2018 Fall Professional Development Course

Electric-Drive Vehicle Technology

Topic 2:

Power Electronics and Traction Motor for Electric-drive Vehicles

October 2 ~ 3, 2018

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1) Why Developing Electric Vehicles
2) Control of Power Electronics
3) DC-AC Inverter
4) DC-DC Converter
5) AC-DC Battery Charger
6) Traction Motor
7) EV Power Electronics On-Board Diagnostics (OBD)
8) Electric Powertrain System Integration

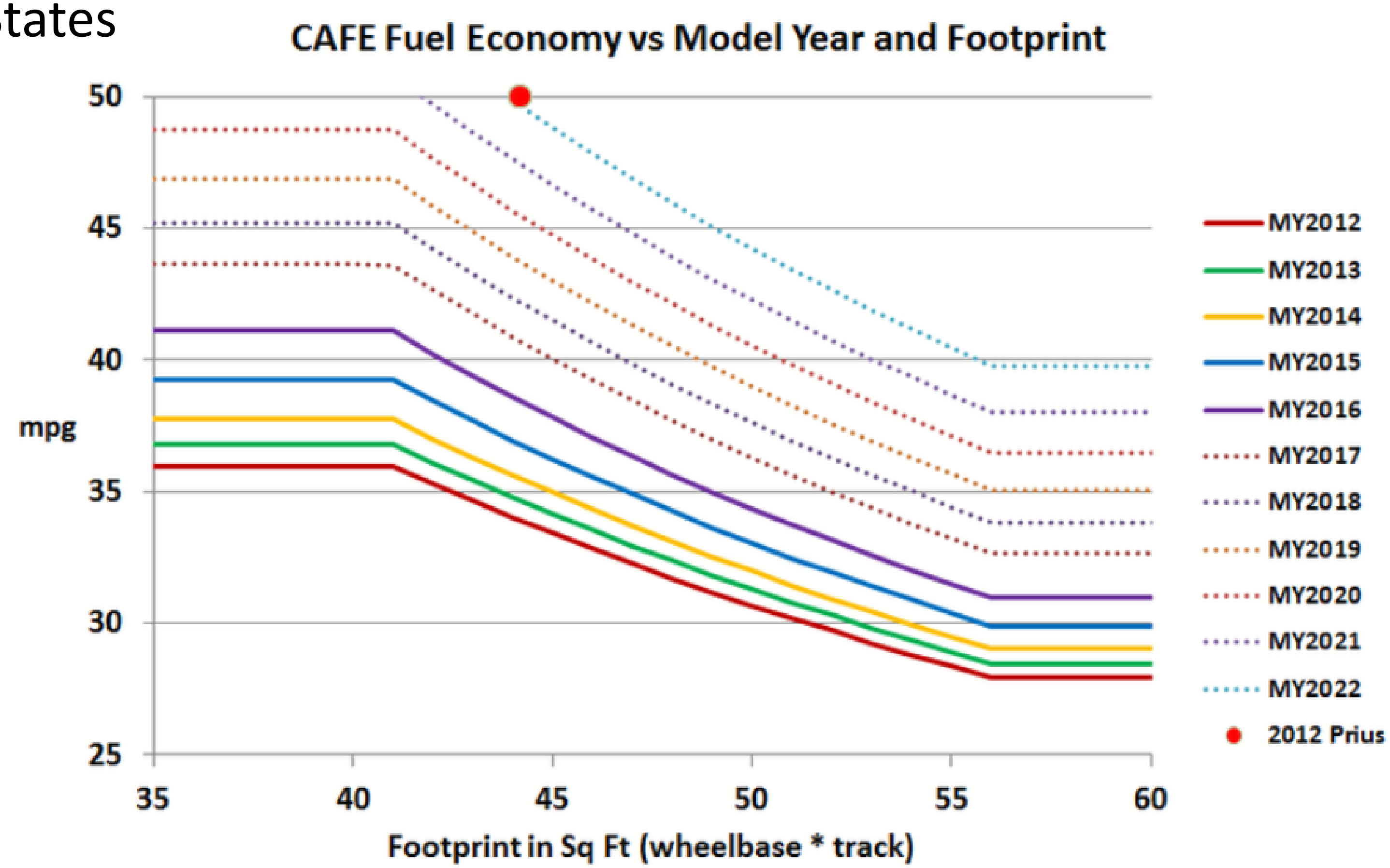
Why Build Electric Vehicle?

- Battery is expensive
- Travel distance is limited
- Take at least 4-12 hours to charge

?

CAFÉ Challenges

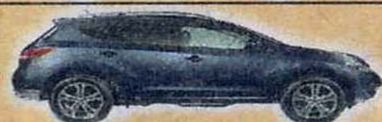
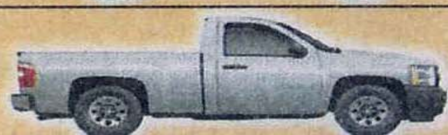
The Corporate Average Fuel Economy (CAFE) standards are regulations to improve the average fuel economy of cars and light produced for sale in the United States



- *August 28, 2012, The Obama Administration finalized groundbreaking standards that will increase fuel economy to the equivalent of 54.5 mpg for cars and light-duty trucks by Model Year 2025*

NEW MILEAGE TARGETS FOR 2025

Automakers must comply with tough, new m.p.g. targets by 2025. The new equation uses a sliding scale for different sizes of vehicles. Here's a look at the mileage targets and estimated window-sticker fuel-economy numbers for 2025 and how they compare with current models. The new targets will be reviewed again in 2017.

Vehicle size (Example)		2012 EPA window sticker combined	Estimated 2025 window sticker combined*	2025 target combined CAFE rating
Compact car (Honda Fit)		30 m.p.g.	45 to 48 m.p.g.	61.1 m.p.g.
Midsize car (Ford Fusion)		25 m.p.g.	41 to 43 m.p.g.	54.9 m.p.g.
Full-size car (Chrysler 300)		21 m.p.g.	35 to 36 m.p.g.	48 m.p.g.
Small SUV (Ford Escape 4wd)		23 m.p.g.	36 to 38 m.p.g.	47.5 m.p.g.
Midsize crossover (Nissan Murano)		20 m.p.g.	32 to 34 m.p.g.	43.4 m.p.g.
Minivan (Toyota Sienna)		21 m.p.g.	29 to 31 m.p.g.	39.2 m.p.g.
Large pickup (Chevrolet Silverado)		17 m.p.g.	25 to 26 m.p.g.	33 m.p.g.

*The 2025 window sticker rating is 20%-30% below the CAFE figure, to account for real-world driving conditions. This also applies to 2012 CAFE and window-sticker fuel-economy ratings.

Sources: National Highway Traffic Safety Administration; EPA; Free Press

DAVID PIERCE/DETROIT FREE PRESS

Source: Detroit News

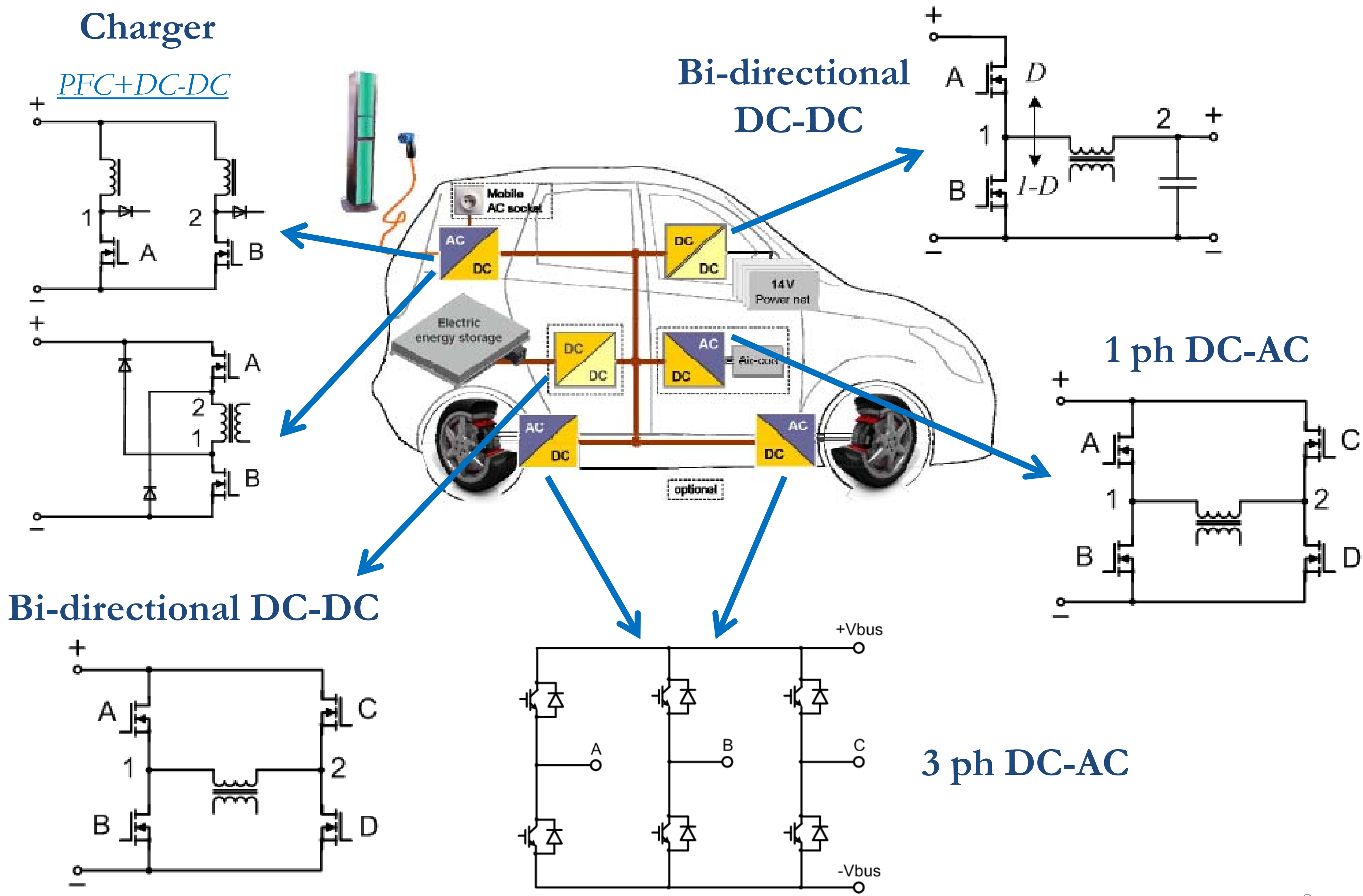
- All automotive OEMs are required to comply with *CAFE* and *Emission Regulation Laws ,* that’s why we are building electric and hybrid electric vehicles.

- Automotive Power Electronics *is the Key Enabler to Achieve Fuel Economy,* CO_2 *Emission Goals and Reduce Oil Dependency.*

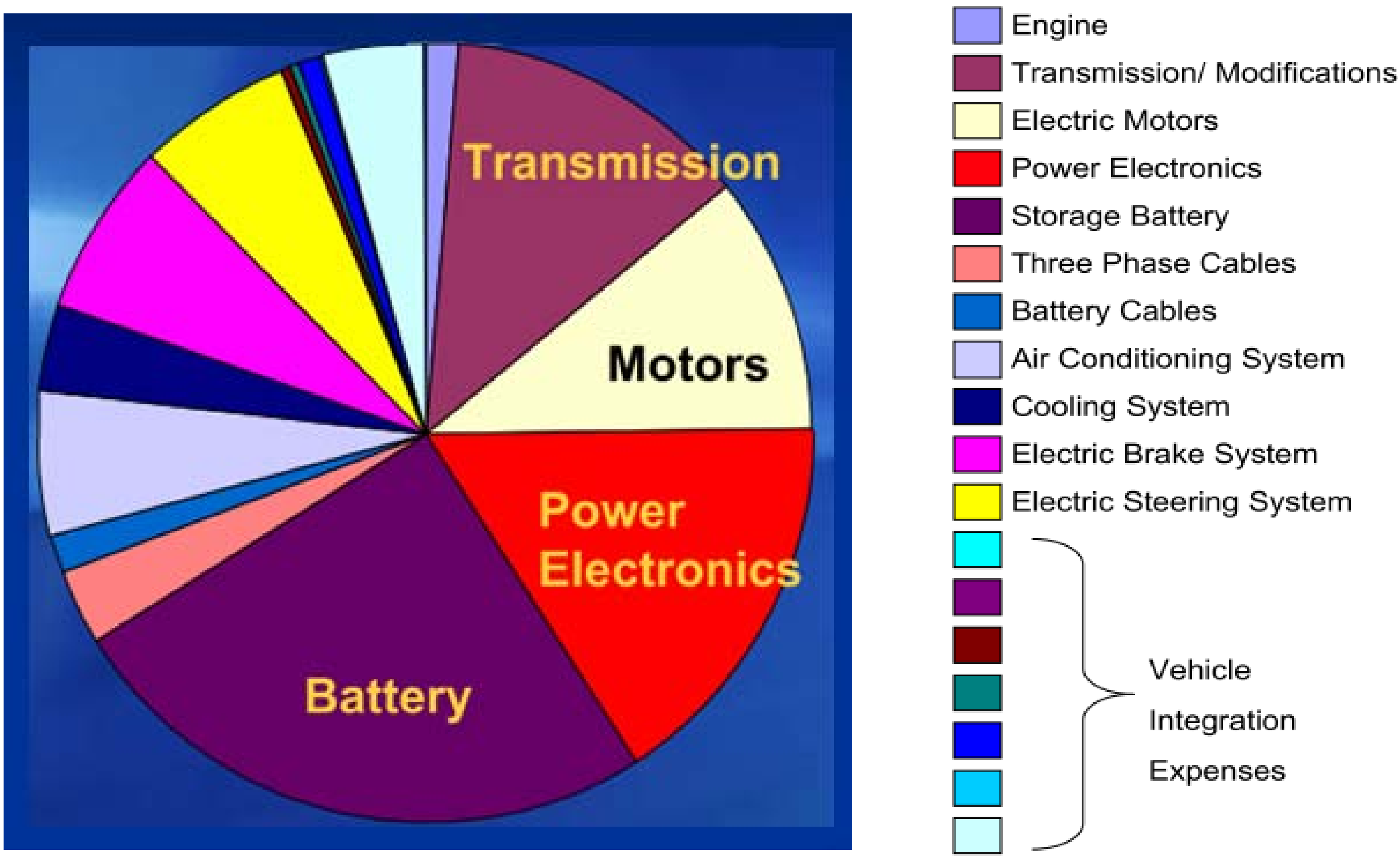
Major Electric Drive Components

1) Traction Motor
   - Permanent Magnet, AC Induction
2) Motor Inverter
   - Converting high voltage DC to 3 phases AC
3) DC to DC Converter (Step Down)
   - Converting high voltage DC to low voltage DC
4) DC to DC Converter (Step Up, Boost))
   - Converting low voltage DC to High voltage DC
5) Battery Management System (BMS)
6) Battery Charger

Automotive Power Electronics for EV



Hybrid Electric Vehicle Material Costs



Power Electronics are over 20% of material costs

Source: APEC 2008

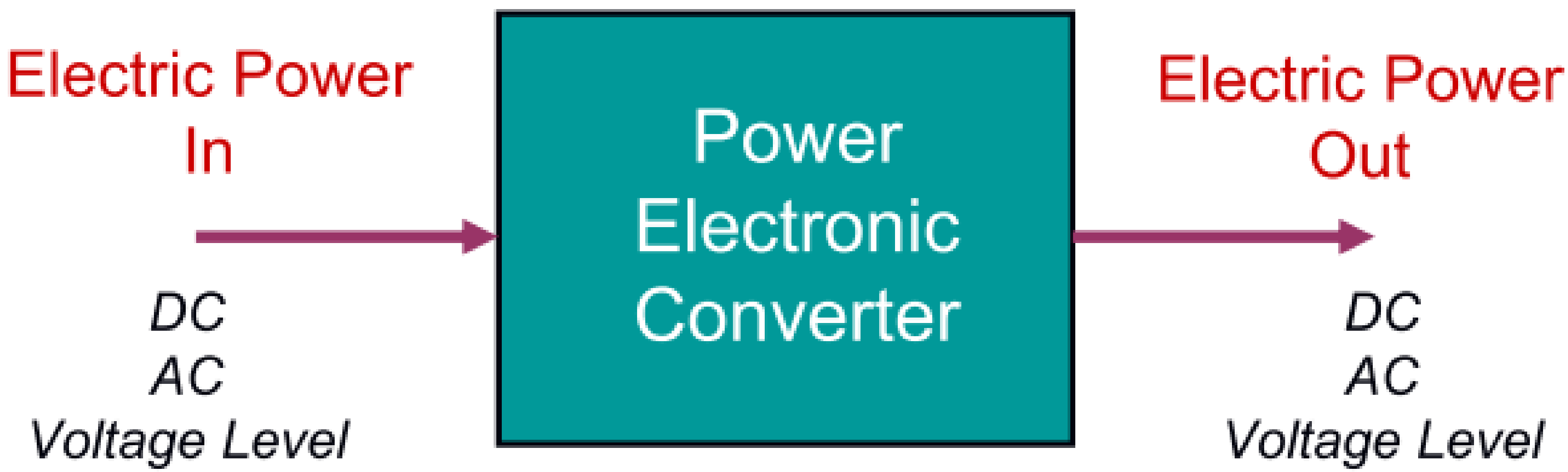
What is Power Electronics

- “***Classical" electronics***, electrical currents and voltage are used to ***carry information***, whereas with ***<u>Power Electronics Carry Power</u>***

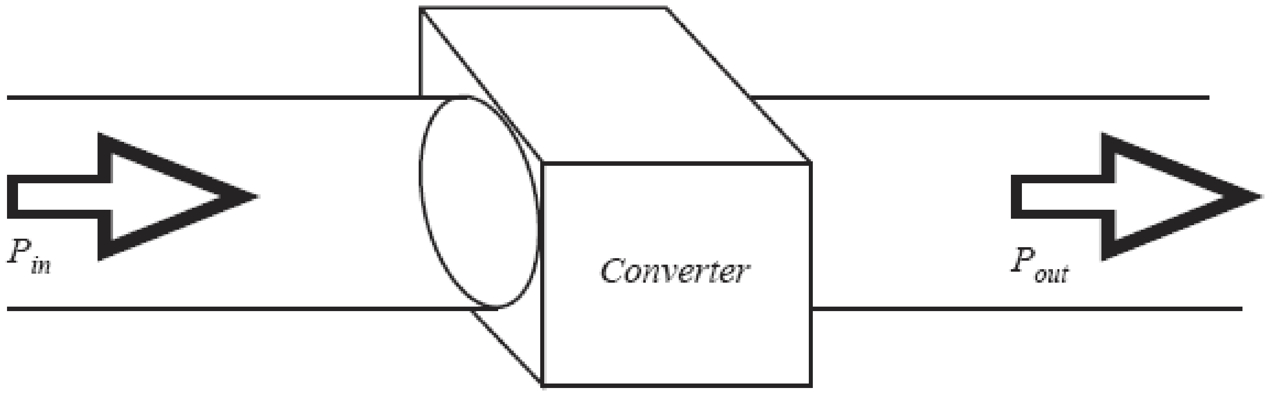
- Power electronics refers to ***<u>Control and Conversion of Electrical Power</u>*** by power semiconductor devices wherein these devices operate as ***<u>switches</u>***

Basics of Power Electronics

- Power Electronics processes electrical power from One Form into Another



Efficiency is Essential for Power Electronics

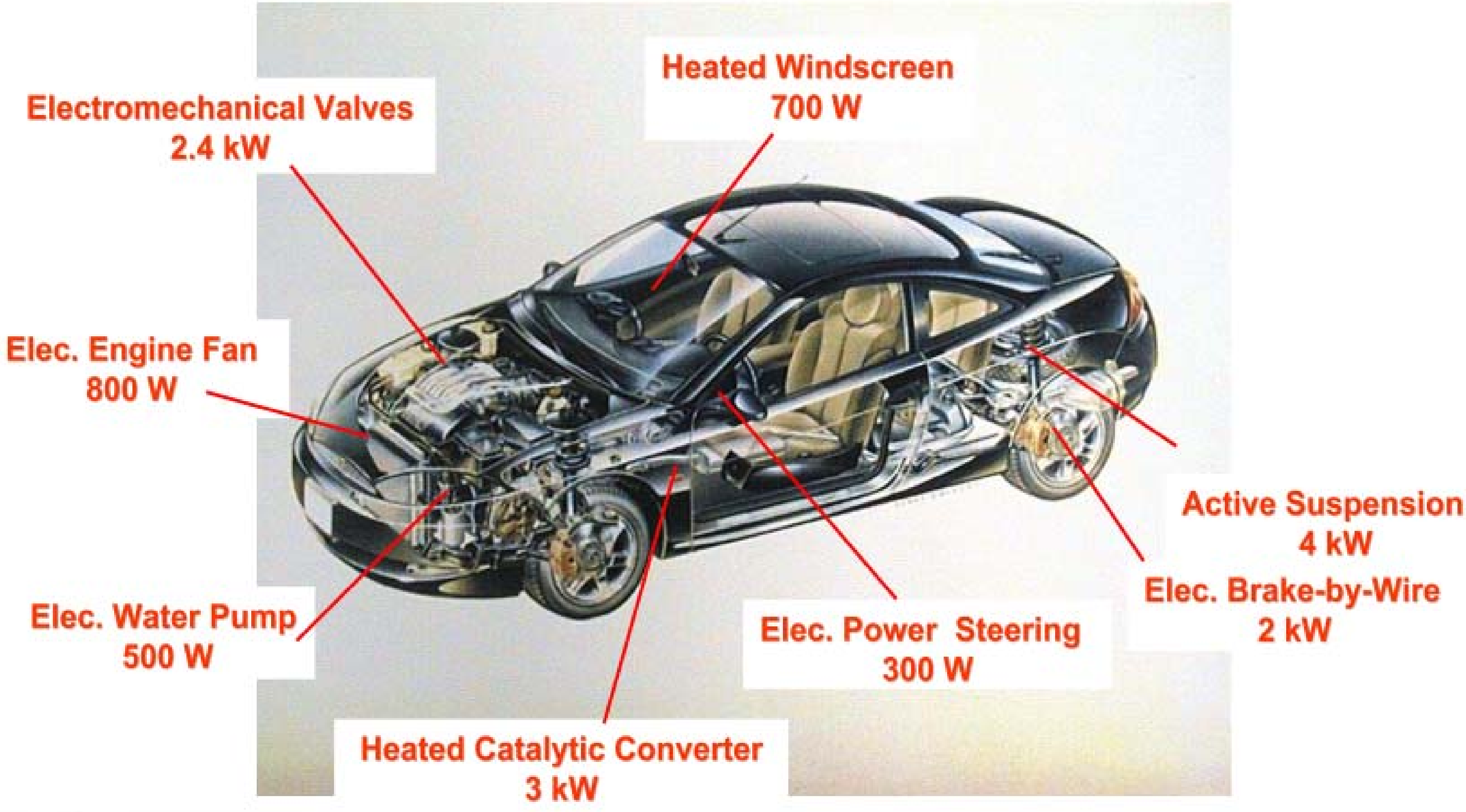


$$\eta = \frac{P_{out}}{P_{in}}$$

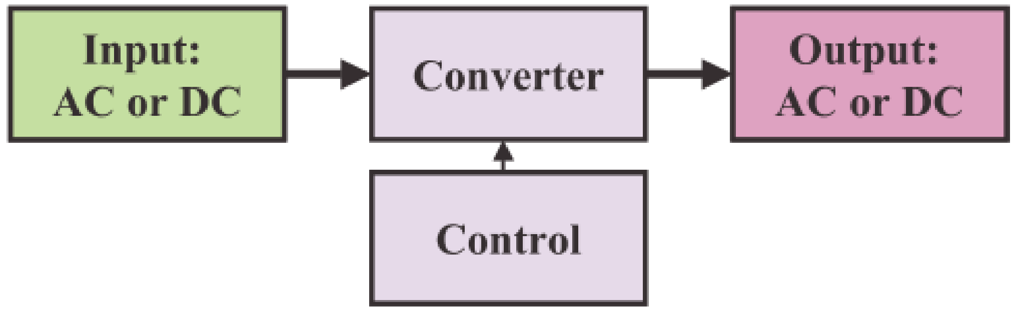
$$P_{loss} = P_{in} - P_{out} = P_{out}\left(\frac{1}{\eta} - 1\right)$$

- High efficiency leads to low power loss within converter
- Small size and reliable operation is then feasible
- Efficiency is a good measure of converter performance

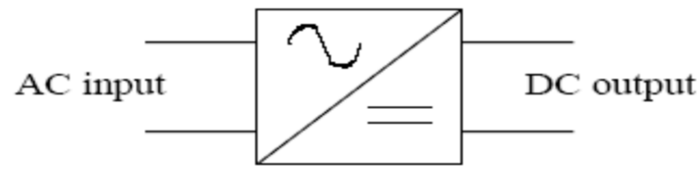
Power Requirements in a Vehicle



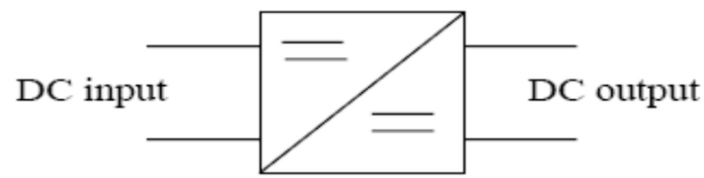
Power Electronics - Converters



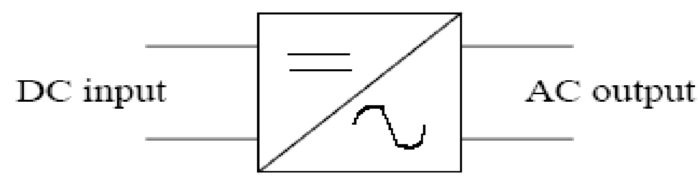
AC to DC: RECTIFIER



DC to DC: CHOPPER

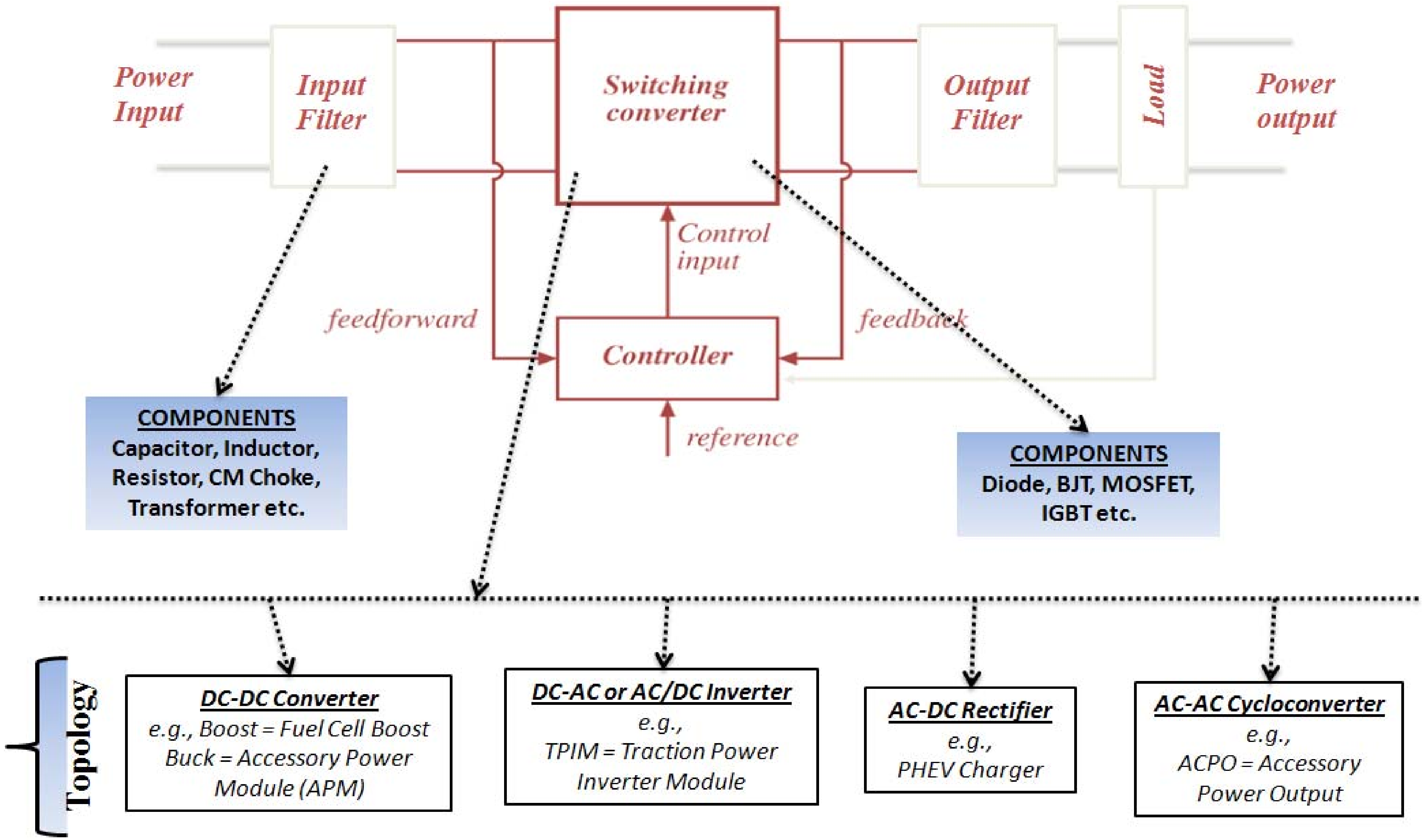


DC to AC: INVERTER



Power semiconductor devices are also used as static **switches**

Typical Power Electronic Devices

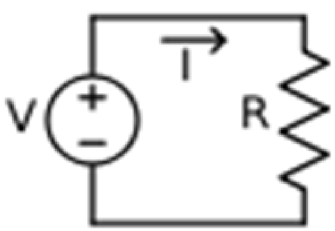


Basic Power Electronics
Passive Components

Resistor

Analogy → Friction

What it does:
A passive device that limits current flow.



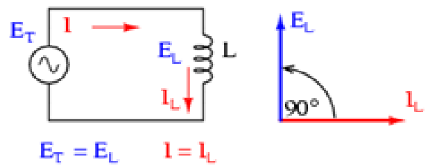
Ohm's Law, $V = I.R$

Application:
Current limiter
Bleeder
Discharge Circuit
Load Bank

Inductor

Analogy → Damper

What it does:
A passive device that opposes rate of change of current flow by dropping a voltage.



$$v(t) = L\frac{di}{dt}$$

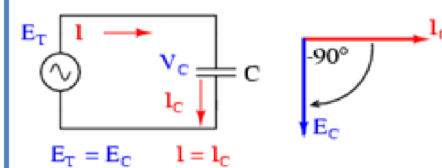
$$E_{\text{stored}} = \frac{1}{2}LI^2$$

Application:
Noise suppression
Filter
Load Bank

Capacitor

Analogy → Spring

What it does:
A passive device that opposes rate of change of voltage by flowing current.



$$i(t) = C\frac{dv(t)}{dt}$$

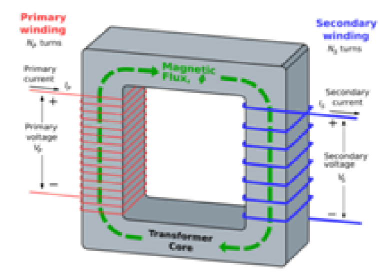
$$U = \frac{1}{2}\frac{Q^2}{C} = \frac{1}{2}QV = \frac{1}{2}CV^2$$

Application:
Noise suppression
Filter/ Snubber
Energy Storage

Transformer

Analogy → Gears

What it does:
Transfers electrical energy from one circuit to another through inductively coupled conductors

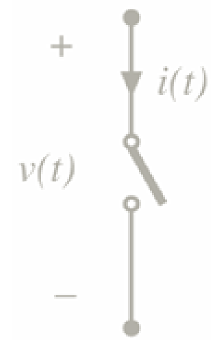


$$\frac{V_s}{V_p} = \frac{N_s}{N_p} \qquad \frac{Is}{Ip} = \frac{Np}{Ns}$$

Application:
Step-up and step-down
Isolating power
Instrumentation

Power Semiconductor Switch

SPST: Single pole single throw

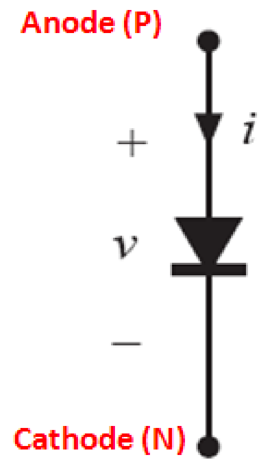



Switch


Relay

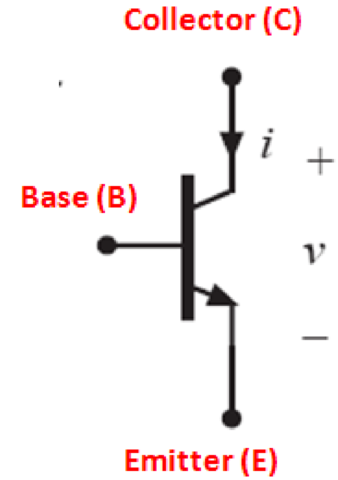
FWD: Free Wheeling Diode

1874
1919



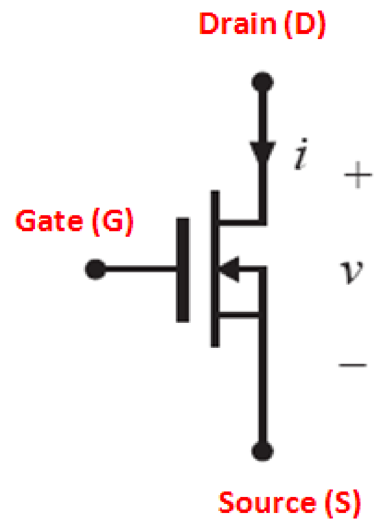
BJT: Bipolar Junction Transistor

1947



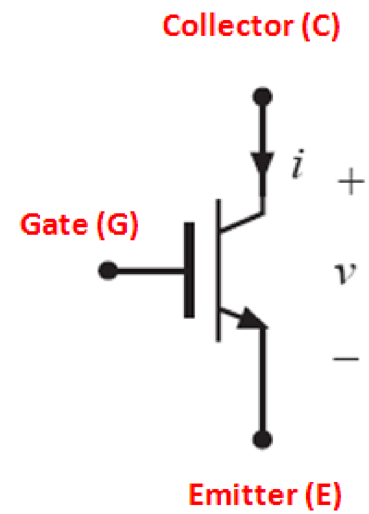
MOSFET: Metal Oxide Semiconductor Field Effect Transistor

1930
1980

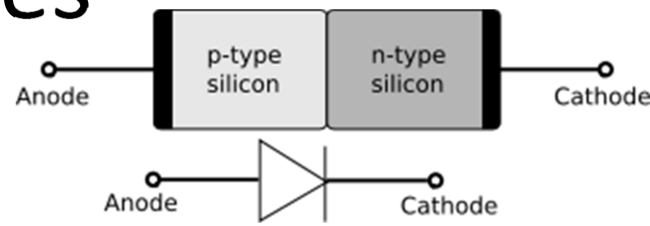


IGBT: Insulated Gate Bipolar Transistor

1980
1990



Semiconductor Devices



- Diode
  - A diode is a two-terminal electronic component that conducts primarily in one direction
  - A semiconductor diode is a crystalline piece of semiconductor material with a p–n junction connected to two electrical terminals
- Transistor
  - Bipolar junction transistor (BJT): uses both electron and hole charge carriers, BJT, IGBT
  - Field-effect transistor (FET): only use one kind of charge carrier, MOSFET, JFET

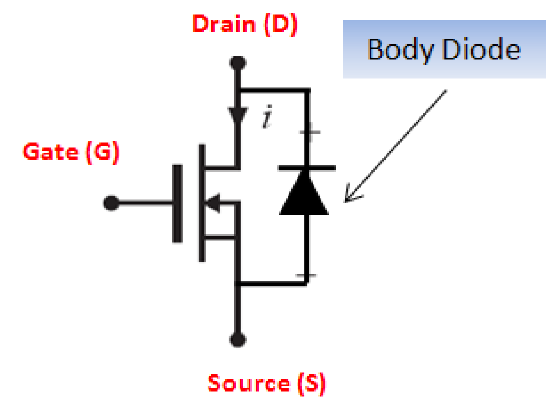
MOSFET
(Metal Oxide Semiconductor FET)

Features:

- ✓An active **two-quadrant** voltage controlled switch
- ✓Conducts both positive and negative on-state current
- ✓Use as an amplifier (linear region) or power switch (saturation region)
- ✓On-resistance increases with temperature, hence easy to parallel
- ✓On-resistance increases with drain current, loss is high at high current

Types:

- ✓12 V to 250 V MOSFET
- ✓150C, 175C, 200C MOSFET
- ✓Discrete, Iso-PAC



Equivalent Ckt

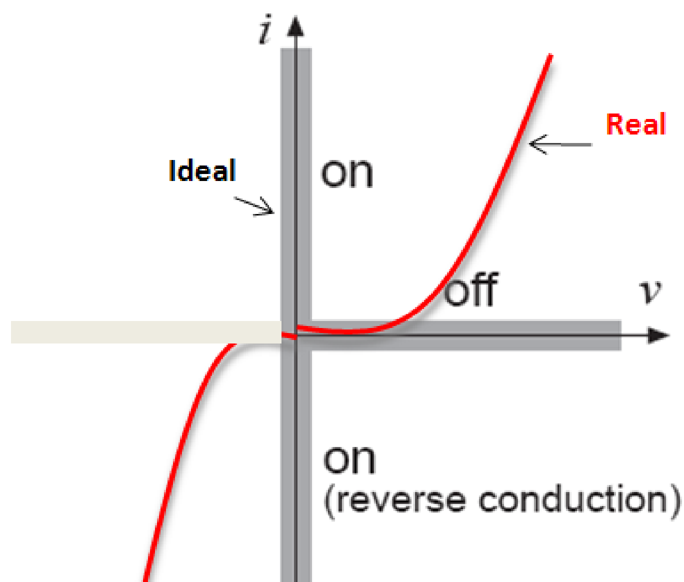
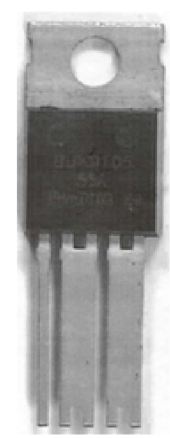


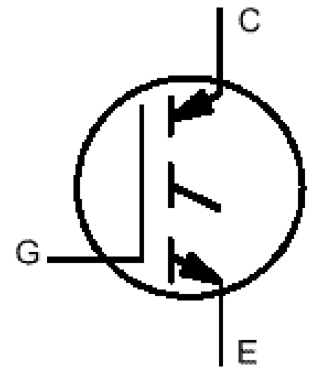
Fig. : V-I Curve (Conduction Curve)



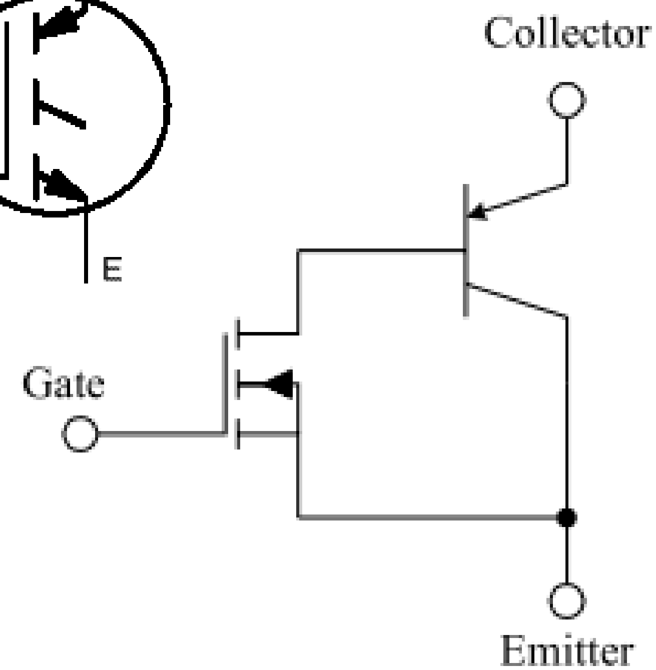
G D S

Power Loss = V. I
= Conduction Loss + Switching Loss

Insulated Gate Bipolar Transistor (IGBT)



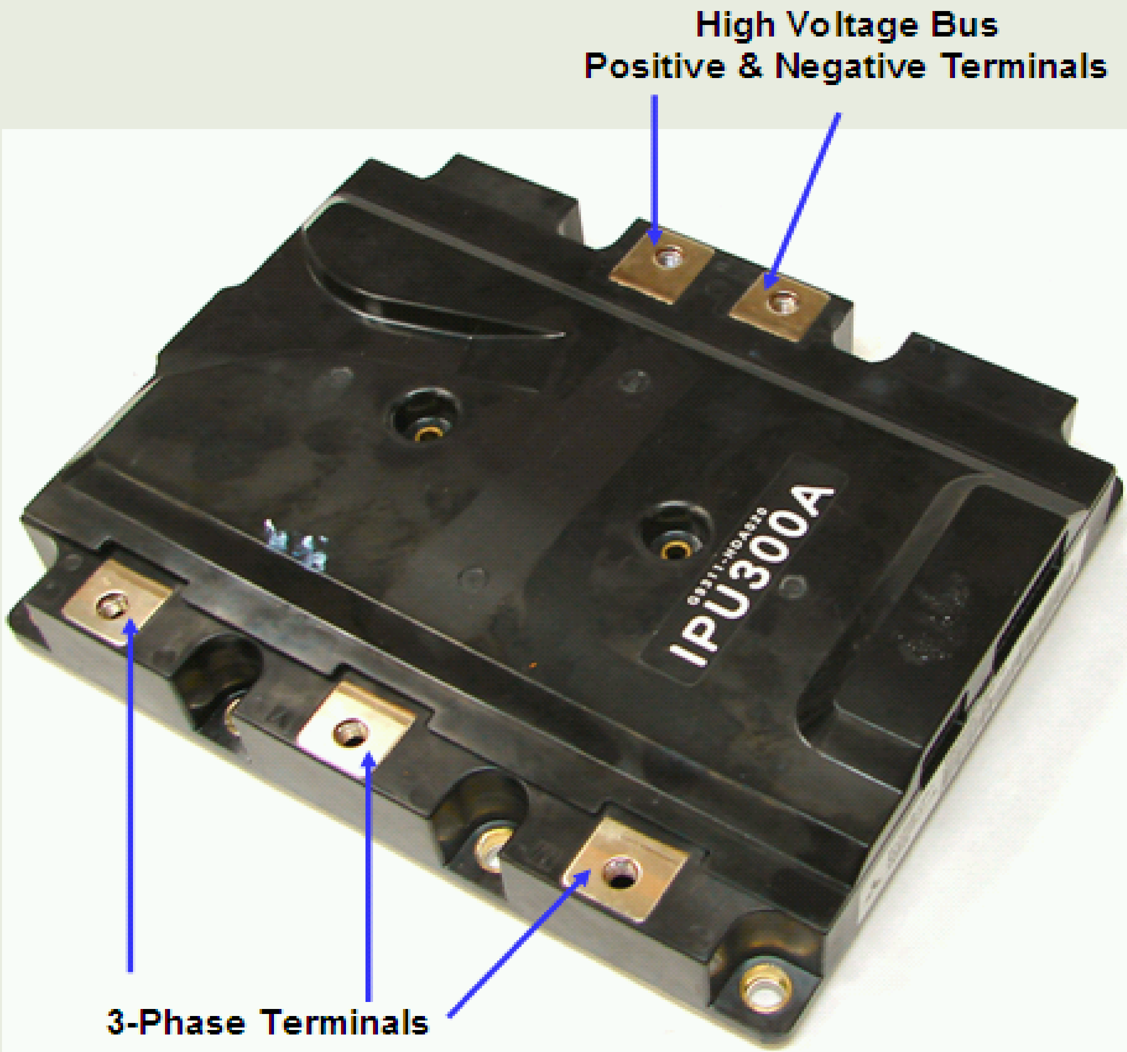
The IGBT combines the simple gate-drive characteristics of MOSFETs with the high-current and low-saturation-voltage capability of bipolar transistors



The IGBT has the output switching and conduction characteristics of a bipolar transistor but **is voltage-controlled like a MOSFET**. In general, this means it has the advantages of high-current handling capability of a bipolar with the ease of control of a MOSFET.

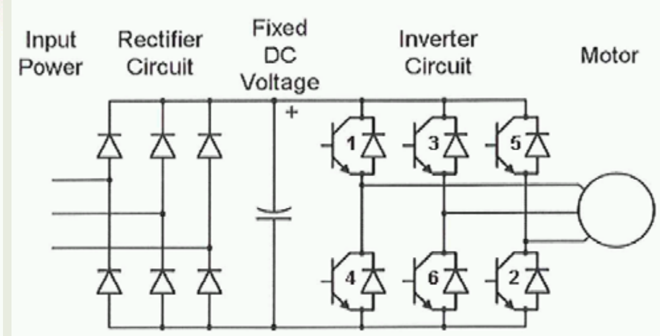
IGBT Comparison Table [1]			
Device Characteristic	Power Bipolar	Power MOSFET	IGBT
Voltage Rating	High <1kV	High <1kV	Very High >1kV
Current Rating	High <500A	Low <200A	High >500A
Input Drive	Current hFE 20-200	Voltage VGS 3-10V	Voltage VGE 4-8V
Input Impedance	Low	High	High
Output Impedance	Low	Medium	Low
Switching Speed	Slow (µs)	Fast (ns)	Medium
Cost	Low	Medium	High

Ford Escape Hybrid IGBT Power Module



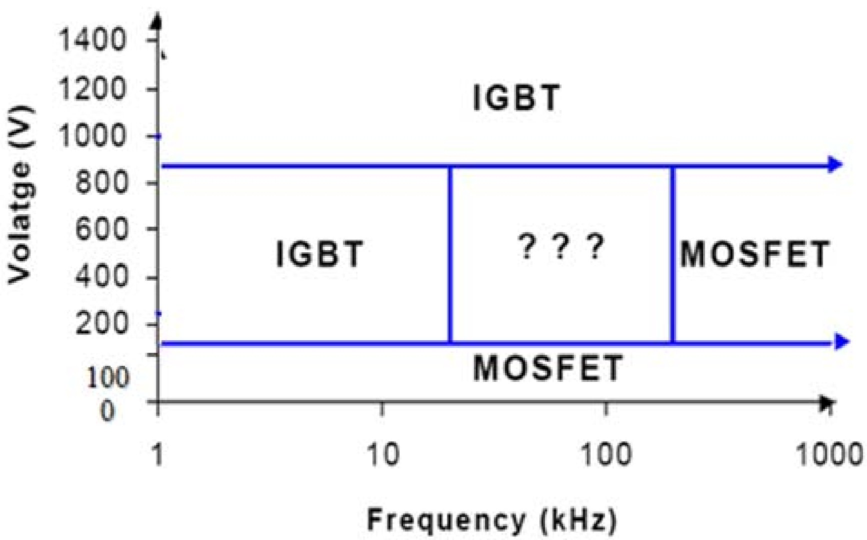
Integrated Power Unit Module
(IPM)
(3-Phase Output Unit)

• Motor drive inverter



IGBT Vs. MOSFET

MOSFET Applications	IGBT Applications
Low Voltage (< 200 Volt)	High Voltage (> 500 V)
Low Power (< 5 kWatt)	High Current, High Power (> 5 kWatt)
High Switching Frequency (> 200 kHz)	Low Switching Frequency (< 20 kHz)
High Conduction Loss, R_{DSON} exponentially increases with drain current	Low Conduction Loss, low forward voltage drop (V_{CE})
Low Switching Loss/ Cycle	High Switching Loss/ Cycle
High overall Efficiency at low load point	High overall Efficiency at medium/ high load points
Application Example: BAS (42V Mild-Hybrid)	Application Example: 2-Mode (300V Strong Hybrid)



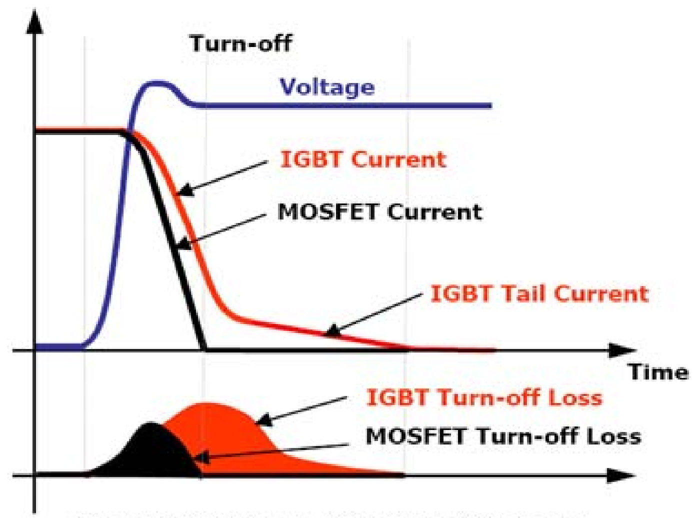
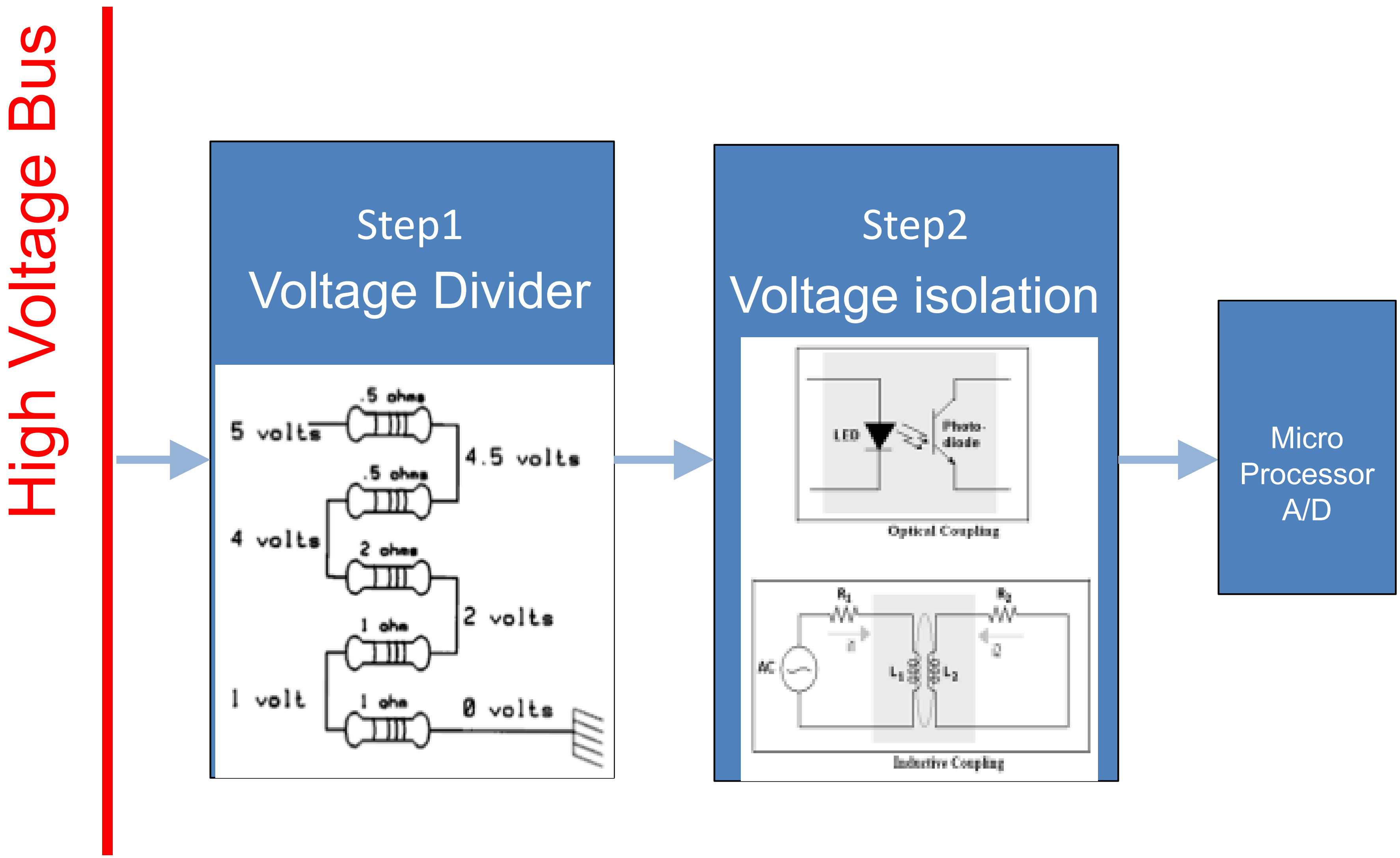


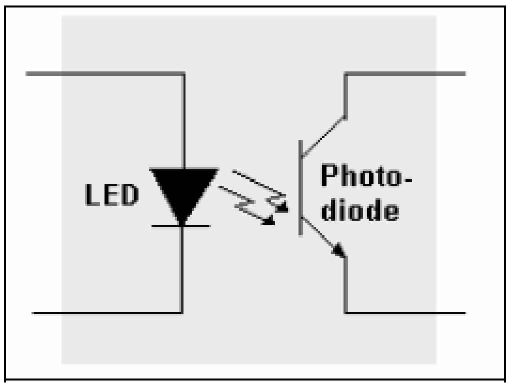
Fig. 5: MOSFET and IGBT turn-off behavior

How to Measure High Voltage in Power Electronics System?

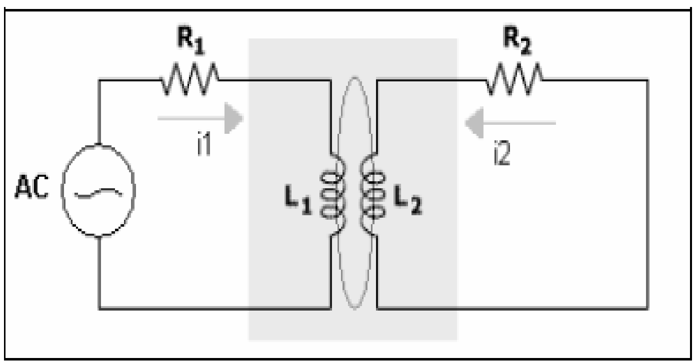


High Voltage Isolation

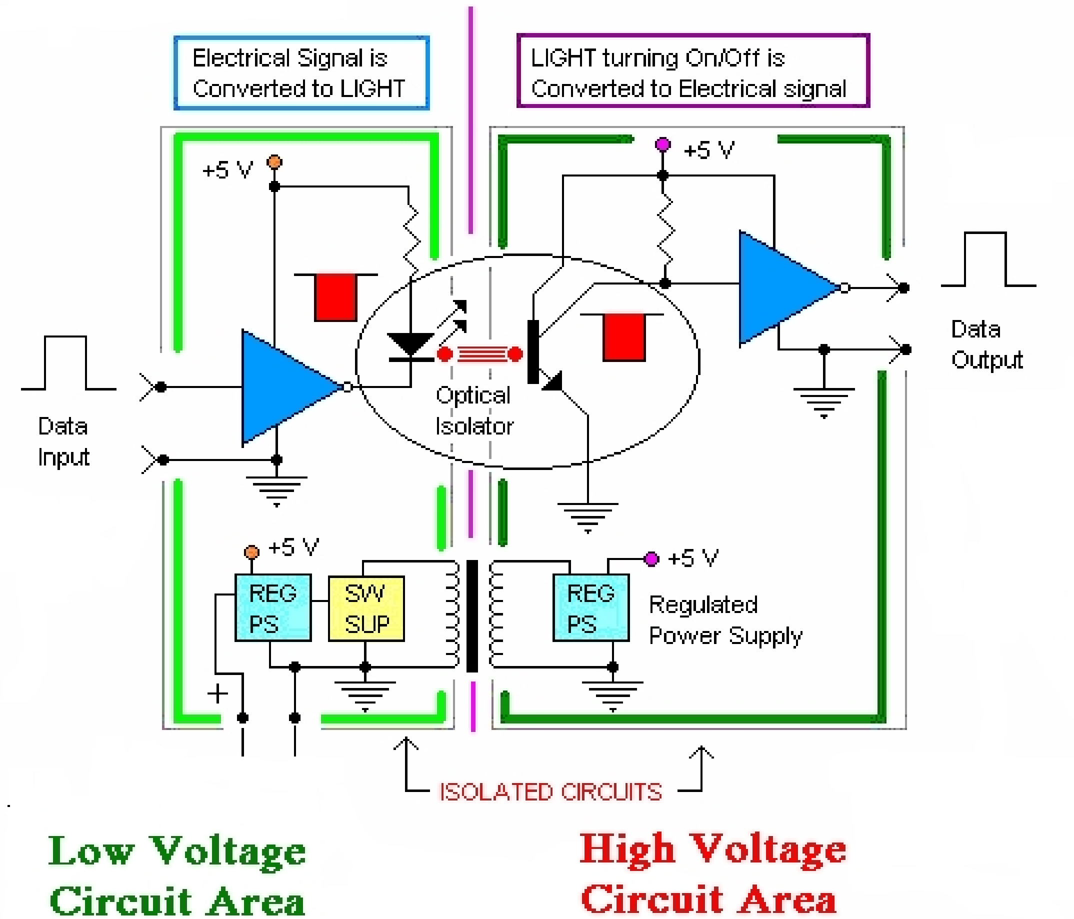
High voltage (50V+) power electronics need to have isolation interfaces to connect to conventional low voltage circuitry (3.3 to 12V)



Optical Coupling

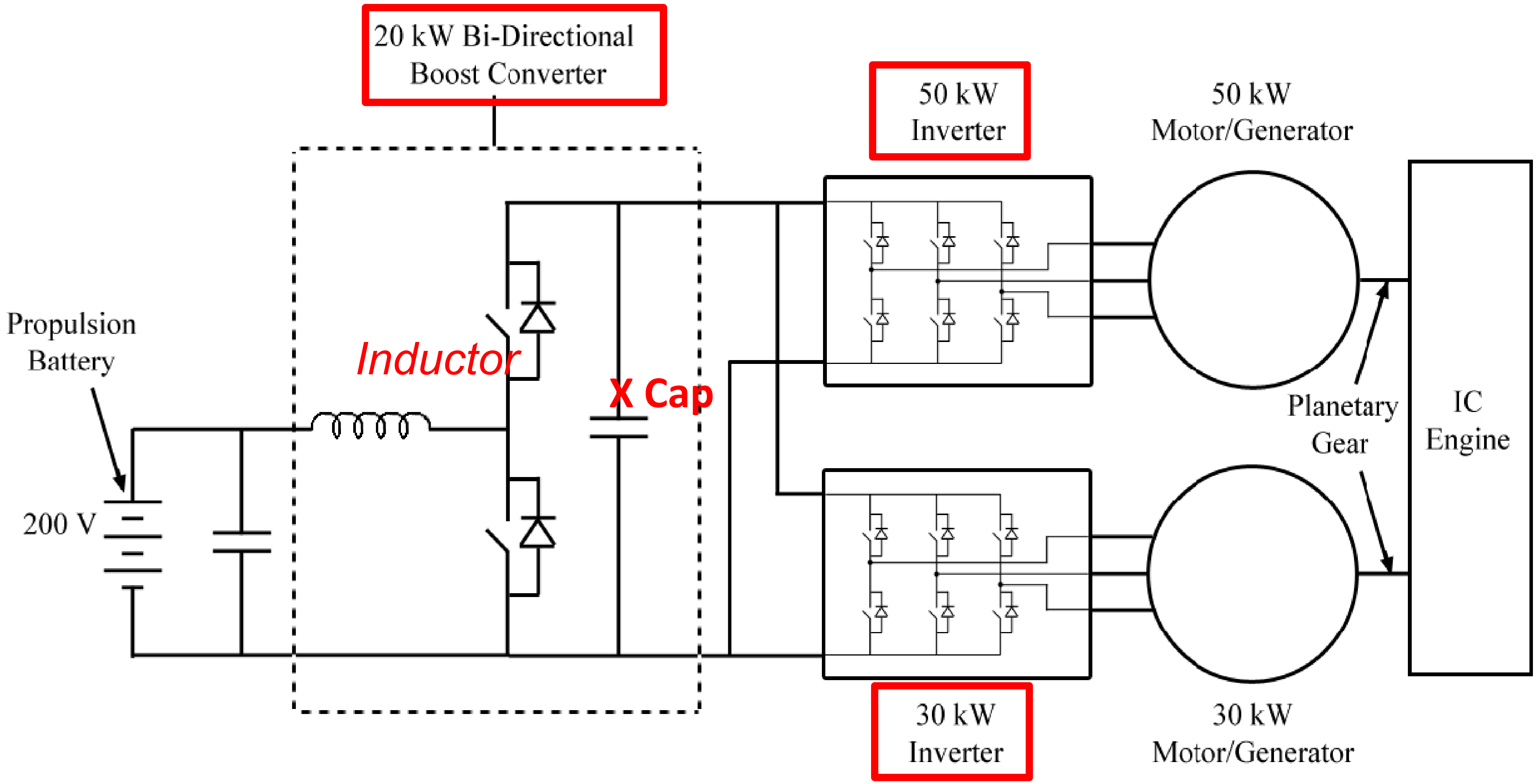


Inductive Coupling



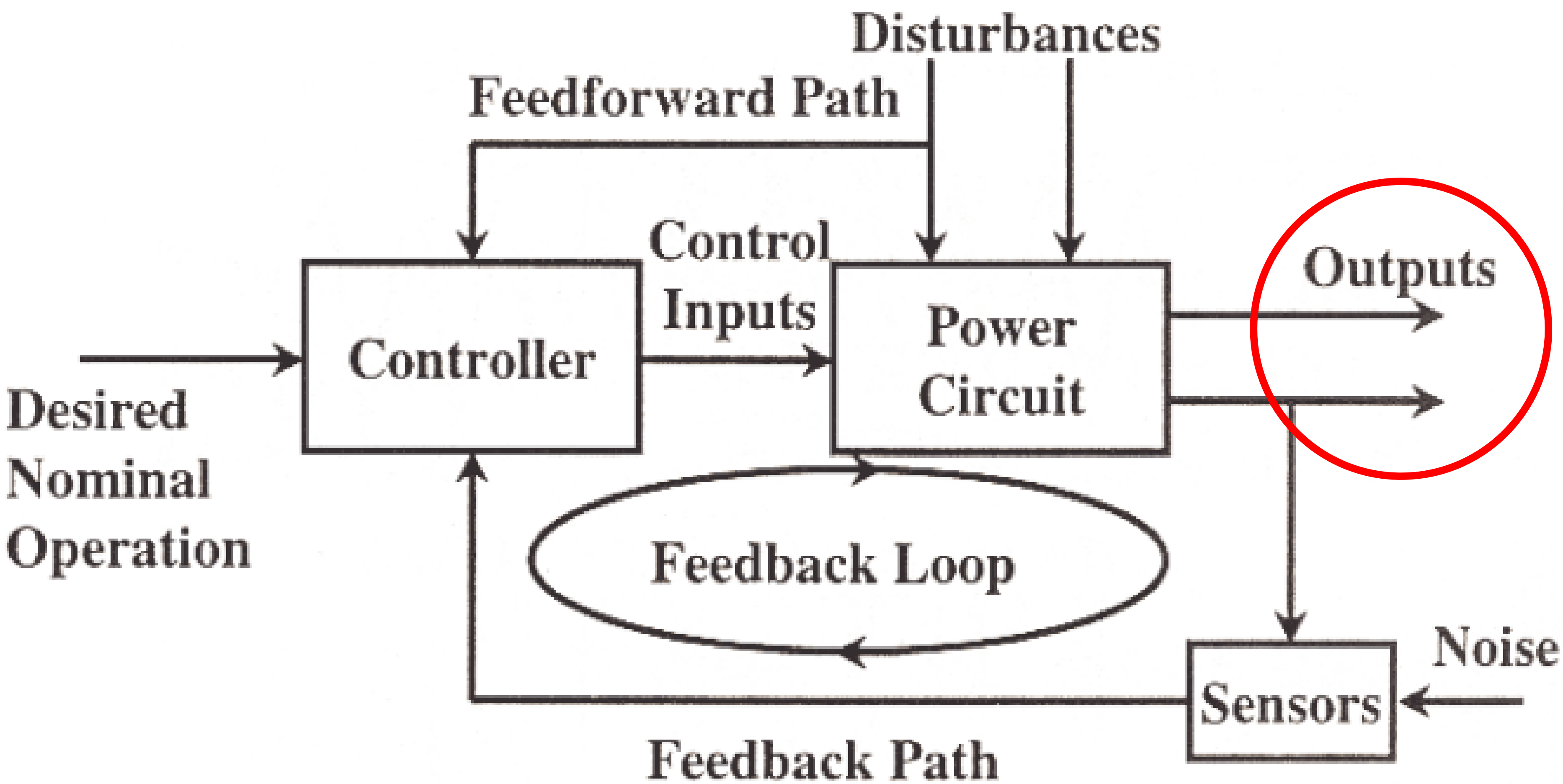
Strong Hybrid Vehicle High Voltage Electrical System

Toyota Prius Drivetrain



Control of Power Electronics

Controls of Power Electronics

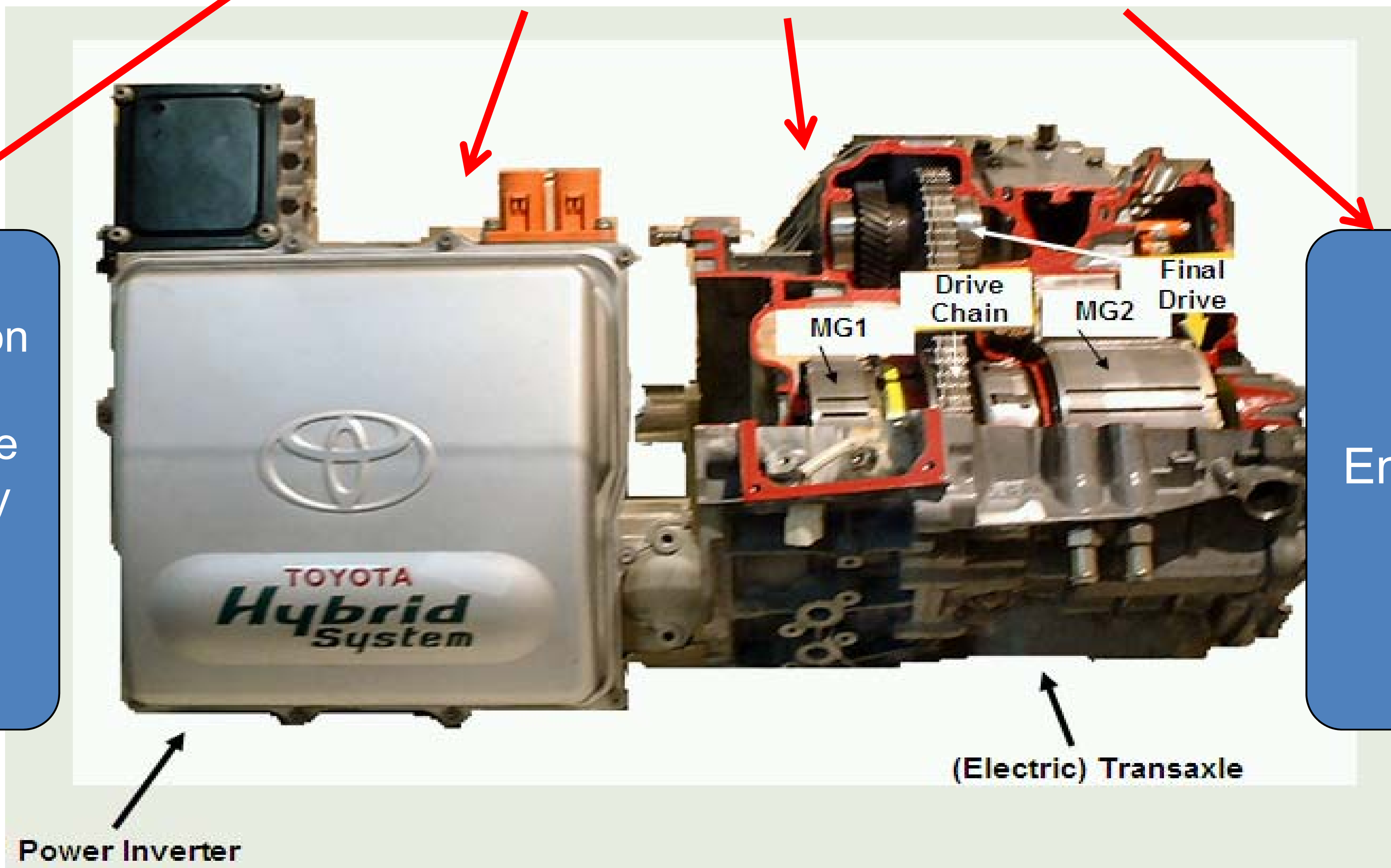


Output voltage ripple and dv/dt requirement are important factors for control system stability that uses DC voltage as feedback

Review: Hybrid Electric Drivetrain

Controller and Control Software

Traction High Voltage Battery

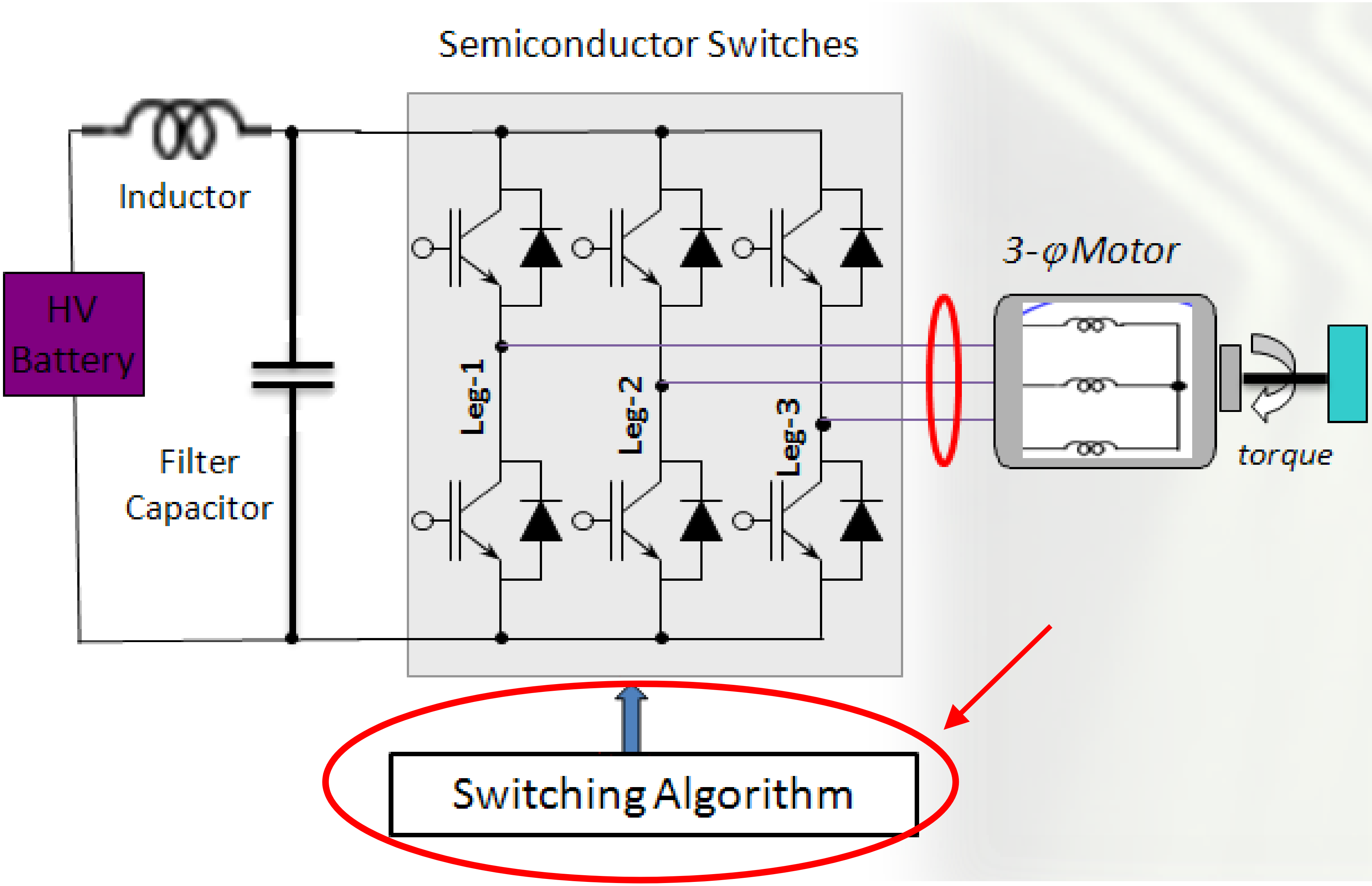


Engine

EV Motor Inverter Control System Input Signals

- Throttle Input (Torque Request)
- Encoder/Resolver (Rotor Position, Speed)
- Phase Current (AC)
- High Voltage (DC)
- Motor, IGBT Temperature
- Brake Inputs

Control of Power Electronics

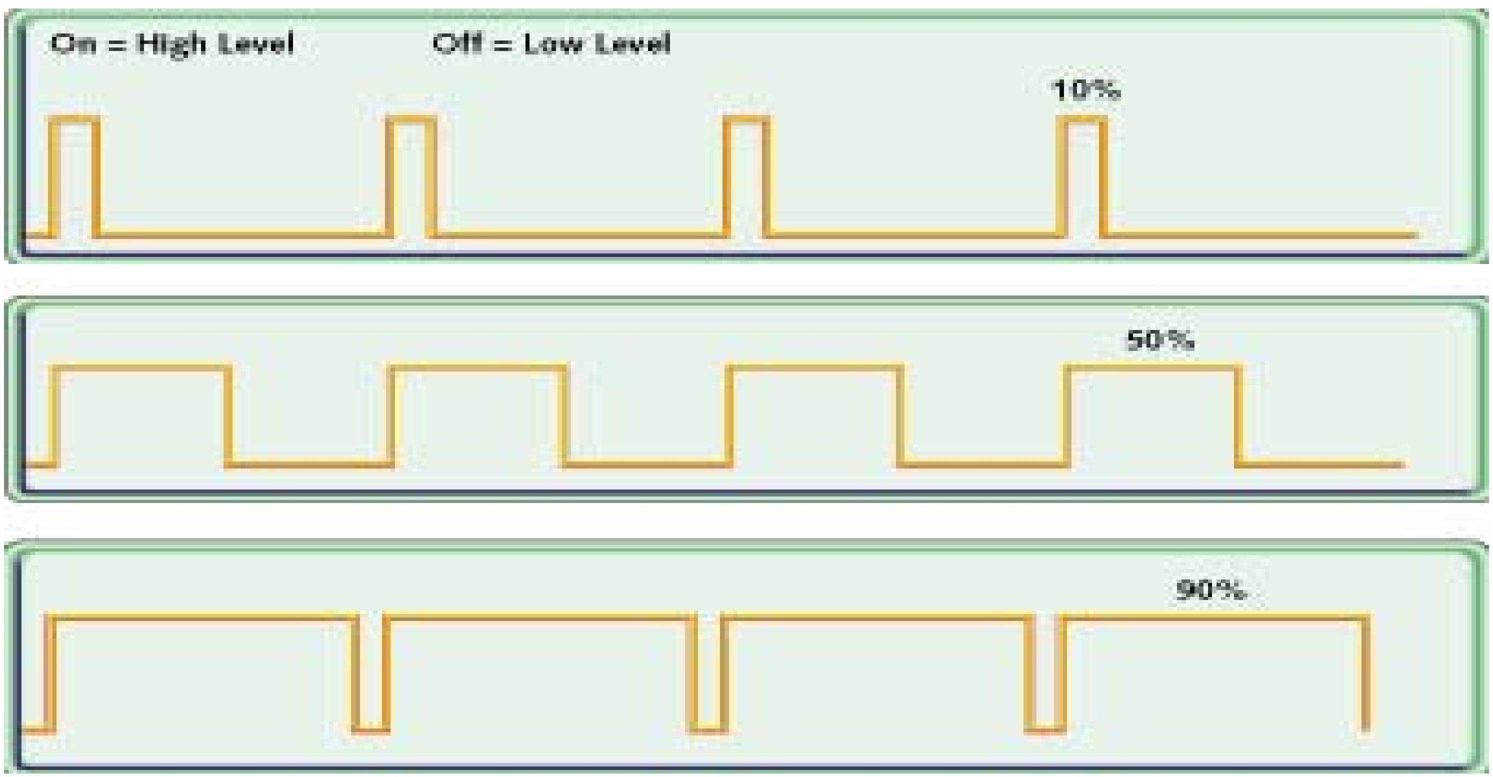


DC/AC Inverter Control Strategies

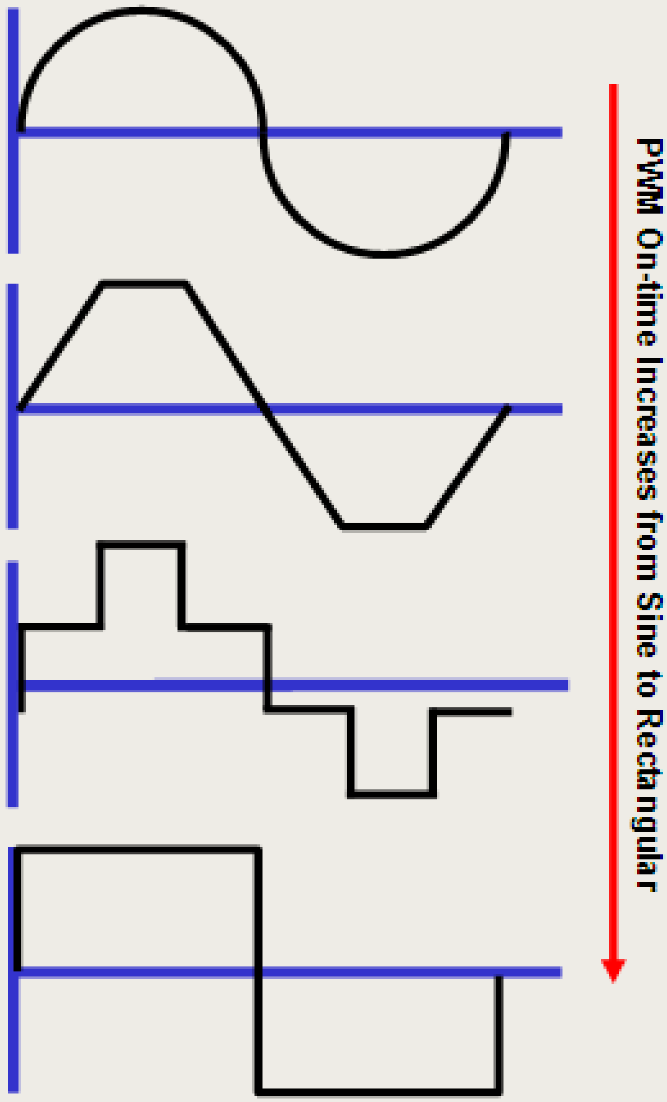
- Motor Control Pulse-Width Modulation (PWM) Waveforms
  - Six Step Wave
  - Sine Wave
  - Trapezoid Wave
  - Square Wave

What is Pulse-Width Modulation?

- The electric power control is performed using power converters. The converters transfer energy from a source in a switched operation mode that ensures high efficiency of the conversion.
- The algorithms that generates the switching functions are called Pulse-Width Modulation techniques.
- PWM is a modulation technique used to encode a message into a pulsing signal, mainly used to control of the power supplied to electrical devices



Motor Control Waveforms – Why So Many???.....To Increase Voltage At Motor



- As the waveforms move from Sine to Rectangular, the PWM patterns to create the waveforms increase the voltage "ON" time to the motor

- The decrease in PWM (and increase in "ON" time) permits the average voltage that is delivered to the motor to increase

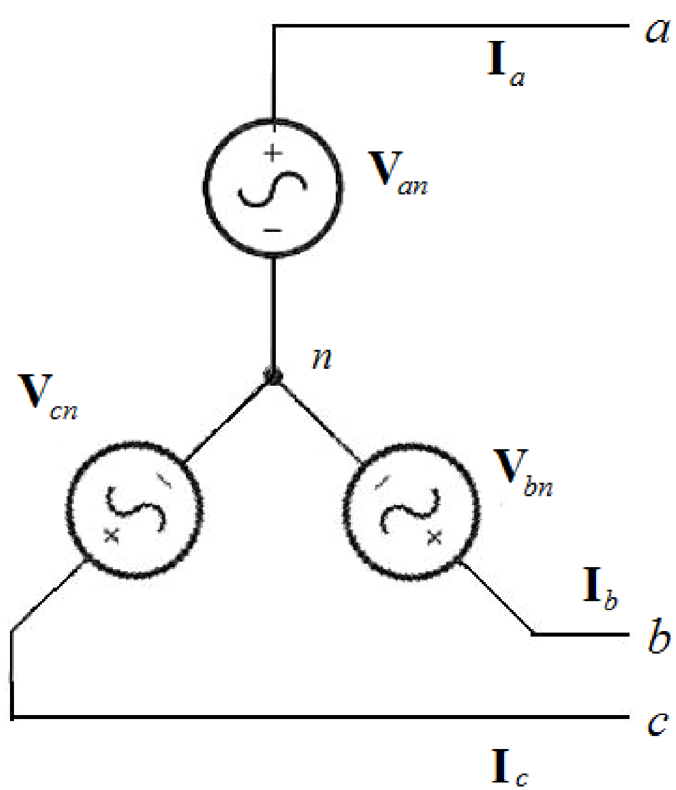
- Therefore, the motor has a higher working voltage that results in higher torque and rpm output

- On some manufacturer systems, ***Overmodulation*** control operates in tandem with voltage ***Boost*** control that provides higher modes of power coupled with waveform control to maximize drive system efficiency for a given driving condition

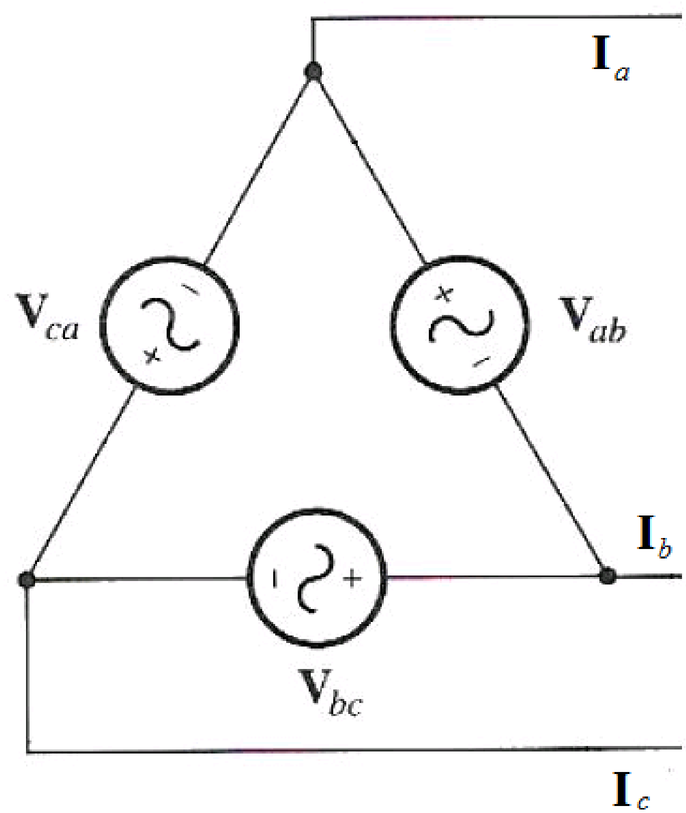
This changing of waveforms as a motor control strategy is termed ***Overmodulation***

Voltages and Currents in a 3-Phase Circuit

Y-connection

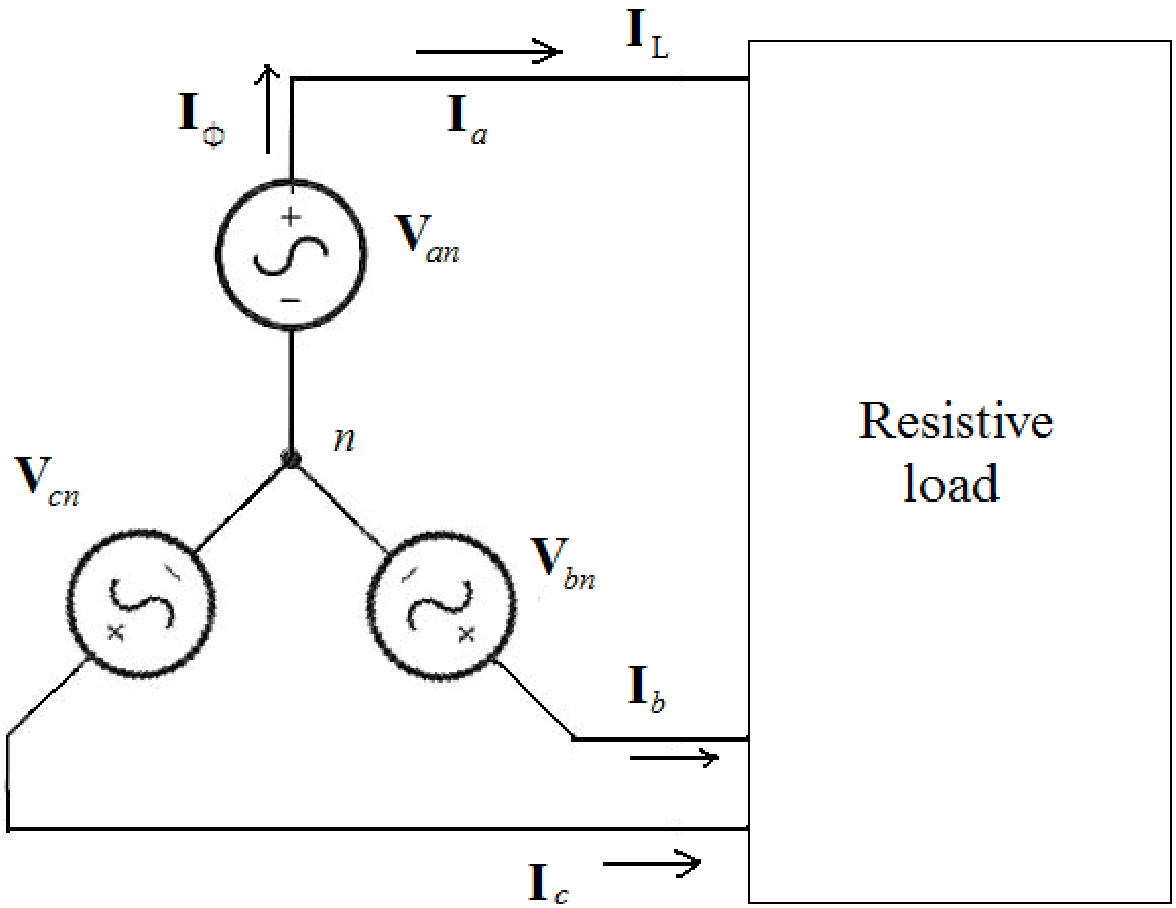


Δ-conncetion



Phase quantities: voltages and currents in a given phase
Line quantities: voltages between lines and currents in lines

Y-Connection



$$\mathbf{V}_{an} = V_\phi \angle 0^\circ$$

$$\mathbf{V}_{bn} = V_\phi \angle(-120^\circ)$$

$$\mathbf{V}_{cn} = V_\phi \angle(-240^\circ)$$

$$\mathbf{I}_a = I_\phi \angle 0^\circ$$

$$\mathbf{I}_b = I_\phi \angle(-120^\circ)$$

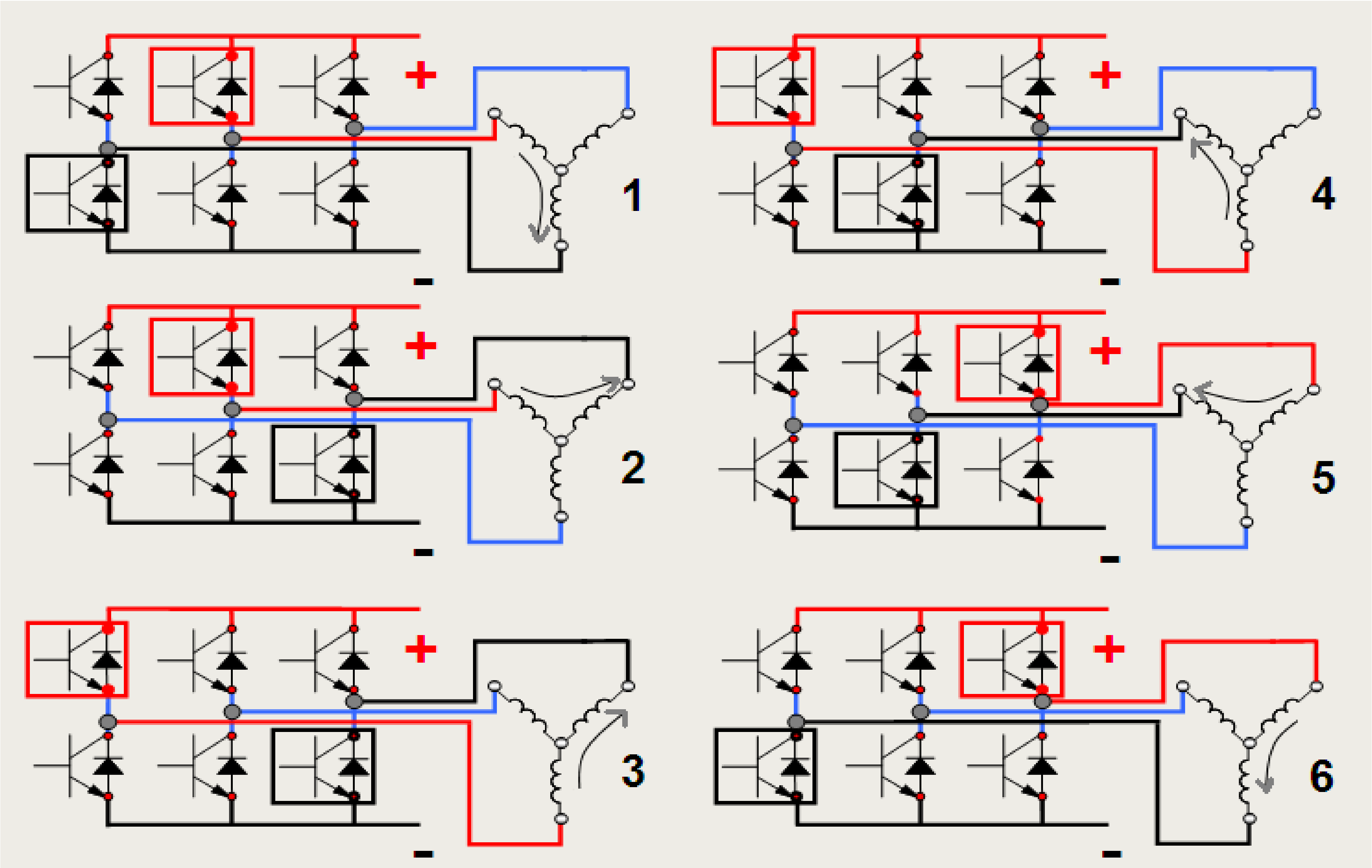
$$\mathbf{I}_c = I_\phi \angle(-240^\circ)$$

$$I_L = I_\phi$$

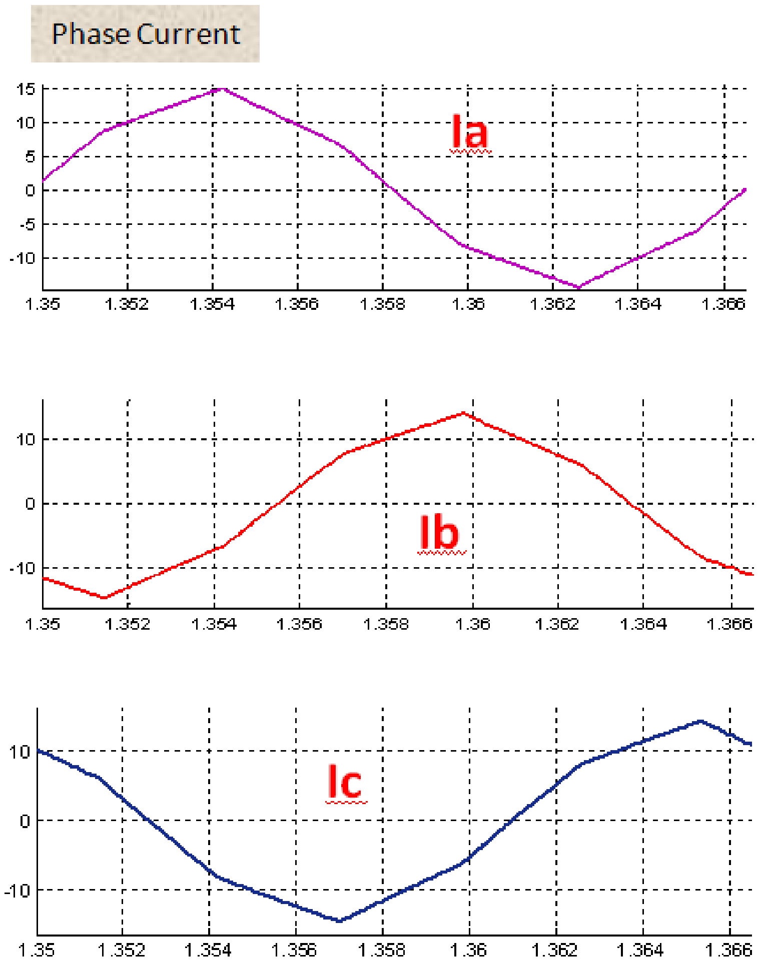
$$\mathbf{V}_{ab} = \mathbf{V}_a - \mathbf{V}_b = \sqrt{3} V_\phi \angle 30^\circ$$

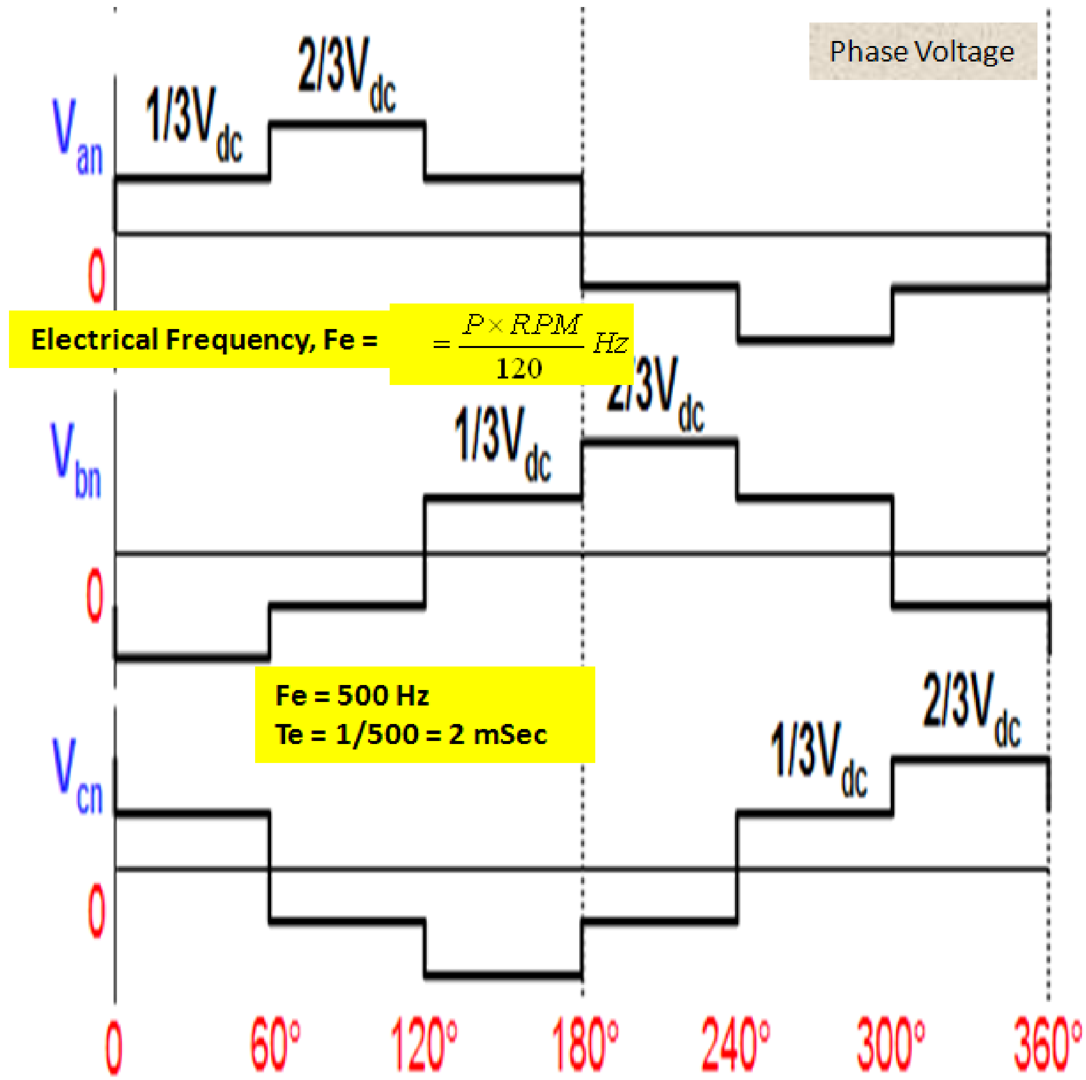
$$V_{LL} = \sqrt{3} V_\phi$$

Six-Step Switching Pattern



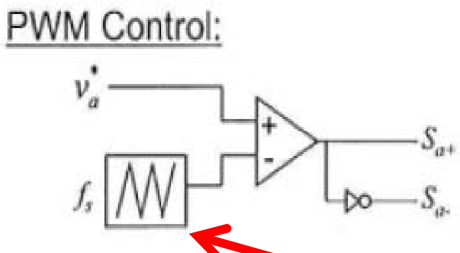
Voltage/ Current for Six-Step Inverter



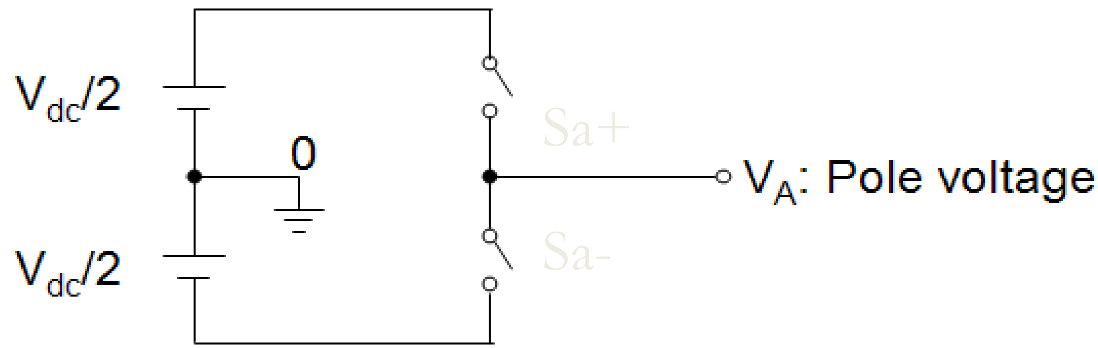


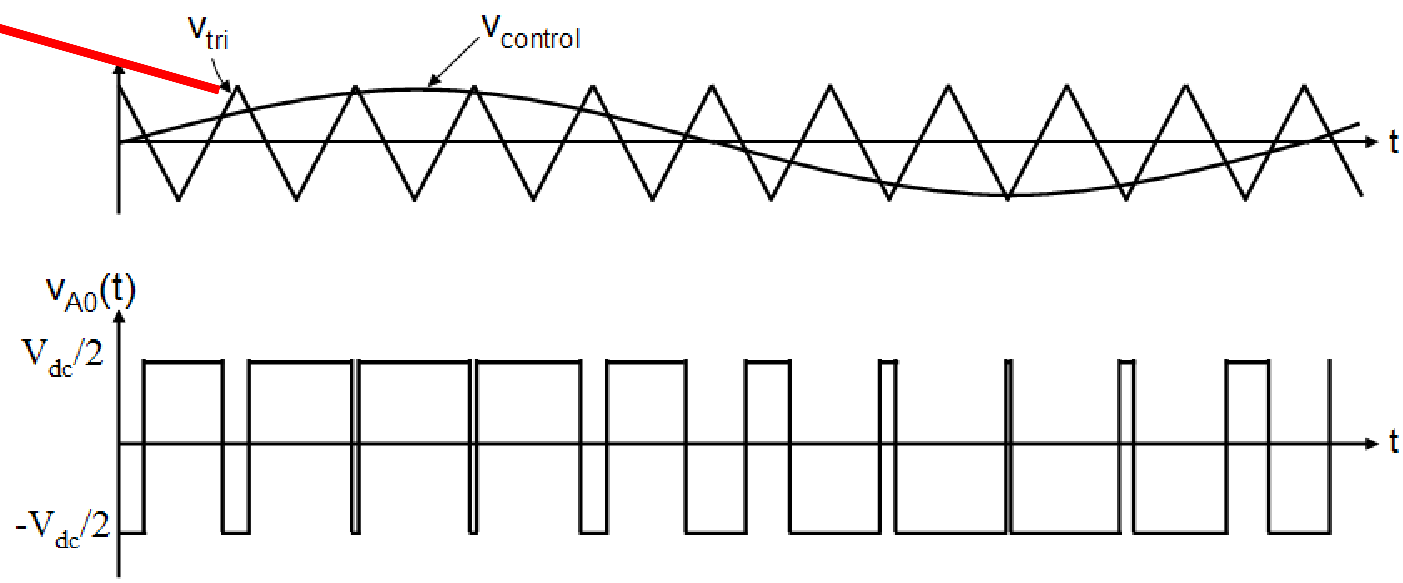
Pulse-Width Modulated VSI

- Pulse-Width Modulation (PWM)



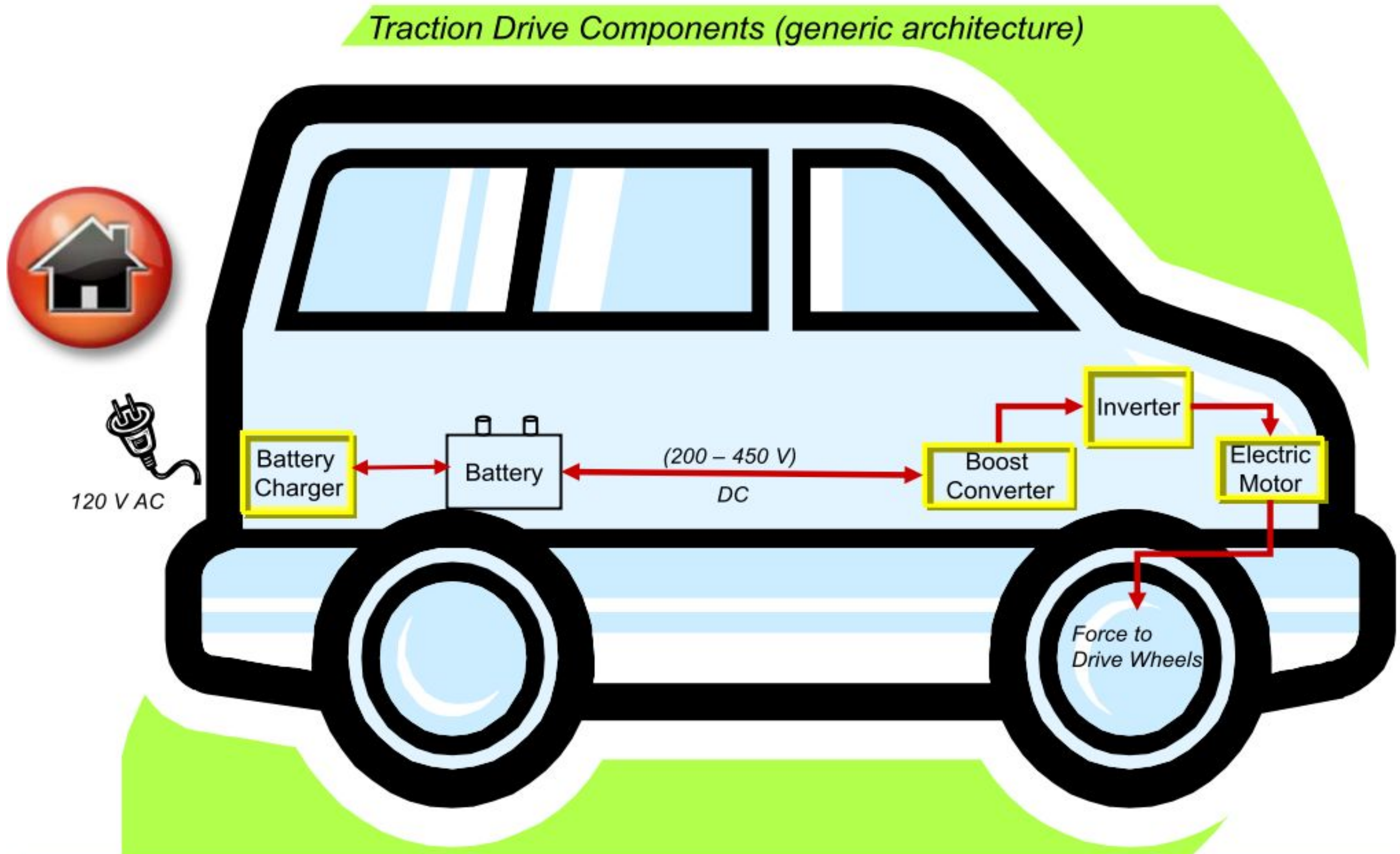
- Control Voltage v^*_a is Compared to a Δ-wave @ f_s
- Fundamental of Leg Output Follows v^*_a





DC-AC Inverter

Traction Drive Component General Architecture



Current power electronics and electric machine technologies must advance to achieve lower cost, smaller and lighter footprints, and higher efficiency to meet marketplace demands.

Traction Drive Components
(varies within vehicle architectures)

- ***Battery charger*** - plug-in vehicles require a battery charger.
- ***Boost converter*** – step up the battery voltage to a higher output voltage when the electronic circuit requires a higher operating voltage than the battery can supply.
- ***Inverter*** – convert direct current (DC) to alternating current (AC) to provide phased power for vehicle traction motors and generators.
- ***Electric motor*** - provide power for driving.

Power Management
(varies within vehicle architectures)

- ***Bi-directional DC-DC converter*** – step up or step down the high battery voltage to move power among vehicle buses to operate accessories, lighting, air conditioning, brake assist, power steering, etc.

Inverter Definition/ Classification

Definition:

Converts DC power to AC power (e.g., "**Motoring**" electrical → mechanical)

AC power to DC power (e. g., "**Generating**" mechanical → electrical)

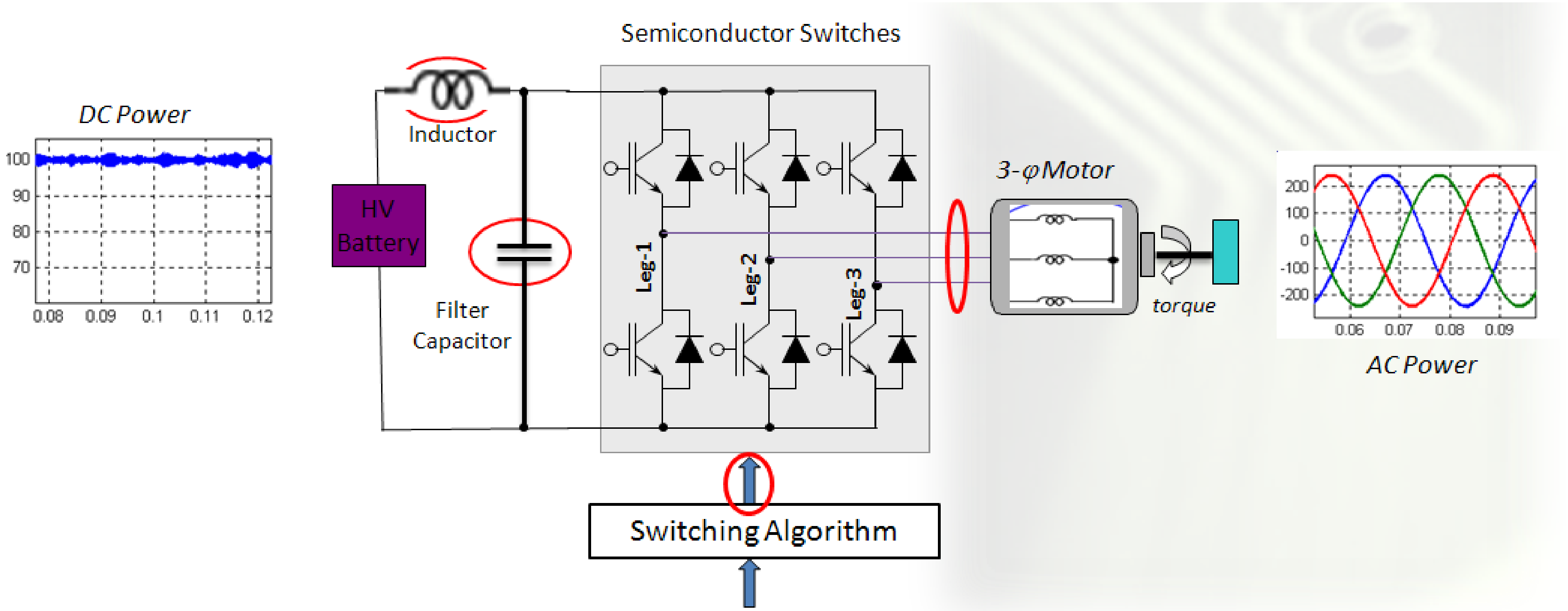
Classification:

a)Voltage Source Inverter (VSI), Current Source Inverter (CSI)

b)Single phase (for single phase load) vs. Three phase (for three phase motor)

c)Sine PWM (CPWM, DPWM), Space Vector PWM, Bang-bang PWM inverter

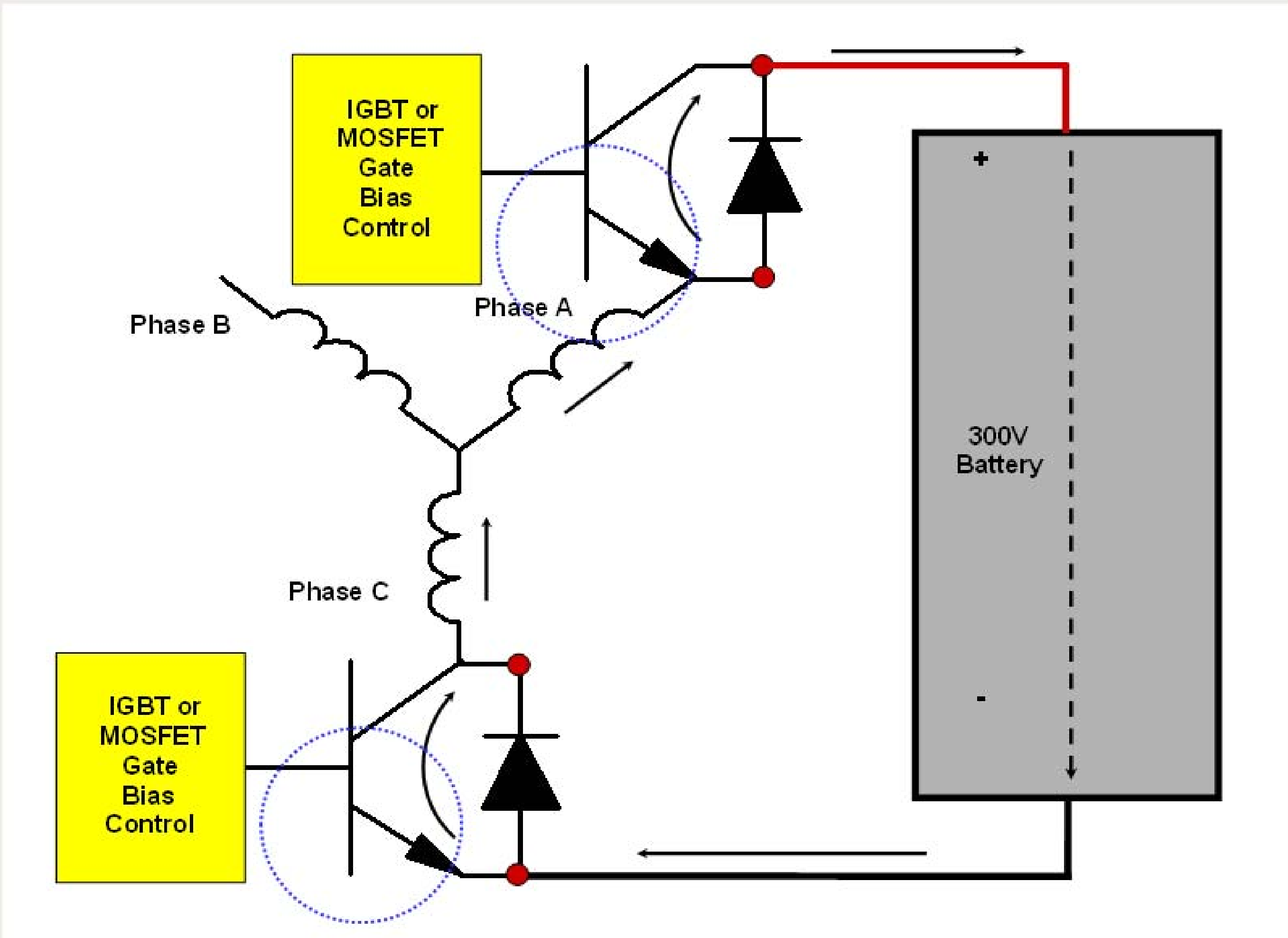
d)Six-Step vs. Pulse-Width Modulated (PWM) inverter



Why use ac instead of dc Voltage/Current ?

ac is more efficient and the oscillating waveform produces polarity changes in an inductor that will produce electrical power created by electro-magnetism

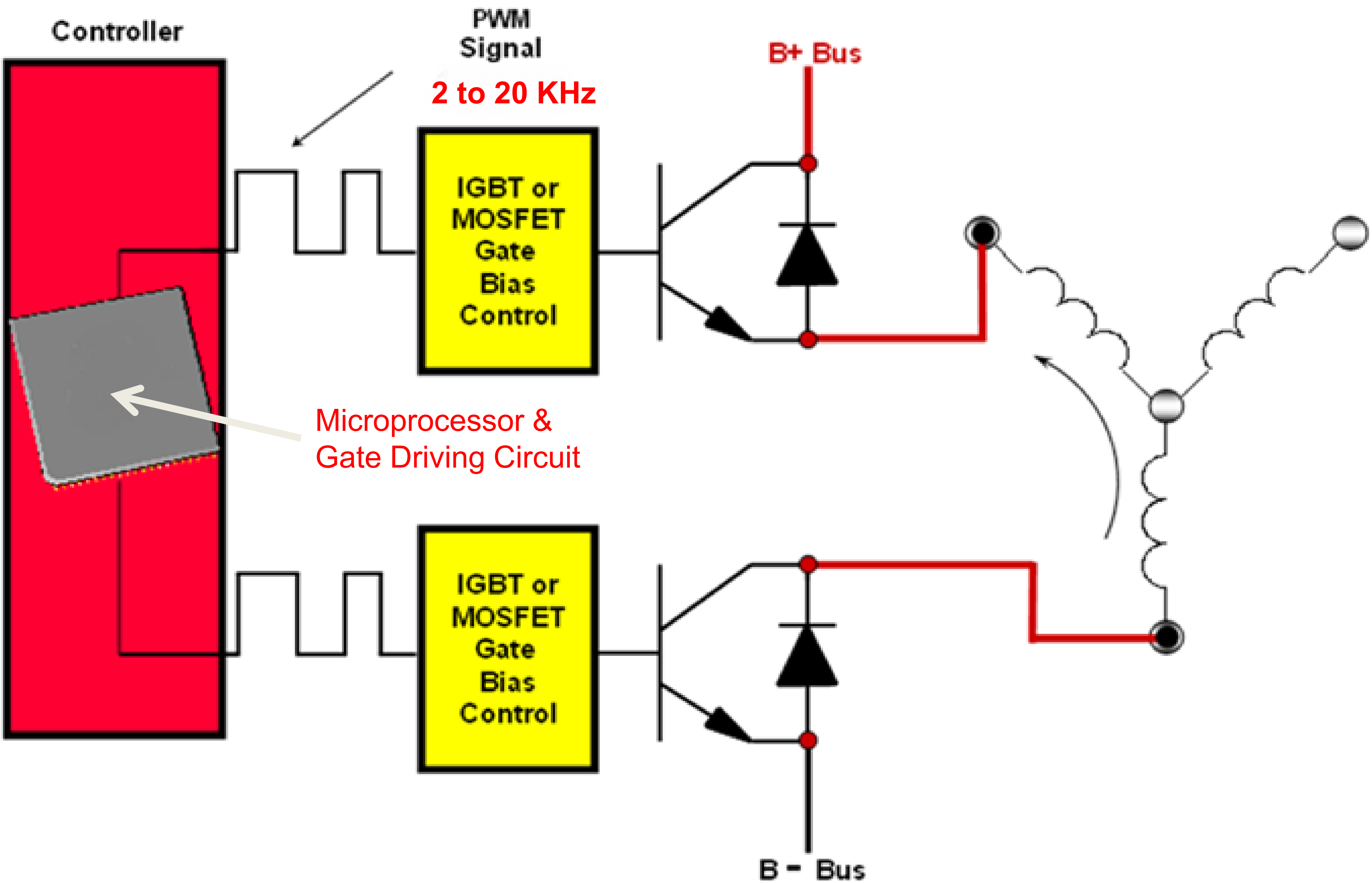
EV Propulsion Mode



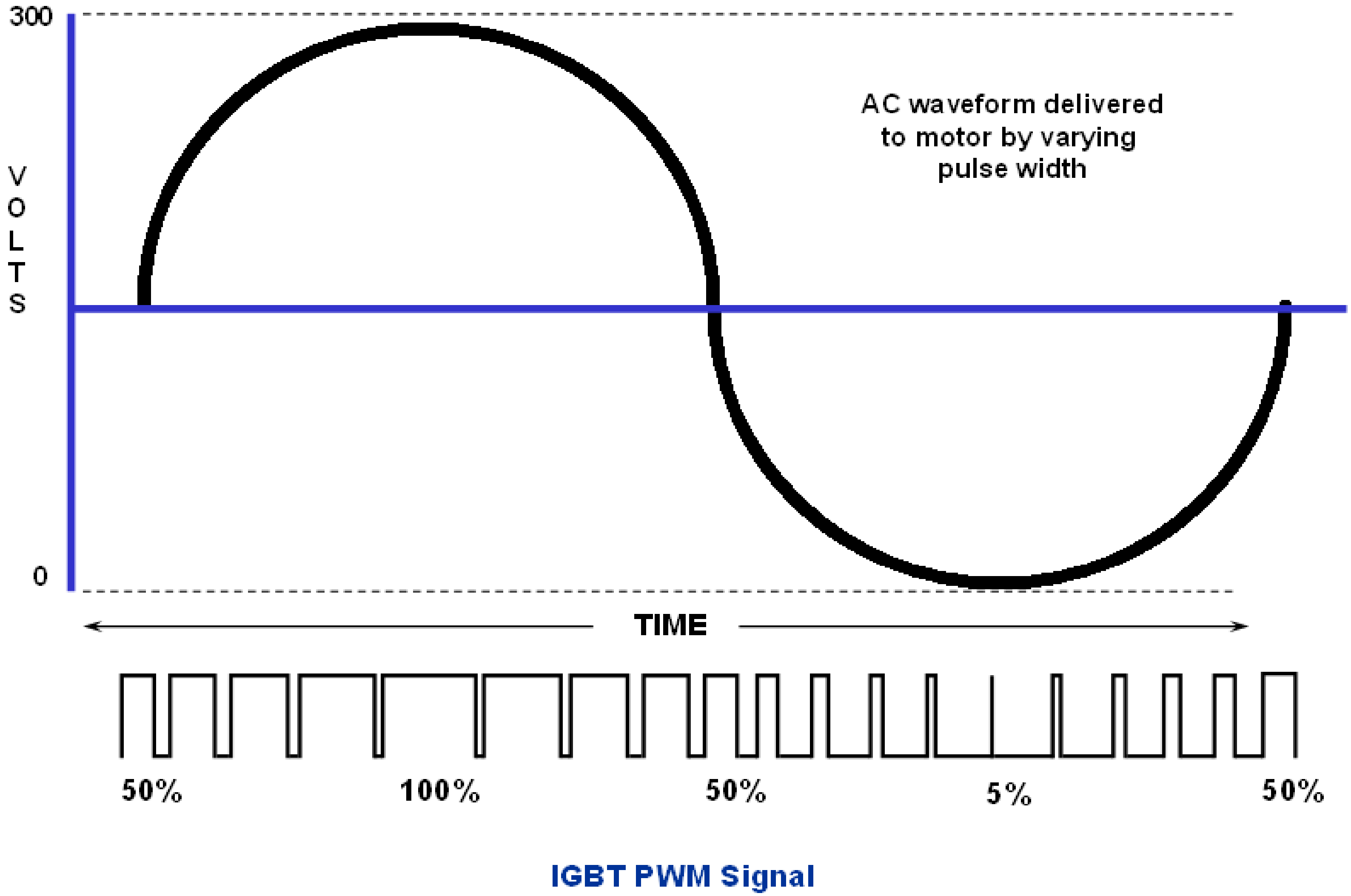
Current flows from Battery Negative Terminal through lower transistor, Phase C to Phase A, upper transistor, and finally to Battery Positive terminal

PWM of transistors gates control amplitude of waveform delivered to motor

Basic Controller and IGBT Drive Circuit

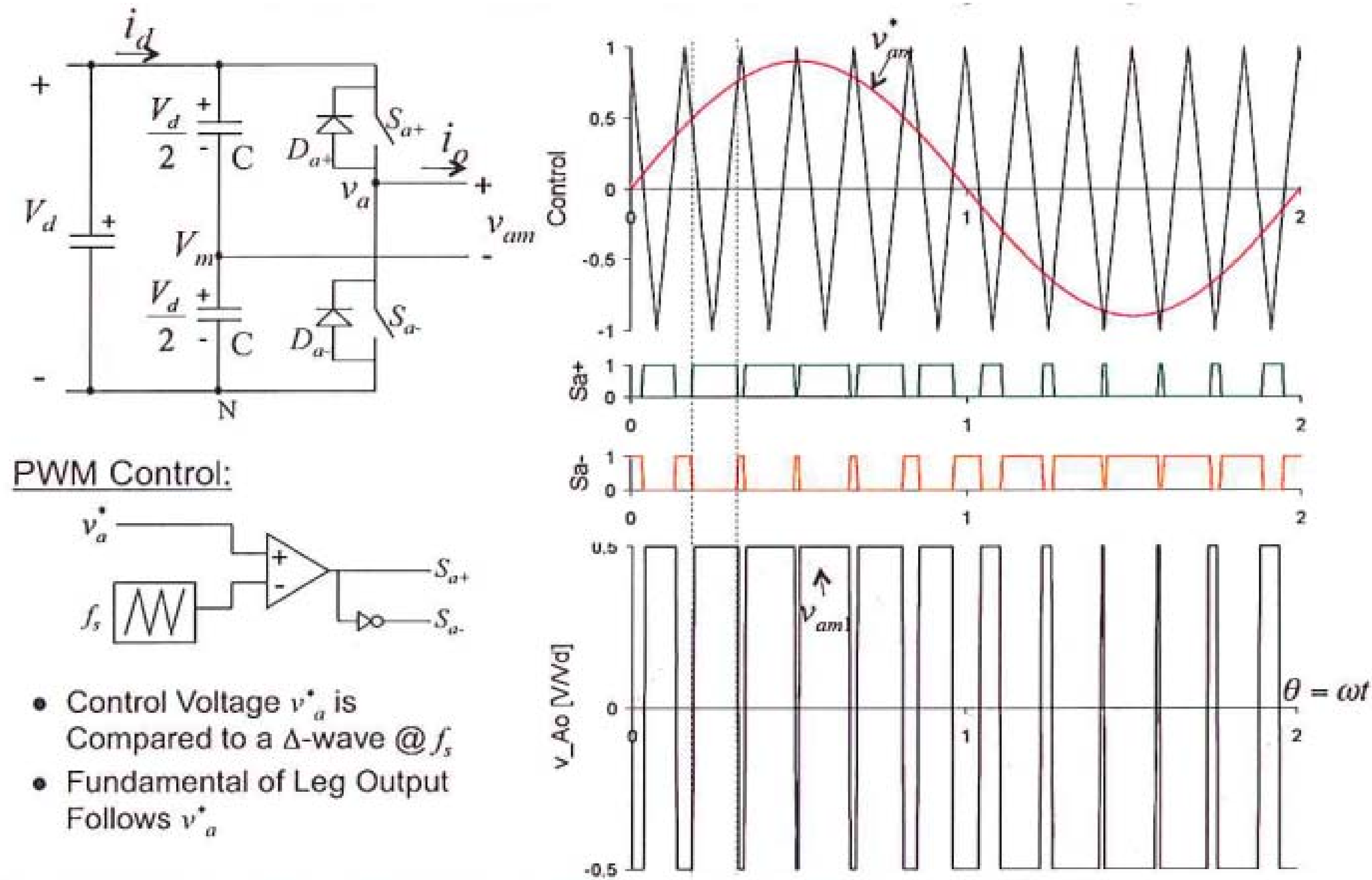


Synthesizing A Sine Wave from Inverter

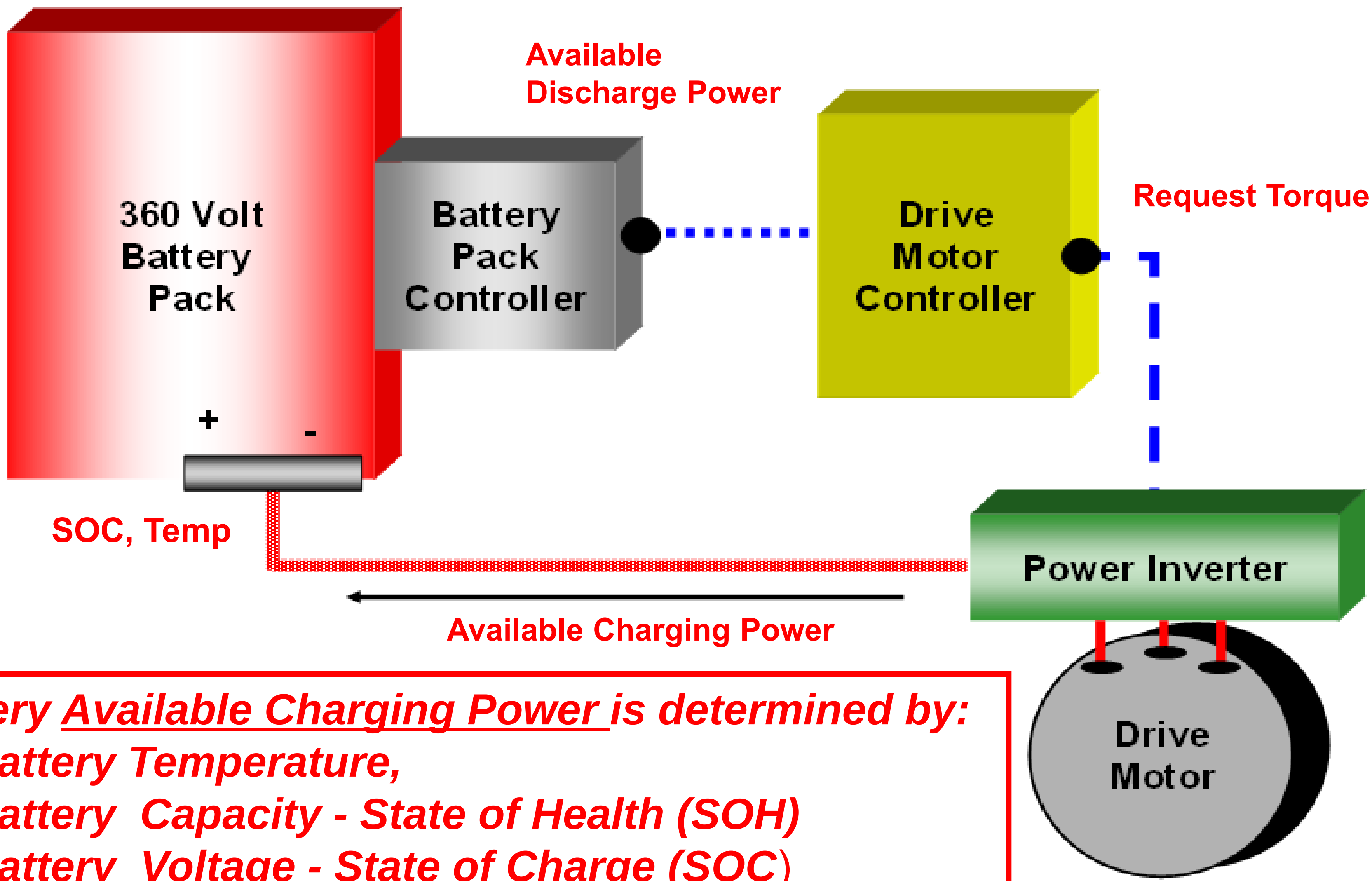


Sine-Triangle Pulse Width Modulation (PWM)

With sine-triangle PWM, the highest possible peak phase fundamental voltage is 0.5Vdc

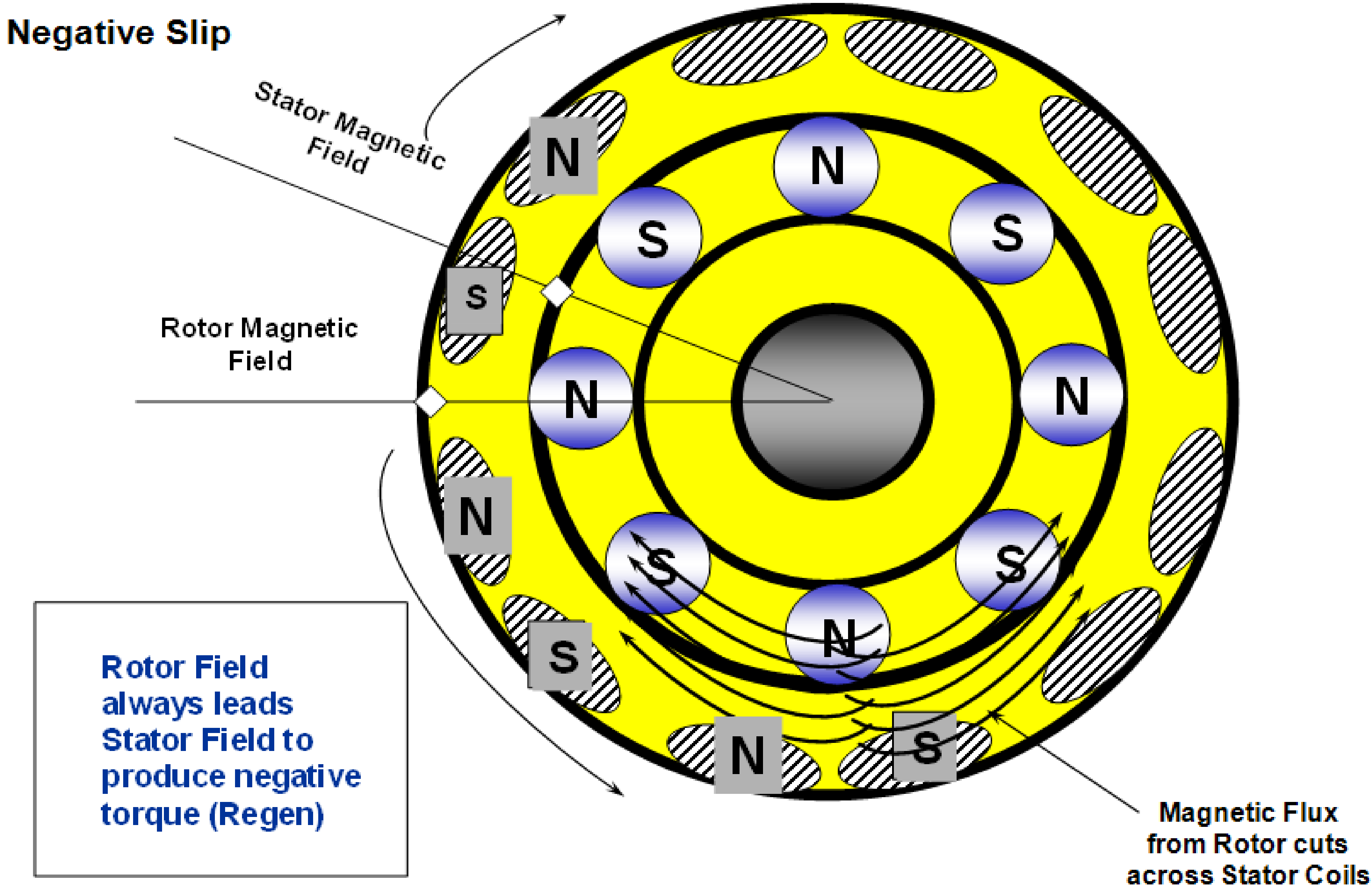


EV Regenerative Brake Operation

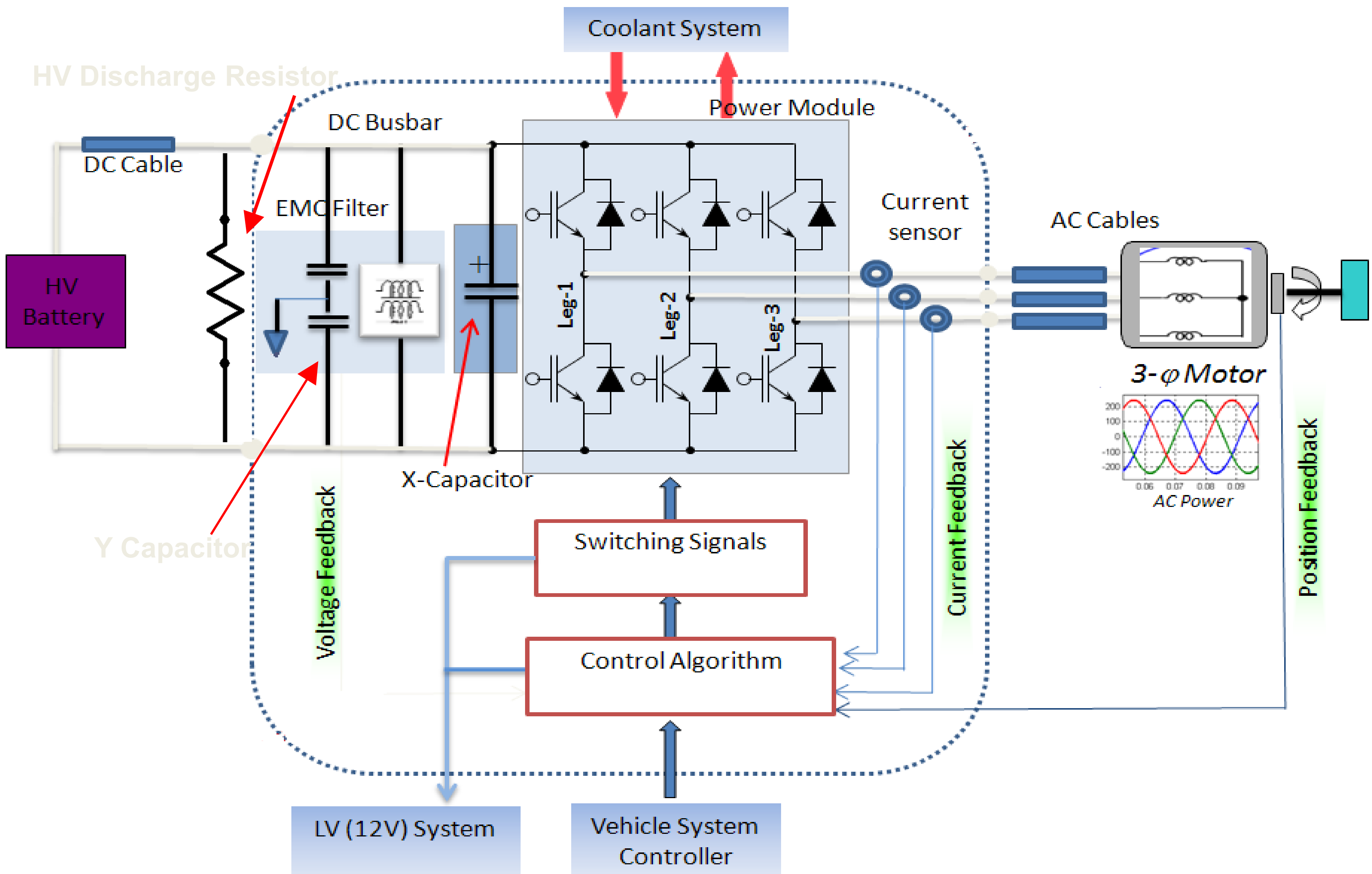


Battery Available Charging Power is determined by:
(1) Battery Temperature,
(2) Battery Capacity - State of Health (SOH)
(3) Battery Voltage - State of Charge (SOC)

Stator Field spins faster than Rotor Field -> Motoring
Rotor Field spins faster than Stator Field -> Generating



Complete EV Propulsion System and DC/AC Inverter Interfaces



2010 Toyota Prius Inverter

DC-AC Inverter + DC-DC Converter + DC-DC Booster

The 3rd Generation Power Control Unit (PCU)

Table 2 Specification of PCU

		Current model	**New model**
Max Total Output	KVA	162	**178**
Max Boost Voltage	V	500	**650**
Generator max current	Arms	75	**88**
Motor max current	Arms	230	**170**
Incoporated main components	-	Boost converter Generator inverter Motor inverter DC/DC converter A/C inverter	Boost converter Generator inverter Motor inverter DC/DC converter MG ECU
Weight	kg	21	**13.5**
Volume	Liters	17.7	**11.2**

Source: SAE 2009-01-1310

2010 Toyota Prius Inverter

The high voltage system has increased the maximum voltage of the boost converter from 500V to 650V. The higher voltage enabled the use of a high-speed, high power of motor with motor speed reduction device. The higher boost voltage leads to downsizing and system efficiency improvement.

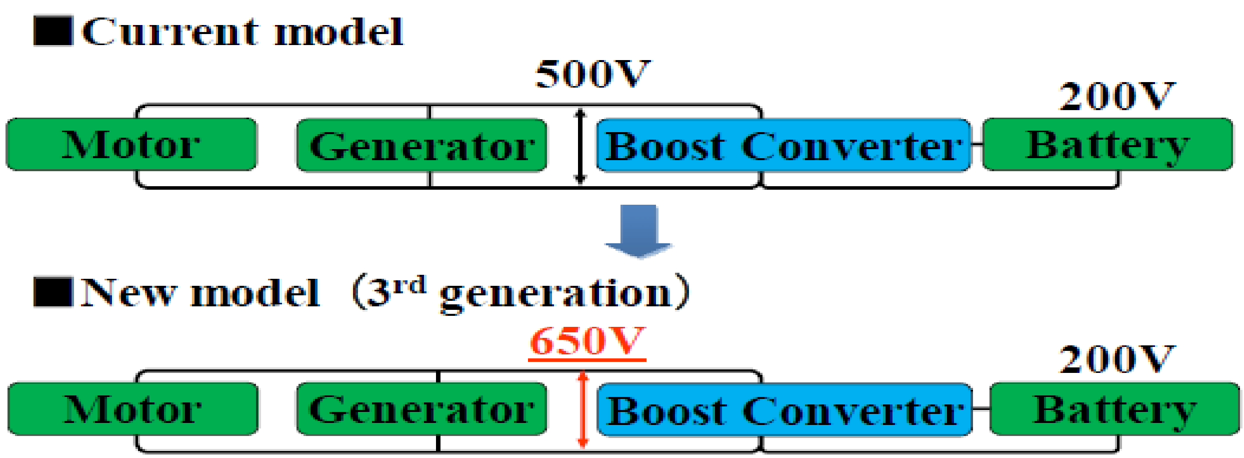


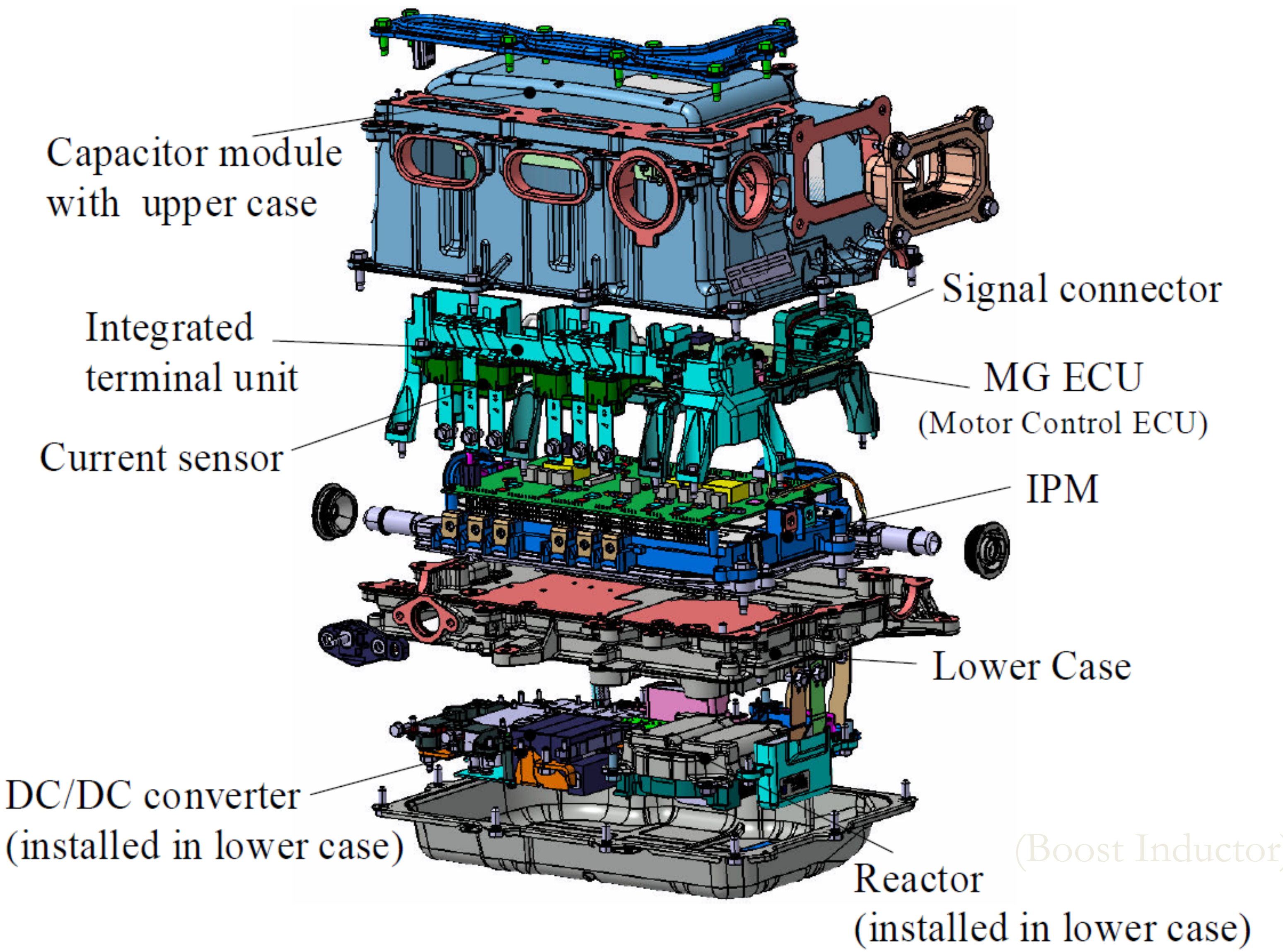
Fig. 2 Composition of HV system

Table 1 Specification of HV system

	Current model	**New model**
Boost Voltage	500V	**650V**
System max output	82kW	**100kW**
Motor max output	50kW	**60kW**
Motor max rotation speed	6000rpm	**13000rpm**
Improvement ration of fuel consumption	-	**14% @100km/h**

Source: SAE 2009-01-1310

2010 Toyota Prius Inverter

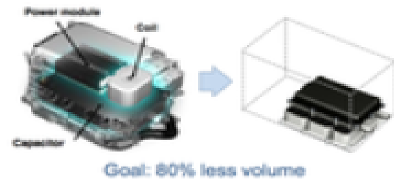


Source: SAE 2009-01-1310

Advanced Automotive Power Electronics Development

Toyota and Denso develop SiC power semiconductor for power control units; targeting 10% improvement in hybrid fuel efficiency

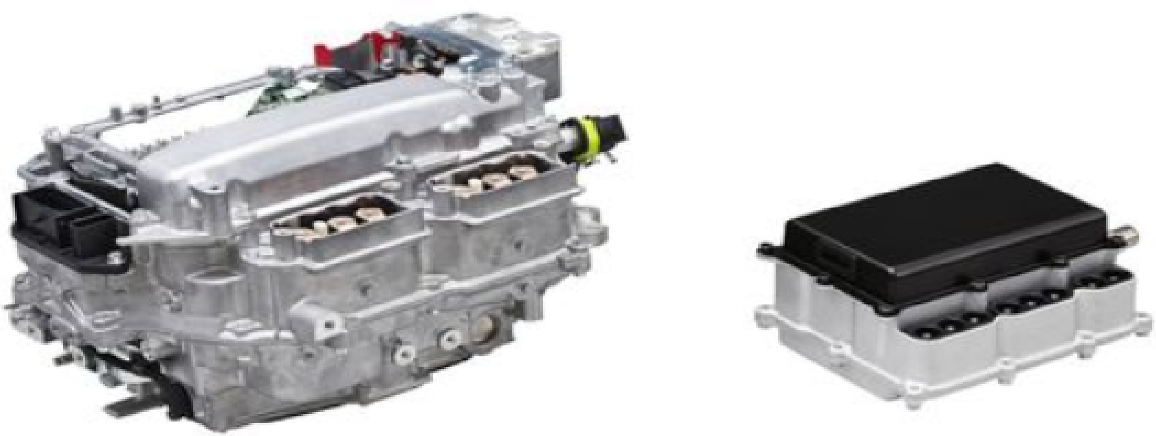
20 May 2014



Toyota intends to leverage the benefits of high frequency and high efficiency of SiC power semiconductors to enable PCU downsizing of 80%. Click to enlarge.

Toyota Motor Corporation, in collaboration with Denso Corporation (Denso) and Toyota Central R&D Labs., Inc. (Toyota CRDL), has developed a silicon carbide (SiC) power semiconductor for use in automotive power control units (PCUs). Toyota will begin test driving vehicles fitted with the new PCUs on public roads in Japan within a year.

Compared to silicon, SiC power semiconductors lose 1/10 the power and drive frequency can be increased by a factor of ten. This enables the coil and capacitor, which account for approximately 40% of the size of the PCU, to be reduced in size. Through use of SiC power semiconductors, Toyota aims to improve hybrid vehicle (HV) fuel efficiency by 10% under the Japanese Ministry of Land, Infrastructure, Transport and Tourism's (MLIT) JC08 test cycle and reduce PCU size by 80% compared to current PCUs with silicon-only power semiconductors.



***Left**:PCU with silicon power semiconductors (Production model). **Right**:PCU with SiC power semiconductors (Future target). Click to enlarge.*

DC/DC Converter

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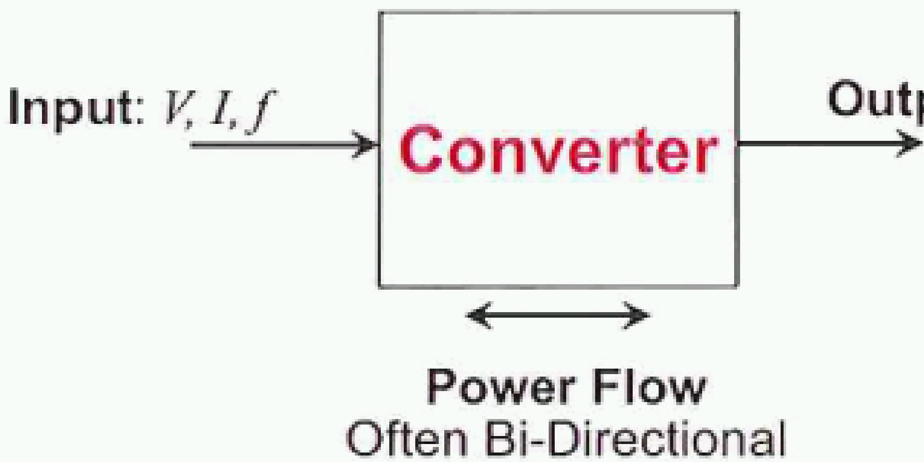
Power Electronics Converters

- Converters are Developed for *Electrical Energy Conversion*:

Conversion	Application
DC-to-DC	Voltage-Level Conversion: Power Supply
AC-to-DC	Rectification: Input Power from AC Line
DC-to-AC	Inverter: Output Power to AC Load
AC-to-AC	AC Voltage/Frequency Control

- In General Power is *Processed* from one Form to Another:



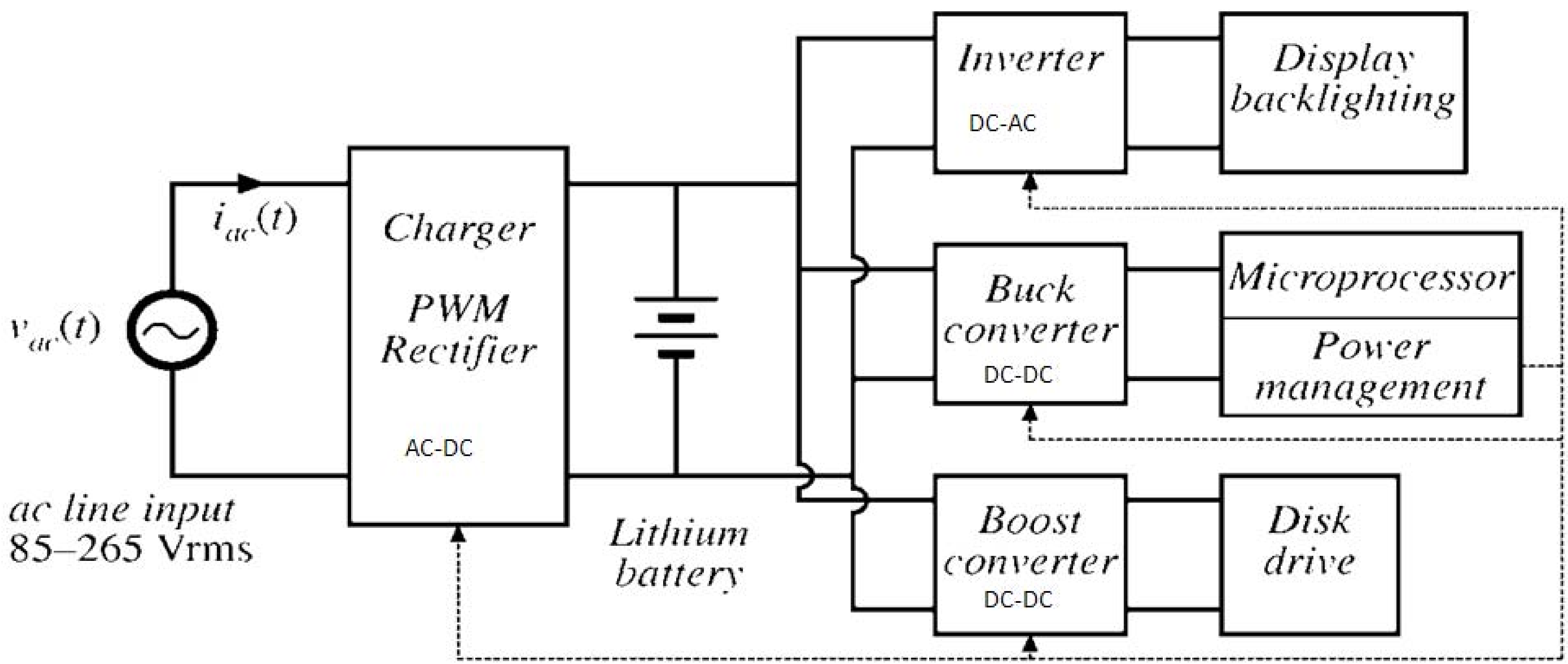
"Electronic Transmission":
$P_{loss} \rightarrow 0$

DC-DC Converters

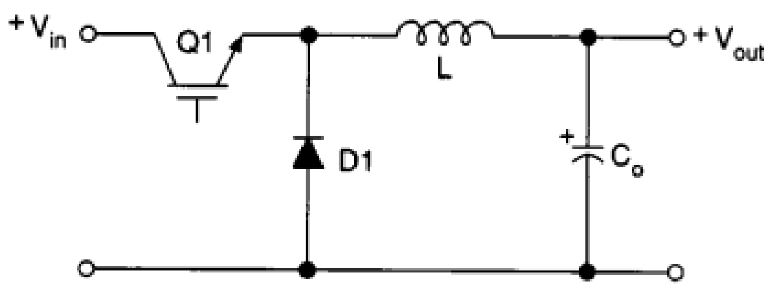
- DC-DC converters are used to convert unregulated dc voltage to regulated or variable dc voltage at the output.
- They are widely used in switch-mode dc power supplies and in dc motor drive applications.
- In dc motor control applications, they are called chopper-controlled drives. The input voltage source is usually a battery or derived from an ac power supply using a diode bridge rectifier. These converters are generally either hard-switched PWM types or soft-switched resonant-link types.
- There are several dc-dc converter topologies, the most common ones being buck converter, boost converter, and buck-boost converter

Power Electronic Applications

A laptop computer power supply system



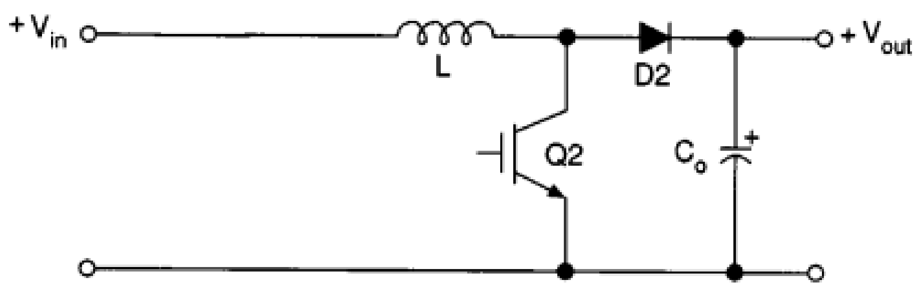
DC to DC Converter Configurations



(a)

(a) Buck Converter

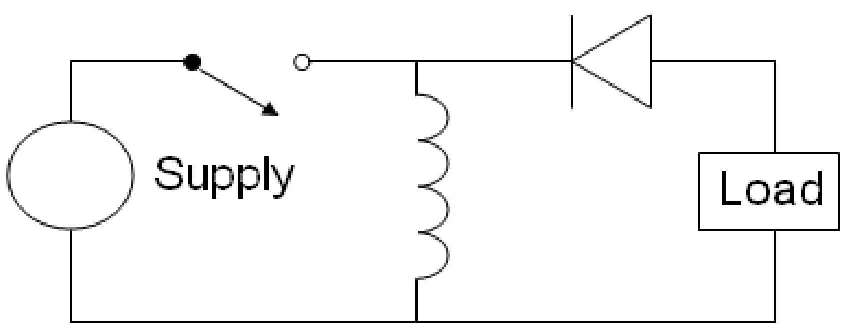
(Step-Down)



(b)

(b) Boost Converter

(Step-Up)

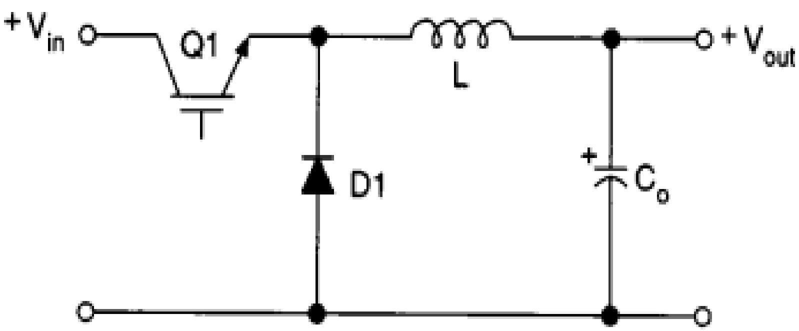


(c)

(c) Buck-Boost Converter

(the output voltage can be higher or lower than input voltage)

Buck Converter



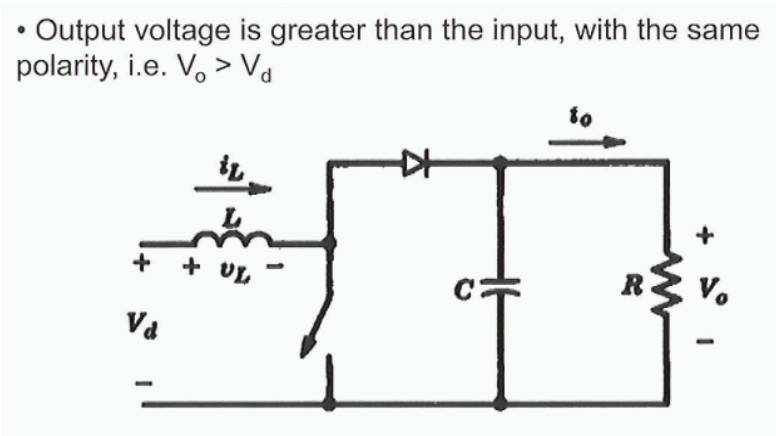
- The average output voltage is given by

$$V_{\text{out}} = DV_{\text{in}}$$

- D is the duty cycle of the switch and is given by D = ton/T
- T is the time for one period
- 1/T is the switching frequency of the power device IGBT

- ***A buck converter is also called a step-down converter.***
- The IGBT or MOSFET acts as a high-frequency switch.
- The IGBT is repetitively closed for a time ton and opened for a time toff.
- During ton, the supply terminals are connected to the load, and power flows from supply to the load. During toff, load current flows through the freewheeling diode D1, and the load voltage is ideally zero.

Boost Converter

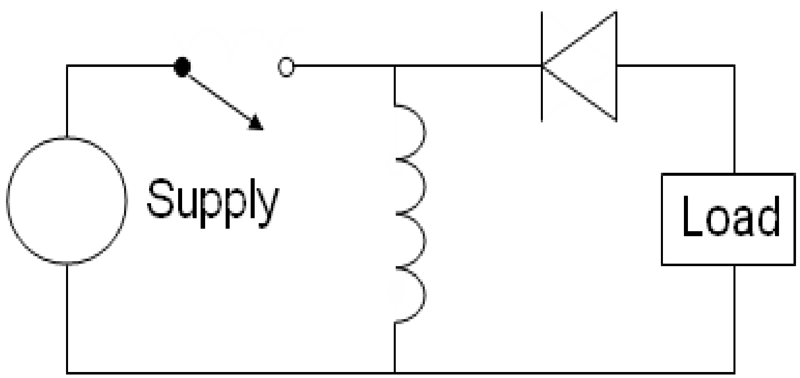


- ***A boost converter is also called a step-up converter.***
- This converter is used to produce higher voltage at the load than the supply voltage.

- When the power switch is on, the inductor is connected to the dc source and the energy from the supply is stored in it.
- When the device is off, the inductor current is forced to flow through the diode and the load.
- The induced voltage across the inductor is negative. The inductor adds to the source voltage to force the inductor current into the load
- The output voltage is given by $$V_{out} = \frac{V_{in}}{1 - D}$$

D in the range 0 < D < 1, the load voltage Vout will vary in the range Vin < Vout < ∞

Buck-Boost Converter



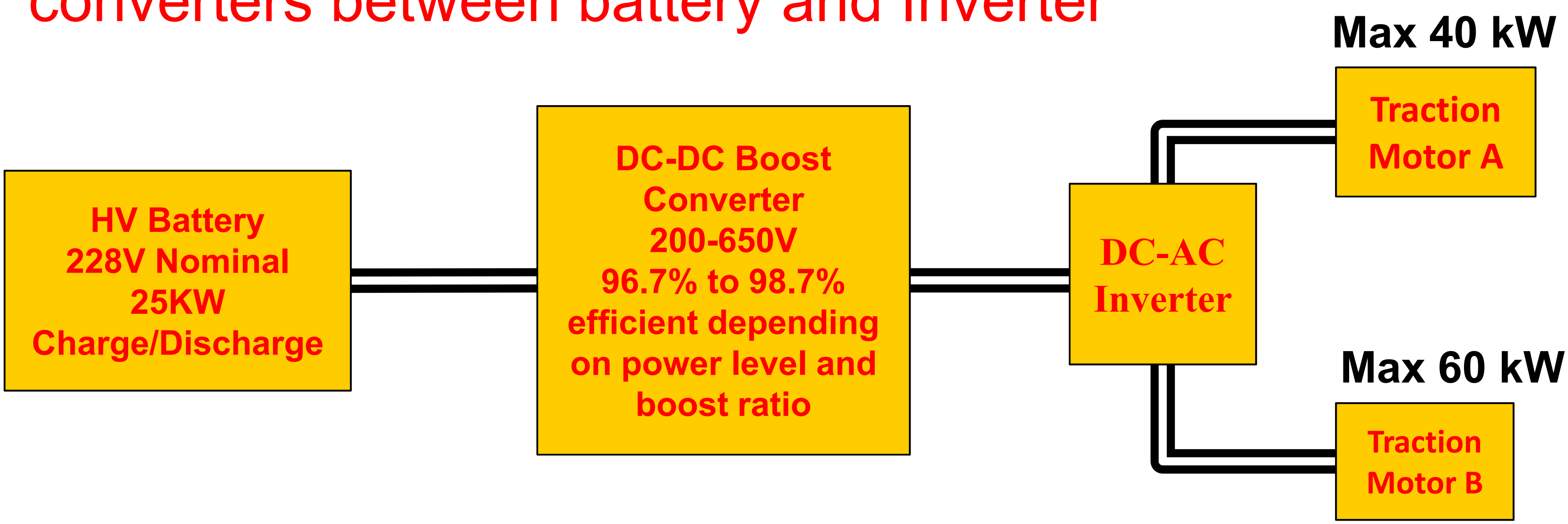
- Buck-Boost Converter allows the output voltage to be higher or lower than the input voltage, based on the duty cycle D.

$$V_{out} = V_{in} \frac{D}{1 - D}$$

- When the power device is turned on, the input provides energy to the inductor and the diode is reverse biased. When the device is turned off, the energy stored in the inductor is transferred to the output. No energy is supplied by the input during this interval.
- In dc power supplies, the output capacitor is assumed to be very large, which results in a constant output voltage.

High Voltage Architecture – Boost Converters In Hybrid Electric Vehicles

- Toyota hybrid systems have DC-DC converters between battery and Inverter



Example: 2010 Toyota Prius System

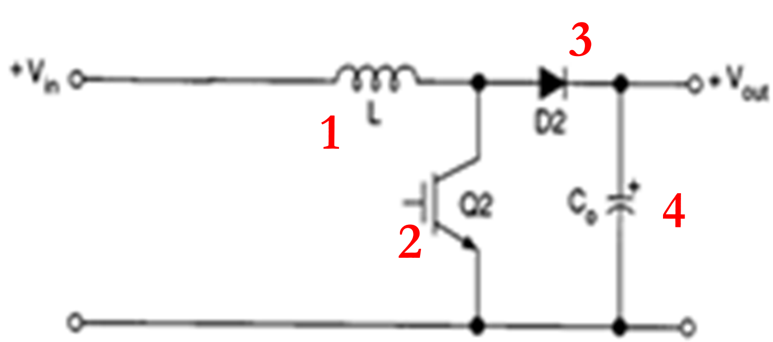
- **Vehicle Mass and Performance Requirements set battery power requirement**

How Regenerative Braking Charge Battery

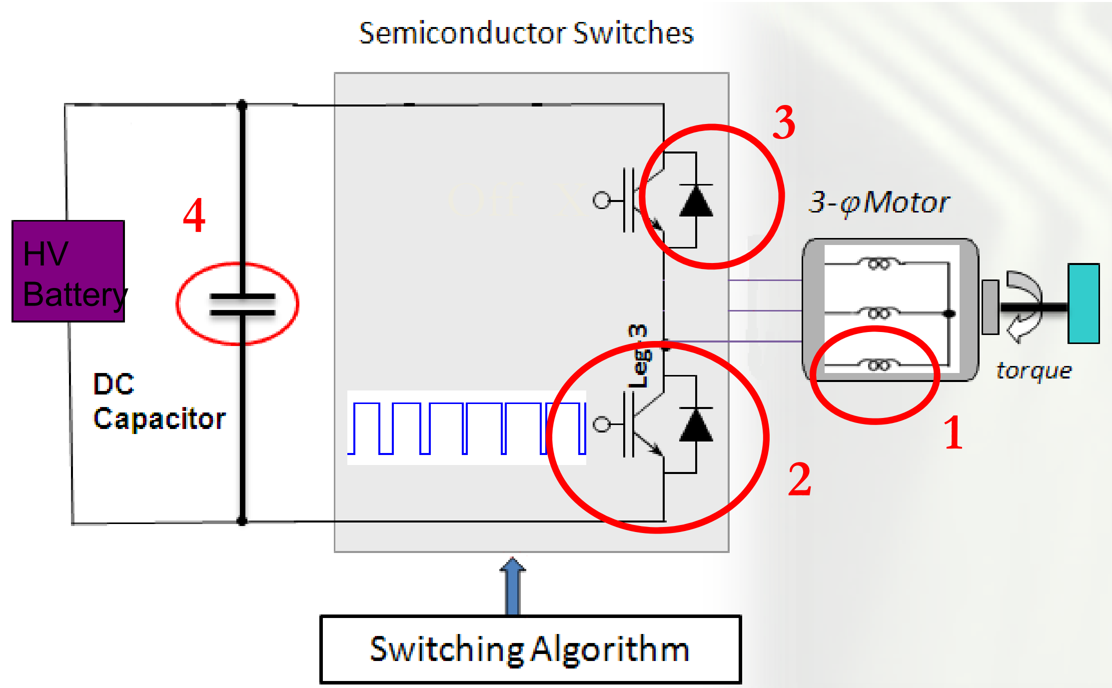
- To charge the battery, the motor has to produce higher voltage than the battery voltage
- If the motor rotor is spinning faster, the rotor magnetic flux is rotating faster then the stator flux, the back emf from motor could be higher then the battery voltage
- How to keep control of the charging when the speed of the rotor (=the speed of drive shaft = the speed of vehicle) is slowing down?
- To get regen at low speeds, you need to put a boost converter between the motor (generator) and the battery
- This will take the lower voltage from the motor (generator) and increase it to a higher voltage to the battery.

Control of Regenerative Voltage

- When regenerating, turn the upper side IGBTs OFF
- The PWM switching of lower side IGBTs.
- The IGBT switch , the motor stator winding (inductance) and DC capacitor act like a boost converter that pushes most of the power flow through the diodes.



Typical Booster Circuit has 4 components

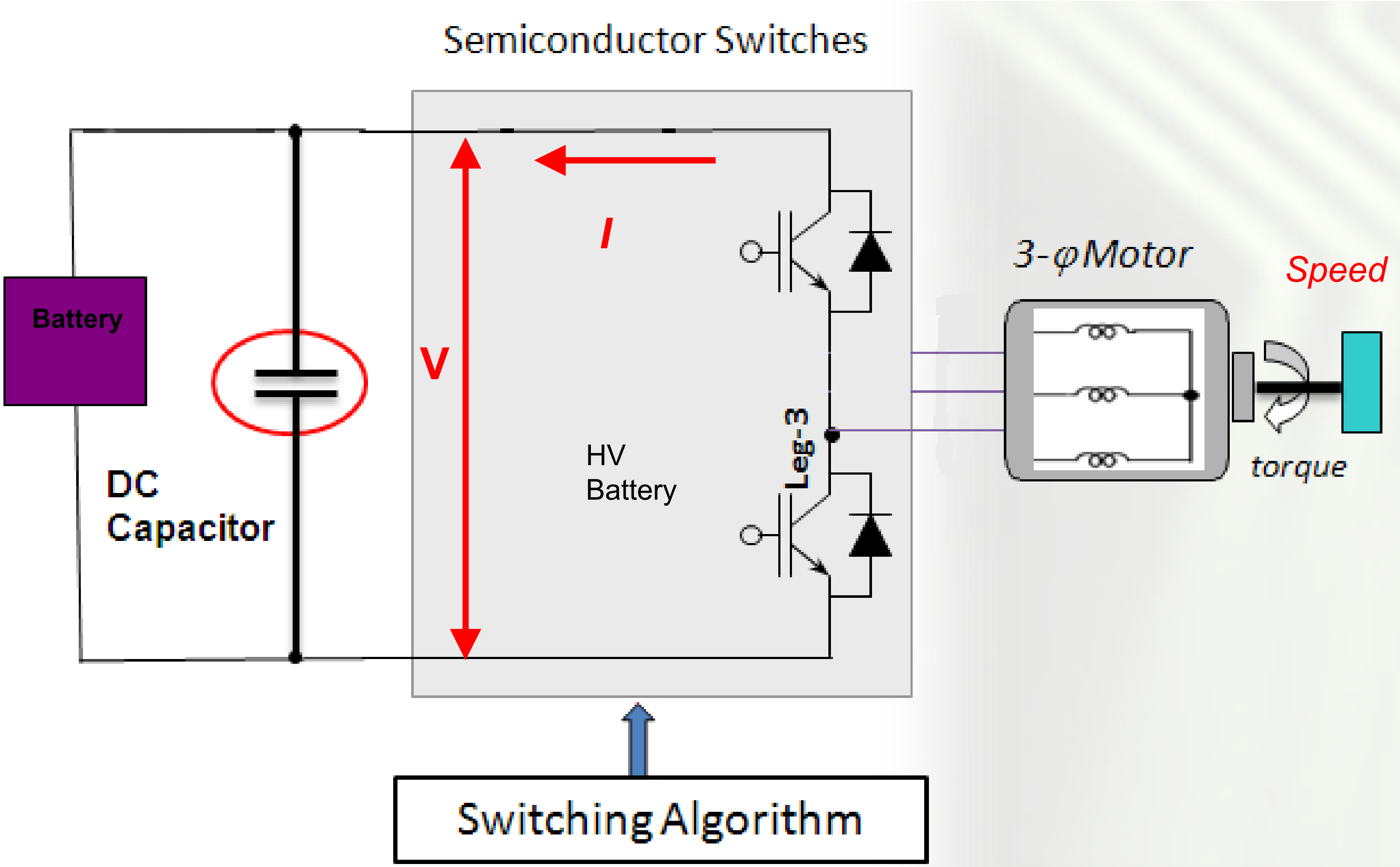


At least one upper transistor stay ON and use two other phases to boot voltage

Regenerative Power Analysis

Battery Charging Power ≈ Motor Mechanical Power

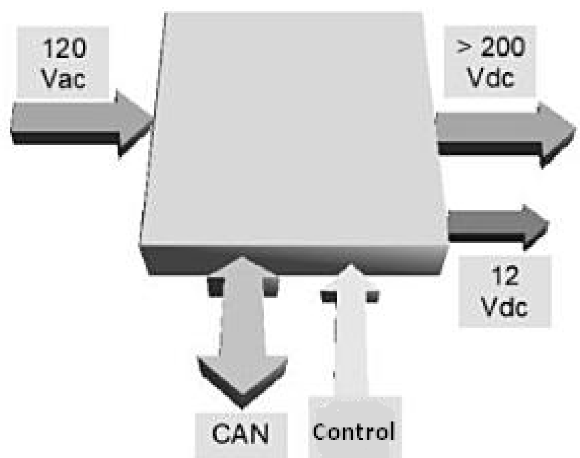
$$V \times I \approx Torq \times Speed$$



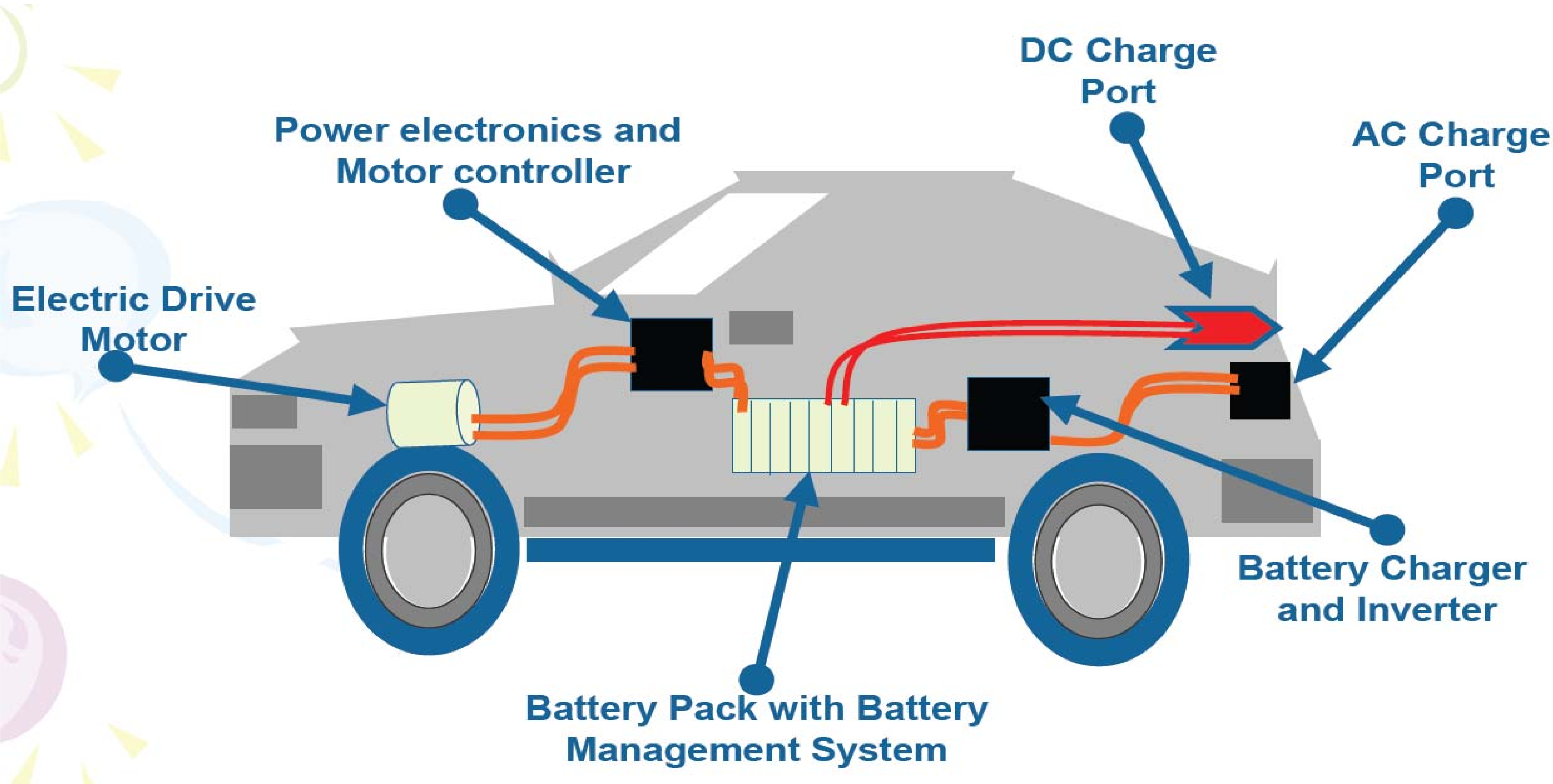
EV, PHEV Battery Charger

EV, PHEV Battery Charger

- The battery charger is an AC/DC converter
- The charger has three key functions
  - Getting the charge into the battery (Charging)
  - Optimizing the charging rate
  - Knowing when to stop (Terminating)
- Battery chargers need good voltage regulation, current limiting and temperature sensing to the battery cells

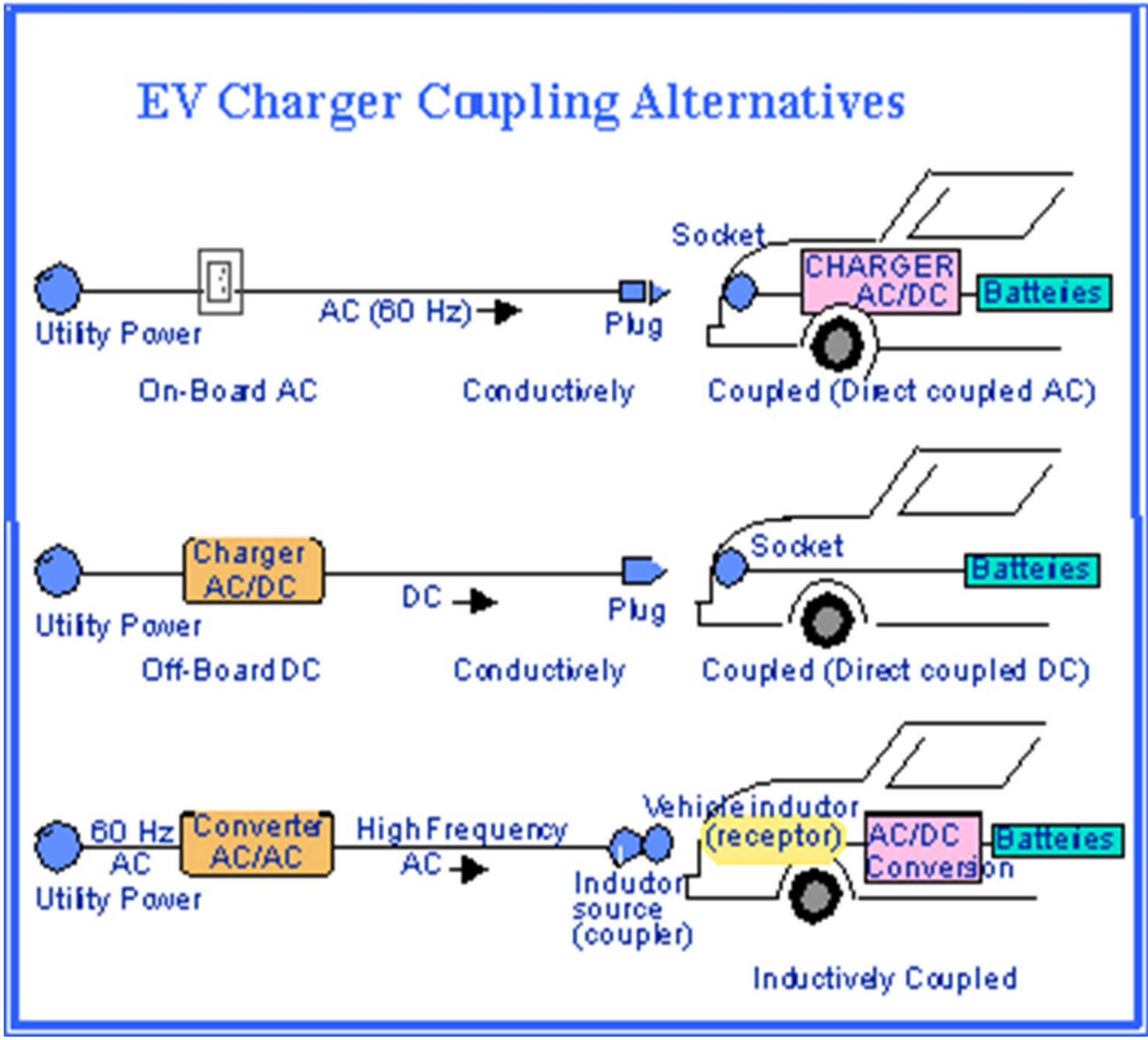


Basic EV Charging System



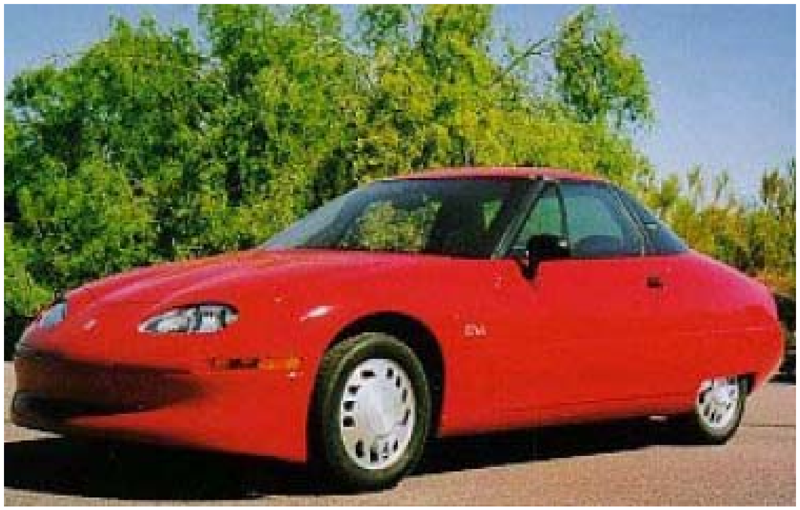
Type of EV, PHEV Battery Charger

- A standalone type which can be compared to a petrol station aimed at fast charge
- On-board type which would be appropriate for slow charge from a house utility outlet during nighttime, when demand of electricity is low
- Off-board charger. A charger with the intelligence and control in the charger stand, not on the vehicle

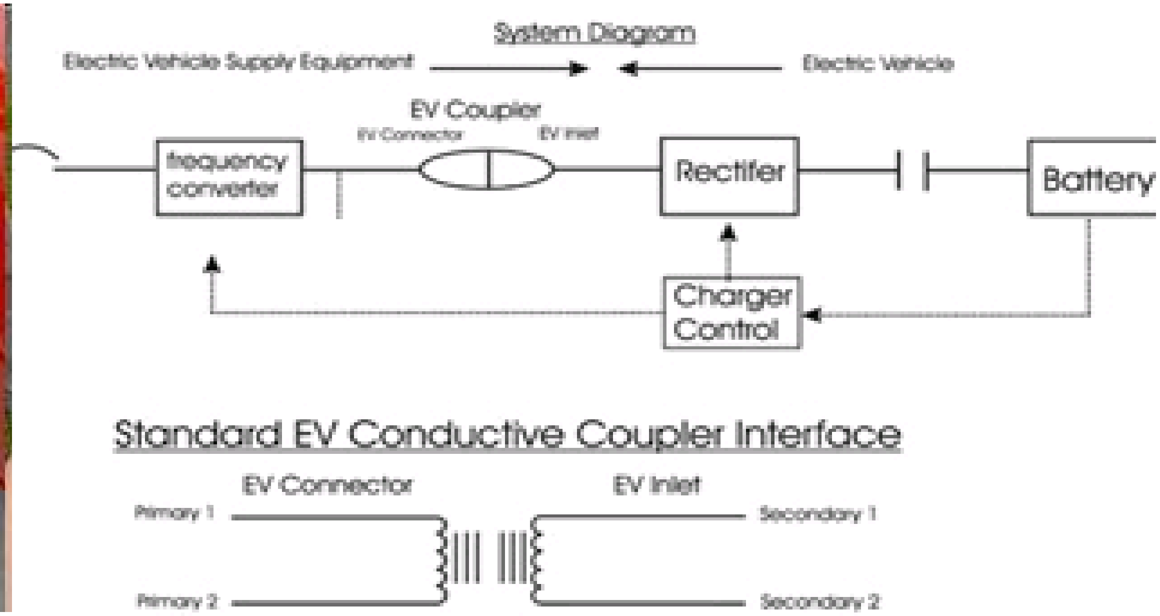


Inductive Charging

GM EV1



- Use an induction coil to create an alternating electromagnetic field from within a charging base station, and a second induction coil in the portable device takes power from the electromagnetic field and converts it back into electrical current to charge the battery. The two induction coils in proximity combine to form an electrical transformer
- SAE J1773 Electric Vehicle Inductively Coupled Charging



Basic Charging Methods

- **Constant Voltage** A constant voltage charger is basically a DC power supply which in its simplest form may consist of a step down transformer from the mains with a rectifier to provide the DC voltage to charge the battery. lithium-ion cells often use constant voltage charging systems
- **Constant Current** Constant current chargers vary the voltage they apply to the battery to maintain a constant current flow, switching off when the voltage reaches the level of a full charge. This design is usually for nickel-metal hydride cells
- **Trickle charge** Trickle charging is designed to compensate for the self discharge of the battery. Continuous charge. Long term constant current charging for standby use. The charge rate varies according to the frequency of discharge. Not suitable for some battery chemistries, e.g. NiMH and Lithium, which are susceptible to damage from overcharging. In some applications the charger is designed to switch to trickle charging when the battery is fully charged.

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Charging rate - Definition

- Charge and discharge rates are often denoted as C or C-rate, which is a measure of the rate at which a battery is charged or discharged relative to the capacity of the battery.
- The C-rate is given by the numerical value of the ratio of the charging or discharging current in A to the capacity of the battery in Ah
- If the capacity is X Ah, at C-rate of 1 the charging or discharging current is X A in 1 hour; while at C-rate of 2 the current is $2X$ A in ½ hour.

Charging Rate

- Batteries can be charged at different rates depending on the requirement. Typical rates are shown below:
  - Slow Charge = Overnight or 14-16 hours charging at 0.1C rate
  - Quick Charge = 3 to 6 Hours charging at 0.3C rate
  - Fast Charge = Less than 1 hour charging at 1.0C rate
- **Slow charging:** Slow charging can be carried out in relatively simple chargers. Lithium ion cells however can not tolerate overcharging or overvoltage and the charge should be terminated immediately
- **Fast Charging**: As the charging rate increases, so do the dangers of overcharging or overheating the battery. Fast charging and quick charging require more complex chargers. Since these chargers must be designed for specific cell chemistries

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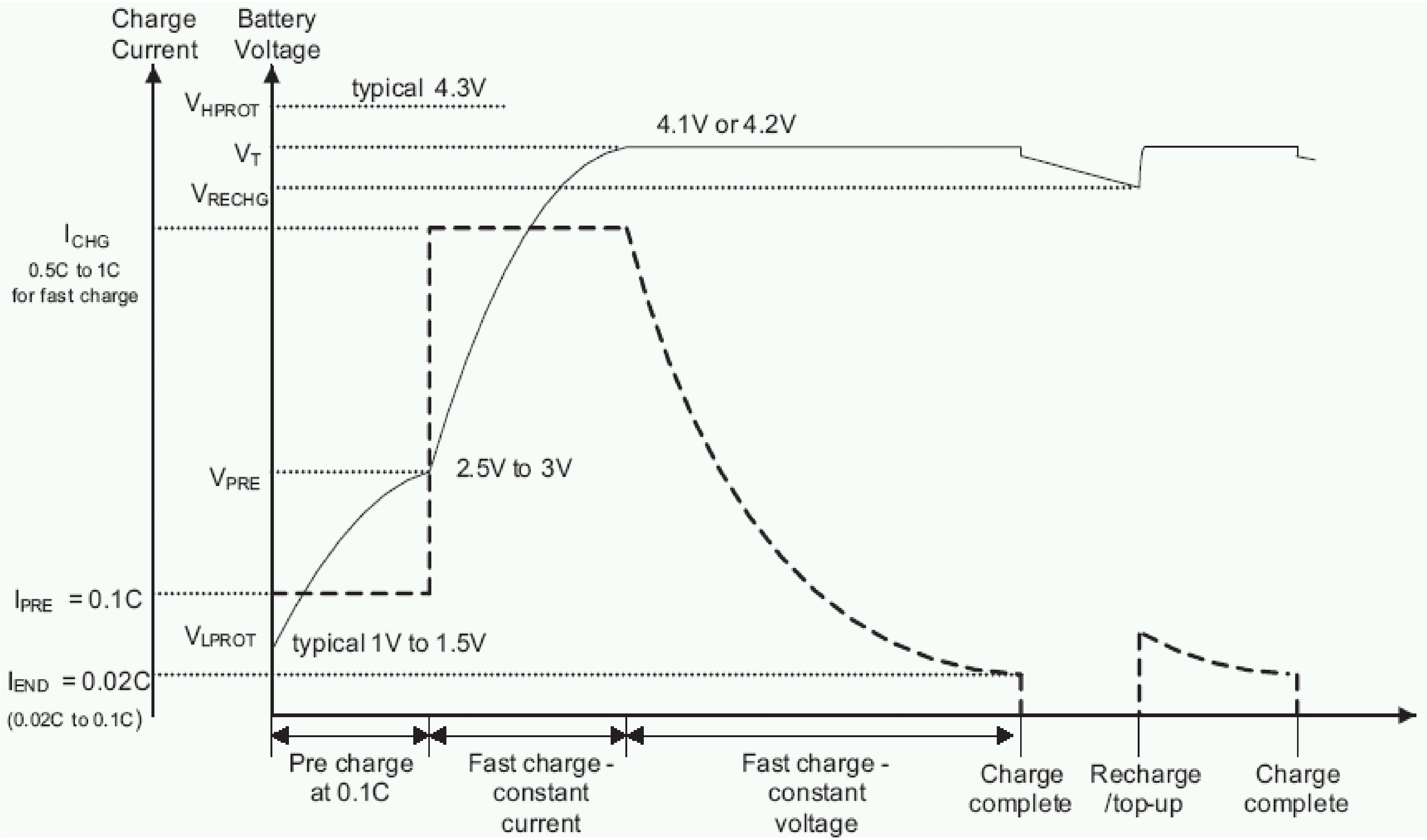
Typical Lithium Ion Cell Charge Profile

Charging method: Constant Voltage - Constant Current



Conductive Charging

- Conductive charging systems use **metal to metal** contact between the Charger connector and the EV's charge inlet (or **charge port**). Similar to most household appliances that use metal-to-metal contact between a power outlet and plug/connector, the use of this system is most common on EVs with **on-board** charging equipment. Safety concerns including inclement weather and incorrectly linked EV-Charger

For EV, PHEV, the charging time may be limited by the available power rather than the battery characteristics

Source: Pasadena Water & Power

Power Level of Conductive Chargers SAE J1772

- **Level 1 Charging.** Charging from a common electrical outlet, which is 120 volts in the United States. The maximum power supplied for Level 1 Charging: Nominal Supply Voltage 120 V. AC single phase; Maximum Continuous Current 12 amps; Branch Circuit Protection 15 amps (minimum); **Nominal Continuous Power 1.44 KW**

Power Level of Conductive Chargers SAE J1772

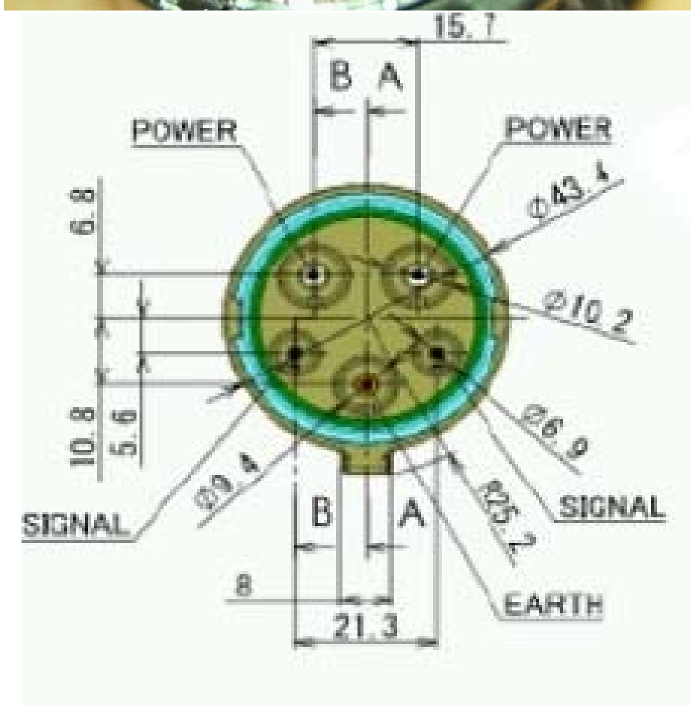
- **Level 2 Charging.** High-power charging, which is 240 volts, 40 amps in the United States. The maximum power supplied for Level 2 Charging: Nominal Supply Voltage 208-240 V. AC single phase; Maximum Continuous Current 32 amps; Branch Circuit Protection 40 amps; **Nominal Continuous Power 3.3-7.6 KW**

Power Level of Conductive Chargers
SAE J1772

- **Level 3 Charging.** Fast charging at 480 volts, 400 amps with three-phase power. A dedicated EV supply equipment capable of replenishing more than half of the capacity of an EV battery as quickly as in ten minutes. The maximum power supplied for Level 3 charging equipment: Nominal Supply Voltage 600V dc (maximum); Maximum Continuous Current 400 amps; **Nominal Continuous Power 60-160 kVA**

SAE J1772

- SAE J1772 is a proposed North American standard for electrical connector for electric vehicles
- It covers the general physical, electrical, and performance requirements for the electric vehicle conductive charge system and coupler
- The connector is designed for single phase electrical systems with 120V or 240V such as those used in North America and Japan
- It is designed to support electrical current up to 70A
- The round 43 mm diameter connector has five pins and will support communication over power lines, to identify the vehicle and control charging.
- The connector is designed to withstand up to 10,000 connection/disconnection cycles and exposure to all kinds of elements
- Supported by GM, Chrysler, Ford, Toyota, Honda, Nissan and Tesla



Source: Wikipedia

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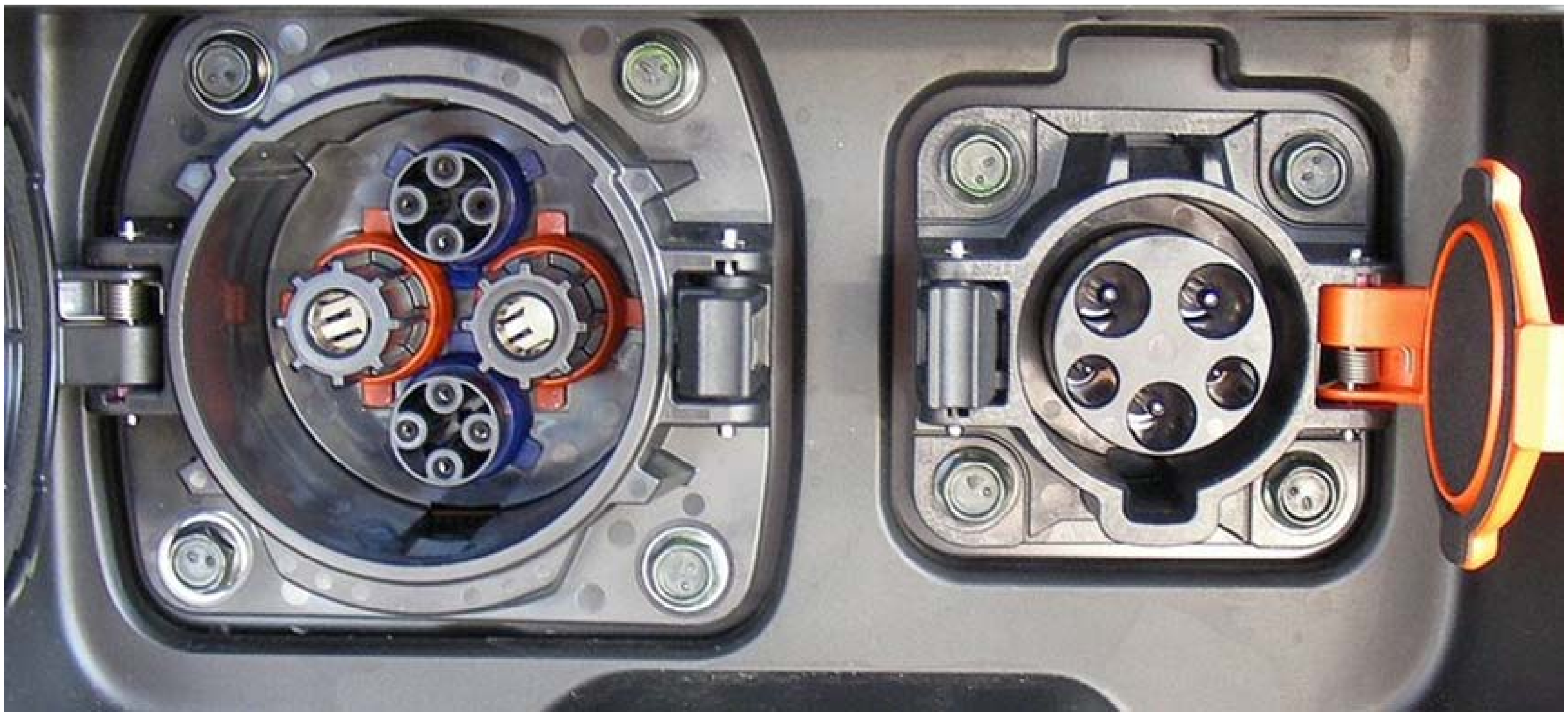
Nissan Leaf Charge Ports

Nissan Leaf with 24 khw battery has two connectors side by side:
a) J1772 connector for Level 1, 120 VAC and Level 2, 240 VAC (1 ph?) charging using built in 3.3 kw charger (about 12.5A)
b) JARI DC connector designed by TEPCO for Level 3 480 VAC 50 kw (nom) for 30 min 80% charge (about 100A). Charger is external and costs 16k!

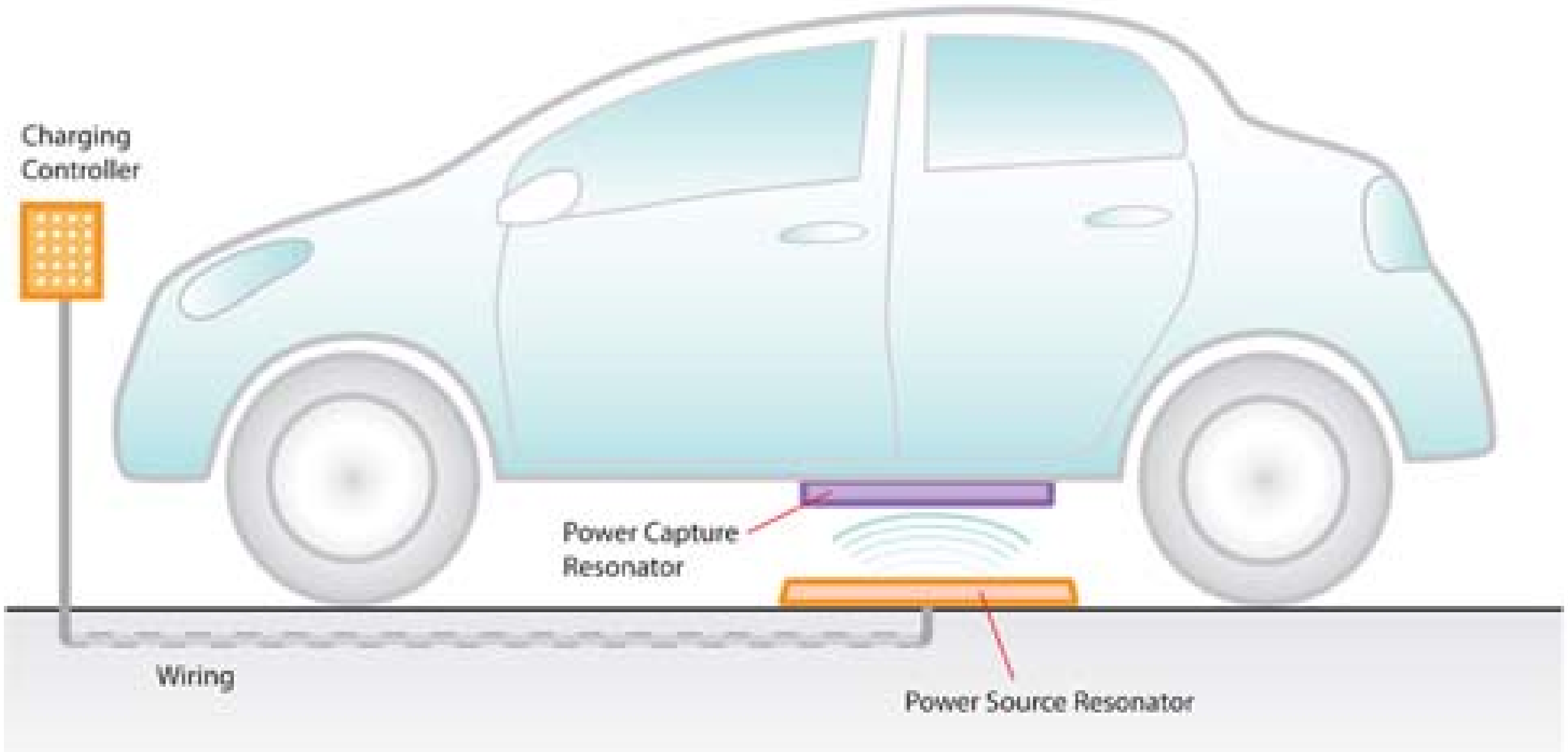


right: J1772 for 120/240 VAC, Level 1/2 (about 3.2 kw, 12.5A)
left: JARI DC connector designed by TEPCO for 480 VAC, Level 3 (about 50 kw, 100A)

The Harmonic Impact of Electric Vehicle Battery Charging

- The potential widespread introduction of the electric vehicle (EV) presents both opportunities and challenges to the power systems engineers who will be required to supply power to EV batteries.
- One of the challenges associated with EV battery charging comes from the potentially high harmonic currents associated with the conversion of ac power system voltages to dc EV battery voltages.
- Harmonic currents lead to increased losses in distribution circuits and reduced life expectancy of such power distribution components as capacitors and transformers.
- Harmonic current injections also cause harmonic voltages on power distribution networks. These distorted voltages can affect power system loads and specific standards exist regulating acceptable voltage distortion.

Electric Vehicle Wireless Charging Systems



- No plugs or charging cords needed
- Non-radiative power transfer uses a magnetic near field
- System can transfer 3.3 KW efficiently across air gaps in excess of 20 cm
- SAE J2954 Wireless Charging Specs are under development

SAE task force agrees on frequency of operation and power classes for wireless power transfer for light-duty plug-in vehicles

15 November 2013

SAE International J2954 Task Force for Wireless Power Transfer (WPT) of Light Duty, Electric and Plug-in Electric Vehicles, has agreed upon two key factors for the Technical Information Report (TIR) on interoperability for the first phase of pre-commercial development: a common frequency of operation (85 kHz) and the definition of three power classes for light duty vehicles: WPT 1, 2 and 3.

Made up of OEMs, WPT Suppliers, industry experts and government representatives, the Task Force plans to complete the TIR in early 2014. The SAE Technical Information Report will be followed by publication of SAE J2954 Standard, based on field data confirmation.

> *A common frequency of operation for WPT is essential for interoperability. After 3 years of international collaboration and investigation within the team, consensus had been reached on a nominal frequency of operation for the light duty vehicle guideline. The SAE team has determined this nominal frequency of 85 kHz for SAE J2954. This frequency lies within an internationally available frequency band. [81.38 - 90.00 kHz].*
>
> —Jesse Schneider, Chair J2954 Taskforce

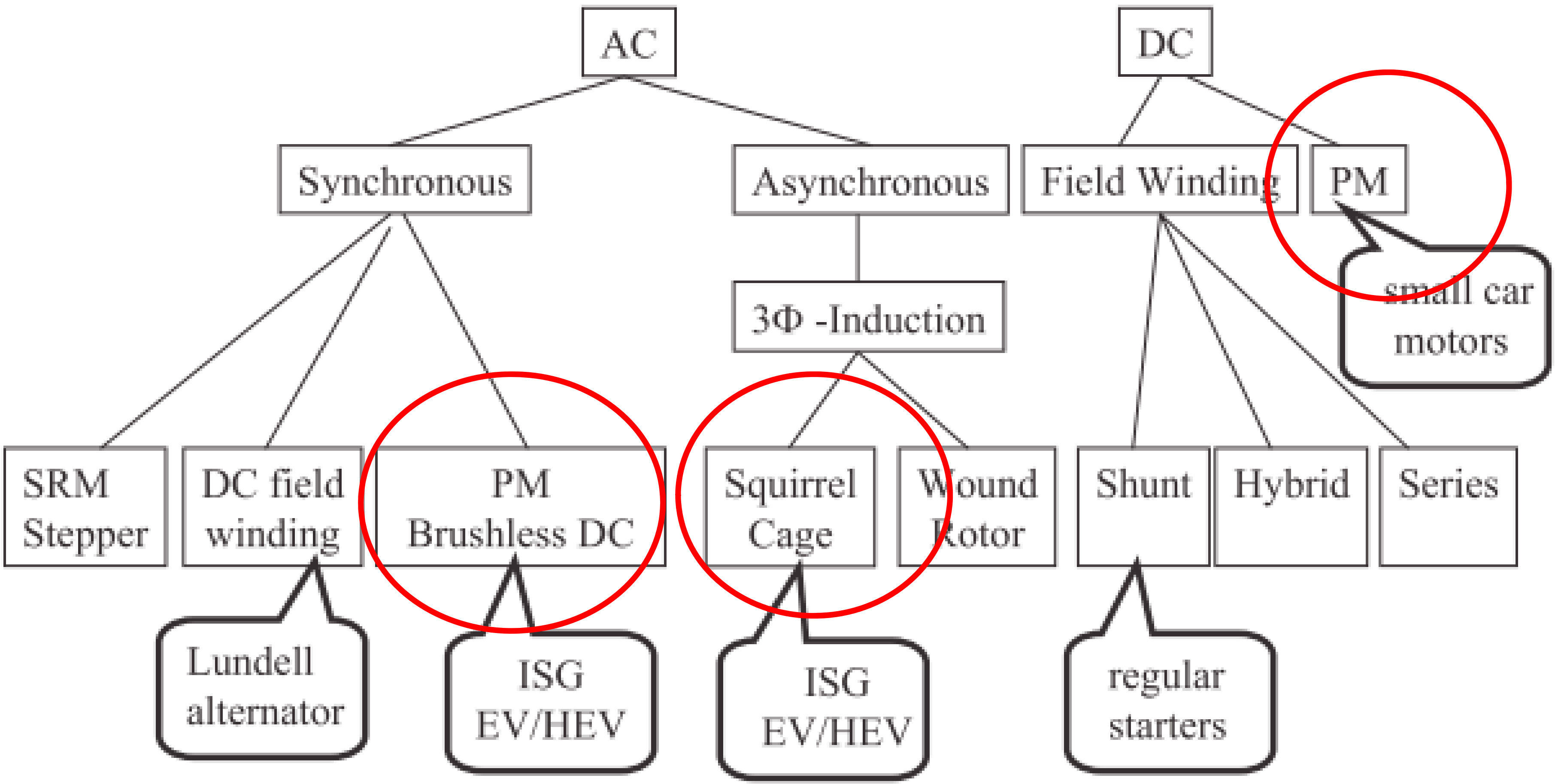
The limits for the three power classes are defined by the maximum input Wireless Power Transfer power rating as shown in the table below:

SAE TIR J2954 WPT Power Classes			
	WPT1	**WPT2 Private/Public Parking**	**WPT3 LD Fast Charge**
Maximum Input WPT Power Rating	3.7 kW	7.7kW	22 kW

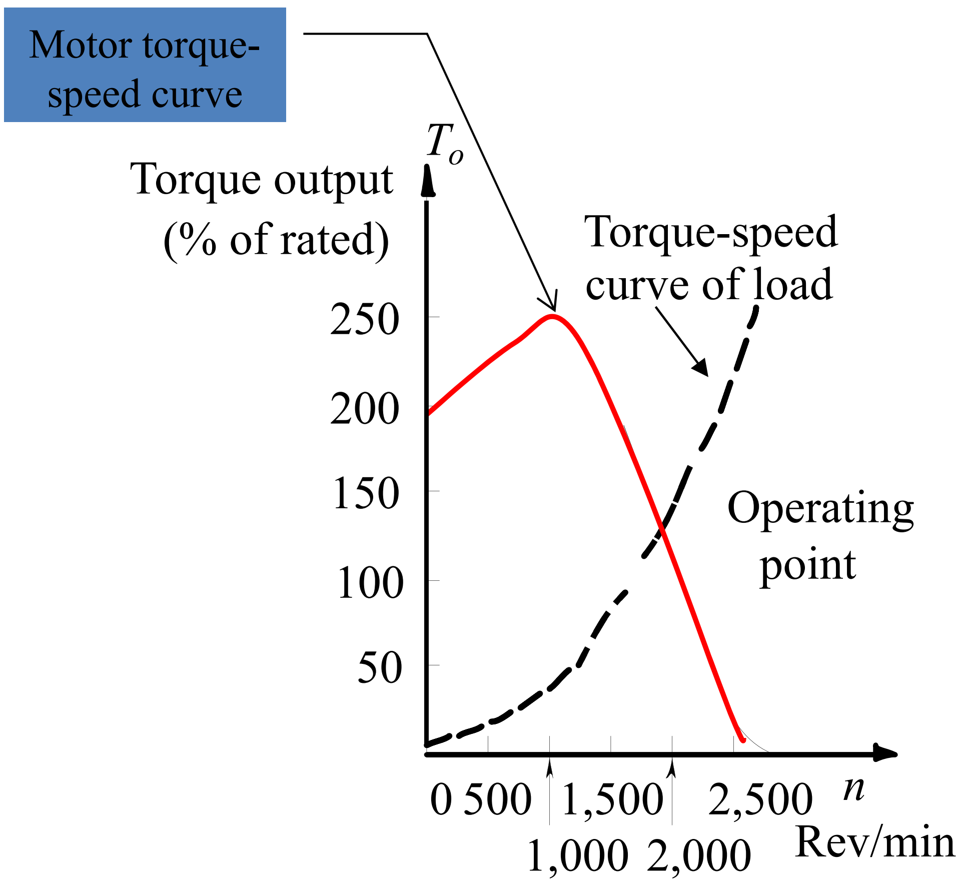
The SAE International Task Force is currently working on completing the remaining interoperability topics, including factors such as the minimum coupling factor "k", alignment, and coil geometries.

EV Traction Motor

Types of Motor for EV Application



Torque-Speed Curves



- Each type of motor has a different torque-speed curve
- The load also has a torque-speed curve
- The two curves intersect at the operating point

Automotive Applications

- Conventional vehicles
  - Starter – DC machines
  - Alternator – AC machine

- Hybrid vehicles – Electric propulsion
  - Permanent magnet brushless motor
  - AC induction motor
  - Switched reluctance motor

DC Machines

Equivalent Circuit of a DC Motor

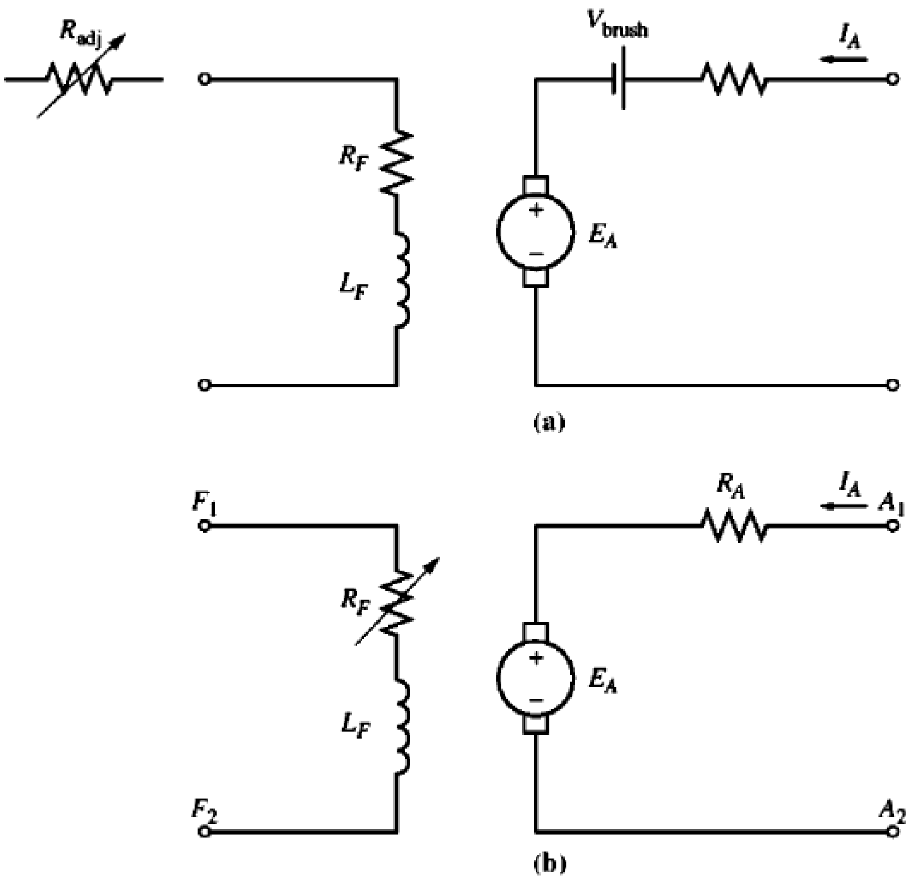


FIGURE 9–2
(a) The equivalent circuit of a dc motor. (b) A simplified equivalent circuit eliminating the brush voltage drop and combining R_{adj} with the field resistance.

Types:

- Separately excited
- Permanent-magnet
- Shunt
- Serious
- Compounded/hybrid

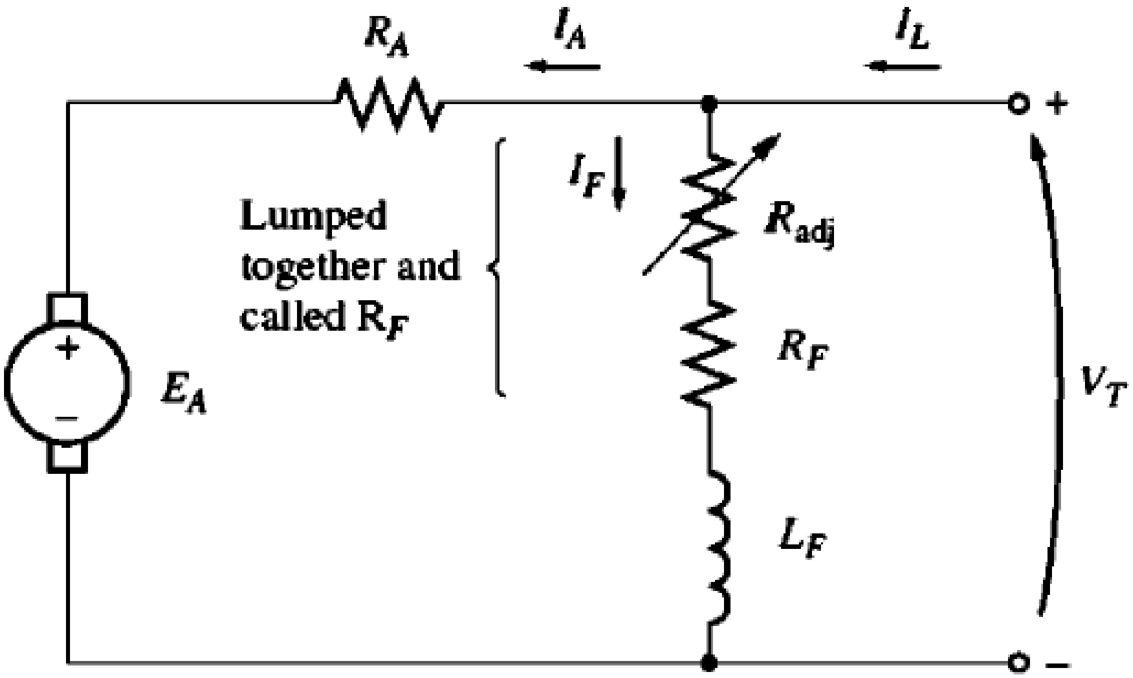
Internal generated voltage

$$E_A = K\phi\omega,$$

Induced torque by machine

$$\tau_{ind} = K\phi I_A$$

Shunt DC Motors



$$V_T = K\phi\omega + I_A R_A = K\phi\omega + \frac{\tau_{ind}}{K\phi} R_A$$

$$\omega = \frac{V_T}{K\phi} - \frac{R_A}{(K\phi)^2}\tau_{ind}$$

$$I_F = \frac{V_T}{R_F}$$

$$V_T = E_A + I_A R_A$$

$$I_L = I_A + I_F$$

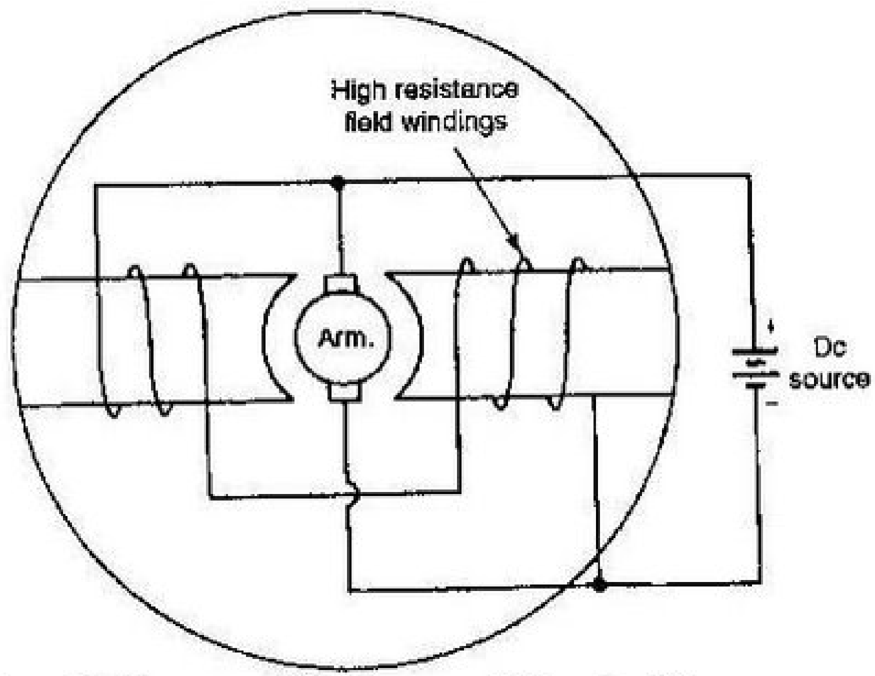
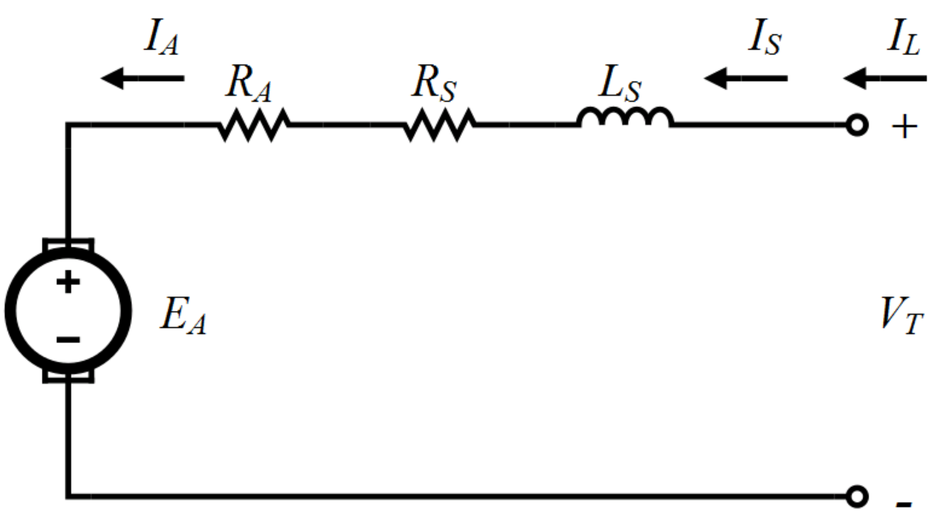


Figure 7: Diagram of shunt-wound DC motor (5)

Series DC Motor

A series DC motor's field windings consist of a relatively few turns connected in series with the armature circuit.

$$\tau_{\text{ind}} = K\phi\, I_A = KcI_A^2 \text{, where } \phi = cI_A$$



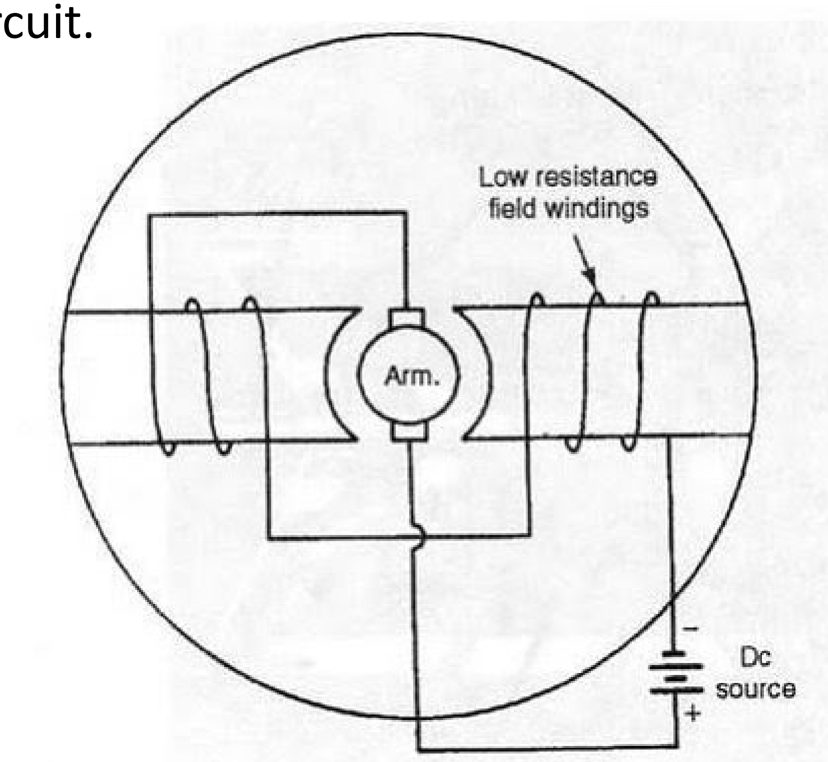


Figure 6: Diagram of series-wound DC motor (5)

$$I_A = I_S = I_L$$

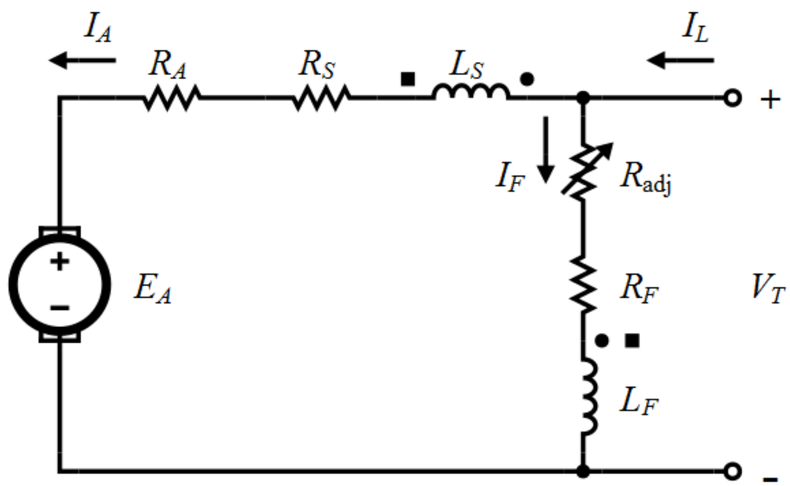
$$V_T = E_A + I_A\,(R_A + R_S)$$

$$V_T = K\phi\omega + \sqrt{\frac{\tau_{ind}}{Kc}}\left(R_A + R_S\right)$$

$$\omega = \frac{V_T}{\sqrt{Kc}}\frac{1}{\sqrt{\tau_{ind}}} - \frac{R_A + R_S}{Kc}$$

Compounded DC Motor

Long shunt



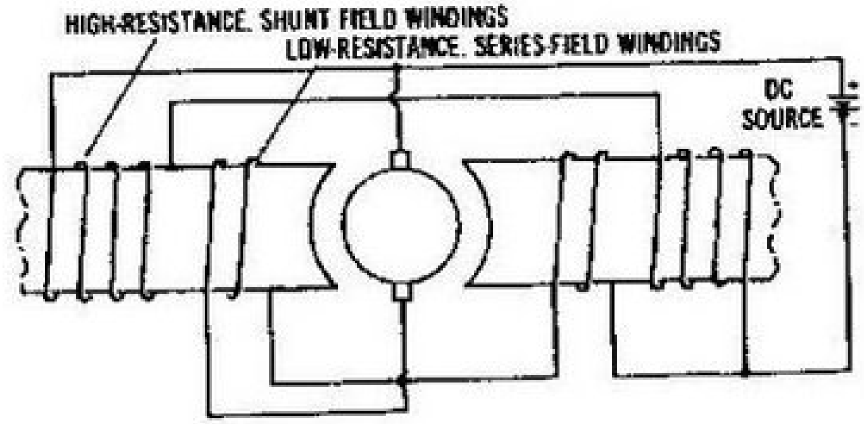
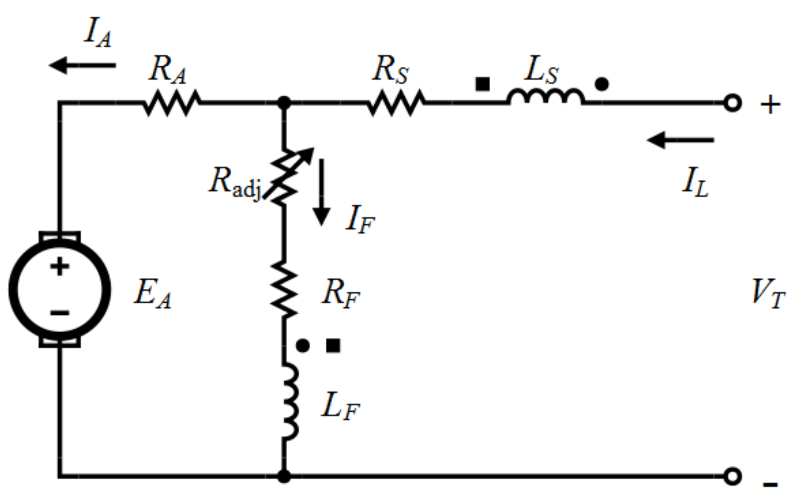
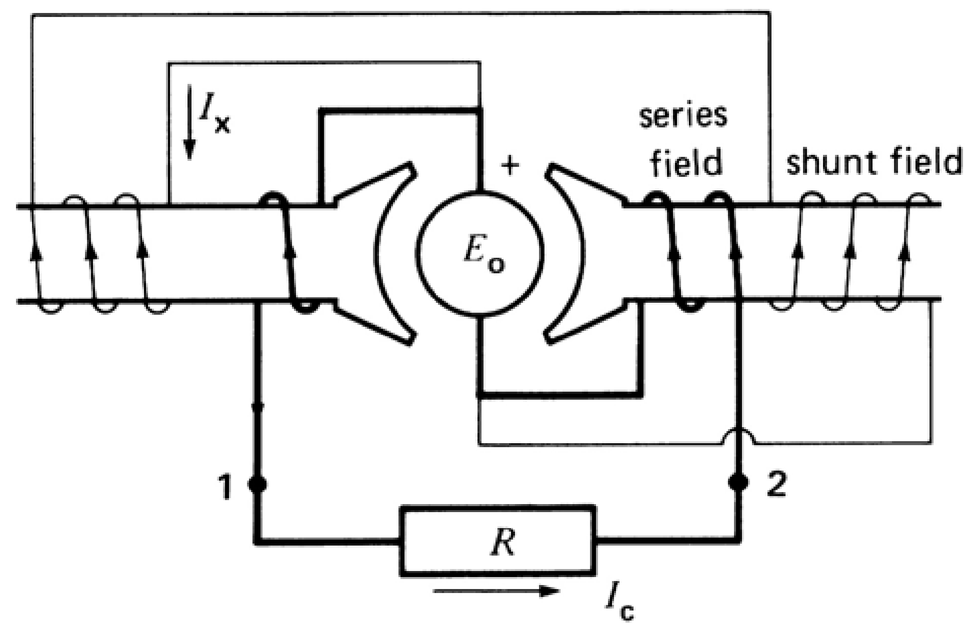


Figure 8: Diagram of compound-wound DC motor (5)





Short shunt

- Cumulatively
- ▪ Differentially

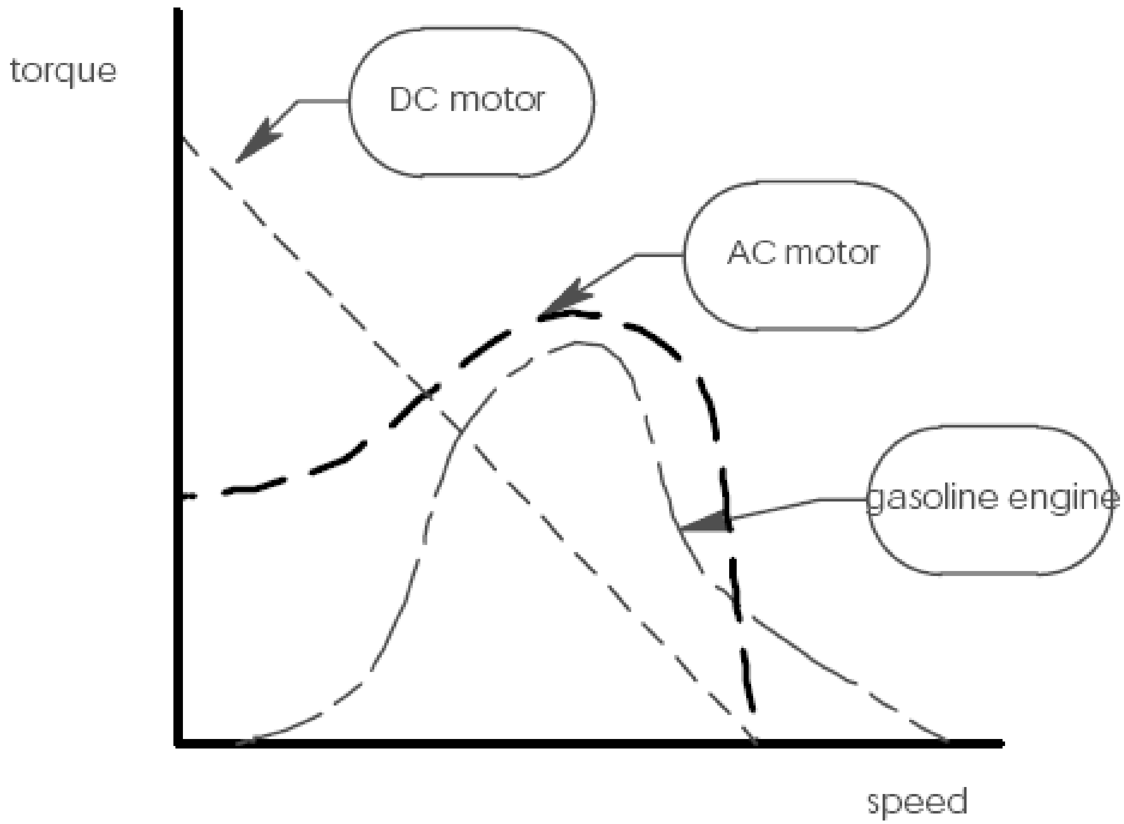
AC Machines

- Field winding or permanent magnets on rotor, armature windings on stator
- Armature windings excited with sinusoidal AC currents, which generate rotating magnetic field that is applied to rotor
- Advantages:
  - No mechanical commutation necessary
- Disadvantages:
  - Control of AC machines more complex, it requires high power (16, 32 bit) microprocessor

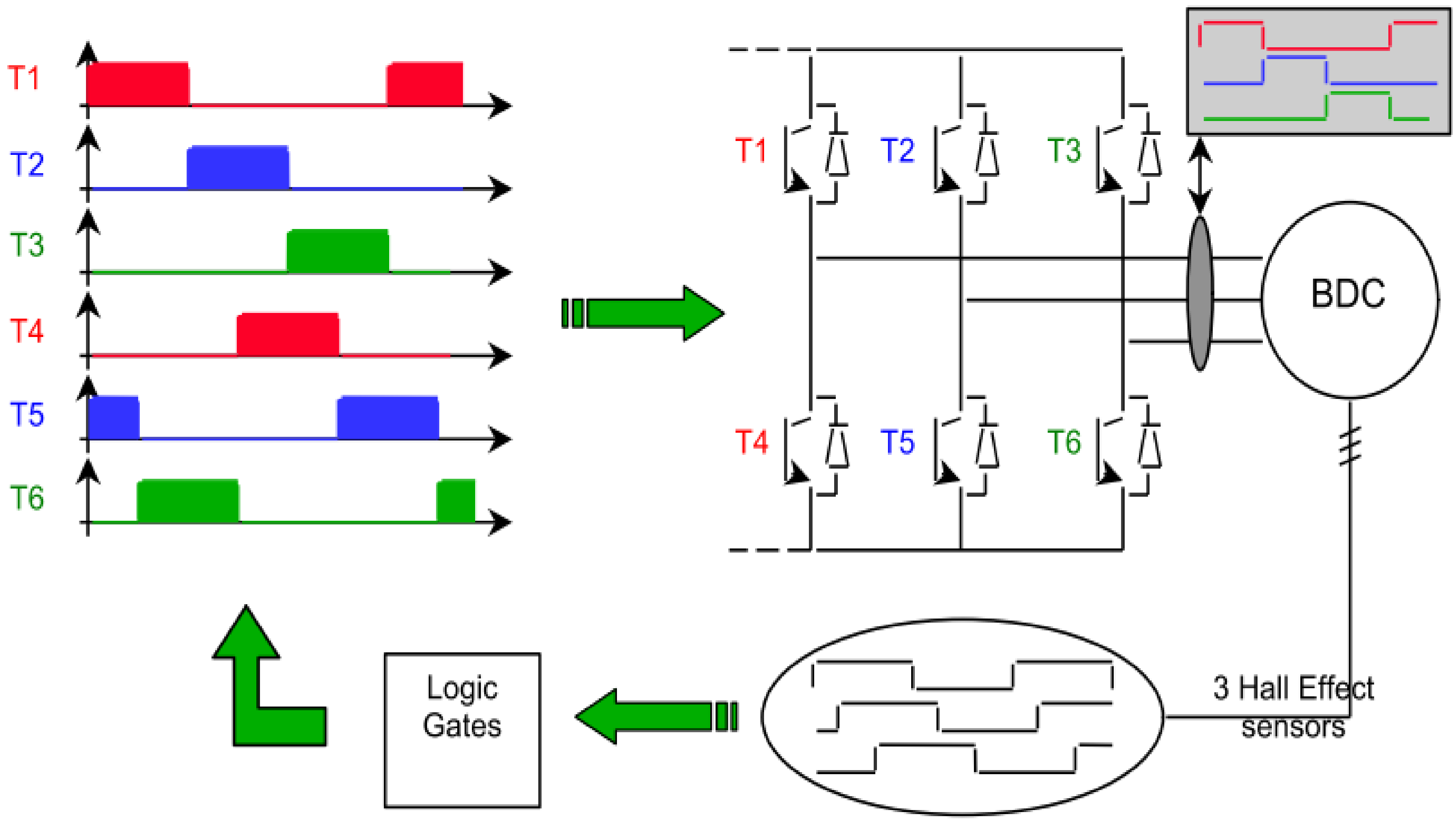
Types of AC Machines

- Synchronous (rotor of machine rotates at same angular velocity as magnetic field)
  - Synchronous reference frame determined by rotor angle (θ_x=P/2 θ_r)
- Asynchronous (rotor of machine rotates at different velocity than magnetic field)
  - Synchronous reference frame aligned with electrical variables

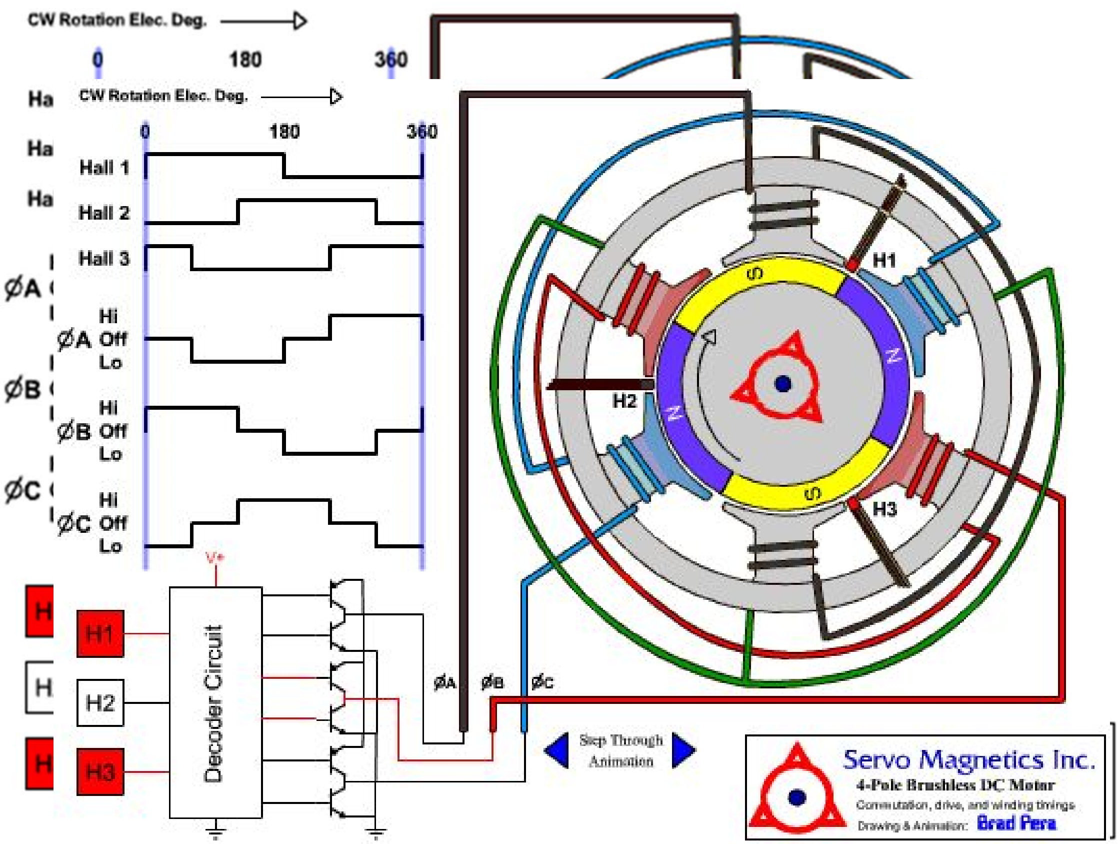
DC, AC Machines and Gasoline Engine Torque-Speed Curves



Brushless DC Drive Principle



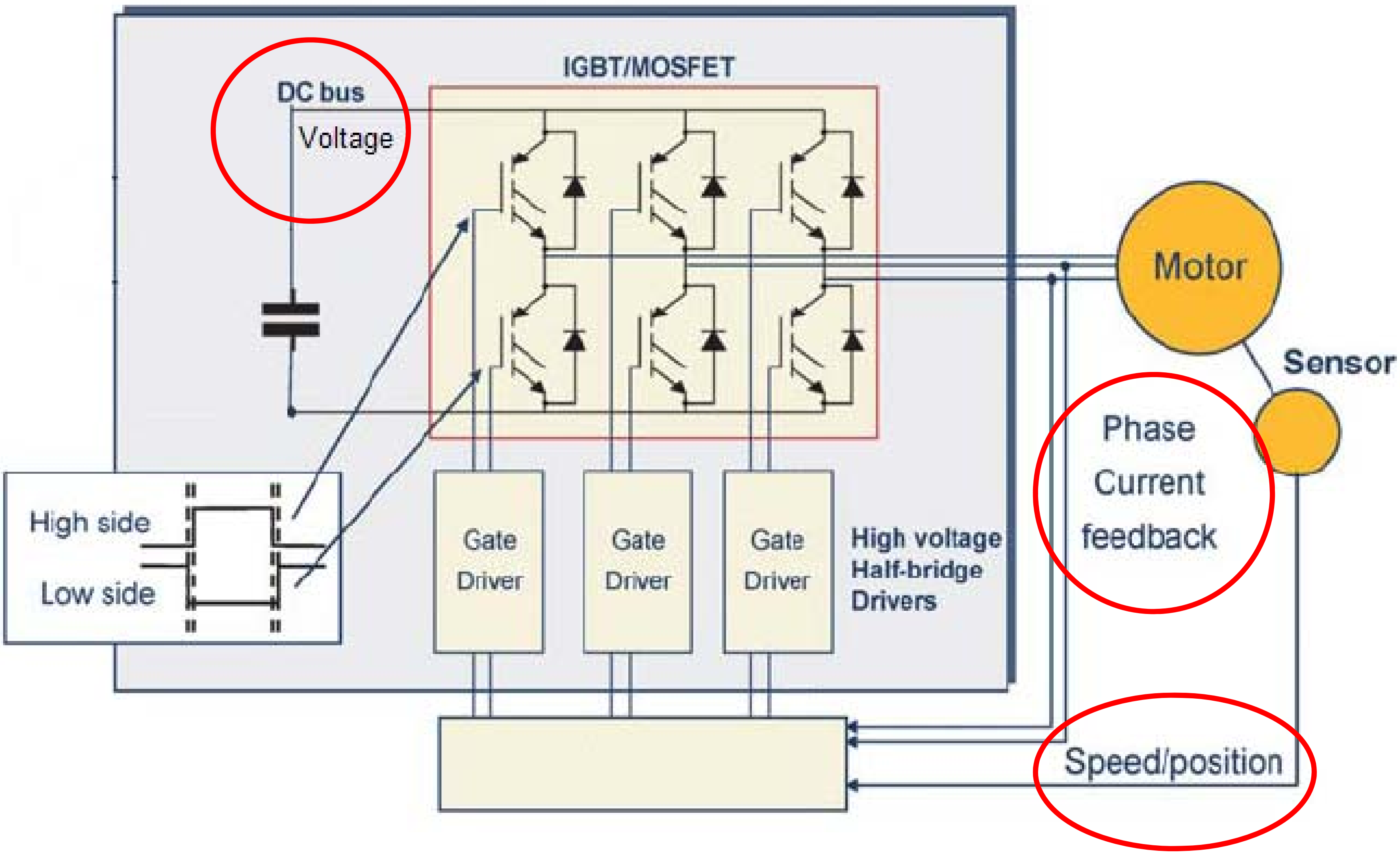
How it Works



- Halls Sensors sense the position of the coils
- The Decoder Circuit turns appropriate switches on and off
- The voltage through the specific coils turns the motor

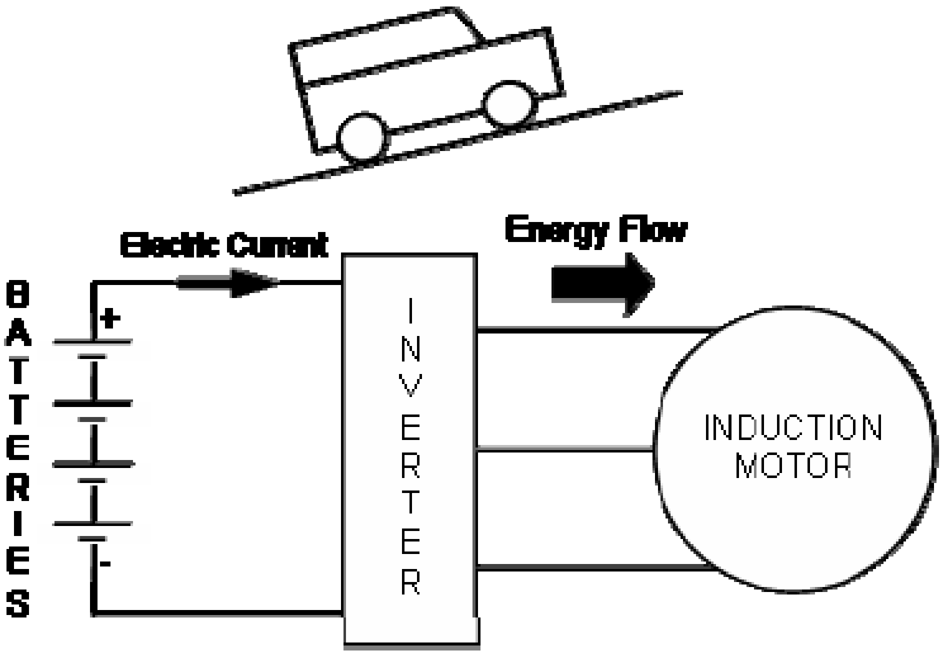
Images courtesy of Servo Magnetics
(http://www.servomag.com/flash/2-pole/2pole-bldc-motor.html)

Brushless DC Motor Control

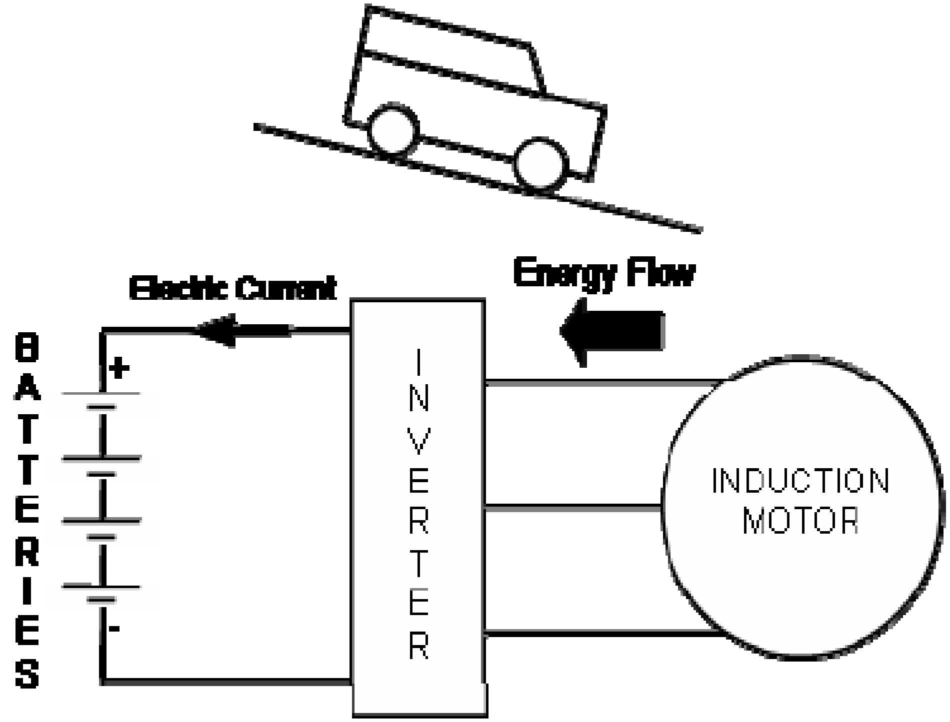


Field-Oriented (Vector) Motor Control

- **Field-oriented control** allows precise and responsive speed control when the load changes, and guarantees optimized efficiency even during transient operation by maintaining perfectly in quadrature the stator and rotor fluxes.
- The Clarke transform converts the 3-axis 120° shifted coordinates (Ia,Ib, Ic) into 2-axis orthogonal ones (Iα, Iβ); the park transform converts the fixed (Iα, Iβ) coordinates into 2-axis rotating coordinates (Id, Iq) linked to the rotor.

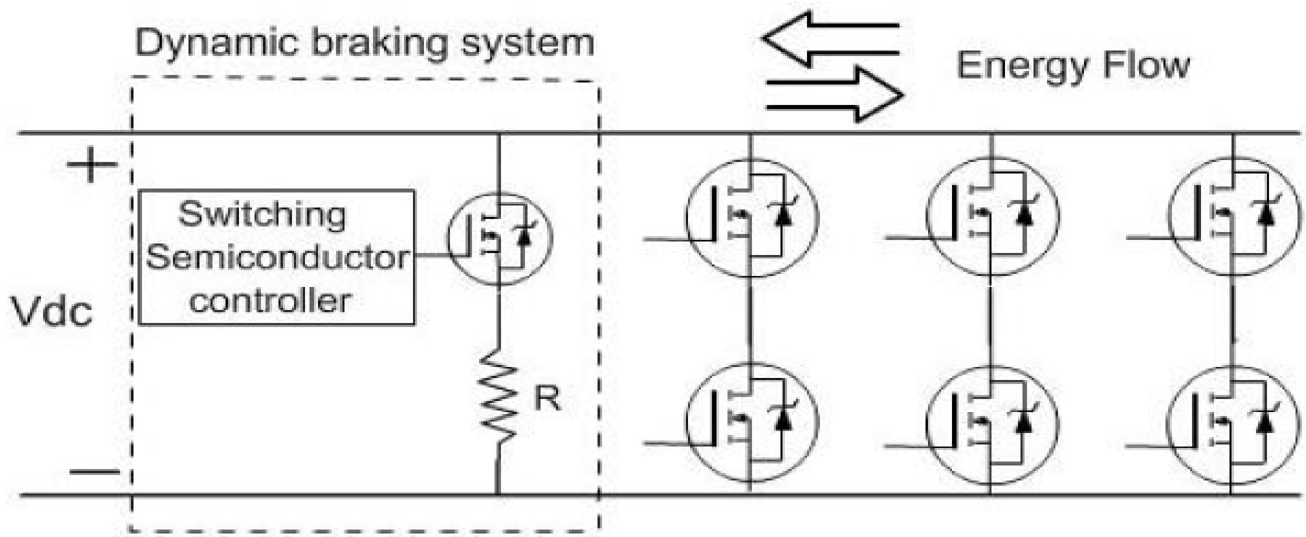


Vehicle in acceleration or keeping constant speed

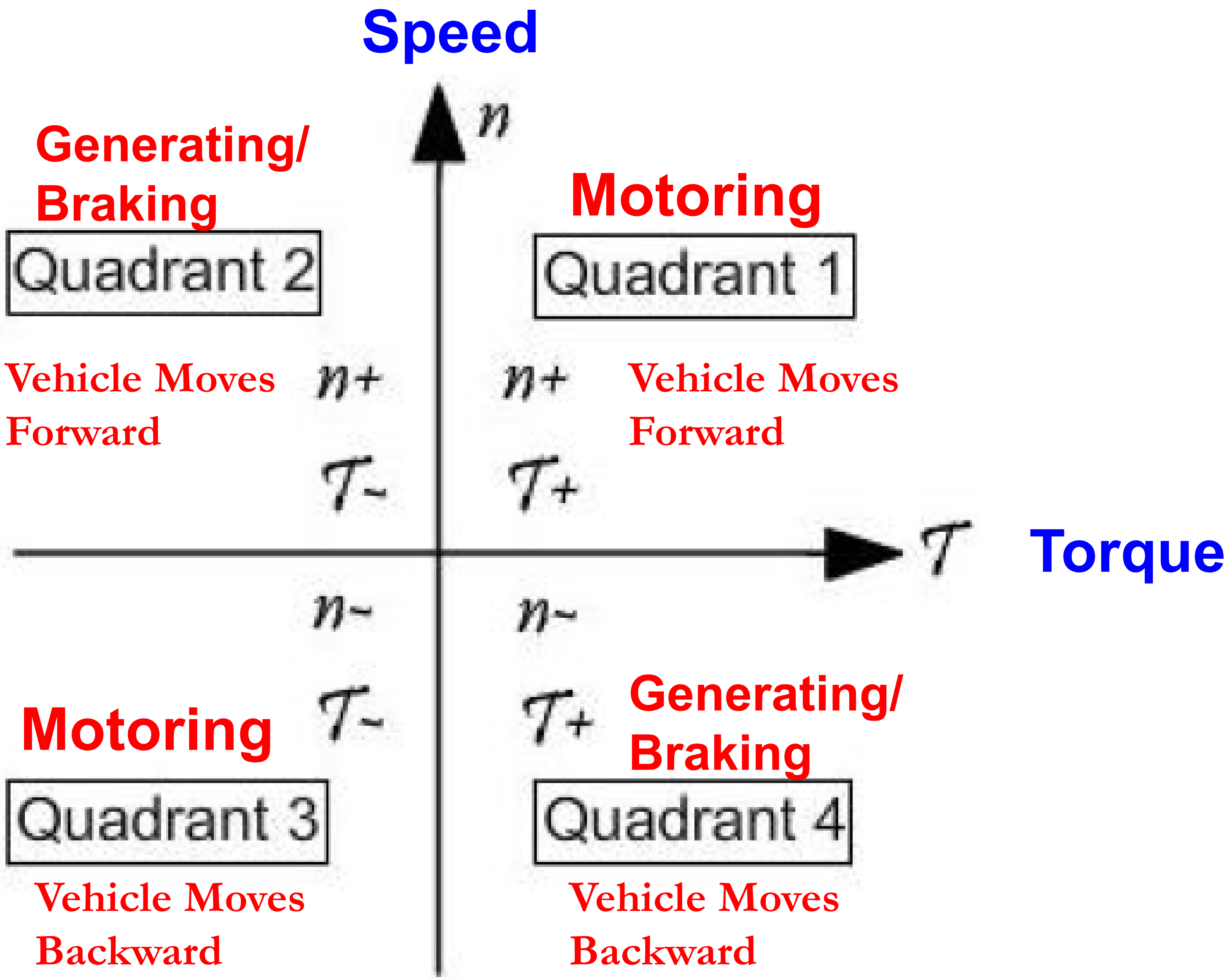


Vehicle braking or in downhill

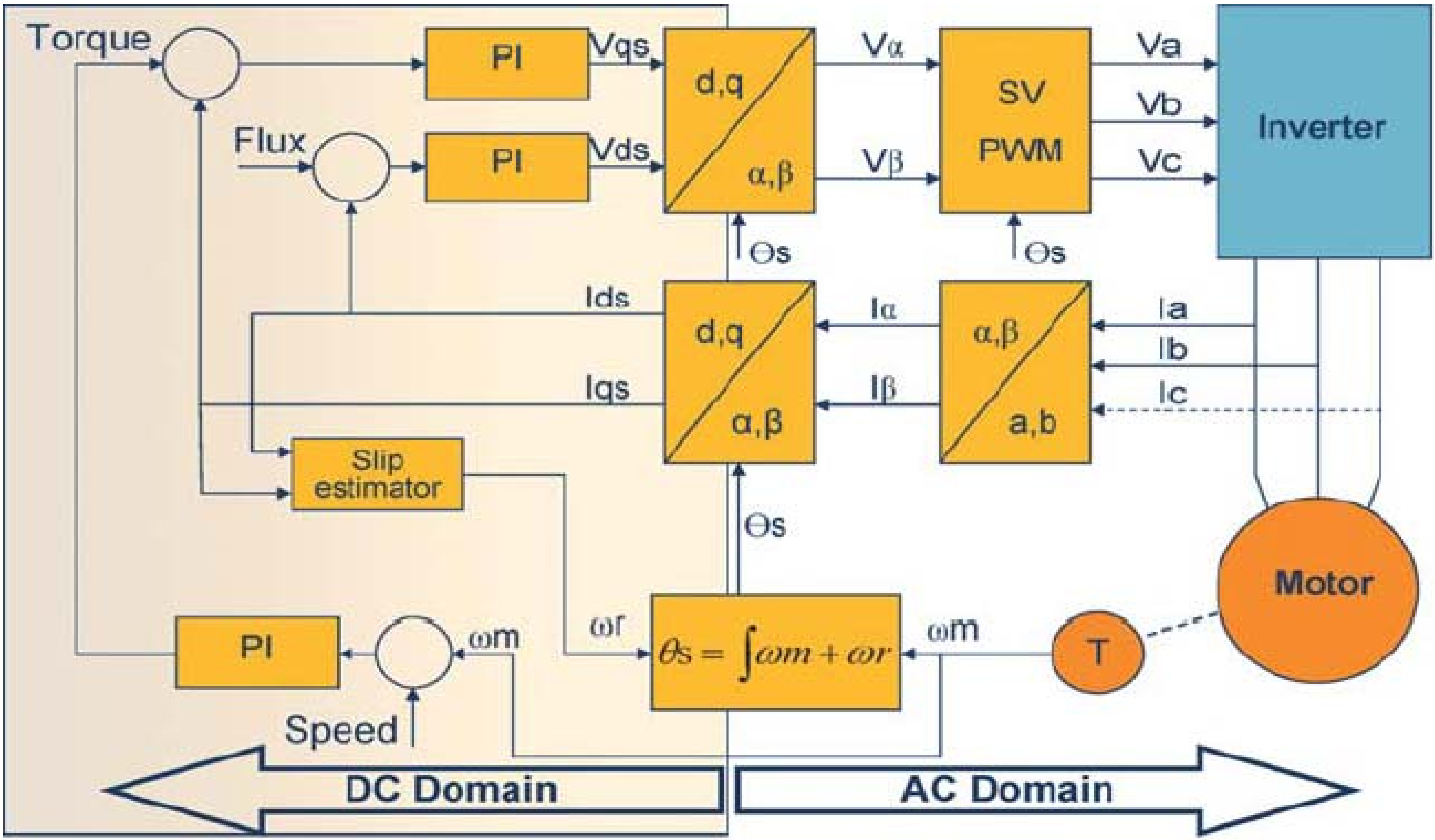
AC Motor Inverter with dynamic braking



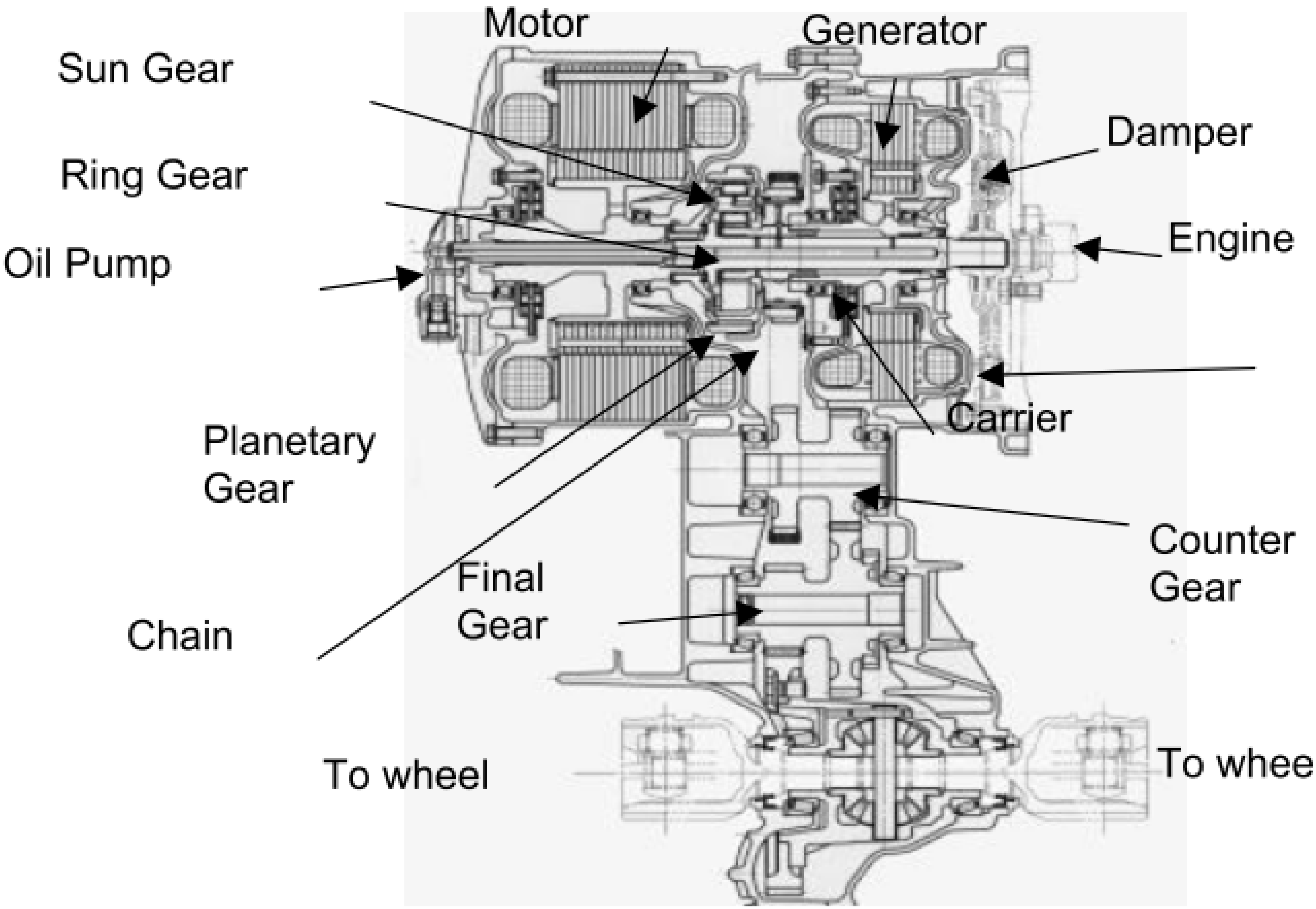
Four Quadrant Traction Motor Operation



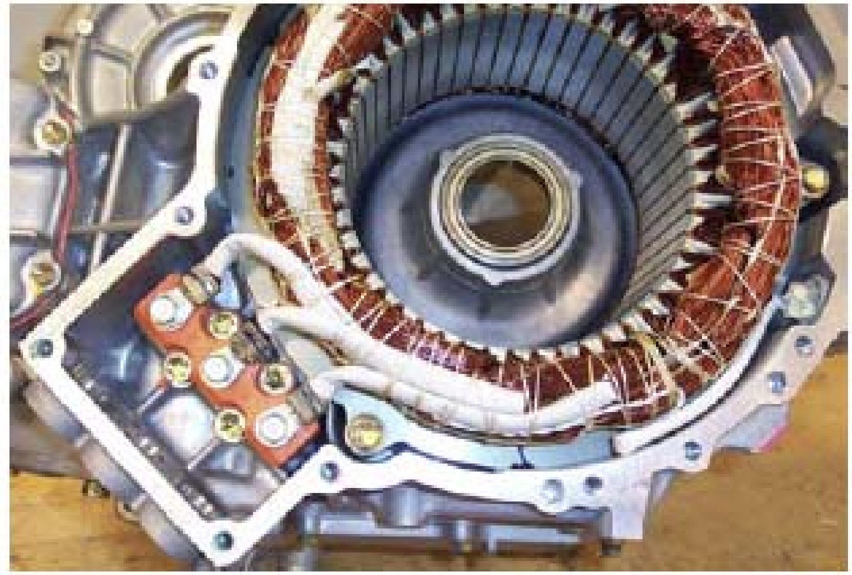
Brushless DC Motor Control

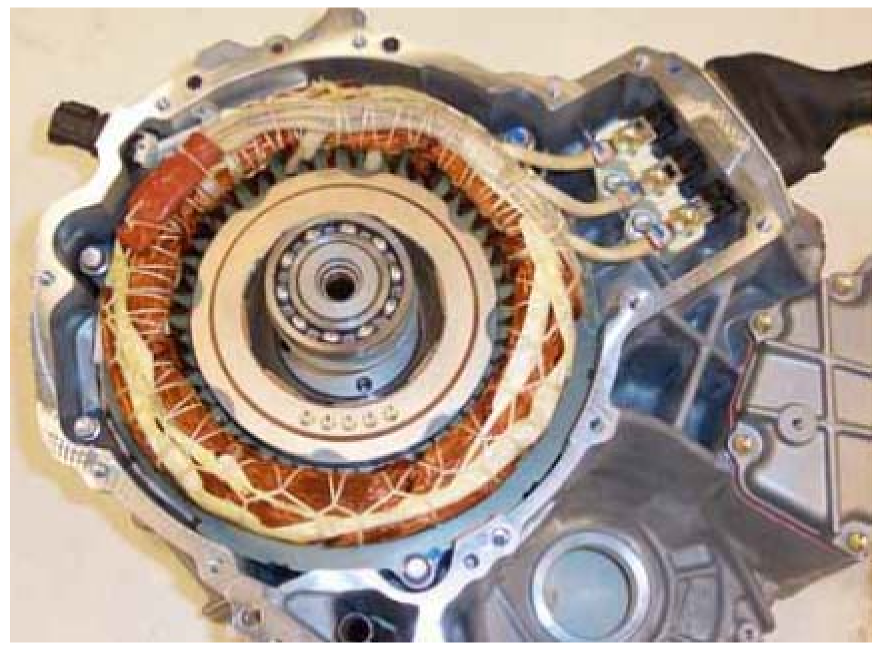


Toyota Prius Traction Motor / Generator

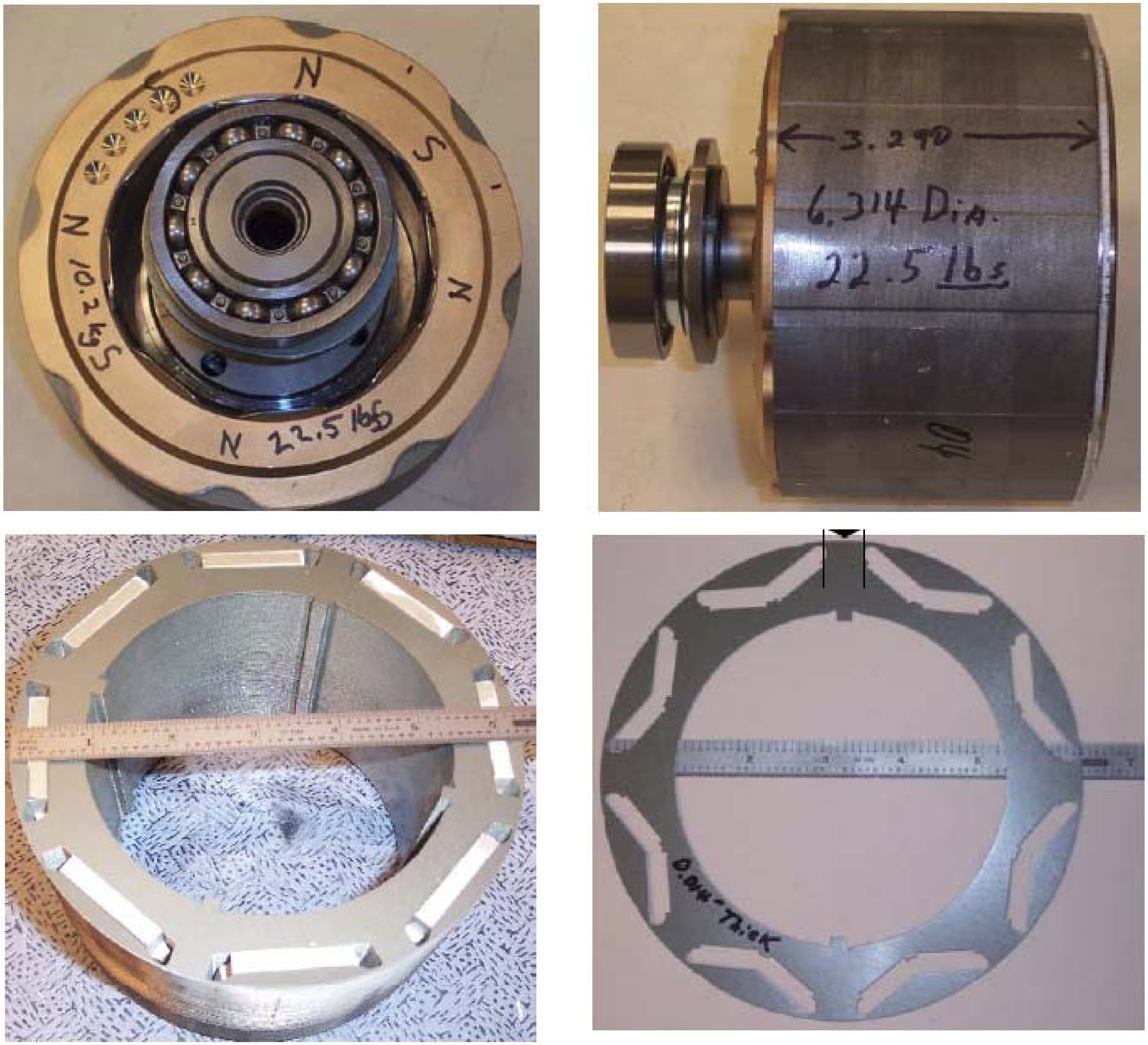


Toyota Prius Traction Motor Stator

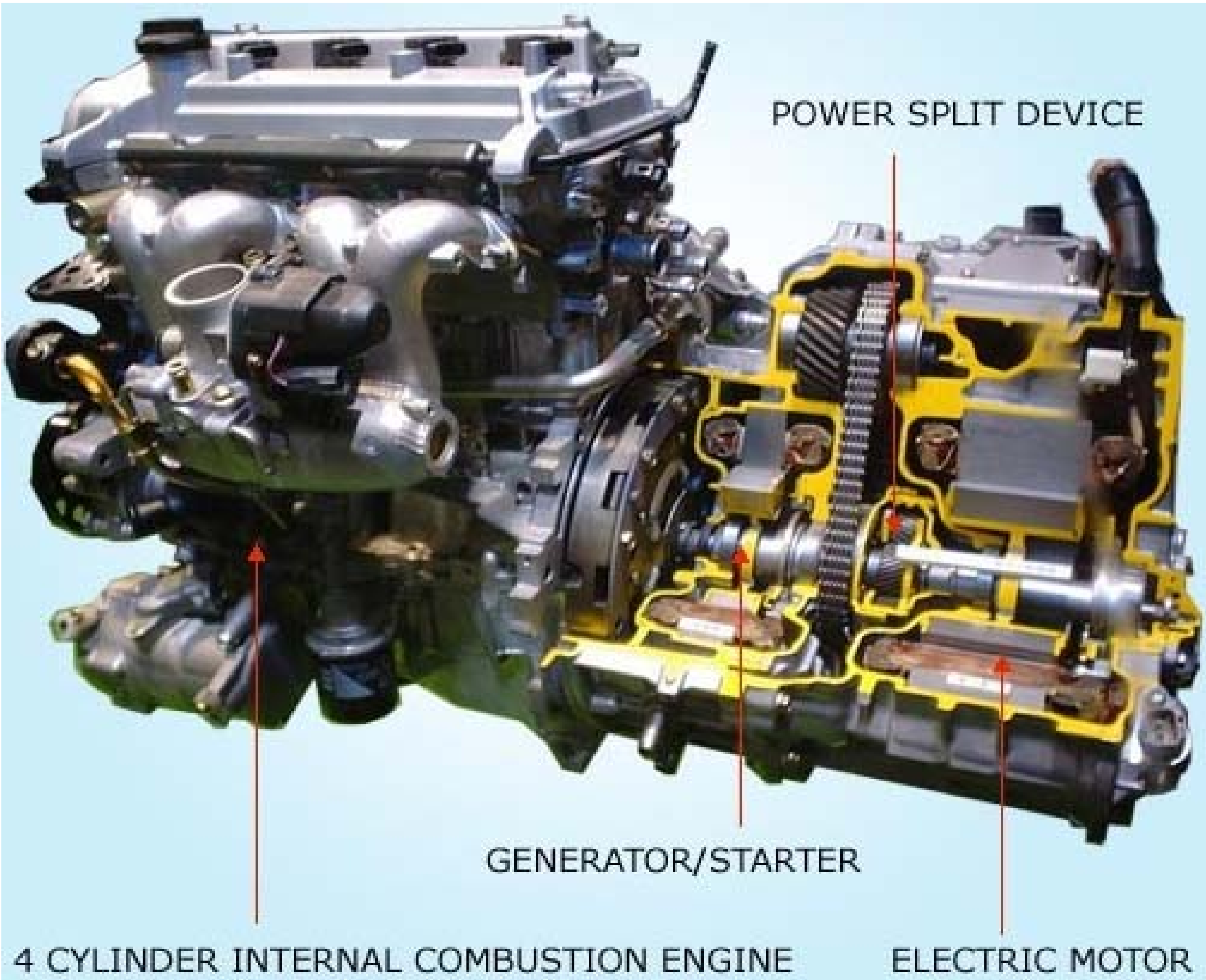




Toyota Prius Traction Motor Rotor



Magnets were inserted into the slots of the rotor core.



Propulsion drive, particularly in parallel or power-split drivetrains where machine only provides fraction of total propulsion power, and must therefore have high power density

Source: *The Clean Green Car Company*

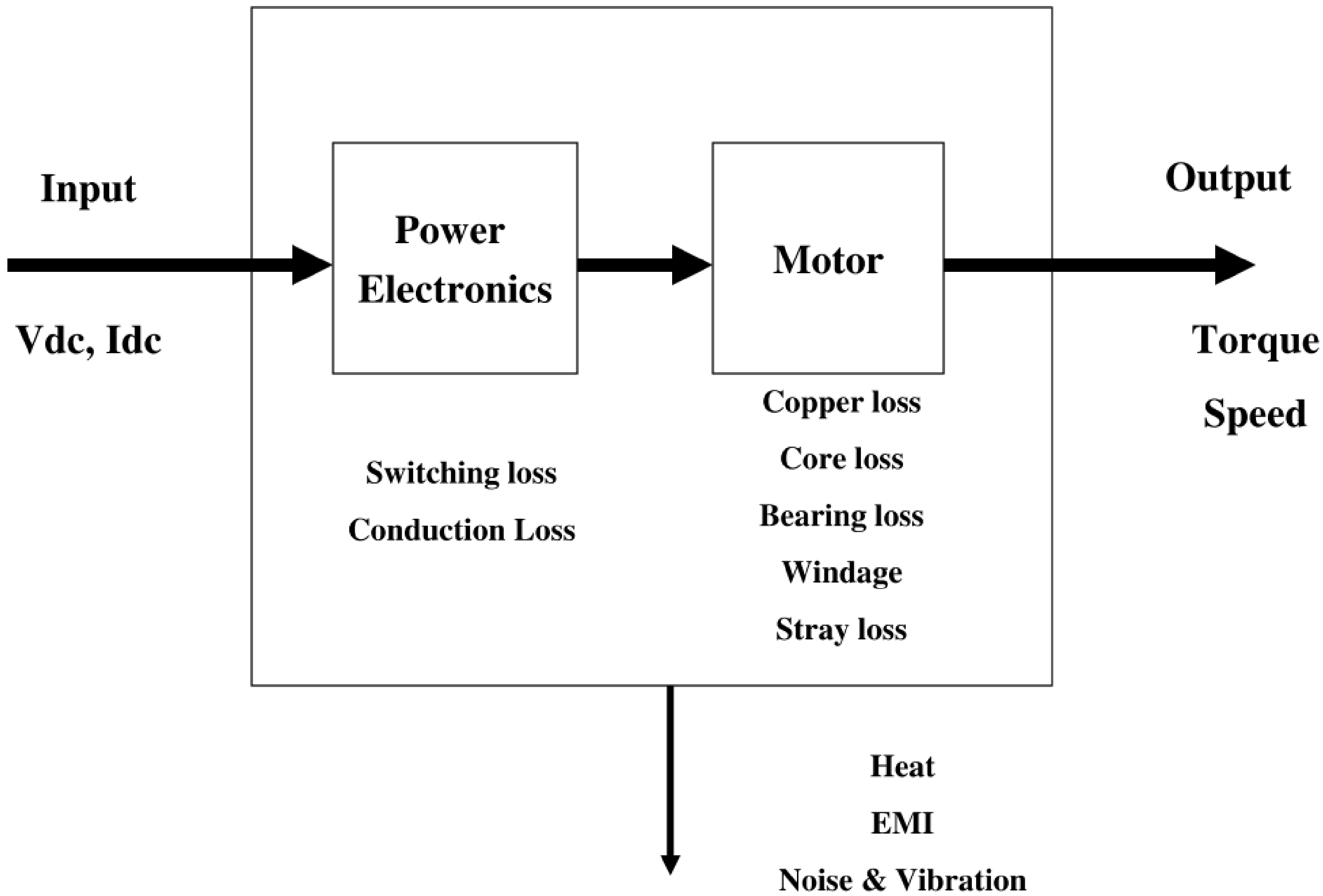
Active Electric Differential (eDifferential)

Source: Schaeffler Group

- The system consists of two different-sized water-cooled permanent magnet synchronous motors, a planetary gear, a transmission for active torque distribution, and a lightweight differential.
- One of the electric motors (105 KW) provides the drive for the wheels; The other (5 KW) regulates the distribution of torque between the wheels.
- (eDifferential) that can be mounted on the front and rear axle. It is available in various types, with the highest level providing torque vectoring by driving power to the necessary wheels.

The Drive Unit and Traction Motors for the 2016 Chevrolet Volt

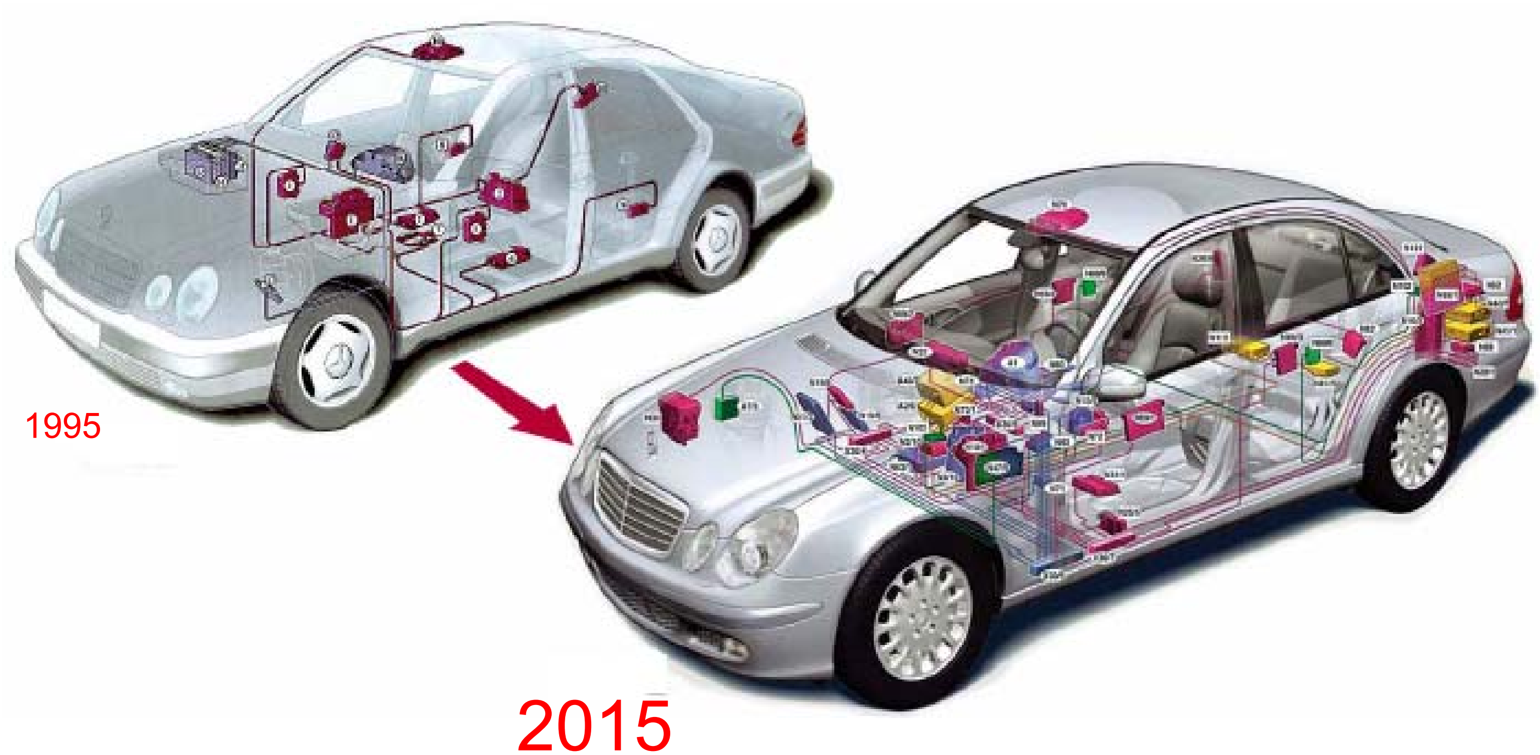
Electric Drivetrain Total Efficiency



EV Power Electronics On-Board Diagnostics (OBD)

Why Vehicle Needs Diagnostics?

Today's high-end automobiles contain many ECUs (Electronic Control Units), Vehicle troubleshooting has become a enormous challenge



Before OBD requires by law….

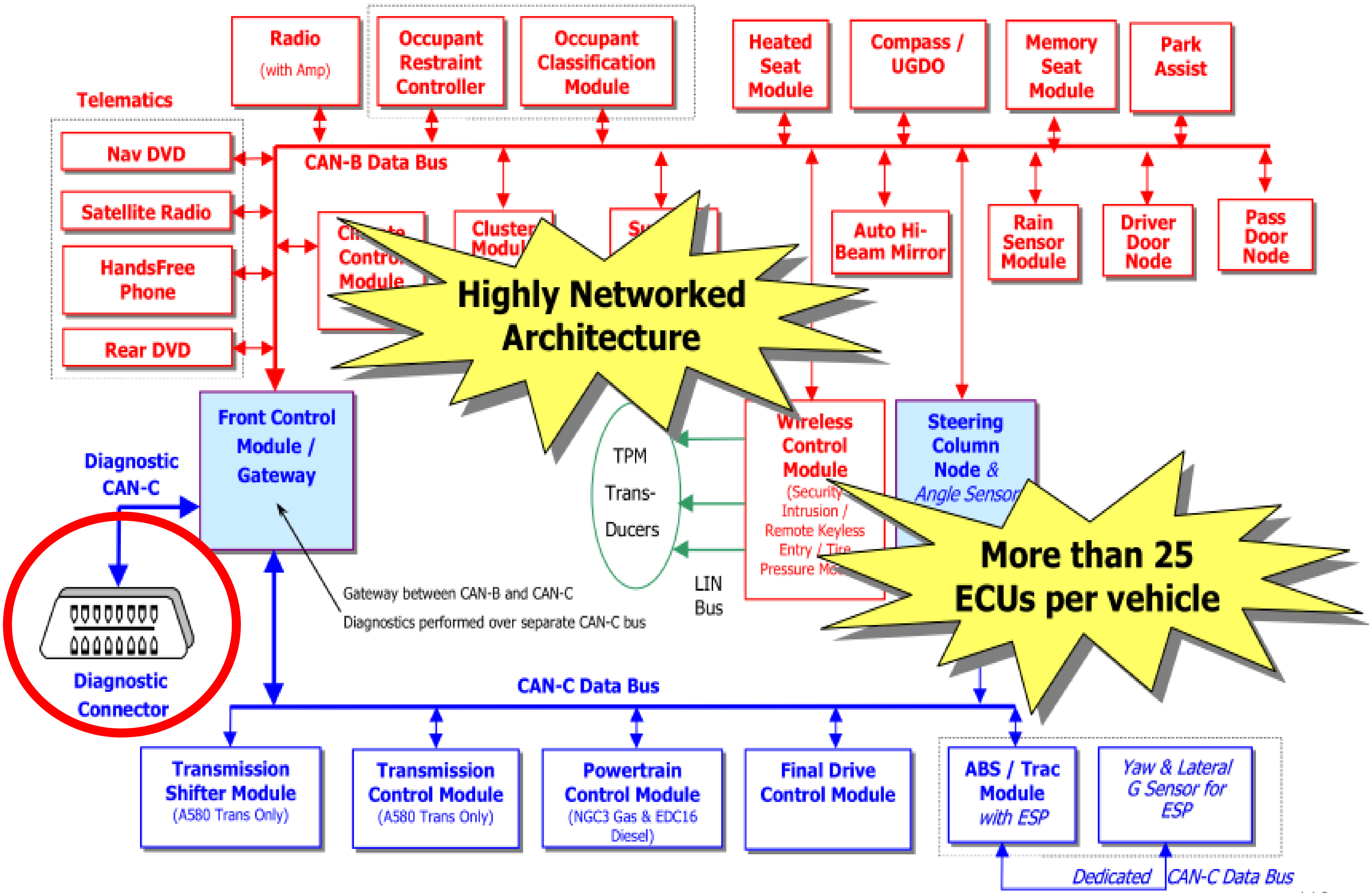
Old Paradigm- open loop, no feedback of machine condition

Two Extremes of Manpower & Resource Waste

Preventive Maintenance Periodic, whether needed or not	⟷	Run-to-Failure No maintenance

Imperatives for New Automated Maintenance Paradigms

- Breakdowns, Unscheduled Maintenance, and Temporary Repairs-
  - add Billions to Manufacturing Costs
  - destroy throughput and Due Date schedules
- Reduced manning levels in Factory Of The Future, Military, Navies
- Complexity of new machinery makes maintenance more complex
- Reduced failure tolerance of Just-in-Time systems
- Small companies cannot afford full-time maintenance technicians
- Ready availability of on-board sensors used for control purposes
- Ease of remote information access over the internet



Radio
(with Amp)
Occupant Restraint Controller
Occupant Classification Module
Heated Seat Module
Compass / UGDO
Memory Seat Module
Park Assist
Telematics
Nav DVD
Satellite Radio
HandsFree Phone
Rear DVD
CAN-B Data Bus
Auto Hi-Beam Mirror
Rain Sensor Module
Driver Door Node
Pass Door Node
Highly Networked Architecture
Front Control Module / Gateway
Diagnostic CAN-C
TPM Trans-Ducers
Wireless Control Module
Steering Column Node & Angle Sensor
More than 25 ECUs per vehicle
LIN Bus
Gateway between CAN-B and CAN-C
Diagnostics performed over separate CAN-C bus
Diagnostic Connector
CAN-C Data Bus
Transmission Shifter Module
(A580 Trans Only)
Transmission Control Module
(A580 Trans Only)
Powertrain Control Module
(NGC3 Gas & EDC16 Diesel)
Final Drive Control Module
ABS / Trac Module with ESP
Yaw & Lateral G Sensor for ESP
Dedicated CAN-C Data Bus

Emissions Control Legislation

California Air Resources Board (ACARB Mail-Out #MSC 97-24): An automotive electronic control module that affects vehicle emission, it needs to be compliant with On Board Diagnostic (OBDII) requirements

Check Engine Light

Design Requirements for Powertrain Electronics

- **Diagnostics**
  - To monitor and detect abnormalities in hardware and software
- **Fault Tolerant**
  - Also known as graceful degradation is the property that enables a system to continue operating properly in the event of the failure of (or one or more faults within) some of its components
- **Fail Safe**
  - Fail-Safe (fail-secure) describes a device or feature which, in the event of failure, fails in a way that will cause no harm or at least a minimum of harm to other devices or danger to personnel

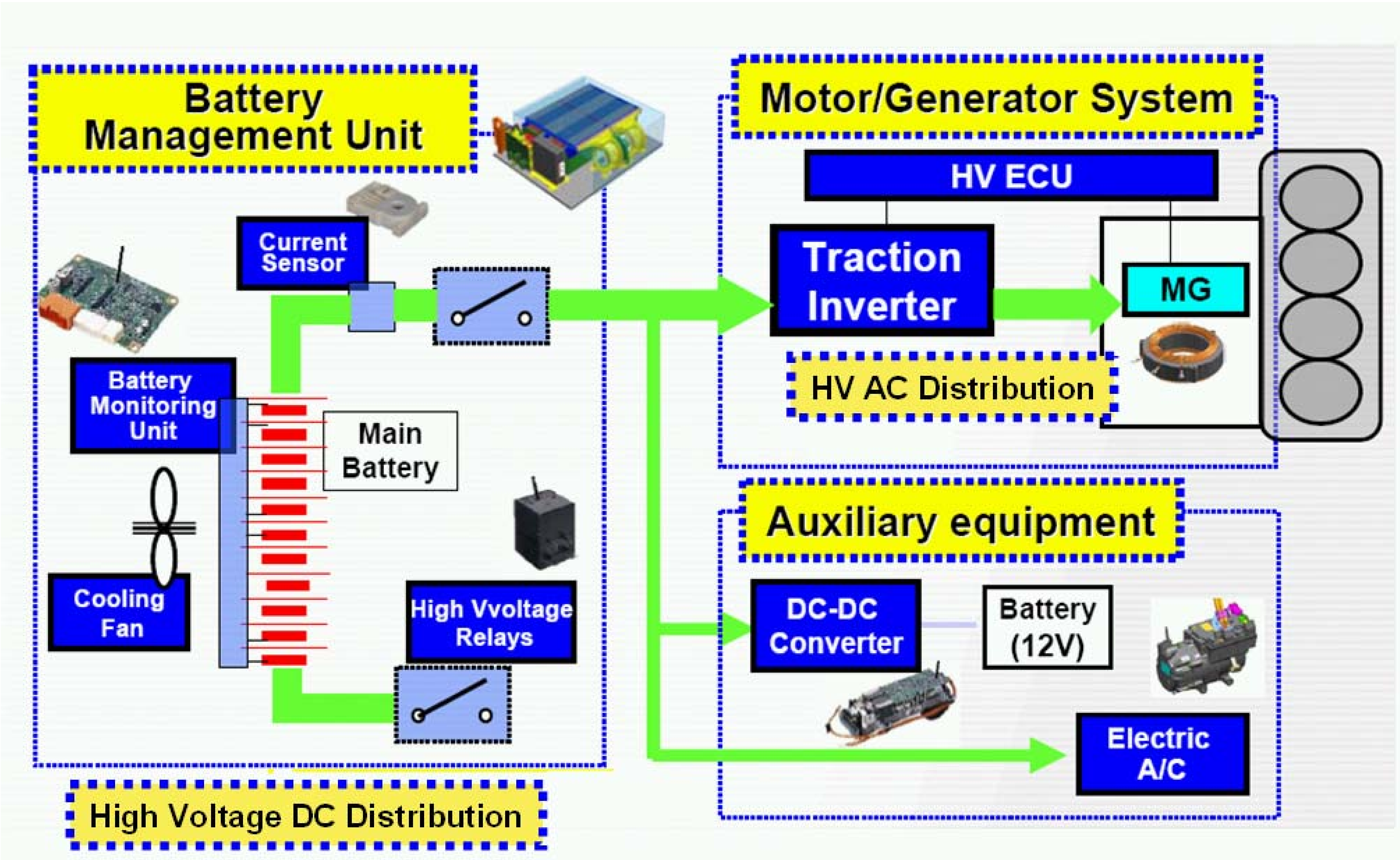
History of Diagnostic Communication Protocols

- 1987 ISO 9141-1 Introduction to vehicle diagnostics
- 1994 ISO 15031-3 SAE J1962 – Diagnostic Connector
- 1996 ISO 14230 SAE J1850 On Board Diagnostic (OBD)
  Key Word Protocol (KWP) 2000 - Flash Programming
- 1997 ISO 9141-3 On Board Diagnostics II (OBDII)
  J1850 PWM – Ford
  J1850 VPW – GM
  ISO 9141 – Chrysler
- 2000 ISO 14230-4 Diagnostics via KWP2000
- 2002 ISO 15765-2 Diagnostics on Controller Area Network (CAN)
  ISO 15031-5 Diagnostic Test Modes
- 2008 CAN protocol is required to be implemented on all passenger vehicles and light duty trucks

Title 13, California Code Regulations, Section 1968.2, Malfunction and Diagnostic System Requirements

- (15.1.5) For hybrids, manufacturers shall submit a plan to the Executive Officer for approval of the hybrid components determined by the manufacturer to be subject to monitoring in section (f)(15.1.1). In general, the Executive Officer shall approve the plan if it includes monitoring of all components/systems used as part of the diagnostic strategy for any other monitored system or component, monitoring of all energy input devices to the electrical propulsion system, monitoring of battery and charging system performance, monitoring of electric motor performance, and monitoring of regenerative braking performance.

Electric Vehicle Propulsion Architecture

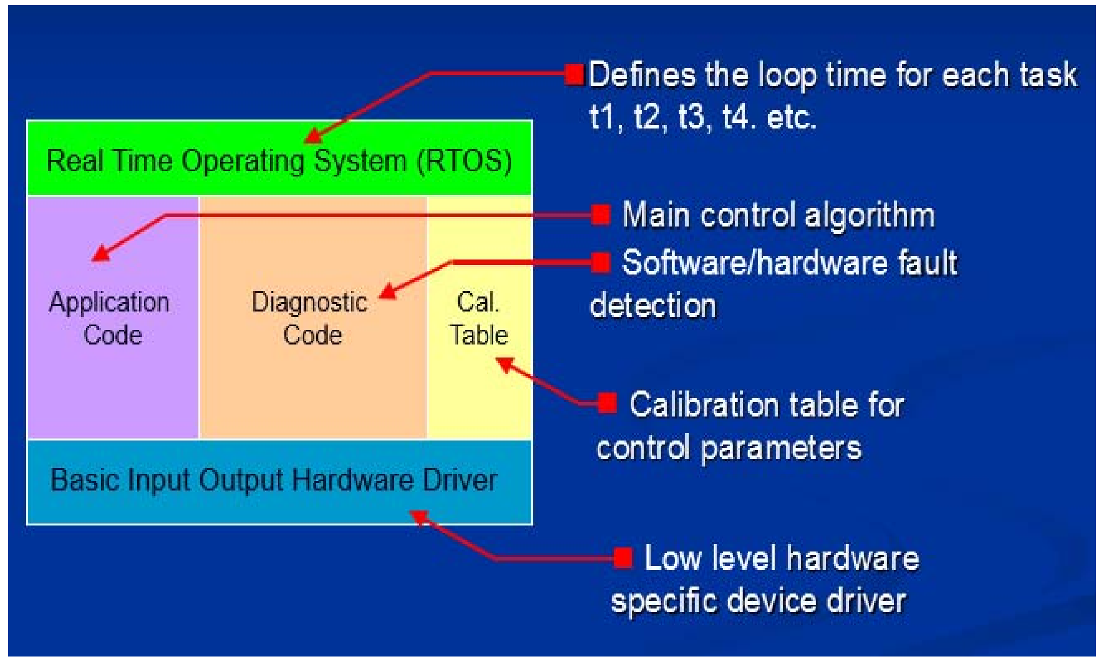


Major Electric Vehicle OBD Systems

1) Traction Motor Inverter
2) High Voltage Battery System
3) High Voltage Interlock Loop
4) High Voltage Isolation breakdown Detection
5) Power Electronics /Motor Coolant System
6) DC/DC Converter
7) Processor Core Software
8) Motor Temperature Sensor
9) Inverter Temperature Sensor
10) Motor Rotor Position Sensor
11) AC Current Sensor

Core Software OBD Techniques

- Power Up/ Power Down memory test
- Complement Data Read/Write to assure the integrity of the data being stored to memory (RAM)
- Checksum comparison to verify program or calibration memory (ROM/FLASH)
- Redundant Coding (Dual Path Software) to store critical code in two different memory areas
- Program Flow Monitoring to include specific Seed and keys to ensure program execution
- Watch dog Timer to detect failures such as timing delays, infinite loops and hung interrupts



Basic Diagnostic Requirements (1)

- Diagnose on-board power supply circuits
  - +3.3V, +5V – Microprocessor
  - +5V – sensors and logic chips
  - +12V – COMS and Op Amps
- Diagnose circuit functions – Hardware
  - Signal conditioning
  - Inputs protection – short to power, short to ground
  - Application specific – device drivers
- Diagnose circuit functions – Software
  - SPI Bus data CRC
  - CAN communication (rolling counter, CRC)
  - RAM, ROM, Flash memory integrity
  - RTOS integrity

Basic Diagnostic Requirements (2)

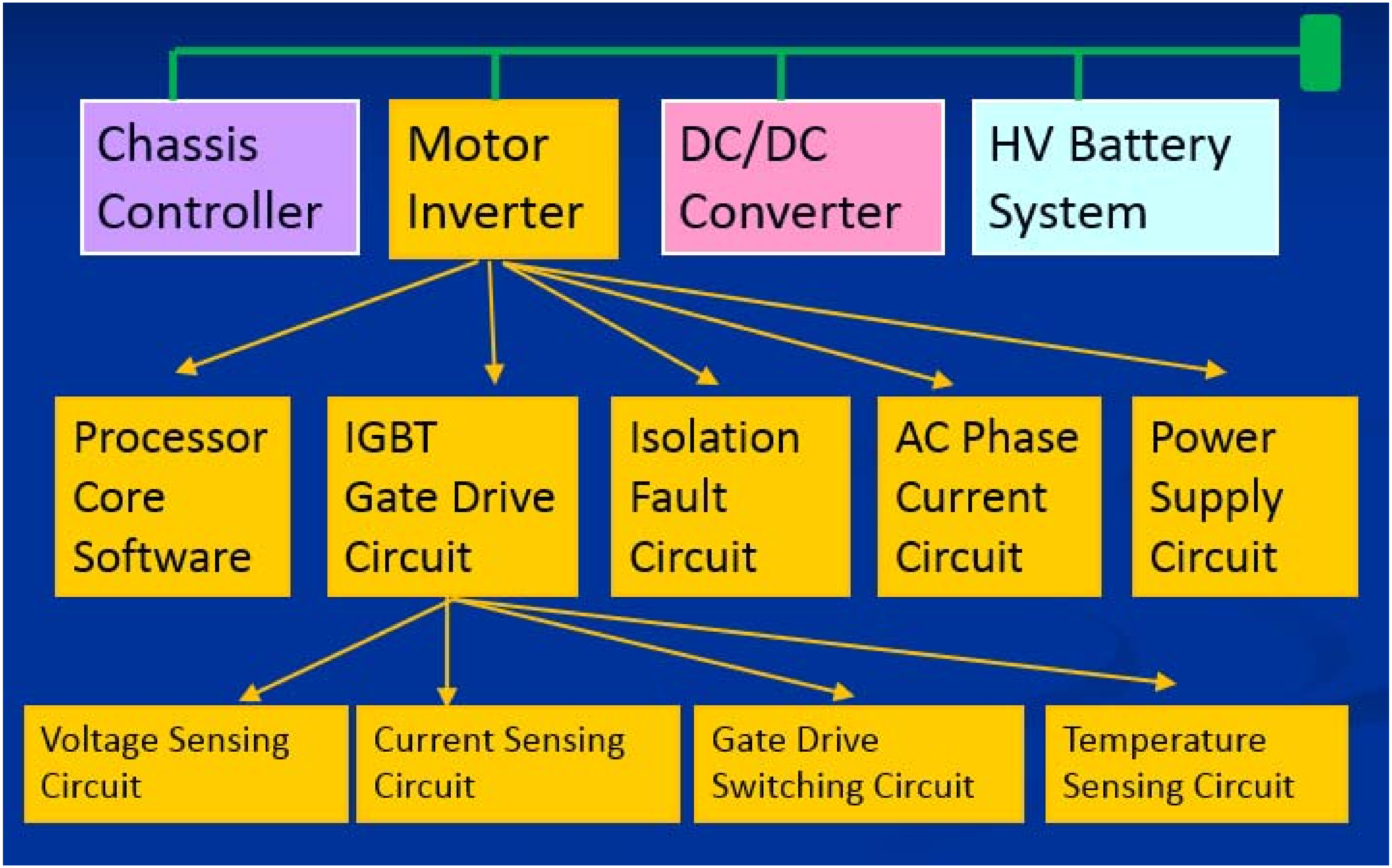
- **Diagnose High Voltage Safety**
  - Isolation detection
    (FMVSS 305, SAE J1766: 500 Ohm/Volt)
  - High voltage DC
  - High voltage AC
  - High voltage interconnection
  - Power electronics

- **Diagnose Controls – Torque Security**
  - Core software operations

SAE J1979 Diagnostic Test Modes

- Mode 01: Show current data
- Mode 02: Show freeze frame data
- Mode 03: Show stored Diagnostic Trouble Codes
- Mode 04: Clear Diagnostic Trouble Codes
- Mode 05: Test results, oxygen sensor monitoring (non CAN only)
- Mode 06: Test results, other component/system monitoring
- Mode 07: Show pending Diagnostic Trouble Codes (detected during current or last driving cycle)
- Mode 08: Control operation of on-board component/system
- Mode 09: Request vehicle information

EV Power Electronics Diagnostic System Structure



Diagnostic – Rationality Check

- Each input signal is compared against all other inputs and against information in the controller to see if it makes sense under the current operating conditions
  - All IGBT temperature sensors should have same temperature readings before inverter starts
  - After engine starts, the coolant temperature sensor signal reading should go higher. If the signal fail to rise after x minutes, it will setup fault code P0483 Cooling Fan Rationality Check Malfunction

Freeze Frame

- A constantly flashing MIL is a sign of a major problem which can cause serious damage if the drivetrain is not stopped immediately.
  - To assist the service technician, OBD II requires the controller to take a “**snapshot**” or freeze frame of all data at the instant an emission-related DTC is set.
- In all cases a "freeze frame" of all sensor readings at the time is recorded in the central computer of the vehicle.

Feds Probe Prius Runaway Acceleration

Car seems OK after a "reboot" but the problem often recurs later
By Joe Benton
ConsumerAffairs.Com

September 10, 2007

Federal safety regulators at the National Highway Traffic Safety Administration have quietly opened an investigation into complaints of "runaway acceleration" in the popular Toyota Prius hybrid, according to a senior official at the agency.

When asked if the agency probe was underway, the senior official responded tersely "yes." Pressed for details, the official said that there is "nothing more to say at this time."

The Toyota Product Communications office is not talking either, not responding to several requests from ConsumerAffairs.Com to discuss the issue of unintended acceleration in the Prius.

Toyota Prius

- Availability
- Battery
- Fuel Gauge
- Insurance Costs
- Service Delays
- Tires
- Transmission
- Happy Hybrid Owners

Test Drive

- Three Lead Feet Meet Little Fuel Sipper

News

- Feds Probe Prius Runaway Acceleration
- Prius Owners Report More

REPORT OF INVESTIGATION: HYBRIDS PLUS PLUG IN HYBRID ELECTRIC VEHICLE

Prepared for:

National Rural Electric Cooperative Association, Inc.

And

U.S. Department of Energy, Idaho National Laboratory

Figure 1--Fire Damaged PHEV Prius

Source: https://crn.cooperative.com/Resources/TechSurveillance/items/2008/FieldReport0613.htm

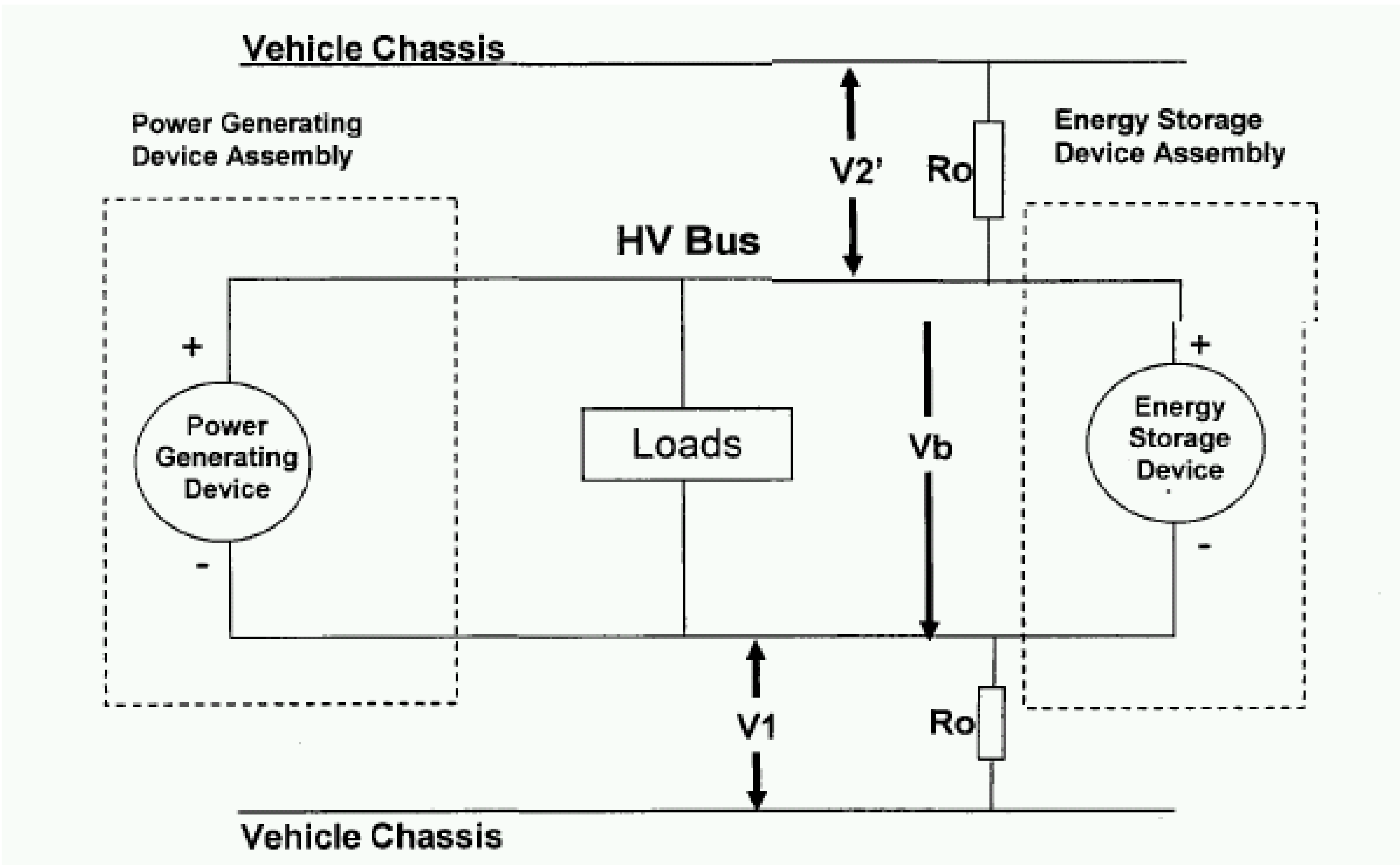
High Voltage System Isolation Breakdown Detection

- **Federal Motor Vehicle Safety Standard (FMVSS) 305**

"The standard is applicable to passenger cars that use more than 48 volts of electricity as propulsion power shall maintain an electrical isolation between the propulsion battery system and the vehicle electricity-conducting structure of not less than 500 ohms/volt"

128

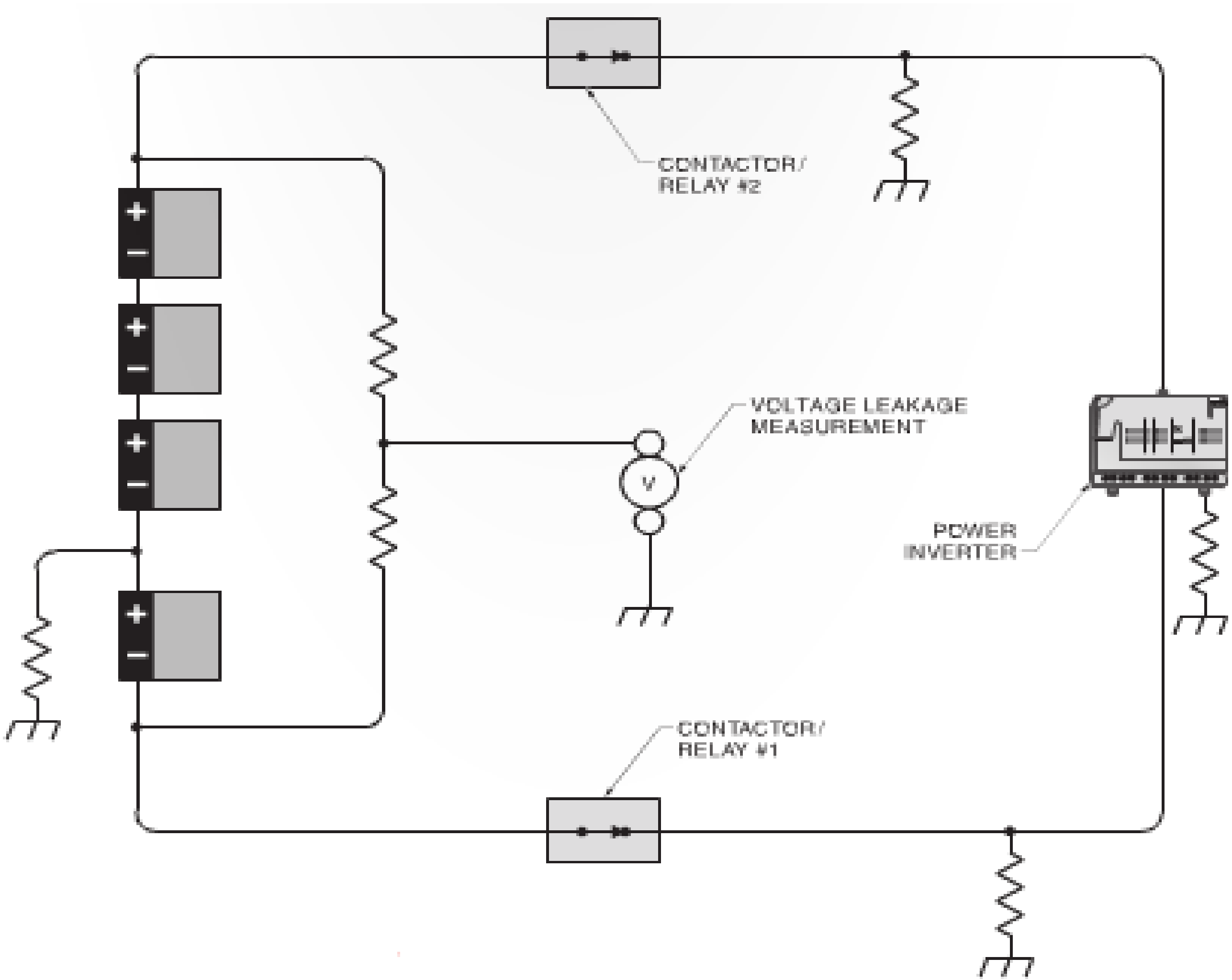
EV Propulsion Battery Electrical Isolation



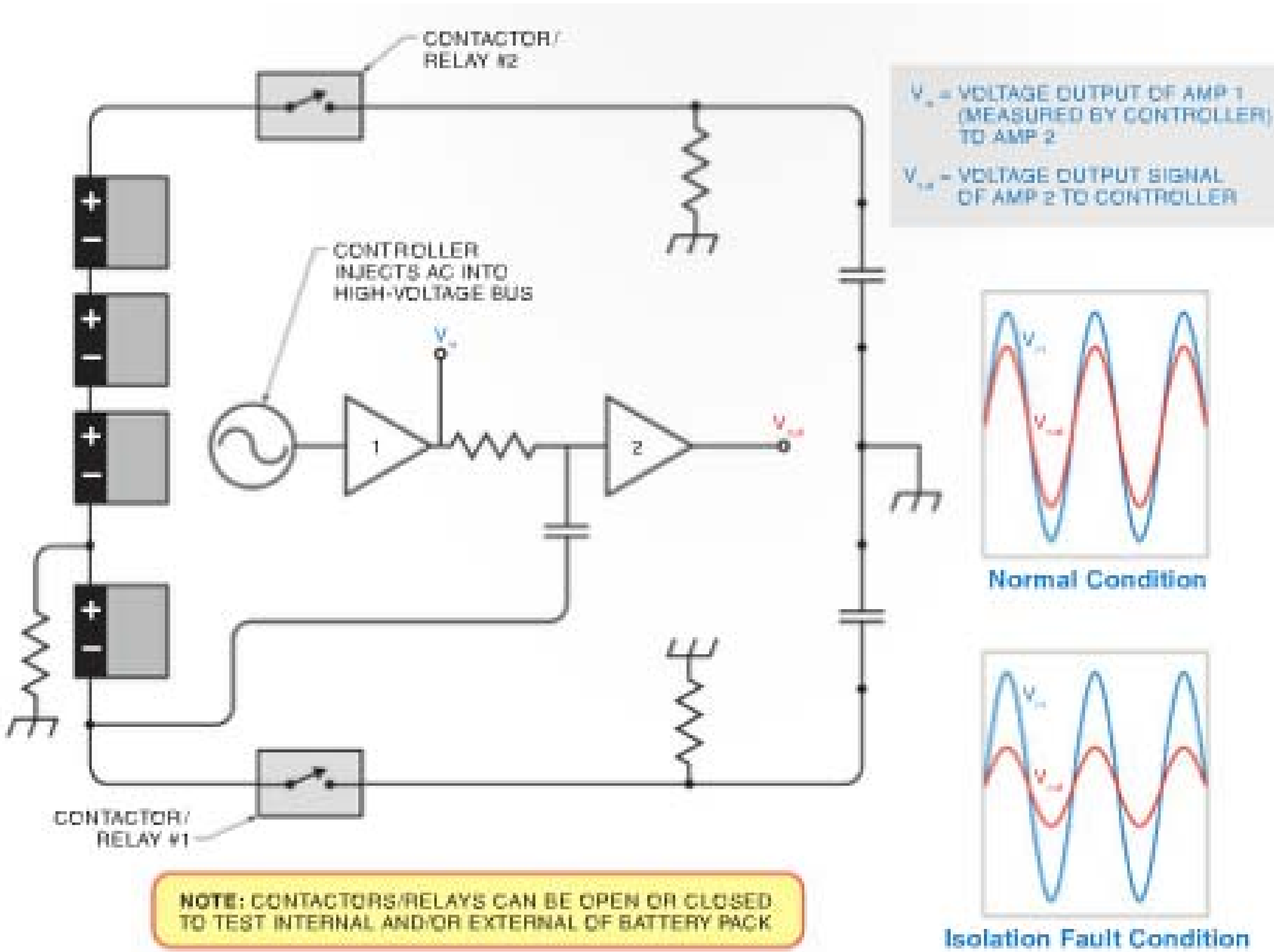
Source: ***Federal Register*** */ Vol. 72, No. 194*

HV Isolation Fault Detection – DC Method

DC isolation fault detection measures the DC leakage for high voltage components and cables on the high voltage bus to chassis ground



HV Isolation Fault Detection – AC Method



AC Isolation Fault Detection. AC isolation fault detection measures both resistance and capacitance of the high-voltage bus circuits by injecting an AC signal onto the bus. This is accomplished by using a resistor-capacitor (RC) circuit. AC isolation detection typically is used to measure the isolation integrity of the battery-pack module string with reference to the vehicle chassis.

Ford Escape Hybrid
High Voltage Battery Pack

High Voltage Battery Pack Total OBD DTCs = 340

- Intrelock circuit
- Precharge circuit
- Cooling fan control circuit
- Air temperature sensor
- Contactor controls circuit
- Pack voltage sense circuit
- Pack current sense circuit
- Pack air flow sense circuit
- Battery 12V system voltage
- Battery cell voltage sense circuit
- Battery module temperature sense circuit
- Service disconnect circuit
- Coolant pump control circuit

SAE Diagnostic Trouble Codes DC/DC Converter

- P0A08 DC/DC Converter Status Circuit / Open
- P0A09 DC/DC Converter Status Circuit Low
- P0A10 DC/DC Converter Status Circuit High
- P0A11 DC/DC Converter Enable Circuit / Open
- P0A12 DC/DC Converter Enable Circuit Low
- P0A13 DC/DC Converter Enable Circuit High
- P0A94 DC/DC Converter Performance
- P0C38 DC/DC Converter Temperature Sensor "A" Circuit
- P0C39 DC/DC Converter Temperature Sensor "A" Circuit Range/Performance
- P0C3A DC/DC Converter Temperature Sensor "A" Circuit Low
- P0C3B DC/DC Converter Temperature Sensor "A" Circuit High
- P0C3C DC/DC Converter Temperature Sensor "A" Circuit Intermittent/Erratic

Source: Delphi

SAE Diagnostic Trouble Codes - Power Supply

- P0560 System Voltage Malfunction
- P0561 System Voltage Unstable
- P0562 System Voltage Low
- P0563 System Voltage High
- P06B0 Sensor Power Supply "A" Circuit/Open
- P06B1 Sensor Power Supply "A" Circuit Low
- P06B2 Sensor Power Supply "A" Circuit High
- P06B3 Sensor Power Supply "B" Circuit/Open
- P06B4 Sensor Power Supply "B" Circuit Low
- P06B5 Sensor Power Supply "B" Circuit High
- P0C0B Drive Motor "A" Inverter Power Supply Circuit / Open
- P0C0C Drive Motor "A" Inverter Power Supply Circuit Low
- P0C0D Drive Motor "A" Inverter Power Supply Circuit High
- P0C0E Drive Motor "A" Inverter Power Supply Circuit / Open
- P0C0F Drive Motor "A" Inverter Power Supply Circuit Low
- P0C10 Drive Motor "A" Inverter Power Supply Circuit High

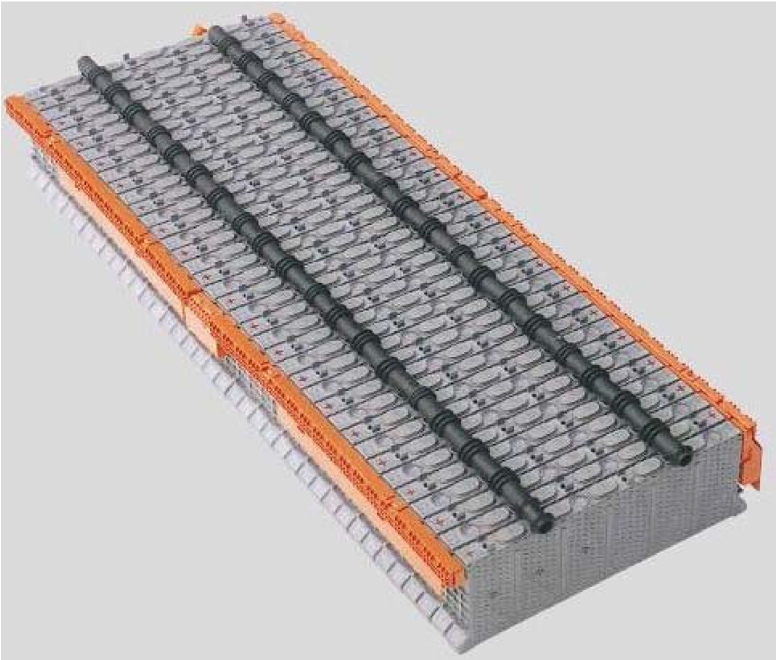
SAE Diagnostic Trouble Codes
Control Processor Core

The core processor monitors itself by using various software monitoring functions

- P0600 Serial Communication Link Malfunction
- P0601 Internal Control Module Memory Check Sum Error
- P0602 Control Module Programming Error
- P0603 Internal Control Module Keep Alive Memory (KAM) Error
- P0604 Internal Control Module Random Access Memory RAM Error
- P0605 Internal Control Module Read Only Memory (ROM) Error
- P0606 Control Processor Fault
- P0607 Control Module Performance

Source: http://www.dieseltalk.com

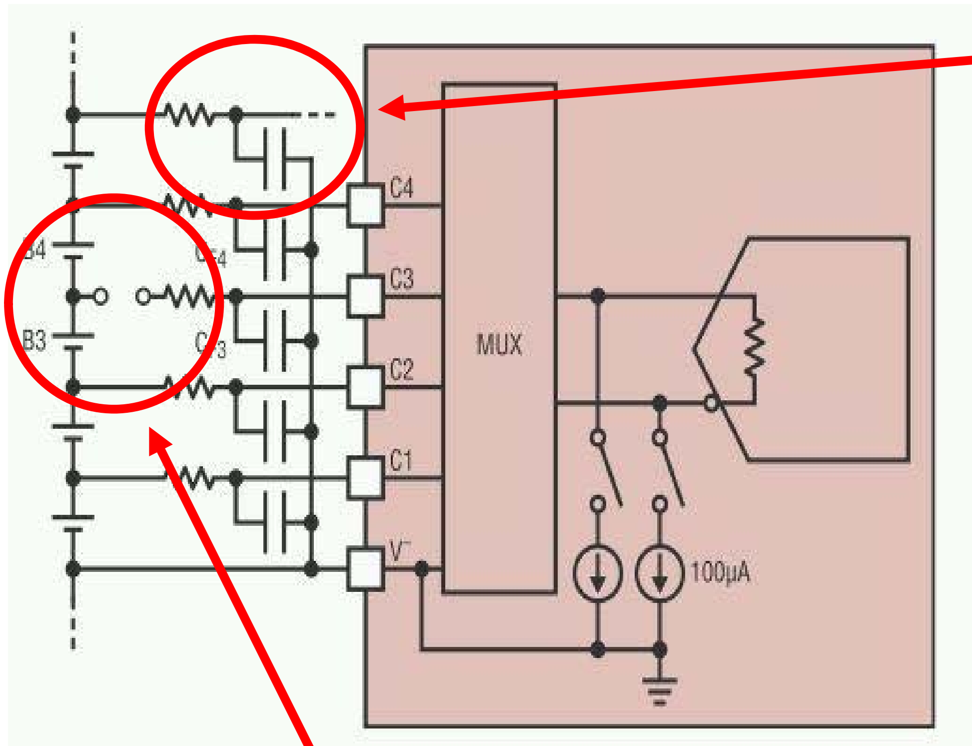
HV Battery Voltage Sense Diagnostics (1-3)



- Automotive high voltage battery systems require that **"no bad cell reading be misinterpreted as a good cell reading"**
- Two of the more common faults that can cause false readings are **open circuits** and **A/D Converter failures**

Source: Delphi

HV Battery Voltage Sense Diagnostics (2-3)



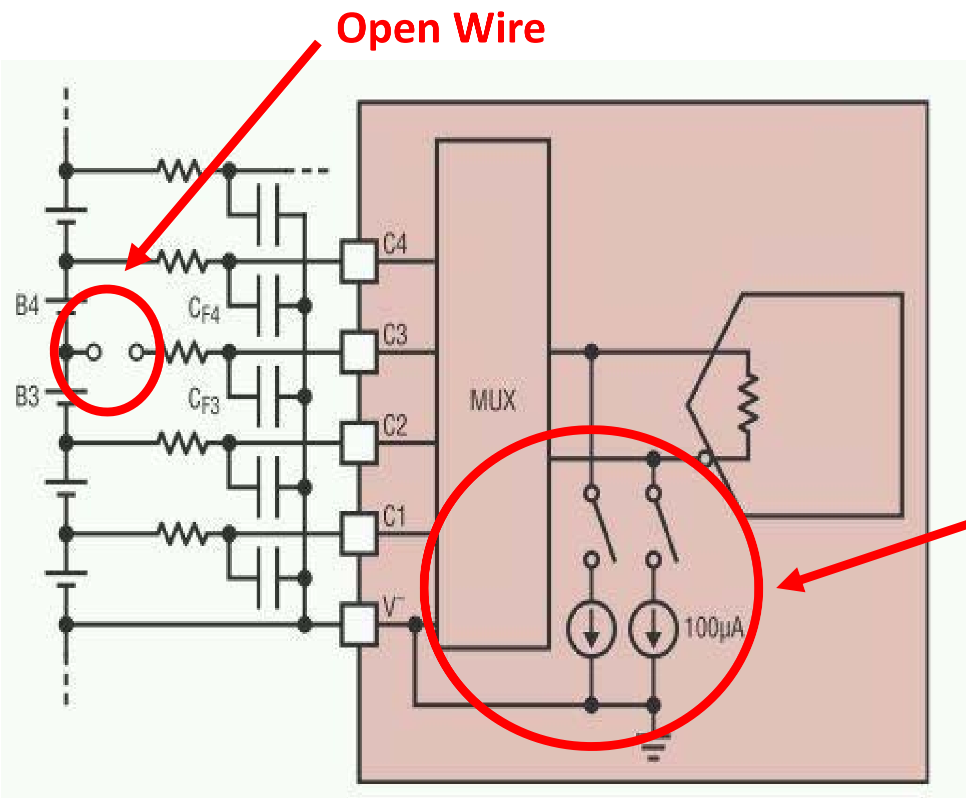
Motor inverter switching noise filter

High-power batteries are often used in noisy environments subject to high dV/dt supply noise and EMI noise from motor inverter

EV, HEV applications may include external noise filtering to improve the quality of the ADC readings. When an RC network is used to filter noise, **an open wire may not produce a zero reading** because the ADC input resistance is too large to discharge the capacitors on the input pin.

Source: Linear Technology

HV Battery Voltage Sense Diagnostics (3-3)



Open wire detection or cell resistance measuring function is required in the Battery Management System (BMS)

The **current source** is used to load the cell inputs. The current source will cause large changes in cell readings if there is an open circuit in the harness.

When input C3 is open, after several cycles of measuring battery cells B3 and B4, the ADC input resistance charges capacitors CF3 and CF4. The resulting potential on input C3 will be approximately midway between C2 and C4. The ADC readings of B3 and B4 may indicate a valid cell voltage when in fact the exact state of B3 and B4 is unknown.

Source: Linear Technology, Delphi

Summary

1) On-Board Diagnostic (OBD) system is required by law for any mass production EVs and HEVs
2) Electric drivetrain design are driven by Performance, Features and the On-Board Diagnostic requirements
3) The purpose of vehicle On-Board Diagnostic System: Diagnosis, Prognosis and Testing
4) OBD = Robustness

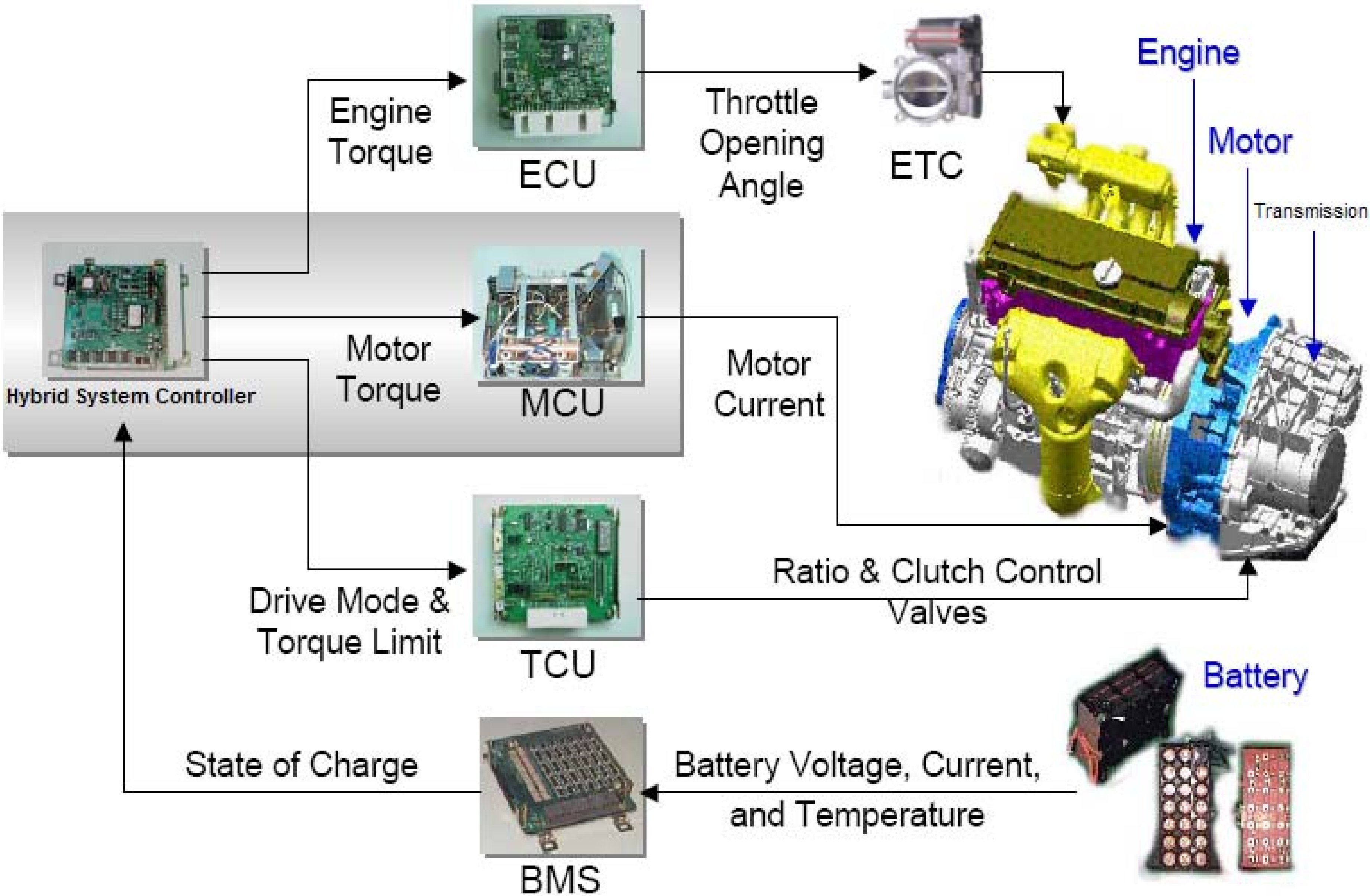
Electric Powertrain System Integration

EV Powertrain
Power Electronics System Integration

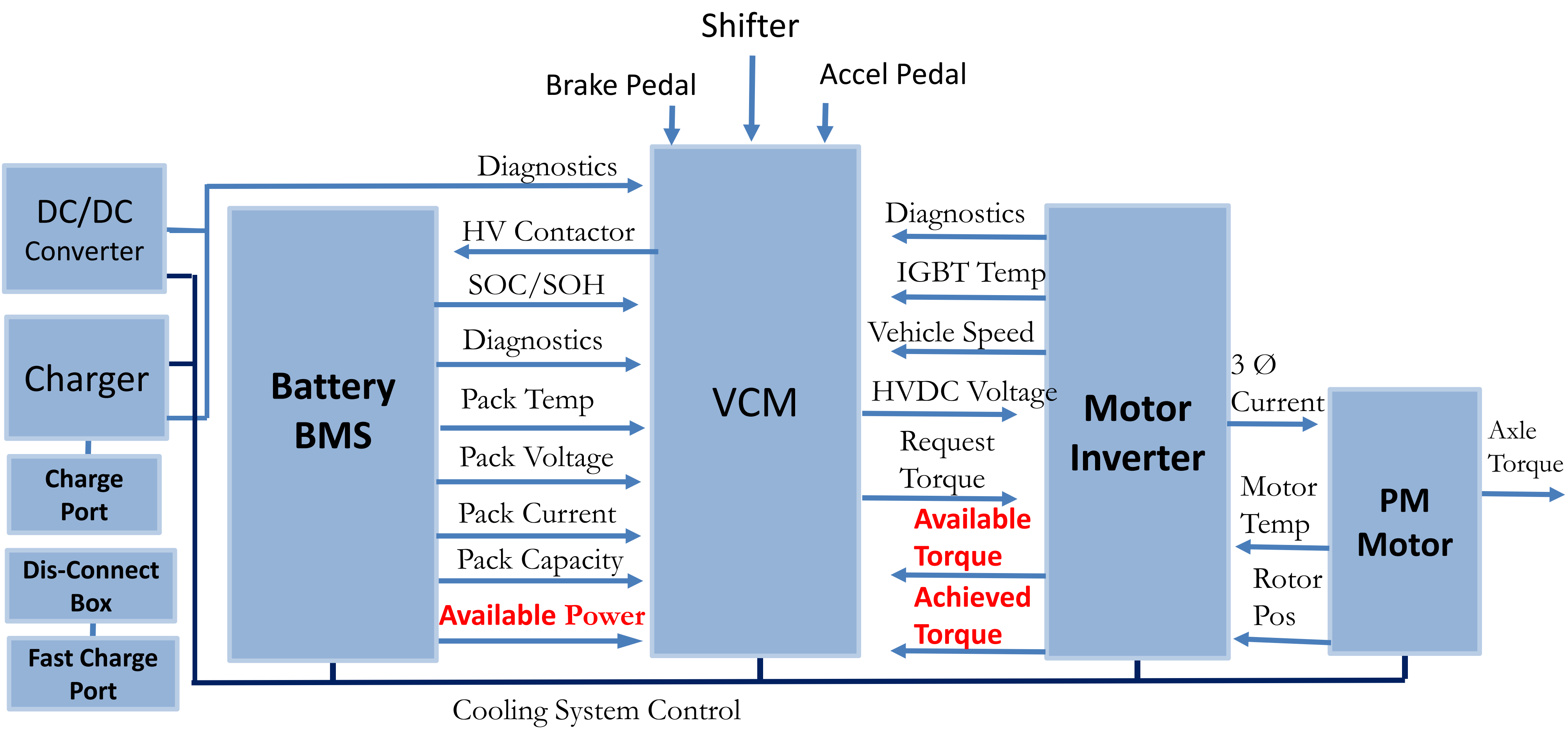
- How to make Battery, Power Electronics and Traction Motor working together?

1) EV Power Flow
2) Battery Power Constrains

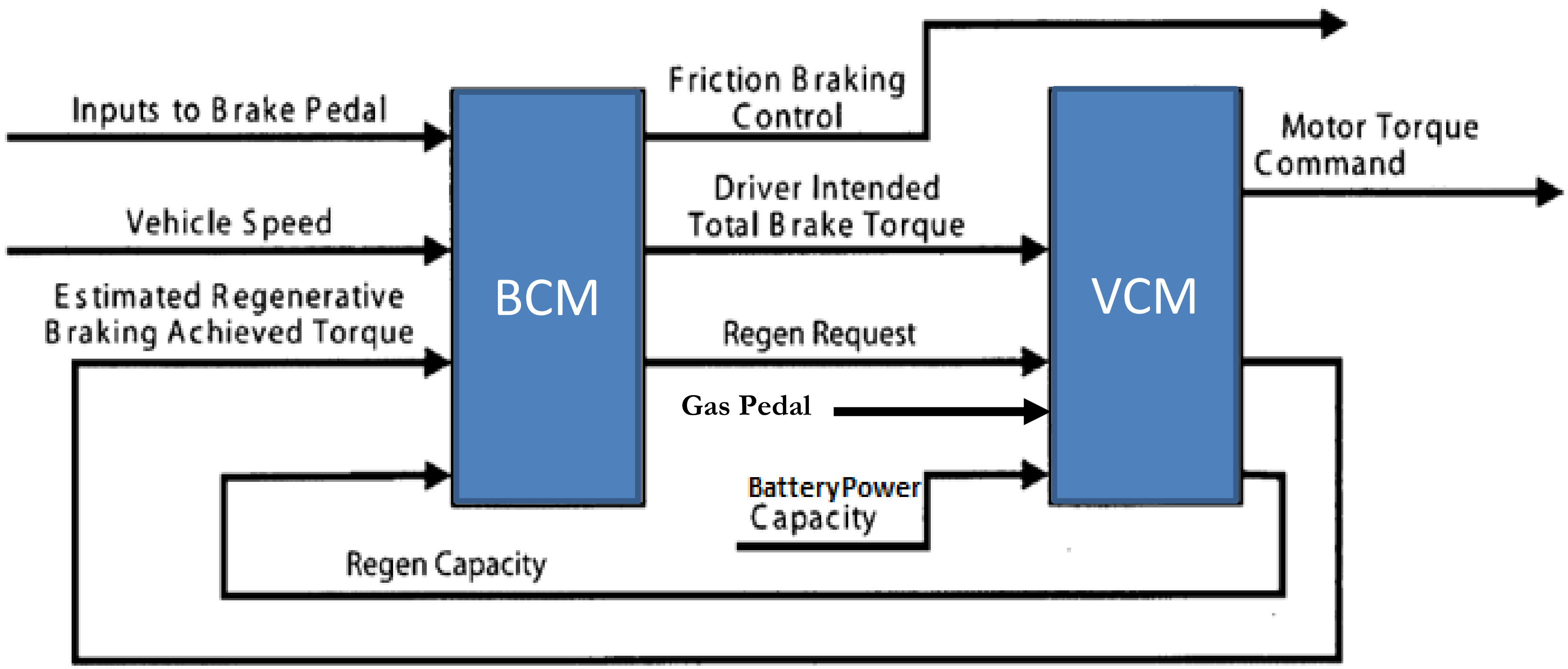
Hybrid Electric Vehicle System Controls Diagram



EV Propulsion System Integration



Vehicle Control Module (VCM)
Brake Control Module (BCM)
Torque Controls Integration Power Flow



Brake → (2)

Regen Blending → (4)

(1)

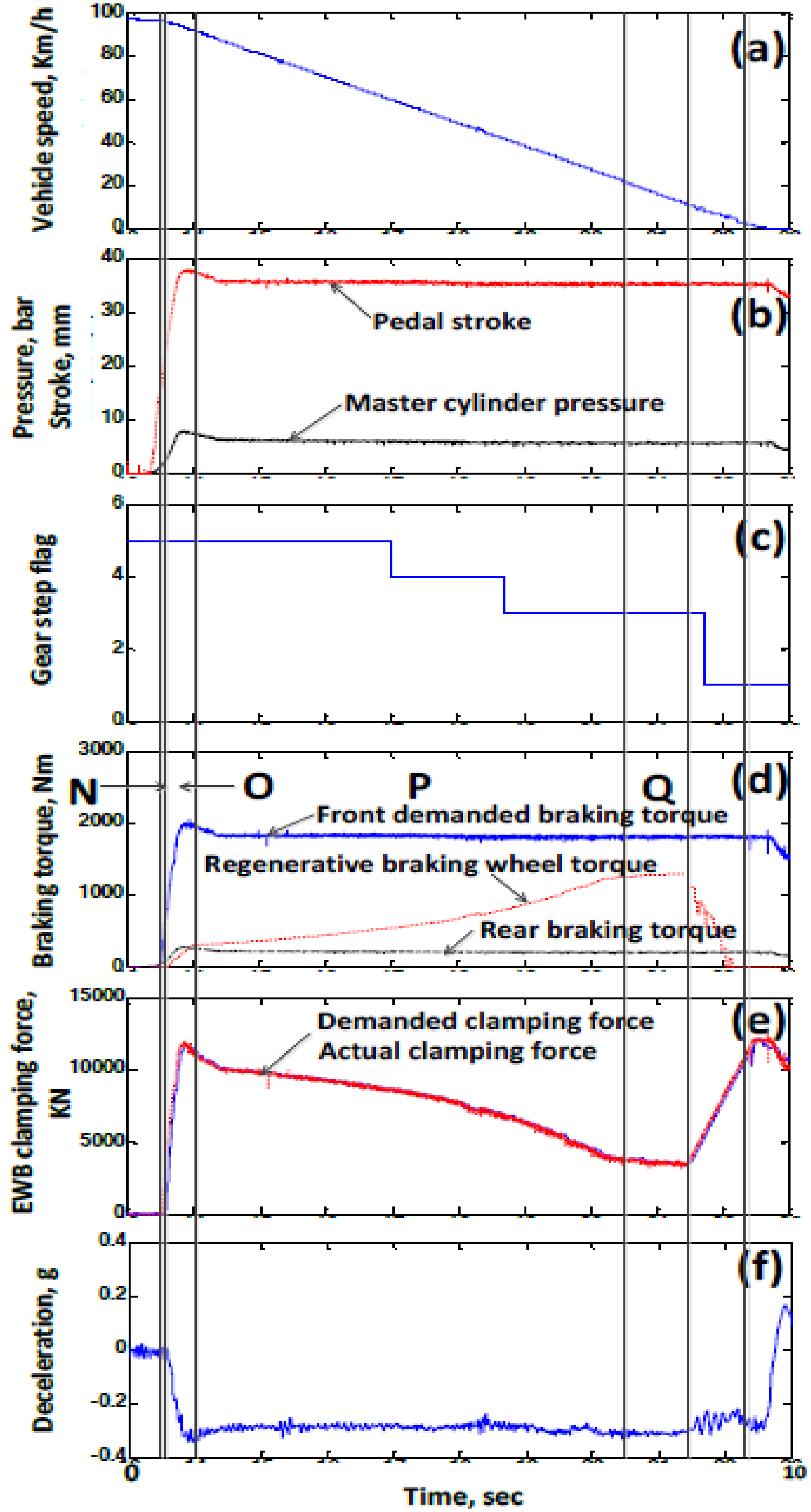
(2)

(3)

(4)

(5)

(6)



VCM, BCM Torque Control Regen Braking Power Flow

EV Powertrain Control Integration

- **Traction motor** is the only propulsion source in EV
- **Battery pack** is the only energy source in the EV
- How to control battery?
- Can we control battery?

Battery Power Control through Controls of Motor Torque

1 - Battery current and voltage.

Motor mechanical power: $P_M = M_M * \omega_M$

Motor electrical power: $P_{\text{Bat}} = U_{\text{Bat}} I_{\text{Bat}}$

$\therefore U_{\text{Bat}} I_{\text{Bat}} = M_M * \omega_M$

$\therefore \boldsymbol{I_{\text{Bat}} \propto M_M}$ and $\boldsymbol{U_{\text{Bat}} \propto M_M}$

2 - Battery Temperature. Battery temperature is a function of the absolute value of battery current; greater utilization increases temperature.

$T_{\text{Bat}} \propto |I_{\text{Bat}}|$

$\therefore \boldsymbol{T_{\text{Bat}} \propto |M_M|}$

3 - Battery life (L_{Bat}). Battery life is a function of the absolute current throughput or AmpHr throughput to the battery.

$$L_{\text{Bat}} \propto \frac{1}{\left|\frac{AmpHr}{Hr}\right|}$$

$$\left|\frac{Amp\cancel{Hr}}{\cancel{Hr}}\right| = |I_{\text{Bat}}|$$

$$L_{\text{Bat}} \propto \frac{1}{|I_{\text{Bat}}|}$$

$$\therefore \boldsymbol{L_{\text{Bat}} \propto \frac{1}{|M_M|}}$$

4 – Battery state of charge is proportional to charge current and inversely proportional to discharge current.

$\text{SOC} \propto I_{\text{Bat, Chrg}}$ and $\text{SOC} \propto \frac{1}{I_{Bat,Dschrg}}$

$\therefore \boldsymbol{SOC \propto M_{M,Chrg}}$ and $\therefore \boldsymbol{SOC \propto \frac{1}{M_{M,Dschrg}}}$

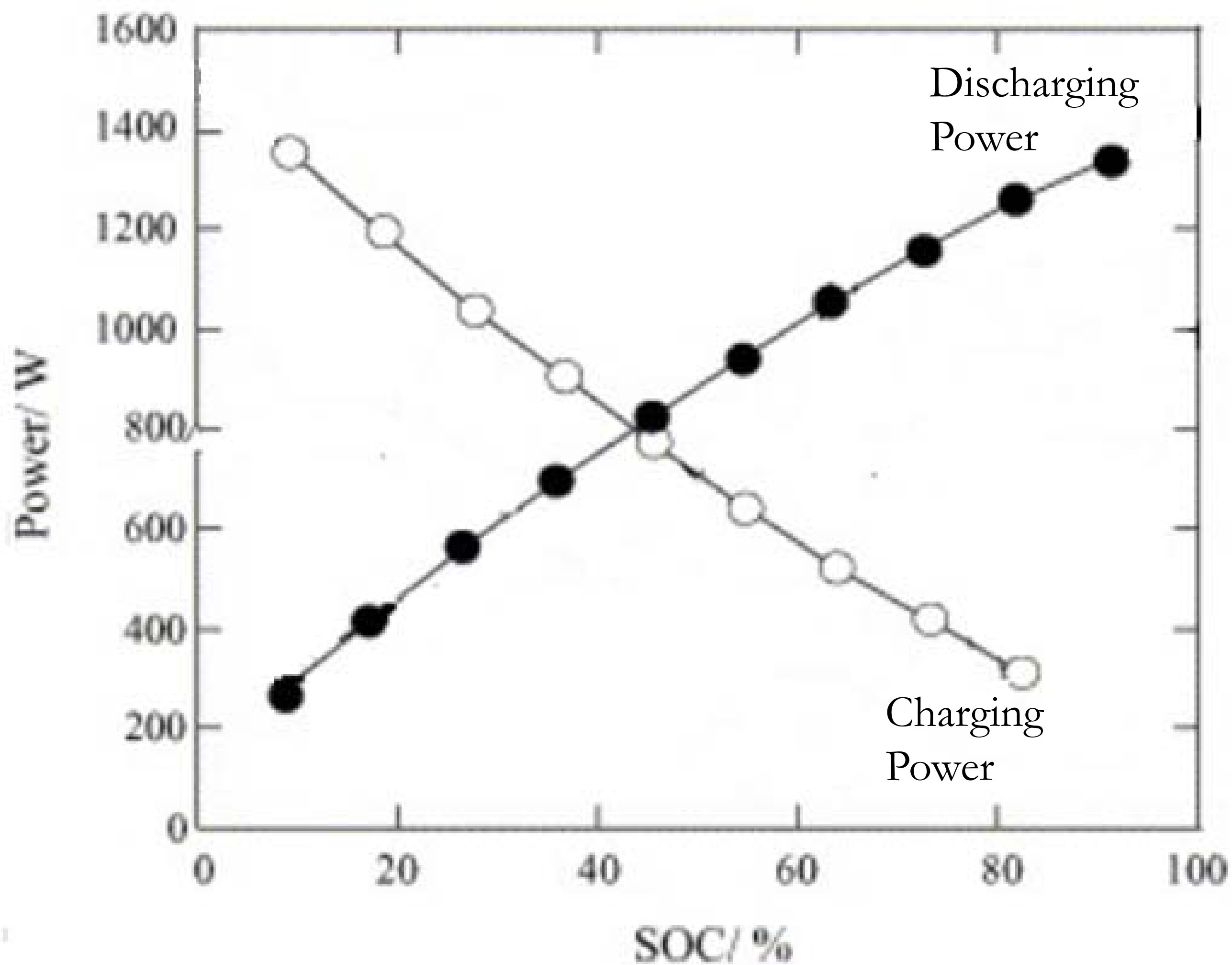
Battery Power Limits

- The primary method used for Energy Storage System control is **Battery Power Limits.**
- The power limits are boundaries within which the system can maximize utilization of the battery pack while maintaining battery life and safety.
- The goal is to meet the driver's output torque request while meeting all constraints and minimizing battery power loss.

- All factors that affect battery life and safety are functions of motor torque

- Therefore we are able to achieve control of the battery by control of motor torque. This is done by **using *Power Limits* to Bound Motor Torque**.

Battery Available Power – Battery Power Limits



Battery Power Limit is a function of SOC, Temperature and Age (SOH)

3 Pairs of Power limits for EV Traction Battery

Discharge Power Limits

1) *Instantaneous Discharge Power Limits*

   Used for discharge events that take up to 100-200 ms in duration.

2) *Short Term Discharge Power Limit*

   Used for discharge events that take up to a few seconds in duration. (Changing Lanes)

3) *Long Term Discharge Power Limit*

   Used for discharge events that take 10-20s in duration (Propulsion Acceleration)

Charge Power Limits

1) *Instantaneous Charge Power Limit*

   Used for charge events that are up to 100-200 ms in duration. (Emergency braking)

2) *Short Term Charge Power Limit*

   Used for charge events that are up to a few seconds in duration. (Pulse braking)

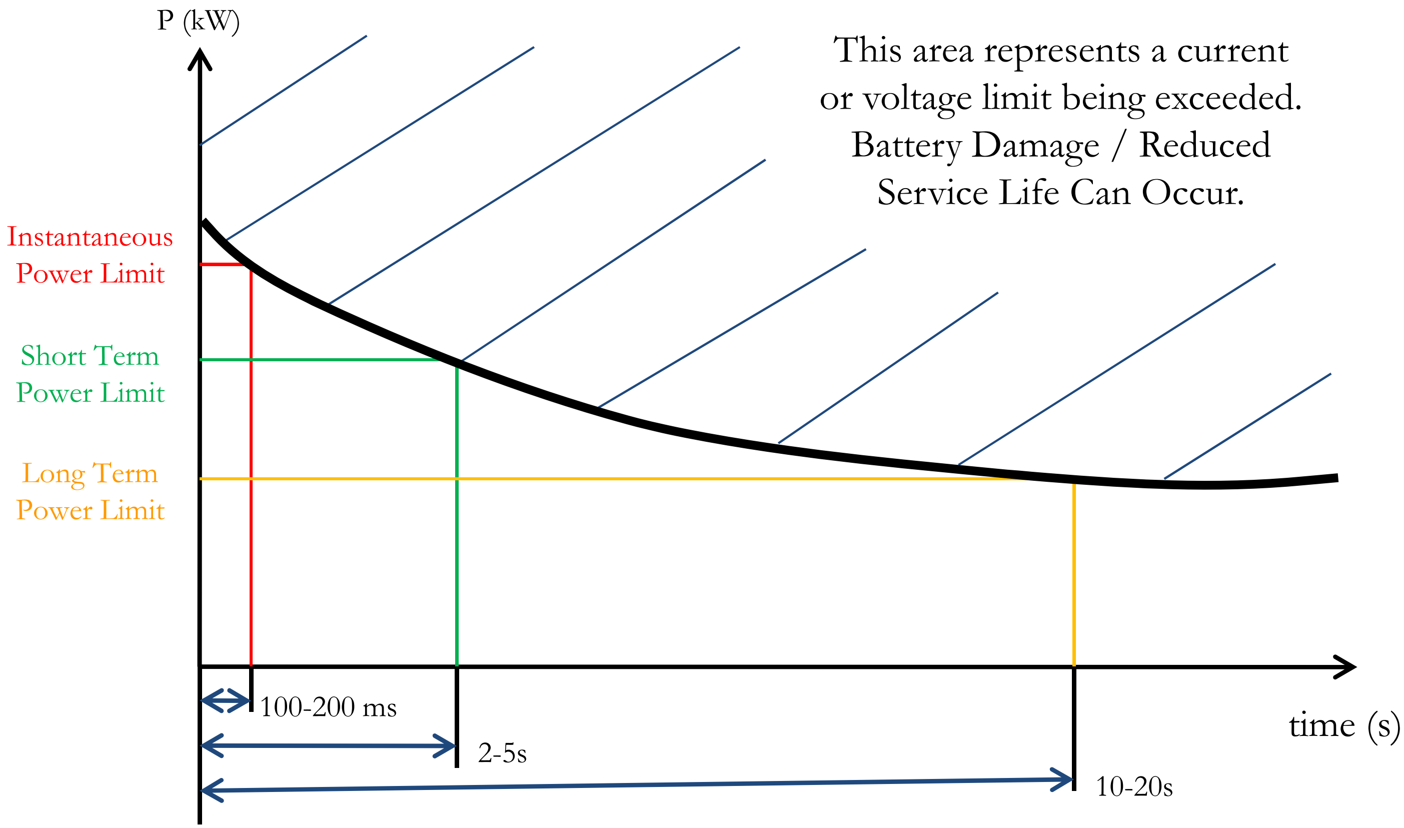
3) *Long Term Charge Power Limit*

   Used for charge events that take 5-10s in duration. (Slow Regen Braking)

- *Battery Instant Charging/Discharging Power*

$$= F\,(SOC,\ SOH,\ SOL)$$

How Battery Power Limits are Determined



- For the current limited case, current is held at a current limit and this curve represents the corresponding battery power.
- For the voltage limited case, the voltage is held at a voltage limit and this curve represents the corresponding battery power.
- The more restrictive of the current or voltage limited case is sent to VCU Operating Strategy (VOS) for system control.

The Ultimate Goal of EV Control Optimization is to Achieve The Longest Driving Distance

"Distance to Empty"

HOW FAR CAN I GO?

Conclusion

1. **Power limits are calculated in real-time.**
2. The power limits are derived from values (i.e. instantaneous resistance) obtained from HPPC (Hybrid Pulse Power Characterization) – a standard test.
3. For Li-Ion, current is the predominant limiter. This is battery cell chemistry driven (i.e. NiMH was more voltage limited). Typically, power limits are current limited in the central region of SOC and voltage limited at the low and high SOC extremes.
4. **Power limits are based on predictions of power at specific points in the future.** As the battery conditions change (SOC, temperature, age), the power limits will change.
5. The battery control strategy is to maximize battery utilization while maintaining Battery life.
6. Battery control can be achieved largely through motor torque control.
7. **The VCU Operating Strategy (VOS) uses power limits as boundaries within which the system can operate.**
8. VOS also uses closed loop current and voltage control to keep these parameters within safe limits.

Questions / Comments

Thank You