METU EE7566
Electric Drives in Electric and Hybrid Electric Vehicles

Emine Bostancı

Office: C-107

Content

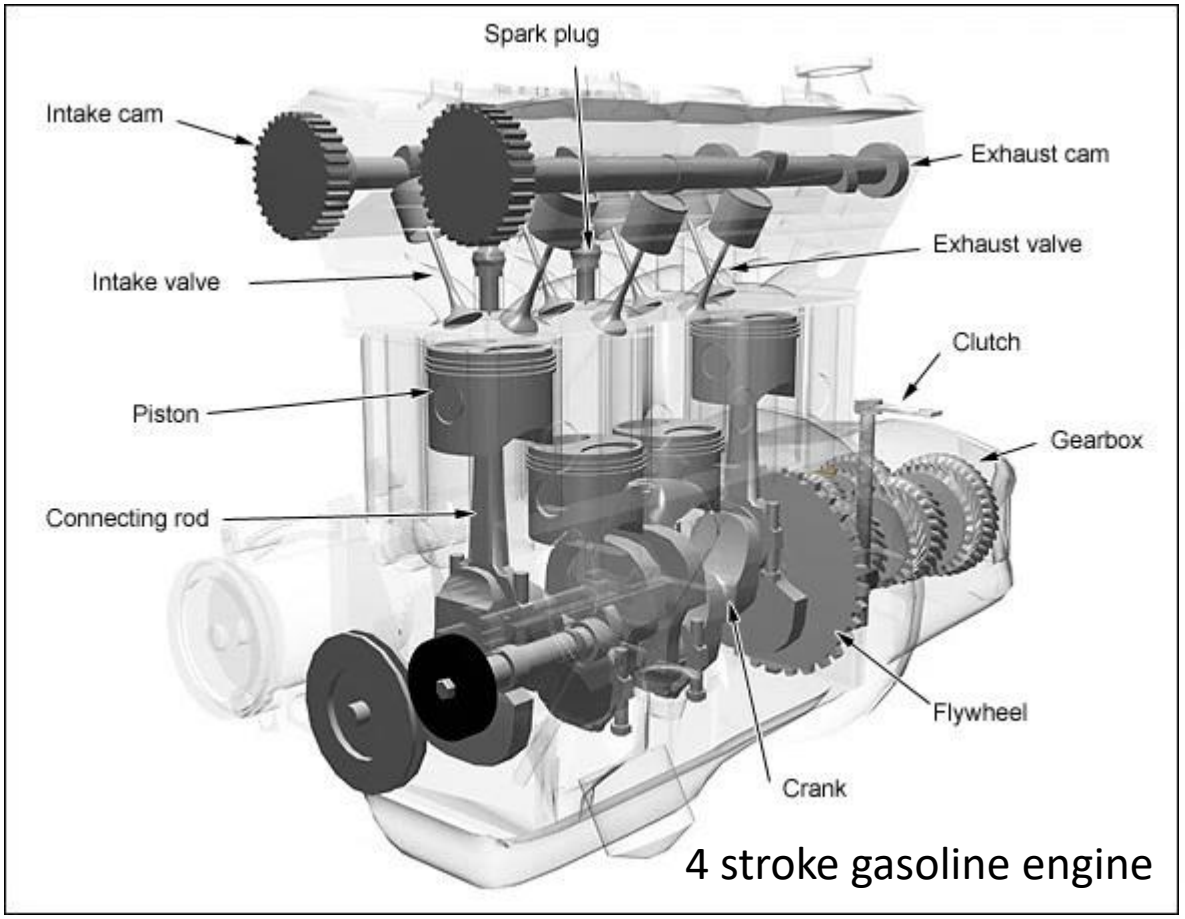
Power Converters

- Internal combustion engine
- Electric machines
- Hydrogen fuel cell
- Electrical-to-electrical
- Mechanical-to-mechanical
- Modes of BEV and HEV

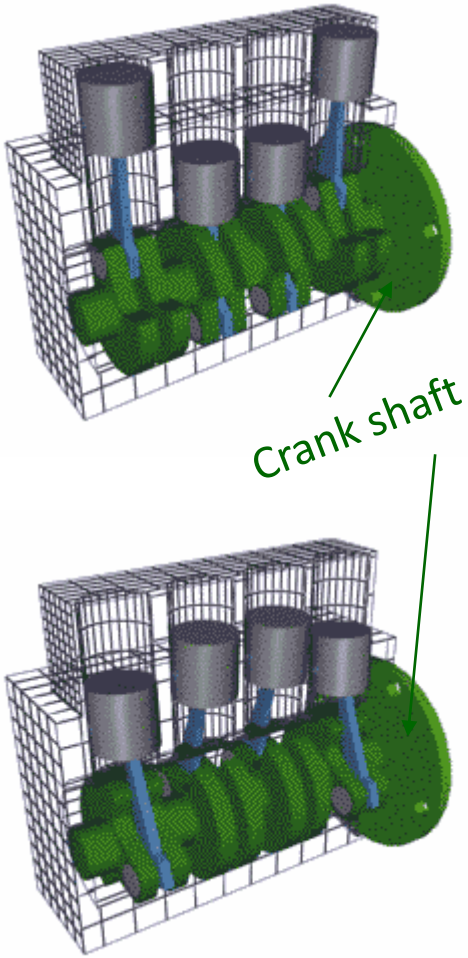
Power Converters – Internal Combustion Engine (ICE)

Chemical reaction when gasoline as fuel used:

$2\ C_8H_{18} + 25\ O_2 \rightarrow 16\ CO_2 + 18\ H_2O$

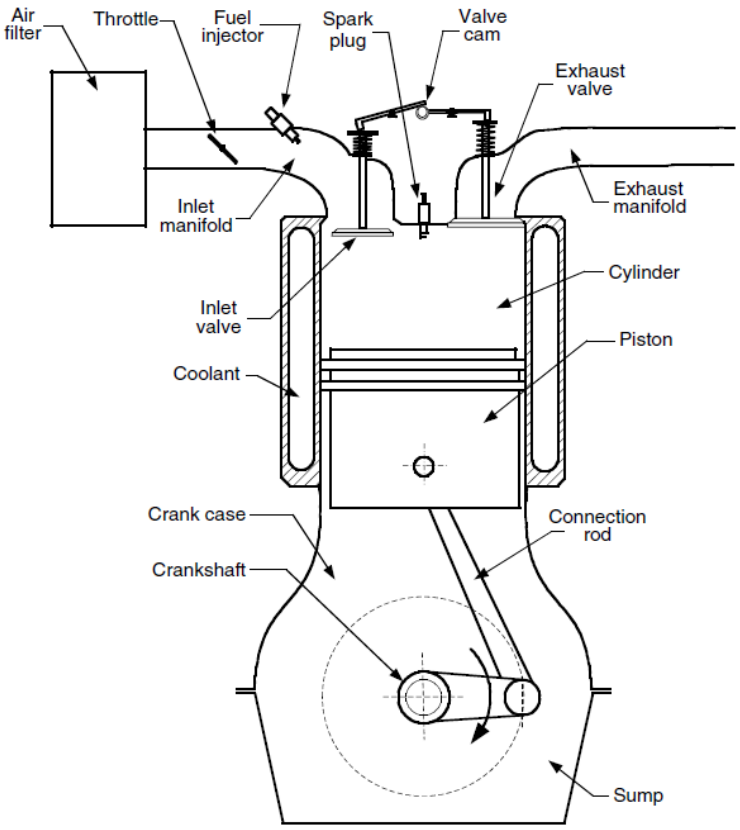


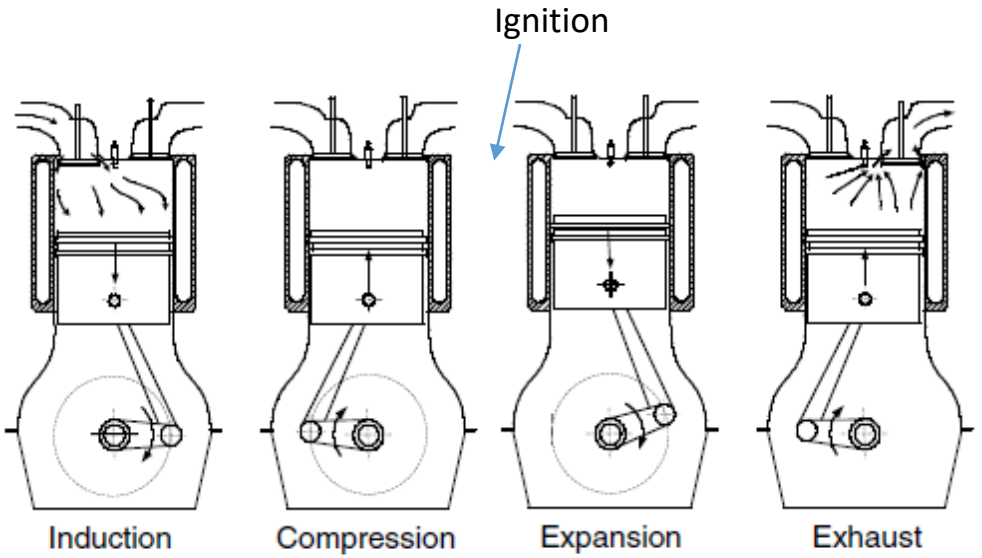
4 stroke gasoline engine



Power Converters – Internal Combustion Engine (ICE)

4 stroke gasoline engine





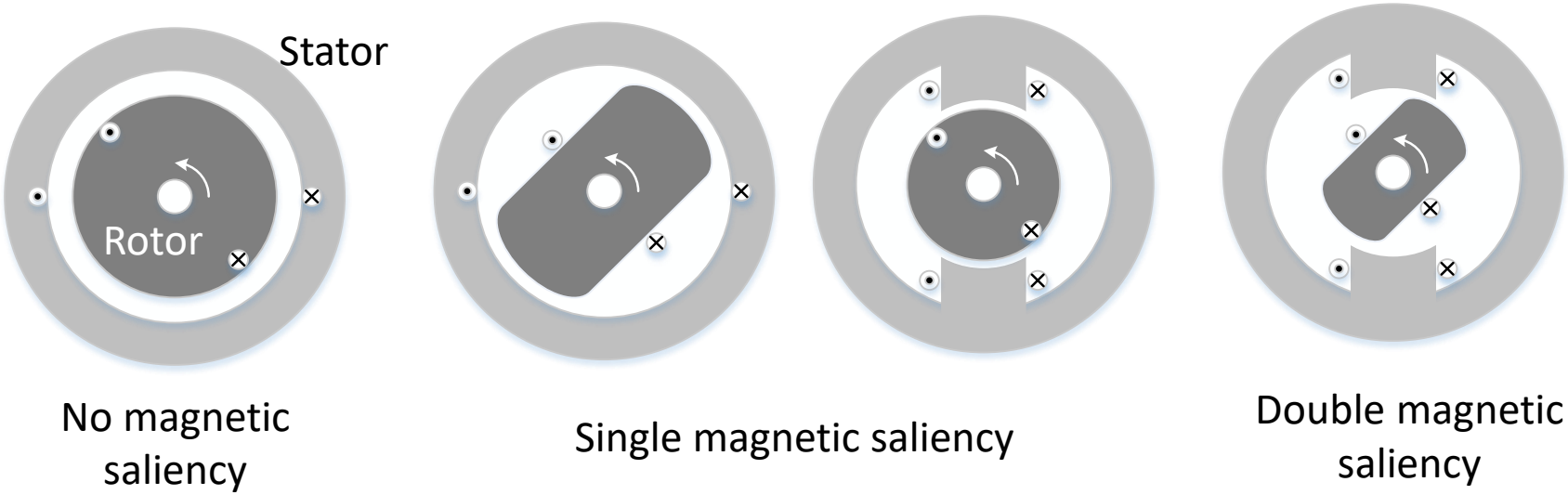
a — straight engine

Animations:
http://auto.howstuffworks.com/engine1.htm
http://auto.howstuffworks.com/engine2.htm
https://en.wikipedia.org/wiki/Four-stroke_engine

Electric Machines Overview

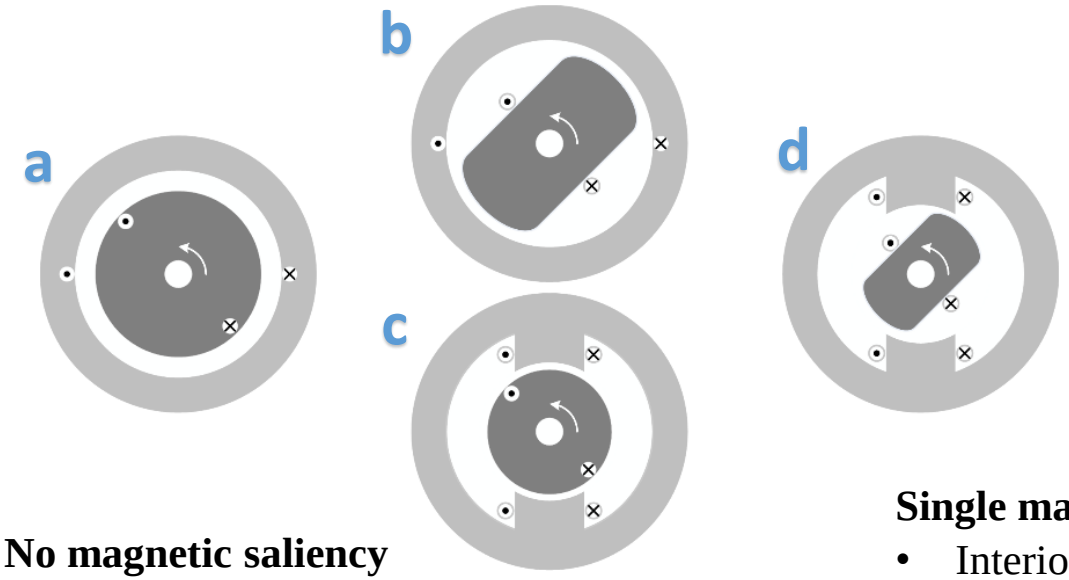
Electromagnetic torque: Two magnetic fields try to align themselves, at least one of them should be controllable

Reluctance torque: System tries to decrease the reluctance, magnetic saliency and controllable magnetic field



Electric Machines Overview

No magnetic saliency	Single mag. saliency	Double mag. saliency



Double magnetic saliency

- Switched reluctance machine (SRM)

Single magnetic saliency

- Interior permanent magnet synchronous machine (IPMSM)
- Synchronous reluctance machine (SyncRel)
- Salient pole synchronous machines (SP-SM)

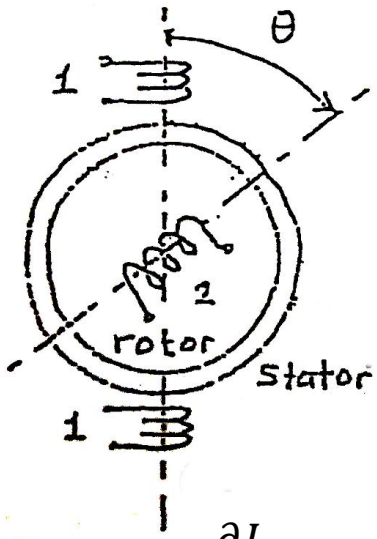
No magnetic saliency

- Induction machine (IM)
- Round rotor synchronous machine (SM)
- Surface mount permanent magnet synchronous machine (SM-PMSM)

➢ The production of a constant average torque is that the stator and rotor fields are standing still to each other, independent of the type of the machine. If both fields (stator & rotor) are rotating at different speeds, a pulsating torque is produced.

Electric Machines Overview

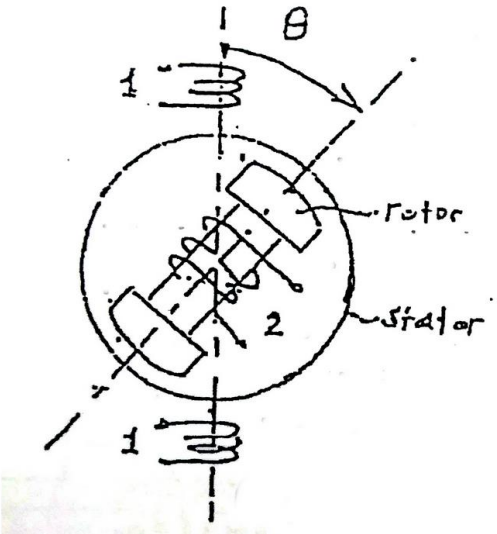
a **No magnetic saliency**



$$T = i_1 i_2 \frac{\partial L_{12}}{\partial \theta}$$

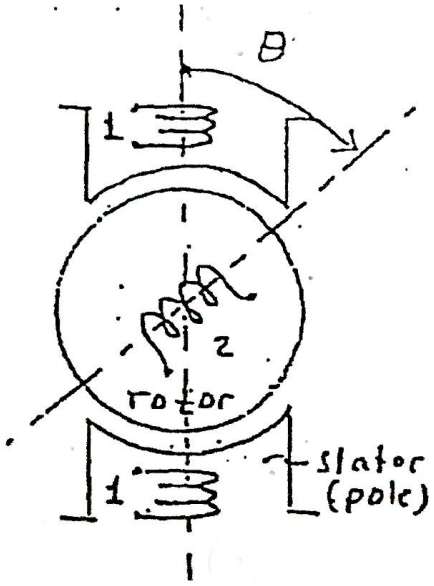
(L_{11} and L_{22} constant)

b **Single magnetic saliency**



$$T = \frac{1}{2} i_1^2 \frac{\partial L_{11}}{\partial \theta} + i_1 i_2 \frac{\partial L_{12}}{\partial \theta}$$ (L_{22} constant)

c **Single magnetic saliency**



$$T = \frac{1}{2} i_2^2 \frac{\partial L_{22}}{\partial \theta} + i_1 i_2 \frac{\partial L_{12}}{\partial \theta}$$

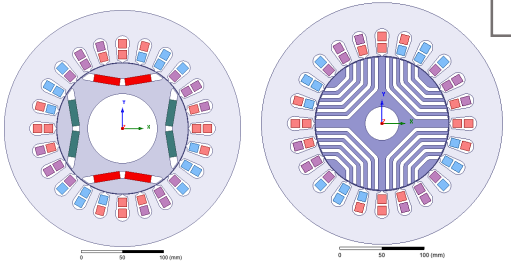
(L_{11} constant)

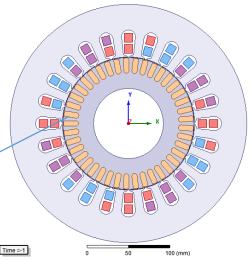
Basic Stator and Rotor Configurations

Electric Machine Type		Rotor & Stator Configuration	i_1	i_2
Synchronous Machines	Cylindrical rotor	a	AC	DC or PM
	Salient pole	b	AC	DC
	Permanent magnet (surface mounted)	a	AC	PM
	Permanent magnet (interior)	b	AC	PM
	Synchronous reluctance	b	AC	=0
	Switched reluctance	d	AC	=0
Induction machine		a	AC	AC
DC machine		c	DC	AC
Universal machine		c	AC	AC

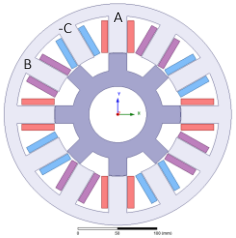
Typical Machine Types

- Stationary Field
  - DC-Machines
    - PM-excited
    - Electrically excited
- Rotating Field
  - Synchronous
    - Radial flux
      - Stator with rotating field winding
        - PM-excited
          - Trapezoidal excitation
          - Sinusoidal excitation
        - Electrically excited
        - Salient pole
      - Modular windings
        - PM-excited
        - Electrically excited
    - Axial flux
    - Transversal flux
  - Asynchronous
    - Rotor with slip rings
    - Squirrel-cage rotor

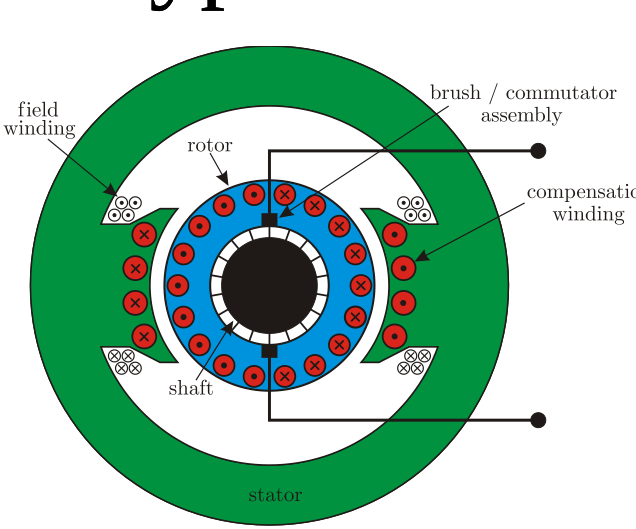


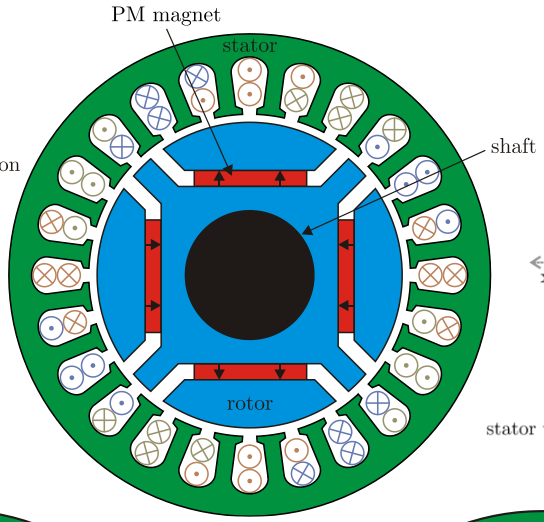


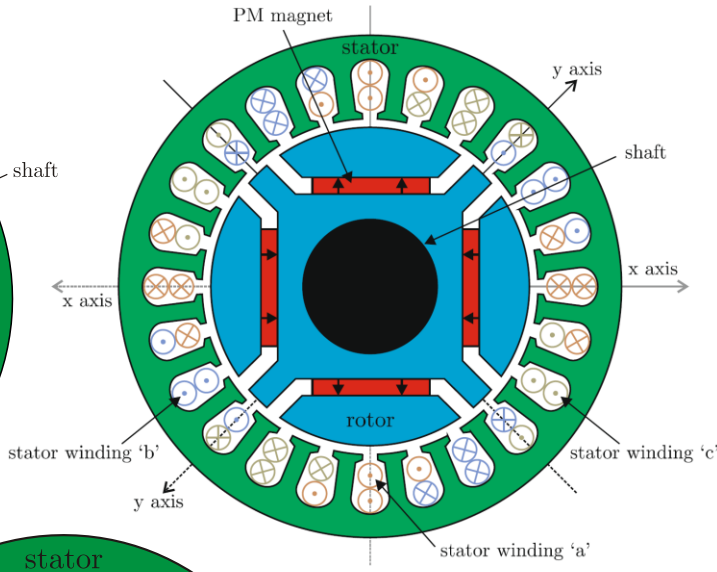
- Switched field
  - Salient pole

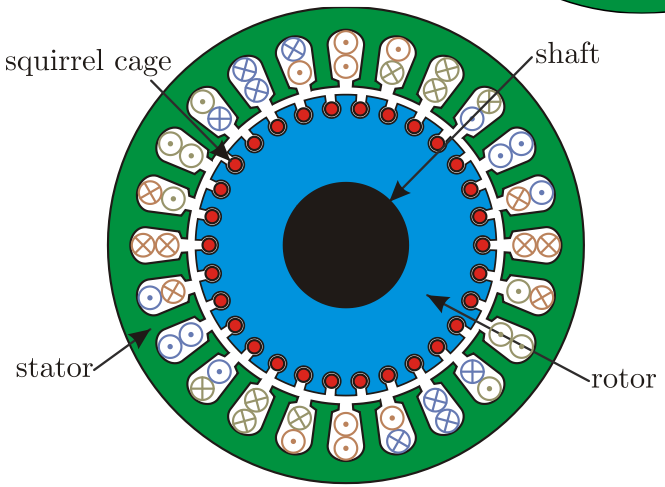


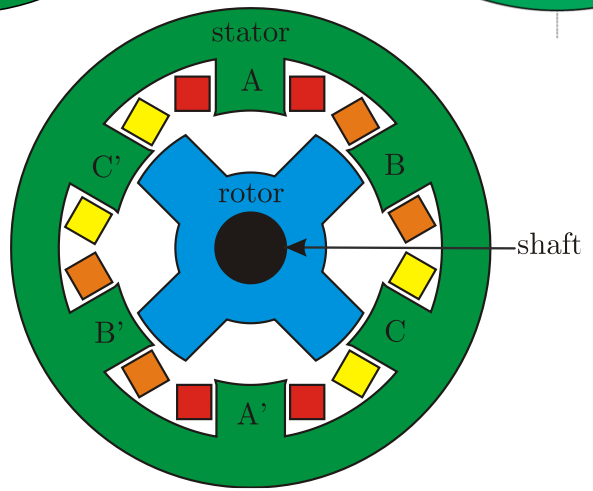
Typical Machine Types







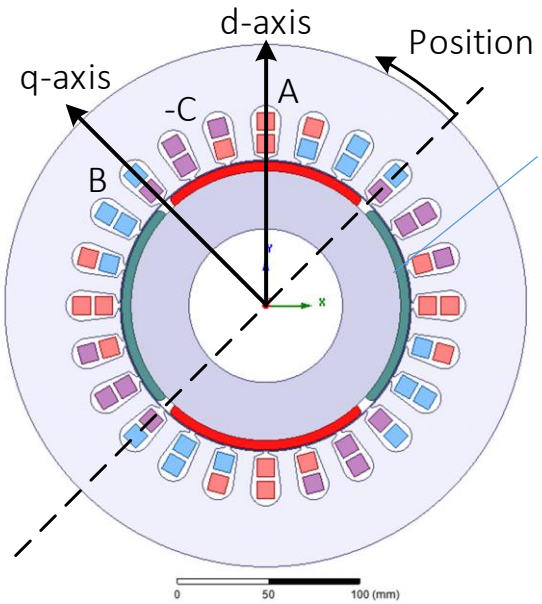




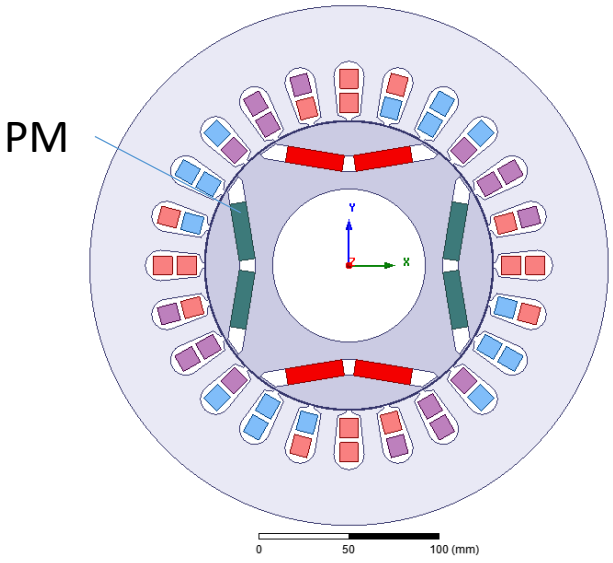
Can you distinguish the types of the machines above?

Typical Machine Types

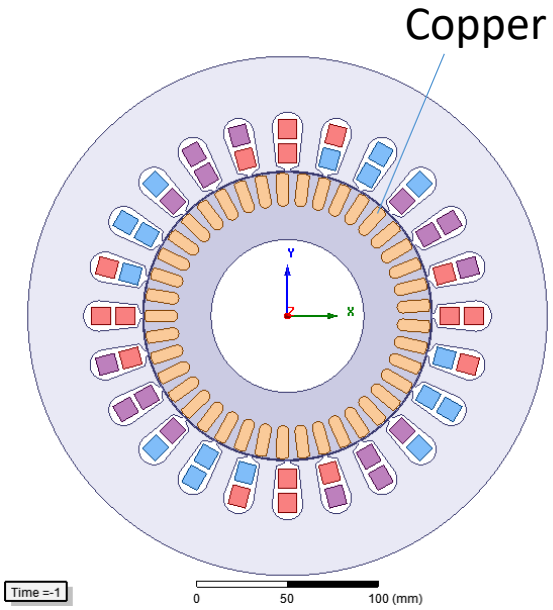
3-phase Rotating Field Machines



Surface mounted PM synchronous machine



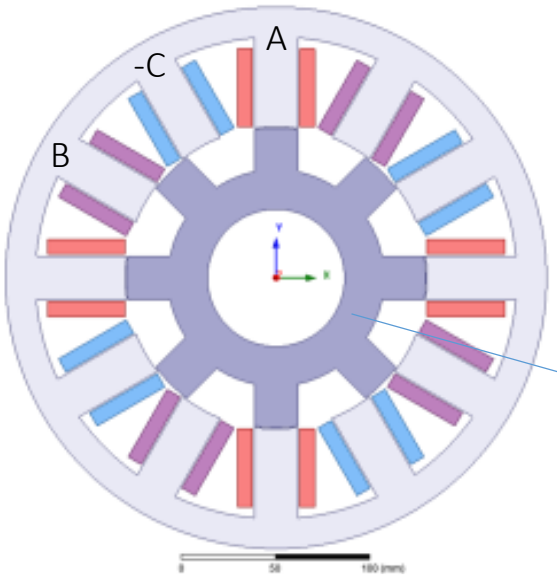
Interior PM synchronous machine



Induction machine

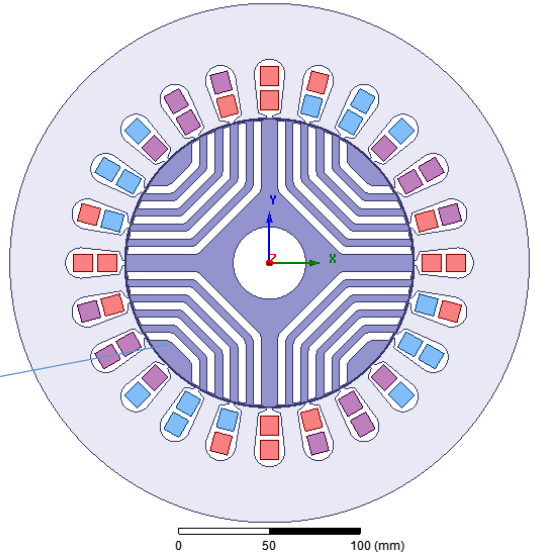
Typical Machine Types

Machines only with Reluctance Torque



Switched reluctance machine

Salient rotor



Synchronous reluctance motor
(Rotating Field)

Power Converters – Hydrogen Fuel Cell

Fuel: hydrogen and oxygen

- A fuel cell is a galvanic cell where chemical energy of a fuel is converted directly into electrical energy by means of electrochemical processes.

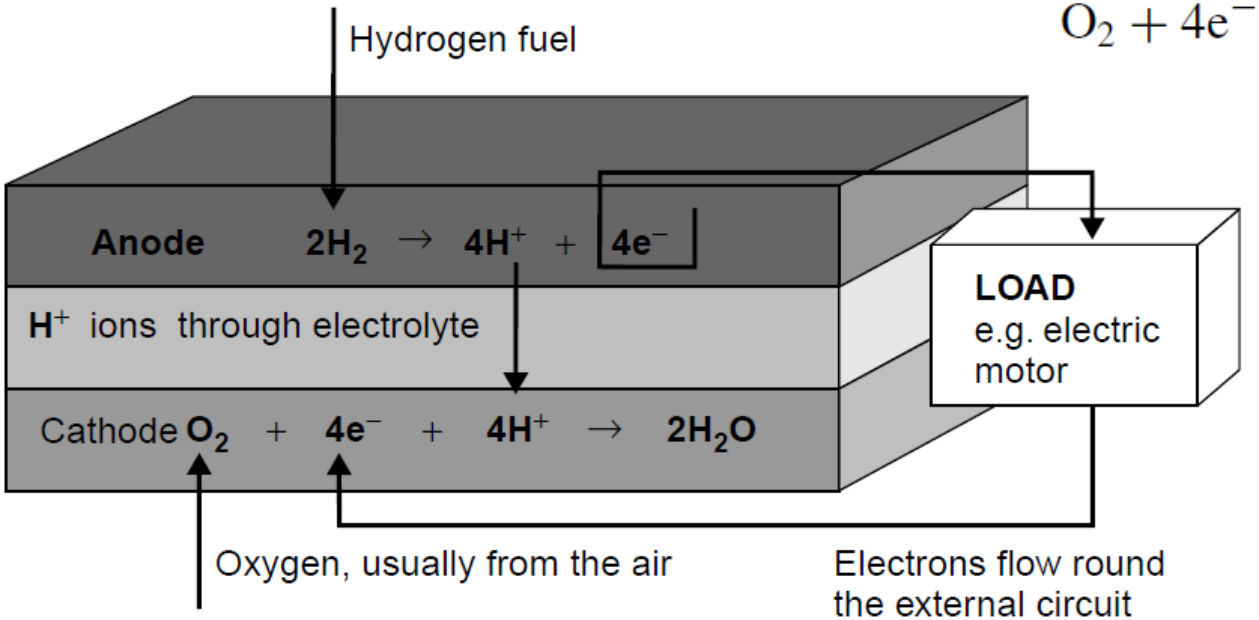
$$2H_2 + O_2 \longrightarrow 2H_2O$$

Anode reaction:

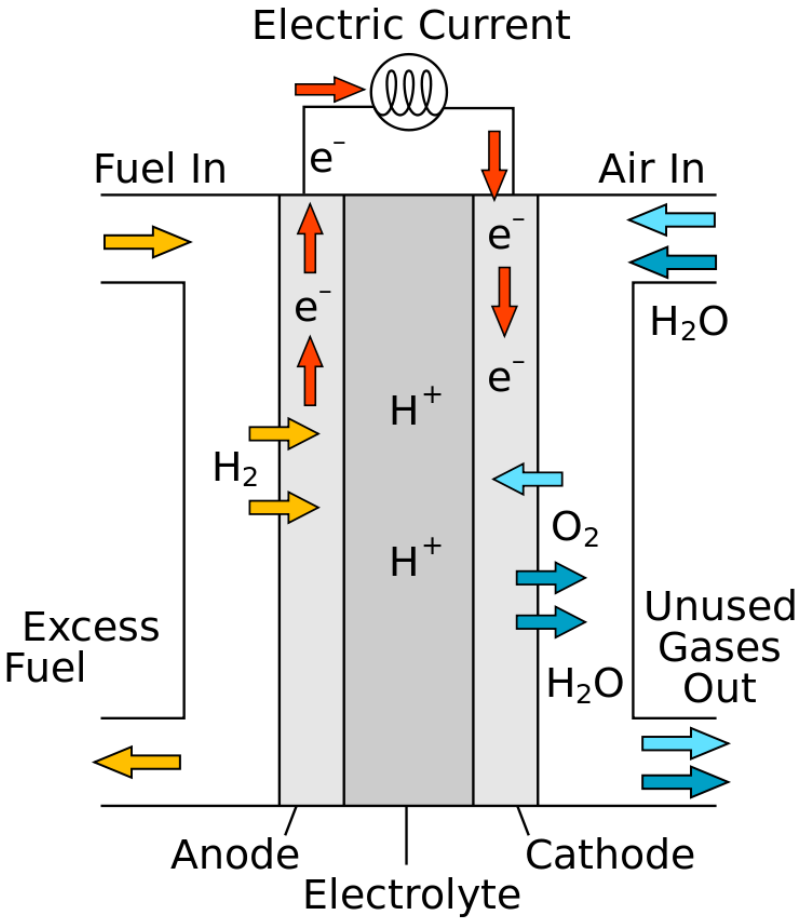
$$2H_2 \longrightarrow 4H^+ + 4e^-$$

Cathode reaction:

$$O_2 + 4e^- + 4H^+ \longrightarrow 2H_2O$$



Power Converters – Hydrogen Fuel Cell



$$2H_2 + O_2 \longrightarrow 2H_2O$$

Anode reaction:

$$2H_2 \longrightarrow 4H^+ + 4e^-$$

Cathode reaction:

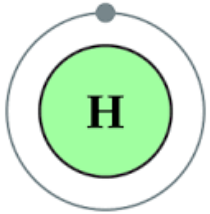
$$O_2 + 4e^- + 4H^+ \longrightarrow 2H_2O$$

https://en.wikipedia.org/wiki/Fuel_cell

Power Converters – Hydrogen Fuel Cell

Fuel cell type	Mobile ion	Operating temp.	Applications and notes
Alkaline (AFC)	OH^-	50–200°C	Used in space vehicles, e.g. Apollo, Shuttle.
Proton exchange membrane (PEMFC)	H^+	30–100°C	Vehicles and mobile applications, and for lower power CHP systems
Direct methanol (DMFC)	H^+	20–90°C	Suitable for portable electronic systems of low power, running for long times
Phosphoric acid (PAFC)	H^+	~220°C	Large numbers of 200 kW CHP systems in use
Molten carbonate (MCFC)	CO_3^{2-}	~650°C	Suitable for medium to large scale CHP systems, up to MW capacity
Solid oxide (SOFC)	O^{2-}	500–1000°C	Suitable for all sizes of CHP systems, 2 kW to multi MW

High temperature: to increase reaction speed

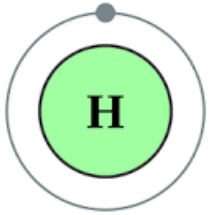


Power Converters – Hydrogen Fuel Cell

Proton exchange membrane (PEMFC)	H^+	30–100°C	Vehicles and mobile applications, and for lower power CHP systems

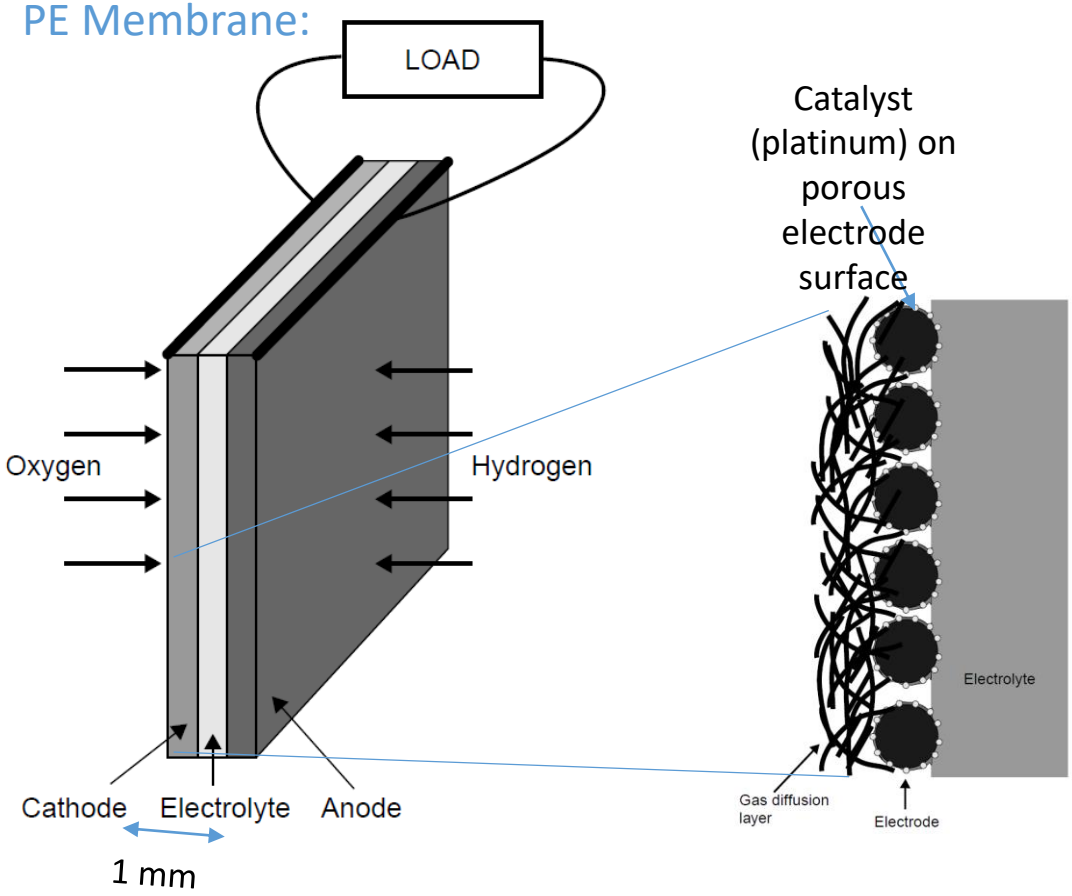
EV applications:

- Simple structure
- Solid electrolyte
- Low temperature
- High power density
- Good efficiency



Power Converters – PEM Hydrogen Fuel Cells

PE Membrane:



- The fuel is supplied to the anode or positive electrode, where electrons are released from the fuel under catalyst.
- The electrons, under the potential difference between these two electrodes, flow through the external circuit to the cathode electrode or negative electrode, where, in combination with positive ions and oxygen, reaction products, or exhaust, are produced.

An **electrolyte** is necessary to conduct the ions from one electrode to the other, but not e^-.

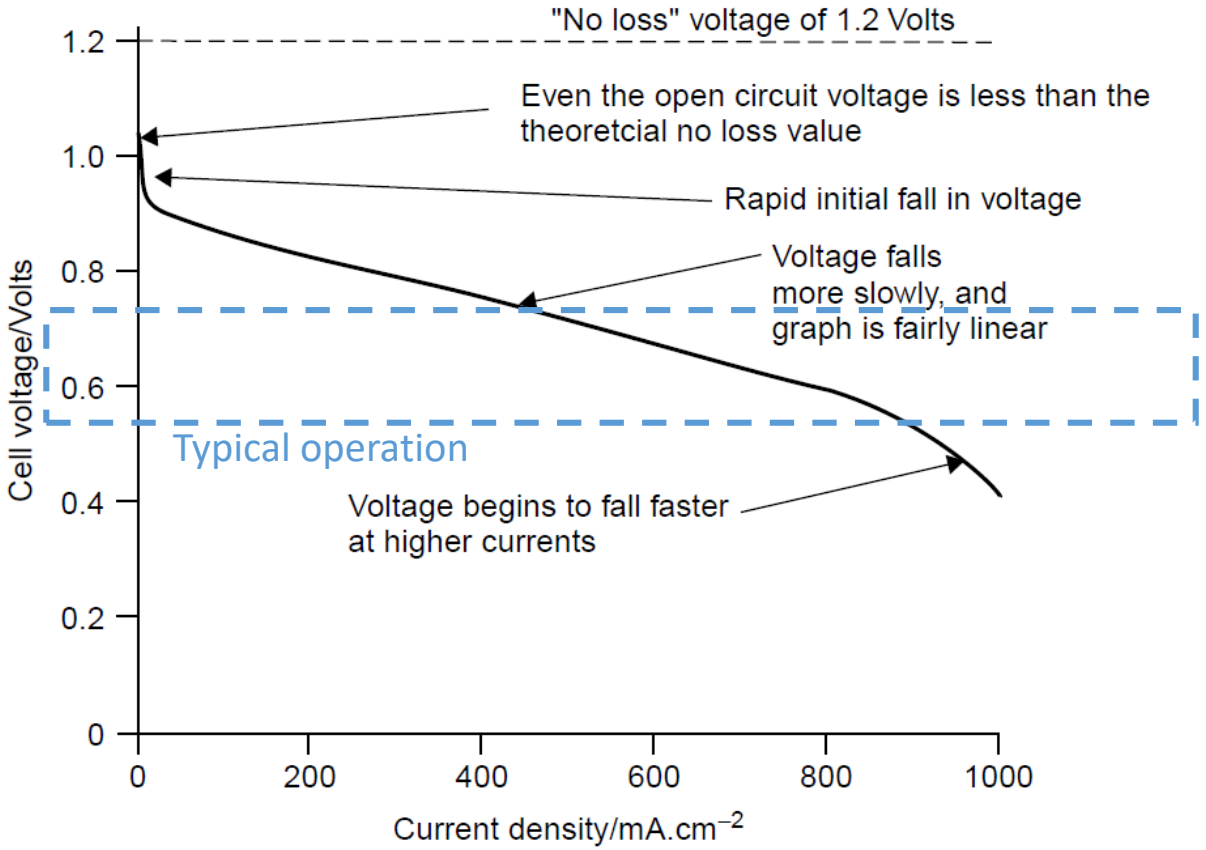
A **catalyst** (Pt) speeds the reactions at low temperatures

Power Converters – PEM Hydrogen Fuel Cells

Cell voltage characteristics:

Initial voltage drop: The activation energy required to drive the reactions at the electrodes, especially at the air cathode

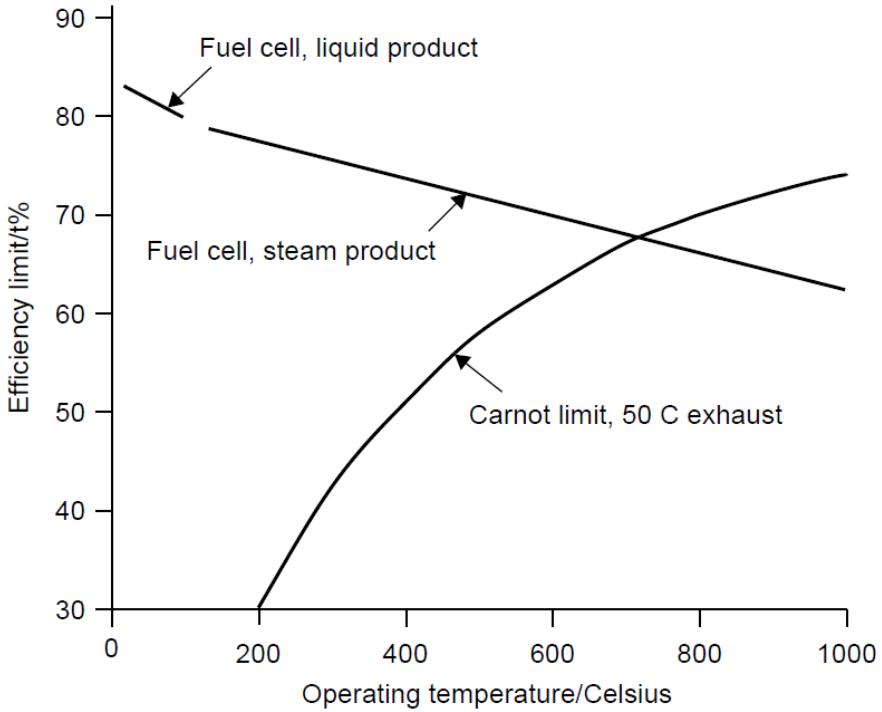
Ohmic voltage drop: The resistance of the electrolyte and the electrodes causes a voltage drop that more or less follows Ohm's law

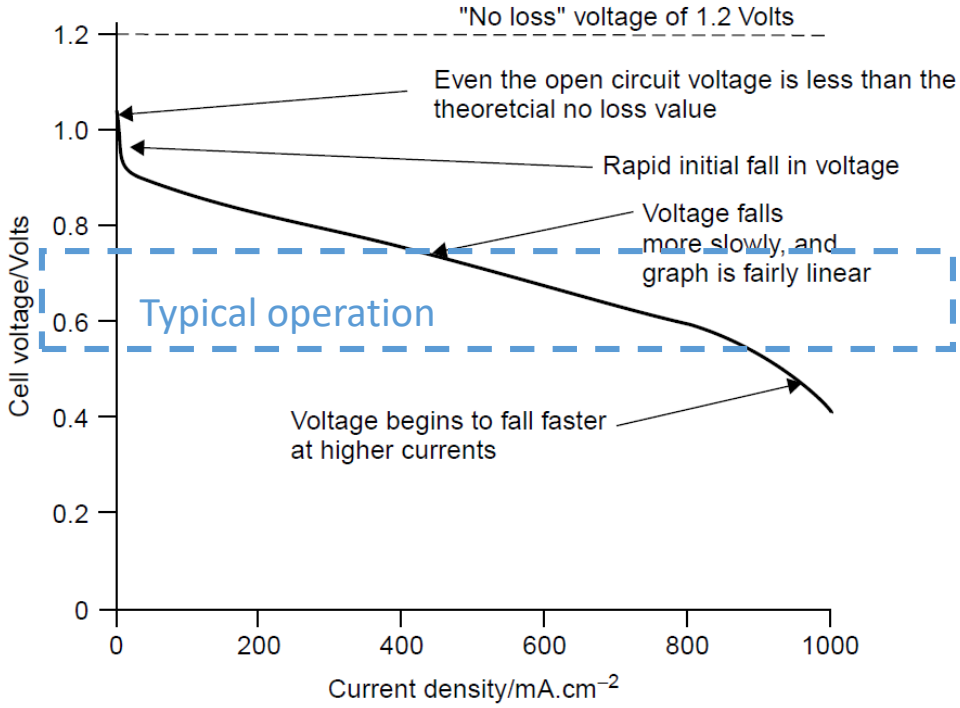


Rapid fall in voltage at higher currents: At very high currents, the air gets depleted of oxygen, as the electrodes are short of reactant.

Power Converters – PEM Hydrogen Fuel Cells

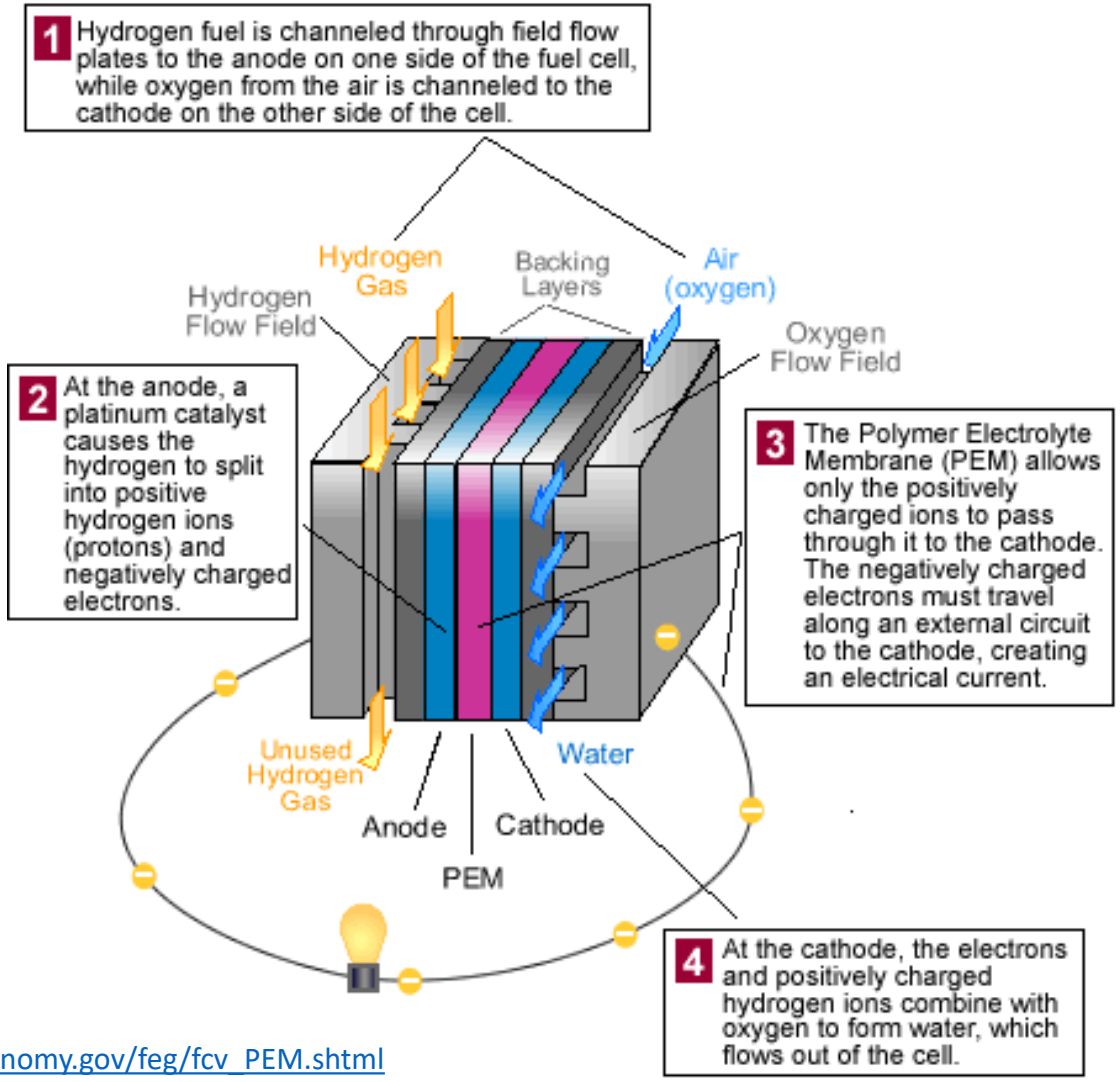
Maximum efficiency limits:





Fuel cell efficiency is high at low current density, however in typical operation region efficiency is around 70%.

Power Converters – PEM Hydrogen Fuel Cells

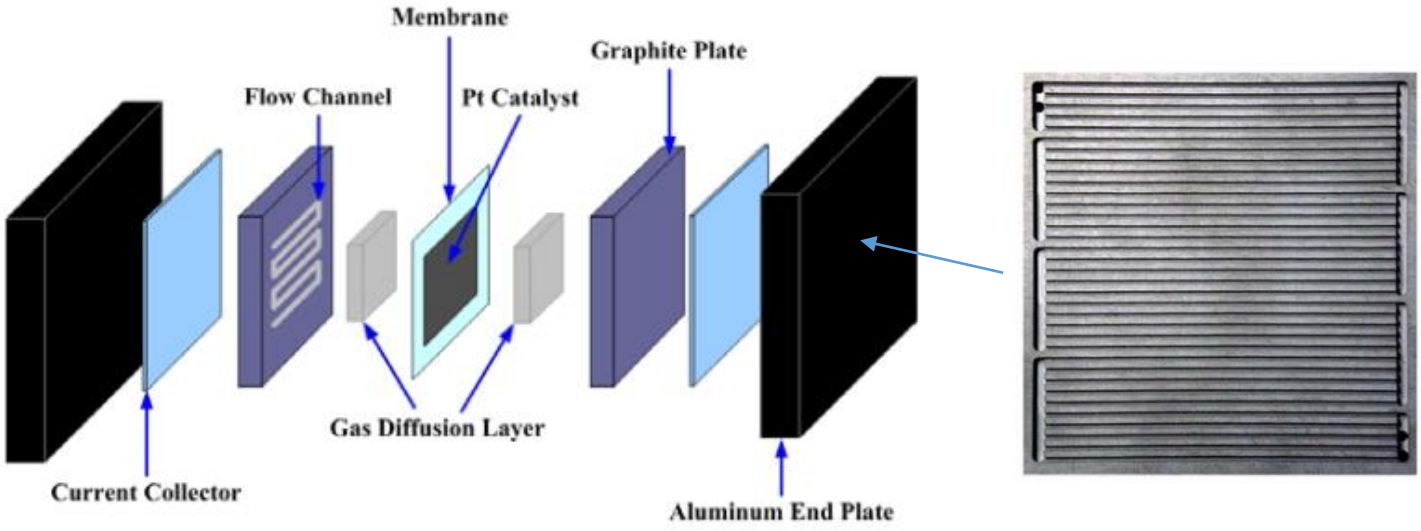


https://www.fueleconomy.gov/feg/fcv_PEM.shtml

Power Converters – PEM Hydrogen Fuel Cells

Cell level challenges:

- CO poisoning of membrane
  - ➢ Hydrogen needs to be pure
- Aging
- Platinum price



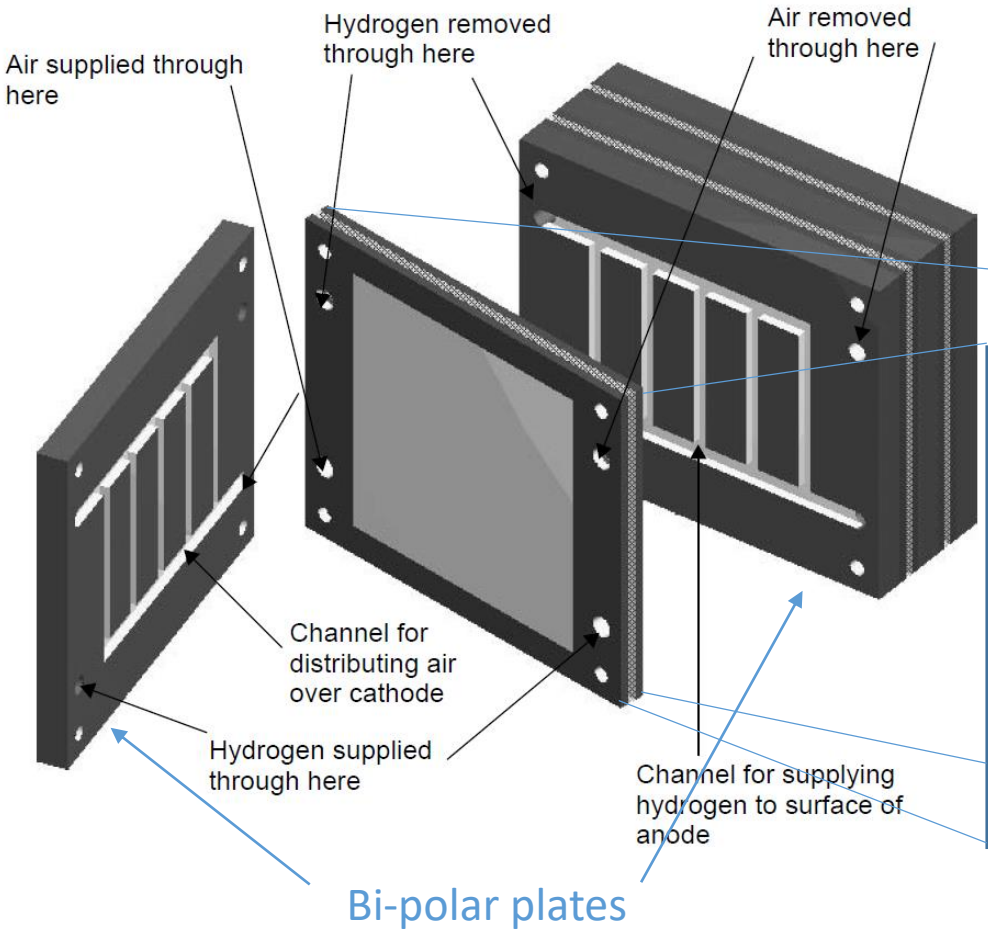
https://www.fueleconomy.gov/feg/fcv_PEM.shtml

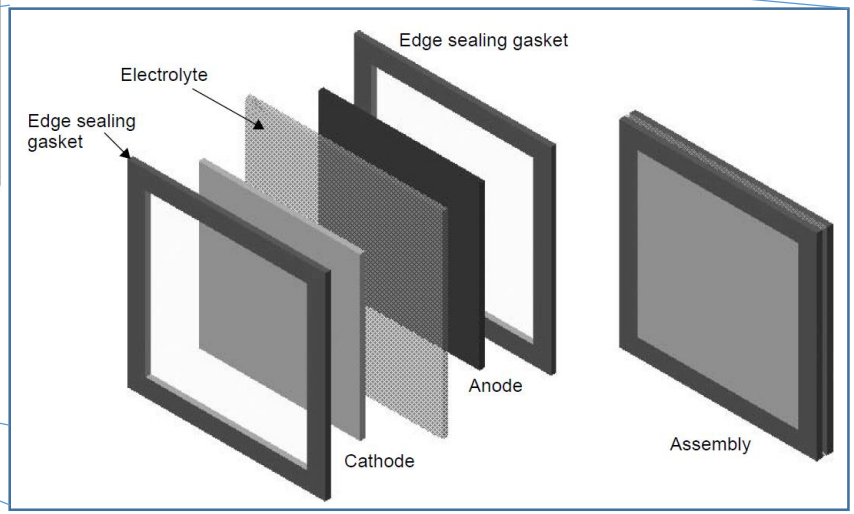
Power Converters – Fuel Cell Stack

To increase the output voltage, we need to stack the fuel cells.

Stack level changes:

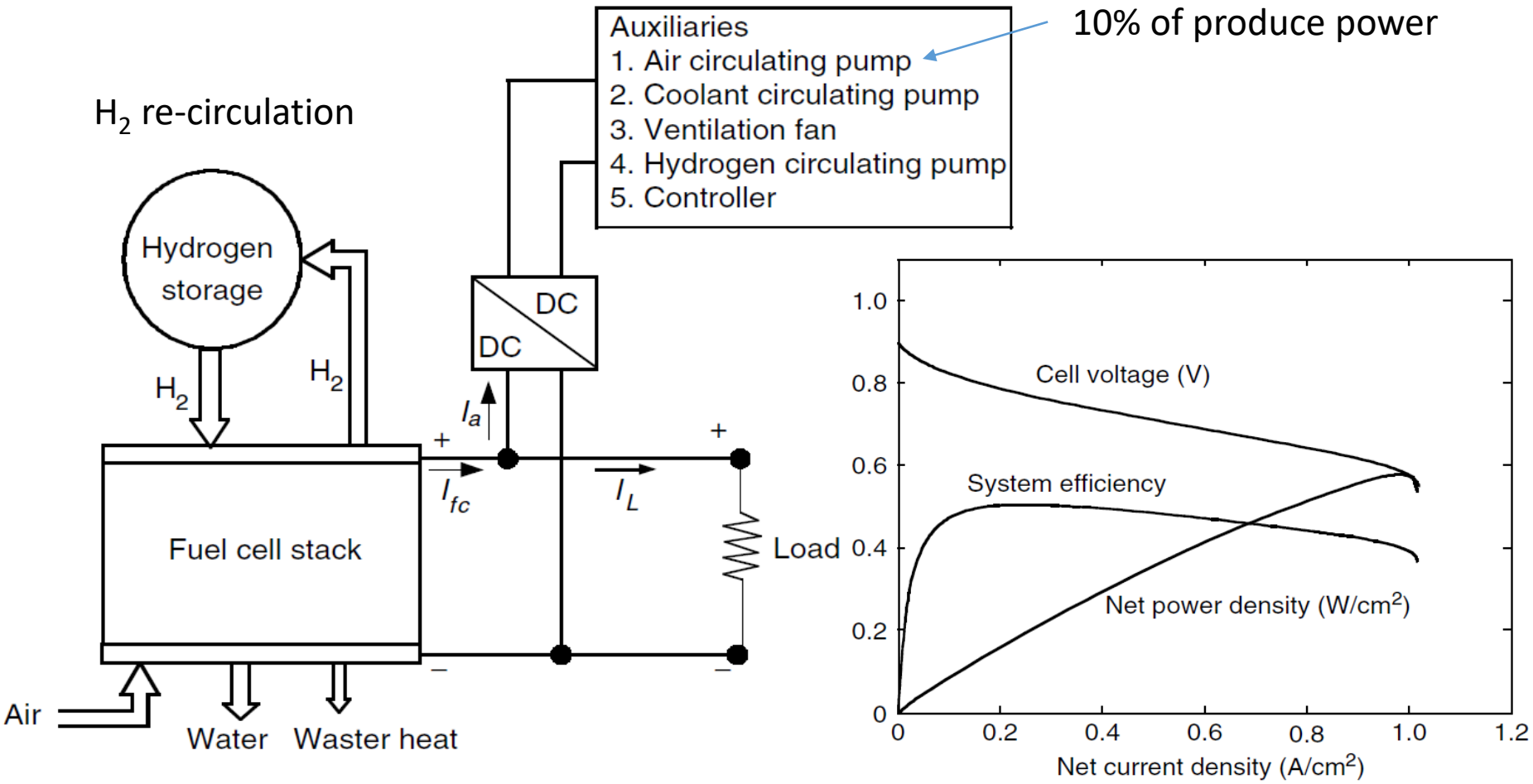
- Stack management
- Keeping H_2 and O_2 separate
- Water management
  - Membrane needs to be humid but not wet
- Cooling channels to remove waste heat



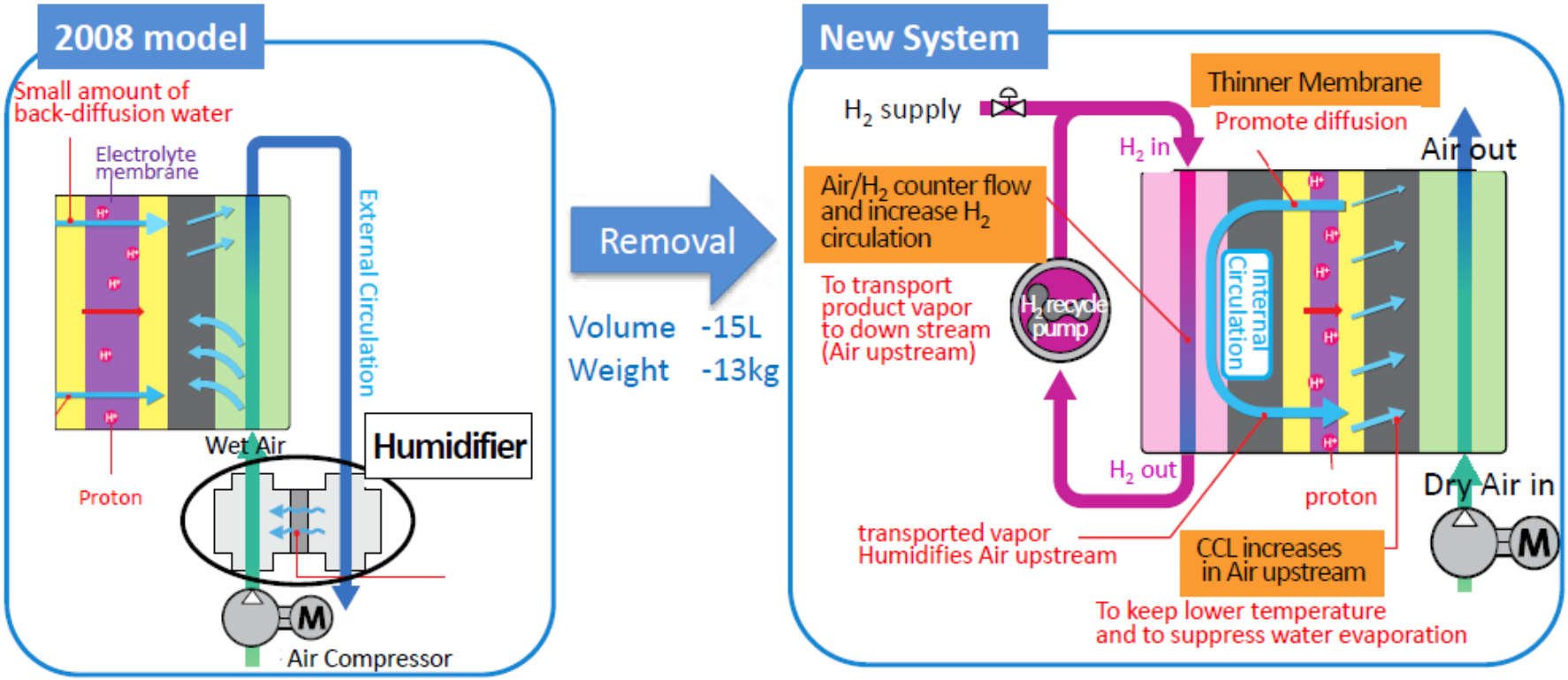


Fuel cell

Power Converters – PEM Fuel Cell System



Fuel Cell of Toyota Mirai



Fuel Cell Stack of Toyota Mirai

2008 model fuel cell stack

New fuel cell stack (MIRAI)

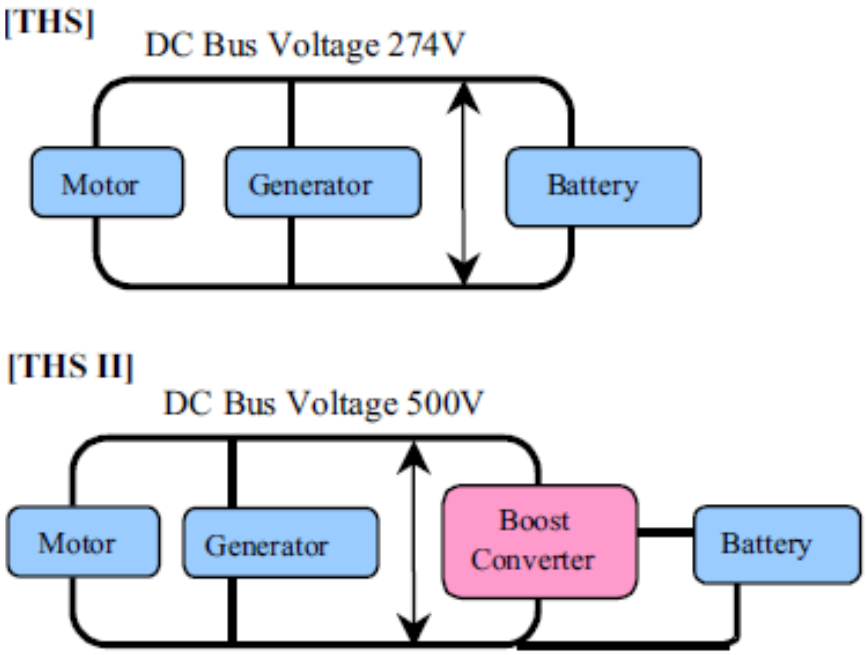
		2008 FC –advanced	MIRAI FC stack
Maximum Power		90kW	114kW
Volumetric power density		1.4kW/L, 0.83kW/kg	3.1kW/L, 2.0kW/kg
Cell	number of cells	400 cells, dual line stack	370 cells, single line stack
	thickness of cell	1.68mm	1.34mm
	flow channel	straight channel	3D fine-mesh flow field

Electrical-to-electrical Energy Converters

DC/DC converter

- Voltage boost

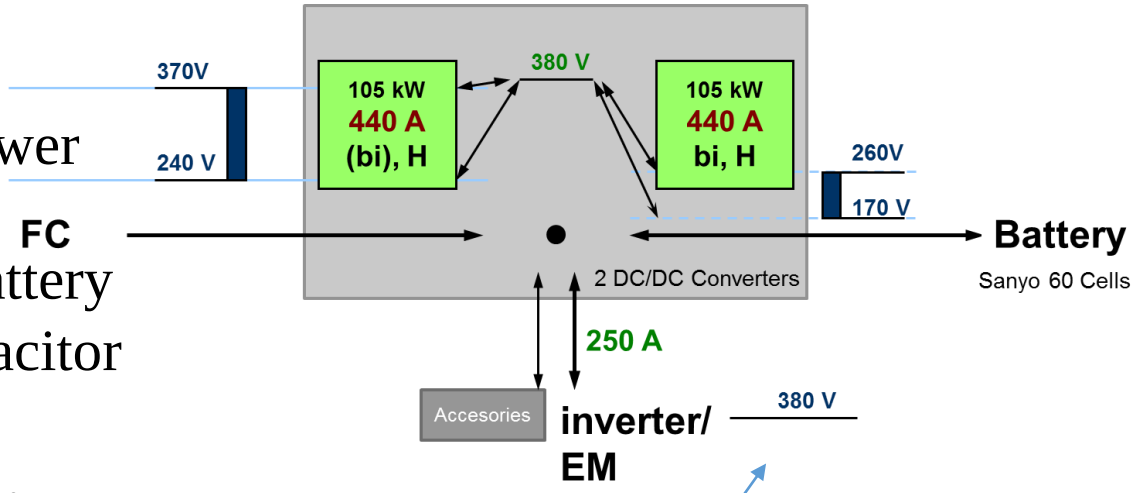
System	THS		THS II	
Vehicle	Prius			SUV
E/G	1.5L			3.3L
Launch	1997	2000	2003	2005
DC Bus Voltage	About 274V		500V	650V
Max. Power	30 kW	33 kW	50 kW	123 kW
Max. Torque	305 Nm	350 Nm	400 Nm	333 Nm
Max. Speed	6000 rpm		6700 rpm	12400 rpm



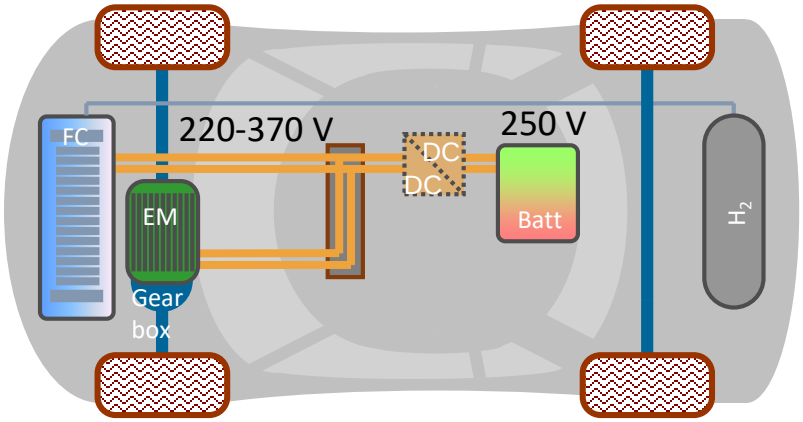
Electrical-to-electrical Energy Converters

DC/DC converter

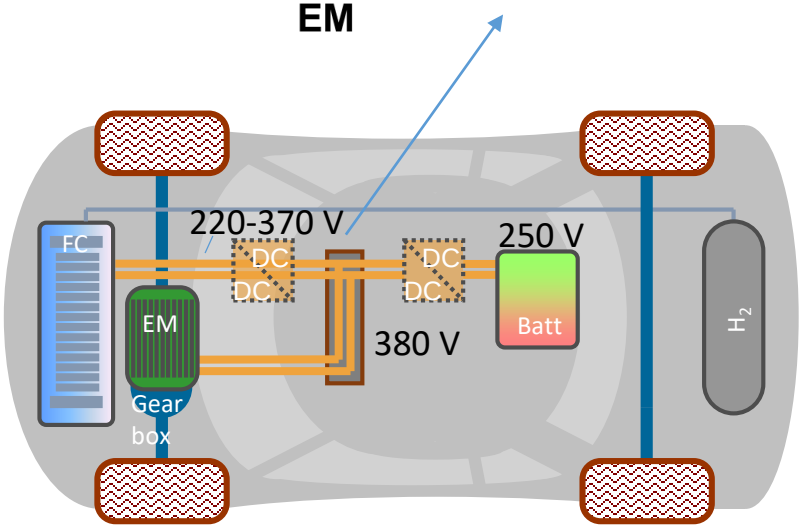
- Voltage boost
- Connect two electric power sources
  - Fuel-cell stack and battery
  - Battery and supercapacitor



Example: Fuel-cell electric vehicle



One DC/DC converter



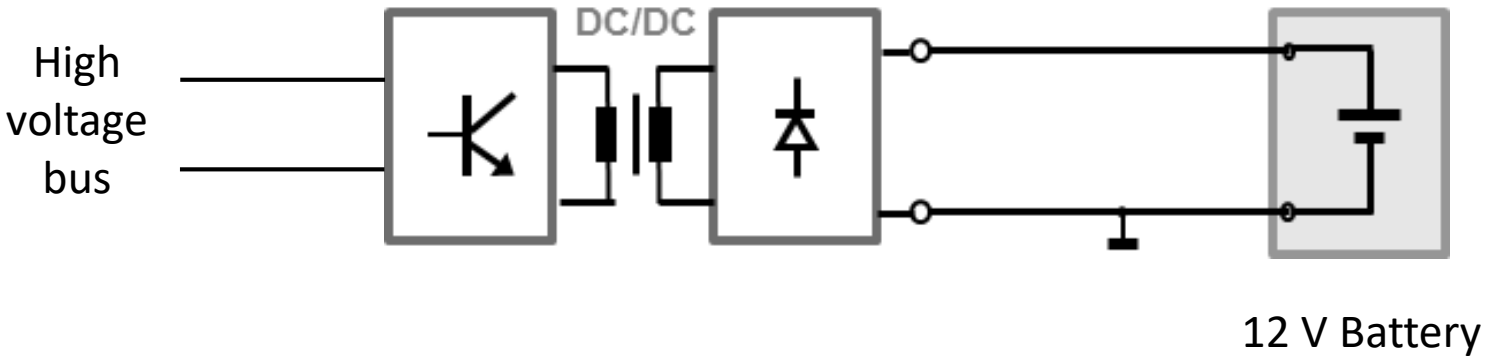
Two DC/DC converters

Electrical-to-electrical Energy Converters

DC/DC converter

- Voltage boost
- Connect two electric power sources
  - Fuel-cell stack and battery
  - Battery and supercapacitor
- Buck converter (isolated)

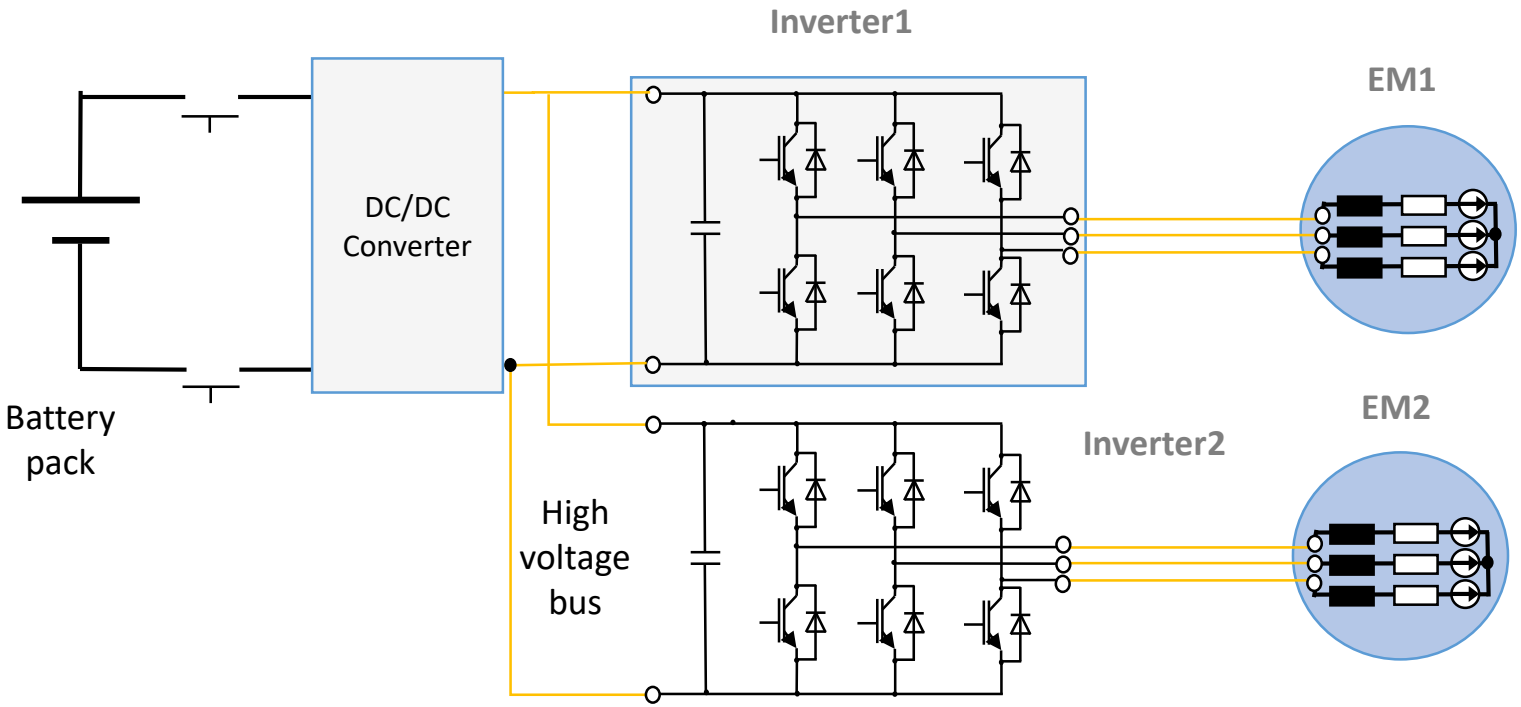
Example: Charging 12 V battery from high voltage battery



Electrical-to-electrical Energy Converters

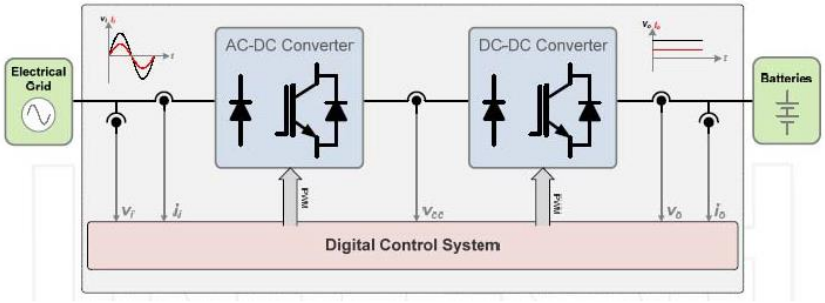
Inverters

- Machine drive

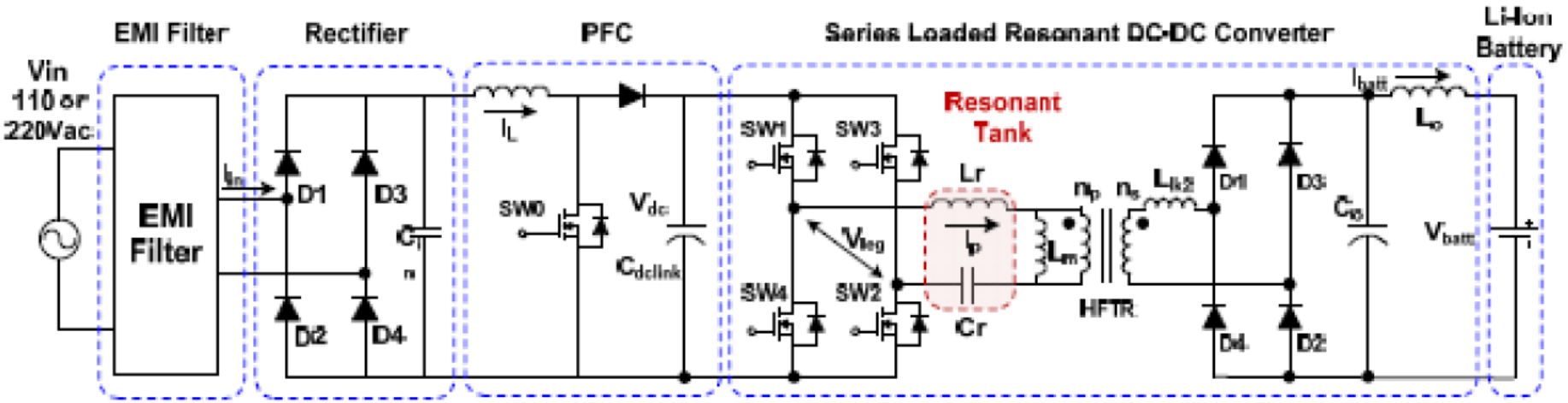


Electrical-to-electrical Energy Converters

Charger



Example on-board charger with galvanic isolation

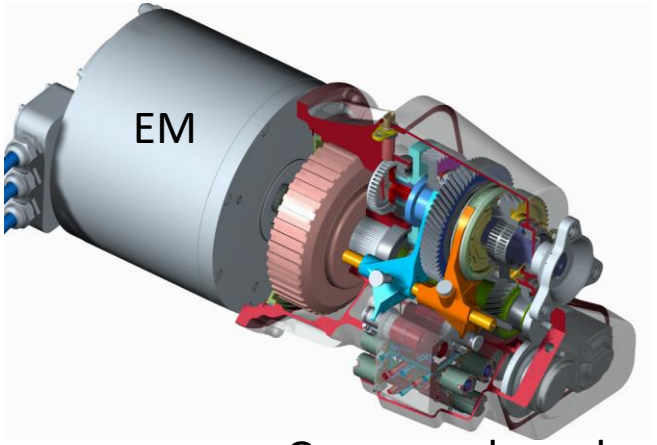


Mechanical-to-mechanical Energy Converters

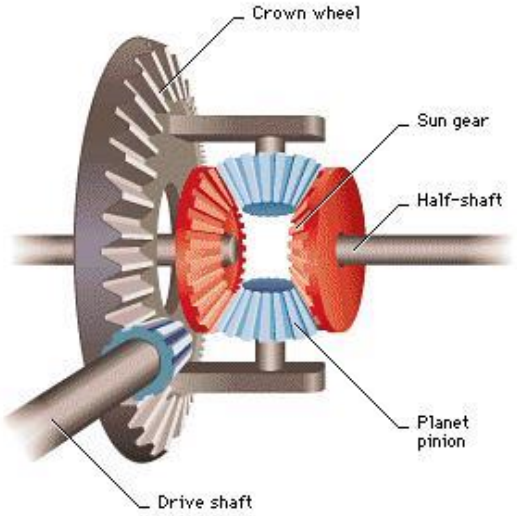
Gear box

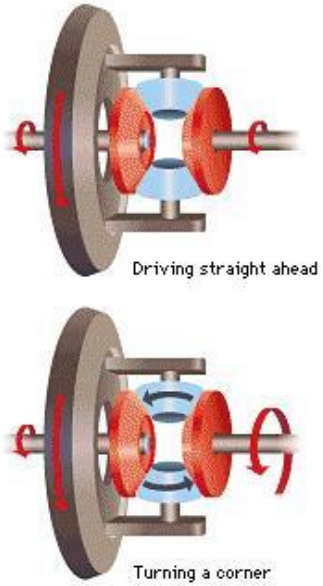
- Manual
- Automatic
- Single or multi speed

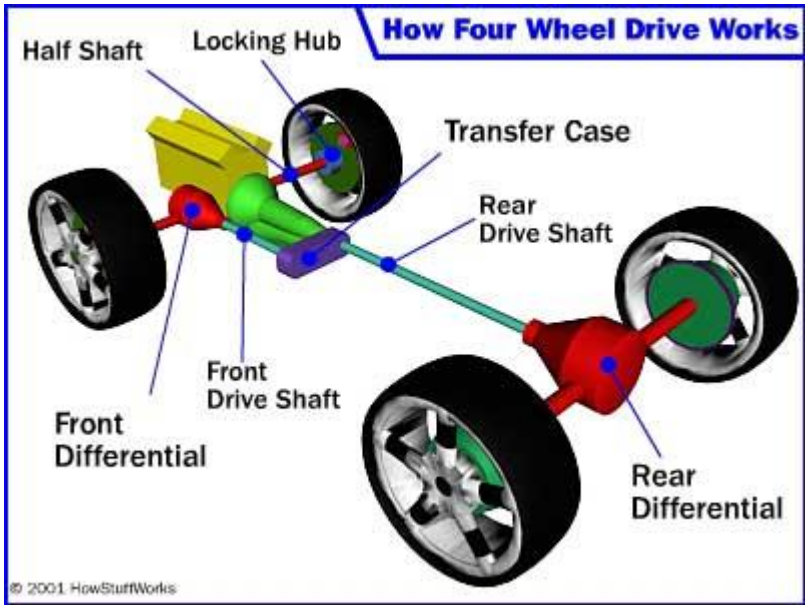
Differential connecting driven wheels



One-speed gearbox





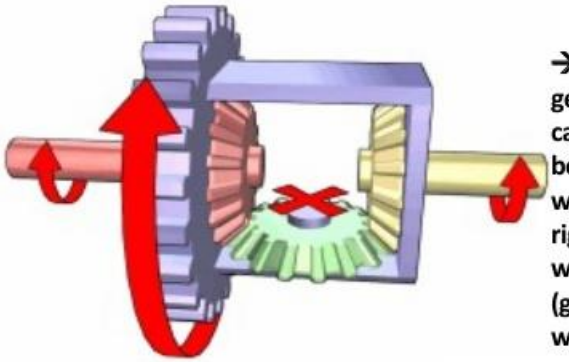


How a Differential works ?

Mechanical-to-mechanical Energy Converters

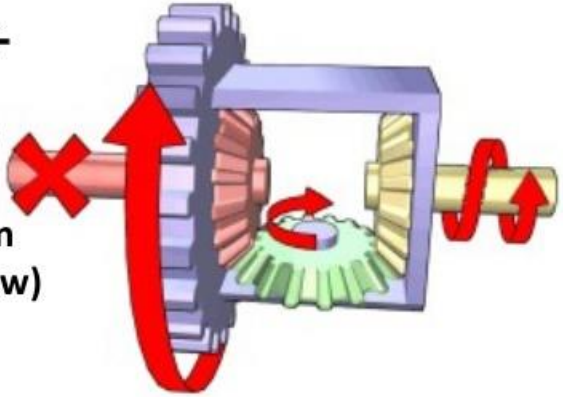
Functions of differential:

- Allow connected wheels to rotate at different speeds
- Speed reduction at ring gear-pinion assembly
- Turn the power flow by 90 degrees



→ Input torque is applied to the ring gear (blue), which turns the entire carrier (blue), providing torque to both side gears (red and yellow), which in turn may drive the left and right wheels. If the resistance at both wheels is equal, the planet gear (green) does not rotate, and both wheels turn at the same rate.

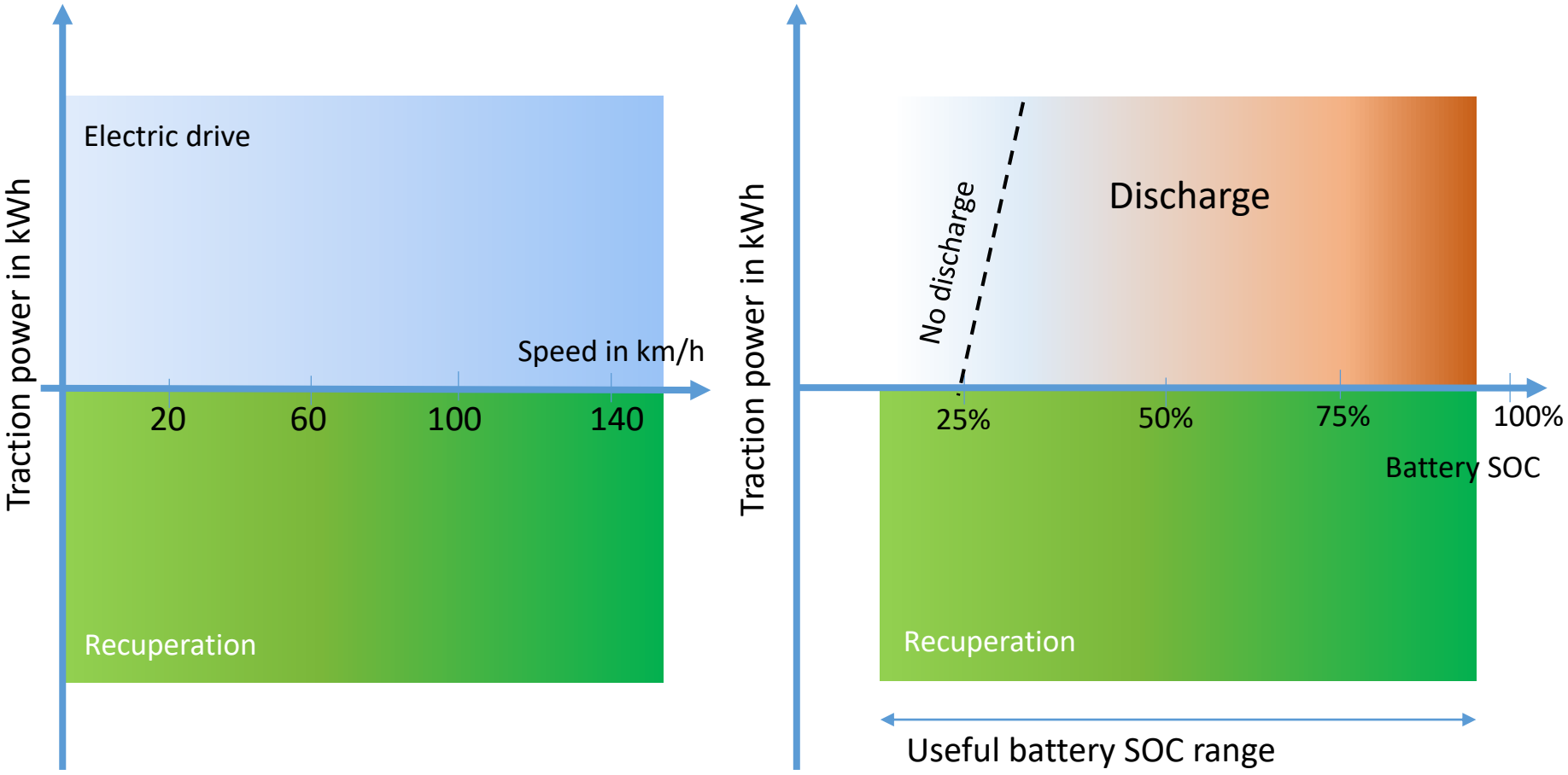
If the left side gear (red) ← encounters resistance, the planet gear (green) rotates about the left side gear, in turn applying extra rotation to the right side gear (yellow)



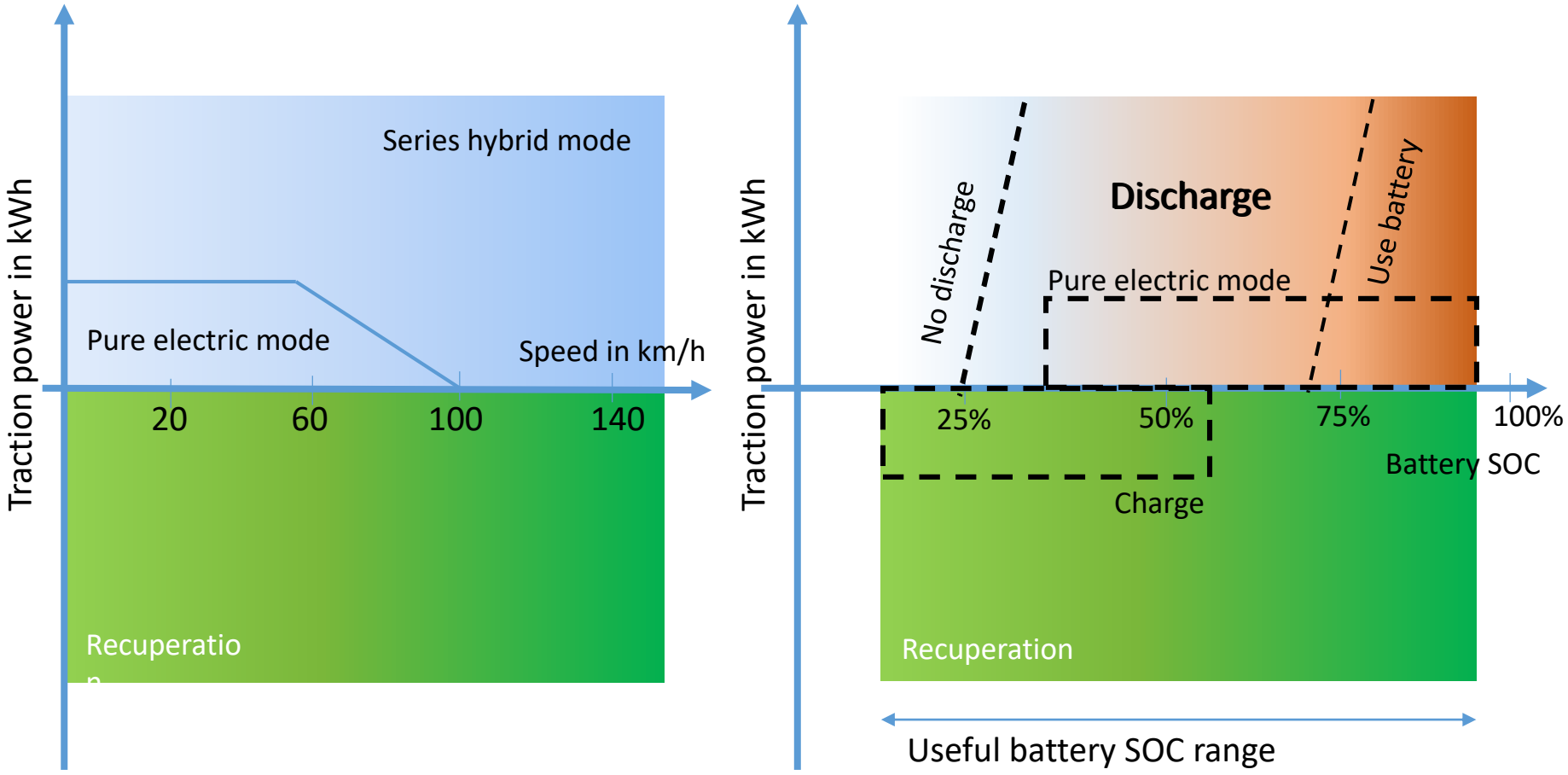
[How a Differential works ?]

[Understanding Limited Slip Differential]

Modes – Battery Electric Vehicle

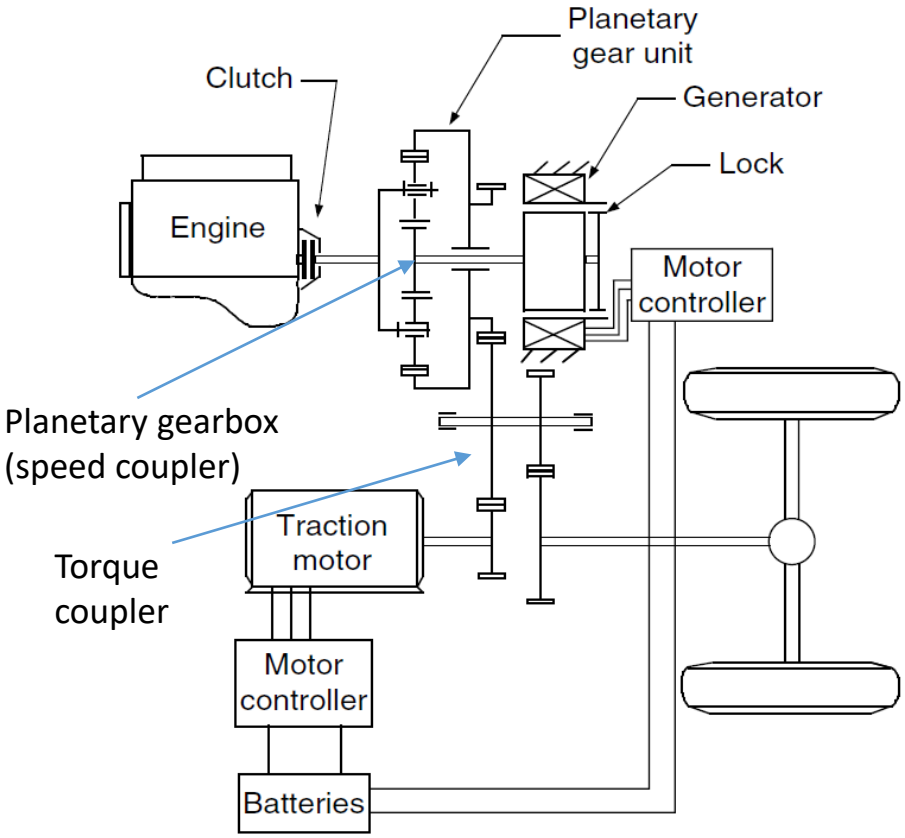


Modes – Battery Electric Vehicle with Range Extender



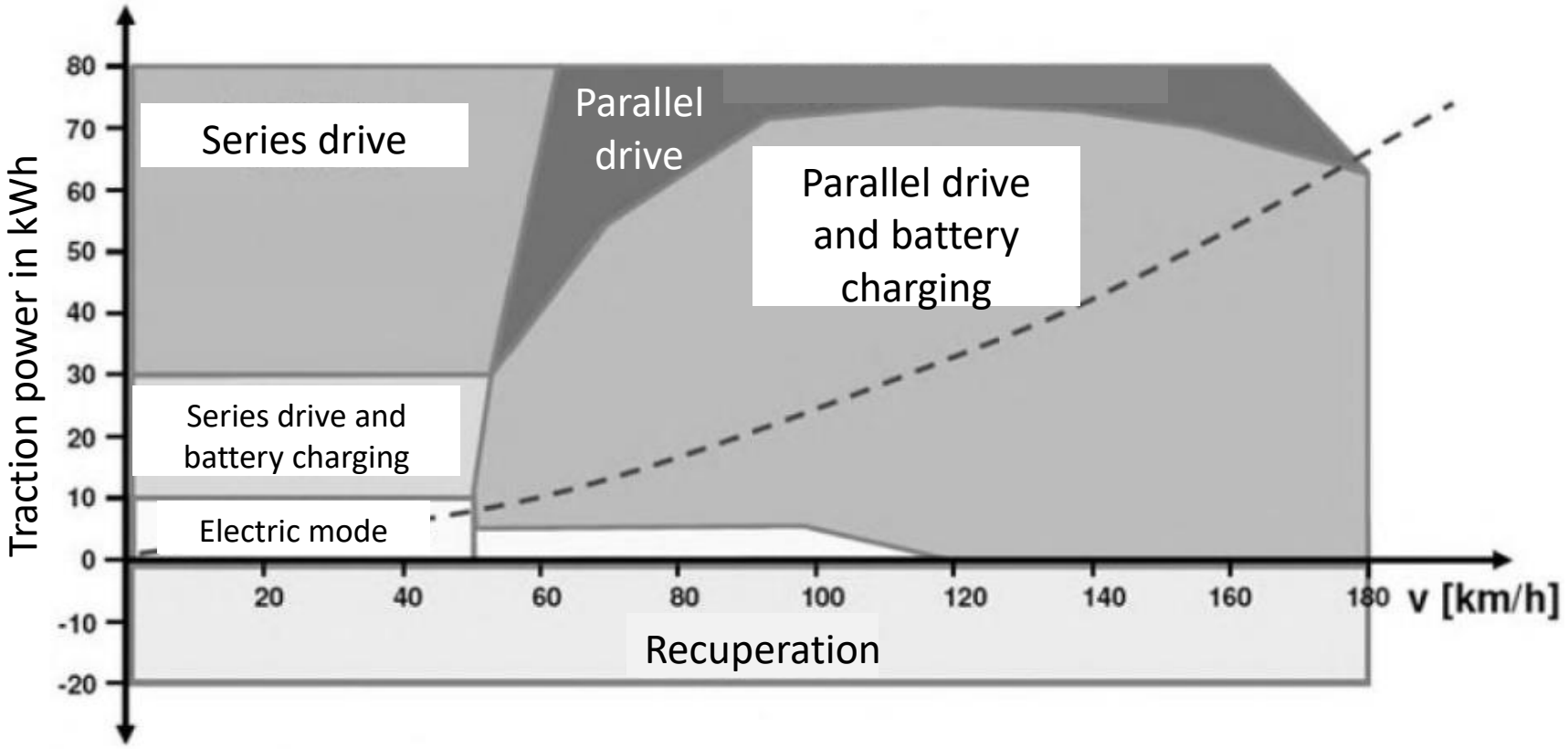
Power Management - Parallel-series Hybrid Electric Vehicle

Parallel-Series Hybrid Electric Drivetrain (with Torque and Speed Couplers)



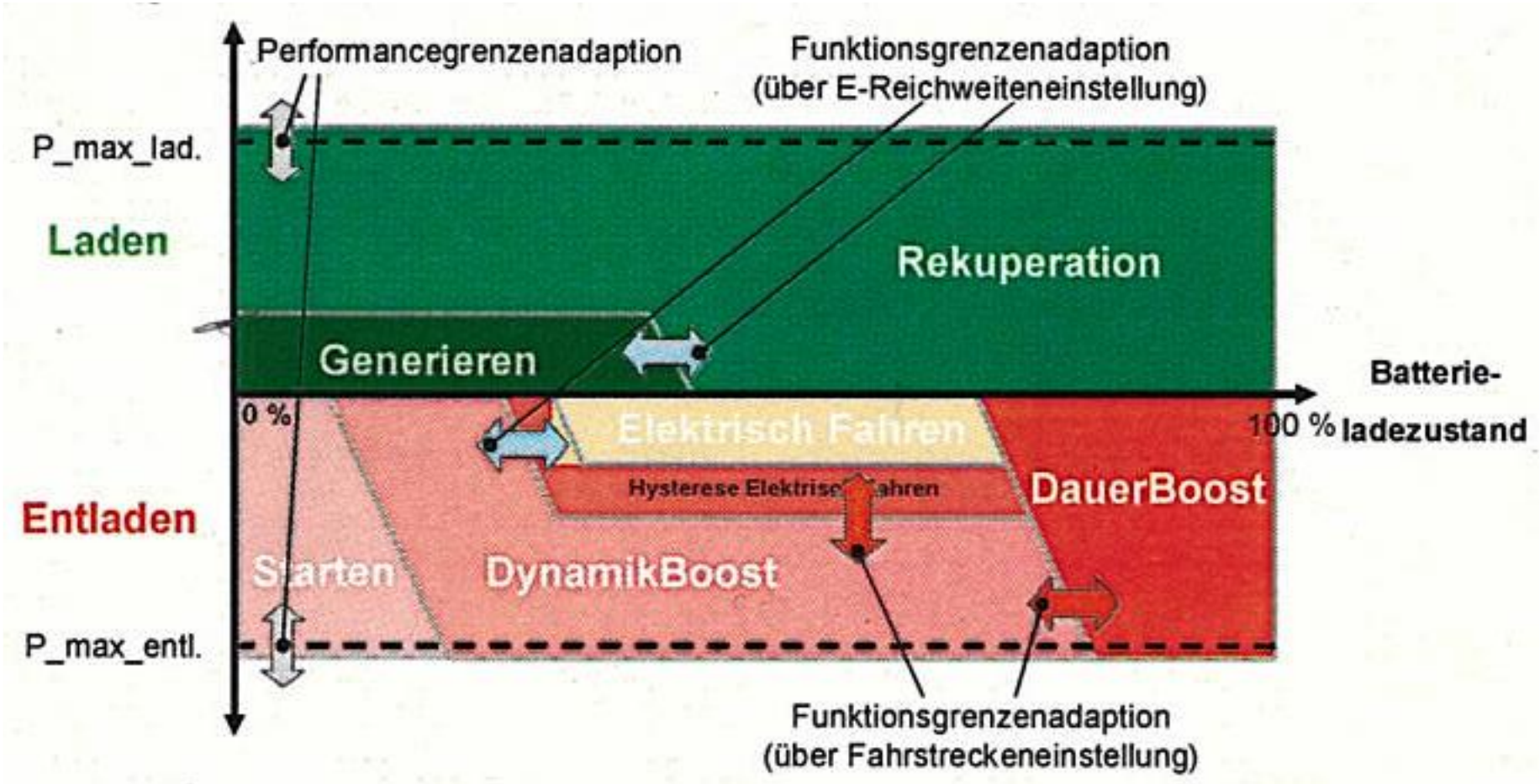
1. Pure electric mode
2. Pure engine mode
3. Series hybrid mode
4. Series hybrid mode & charging
5. Parallel hybrid mode & charging
6. Regenerative braking mode
7. Battery charging at stand still

Power Management - Parallel-series Hybrid Electric Vehicle



Twindrive:
https://www.youtube.com/watch?v=oLEBREiPzFQ

Energy Management - Parallel-series Hybrid Electric Vehicle



Textbooks:

Ehsani, M. and Gao, Y. and Emadi, A., “Modern Electric, Hybrid Electric, and Fuel Cell Vehicles: Fundamentals, Theory, and Design”, 2nd Edition, CRC Press LLC, 2009.

Chau, K. T., “Electric Vehicle Machines and Drives: Design, Analysis and Application” Wiley-IEEE Press, August 2015.

Audi Quattro Eskimo | Commercial | HD

Buying a Volkswagen from an old lady...

The future we're building -- and boring | Elon Musk (39:50 min)

I am just trying to think about the future and not be sad!

The Truth about Hydrogen

Hydrogen Fuel Cell & Battery Electric Vehicles — Technology Rundown