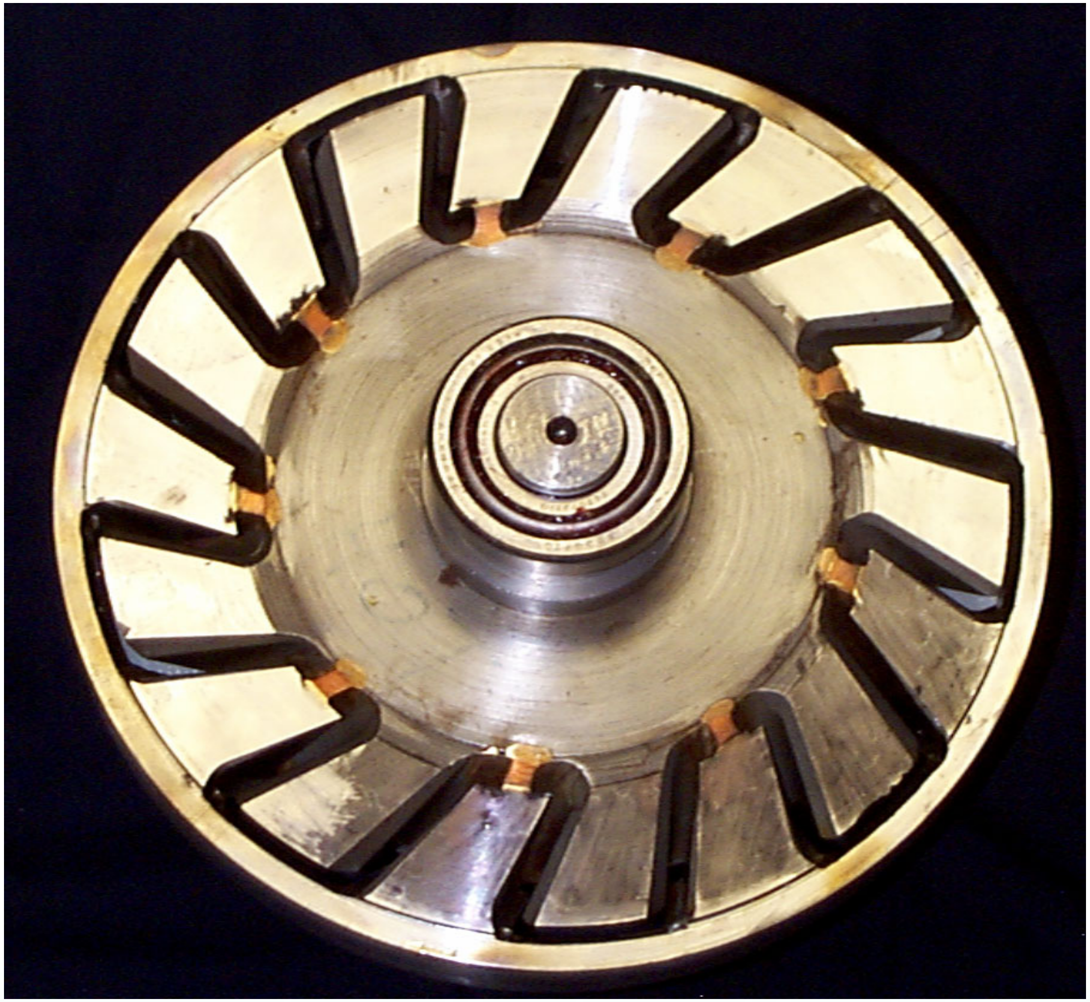
The power rating of the energy recovery circuit for a three-phase inverter, P_R, is determined by the snubber capacitance, C_S; dc link voltage, V_{dc}; inverter switching frequency, f_{sw}; stray inductance, L_s; square of the decrease in the dc link current over each switching instance, $\Delta I^2_{dc(k)}$; and fundamental frequency, f_m, according to

$$P_R = 6C_S V_{Cs0}^2 f_{sw} + \underline{f_m L_s \sum_k (\Delta I_{dc(k)}^2)}$$

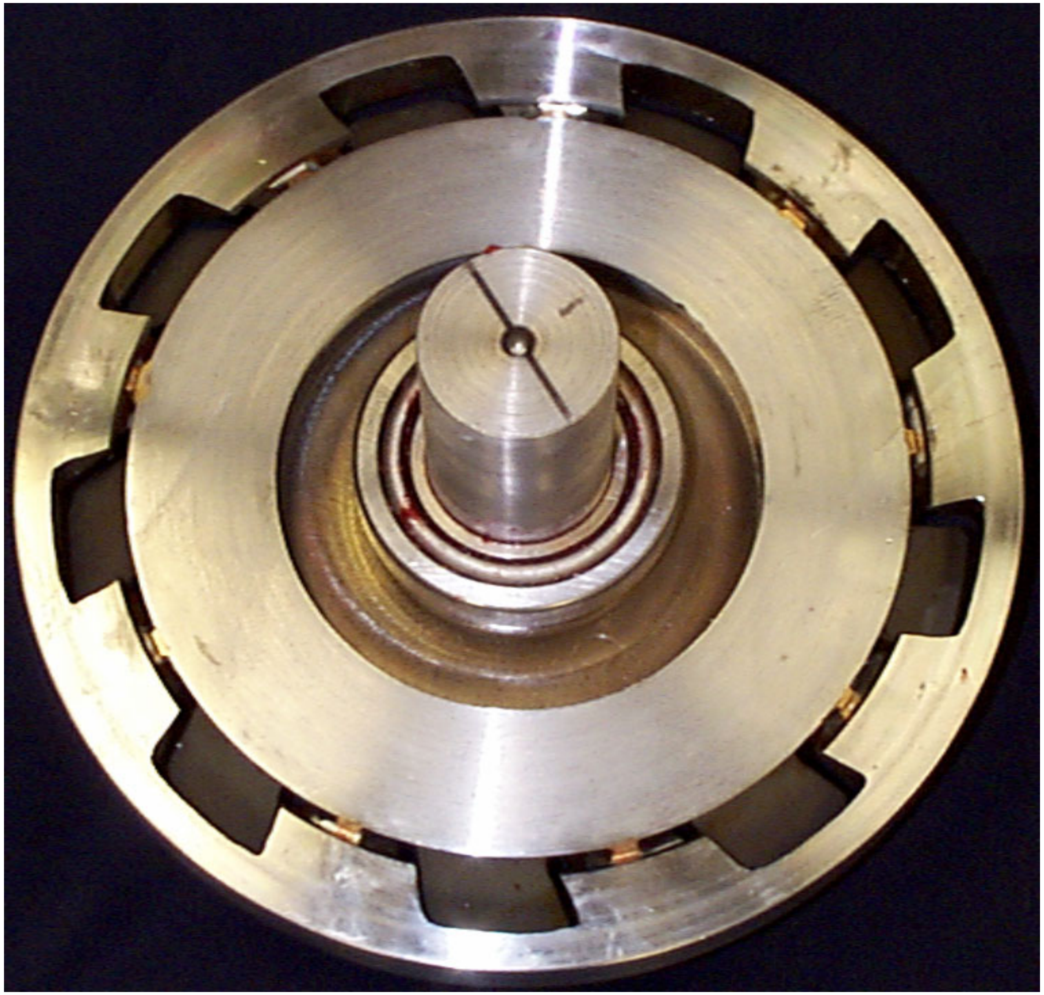
$$\approx f_{sw}(6C_S V_{Cs0}^2 + 4.31 L_s I_{Lrms}^2)$$

I_{Lrms}: rms load current, assuming a 3-phase sinusoidal current

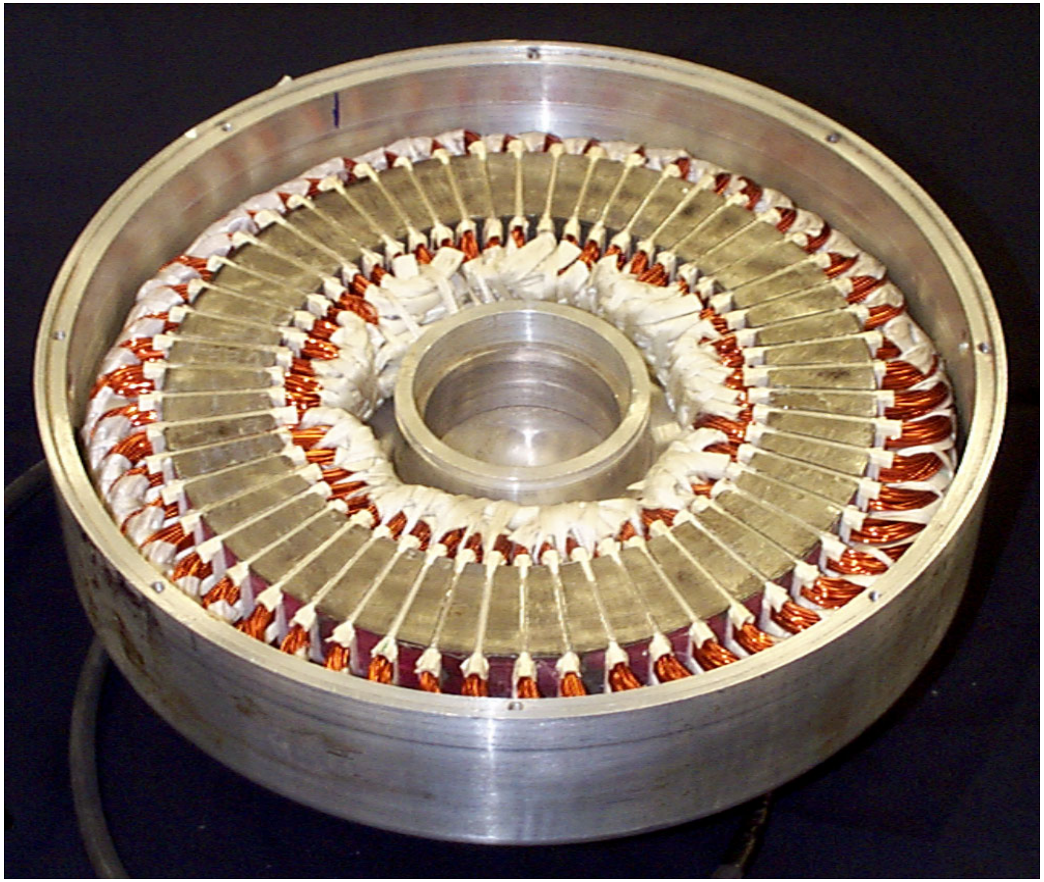
One Side of Rotor



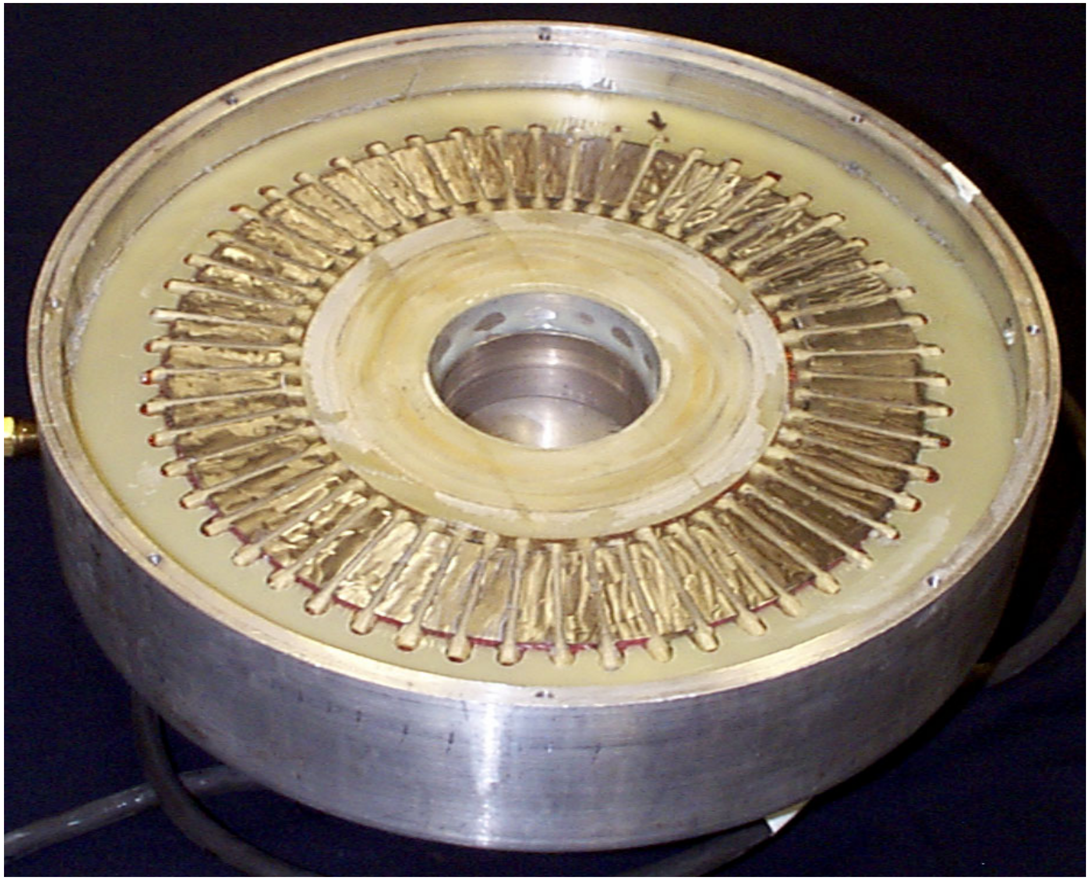
Other Side of Rotor



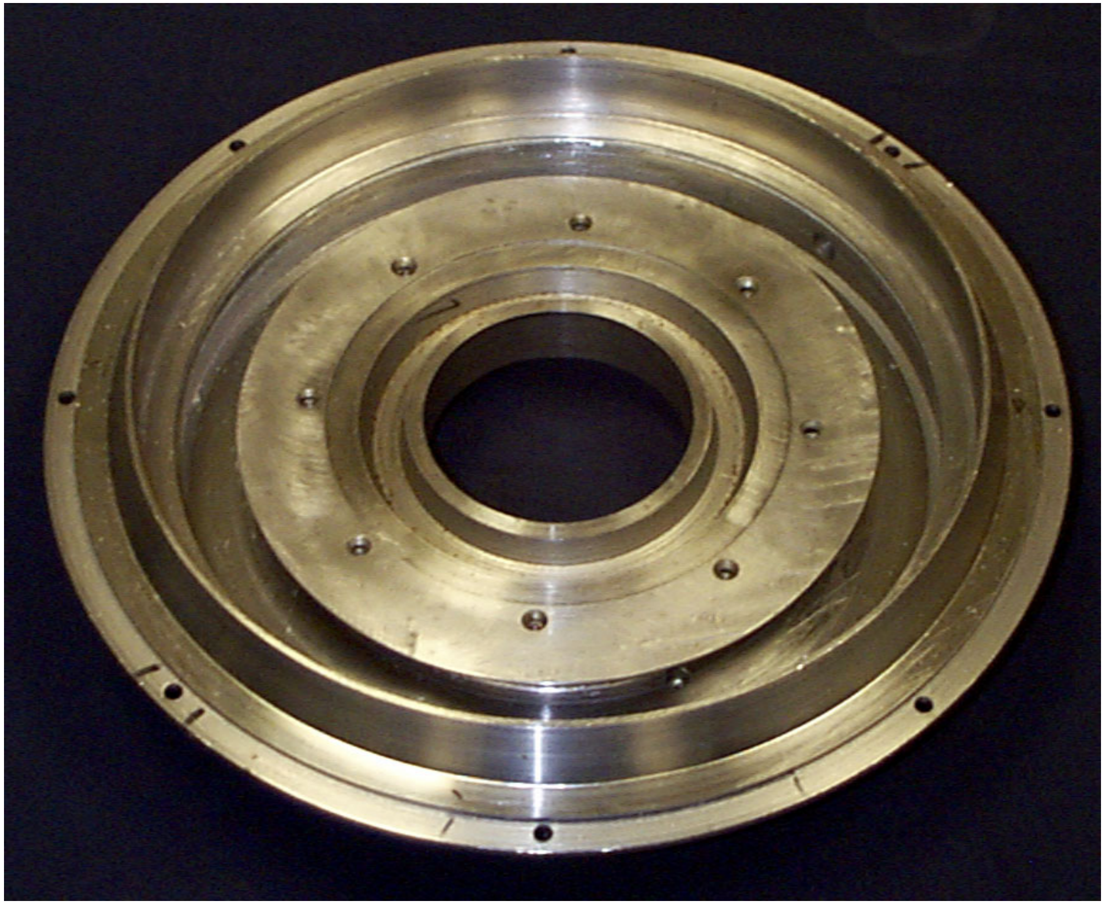
Wound Stator



Sealed Oil-Cooled Stator Winding

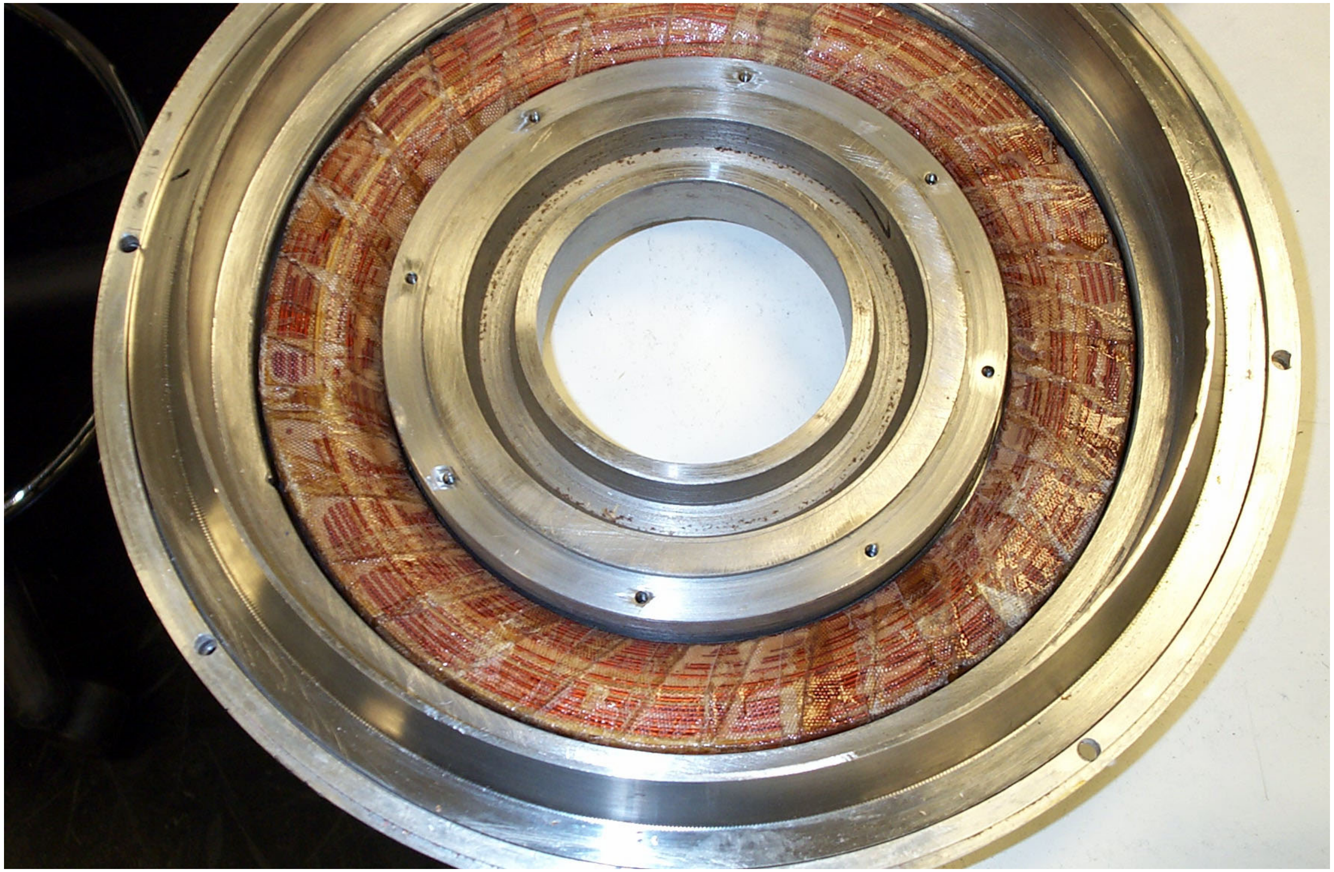


End Bracket

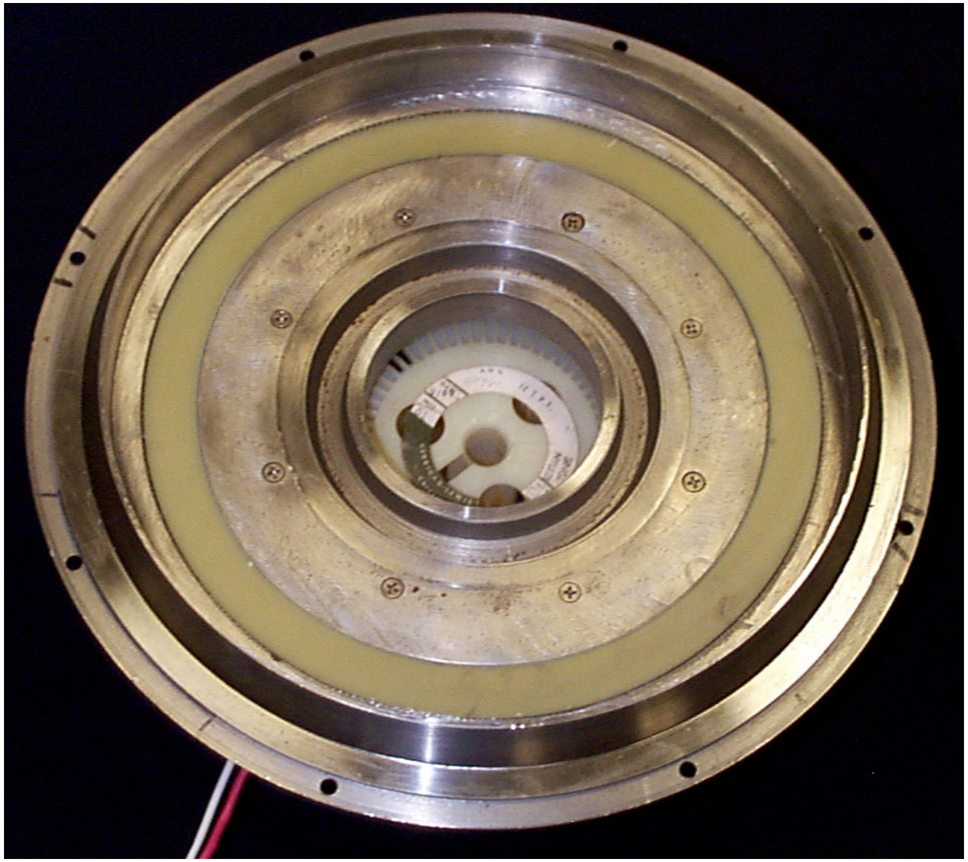


Excitation Coil

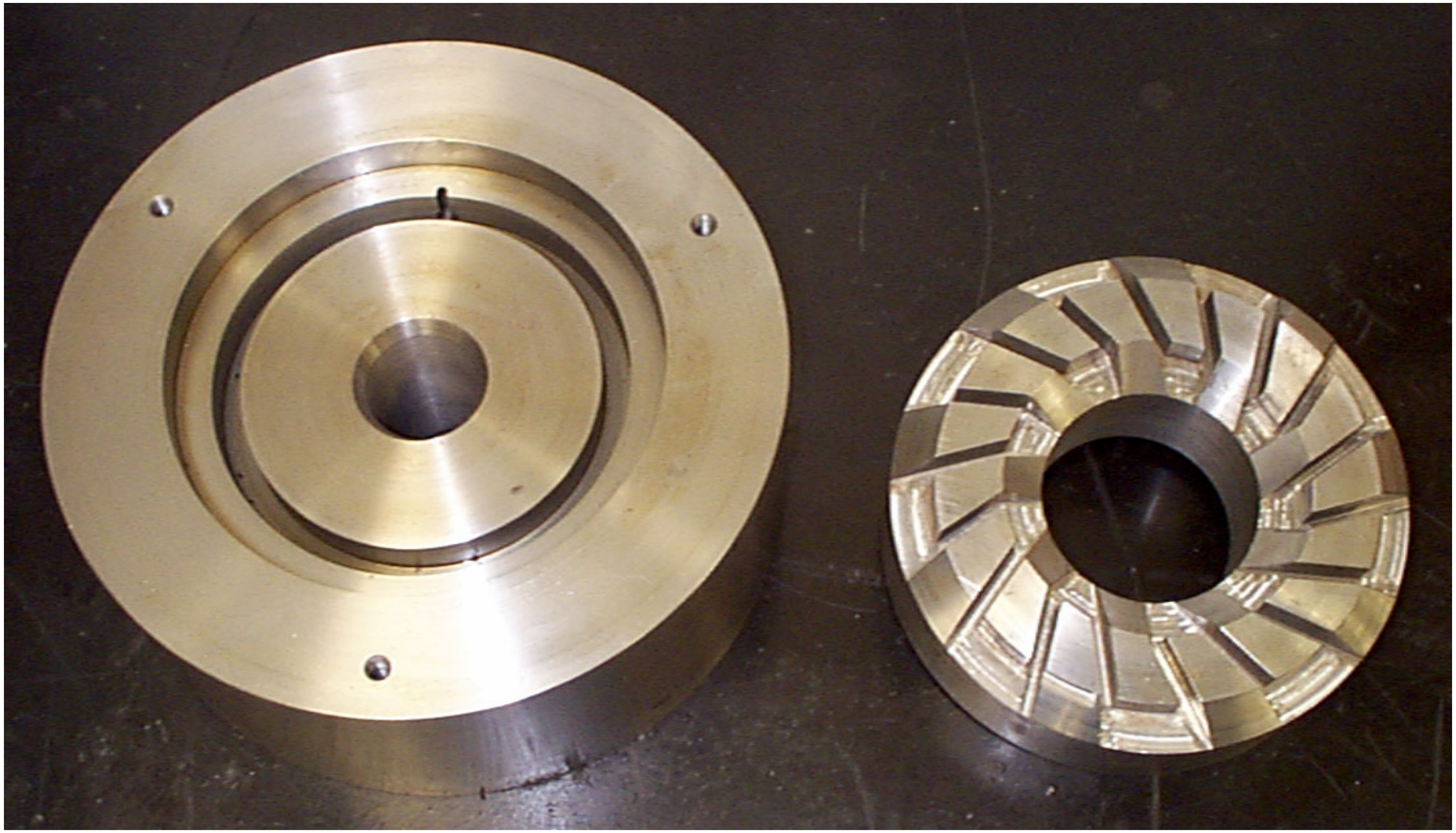
End Bracket with Excitation Coil



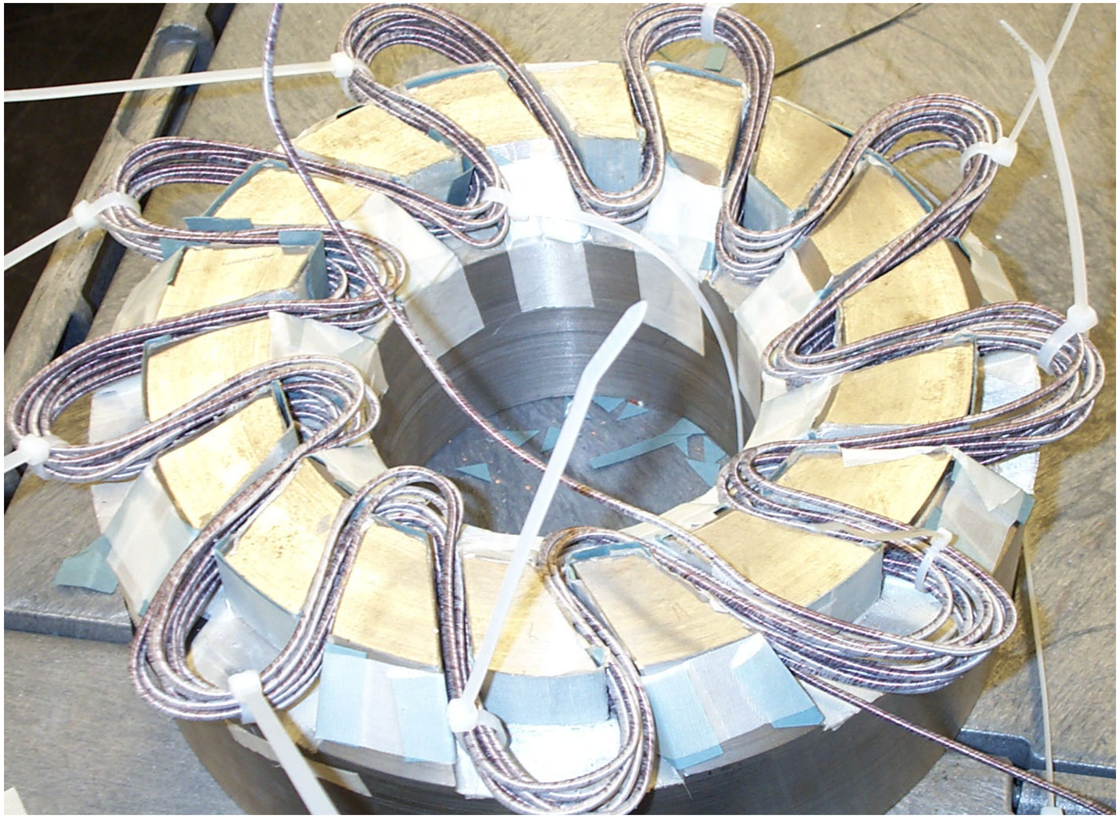
Sealed Oil-Cooled Excitation Coil



Fixtures for Charging Rotor PM



Putting Coils in Fixture



Injected PM Made of MQP-S