Vehicle Propulsion Systems
Lecture 4

Introducing Electromobility
Hybrid Powertrains, Topologies and Component Modeling

Lars Eriksson
Professor

Vehicular Systems
Linköping University

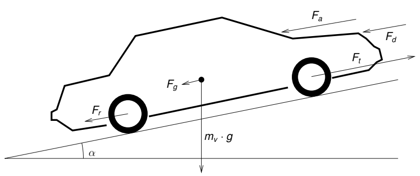
April 2, 2020

Outline

The Vehicle Motion Equation

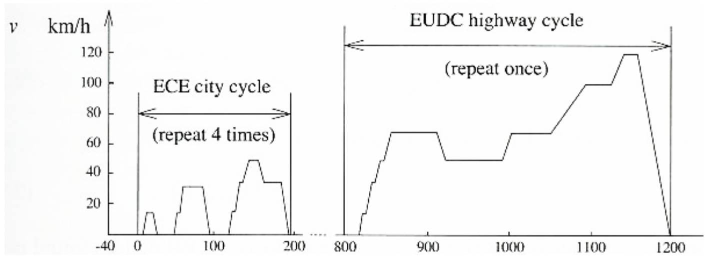
Newtons second law for a vehicle

$$m_v \frac{d}{dt} v(t) = F_t(t) - (F_a(t) + F_r(t) + F_g(t) + F_d(t))$$



- F_t – tractive force
- F_a – aerodynamic drag force
- F_r – rolling resistance force
- F_g – gravitational force
- F_d – disturbance force

Energy consumption for cycles



Numerical values for MVEG-95, ECE, EUDC

$$\text{air drag} = \frac{1}{x_{tot}} \sum_{i \in trac} \bar{v}_i^3 \, h = \{319, 82.9, 455\}$$

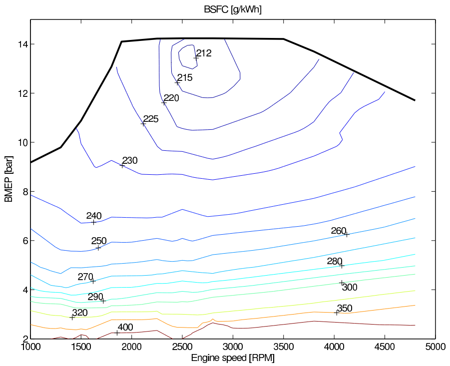
$$\text{rolling resistance} = \frac{1}{x_{tot}} \sum_{i \in trac} \bar{v}_i \, h = \{.856, 0.81, 0.88\}$$

$$\text{kinetic energy} = \frac{1}{x_{tot}} \sum_{i \in trac} \bar{a}_i \, \bar{v}_i \, h = \{0.101, 0.126, 0.086\}$$

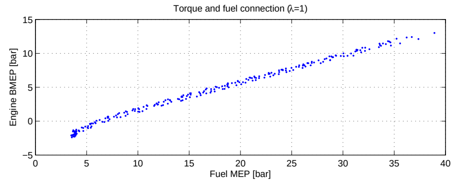
$$\bar{E}_{\text{MVEG-95}} \approx A_f \, c_d \, 1.9 \cdot 10^4 + m_v \, c_r \, 8.4 \cdot 10^2 + m_v \, 10 \quad kJ/100km$$

Engine Efficiency Maps

Measured engine efficiency map
–Used very often for fuel economy estimation and optimization.



Willans line approximation



- Affine relationship – Linear with offset

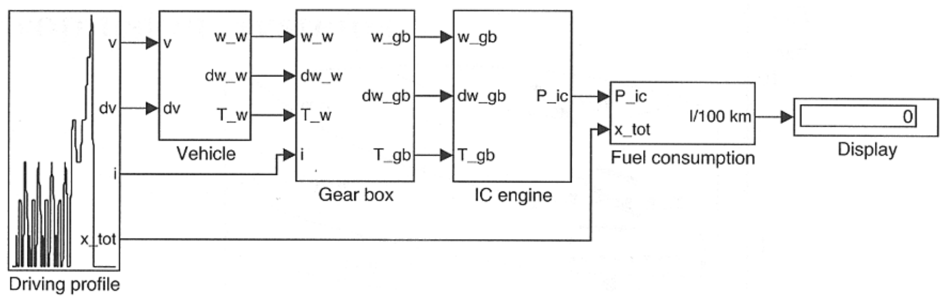
$$p_{me} = e(\omega_e) \cdot p_{mf} - p_{me,0}(\omega_e)$$

- Engine efficiency:

$$\eta_e = \frac{p_{me}}{p_{mf}}$$

Model implemented in QSS

Conventional powertrain.

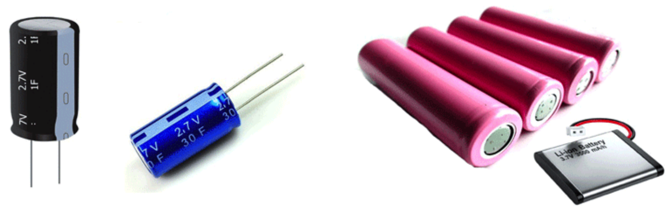


Efficient computations are important
–For example if we want to do optimization and sensitivity studies.

Outline

Definition

What characterizes a Hybrid-Electric Vehicle
- Energy carrier is a fossil-fuel.
- Presence of an electrostatic or electrochemical energy storage system.



Combining combustion engine and larger electrical machines (starter motor, and generator).

Potential for Energy Savings

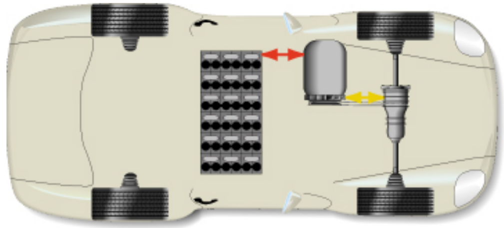
Benefits of Hybrid-Electric Vehicles

- Downsize engine while maintaining maximum power requirement
- Recover energy during deceleration (recuperation)
- Optimize energy distribution between prime movers
- Eliminate idle fuel consumption by turning off the engine (stop-and-go)
- Eliminate the clutching losses by engaging the engine only when the speeds match

Possible improvements are counteracted by a 10-30% increase in weight.

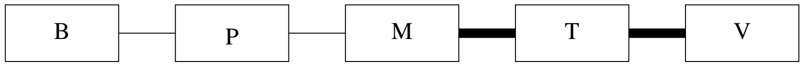
Electric Vehicles

Basic EV topology



Sketch of the energy paths (Thin=Electric, Thick=Mechanic)

Electric vehicle



Electric Vehicles

- Contain basic elements of HEV.
- Not “interesting”, for control optimization.
  - No in-depth coverage in the course.
- Interesting from the design point of view.
  - Possible extra task.
    Send e-mail to me...
- Drawbacks compared to a conventional vehicle
  - Refueling time (Range anxiety)
  - Low range/weight
  - Large investment, expensive batteries

Niche vehicles ⇒ Public acceptance

- EV:s and Plug-in EV:s are hot in media
- Development of plug-less vehicles –Charge while driving, electric roads
- Range extenders (transition to series hybrid)

Electric Vehicles – From Niche to Public

- Many cars in early 1900 were electric
- Applications requiring zero-emissions
  - Indoor vehicles, forklifts, mines . . .
  - In-city distribution vehicles
  - Zero emission vehicle requirements
- Attention in Niched vehicles

Lightning

Tesla Roadster

- Public acceptance and adoption

- Nissan Leaf, Tesla Model S, Polestar 2...

Outline

Basic configurations

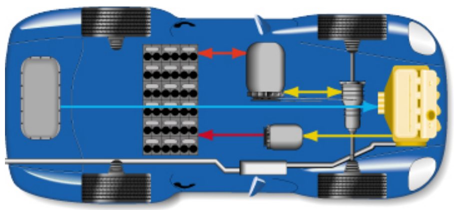
Basic classification of hybrids

- Series hybrid
- Parallel hybrid
- Series-parallel or combined hybrid

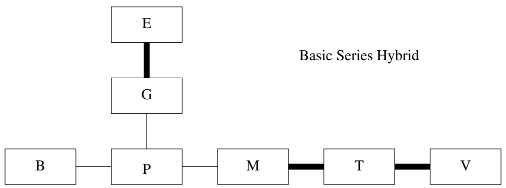
There are additional types that can not be classified into these three basic types

- Sometimes Called Complex Hybrid

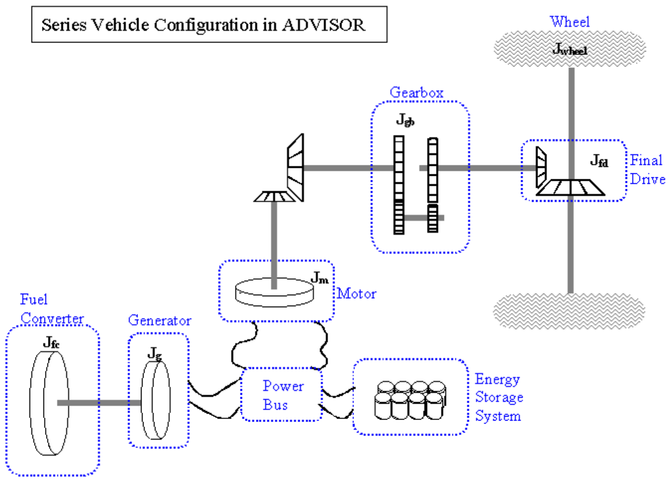
Series Hybrid – Topology



Sketch of the topology



Series Hybrid

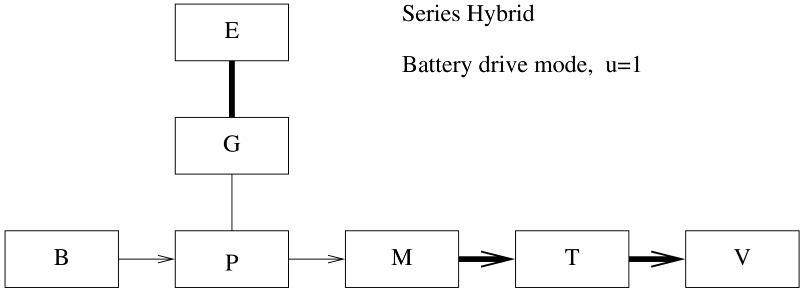


Series Hybrid – Modes and Power Flows

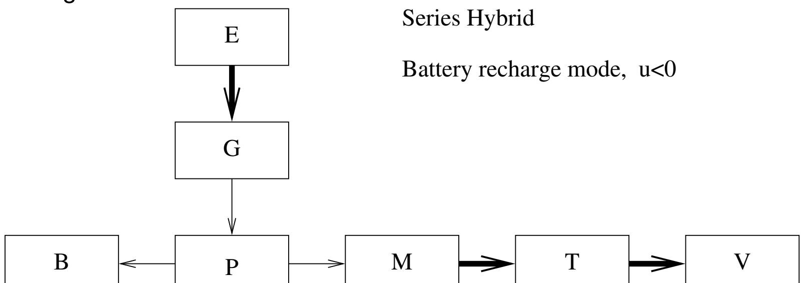
The different modes for a series hybrid

$$u \approx P_{batt} / P_{vehicle}$$

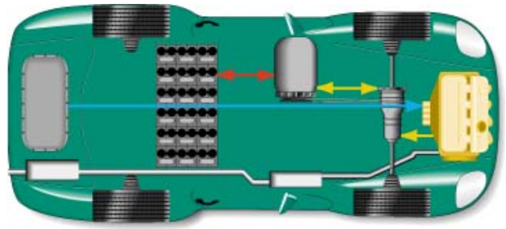
Battery drive mode



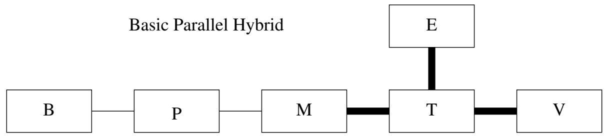
Battery recharge mode



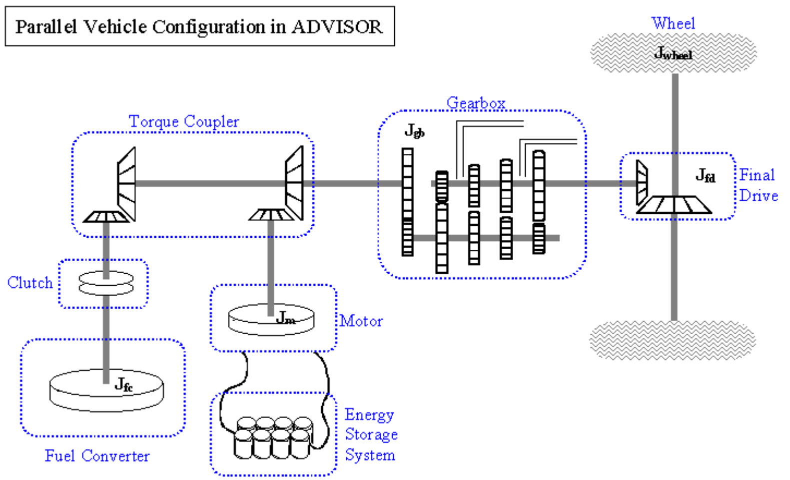
Parallel Hybrid – Topology

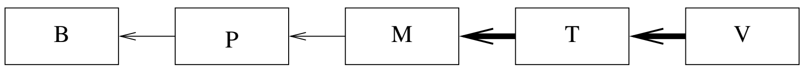


Sketch of the topology



Parallel Hybrid – Topology



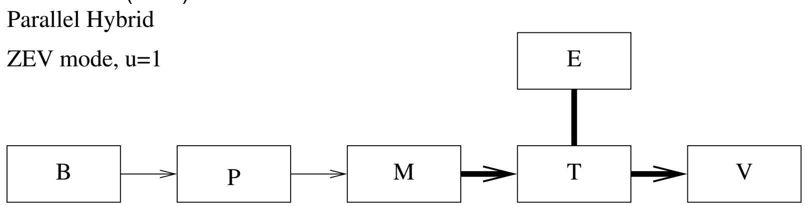


Parallel Hybrid – Modes and Power Flows

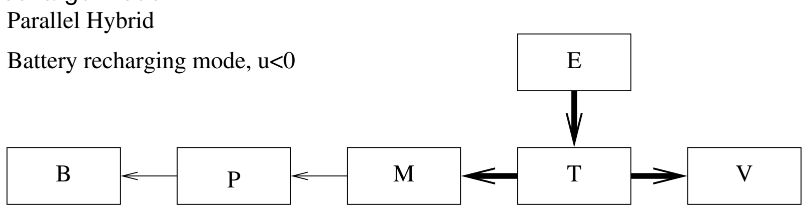
The different modes for a parallel hybrid

$$u \approx P_{batt} / P_{vehicle}$$

Battery drive mode (ZEV)



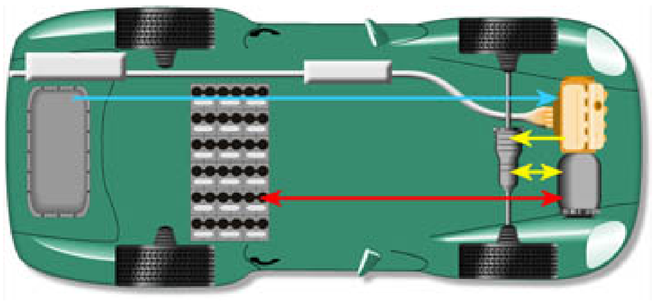
Battery recharge mode



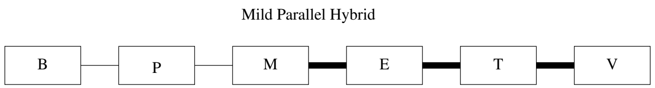
Power assist mode

Parallel Hybrid

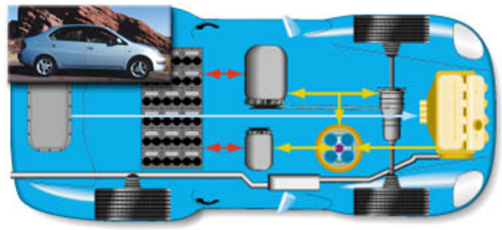
Mild Parallel Hybrid – Topology



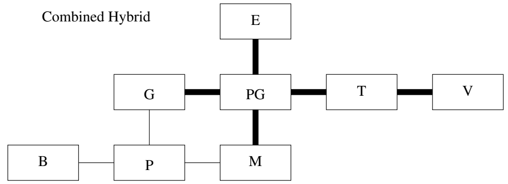
Sketch of the topology



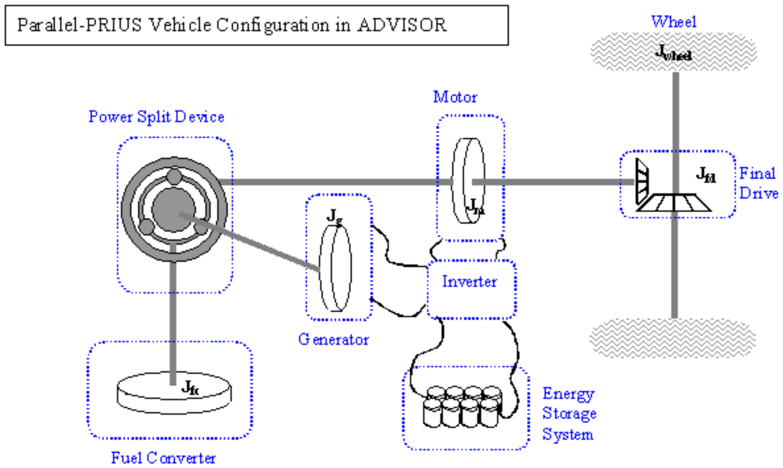
Combined Hybrid – Topology



Sketch of the topology



Combined Hybrid – Topology

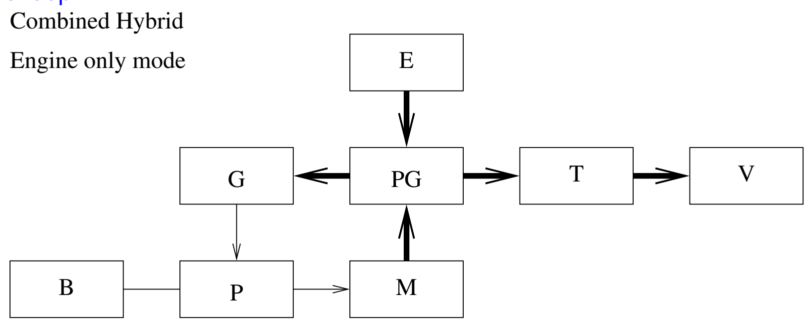


Combined Hybrid with PGS – Modes and Power Flows

The different modes for a combined hybrid

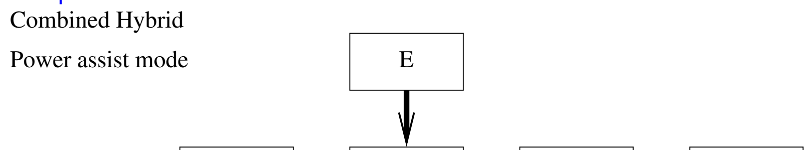
Conventional vehicle

–Note the loop

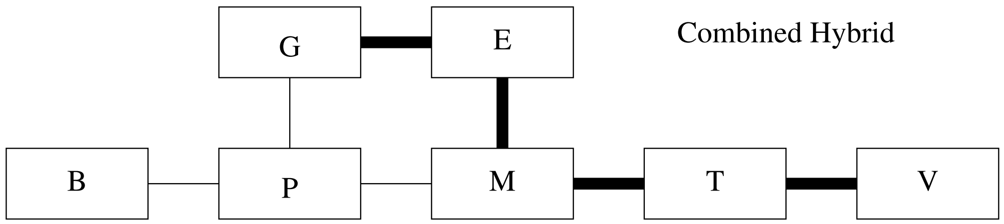


Power assist mode

–Note the loop



Combined Hybrid Without Planetary Gear



Degree of Hybridization and Their Features

Definition: Degree of hybridization

–The ratio between electric motor power and engine power

- Electric Vehicle – 100%
- Implemented hybrid concepts in cars
  Degree of hybridization varying between 15–55%
- True mild hybrid concepts
  Degree of hybridization varying 2–15%

Feature	Conv.	Micro	Mild	Full	Plug-in
Shut of engine at stop-lights and stop-go traffic		(x)	X	X	X
Regenerative braking and operates above 42 V			X	X	X
Electric motor to assist a conventional engine			X	X	X
Can drive at times using only the electric motor				X	X
Recharges batteries using the wall plug with at least 32 km range on electricity					X

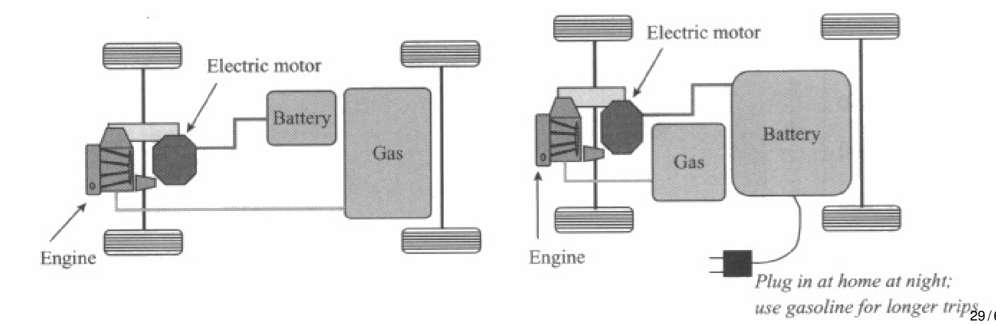
State OF Charge – SOC

- Charge condition for the battery.
- Full range SOC $\in$ 0–100%.
- Used range SOC $\in$ 50–70%.
- A fairly difficult and much studied problem
- Next step State Of Health (SOH), active research on models that include aging.

Charge Sustaining Strategy

Charge Sustaining Strategies

- Basic control problem for a hybrid
  SOC after a driving mission is the same as it was in the beginning
  –Important for fuel economy comparisons.
- Plug-in hybrids
  Not charge sustaining: Two modes, Charge depletion $\rightarrow$ Charge sustain



(*a*) Charge sustaining, or H0, hybrid architecture (*b*) Plug-in hybrid with electric range capability.

Outline

Electric Motors – Classification

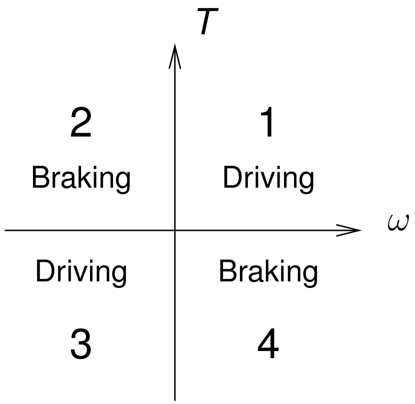
Electric motors are often classified into four groups
(there are other classifications)

- DC-Machines
- Synchronous machines (sometimes including brushless DC-motor)
- Asynchronous machines
- Reluctance machines

There are also other devices:
Stepper motors (Digitally controlled Synchronous Machine), Ultrasonic motors.

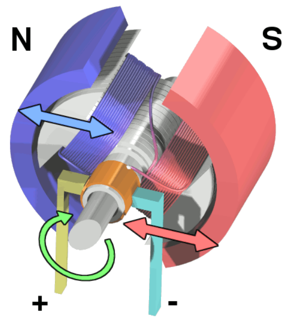
–Separate course: TSFS04 Electrical Drives.

The 4 Quadrants



1 - Motor, 4 - Generator, 2,3 - Reversing

Brushed DC-Machine



Wikipedia picture

Brush-type DC motor:

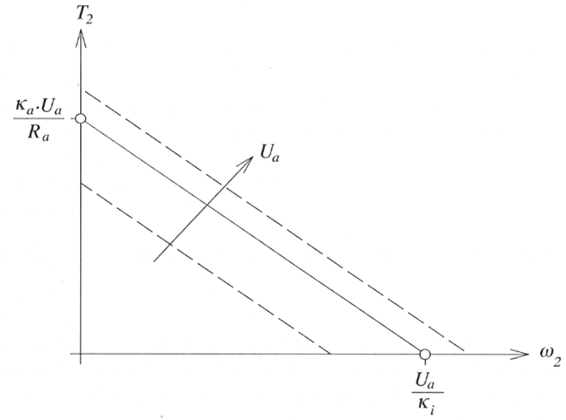
- Rotor
- Stator
- Commutator
- Two subtypes:
  –Permanent magnet
  –Separately excited

Pros and cons

+ Simple to control
– Brushes require maintenance

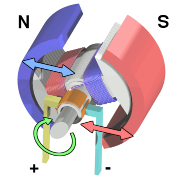
DC-motor torque characteristics

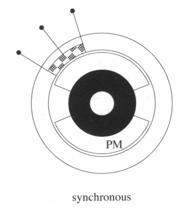
Characteristics of a separately excited DC-motor



Brushless DC-Motor (BLDC)

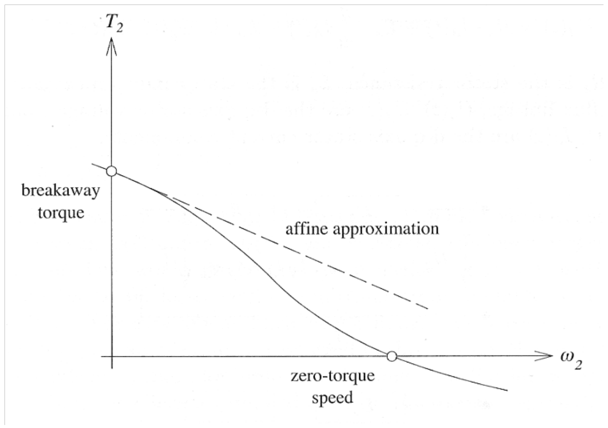
- Solves DC commutator and brushes problem
  - Replace electromagnet in rotor with permanent magnet (PM).
  - Rotate field in stator.
- DC-motor is misleading
  - DC source as input
  - Electronically controlled commutation system AC
- Close to linear relations between
  - current and torque
  - voltage and rpm





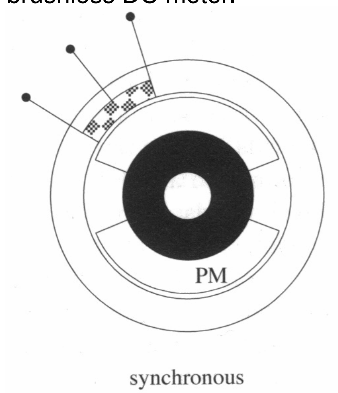
Torque Characteristics

Brushless DC



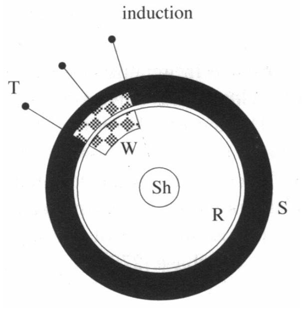
Synchronous AC machines

- AC machine
- Rotor follows the rotation of the magnetic field
- Has often *permanent magnets* in rotor
  –This is the same as the brushless DC motor.



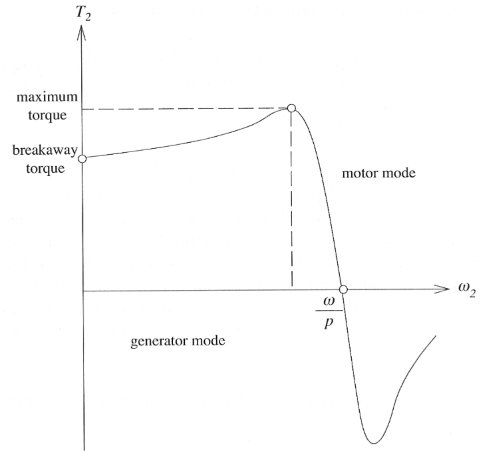
Asynchronous AC machines – Induction motors

- Stator has a rotating magnetic fiels
- Rotor has a set of windings, *squirrel cage*
  –See separate animation.
- Electric field induces a current in the windings
- Torque production depends on slip.



Torque Characteristics

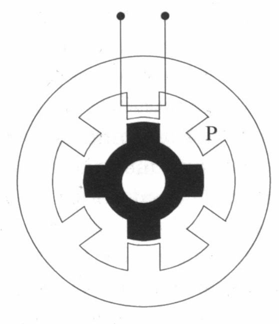
–Induction AC motor



Reluctance machines

Reluctance = Magnetic resistance.

- Synchronous machine
- Rotating field
- Magnetic material in the rotor
- Rotor tries to minimize the reluctance



switched reluctance

Electrical Machines in Hybrids

Machines encountered

- Separately excited DC
- Permanent magnet synchronous DC
- Induction motors
- Switched reluctance machines – Interesting as they do not use rare earth metals

AC motors (compared to DC motors)

Less expensive but more sophisticated control electronics, gives higher overall cost.
Higher power density, higher efficiency.

AC motors (permanent magnet vs induction motors)

Averaged values from Advisor database.

	Efficiency	Power density
permanent magnet	92.5 %	0.66 kW/kg
induction motors	90.5 %	0.76 kW/kg

Motor – Modeling

Quasistatic (equations are general)

- Power relationships:
  –input power $P_1(t)$
  –delivered power $P_2(t) = T_2(t)\,\omega_2(t)$
- Efficiency usage

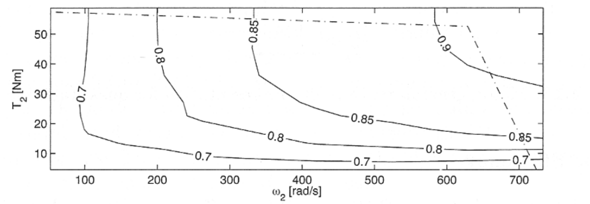
$$P_1(t) = P_2(t)/\eta_m(\omega_2(t), T_2), \qquad P_2(t) > 0$$

$$P_1(t) = P_2(t) \cdot \eta_m(\omega_2(t), -T_2), \qquad P_2(t) < 0$$

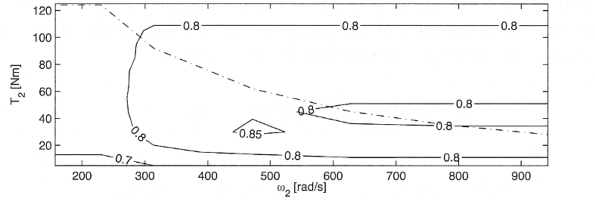
- Description of the efficiency in look-up tables
- Willans line to capture low power performance

First quadrant maps for η_m – AC machines

PM Synchronous



Induction motor, Asynchronous AC



Extending the Maps for η_m

- Traditional first quadrant drive is normally well documented
  –Supplier information for $\eta_m(\cdots)$
- Electric motor drive

$$P_2(t) = \eta_m(\omega_2(t), T_2) \cdot P_1(t), \qquad P_2(t) > 0$$

- Electric generator load

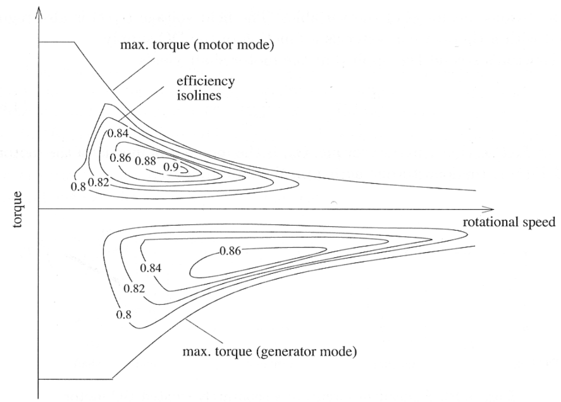
$$P_1(t) = \eta_g(\omega_2(t), T_2) \cdot P_2(t), \qquad P_2(t) < 0$$

- How to determine η_g?
- Method 1: Mirror the efficiency map

$$\eta_m(\omega_2(t), -T_2) = \eta_g(\omega_2(t), T_2)$$

- Method 2: Calculate the power losses and mirror them
- Method 3: Willans approach

Two Quadrant Maps for η_m



Mirroring efficiency is not always good if you need to estimate regenerative braking current

Motor – Modeling

- More advanced models
  - Use component knowledge: Inductance, resistance
  - Build physical models
- Dynamic models are developed in the book

Some examples of motors in the devices near us

A regular DVD player taken to pieces – It has three different types of motors.

1. A normal DC motor for opening the tray
2. A BLDC motor for rotating the disc
3. A stepper motor for controlling the position of the laser head

Outline

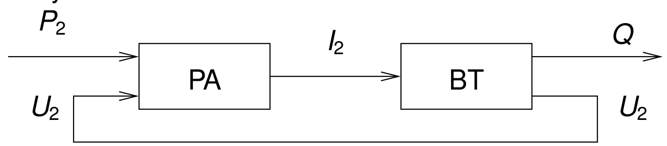
Batteries

- Energy storage devices – Energy density important
- Performance – Power density important
- Durability

Battery type	Energy Wh/kg	Power W/kg	cycles
Lead-acid	40	180	600
Nickel-cadmium	50	120	1500
Nickel-metal hydride	70	200	1000
Lithium-ion	130	430	1200

Modeling in QSS Framework

- Causality for Battery models in QSS.



- Models have three components
  - The first component is

$$I_2(t) = \frac{P_2(t)}{U_2(t)}$$

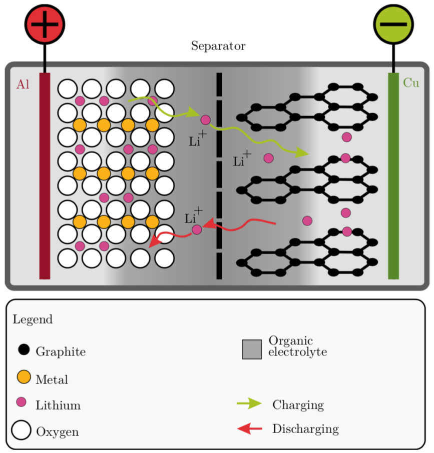
  - The other, the relation between voltage and terminal current SOC

$$U_2(t) = f(SOC(t), I_2(t), \ldots)$$

  - The third is the integration of current to Q (i.e. SOC)

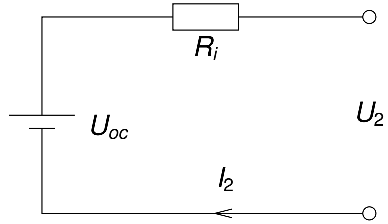
$$Q(t) = \int_0^t I_2(\tau)d\tau \qquad SOC(t) = \frac{Q(t)}{Q_0}$$

The Lithium Ion Battery



Standard model

Simple model for the battery
–Open circuit voltage $U_{oc}(SOC)$

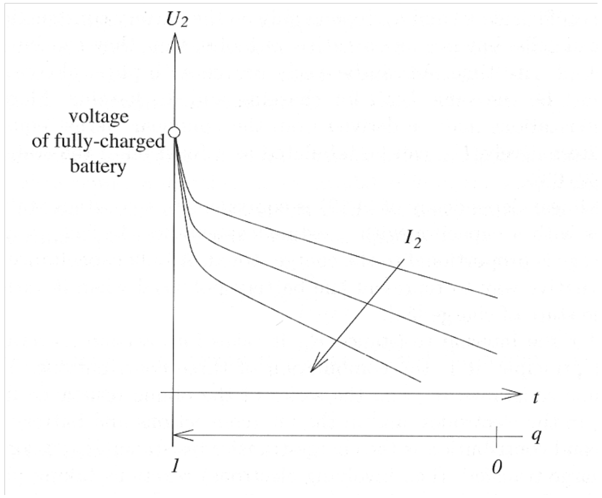


Output voltage

$$U_2 = U_{oc}(SOC) - R_i I_2$$

This is the model that will be used in the hand in assignment in this course.

Voltage and SOC - Discharge with Different Currents



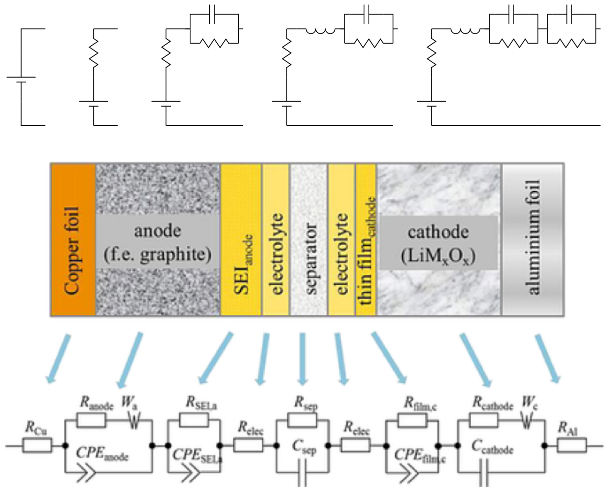
Output Voltage

$$U_2 = U_{oc}(SOC) - R\,I$$

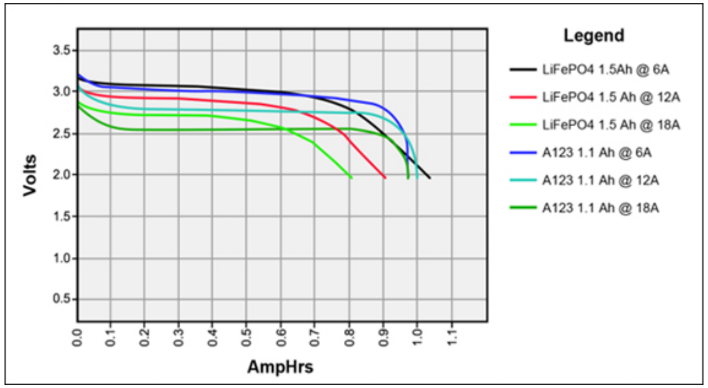
Higher current has 2 effects.

- Higher resistive losses
  –Voltage drop
- Quicker depletion of SOC
  –Steeper voltage ramp

More Advanced Battery Models – Equivalent Circuit



Voltage and SOC

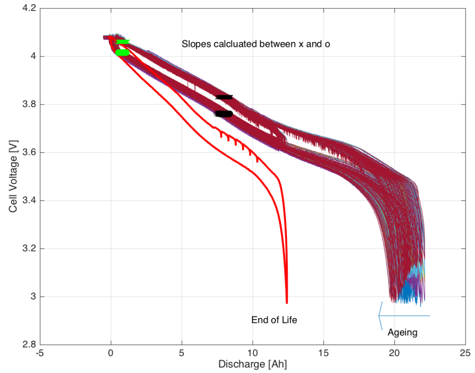


Typical characteristics. Can extract inner resistance, and capacity.

(Source: batteryuniversity.com)

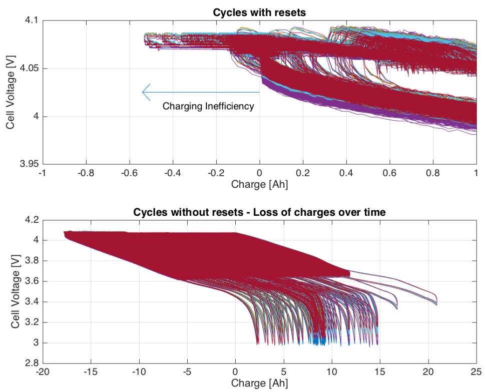
Battery Ageing – Lithium Ion Batteries

Battery data from Alelion in Gothenburg, 550 days 2048 cycles.
Aging is visible over the cycles.



SOC drift over time – Coulombic Inefficiency

Top: Reset so the cycle starts at 0 Ah every cycle.
Bottom: No reset, charge drifts, $2 \cdot 10^{20}$ electrons lost per cycle.



Battery – What is the Efficiency of a Battery?

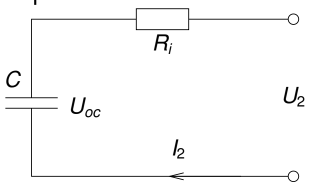
- Efficiency definition is problematic
  - Not an energy converter
  - Energy storage
    –Charging: Inserting energy
    –Driving: Extracting energy
  - How much is lost, will depend on the cycle

Battery Lecture

Batteries are an important component in the future of electromobility
A separate lecture devoted to batteries will be available after easter

Supercapacitors

- Supercapacitors and ultracapacitors
- High power density
  –Used as short time scale energy buffer.
  –Load leveling to the battery.
- Very similar to battery in modeling
  Exchange the battery for a capacitor in the circuit below.



$$U_{oc}(t) = \frac{Q(t)}{C} = \frac{1}{C}\int I(t)dt$$

- Efficiency definitions – Same as for Batteries.

Outline

Power Links

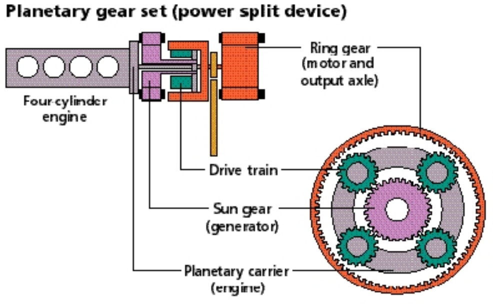
- The battery is a DC component (can have several battery packs)
- The grid is an AC system
- Need electrical glue components
  - DC-DC converters
  - Inverters, DC-AC converters for AC machines
  - Inverters, AC-DC converters for charging
- Modeling of Power Links
  - Model the power losses
  - Willans line models

Torque couplers

- Components that are included to act as
  - Glue for mechanical systems acting on the same shaft
- Can include:
  - Gears in the coupling equation
  - Planetary gear-sets (power split devices)
  - Clutches to engage and disengage components
- Basic equations and models
  - Angular velocities from geometric gear ratios
  - Torque transmission (from power balances)
  - Sub models for friction and other losses

Power Split Devices

- Manage power splits between different components
- Important component for achieving flexibility
- Modeling approach: Speed relations with torque from power balance.



Can add more planetary gears. For example: Prius Gen 1 $\rightarrow$ Gen 2.