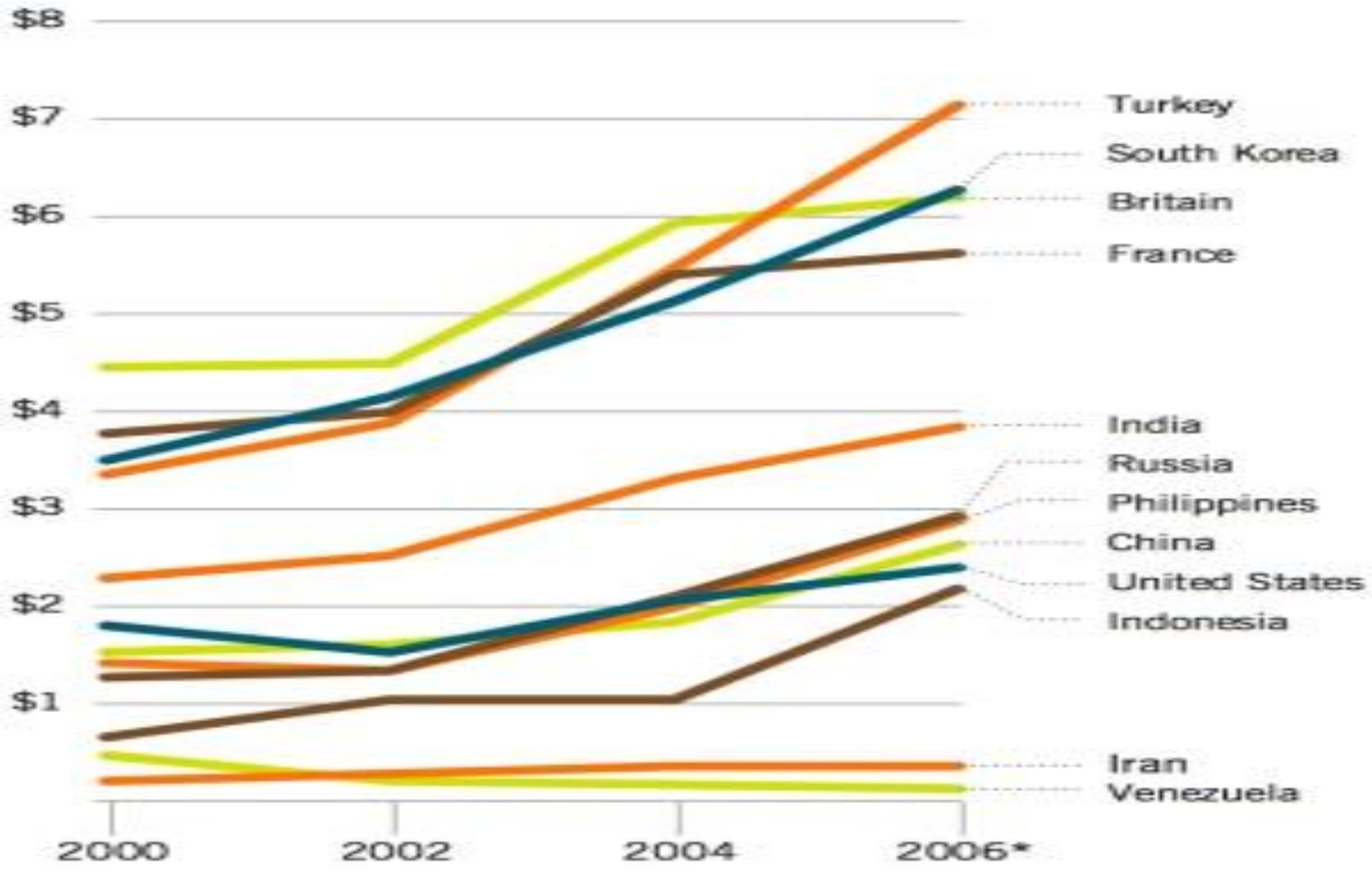
A Tutorial on Hybrid Electric Vehicles: EV, HEV, PHEV and FCEV

- Dr. James Gover, IEEE Fellow
  Professor of Electrical Engineering

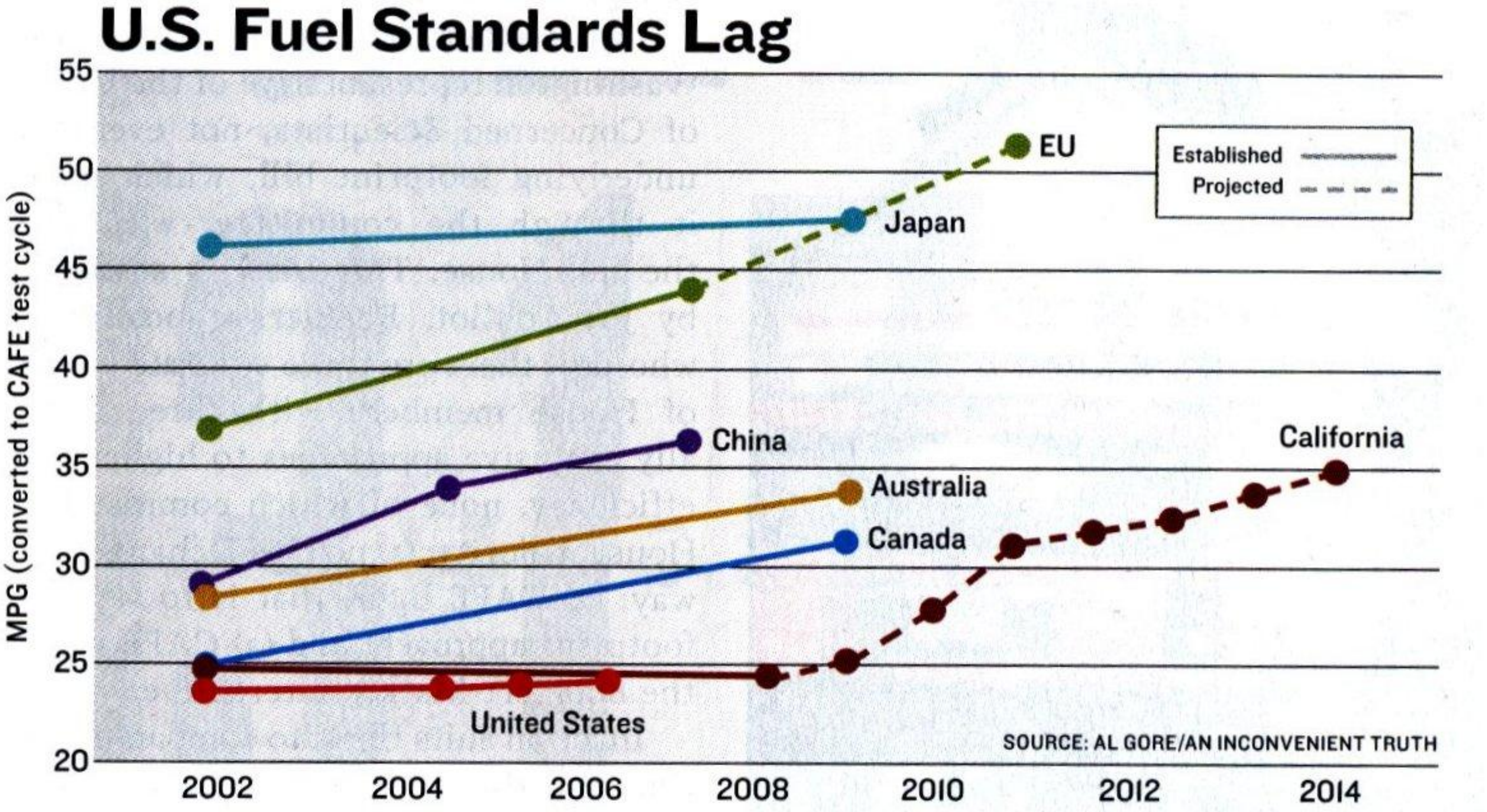
  Kettering University

Gasoline Prices Are Driving Commercial HEV Development



Gerhard Metschies, *Pain at the Pump*, Foreign Policy, July/August, 2007, p.28.

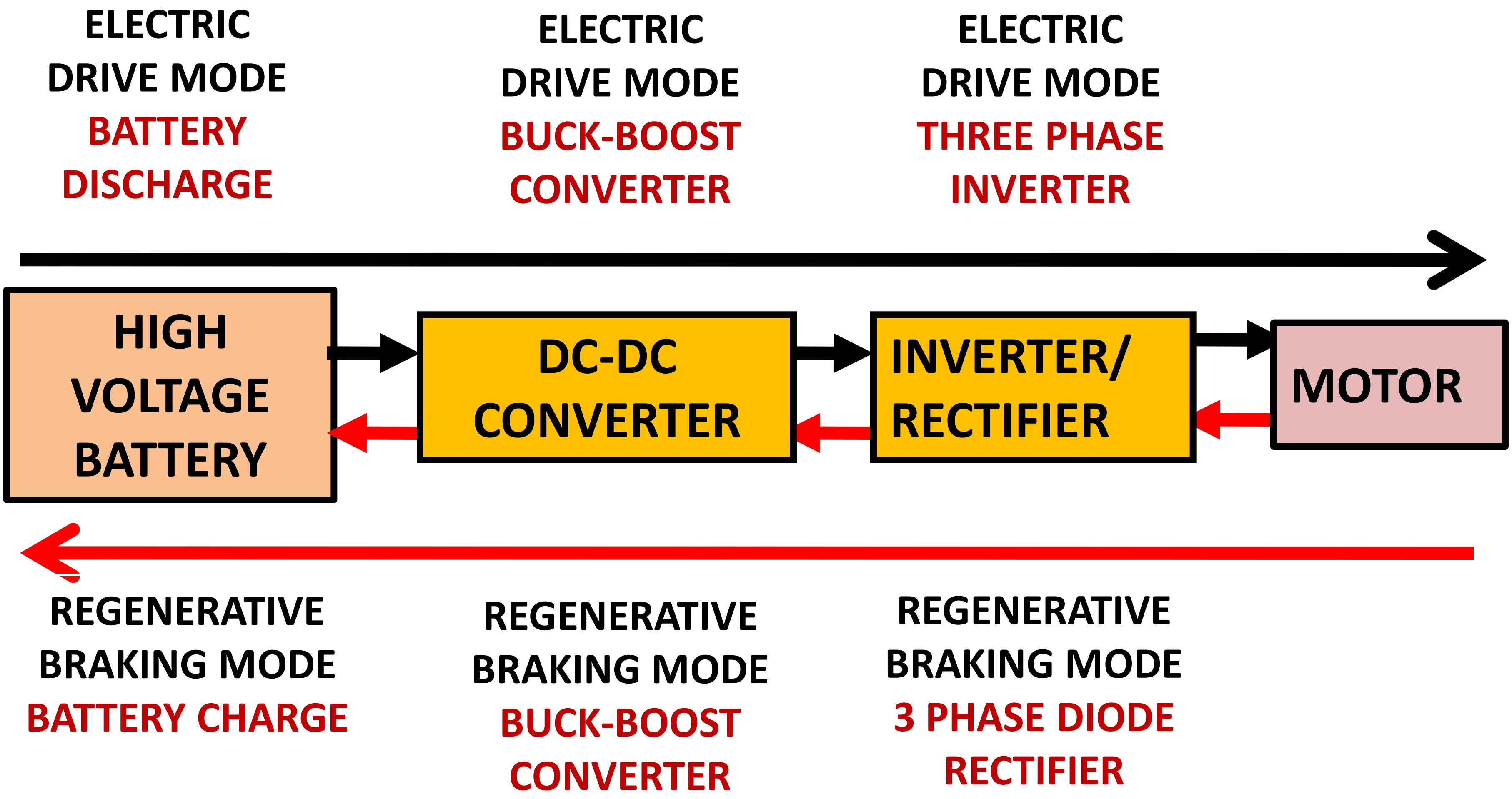
Nations' Fuel Standards Are Driving HEV Development



SOURCE: AL GORE/AN INCONVENIENT TRUTH

<u>IEEE Spectrum</u>, September, 2006.

Power Electronics in Hybrid Vehicles



ELECTRIC
DRIVE MODE
BATTERY
DISCHARGE

ELECTRIC
DRIVE MODE
BUCK-BOOST
CONVERTER

ELECTRIC
DRIVE MODE
THREE PHASE
INVERTER

HIGH
VOLTAGE
BATTERY

DC-DC
CONVERTER

INVERTER/
RECTIFIER

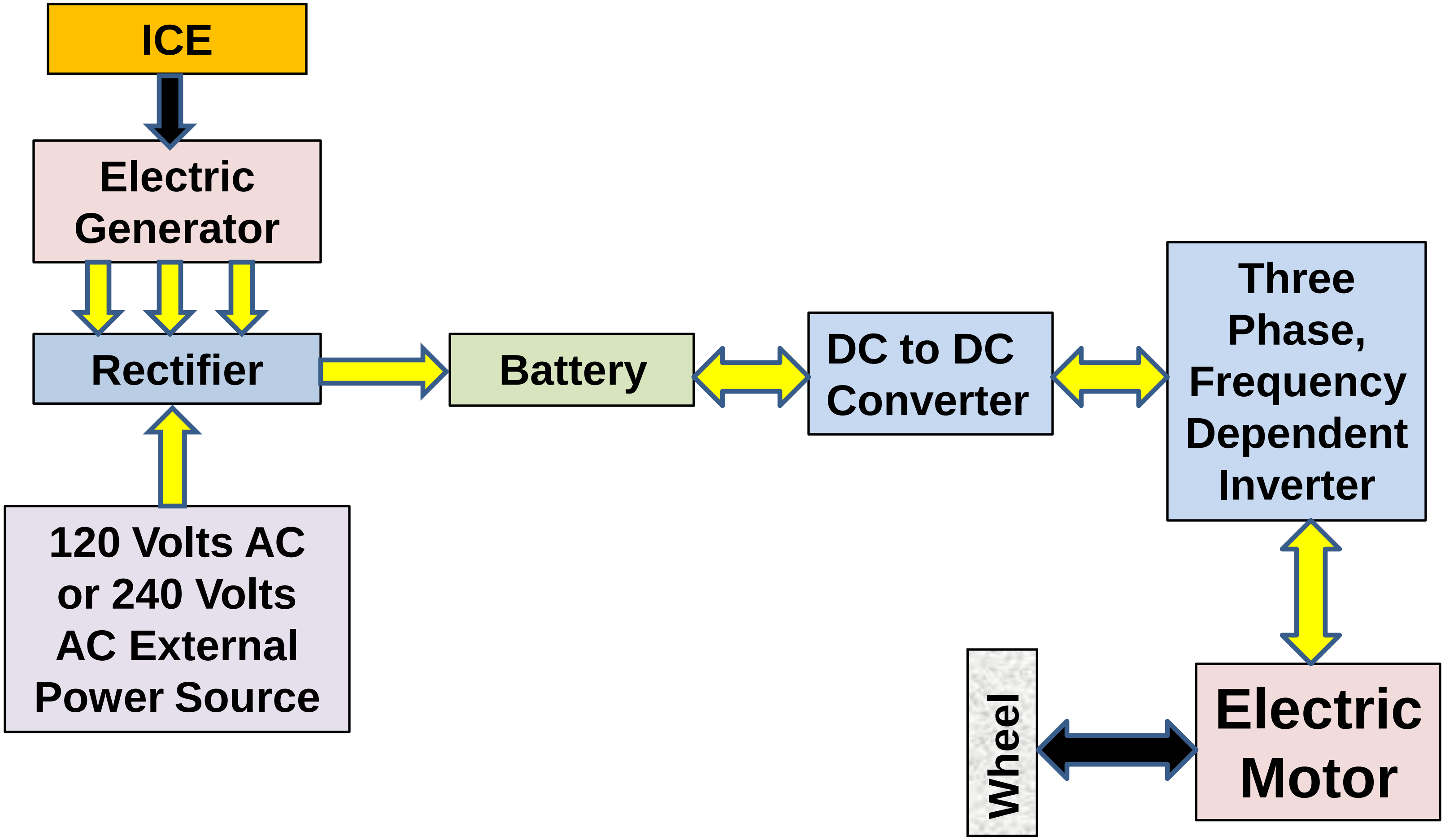
MOTOR

REGENERATIVE
BRAKING MODE
BATTERY CHARGE

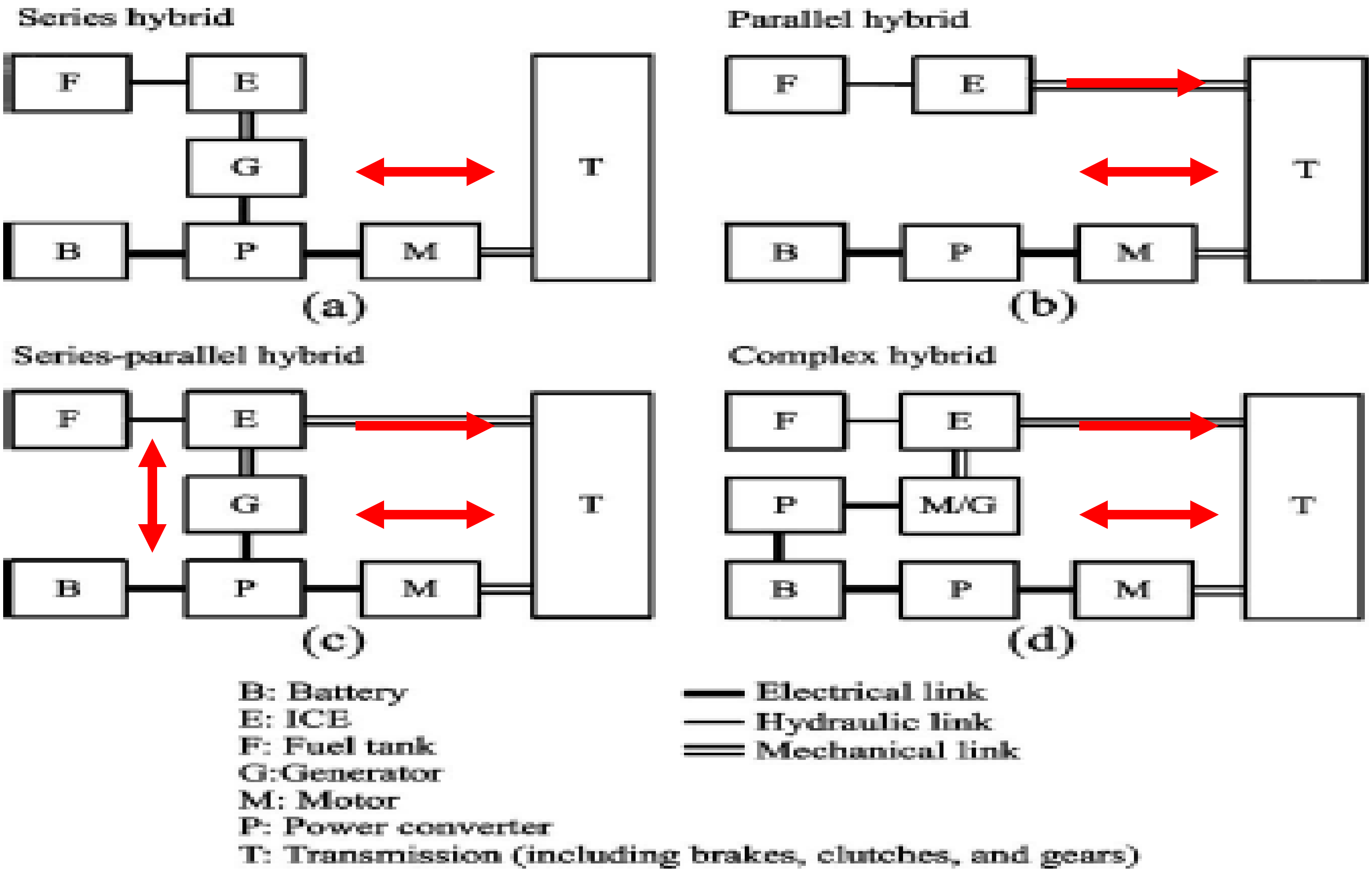
REGENERATIVE
BRAKING MODE
BUCK-BOOST
CONVERTER

REGENERATIVE
BRAKING MODE
3 PHASE DIODE
RECTIFIER

Energy Flow Diagram for Series PHEV

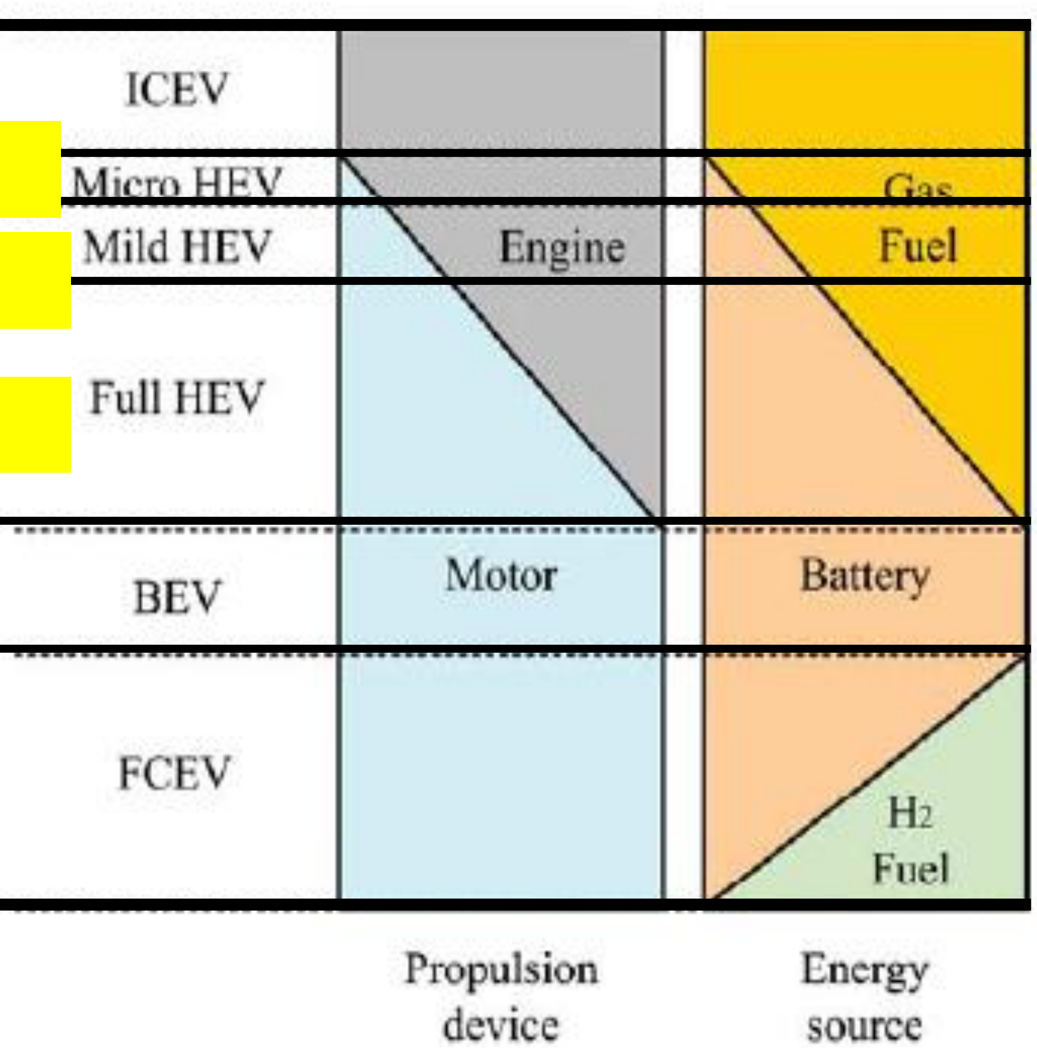


Systems Architectures of HEVs



C.C. Chan, *The State of the Art of Electric Hybrid, and Fuel Cell Vehicles*, Proceedings of the IEEE, April, 2007.

Types of EVs



Internal Combustion Engine

Belt Driven Integrated Starter Generator (ISG):
3-5kW With Idle Stop and Regenerative Braking

Integrated Starter Generator: 7-12kW With Idle Stop,
Regenerative Braking & Downsized ICE

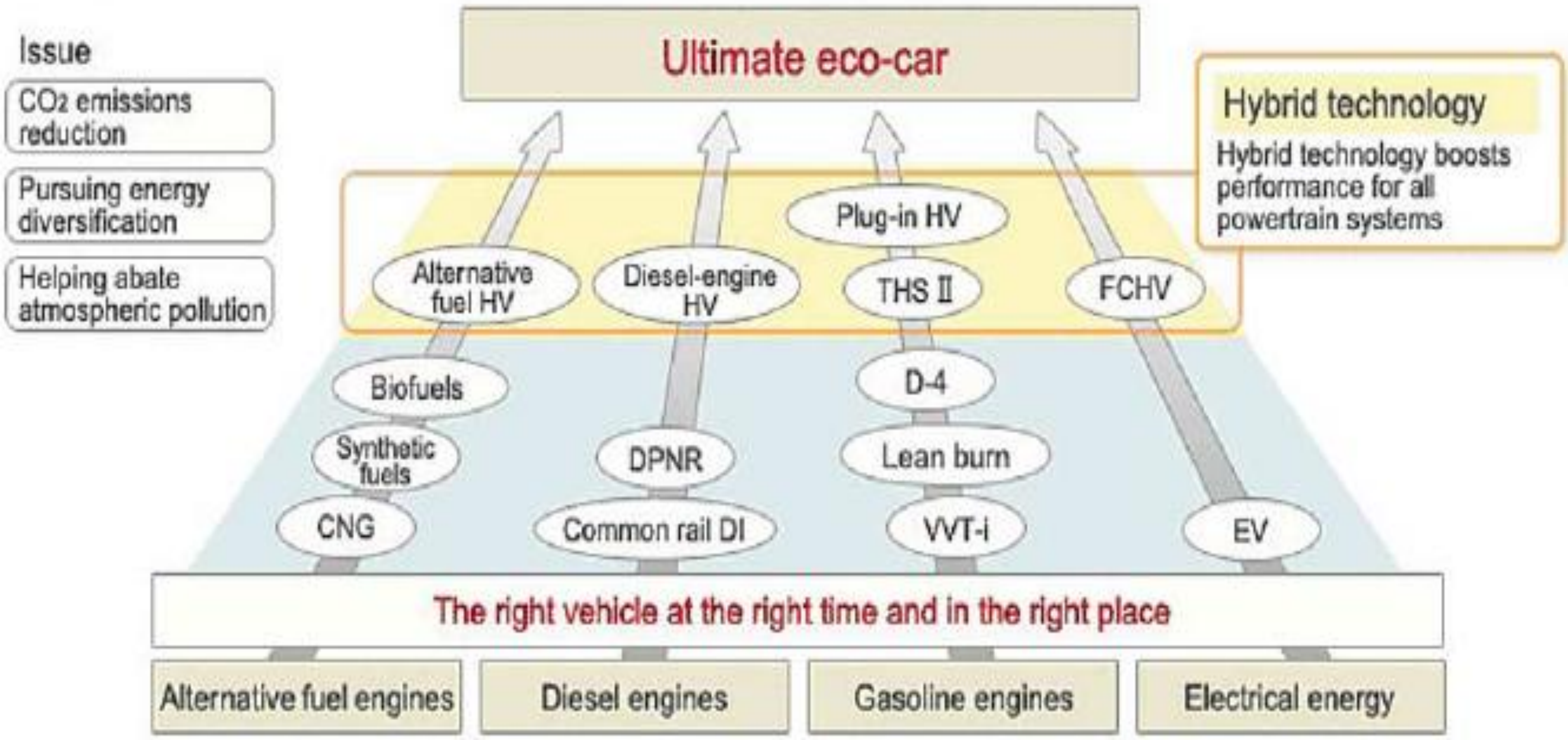
30-50 kW, 200-500 Volts With Electric Launch, Idle Stop,
Regenerative Braking & Downsized ICE

Battery Powered Electric Vehicles

75-100 kW Fuel Cell Electric Vehicles

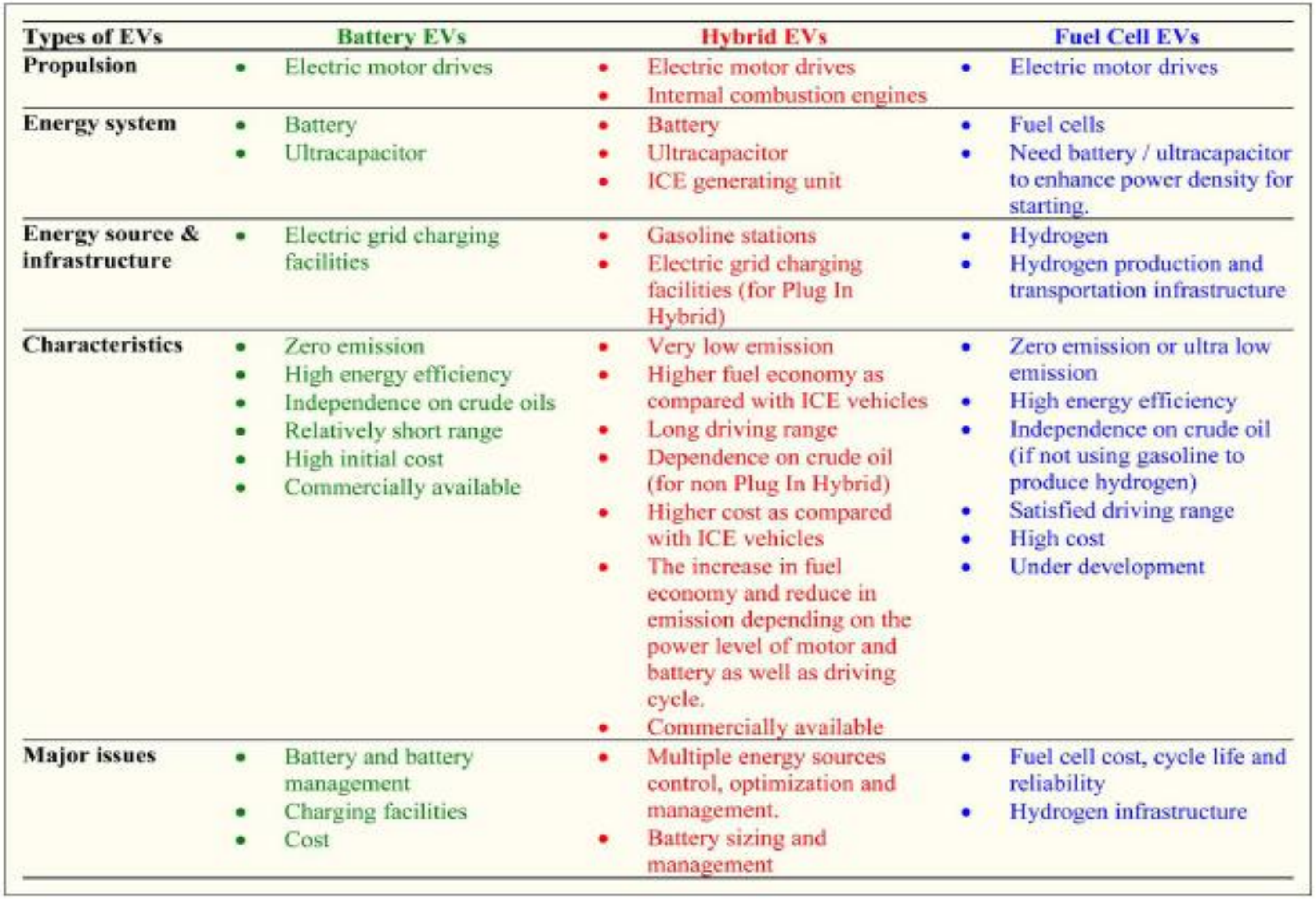
K. T. Chau and C.C. Chan, *Emerging Energy-Efficient Technologies for Hybrid Electric Vehicles,* Proceedings of the IEEE, April, 2007.

Toyota Hybrid Roadmap



C.C. Chan, *The State of the Art of Electric Hybrid, and Fuel Cell Vehicles*, Proceedings of the IEEE, April, 2007.

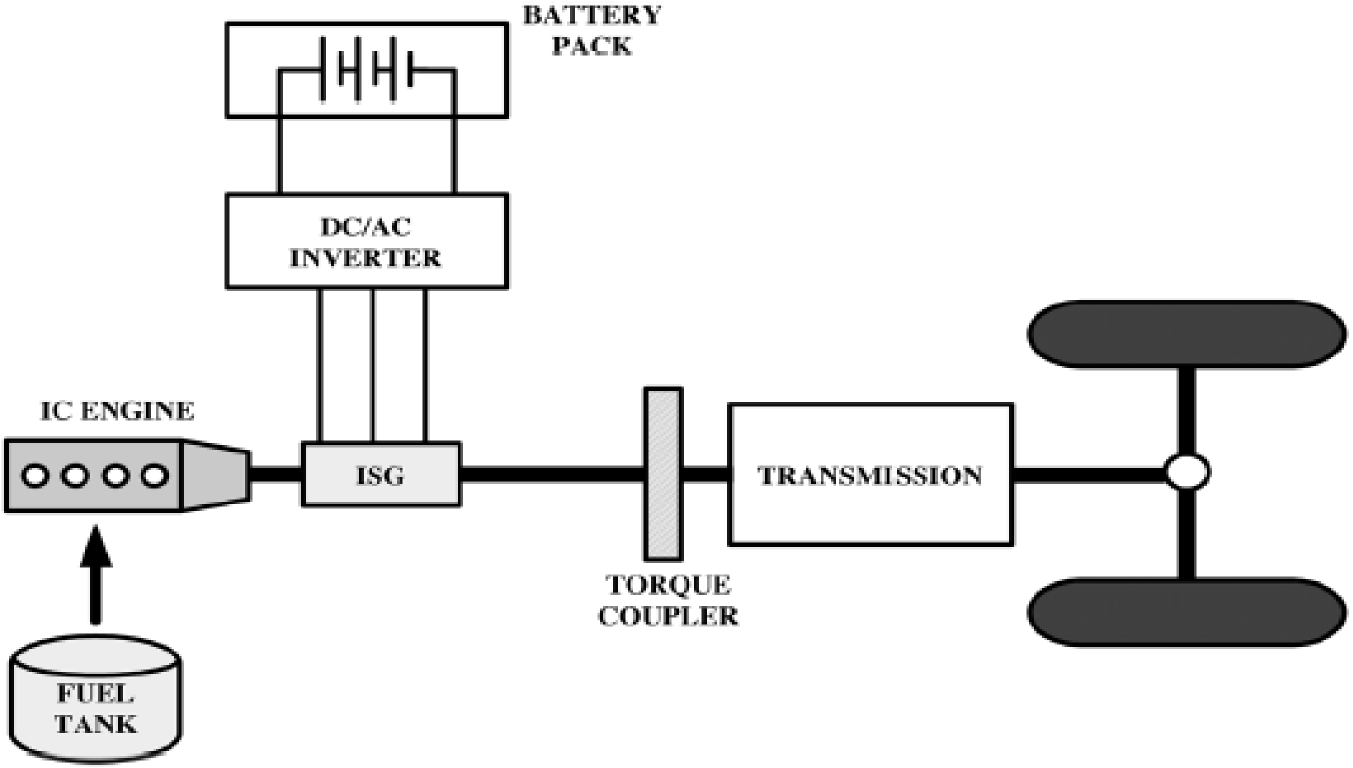
Characteristics of EVs, HEVs, PHEVs and FCEVs



Types of EVs	Battery EVs	Hybrid EVs	Fuel Cell EVs
Propulsion	• Electric motor drives	• Electric motor drives • Internal combustion engines	• Electric motor drives
Energy system	• Battery • Ultracapacitor	• Battery • Ultracapacitor • ICE generating unit	• Fuel cells • Need battery / ultracapacitor to enhance power density for starting.
Energy source & infrastructure	• Electric grid charging facilities	• Gasoline stations • Electric grid charging facilities (for Plug In Hybrid)	• Hydrogen • Hydrogen production and transportation infrastructure
Characteristics	• Zero emission • High energy efficiency • Independence on crude oils • Relatively short range • High initial cost • Commercially available	• Very low emission • Higher fuel economy as compared with ICE vehicles • Long driving range • Dependence on crude oil (for non Plug In Hybrid) • Higher cost as compared with ICE vehicles • The increase in fuel economy and reduce in emission depending on the power level of motor and battery as well as driving cycle. • Commercially available	• Zero emission or ultra low emission • High energy efficiency • Independence on crude oil (if not using gasoline to produce hydrogen) • Satisfied driving range • High cost • Under development
Major issues	• Battery and battery management • Charging facilities • Cost	• Multiple energy sources control, optimization and management. • Battery sizing and management	• Fuel cell cost, cycle life and reliability • Hydrogen infrastructure

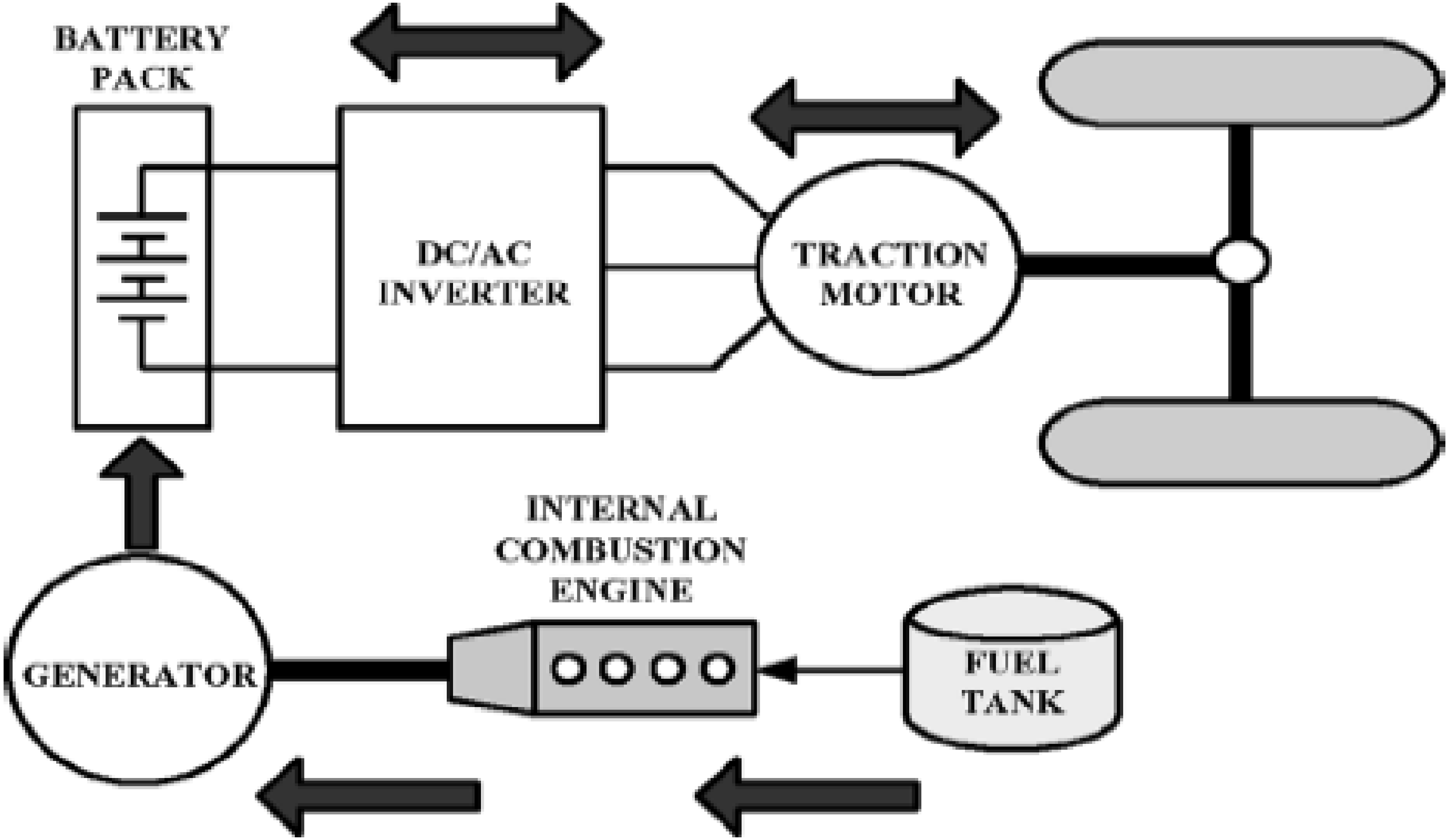
C.C. Chan, ***The State of the Art of Electric Hybrid, and Fuel Cell Vehicles***, **Proceedings of the IEEE, April, 2007.**

Integrated Starter-Generator Based 42 Volt System



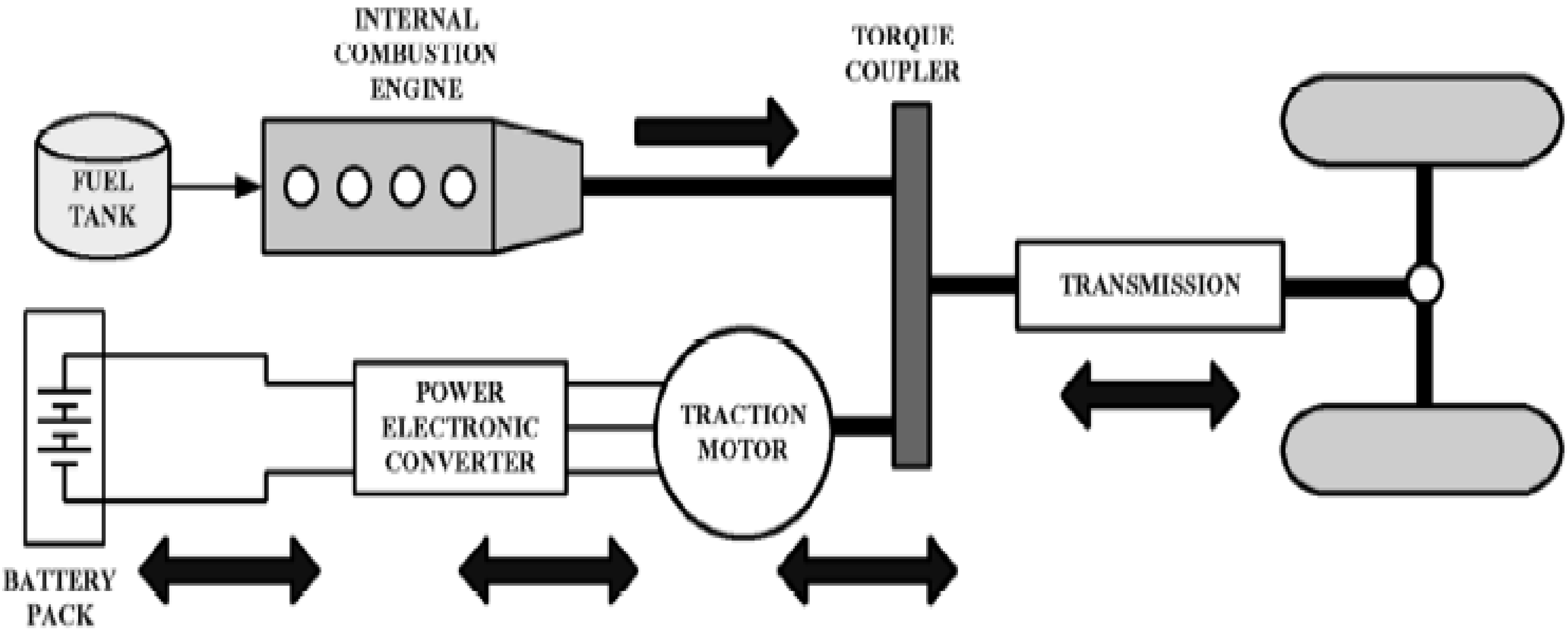
Ali Emadi, Kauskik Rajashekara, Sheldon Wiliamson and Srdjan *Lukic,Topological Overview of Hybrid Electric and Fuel Cell Vehicular Power System Architectures and Configurations*, IEEE Transactions on Vehicular Technology, Vol. 54, No. 3, May 2005

Series Hybrid System



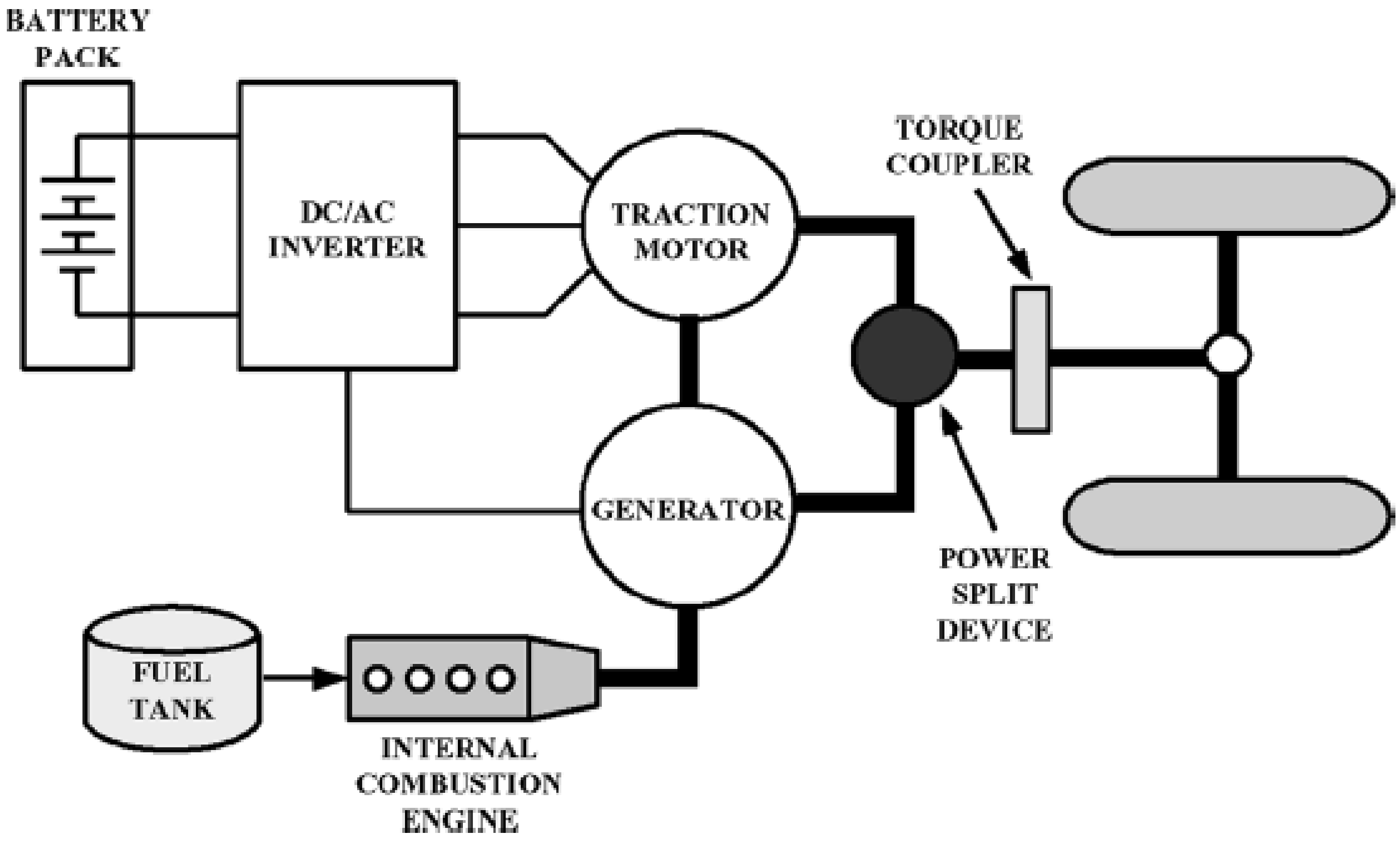
Ali Emadi, Kauskik Rajashekara, Sheldon Wiliamson and Srdjan *Lukic,Topological Overview of Hybrid Electric and Fuel Cell Vehicular Power System Architectures and Configurations*, IEEE Transactions on Vehicular Technology, Vol. 54, No. 3, May 2005

Parallel HEV Drive Train



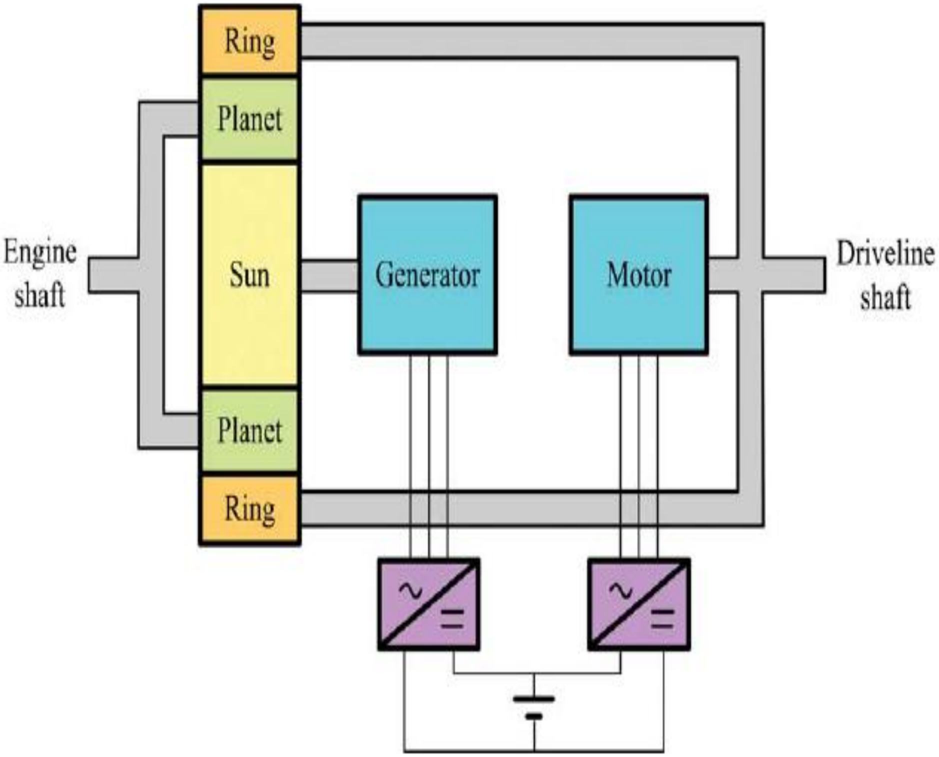
Ali Emadi, Kauskik Rajashekara, Sheldon Wiliamson and Srdjan *Lukic,Topological Overview of Hybrid Electric and Fuel Cell Vehicular Power System Architectures and Configurations*, IEEE Transactions on Vehicular Technology, Vol. 54, No. 3, May 2005

Series/Parallel HEV Hybrid

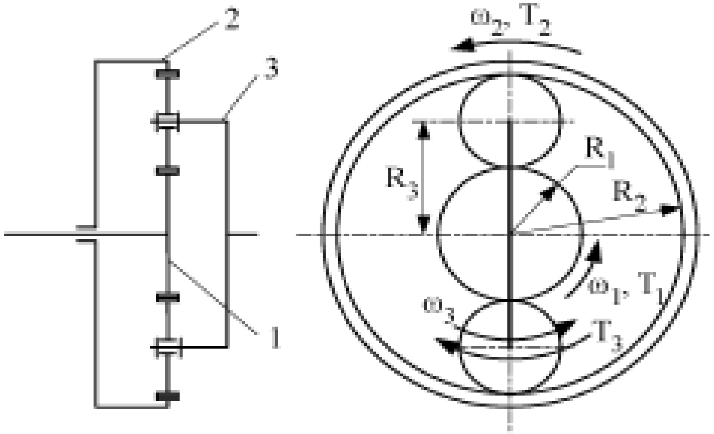


Ali Emadi, Kauskik Rajashekara, Sheldon Wiliamson and Srdjan ***Lukic,Topological Overview of Hybrid Electric and Fuel Cell Vehicular Power System Architectures and Configurations*****,** **IEEE Transactions on Vehicular Technology, Vol. 54, No. 3, May 2005**

Planetary Gear Set



Planetary gear unit

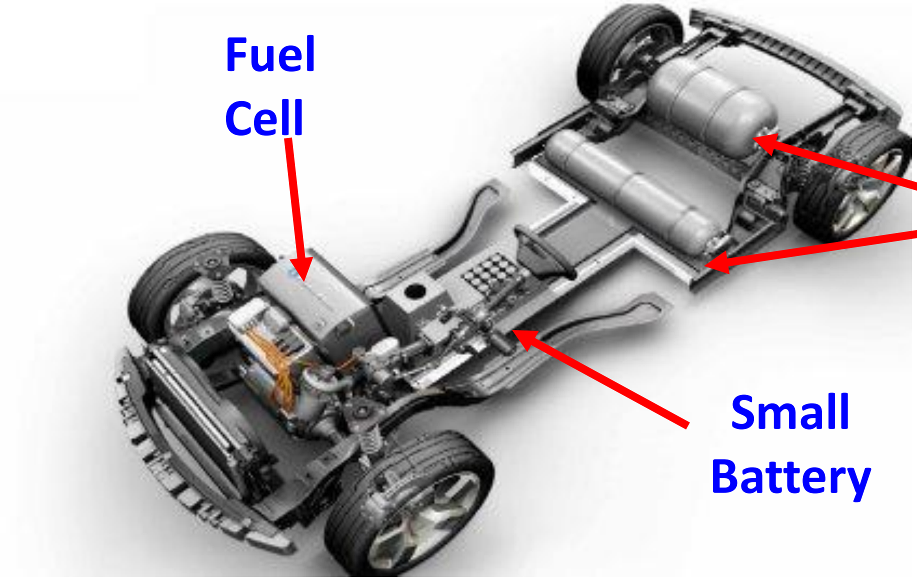


$$\omega_3 = \frac{R_1}{2R_3}\omega_1 + \frac{R_2}{2R_3}\omega_2$$

$$T_3 = \frac{2R_3}{R_1}T_1 = \frac{2R_3}{R_2}T_2$$

Mehrdad Ehsani, Yimin Gao, and John M. Miller, *Hybrid Electric Vehicles: Architecture and Motor Drives*, Proceedings of the IEEE, April, 2007.

FCEV & PHEV Volt Concepts

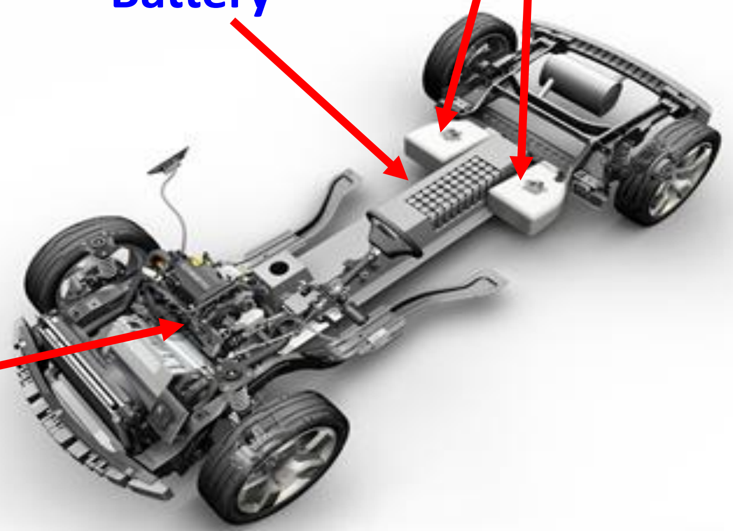


Fuel Cell

Hydrogen Tanks

Small Battery

FCEV Option



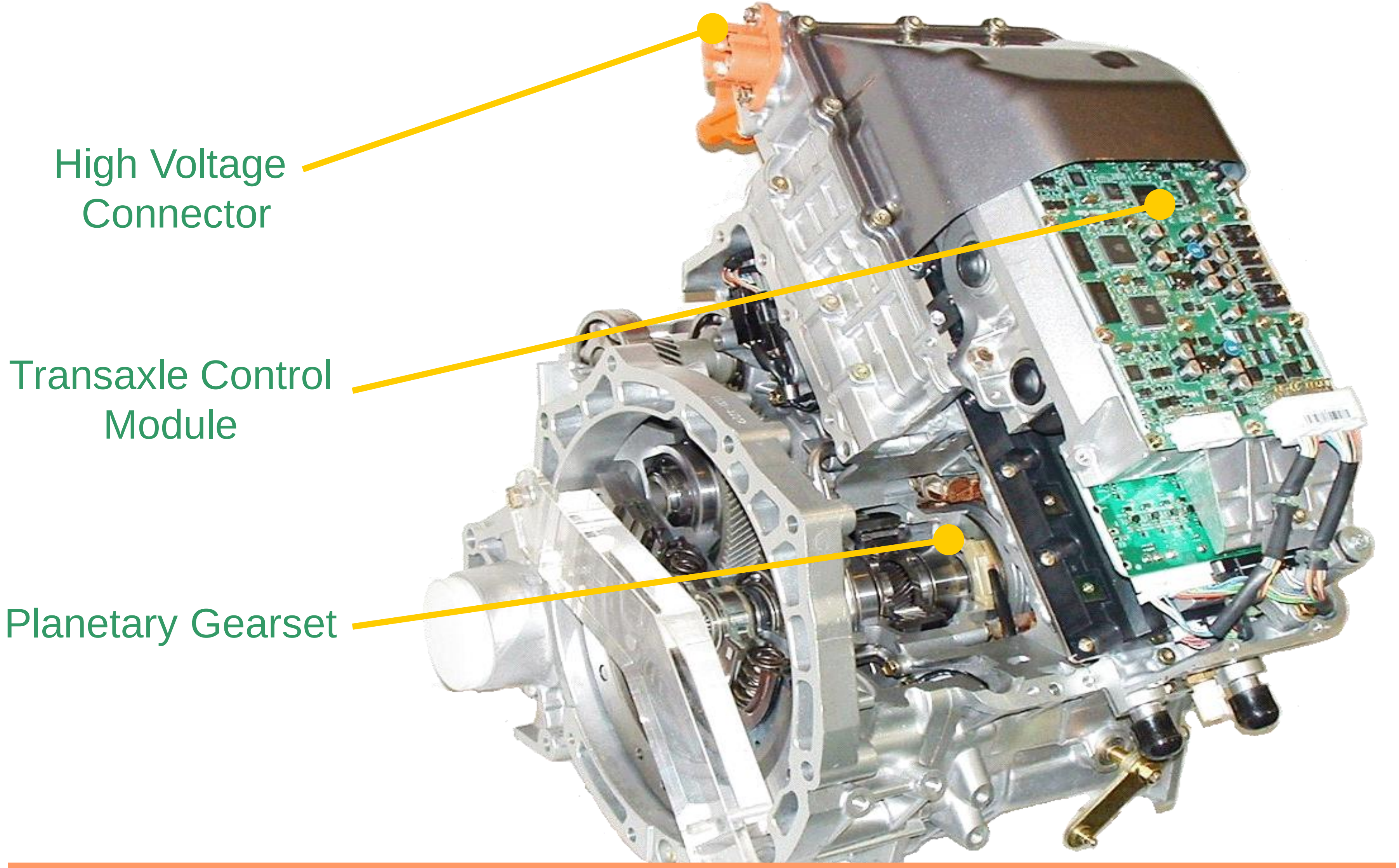
Fuel Tanks

Large Battery

ICE

PHEV Option

Escape Hybrid Transaxle Cut-Away



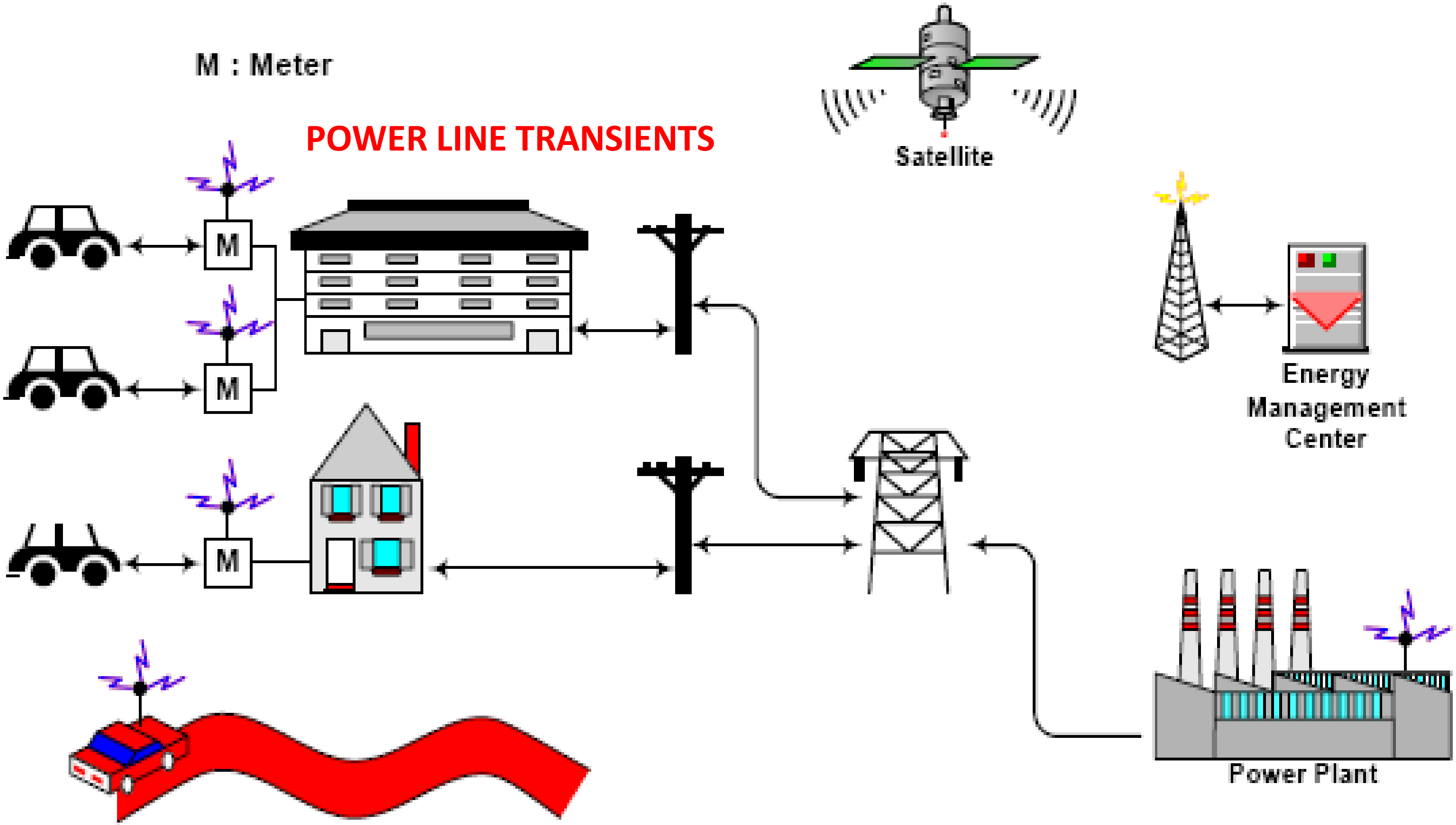
High Voltage Connector

Transaxle Control Module

Planetary Gearset

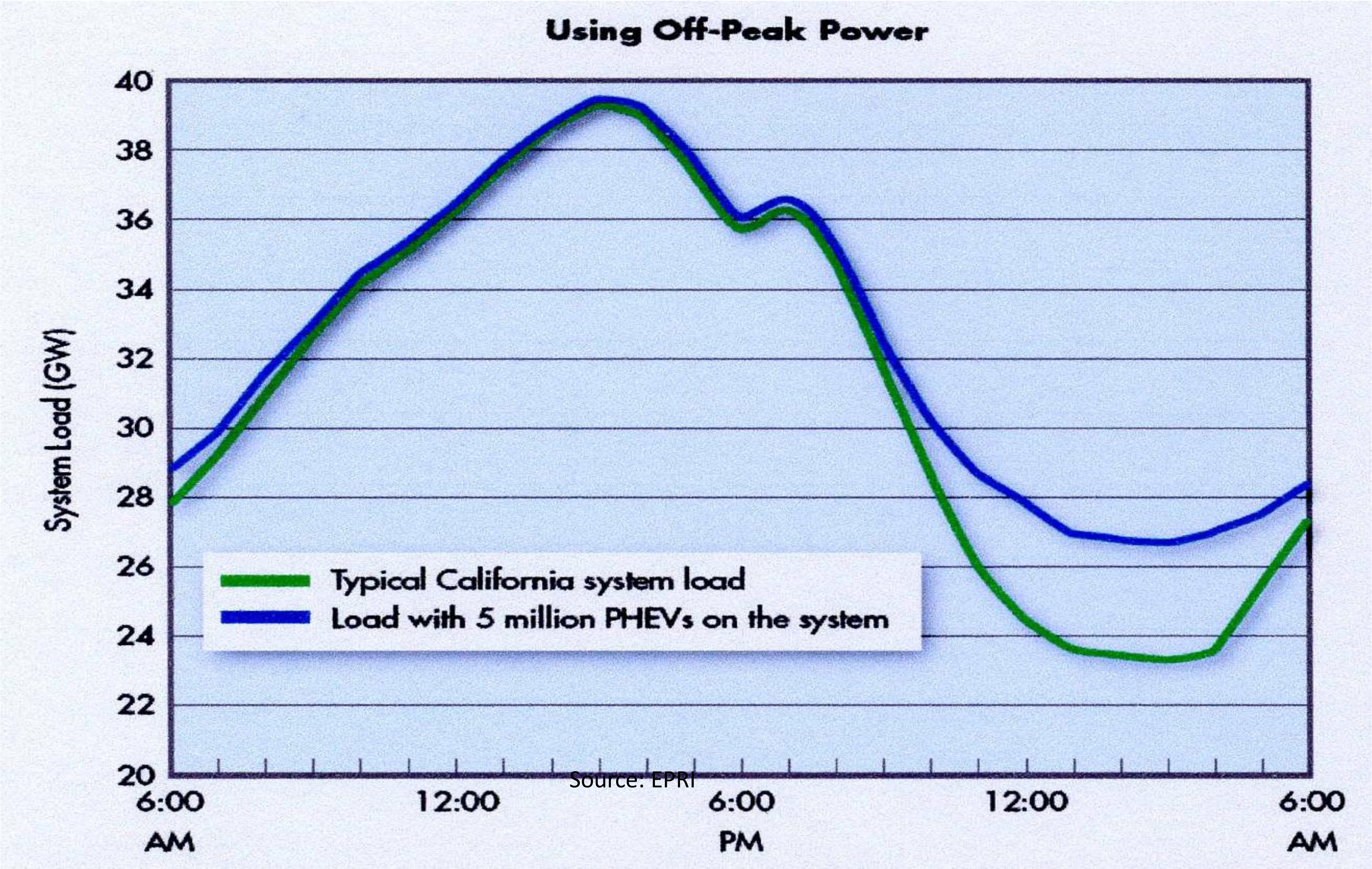
Stefan Pototschnik, Overview of the Ford Escape Hybrid, Sept. 12, 2006, Kettering University.

Integration of PHEVs On Grid



Mehdi Ferdowski, Plug-in Hybrid Vehicles – A vision for the Future, 2007 IEEE VPPPC

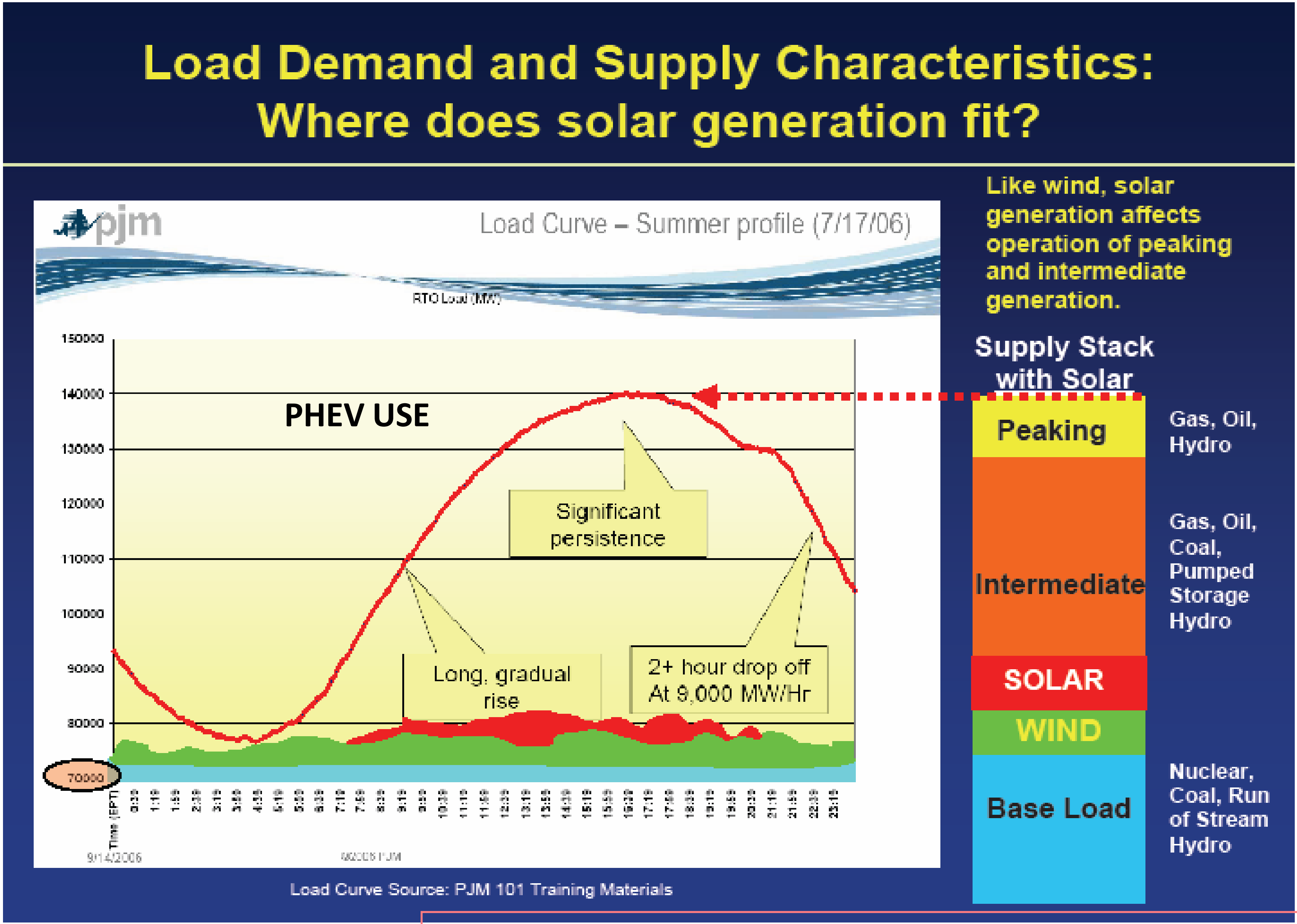
Night Electricity Is the Fuel for PHEV



Source: EPRI

Thomas Schneider*, Transportation Efficiency Through Electric Drives and the Power Grid,* **Capitol Hill Forum, Plug-in Hybrid Electric Vehicles: Towards Energy Independence***,* **July 10, 2007***.*

PHEV Energy Storage Used for Power Peaking



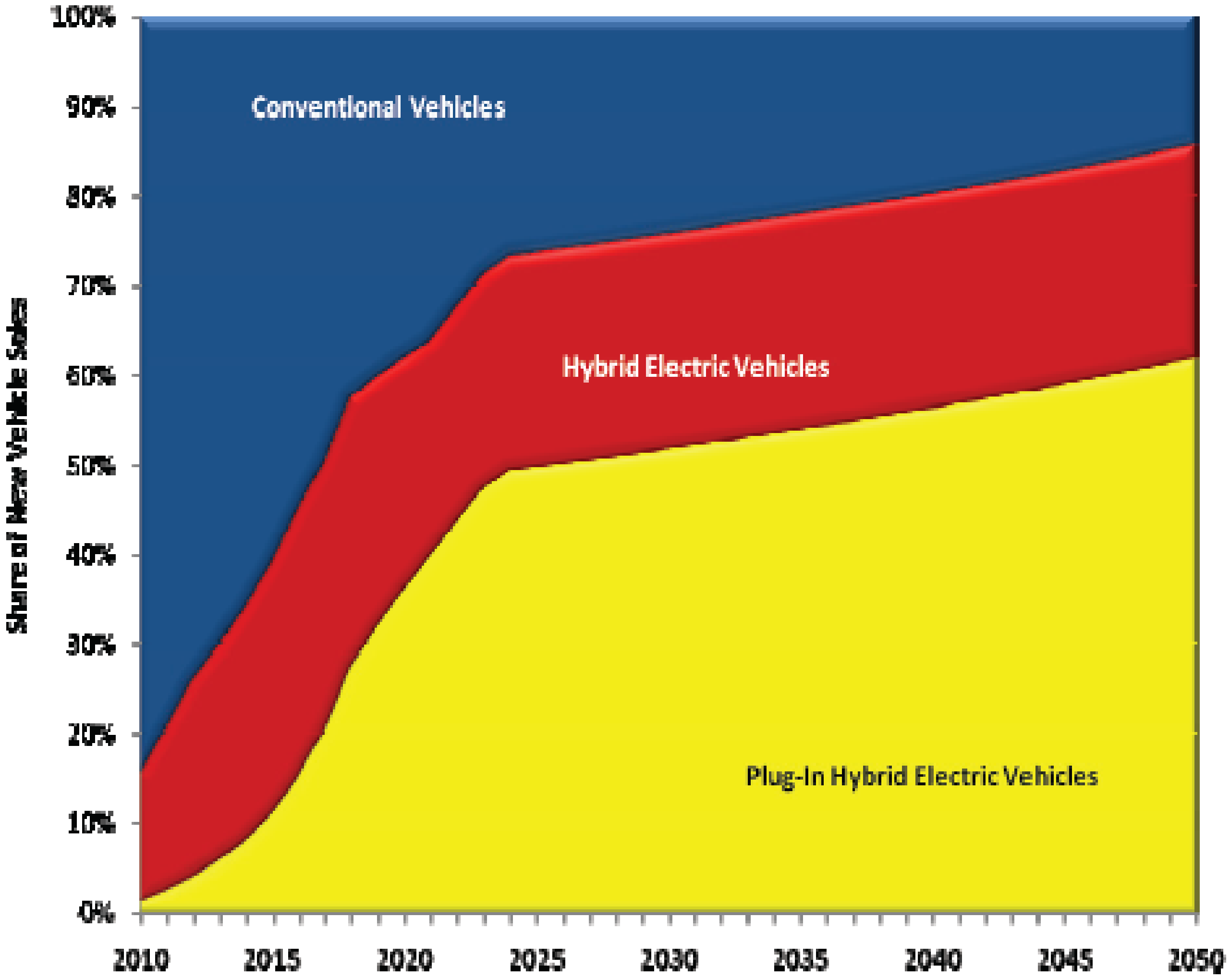
Load Demand and Supply Characteristics: Where does solar generation fit?

Like wind, solar generation affects operation of peaking and intermediate generation.

Load Curve Source: PJM 101 Training Materials

Harold Adams, Planning Considerations for a Carbon Constrained Grid, 10/2007

EPRI Assumptions for New Car US Sales



Assumed new car market share for the Medium PHEV scenario for conventional vehicles, hybrid electric vehicles, and plug-in hybrid electric vehicles for each vehicle category

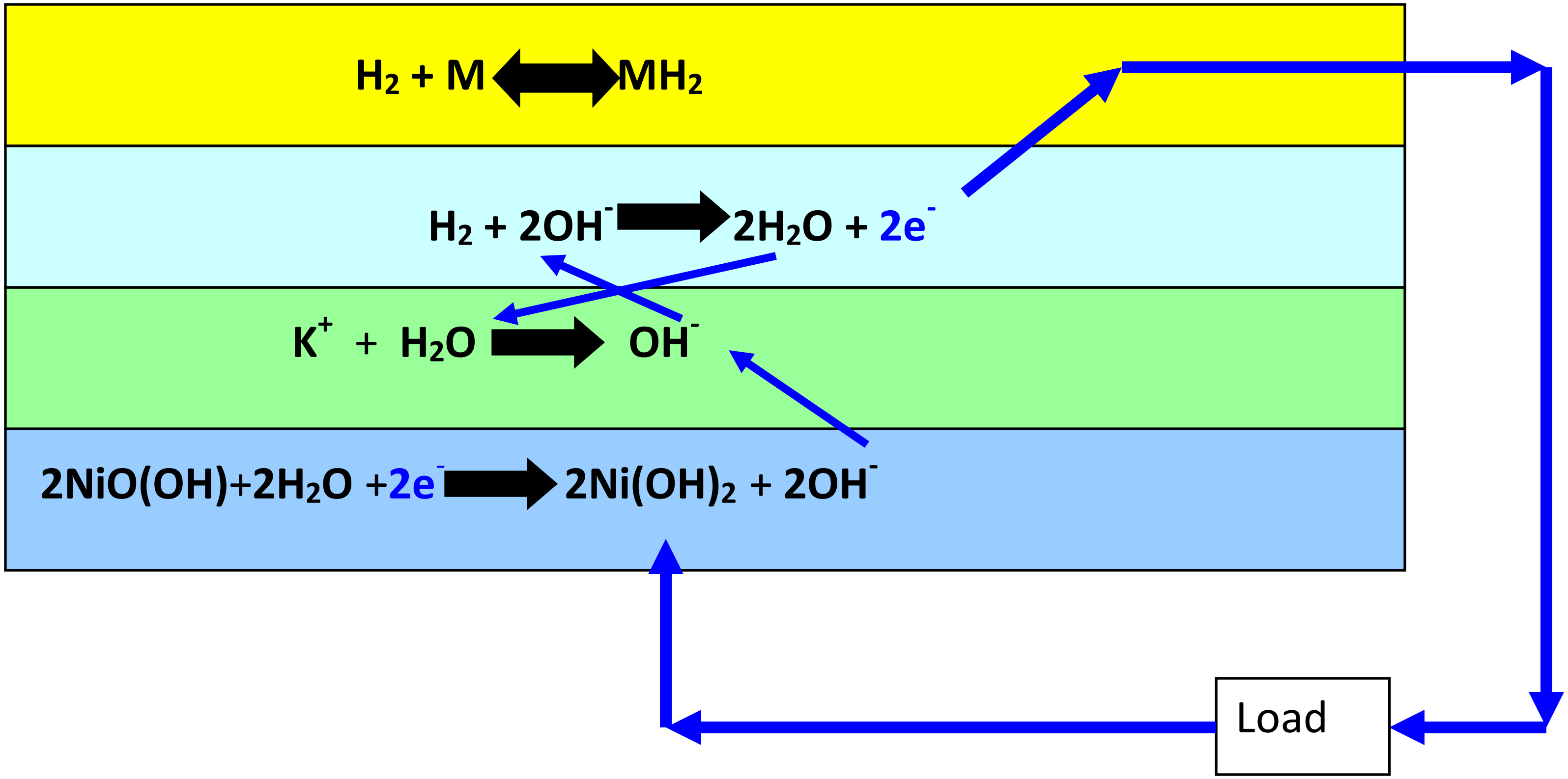
Environmental Assessment of Plug-In Hybrid Electric Vehicles, Volume 1: Nationwide Greenhouse Gas Emissions. EPRI, Palo Alto, CA: 2007. 1015325.

Two Battery Types Are Preferred for Hybrid-Electric Vehicles

- **Nickel Metal Hydride (NiMH)**
  - Introduced near end of 20th century
  - Similar performance to NiCad battery but its energy and power densities are higher and it charges faster
  - The metals into which hydrogen is adsorbed are proprietary
  - The battery cell must be sealed in order to keep air from reacting with the hydride
  - Battery can require cooling if charged fast
- **Lithium Ion**
  - Introduced in early 1990s.
  - Precise voltage control is needed when charging battery because if too high, battery can be damaged and if too low, battery will be undercharged
  - Because of its considerable weight advantage over other battery types, it is highly attractive for future hybrid electric vehicles
  - Large batteries are prohibitively expensive

NiMH Battery Discharge Reactions

Metal alloy sponge that absorbs and then gives back hydrogen



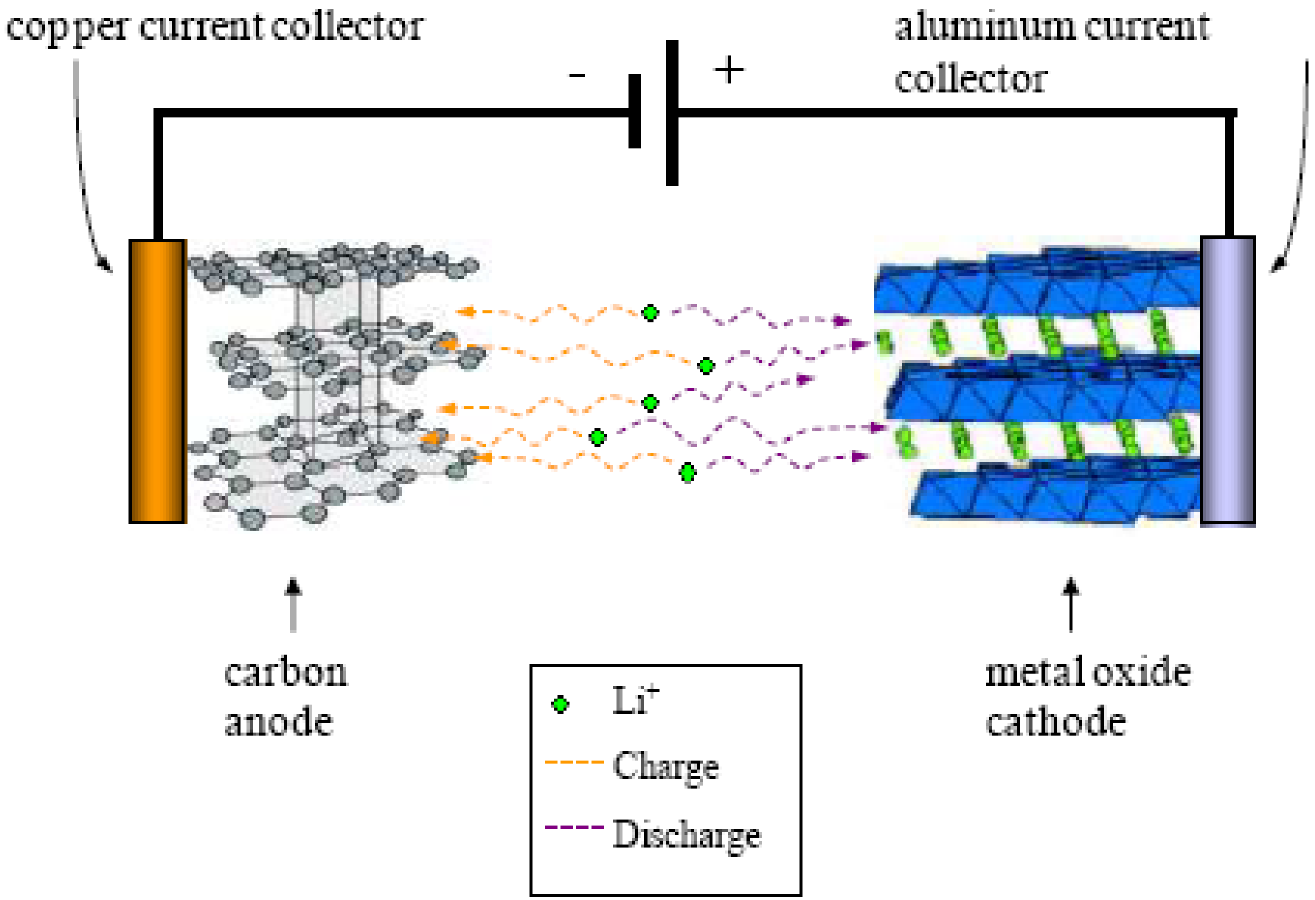
$H_2 + M \leftrightarrow MH_2$

$H_2 + 2OH^- \rightarrow 2H_2O + 2e^-$

$K^+ + H_2O \rightarrow OH^-$

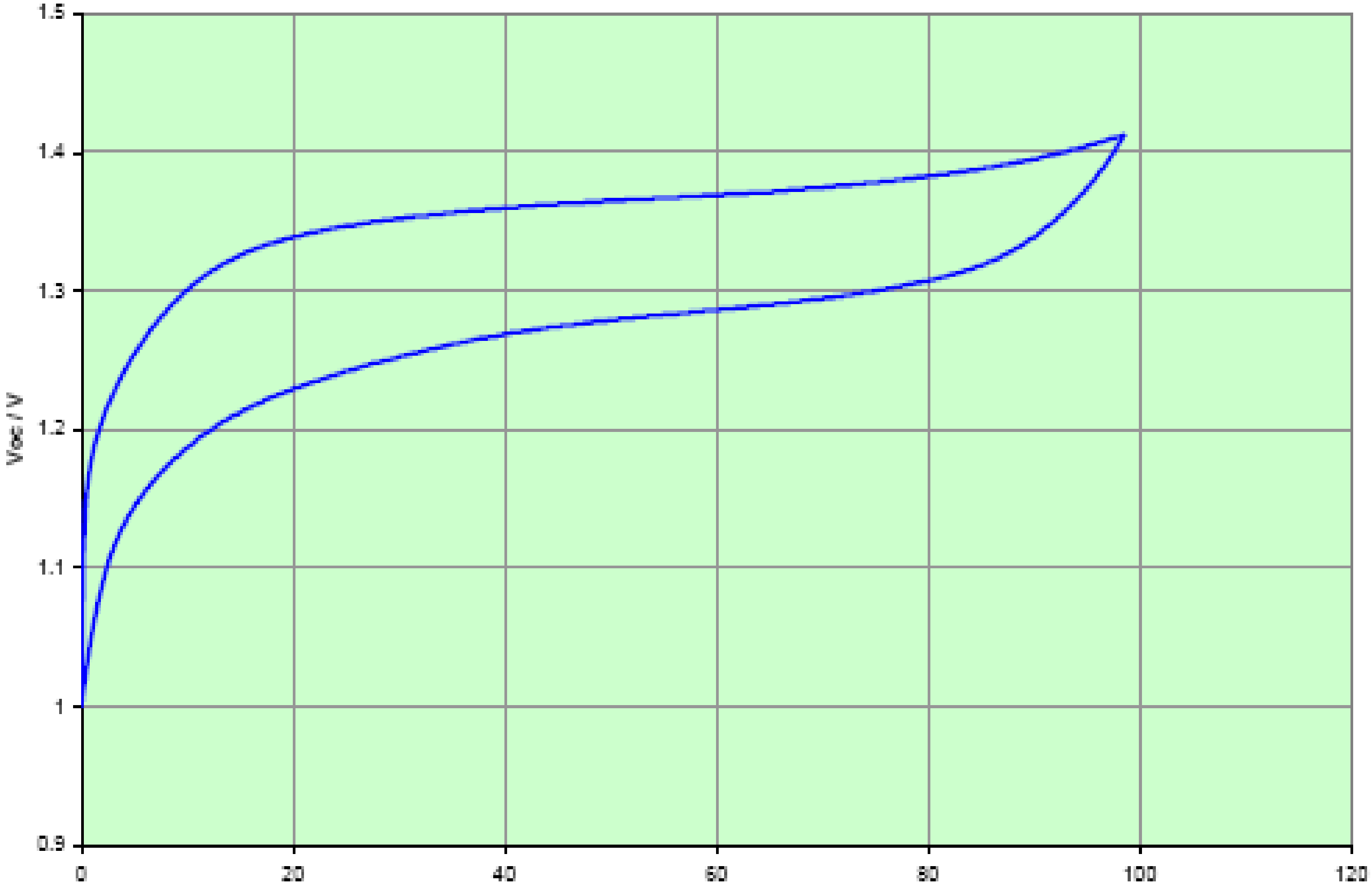
$2NiO(OH) + 2H_2O + 2e^- \rightarrow 2Ni(OH)_2 + 2OH^-$

Charge Flow in Li-Ion Battery



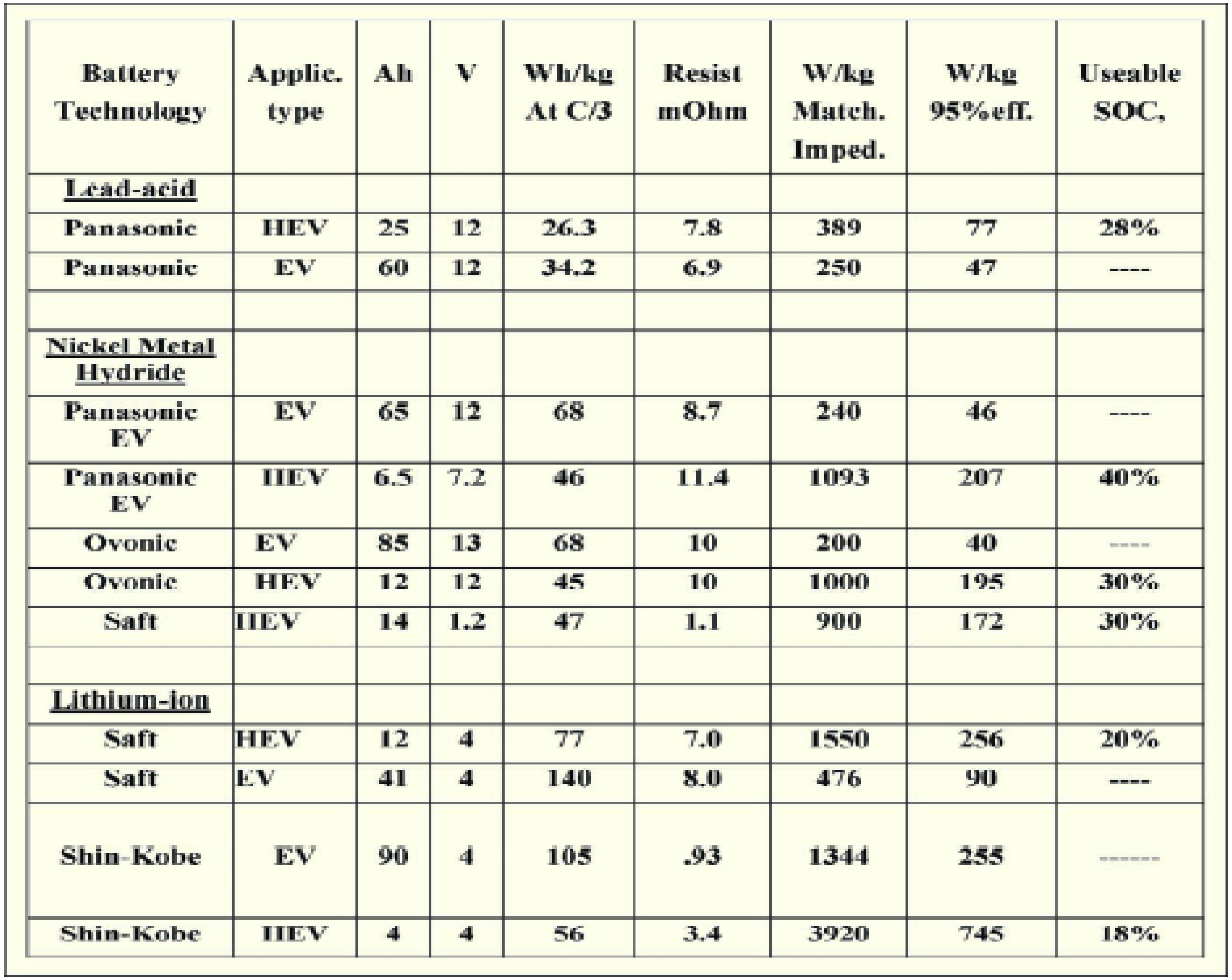
Steven Vance, Parallel-Cell Connection in Lithium-Ion Battery, Kettering University Senior Thesis, 12/08

Hysteresis Effect in NiMH Battery Cell



Steven Vance, Parallel-Cell Connection in Lithium-Ion Battery, Kettering University Senior Thesis, 12/08

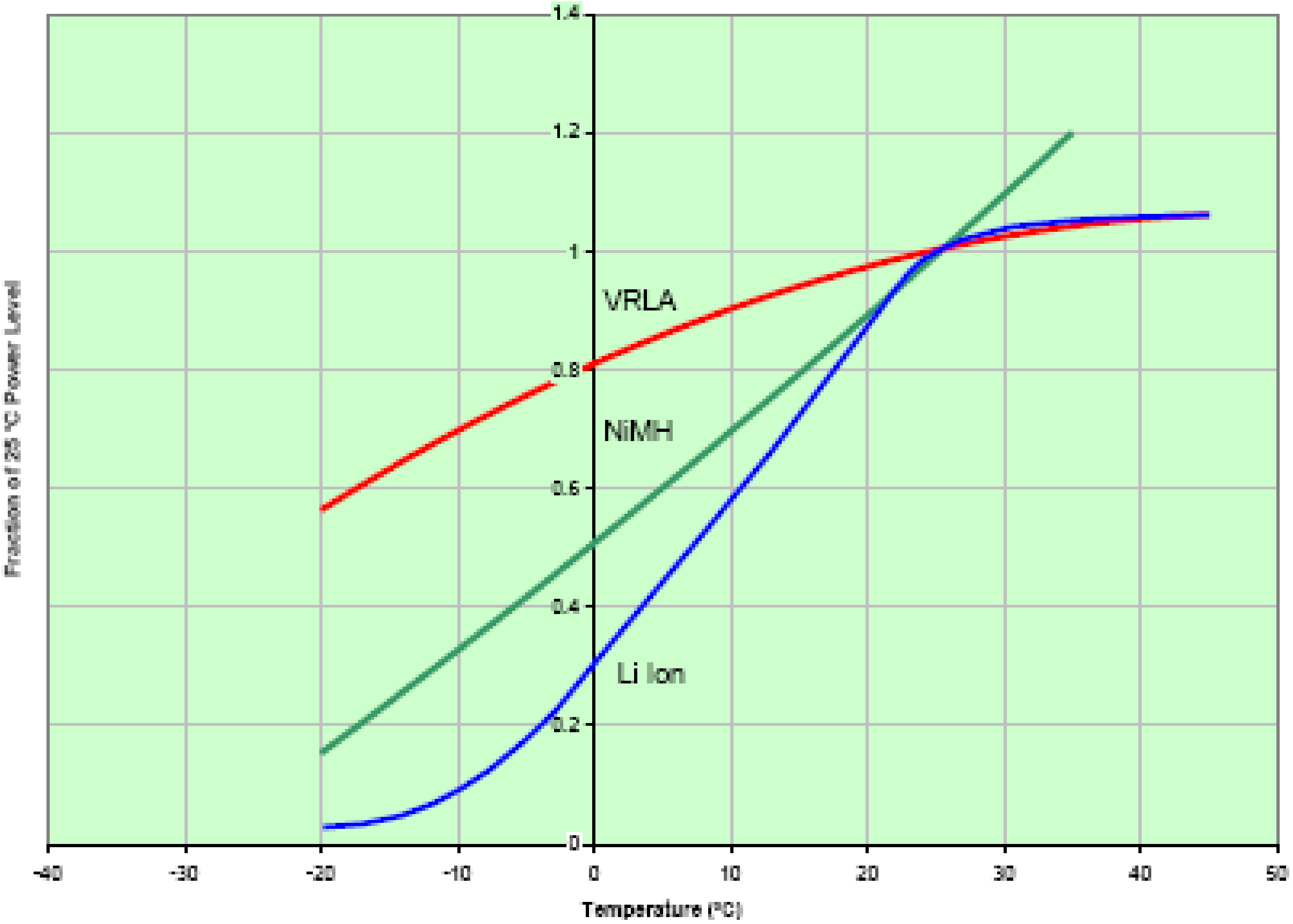
Comparison of Performance of Battery Types Used in HEV



Battery Technology	Applic. type	Ah	V	Wh/kg At C/3	Resist mOhm	W/kg Match. Imped.	W/kg 95%eff.	Useable SOC.
Lead-acid								
Panasonic	HEV	25	12	26.3	7.8	389	77	28%
Panasonic	EV	60	12	34.2	6.9	250	47	----
Nickel Metal Hydride								
Panasonic EV	EV	65	12	68	8.7	240	46	----
Panasonic EV	HEV	6.5	7.2	46	11.4	1093	207	40%
Ovonic	EV	85	13	68	10	200	40	----
Ovonic	HEV	12	12	45	10	1000	195	30%
Saft	HEV	14	1.2	47	1.1	900	172	30%
Lithium-ion								
Saft	HEV	12	4	77	7.0	1550	256	20%
Saft	EV	41	4	140	8.0	476	90	----
Shin-Kobe	EV	90	4	105	.93	1344	255	------
Shin-Kobe	HEV	4	4	56	3.4	3920	745	18%

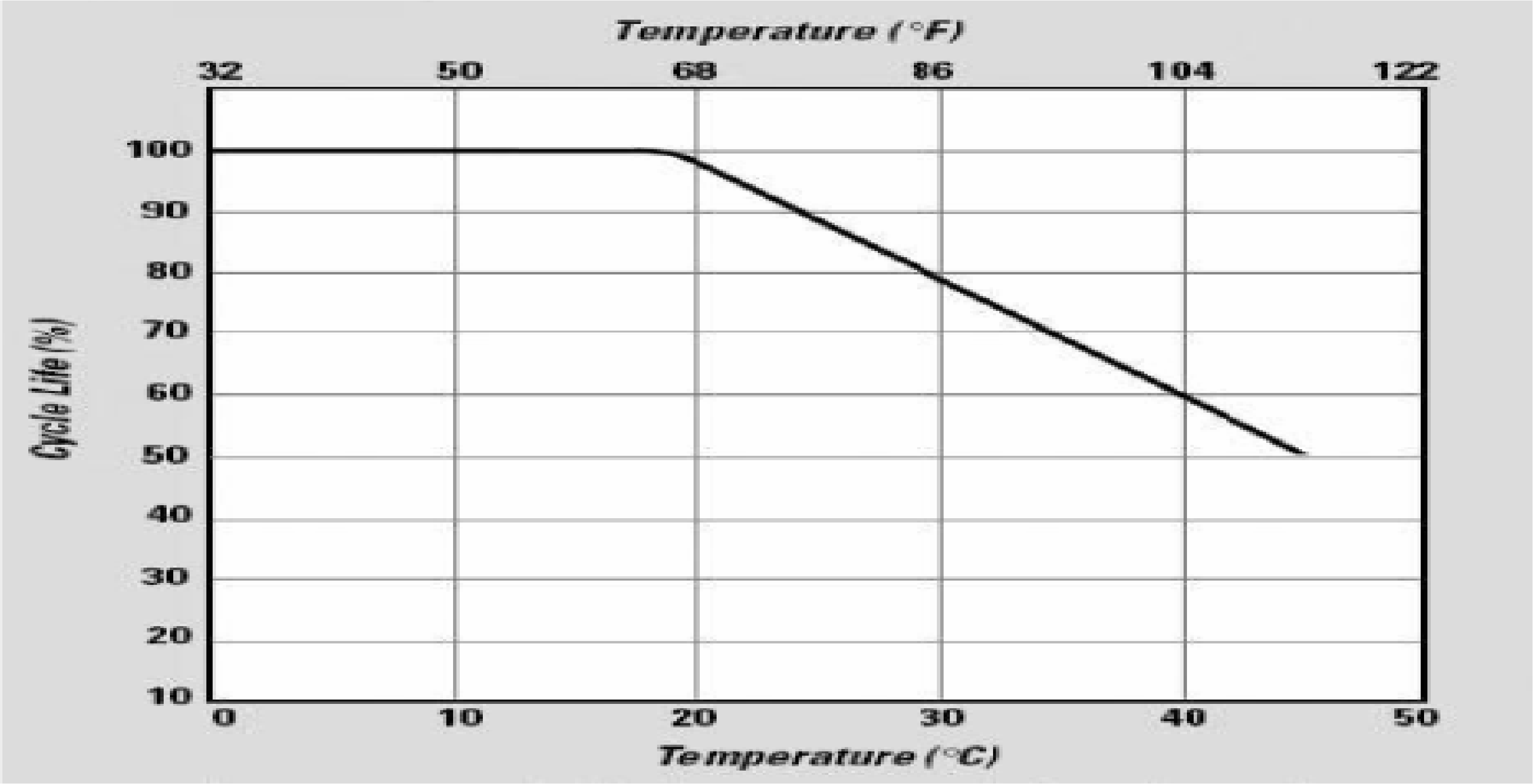
Andrew F. Burke, *Batteries and Ultracapacitors for Electric, Hybrid, and Fuel Cell Vehicles*, Proceedings of the IEEE, April, 2007.

Battery Power as Function of Temperature



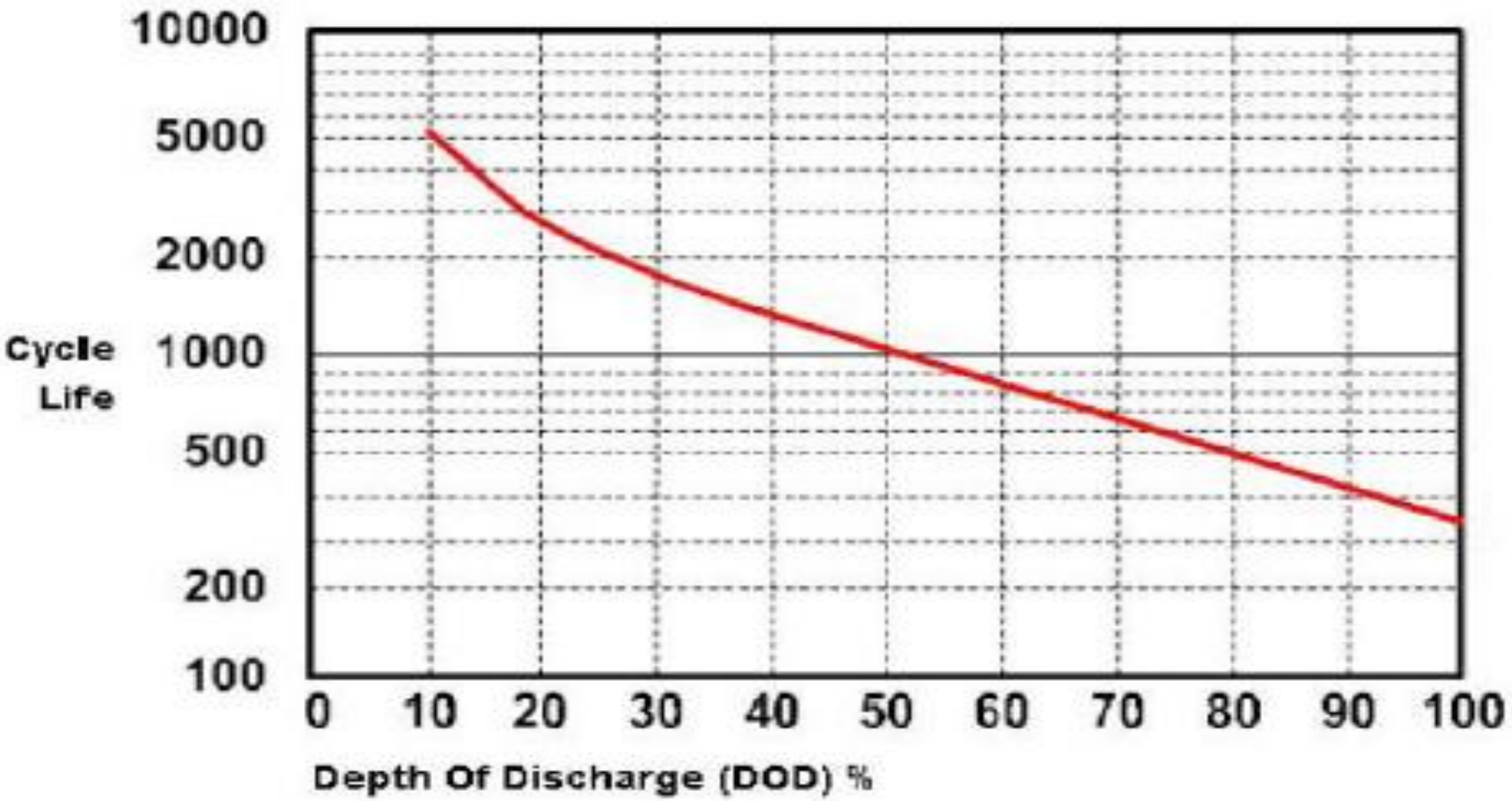
Steven Vance, Parallel-Cell Connection in Lithium-Ion Battery, Kettering UniversitySenior Thesis, 12/08

Effect of Temperature on NiMH Battery Performance



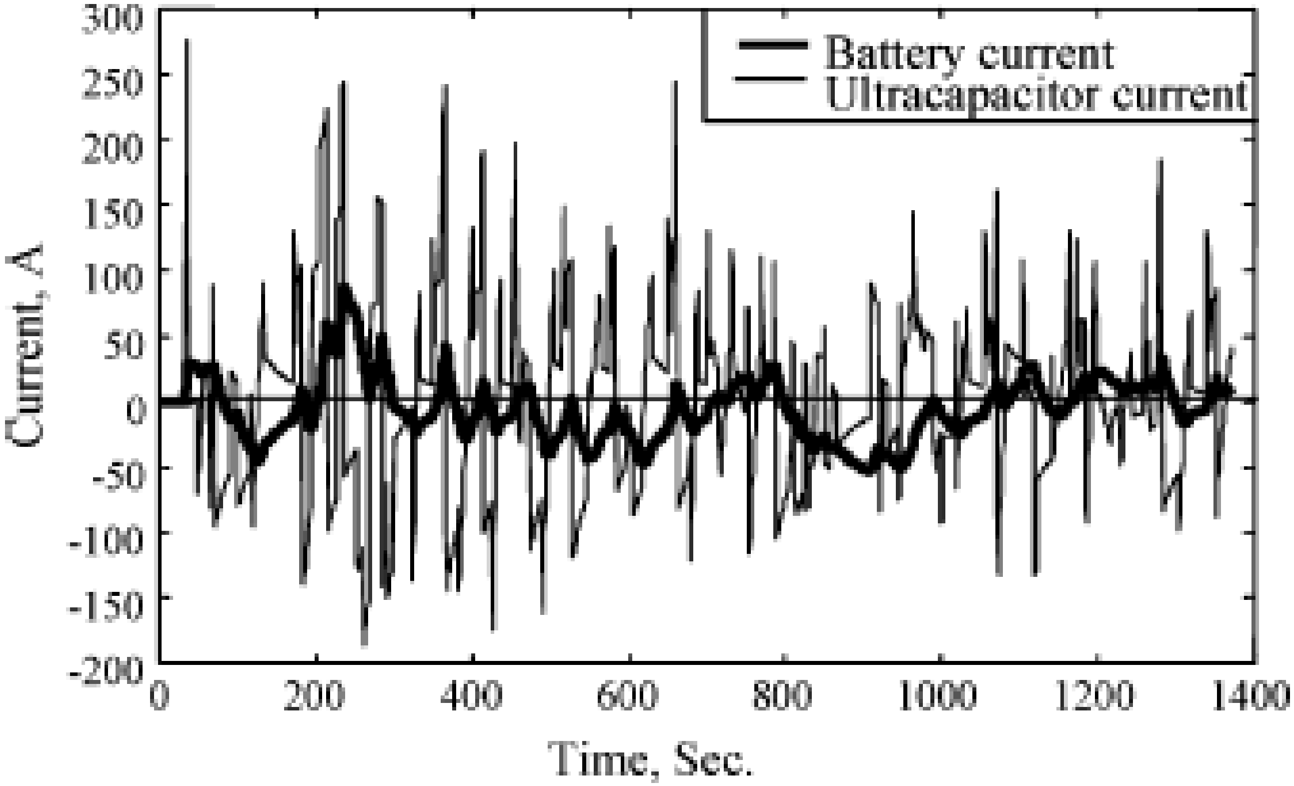
L. Serraro, Z. Chehab, Y. Guezennec and G. Rizzoni, *An Aging Model fo NI-MH Batteries for Hybrid Electric Vehicles*, IEEE VTS Vehicle Power and Propulsion Conference, July, 2005.

Dependence of NiMH Cycle Life on Depth of Discharge



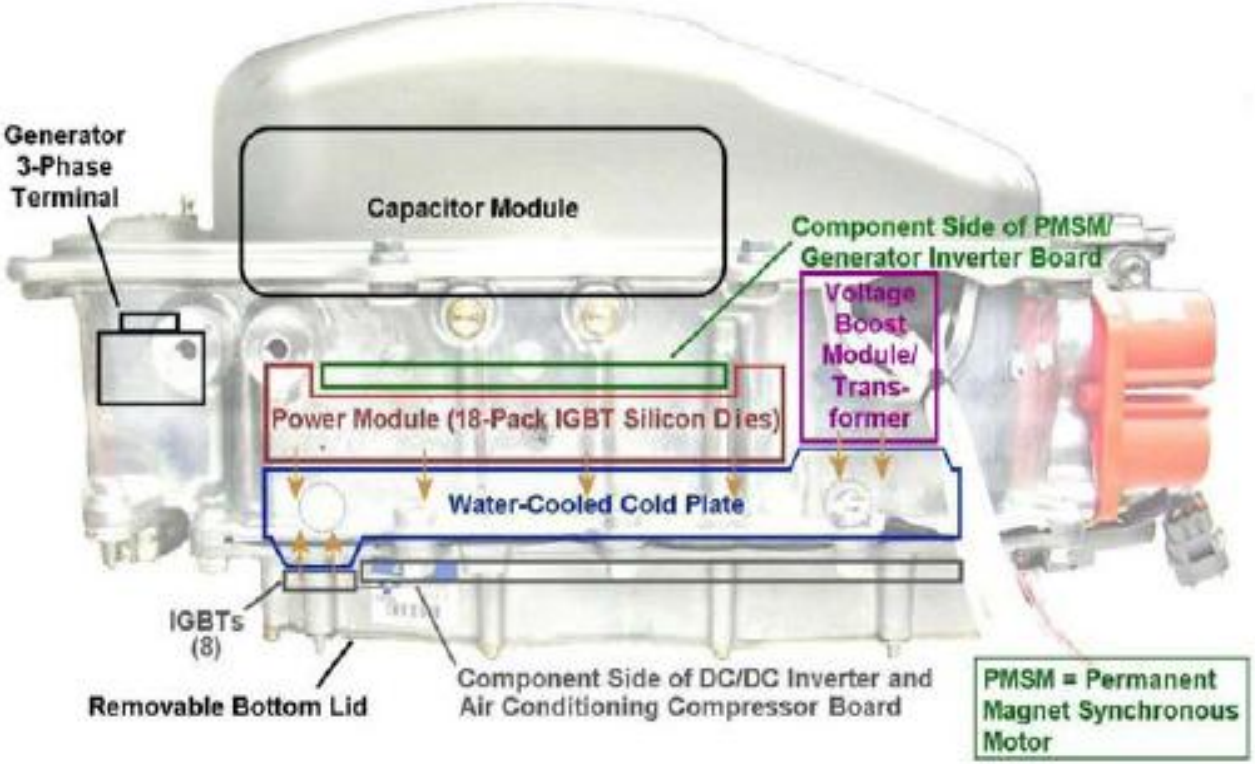
L. Serraro, Z. Chehab, Y. Guezennec and G. Rizzoni, *An Aging Model fo NI-MH Batteries for Hybrid Electric Vehicles*, IEEE VTS Vehicle Power and Propulsion Conference, July, 2005.

Ultracapacitors Reduce Battery Surge Currents and Increase Battery Life



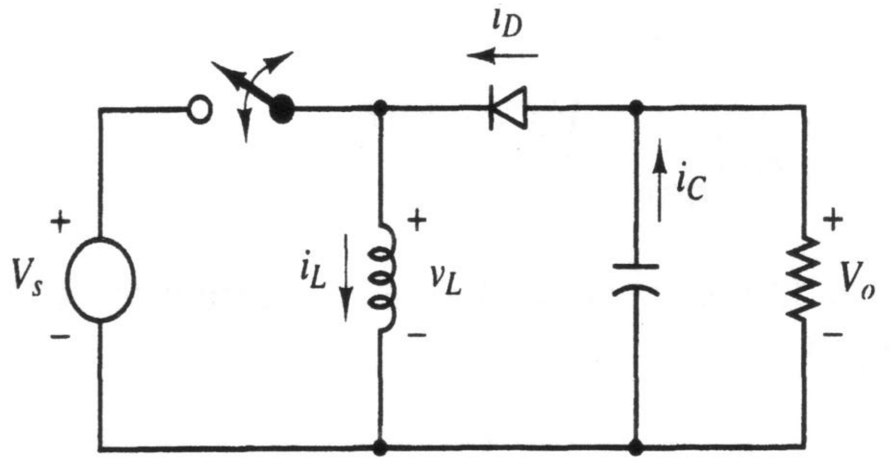
Andrew F. Burke, ***Batteries and Ultracapacitors for Electric, Hybrid, and Fuel Cell Vehicles*****,** **Proceedings of the IEEE, April, 2007.**

Packaging of Prius Power Electronics



Staunton, Ayers, Marlino, Chiasson,& Burress, *Evaluation of 2004 Toyota Prius Hybrid Electric Drive System*, ORNL/TM-2006/423, May, 2006.

Buck-Boost DC-DC Converter- Continuous Mode

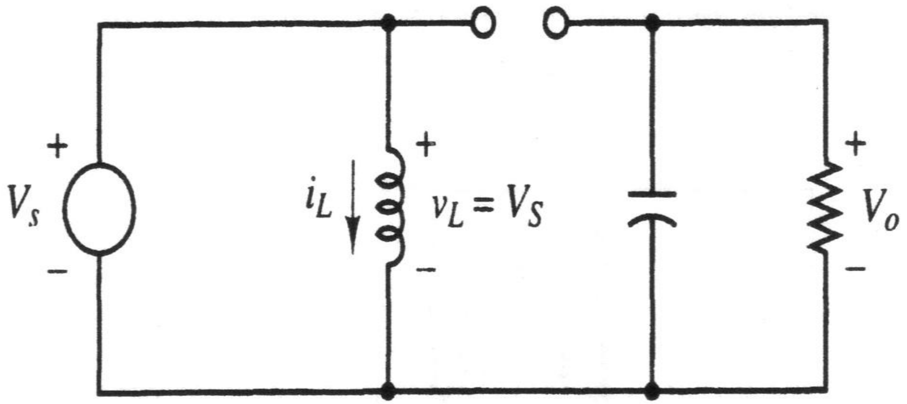


$$\frac{V_o}{V_s} = -\frac{D}{1-D}$$

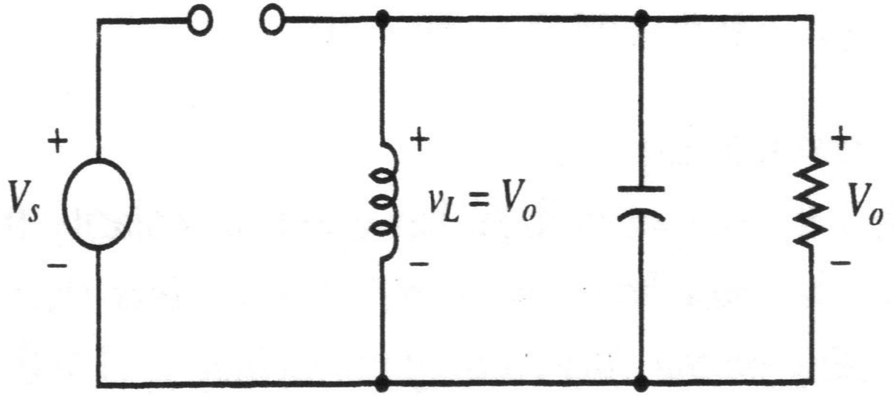
$$\frac{\Delta V_o}{V_o} = \frac{D}{RCf}$$

$$L_{\min} = \frac{(1-D)^2 R}{2f}$$

Note Ripple Voltage



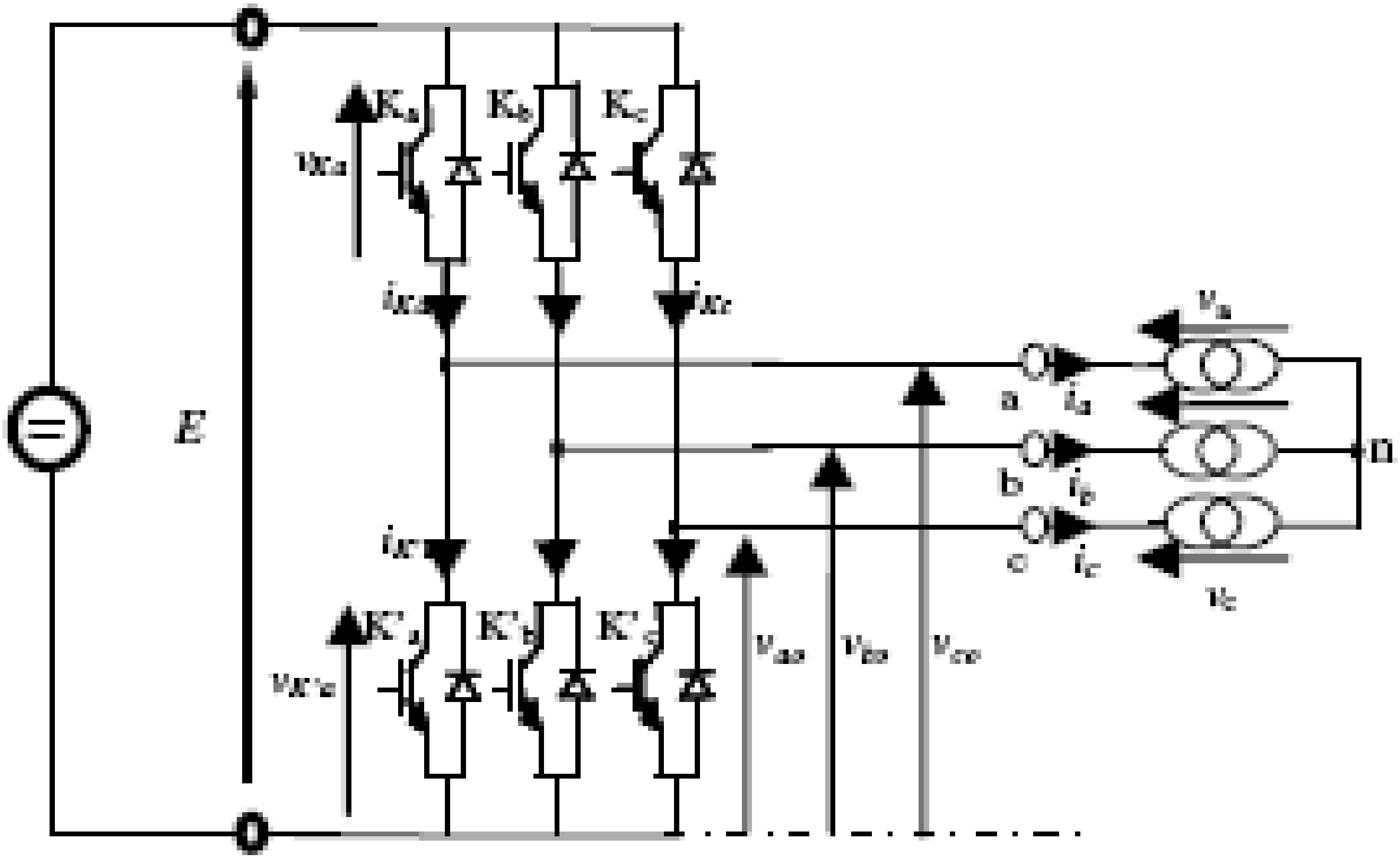
Switch Closed



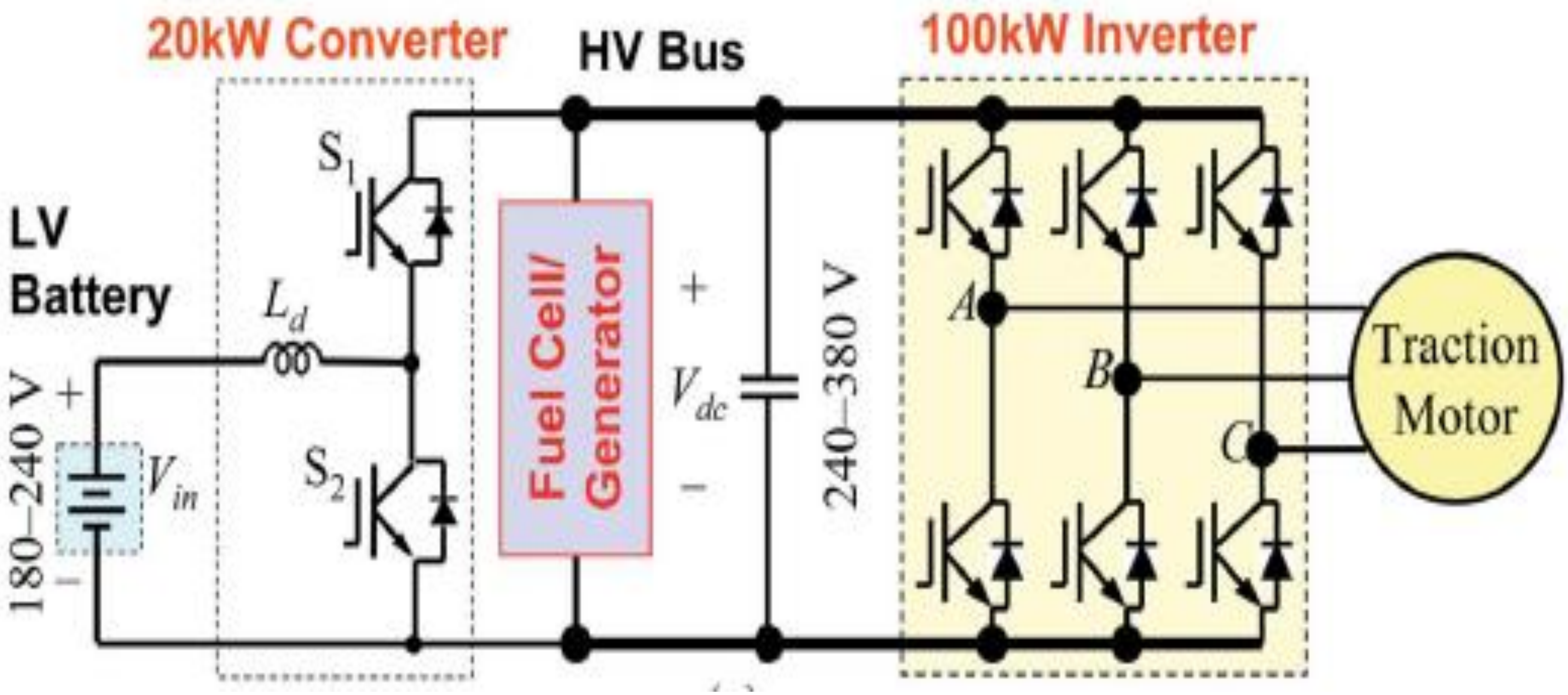
Switch Open

Hart, p. 201

Inverter Schematic

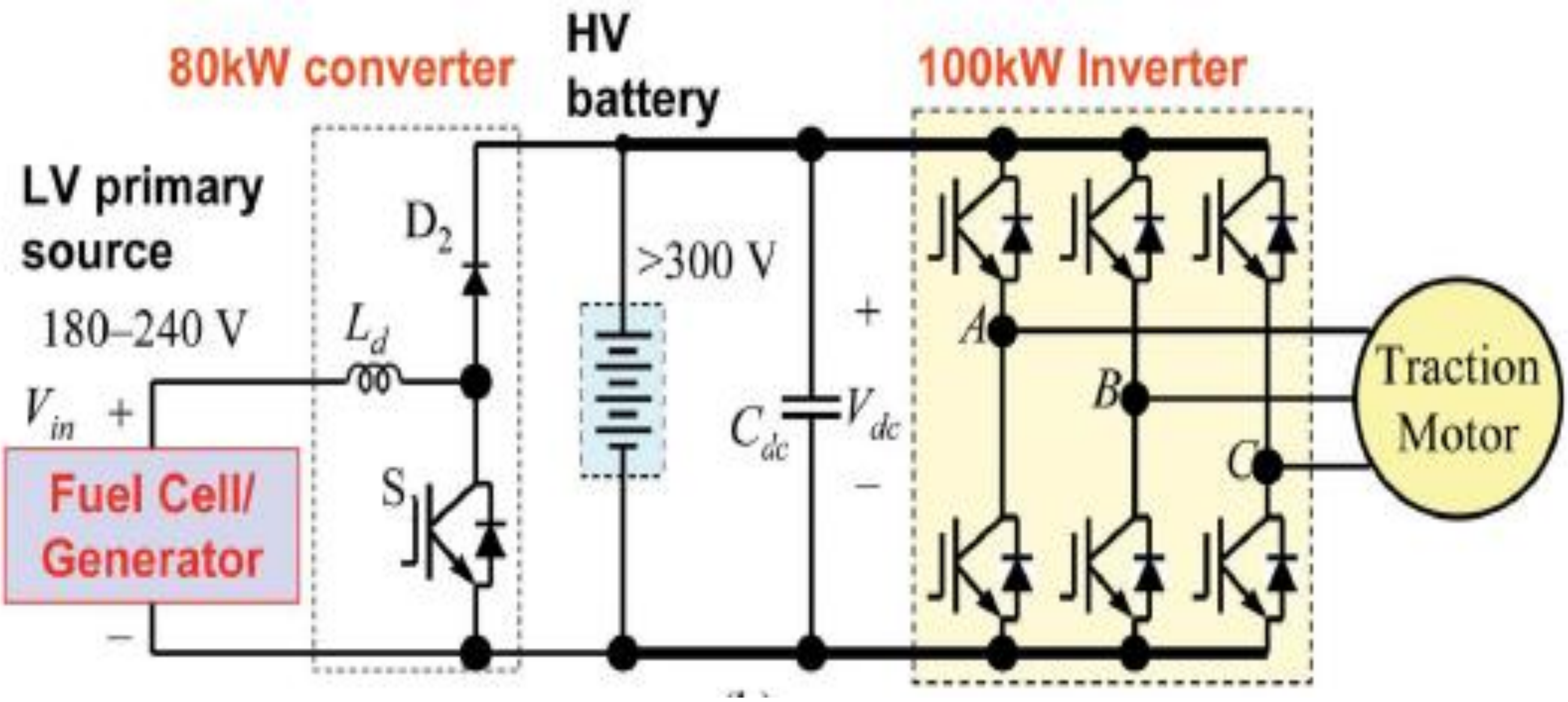


Low Voltage Battery, High Voltage Fuel Cell



Sih-sheng Lai and Douglas J. Nelson, *Energy Management in Hybrid Electric and Fuel Cell Vehicles*, Proceedings of the IEEE, April, 2007.

Low Voltage Fuel Cell, High Voltage Battery



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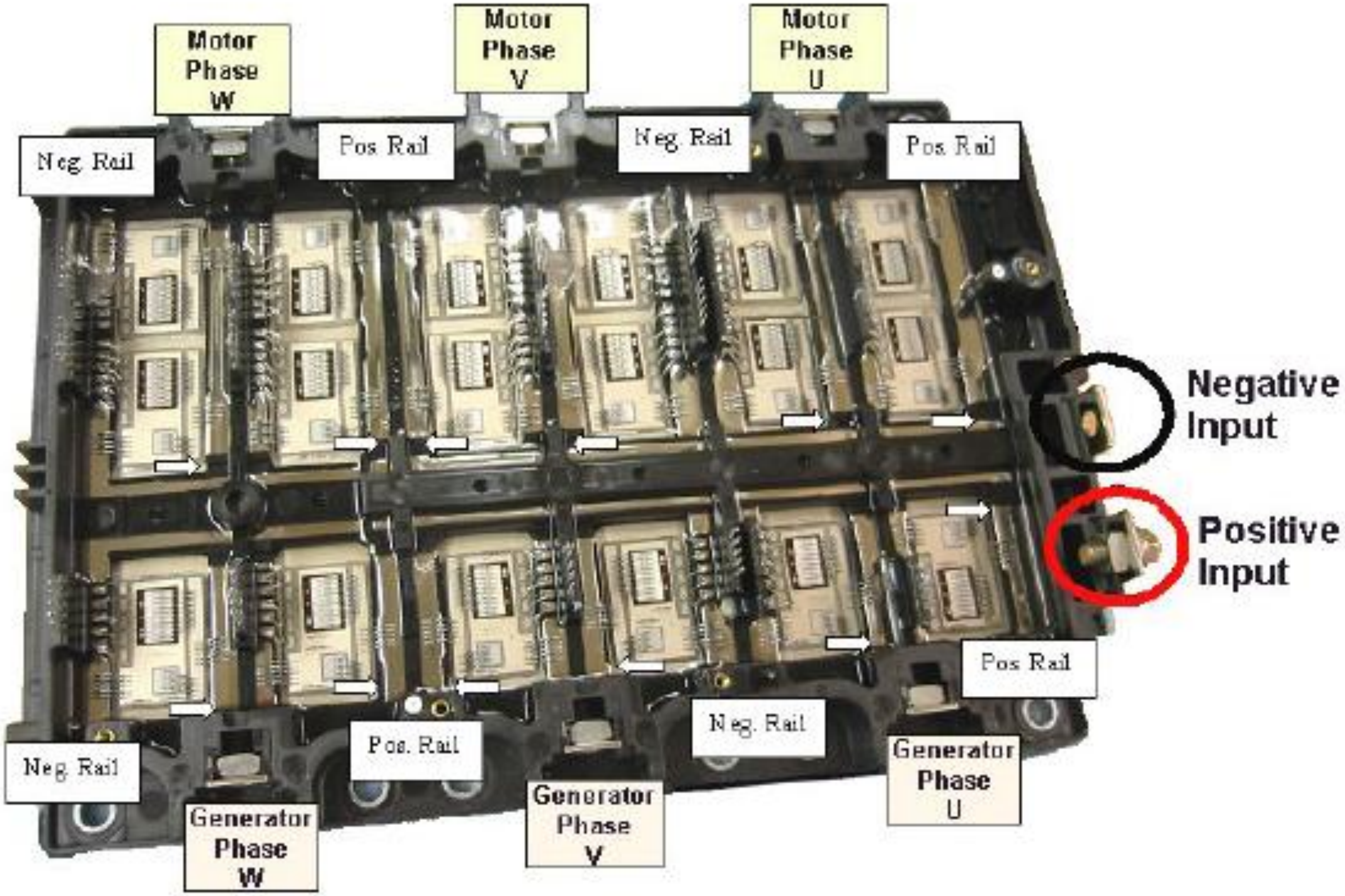
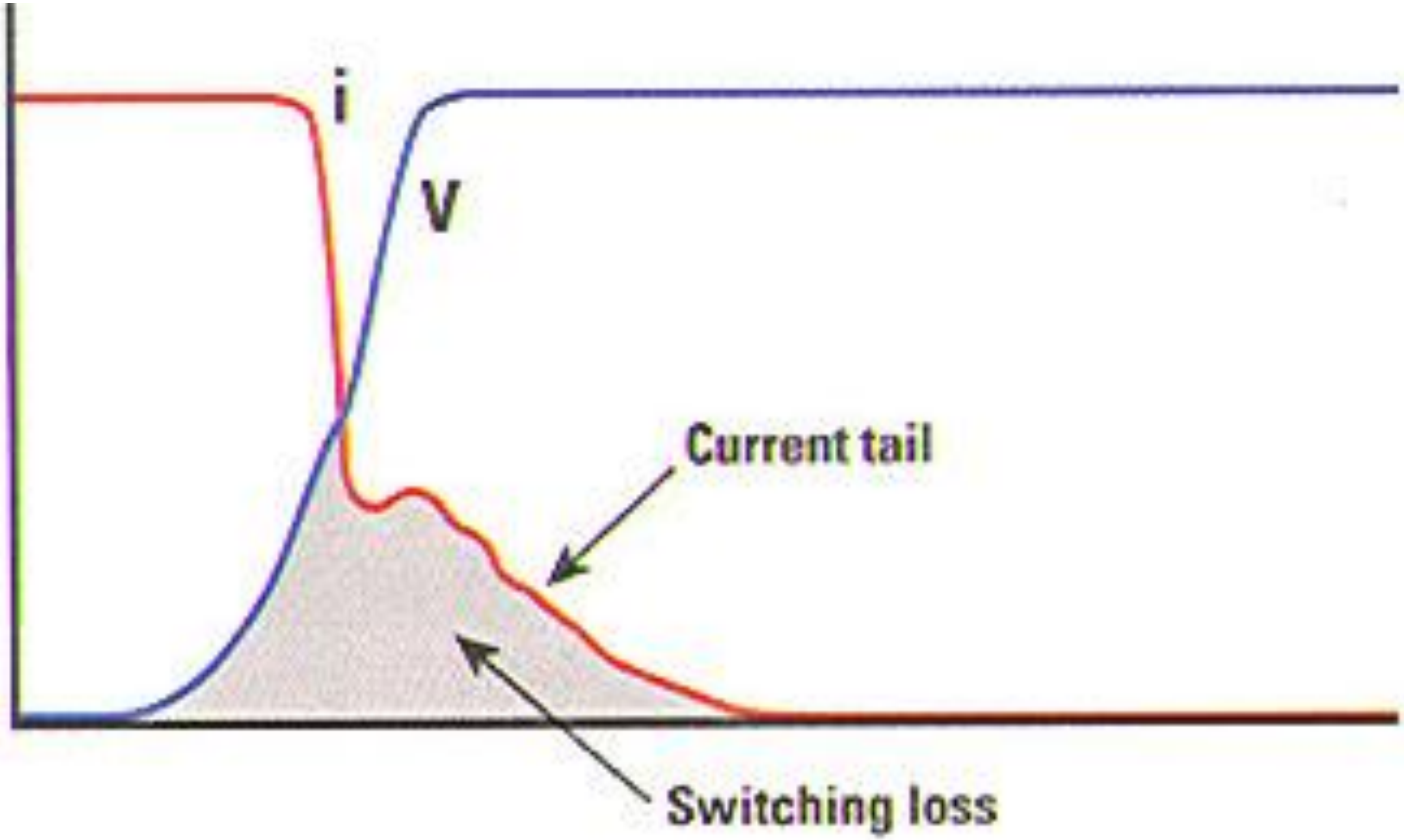
Prius Inverter IGBT/Diode Package

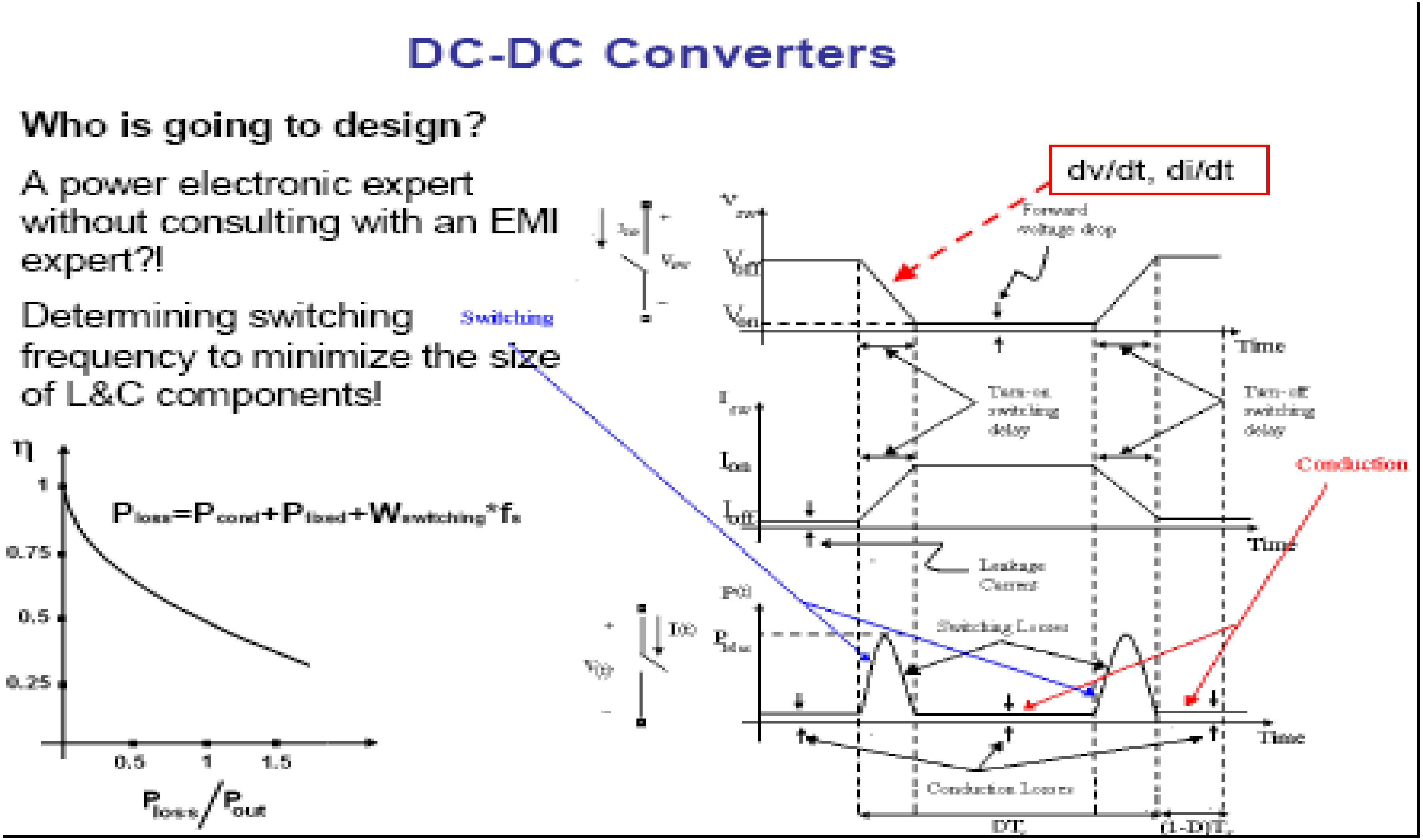


Staunton, Ayers, Marlino, Chiasson,& Burress, *Evaluation of 2004 Toyota Prius Hybrid Electric Drive System*, ORNL/TM-2006/423, May, 2006.

Time Dependence of IGBT Switch Turn-Off



Switching Losses



DC-DC Converters

Who is going to design?

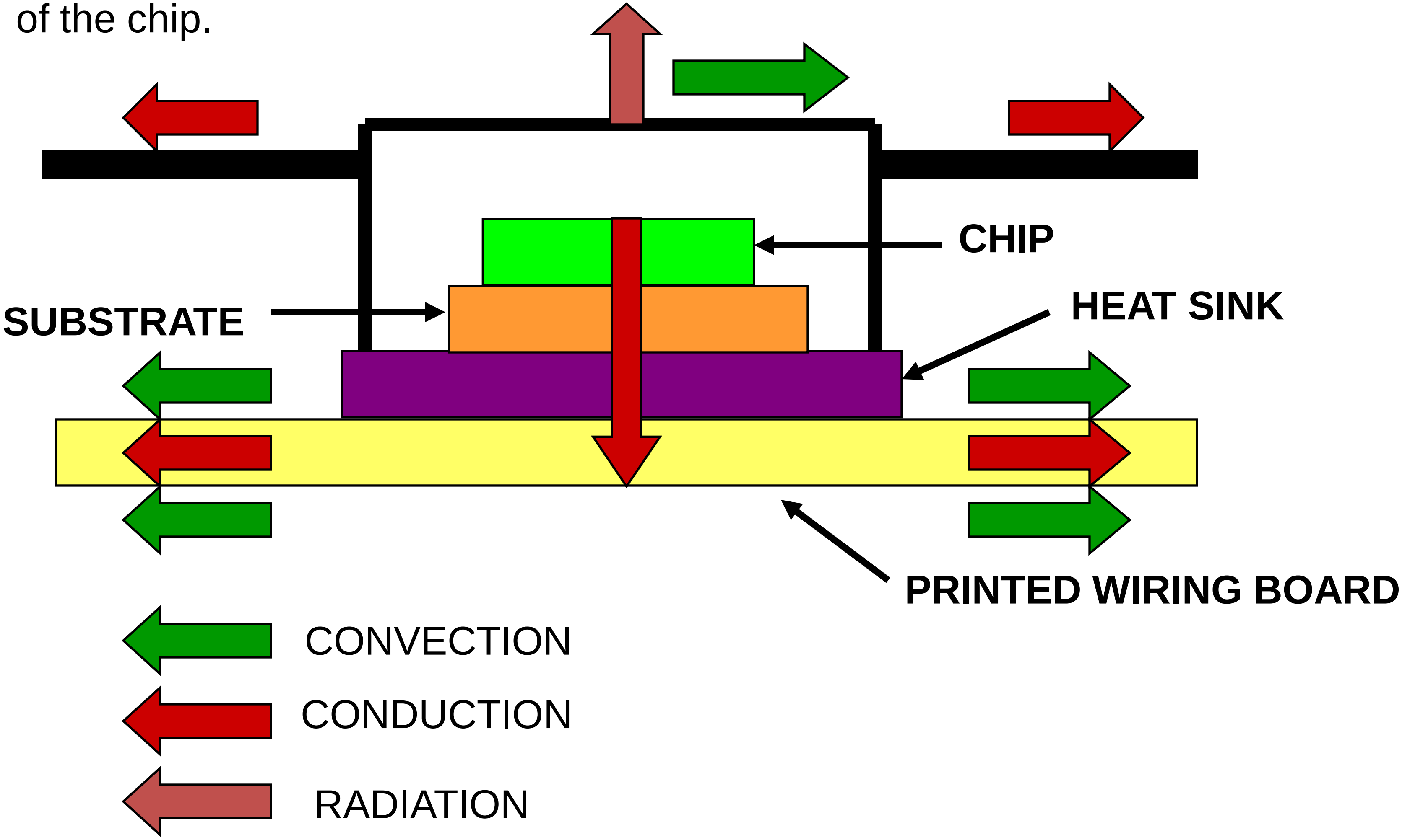
A power electronic expert without consulting with an EMI expert?!

Determining switching frequency to minimize the size of L&C components!

$P_{loss}=P_{cond}+P_{fixed}+W_{switching}*f_s$

Heat Removal Mechanisms from Chip Without Special Cooling

In ICs with conventional packaging, the heat generation is at the top surface of the chip.



CHIP

SUBSTRATE

HEAT SINK

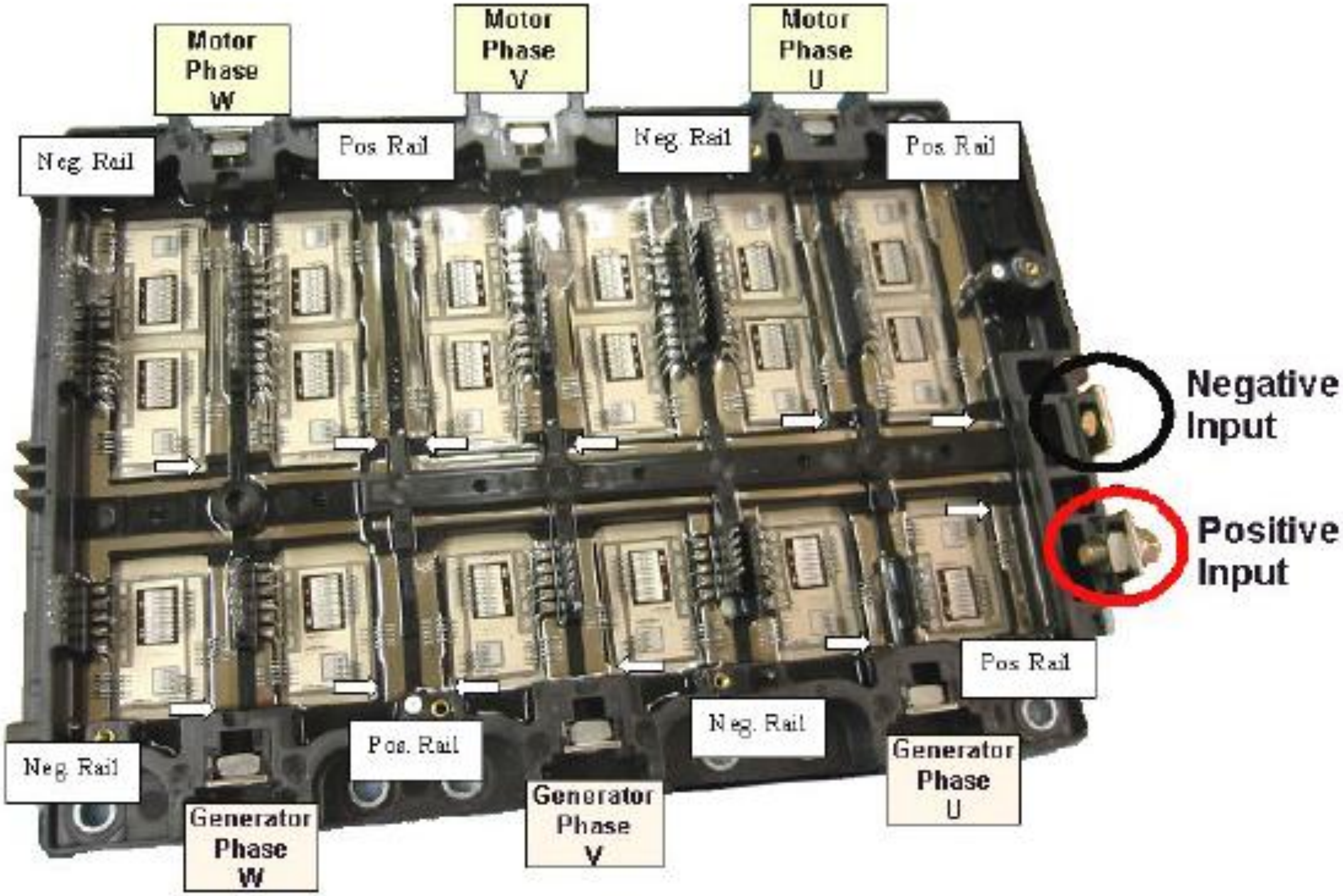
PRINTED WIRING BOARD

CONVECTION

CONDUCTION

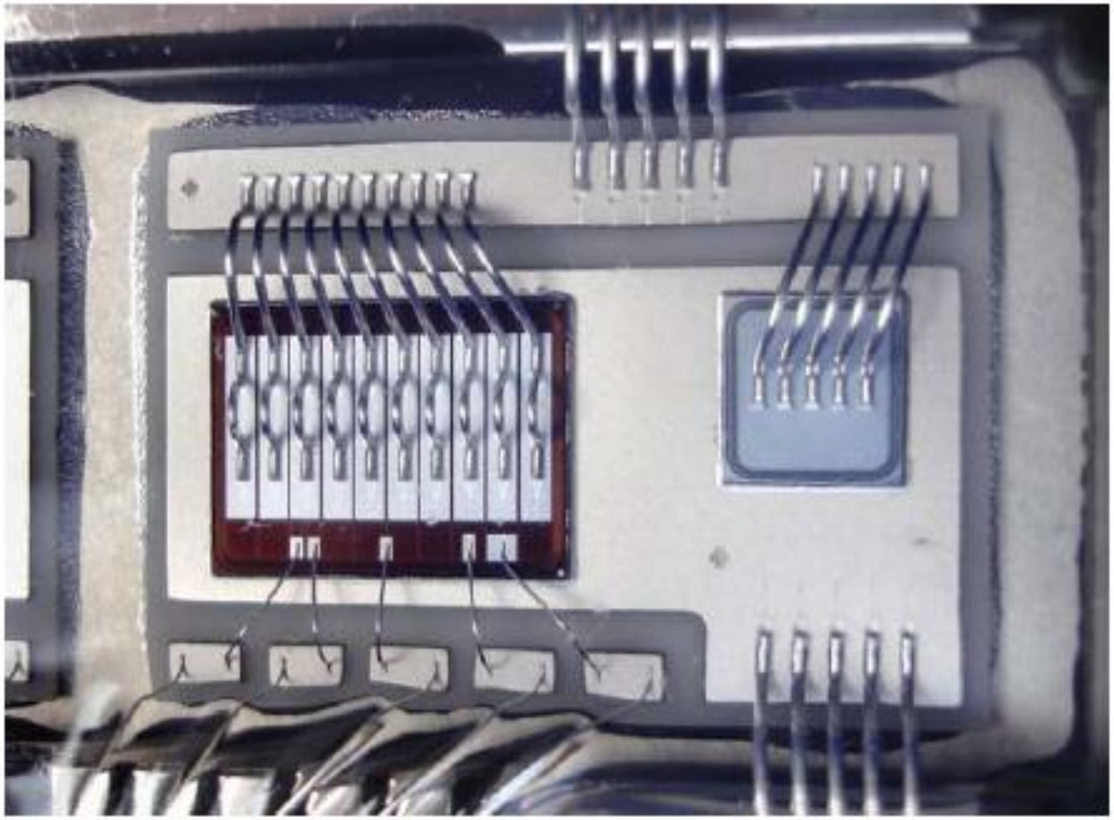
RADIATION

Prius Inverter IGBT/Diode Package



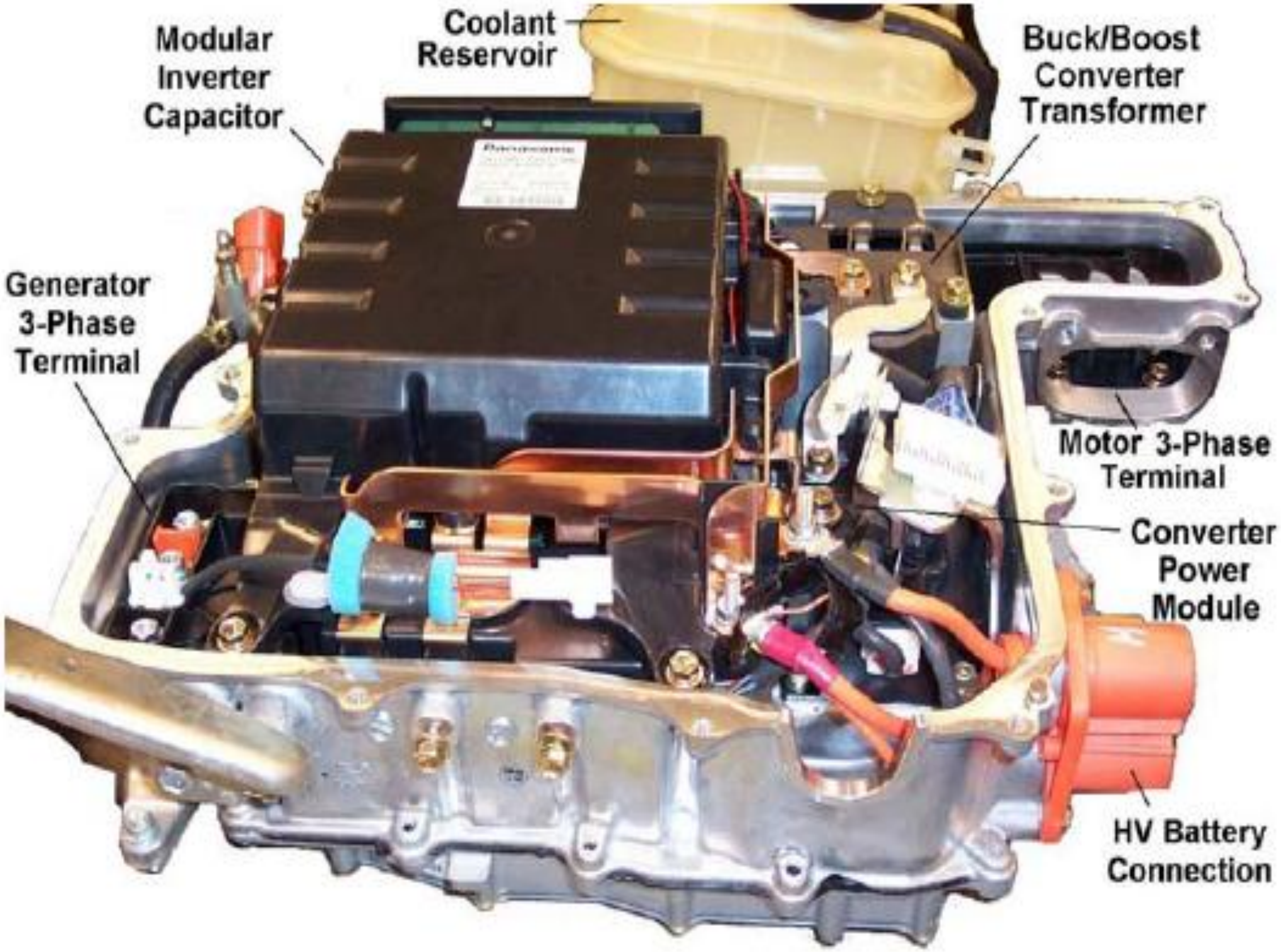
Staunton, Ayers, Marlino, Chiasson,& Burress, *Evaluation of 2004 Toyota Prius Hybrid Electric Drive System*, ORNL/TM-2006/423, May, 2006.

IGBT-Diode Pair



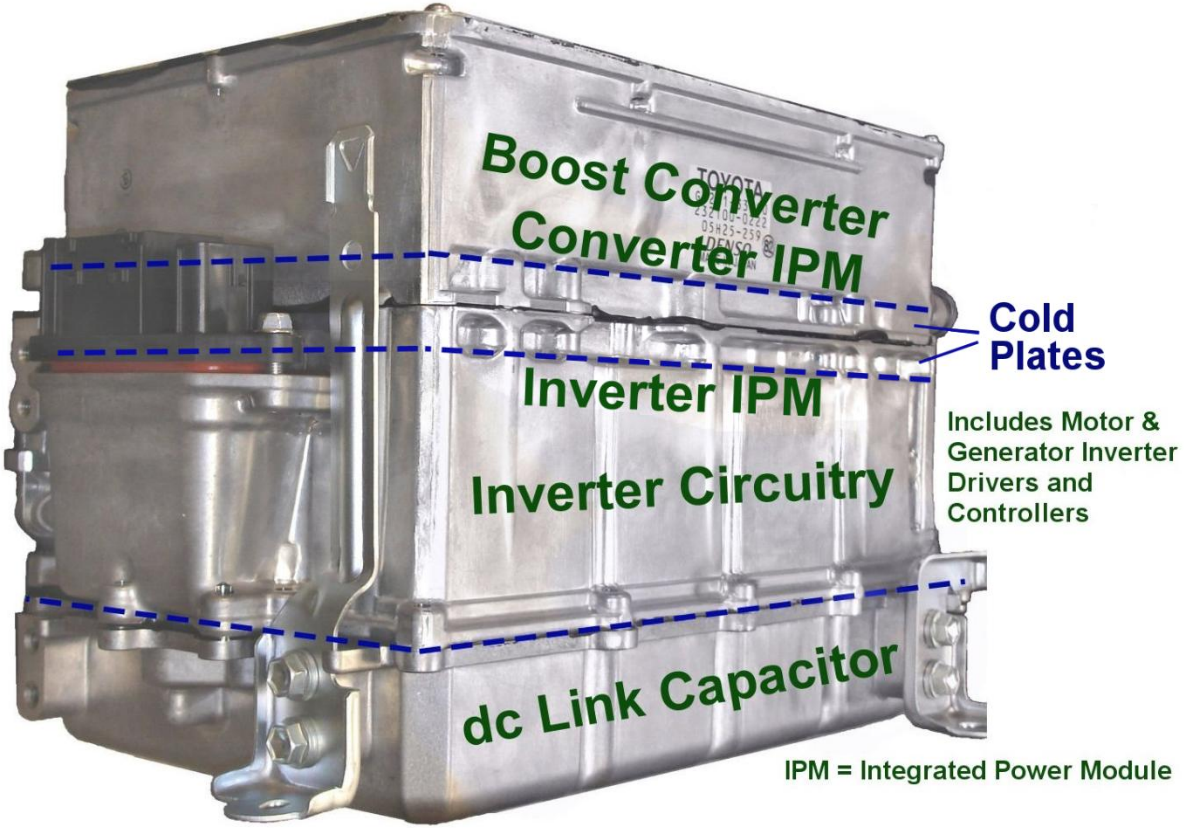
Staunton, Ayers, Marlino, Chiasson,& Burress, *Evaluation of 2004 Toyota Prius Hybrid Electric Drive System*, ORNL/TM-2006/423, May, 2006.

Overview of Packaging in Prius Inverter/Converter



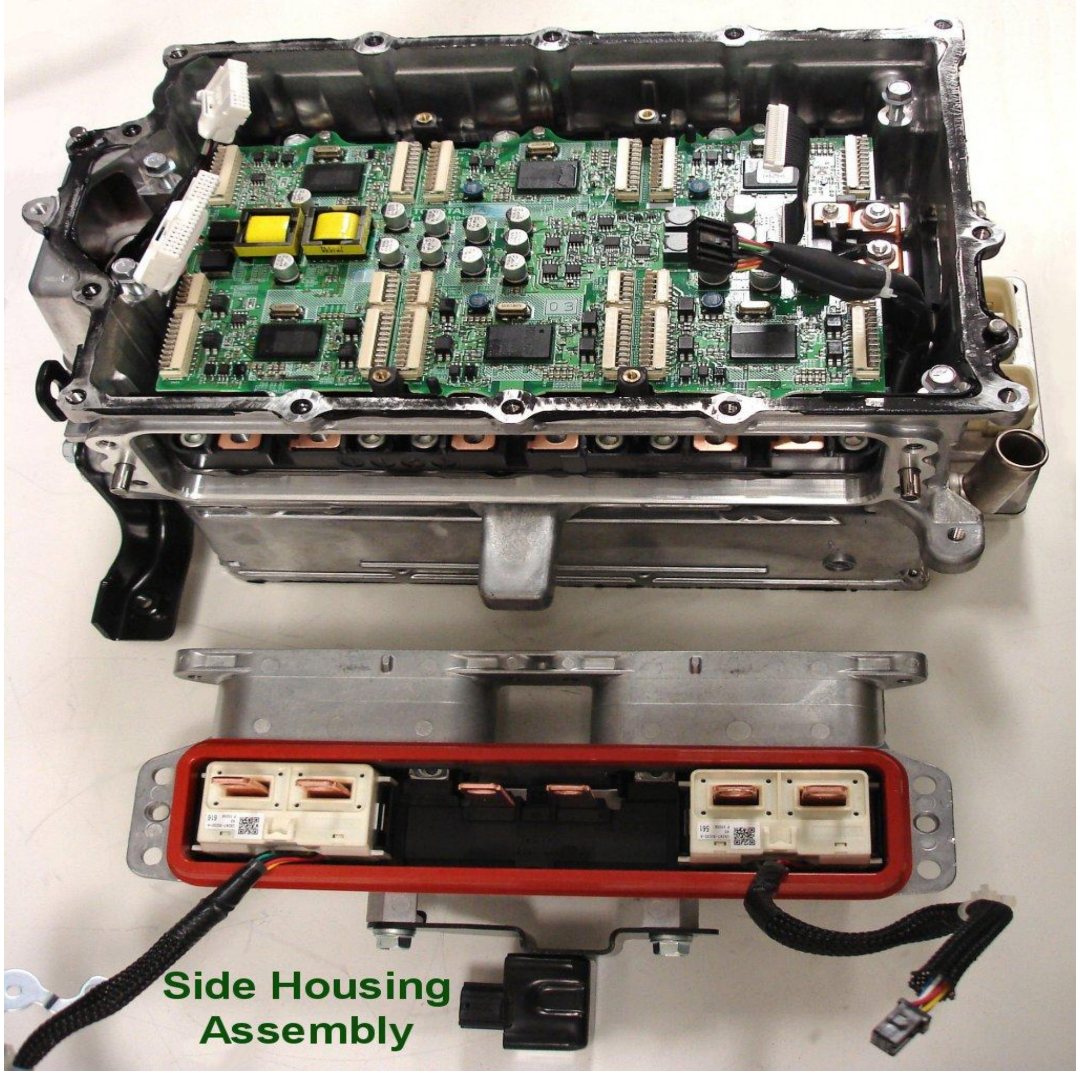
Staunton, Ayers, Marlino, Chiasson,& Burress, *Evaluation of 2004 Toyota Prius Hybrid Electric Drive System*, ORNL/TM-2006/423, May, 2006.

Toyota Camry Hybrid Integrated Power Module



IPM = Integrated Power Module

Camry HEV Inverters with Top Circuit Board and Side Housing Removed

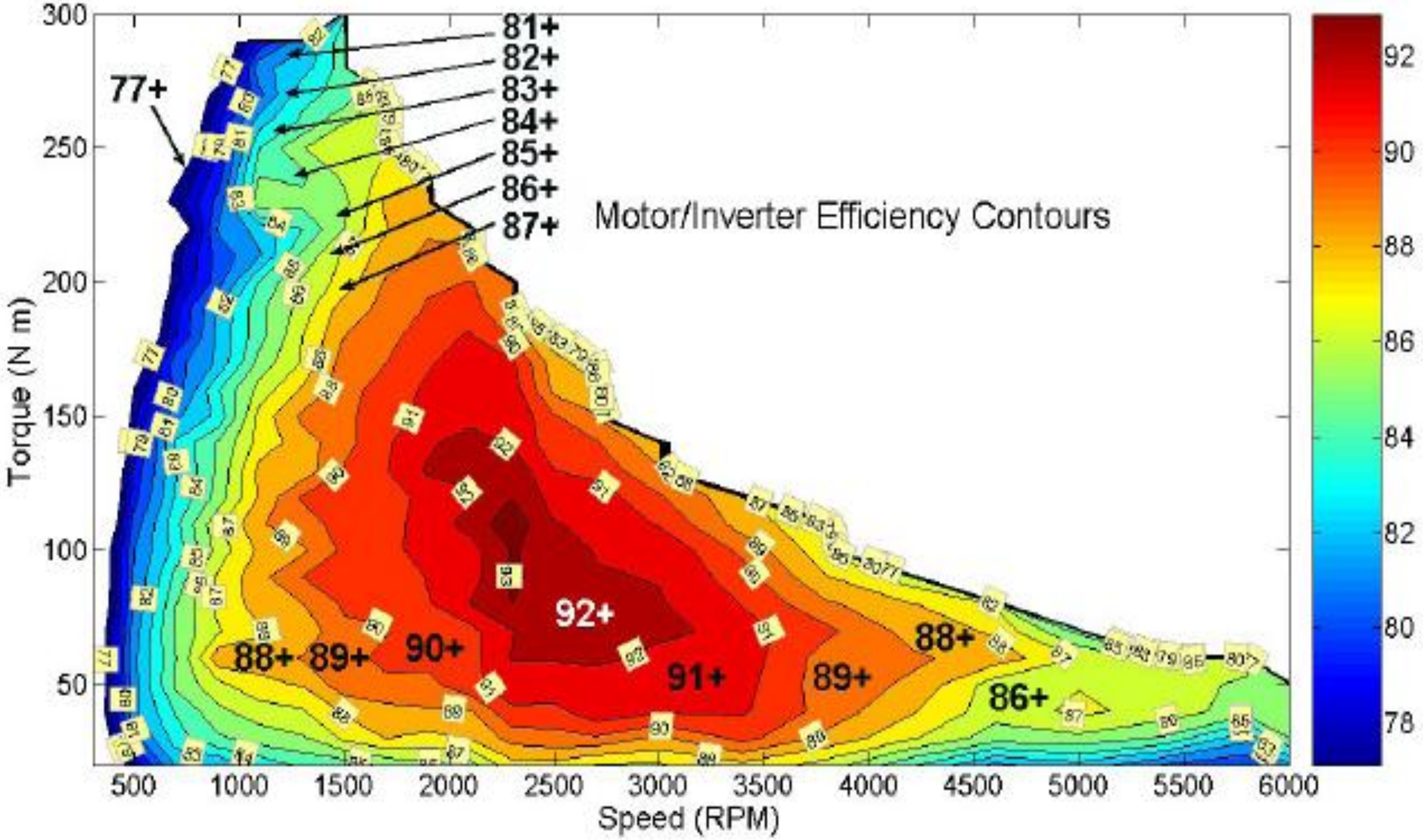


Toyota HEV Packaging Innovation: Comparison of Prius and Camry Inverters and Converters

Parameter	**Camry**	**Prius**
Motor inverter peak specific power (without converter), kW/kg	105/~7.5=**~14**	50/8.8= **5.7**
Motor inverter peak power density (without converter), kW/L	105/~6 =~**17.5**	50/8.7=**5.7**
Buck/boost converter specific power, kW/kg	30/~7.6=**~3.9**	20/4.8=**4.2**
Buck/boost converter power density, kW/L	30/2.9=**10**	20/5.9=**3.4**[1]

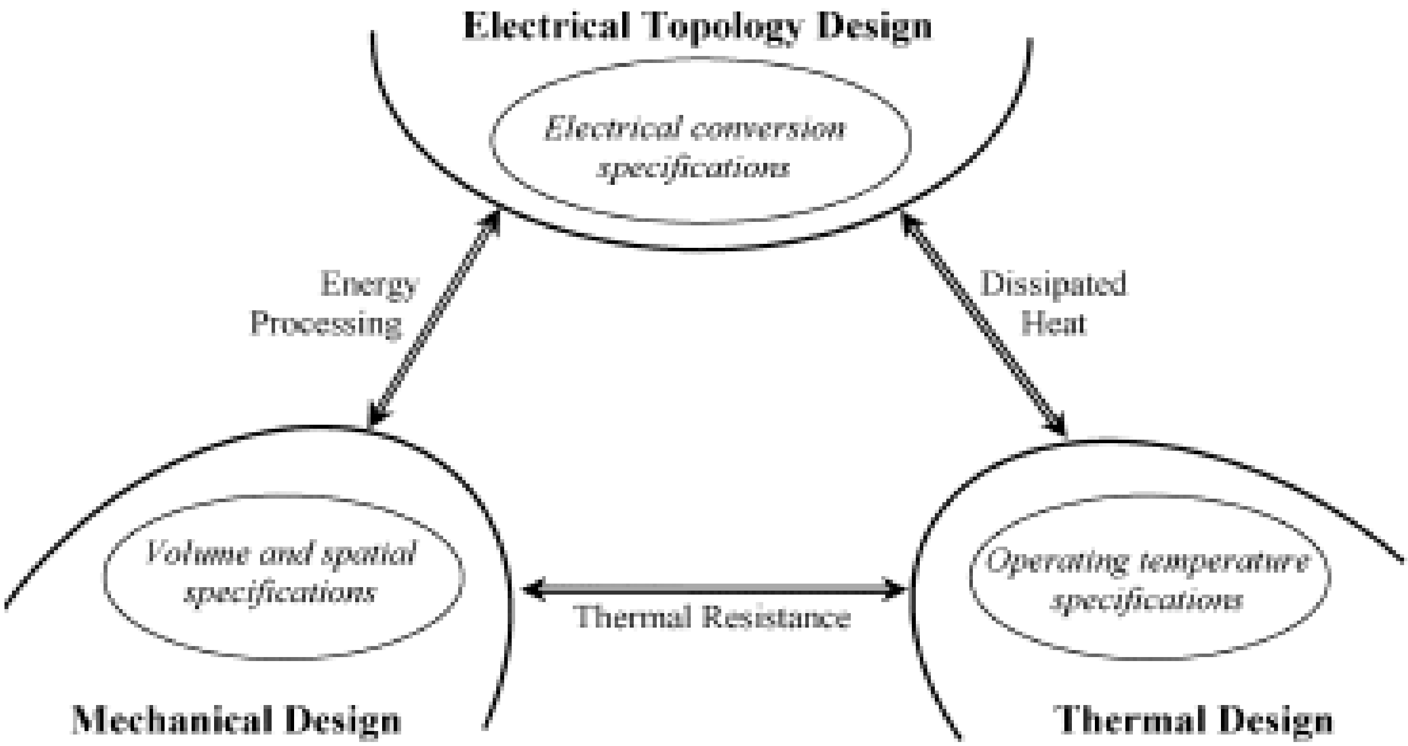
[1] This low converter power density is largely the result of the non-optimal packaging of the converter filter capacitor in the Prius inverter/converter housing

Toyota Electric Drive Innovation: Prius Combined Inverter/Motor Efficiency Map

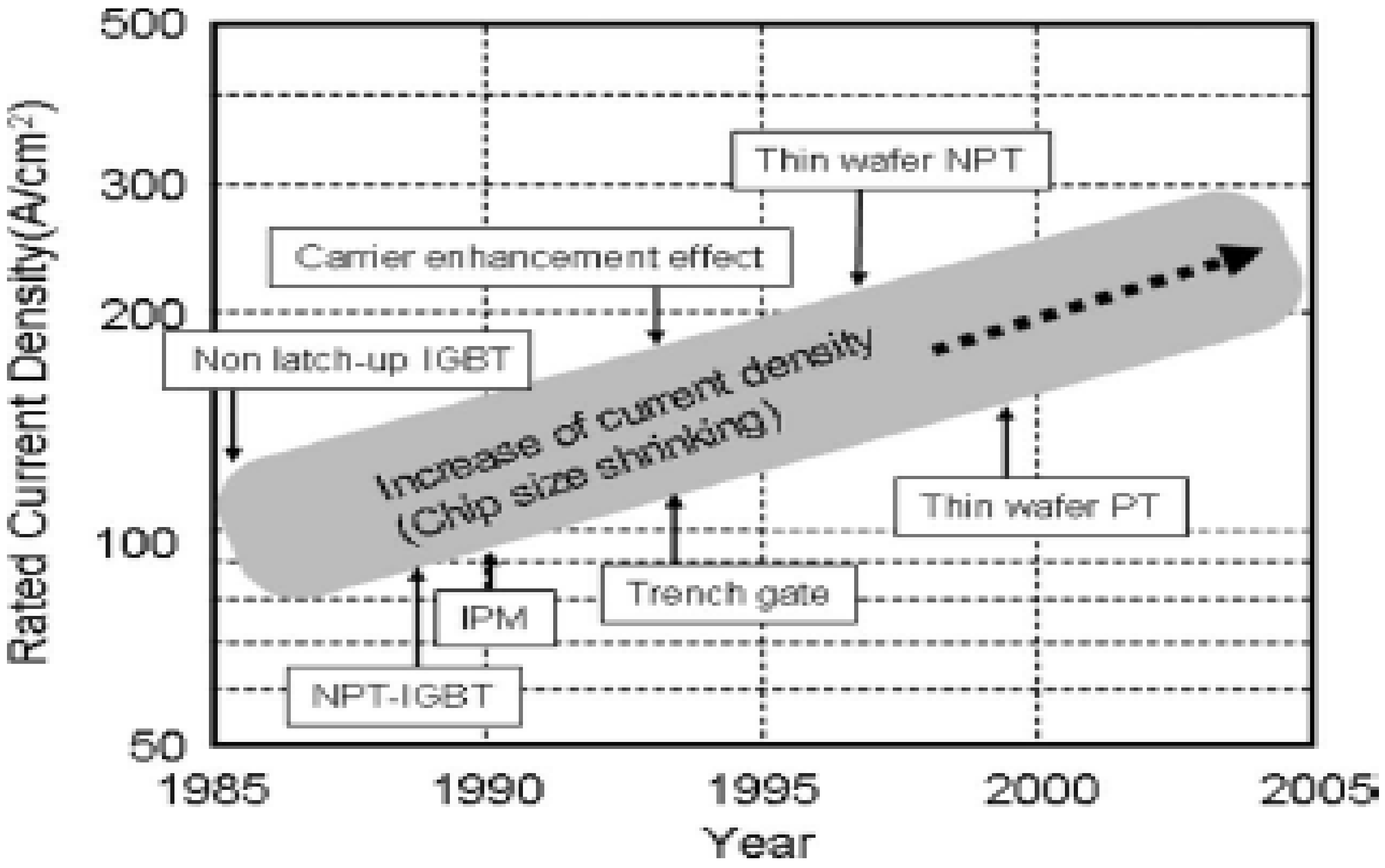


Staunton, Ayers, Marlino, Chiasson,& Burress, Evaluation of 2004 Toyota Prius Hybrid Electric Drive System, ORNL/TM-2006/423, May, 2006.

Three Dimensions of Power Electronics Design

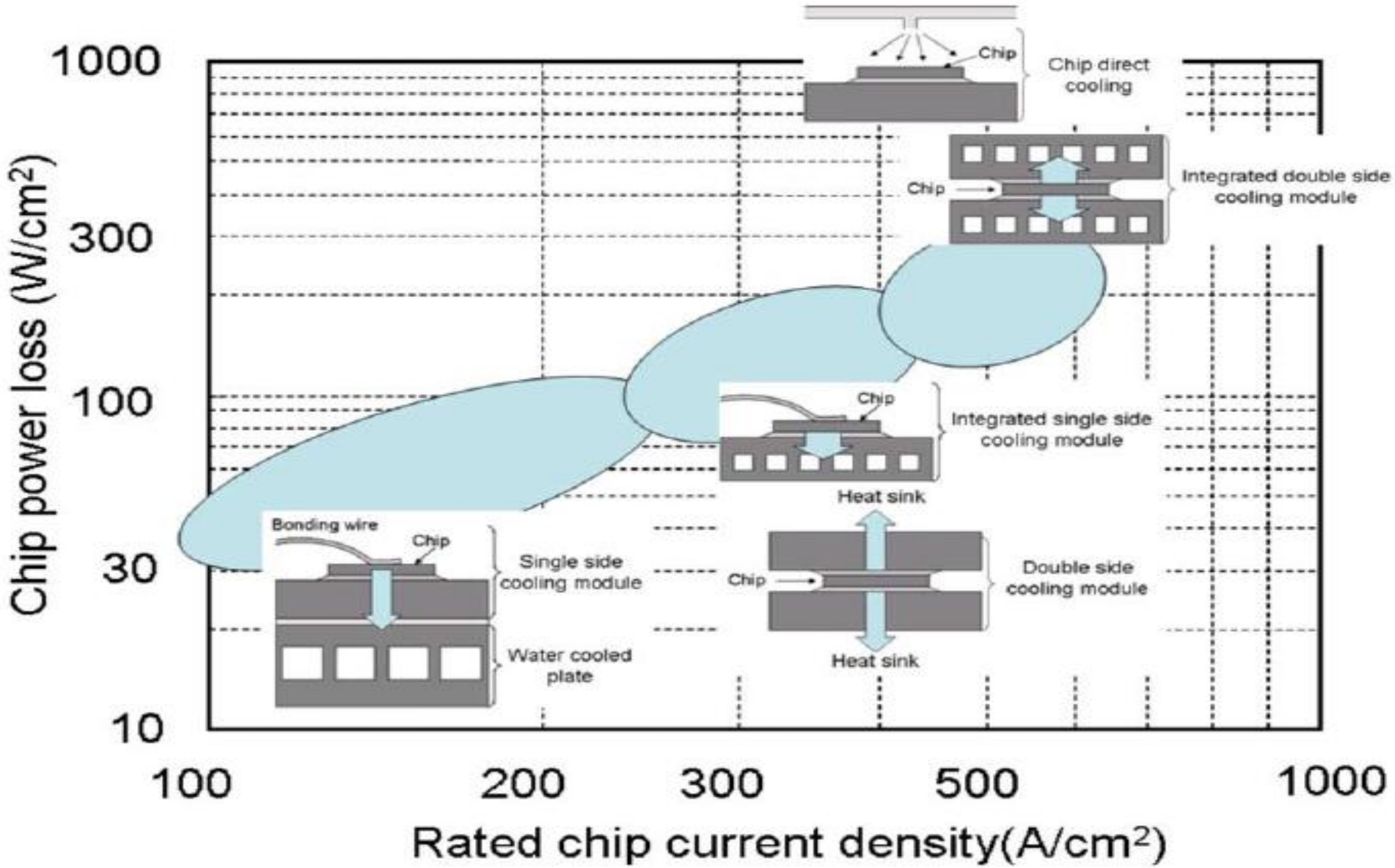


Steady Innovation Stream for IGBTs



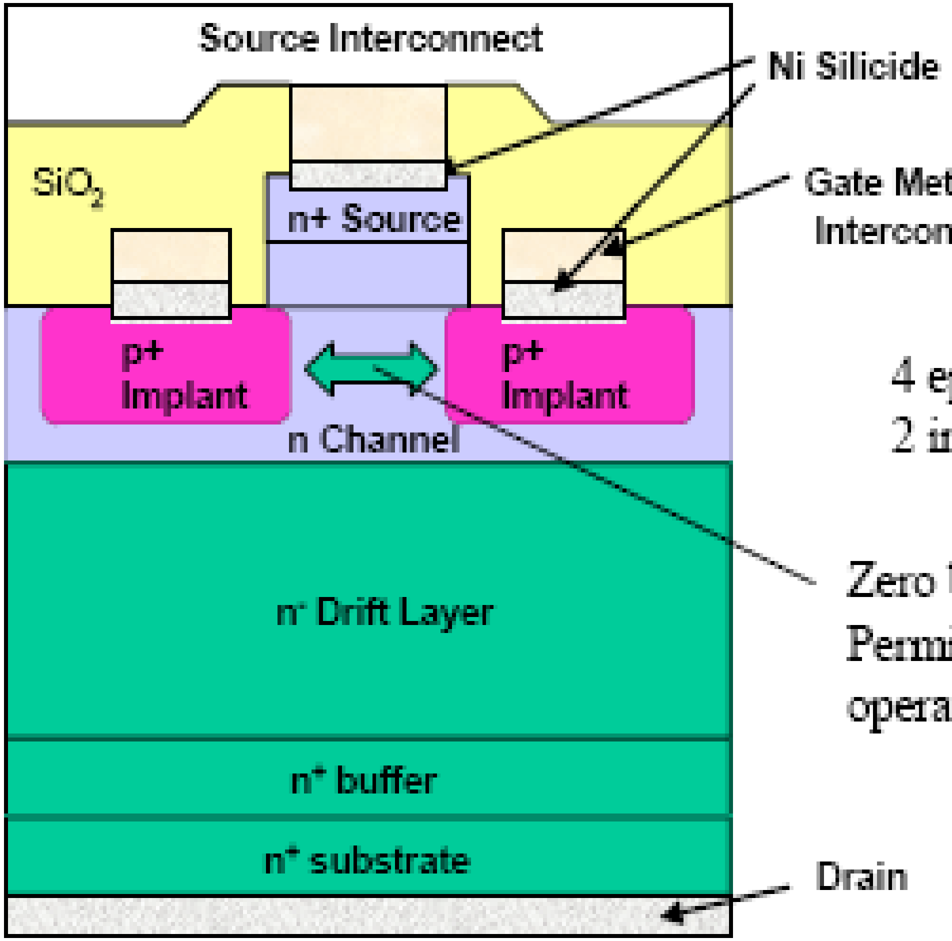
Z. John Chen and Ichiro Omura, *Power Semiconductor Devices for Hybrid, Electric and Fuel Cell Vehicles*, Proceedings of the IEEE, April, 2007.

Evolution of Power Packaging Technology



Z. John Chen and Ichiro Omura, *Power Semiconductor Devices for Hybrid, Electric and Fuel Cell Vehicles*, <u>Proceedings of the IEEE,</u> April, 2007.

Cross-Section of Normally-On Ion-Implanted SiC VJFET.

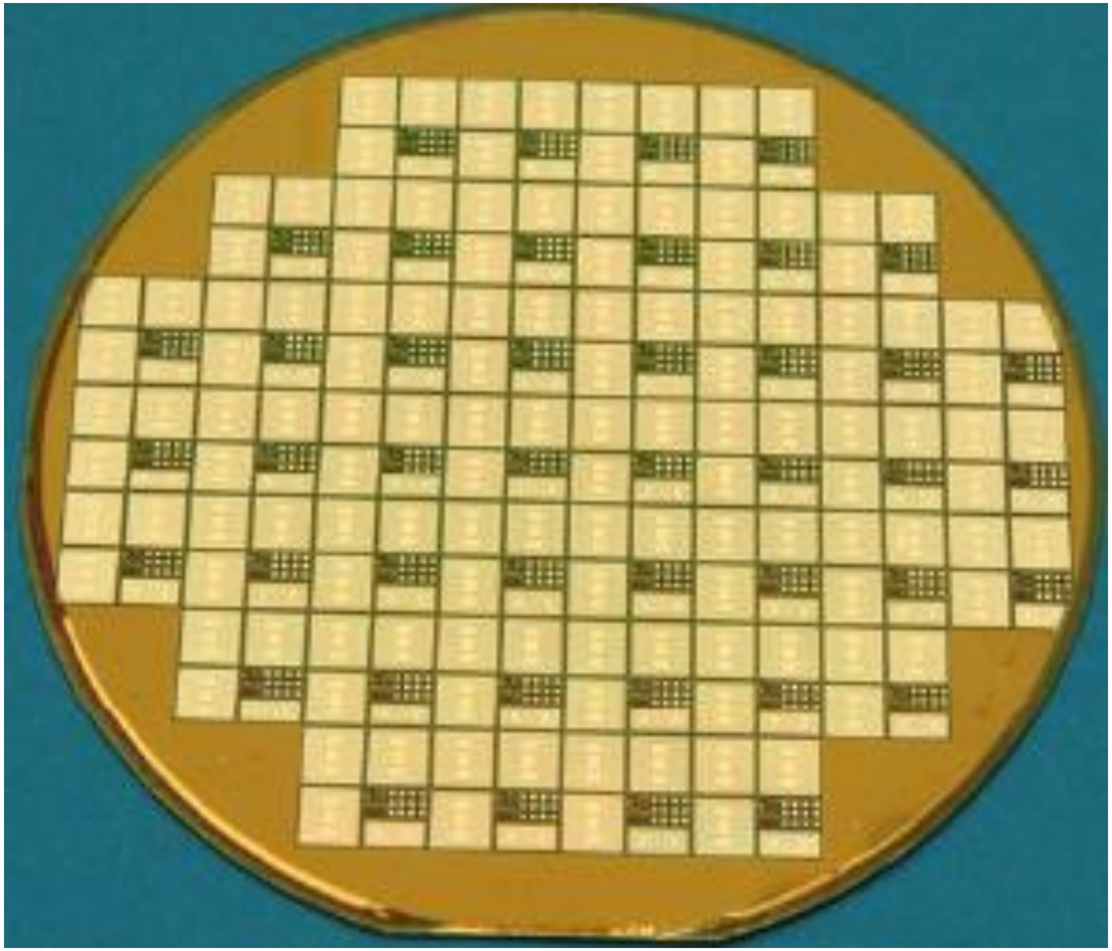


4 epitaxial layers
2 implant regions

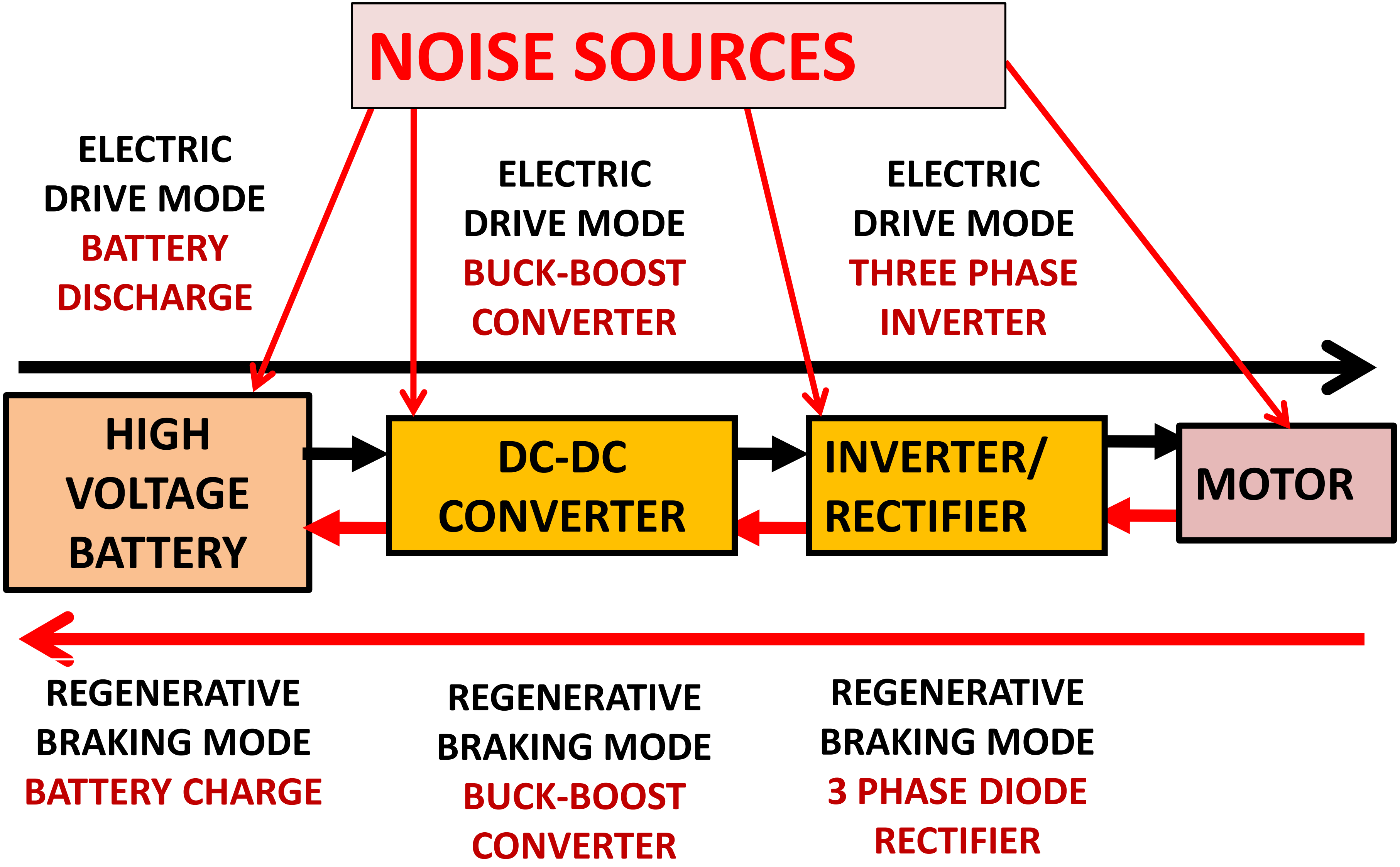
Zero bias depletion
Permits normally-off
operation

Not to Scale

0.19 Square Cm VJFETs Fabricated on a 3-Inch 4H-SiC Wafer



Power Electronics Noise in Hybrid Vehicles



NOISE SOURCES

ELECTRIC
DRIVE MODE
BATTERY
DISCHARGE

ELECTRIC
DRIVE MODE
BUCK-BOOST
CONVERTER

ELECTRIC
DRIVE MODE
THREE PHASE
INVERTER

HIGH
VOLTAGE
BATTERY

DC-DC
CONVERTER

INVERTER/
RECTIFIER

MOTOR

REGENERATIVE
BRAKING MODE
BATTERY CHARGE

REGENERATIVE
BRAKING MODE
BUCK-BOOST
CONVERTER

REGENERATIVE
BRAKING MODE
3 PHASE DIODE
RECTIFIER

Inverter Common Mode Noise

The output voltages of a power converter (Va, Vb, Vc) are not the phase voltages. The load phase voltages and a common mode voltage (Vn) can be derived based on the power converter voltages as below:

$$Va=Van+Vn$$

$$Vb=Vbn+Vn$$

$$Vc=Vcn+Vn$$

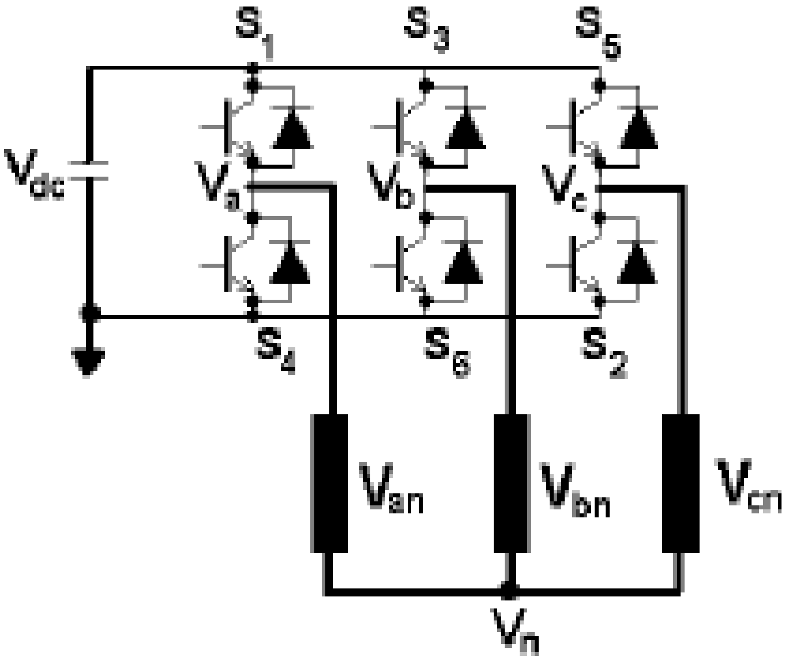
$$Va+Vb+Vc=Van+Vbn+Vcn+3Vn$$

$$Va+Vb+Vc=(Van+Vbn+Vcn)+3Vn$$

$$Va+Vb+Vc=3Vn$$

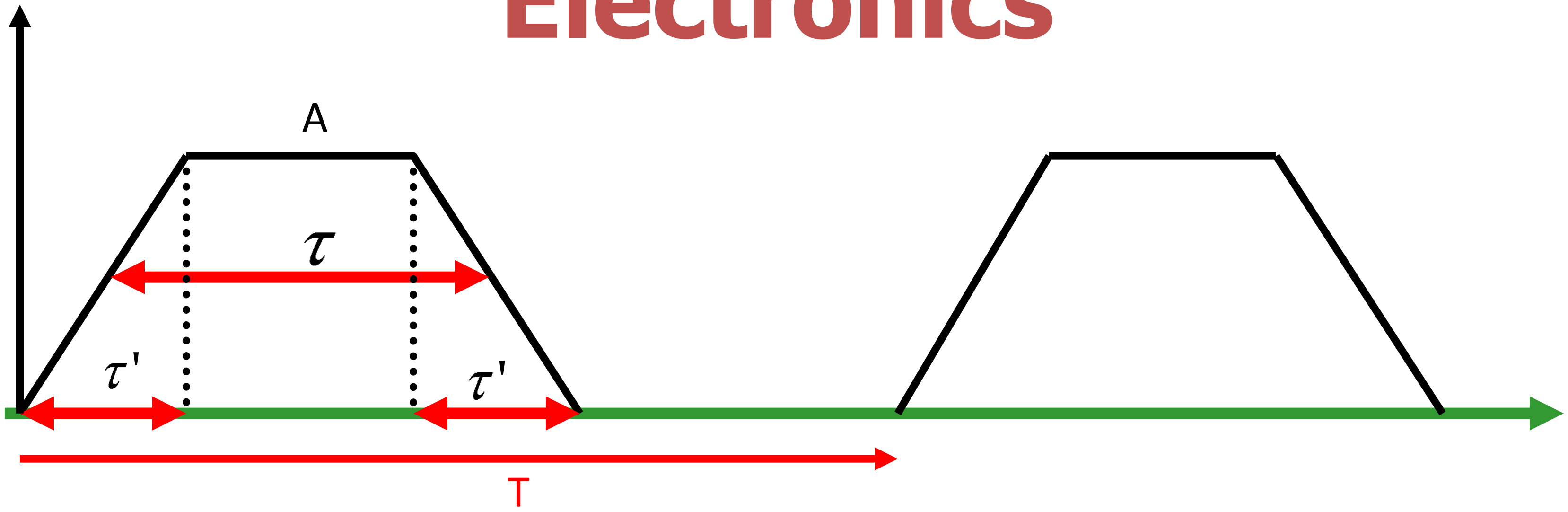
$$Vn=(Va+Vb+Vc)/3$$

Zero



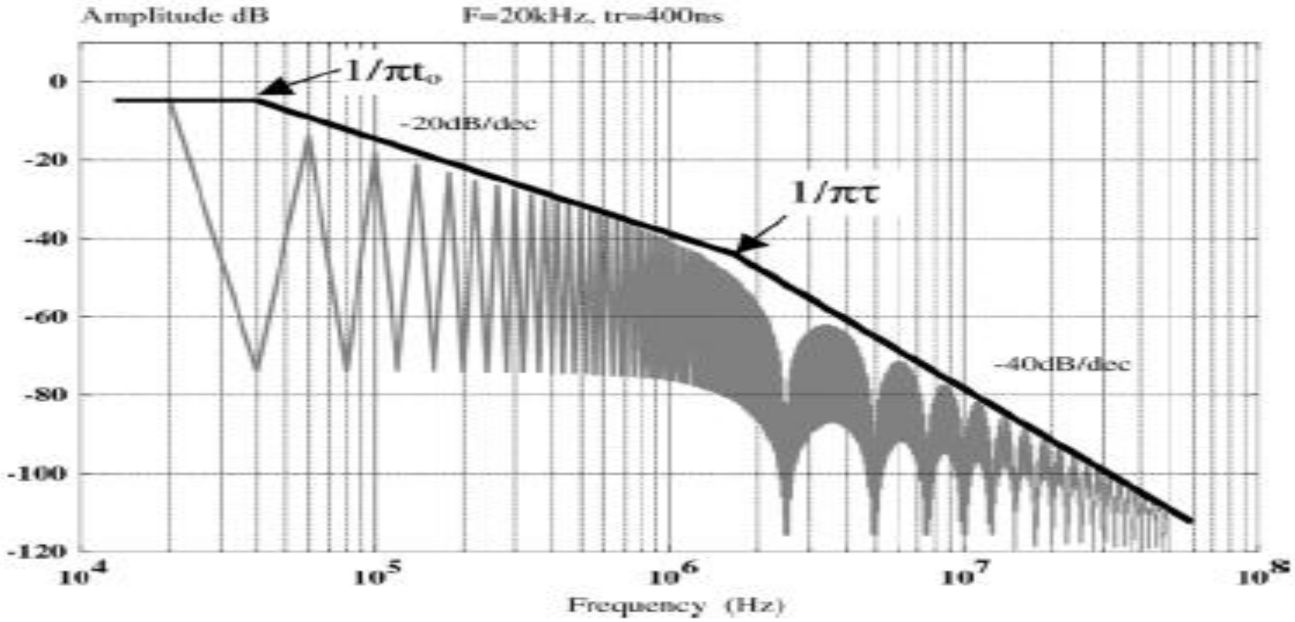
Firuz Zare, *EMC and Modern Power Electronics*, Tutorial, 2007 IEEE International Symposium on EMC

Noise Spectrum Due to IGBT or MOSFET Switching in Power Electronics



$$C_n = \frac{2A\tau}{T}\left[\frac{Sin(\frac{n\pi\tau}{2T})}{\frac{n\pi\tau}{2T}}\right]\left[\frac{Sin\,\frac{n\pi\tau'}{2T}}{\frac{n\pi\tau'}{2T}}\right]$$

Frequency Spectrum of an Ideal Trapezoid Signal



Trapezoid signal amplitude = 1, Frequency = 20kHz, Rise time = Fall time = 400ns = tau, full width at half max of current = 25 microseconds = t_0.

F. Costa and D. Magnon, *Graphical Analysis of the Spectra of EMI Sources in Power Electronics,* IEEE Transactions on Power Electronics, Vol. 20, No. 6, Nov. 2005.

Electrical Behavior of Ball Bearings

Impedance of a Ball Bearing is an important factor in AC drive systems.

There is a capacitive coupling between the upper and lower traces, but this capacitor is a nonlinear component. During normal operation, the separations between the balls and traces vary randomly and change the capacitance value.

The model of a ball bearing is shown in this figure which consists of a capacitor and a switch. A lubricated grease in the ball bearing cannot stand at high voltage and a short circuit through the lubricated grease may happened and this phenomenon can be modelled as a switch.

Firuz Zare, *EMC and Modern Power Electronics*, Tutorial, 2007 IEEE International Symposium on EMC

Effects of Inverter Generated Common Mode Noise on Motors

- Leakage Currents or Bearing Current Going to Ground Through Stray Capacitance Between Stator and Rotor Can Create Skin Currents on Auto Body. (Very low impedance at high frequency.)
  - Want CM return currents to flow on cable shield so no external electromagnetic field generated.
- Shortened Insulation Lifetime of Stator Windings.
- Pitting of Bearings.