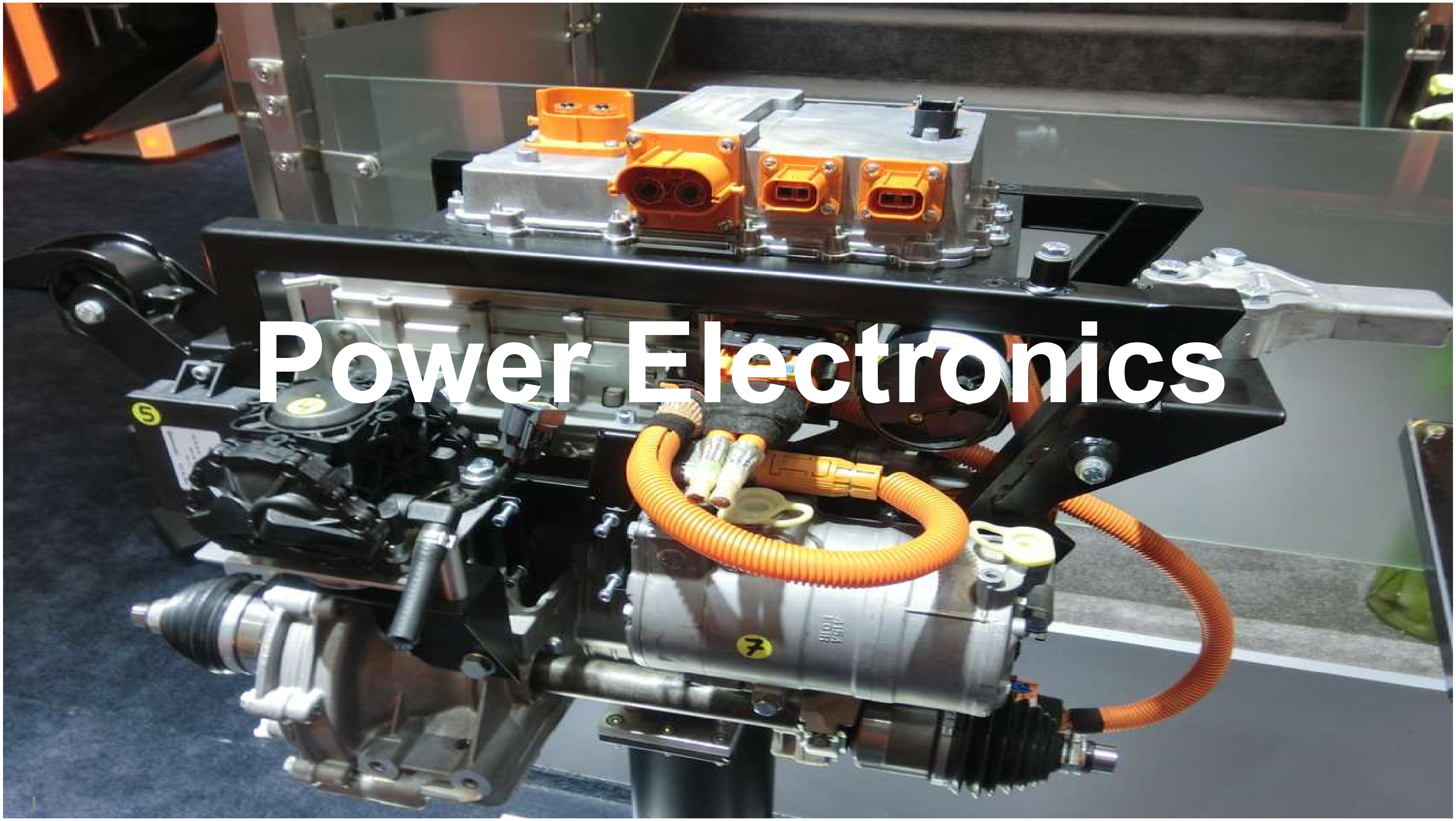
Power Electronics



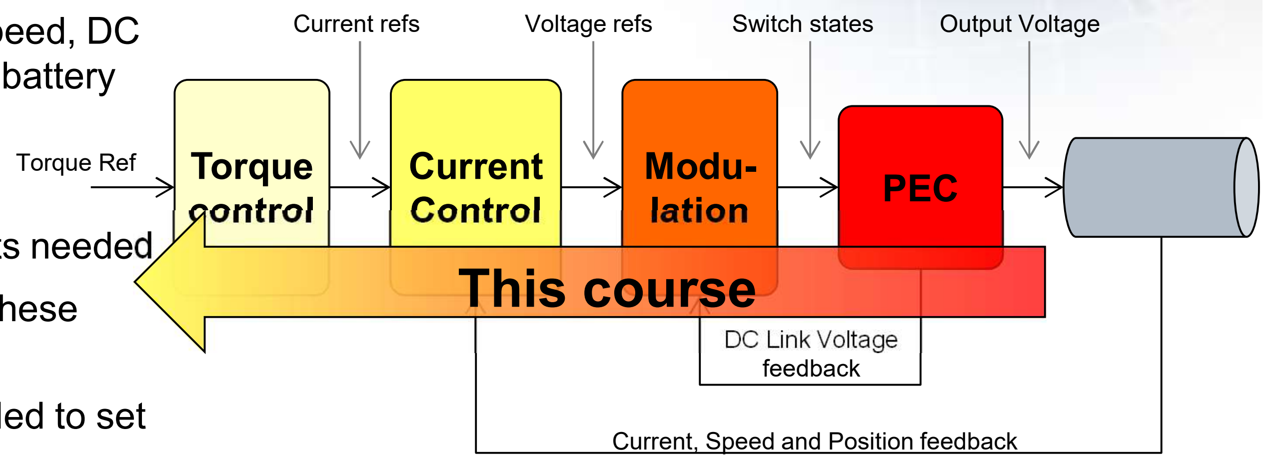
Lecture 1 – Introduction & Basic Switching

We want torque !

- We are mainly interested in the mechanical torque on the electrical machine shaft
- But, the torque is the result of a complex interaction of electric voltages and currents, magnetic fluxes and mechanical layout
- Our source is (usually) a DC Voltage, that ...
  - we convert to AC with PWM and feed to the electrical machine to ...
  - control the machine currents such that the mechanical torque becomes the one we want.
- Against us we have:
  - A machine that require voltages that increase with speed
  - A battery with limited and almost constant voltage
  - A converter that needs to be controlled in a microsecond time scale

How we do it?

- We start knowing:
  - The desired torque
  - Lots of system states, like speed, DC link voltage, phase currents, battery SOC, ...
- We calculate:
  - The traction machine currents needed
  - The voltages needed to set these currents
  - The modulation pattern needed to set these voltages
- We modulate the swithes accordingly !



Why Power Electronics?

- **The efficiency of a linear amplifier (converter) has a theoretical upper limit of 78.5 %**
- **This is sufficient in many low power applications, such as home audio**
- **In trains the rated power may be as high as 4-8 MW**
- **For an efficiency of 78.5 % the losses would be 0.86-1.72 MW**
- **This means that huge amounts of power and money would be lost**

  ... but the main problem would be thermal management, i.e. handling the heat power
- **Typically, the efficiency of a power electronic switch mode converter is >98 %**

Simple low power amplifiers

A

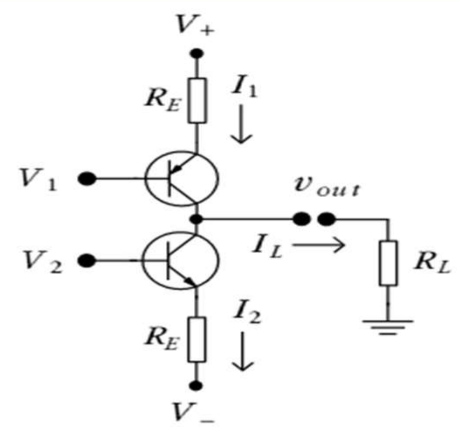
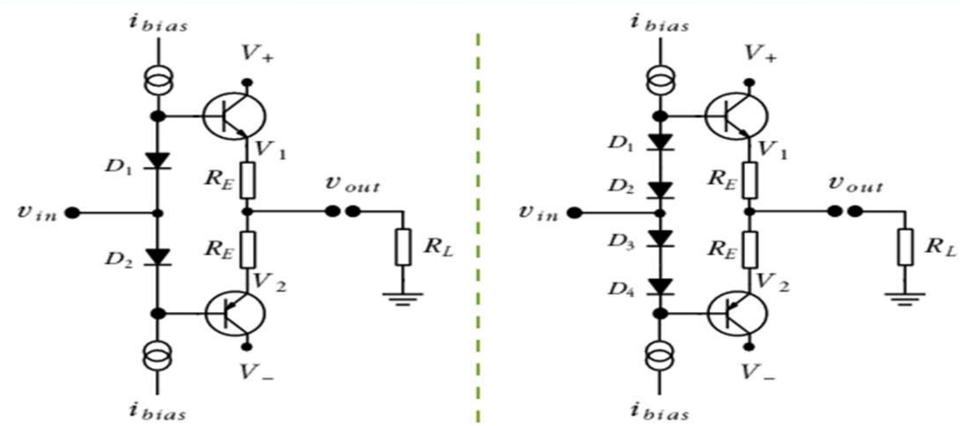


Figure 2·3 — Push-Pull Output

Eff = 20 – 25%

B och AB



2·4a Class B

2·4b Class AB

Figure 2·4 — Class B and AB Power stages

Eff = 60 %

Class D Audio Amplifiers

Product description | Specifications | User manual | Wiring schematics

Hypex UcD2k 1x2000W Universal Class D Amplifier Module

The UcD2k amplifier module is an entry level high-end class D amplifier from Hypex. The UcD2k is known for its high performance, reliability and ease of use. The UcD2k comes with the required UcD Signal Cable.

Specifications for: UcD2k 1x2000W Universal Class D Amplifier Module

Rated power output (RMS)	2500 watts at 4 ohms 1600 watts at 8 ohms 2000 watts at 2 ohms
Minimum load	1 ohm
Efficiency	92 %
Signal-to-noise ratio (SNR)	-
Distortion	0.02 % (20-20,000 Hz @ 0.5 x Rated power output)
Frequency response	10 - 50,000 Hz
Gain	34 dB
Input sensitivity	2.25 Vrms for rated power output
Input impedance	100k ohms
Amplifier Classification	Class D
Circuit Topology	UcD®
Speaker output channels	1
Power Requirements	50 - 98 VDC (symmetric supply +/-) 13 - 15 VDC (driver supply voltage)
Power inlet connector	Crimp/solder connection tabs
Current limit	50 A
Under/over voltage protection	✓
Dimensions (L x W x H)	141 x 108 x 38 mm

What is Power Electronics used for?

- **All kinds of electrical drives where electrical power is transfered to mechanical and variable speed is required such as**
  - *Traction applications such as trains, electrical vehicles and ship propulsion*
  - *Pumps and fans*

- **All kinds of electrical drives where electrical power is transfered to mechanical and position control (servo) is required such as**
  - *Robots, cranes*

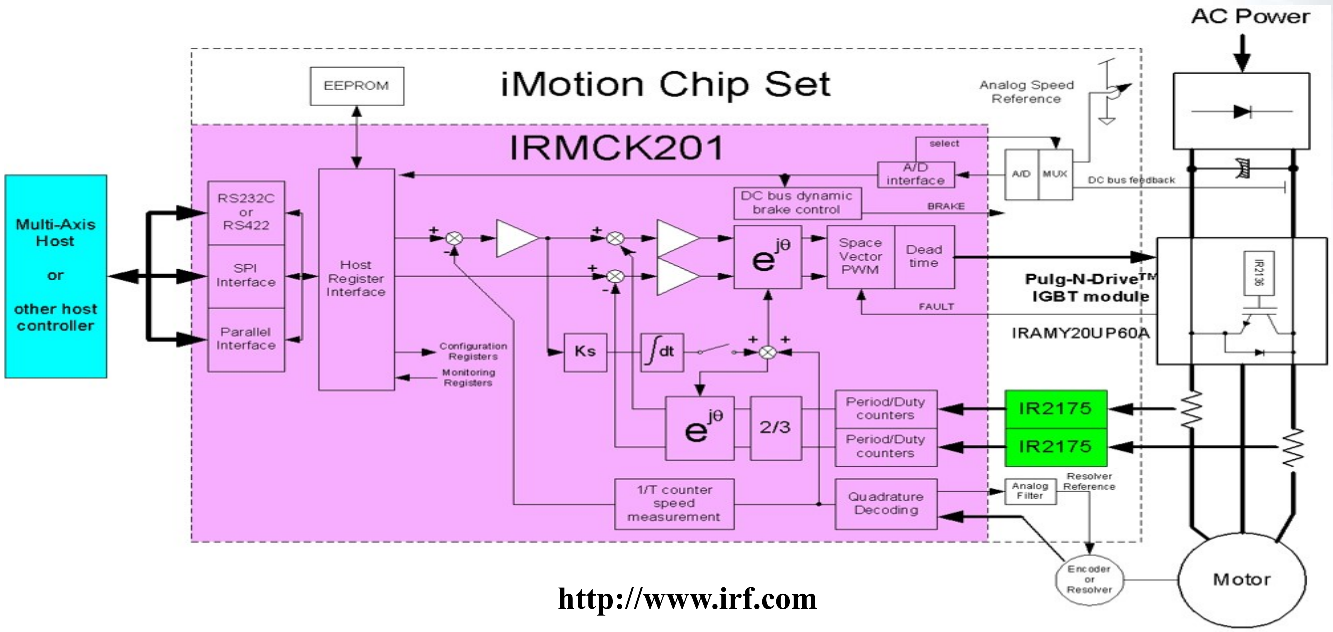
- **Power system applications such as**
  - *HVDC (up to 3000 MW), Transistor based HVDC*
  - *Feeding and priming power from renewable energy sources (solar, wind, ...)*
  - *Active power filters, reactive power compensation, ...*

- **Power supplies**
  - *Computers, tv-sets, ...*
  - *Battery chargers for computers, mobile phones, hand-held tools, ...*

- **Back-up power, i.e. uninteruptable power supplies**

- **Many other applications**

Electrical Motor Drives



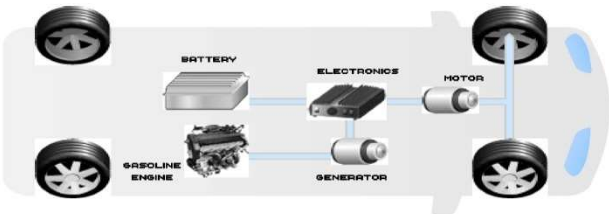
http://www.irf.com

http://www.semikron.com

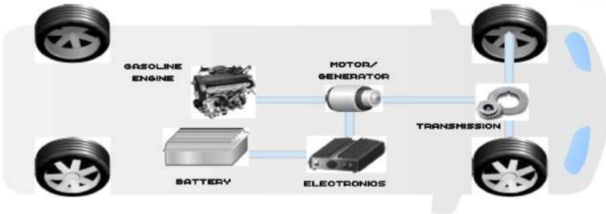
http://www.abb.com

Typical Motor Drive Applications
- Except pumps, fans, cranes, …

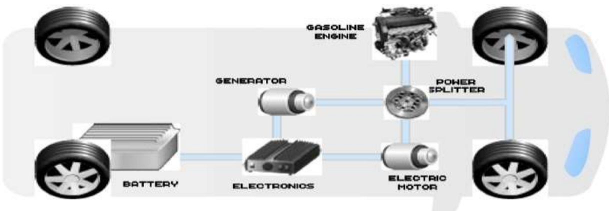
Traction: for example trains and hybrid vehicles



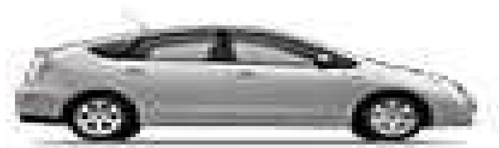
Series Hybrid
http://www.hybridcenter.org/



Prallel Hybrid
http://www.hybridcenter.org/



Series-Parallel Hybrid
http://www.hybridcenter.org/

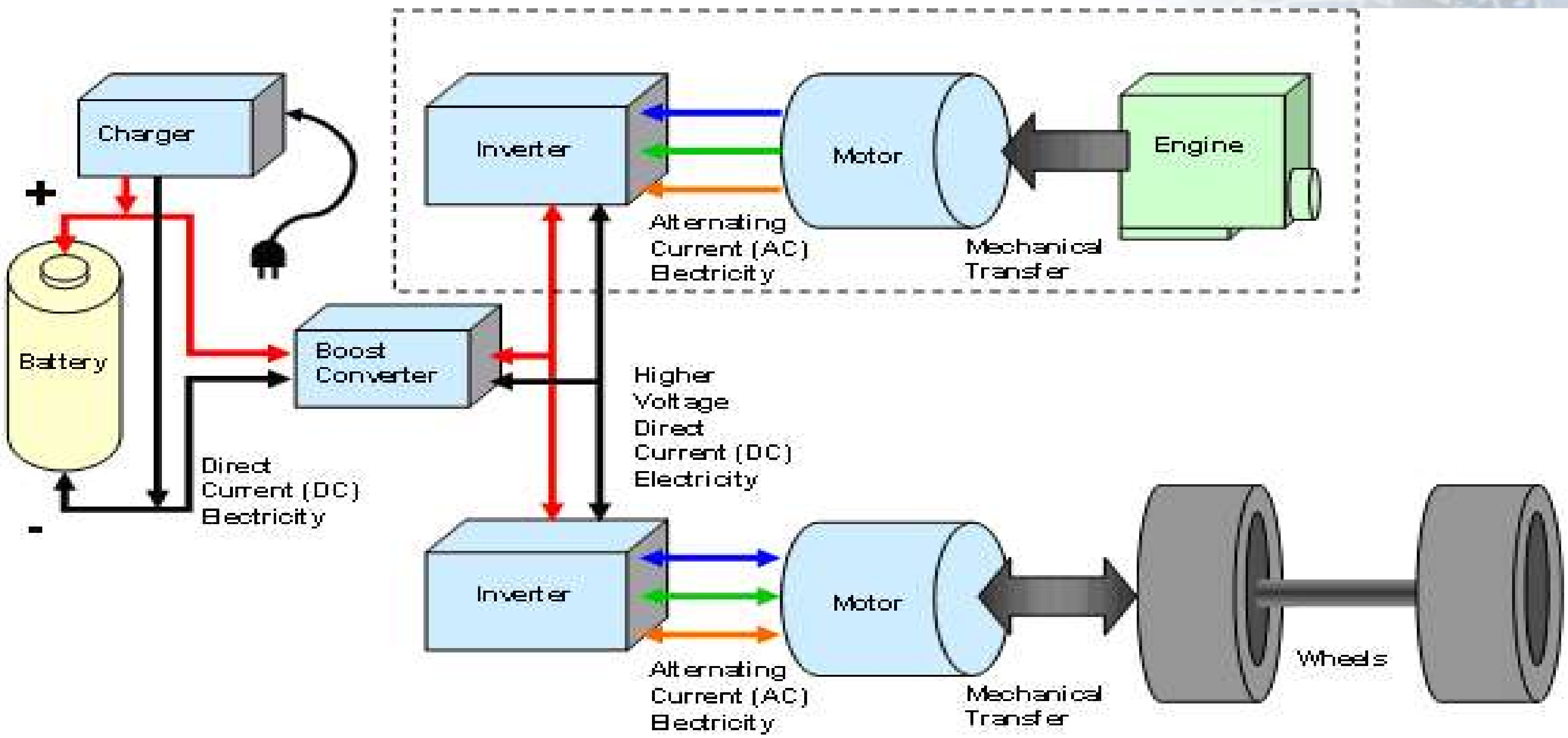


http://www.toyota.com/

Robotics

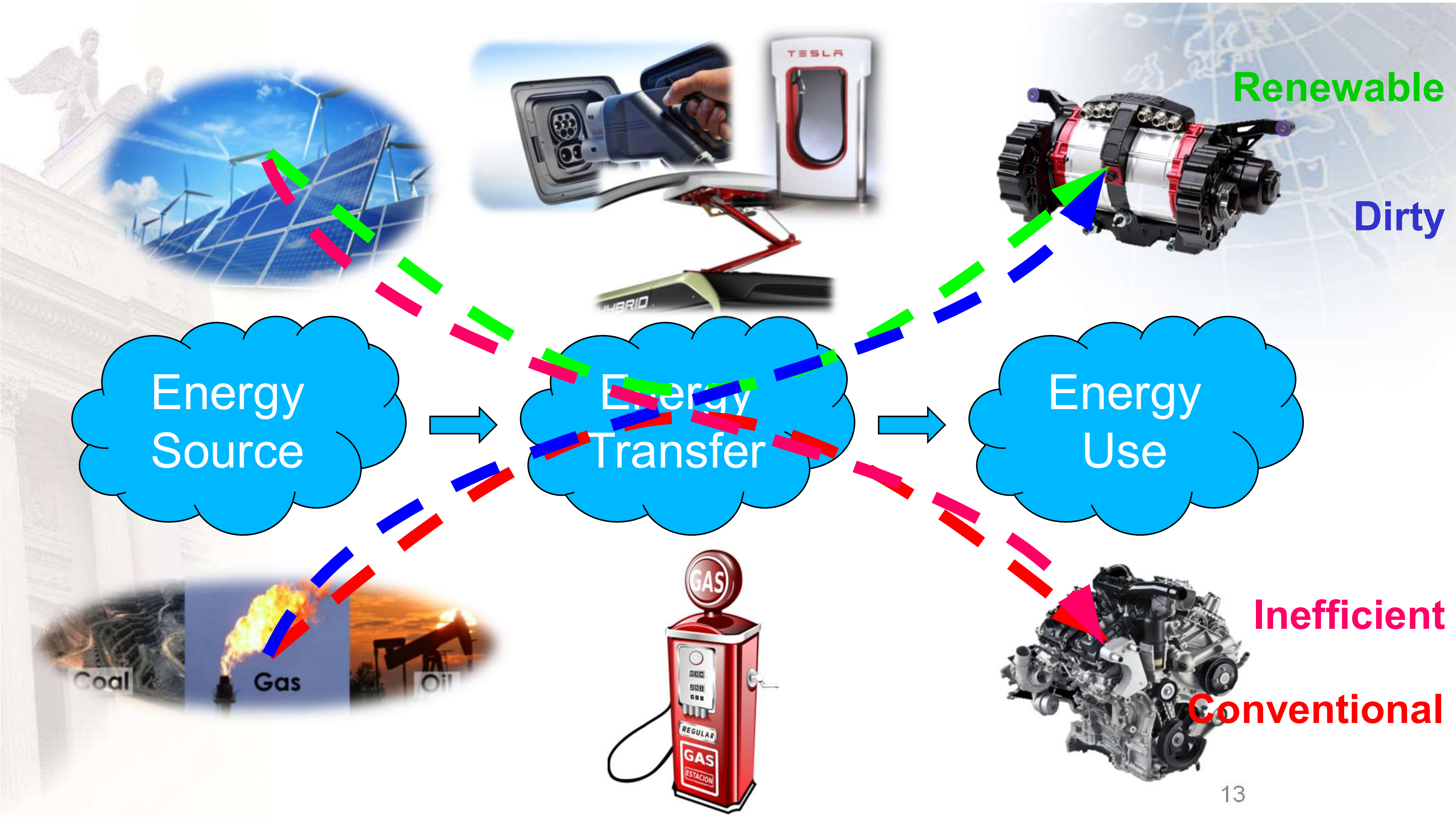
http://www.abb.com

Energy Conversion in Hybrid Vehicles



EV Charging

Professor Mats Alaküla
*Industrial Electrical Engineering at **Lund University***
*Senior Technology Advisor, **AB Volvo***
*Scientific Leader, **Swedish Electro Mobility Research Centre***


Energy Source
Energy Transfer
Energy Use
Renewable
Dirty
Inefficient
Conventional
Coal
Gas
Oil
TESLA
HYBRID
GAS
REGULAR
GAS
ESTACION

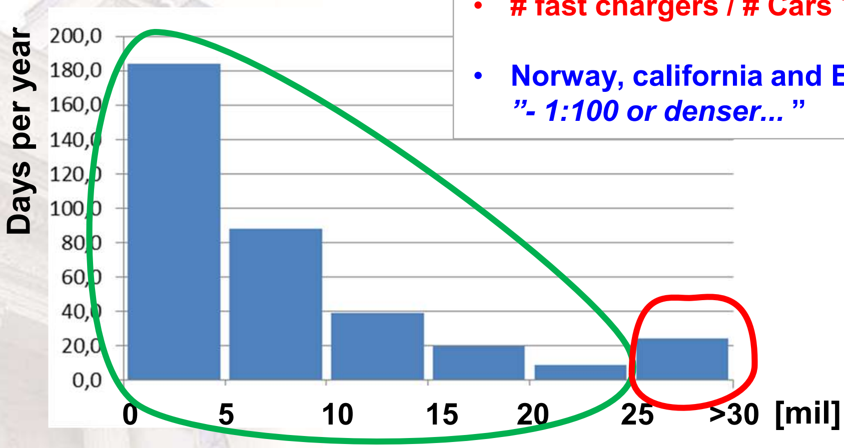
The last Century

The Charging Challenge is NOT new ...

Possibilities

Car charging needs

- # fast chargers / # Cars ?
- Norway, california and EU says:
  "- 1:100 or denser… "

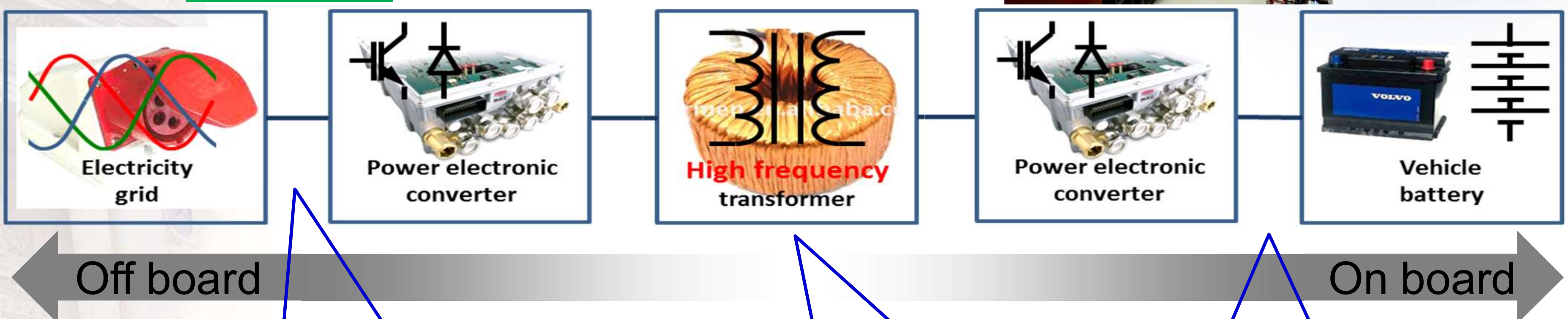


- 1 gasstations / 5000 cars
- 1 fast charger / 100 cars
- = 50 fast chargers / gas station !!!

… in average, in Sweden

Static Charging

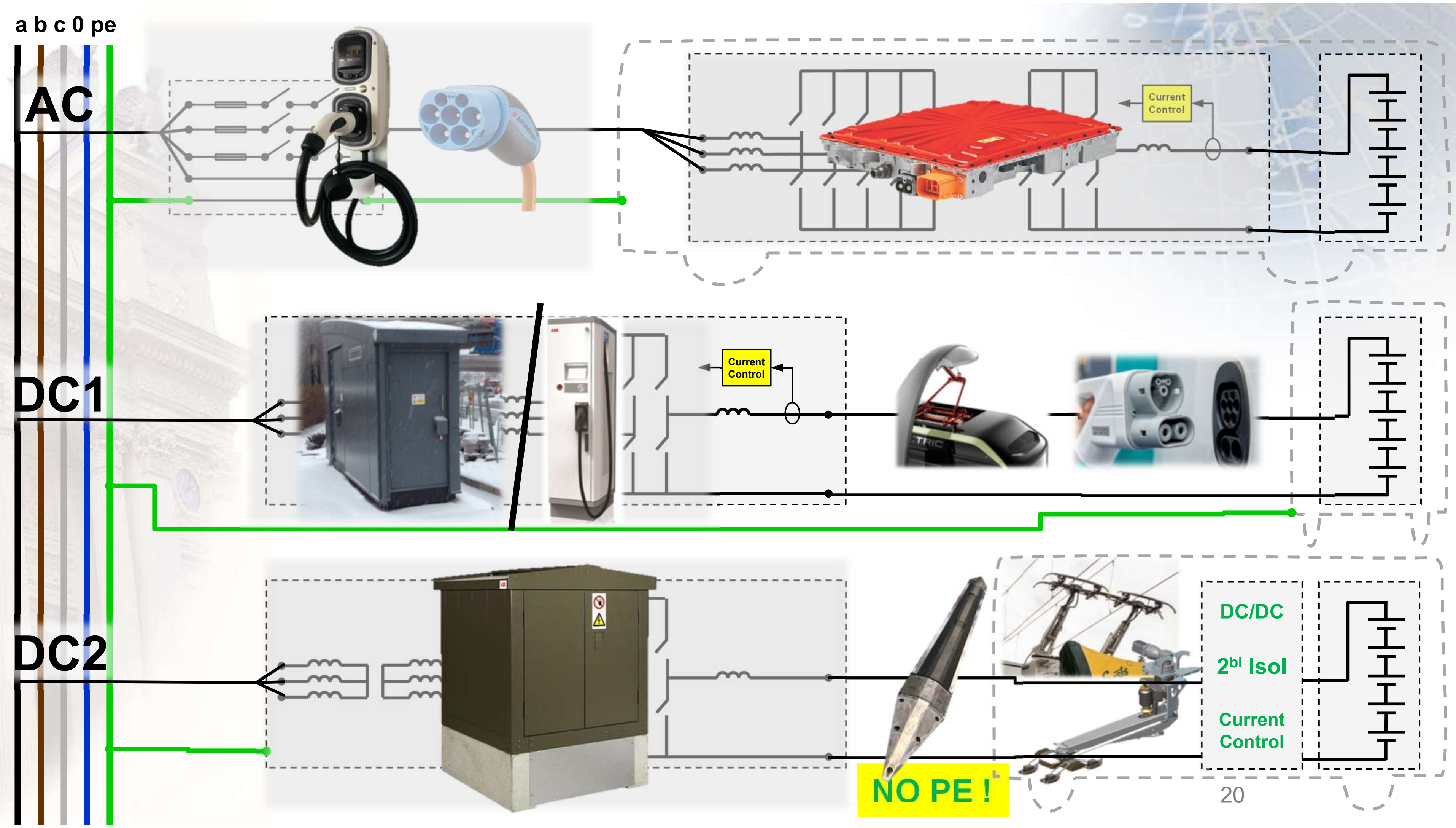
On board / Off board = AC / DC

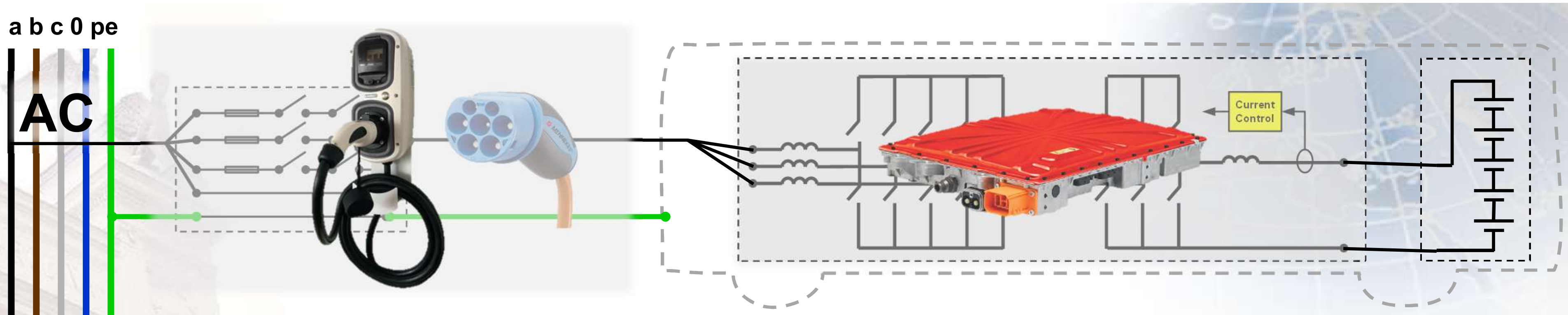


- **”AC Charging”**
- **Automation missing**
- **High power plug missing?**
- 10...100 MW/m²

- **”Wireless Charging”**
- 10...100 kW/m²

- **” DC Charging”**
- **Automation missing**
- 10...100 MW/m²


a b c 0 pe
AC
Current
Control
DC1
Current
Control
DC2
DC/DC
2bl Isol
Current
Control
NO PE !

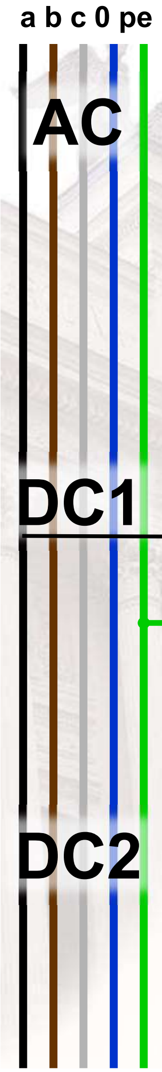


- 3 phase plug limited to 63 A
- Max charging power 44 kW
- Available from all OEMs for night time charging

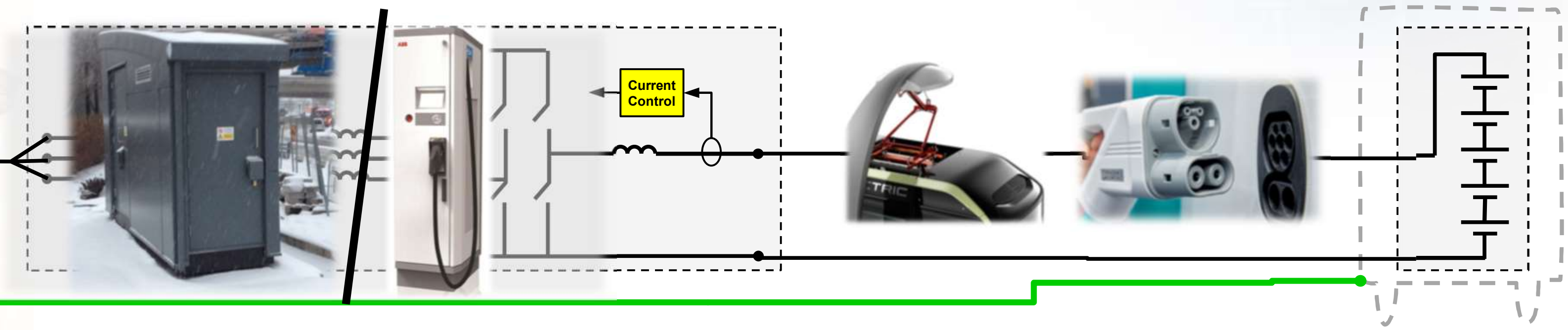
- E.g. 200 kWh in 5 hours night time.

- NOT Enough for Opportunity Charging at +100 kW

- New Plug Needed for higher power levels!

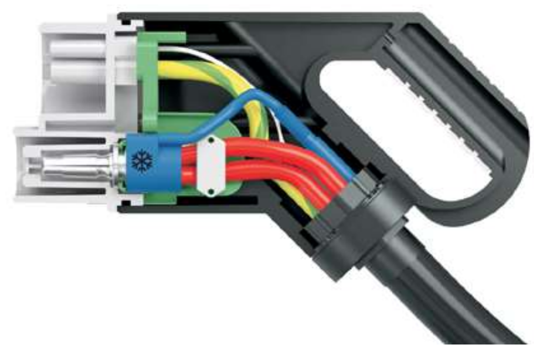


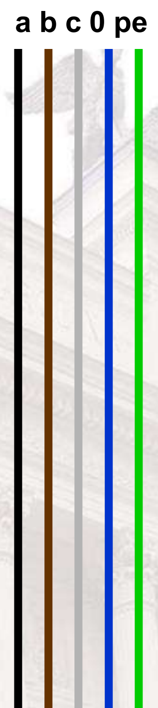
- OppCharge an open ”standard”, capable of up to 600 kW
- Expensive stations, not compatible with most truck applications



- CCS/DC normally limited to 200 A.
- @ 750 V this gives 150 kW, e.g 4x0.25h = 150 kWh
- NOT automatic

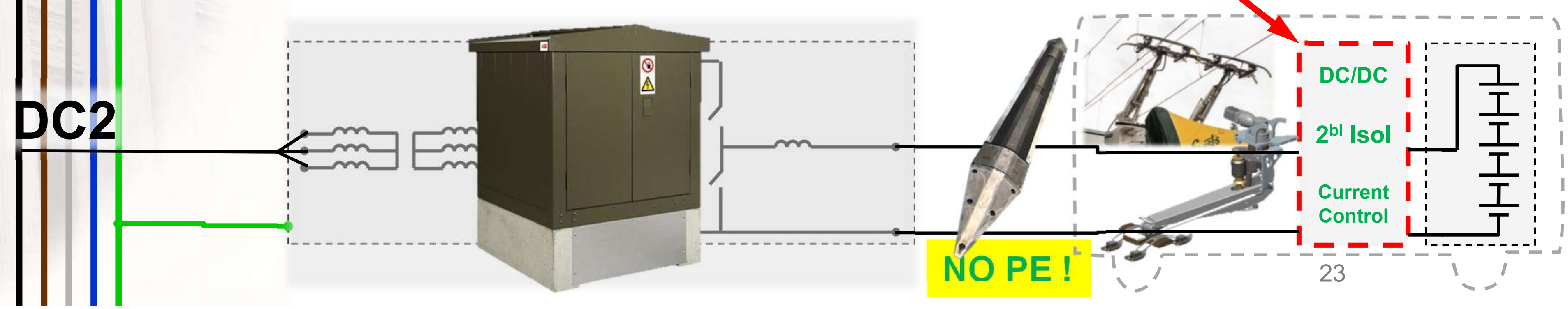
- Pushed towards 500 A with water cooling = 375 kW @ 750 V





- Siemens eHighway is currently leading
- Others follow very soon
- Significant battery size reduction (-60%...-80%)
- 150 kWh instead of 600 kWh

- No protective earth – requires special safety solutions



Tesla Semi Analysis ...

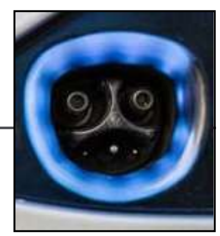
Technical facts

Given Facts

- GVW = 80000 lbs = 36 287 kg
- Drag Coefficient = Cd = 0.36
- Drivetrain: 4 PM motors from Model 3
- Acceleration 0-60 mph = 0-97 km/h
  - Tractor only: 5 seconds
  - Full load (80000 lbs): 20 seconds
- Hill climbing: 5 % slope @ 65 mph = 105 km/h
- Range: 300/500 miles = 483/805 km
- Charging time: 400 miles = 644 km in 30 minutes

Calculated Facts

- Energy consumption = about 1 kWh/km
- Tractor weight = 9 tons
- Traction motors = 4 x 137/192 kW (cont/peak)
- Battery Energy = 850 – 950 kWh (depends on DoD)
- Battery Weight = 4.2 – 4.7 tons (@ 0.2 kWh/kg)
- Charging power
  = almost 1.3 Megawatt for Fast Charging
  = 100 kW for Night Time Charging
- MEGA Charging Connector: Seems to be 4xSUPER Charging Connector

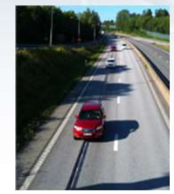


X 4 =

Dynamic Charging

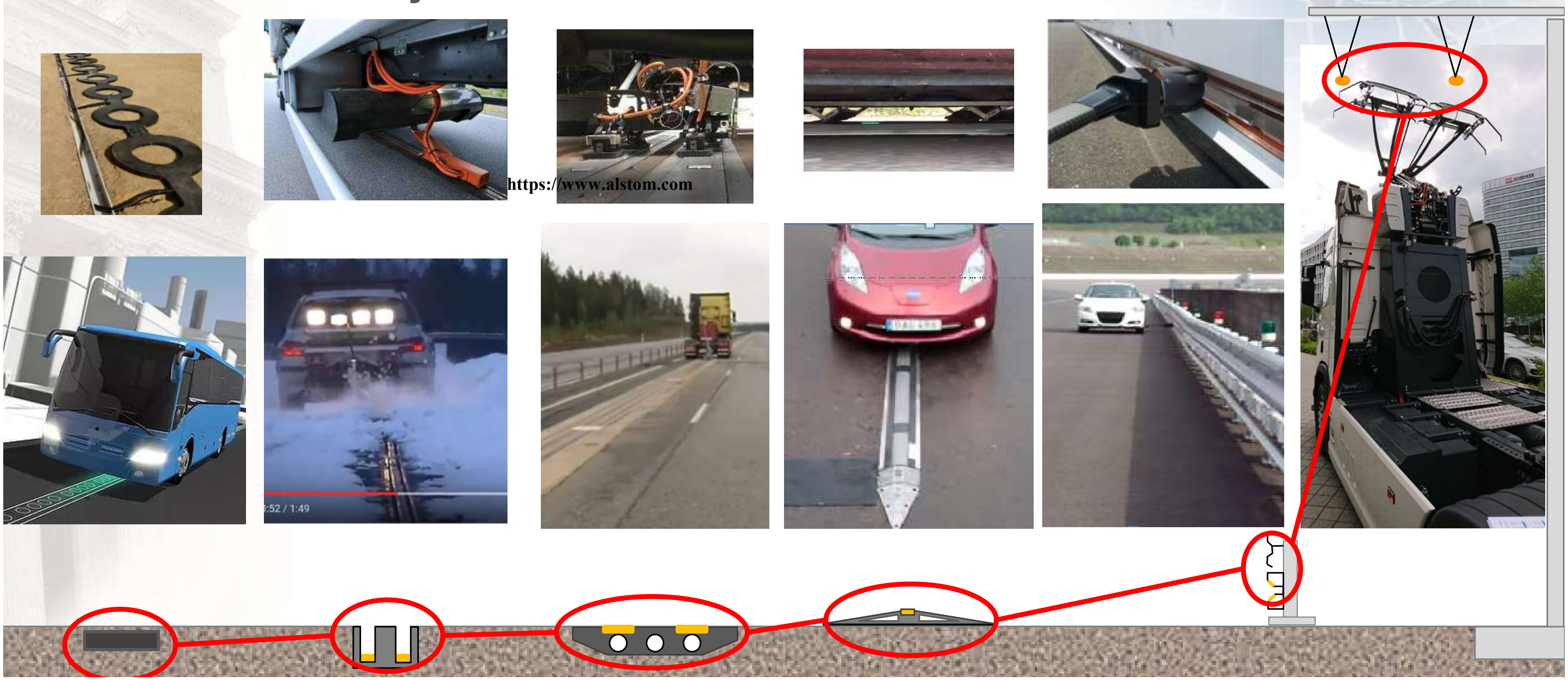
Electric Road Systems (ERS) – Continuous charging

- Transfer energy to vehcles in motion
- Traditionally in Trains, Trams and Trolley Buses
- Different technologies, different connections
- Several different technology demonstrations under way

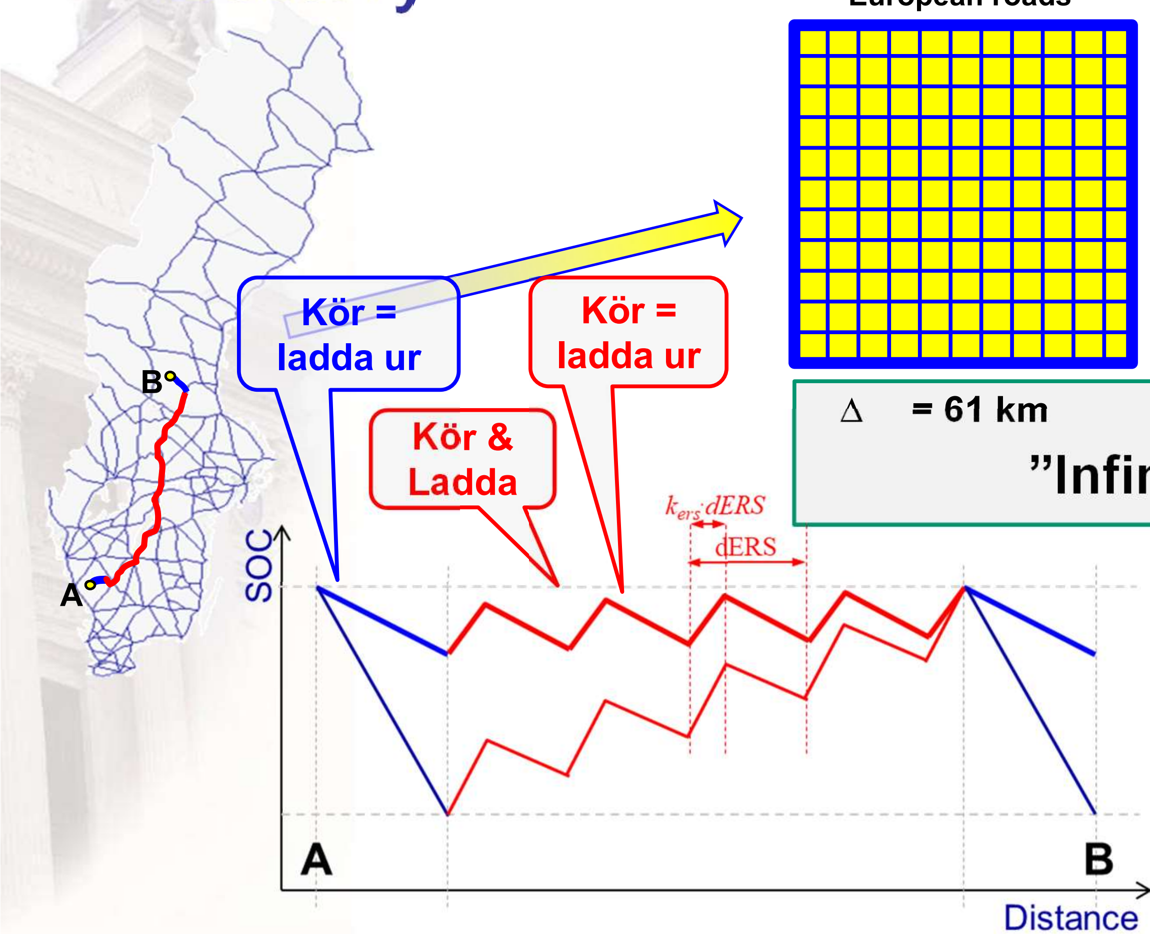
	Top	*Side*	*Below*
Conductive			
Inductive	X	X	
Capacitive	X	X	

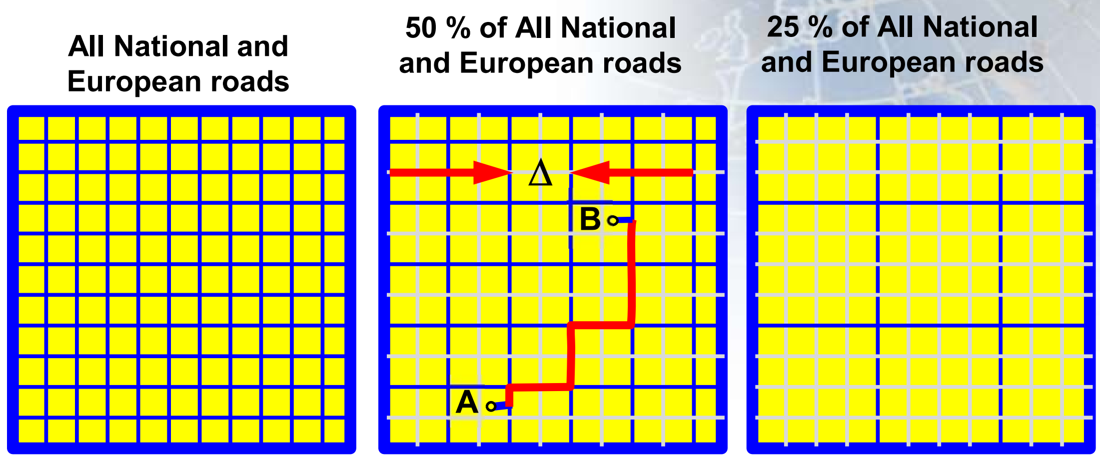
Suppliers considered in Sweden ...

Electreon | Elways | Alstom | Elonroad | Honda | Siemens



Battery reach

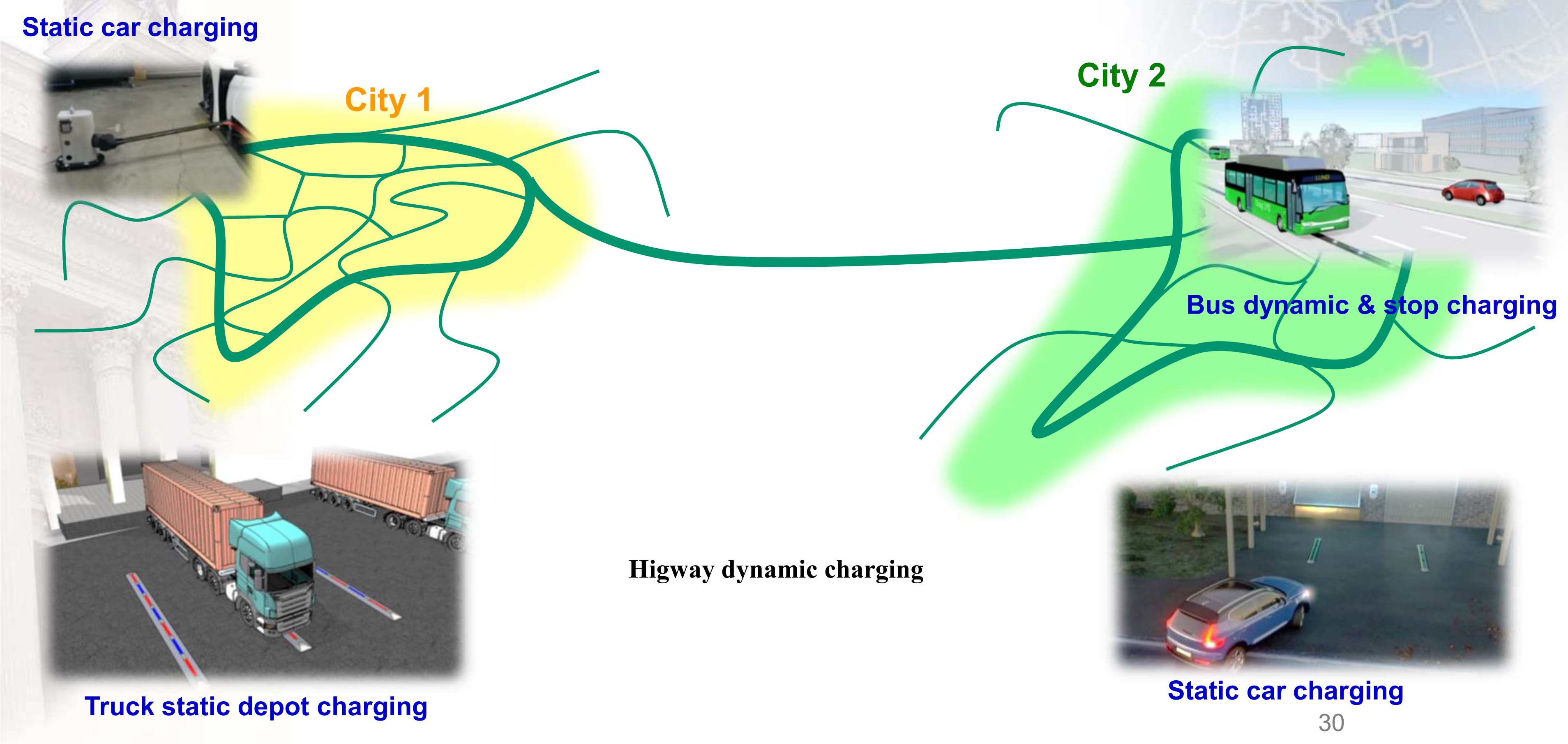




Δ = 61 km Δ = 134 km Δ = 336 km

”Infinite range Extender”

ERS between cities and static charging in cities



Not ERS all the way...

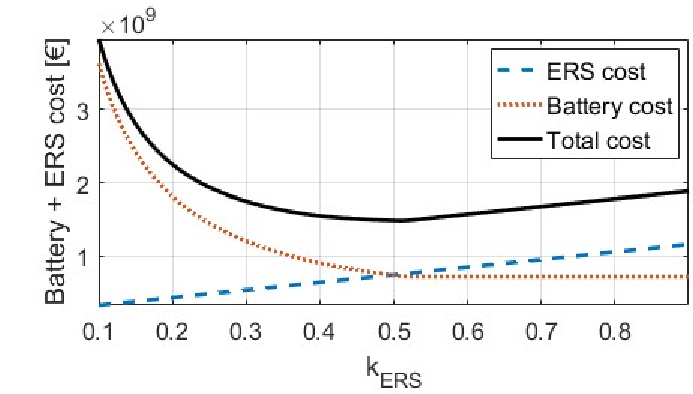
- No ERS

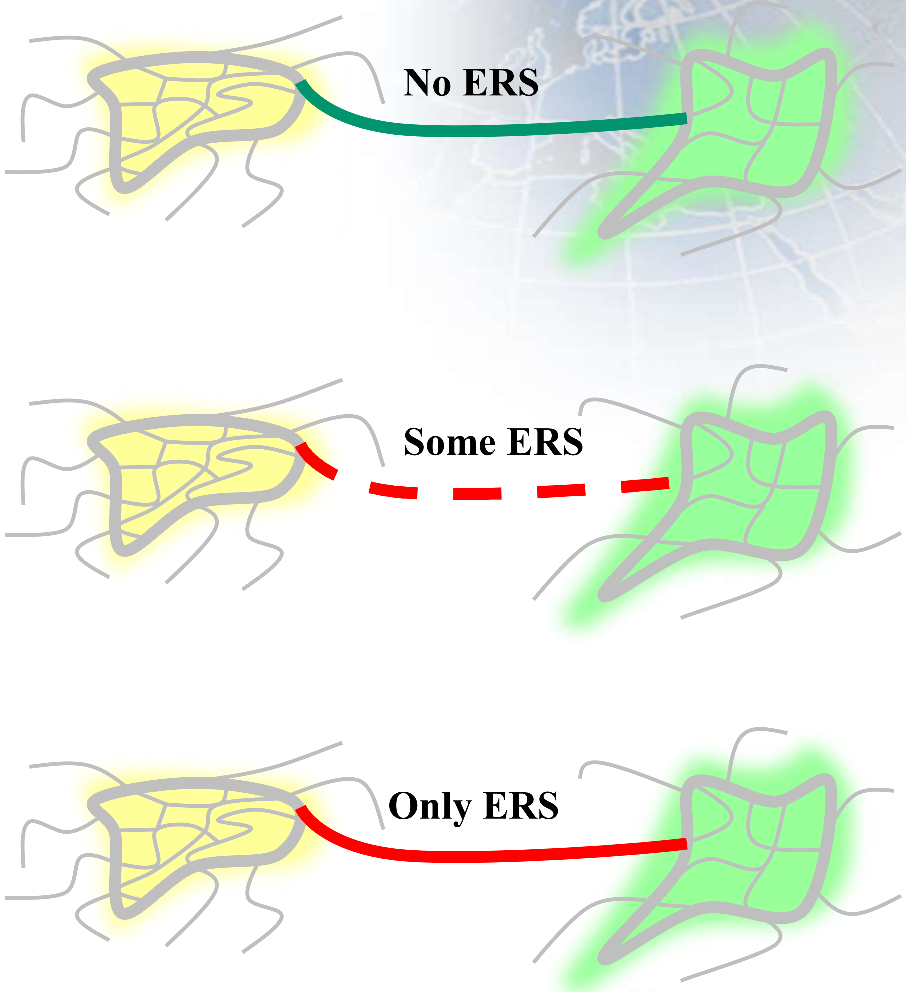
  = No ERS cost, high battery cost
- Some ERS

  = Reduced battery cost, some ERS cost
- Only ERS

  = Low battery cost, high ERS cost

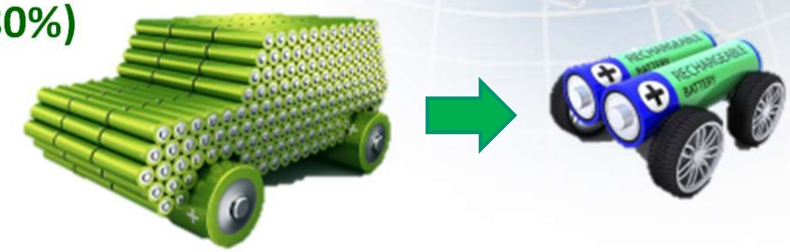
- There is an optimum





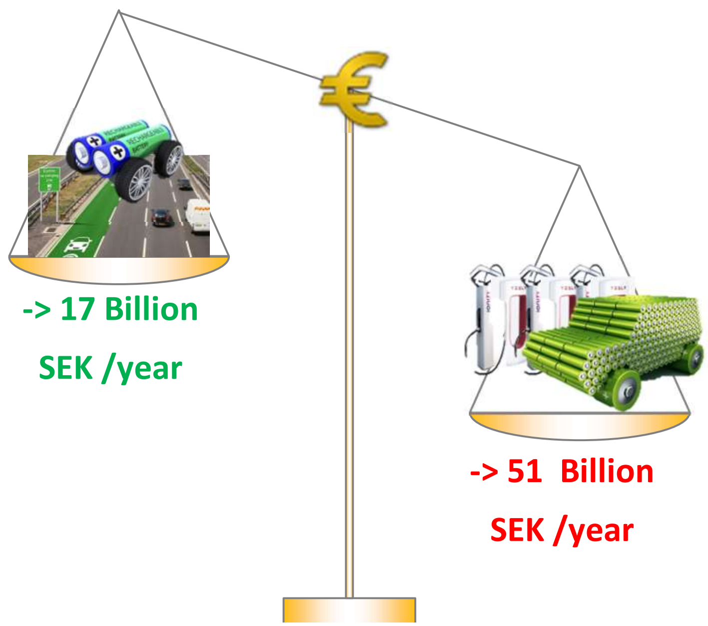
Possibilities and Challenges

- **Possibilities:**
  - **Large reduction of battery need (-50% … -80%)**
    - Cheaper, lighter and more energy efficient vehicles
  - **No need for fast chargers**
    - Only night time + ERS
- **Challenges**
  - Road installation and maintenance
  - Electro magnetic, thermal and mechanical safety
  - Legal and business aspects



A fast cost comparison

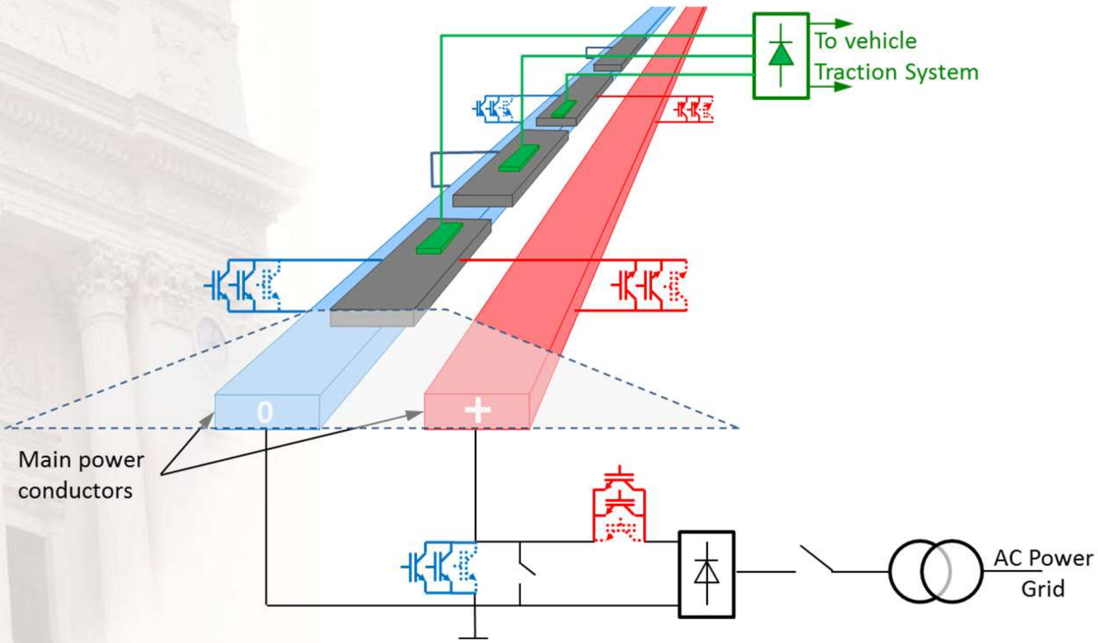
- 5 million **cars** á **15 kWh** batteries á 1000 SEK/kWh @ 10 years lifetime
  -> 7 Billion SEK/year
- 50 000 **Heavy Duty Trucks** á **100 kWh** batteries á 1000 SEK/kWh @ 2 years lifetime
  -> 2 Billion SEK/year
- 15 600 km National and European road á 10 Million SEK/km @ 20 years lifetime
  -> 8 Billion SEK/year



- 5 million **cars á 75 kWh** batteries á 1000 SEK/kWh @ 10 years lifetime
  -> 38 Billion SEK/year
- 50 000 **Heavy Duty Trucks á 500 kWh** batteries á 1000 SEK/kWh @ 2 years lifetime
  -> 12 Billion SEK/year
- 50 000 ”**Super**Chargers” á 150 kW á 6000 SEK/kW @ 25 years lifetime
  -> 1 Billion SEK/year

  500 ”**MEGA**Chargers” á 1000 kW á 6000 SEK/kW @ 25 years lifetime
  -> 0,12 Billion SEK/year

Elonroad


To vehicle
Traction System
0
+
Main power
conductors
AC Power
Grid

Other applications
of
Power Electronics

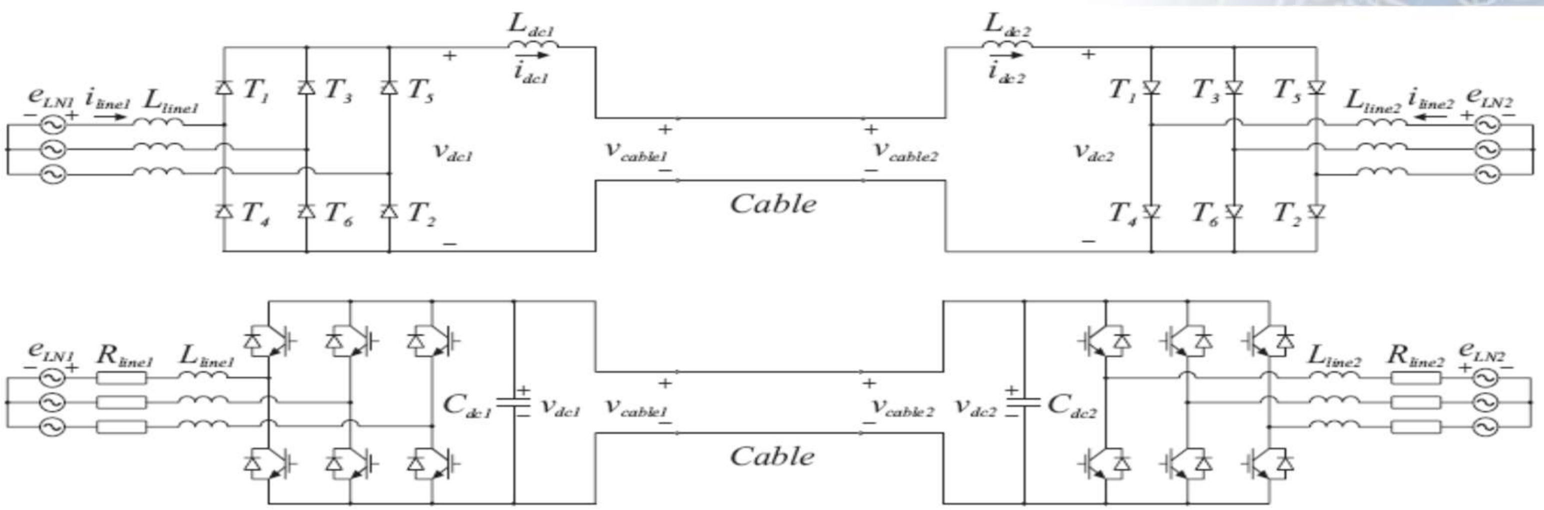
Frequency Conversion

- Japan East / West
- 50/60 Hz
- 600 MW

HVDC

- Japan: Hokkaido to Honshu / 600 MW

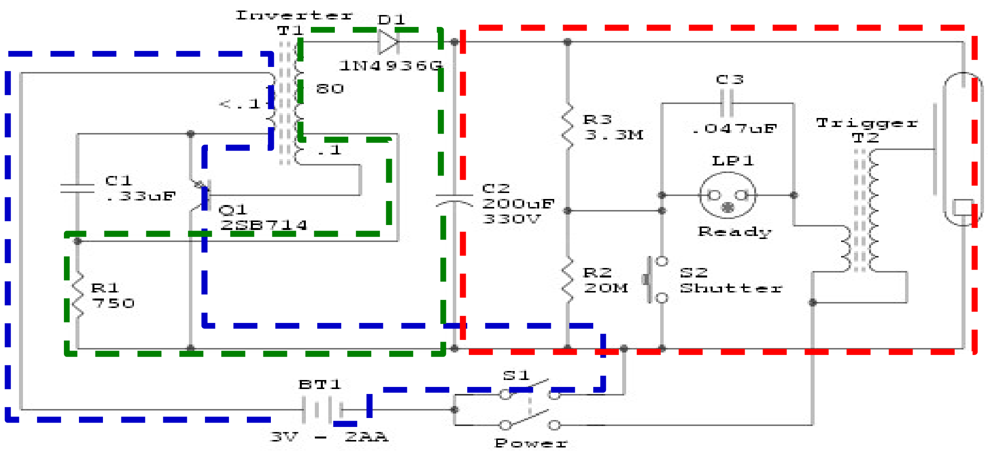
HVDC and Transistor Based HVDC



http://swepollink.svk.se/

http://www.abb.com/

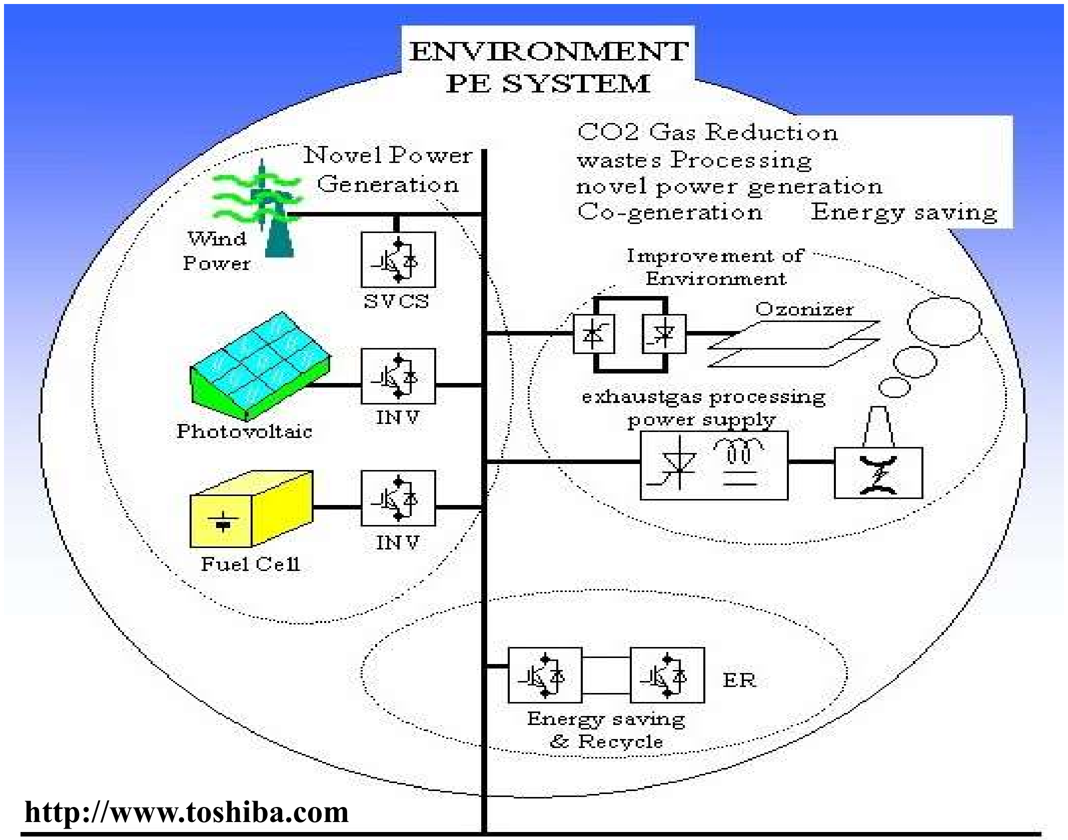
Camera with flash



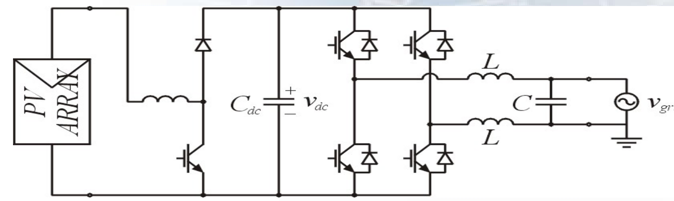
Kodak Ektralite 10 Flash Unit

Audio amplifiers

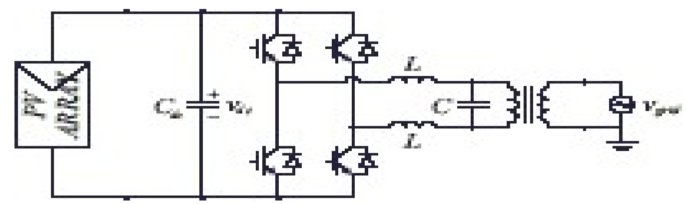
Renewable Energy Systems



Converters Suitable for Solar Cells

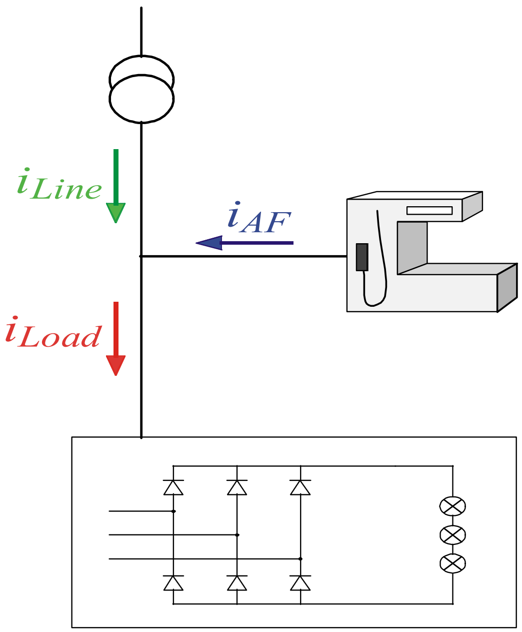


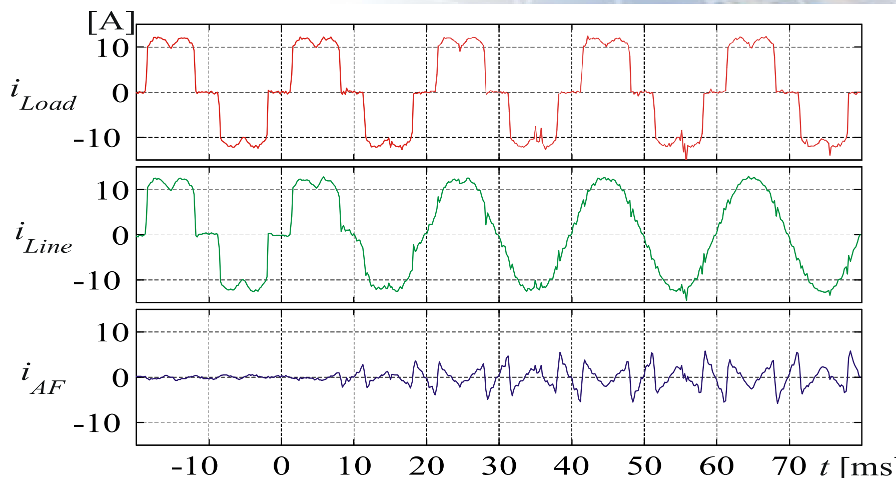
Without transformer

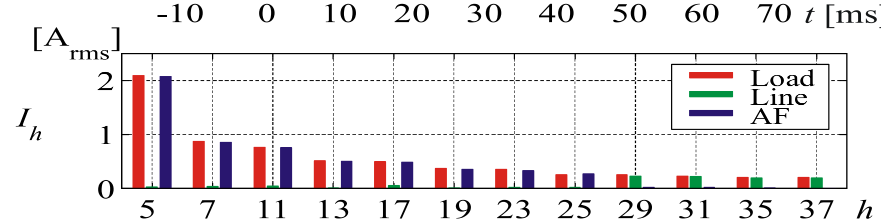


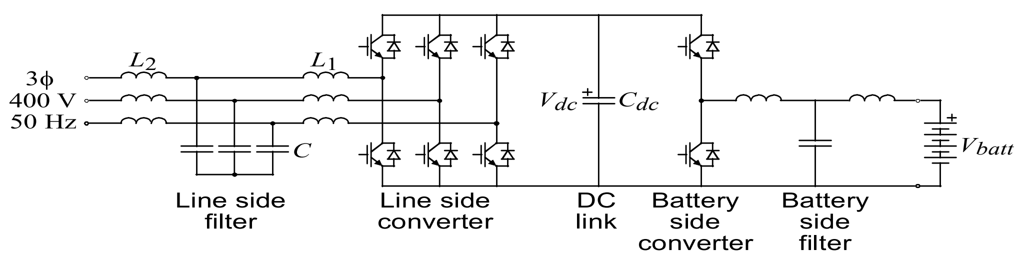
With transformer

Active Filters



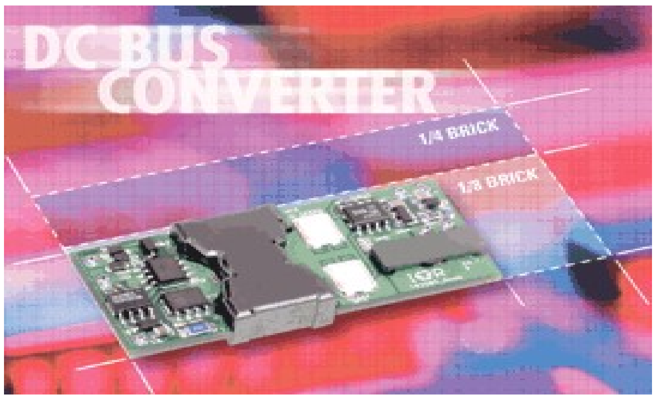


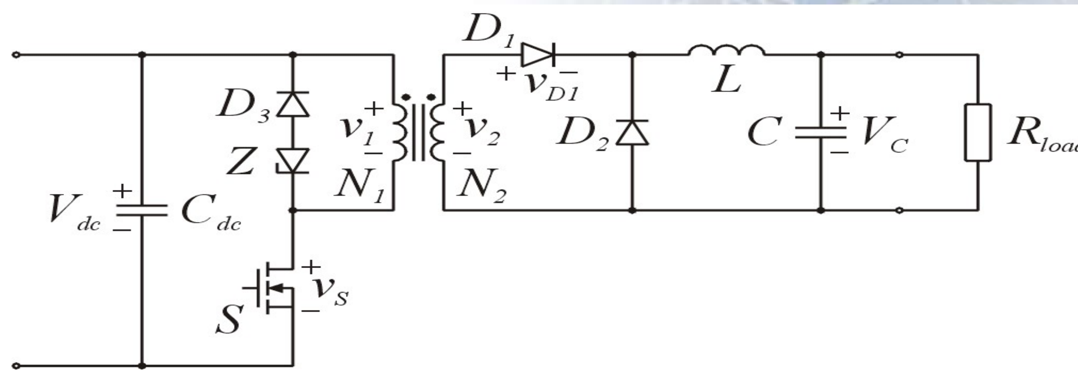


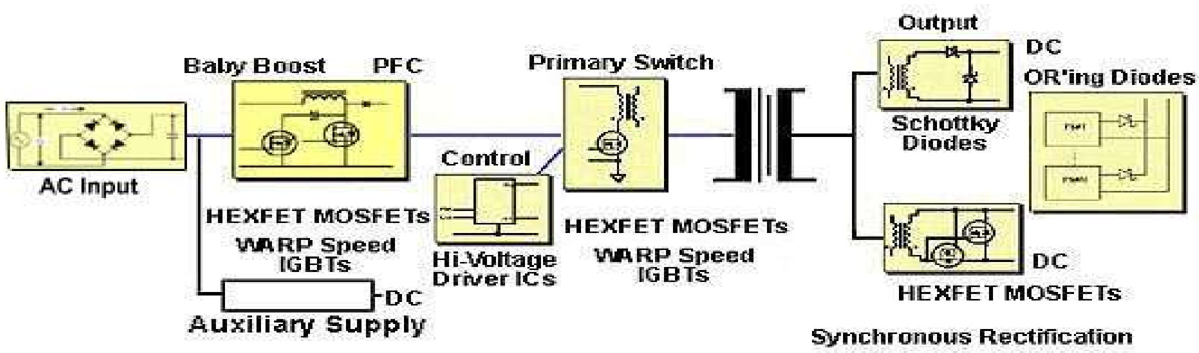


Switch Mode Power Supplies

- Forward Converter







http://www.irf.com

Thank You!

The Course 2021

- Lectures 2 times a week
- 2…3 exercises a week
- 6 labs with home assignments / simulation exercises:
  - The Flyback Converter
  - The H-bridge
  - Speed Control with a DC Machine
  - Control of an Active Power Filter
  - Control of PM Machines
  - Control of Induction Machines

Teaching Plan 2021

Calendar Week	Date	Time	Event Lecture, Exercise, Preparation	Topic	Teacher	Note (deadlines)
3	2021-01-18	15:15-17:00	L	Intro + Semiconductors and bridges	Mats	
	2021-01-19	13:15-15:00	L	Bridges, switch dynamics, snubbers	Mats	
	2021-01-21	13:15-15:00	E	Semiconductors, bridges etc	Mats	
	2021-01-21	15:15-17:00	E	Semiconductors, bridges etc	Mats	
	2021-01-22	10:15-12:00	P	Flyback Simulation preparation (Ltspice)	Akanksha	
4	2021-01-25	13:15-15:00	L	DC/DC conv +1 phase modulation	Mats	
	2021-01-25	15:15-17:00	E	DC/DC conv +1 phase modulation	Mats	
	2021-01-27	10:15-12:00	P	Flyback Lab preparation	Akanksha	Flyback simulation report
	2021-01-27	13:15-15:00	L	H-bridge + 2 phase modulation (+ thermal)	Mats	
	2021-01-29	10:15-12:00	P	H-bridge Simulation preparation (+ support on Flyback Lab)	Akanksha	
5	2021-02-01	13:15-15:00	L	Position and Speed control	Mats	
	2021-02-01	15:15-17:01	E	Position and Speed control	Mats	
	2021-02-03	10:15-12:00	L	DC Current Control	Mats	Flyback lab report
	2021-02-03	13:15-15:00	E	DC Current Control	Mats	
	2021-02-05	08:15-10:00	P	H-bridge Lab preparation + thermal	Akanksha	H-bridge simulation report
6	2021-02-08	13:15-15:00	L	Torque generation	Mats	
	2021-02-08	15:15-17:01	E	Torque generation	Mats	
	2021-02-10	10:15-12:00	L	DC Machine Theory and Control	Mats	
	2021-02-10	13:15-15:00	E	DC Machine Theory and Control	Mats	
	2021-02-12	08:15-10:00	P	DC-machine Simulation preparation	Samuel	H-bridge lab report
7	2021-02-15	13:15-15:00	L	AC-power + 3 phase modulation	Mats	
	2021-02-15	15:15-17:01	E	AC-power + 3 phase modulation	Mats	
	2021-02-17	10:15-12:00	P	DC-machine Lab preparation	Samuel	DC-machine simulation report
	2021-02-17	13:15-15:00	L	AC Current Control	Mats	
	2021-02-19	08:15-10:00	E	AC Current Control	Mats	
8	2021-02-22	13:15-15:00	L	Static VAr compensation	Mats	
	2021-02-22	15:15-17:01	E	Static VAr compensation	Mats	
	2021-02-24	10:15-12:00	L	Active Filters, design & control	Mats	
	2021-02-24	13:15-15:00	E	Active Filters, design & control	Mats	
	2021-02-26	08:15-10:00	L	Guest lecture Active Power Filters	Mats	DC-machine lab report
9	2021-03-01	13:15-15:00	L	Passive components (Ind&Cap)	Mats	
	2021-03-01	15:15-17:01	E	Passive components (Ind&Cap)	Mats	
	2021-03-03	10:15-12:00	L	Inductor design	Mats	
	2021-03-03	13:15-15:00	E	Inductor design	Mats	
	2021-03-05	08:15-10:00	-	Spare	Mats	
10	No teaching					
11	Exam period					

Calendar Week	Date	Time	Event Lecture, Exercise, Preparation	Topic	Teacher	Note
12	2021-03-23	13:15-15:00	L	Synchronous Machine and PMSM	Mats	
	2021-03-23	15:15-17:01	E	Synchronous Machine and PMSM	Mats	
	2021-03-25	13:15-15:00	P	AF simulation preparation	Max	
	2021-03-25	15:15-17:01	L	Control of PMSM, incl FW	Mats	
13	2021-03-30	13:15-15:00	E	Control of PMSM, incl FW	Mats	
	2021-03-30	15:15-17:01	L	Semiconductor I	Mats	
	2021-03-31	13:15-15:00	E	Semiconductor I	Mats	
	2021-03-31	15:15-17:01	P	AF lab preparation	Max	AF simulation report
14	Exam period					
15	Exam period					
16	2021-04-20	13:15-15:00	L	Semiconductor II	Mats	
	2021-04-20	15:15-17:01	E	Semiconductor II	Mats	
	2021-04-22	13:15-15:00	L	Thermal modelling (losses)	Mats	
	2021-04-22	15:15-17:01	P	PMSM simulation preparation	Samuel	AF lab report
17	2021-04-27	13:15-15:00	E	Thermal modelling (Losses)	Mats	
	2021-04-27	15:15-17:01	P	PMSM lab preparation	Samuel	
18	2021-04-04	13:15-15:00	L	Thermal modelling (Cooling)	Mats	
	2021-04-04	15:15-17:01	E	Thermal modelling (Cooling)	Mats	PMSM simulation report
	2021-04-06	13:15-15:00	L	IM Modelling and Control	Mats	
	2021-04-06	15:15-17:01	E	IM Modelling and Control	Mats	
19	2021-05-11	13:15-15:00	P	IM simulation preparation	Samuel	
	2021-05-11	15:15-17:01	L	EMC I	Mats	PMSM lab report
20	2021-05-18	13:15-15:00	E	EMC I	Mats	
	2021-05-18	15:15-17:01	P	IM lab preparation	Samuel	
	2021-05-20	13:15-15:00	L	Guest lecture	TBD	IM simulation report
	2021-05-20	15:15-17:01	-	Spare	-	
21	2021-05-25	13:15-15:01	L	Resonant and Multilevel converters	Mats	
	2021-05-25	15:15-17:02	E	Summary and recap before exam	Mats	
	2021-05-27	13:15-15:01	P	Exam preparations	Mats	IM lab report
	2021-05-27	15:15-17:02	P	Exam preparations	Mats	
22	2020-06-03	15:00-19:00	Written Exam			

Home Assignments

- Content as similar as possible to the labs
- Prepares you for the lab
- Diagnostic tests can be used before the labs – You must pass!

Covid-19 limitations

- To start with, we will do everything via Internet
  - Lectures, Exercises, Labs
- IF, or WHEN, it is possible, we will return to F2F teaching

- The Labs are the trickiest part !
  - Based on filmed lab moments that you analyse

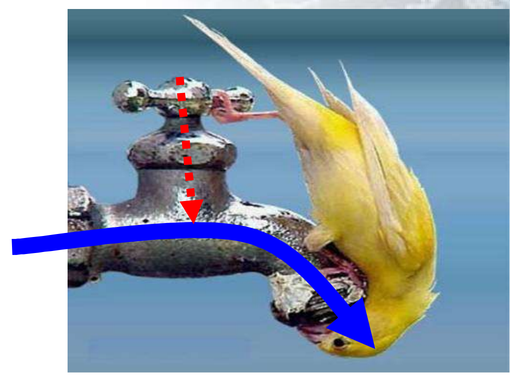
Teachers

- Lectures:
  - Mats Alakūla, professor
- Course assistance, simulation exercises and Labs:
  - Akanksha Upadthey, PhD student
  - Max Collins, PhD student
  - Samuel Estenlund, PhD Student

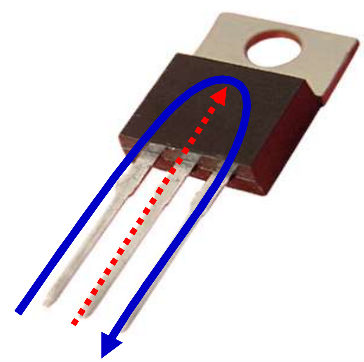
Components

Components 1 : The transistor

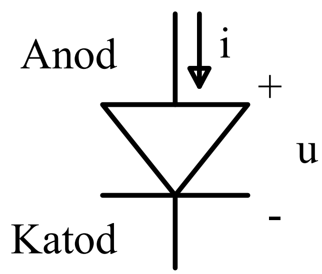
- Works like a valve for electric current
- Compare to a water tap
  - Control a big flow with a small movement
  - Flow x Pressure drop = Power
  - Heats the water (a little)

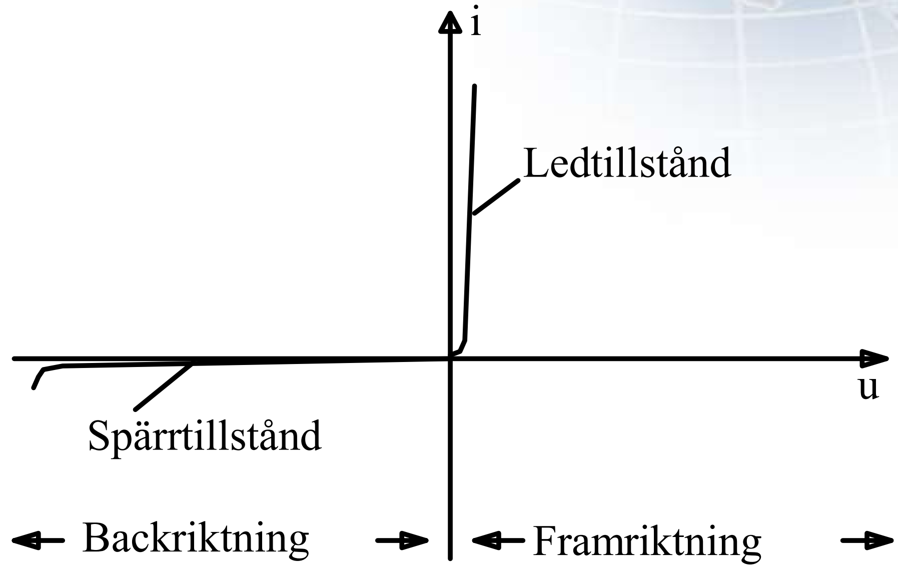


- A transistor
  - Controls a big current with a small current
  - The voltage drop across the transistor x the current = Power
  - Heats the transistor (a lot)

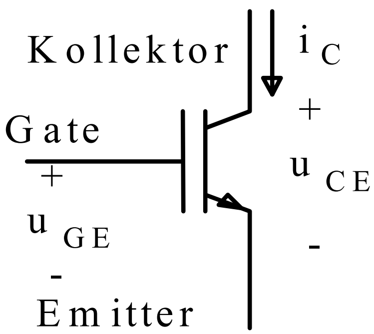


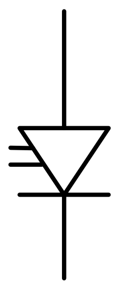
Components 2: The Diode



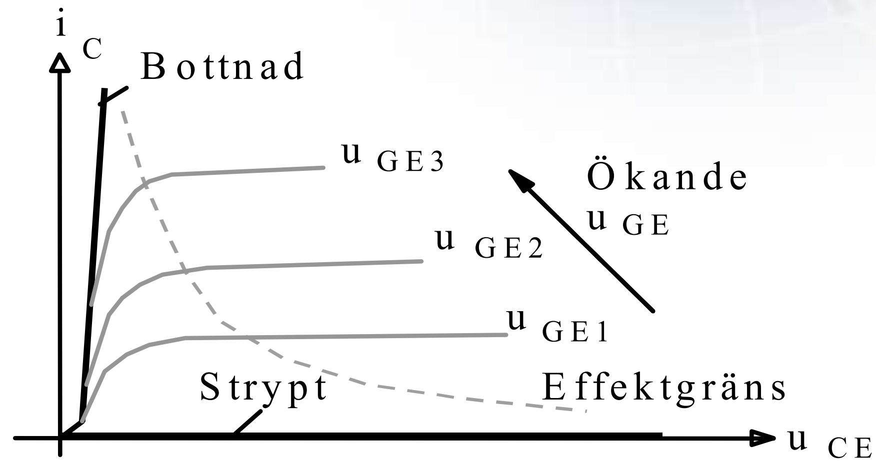


Components 3: The IGBT – transistor





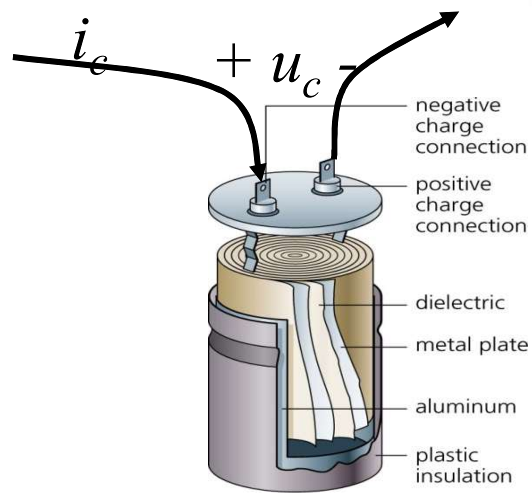
Symbol



Components 4: The Capacitor

- Stores electric current with increasing voltage like a hydrophore stores a fluid or gas with increasing pressure

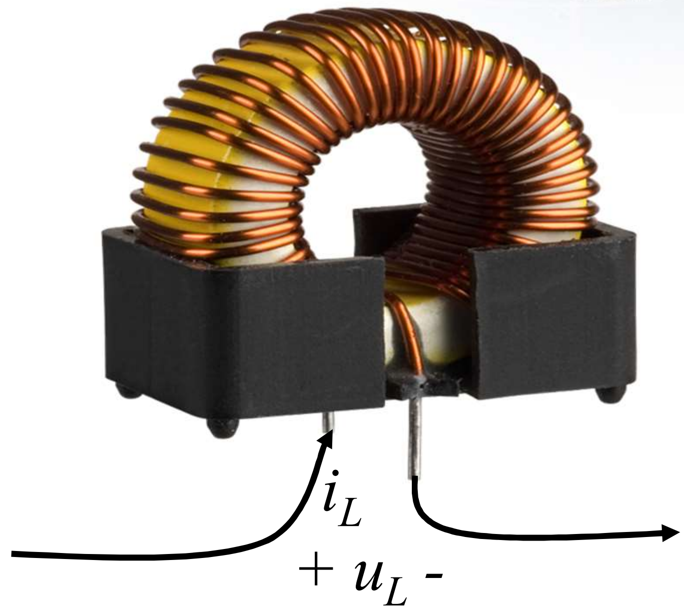
$$\frac{du_c}{dt} = \frac{1}{C} \cdot i$$



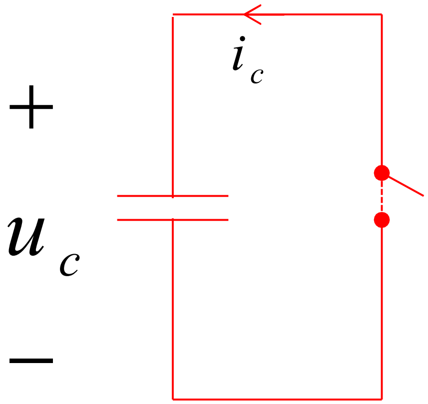
Components 5: The Inductor

- Stores currrent into magnetic energy like a flywheel stores torque into speed and mechanical energy

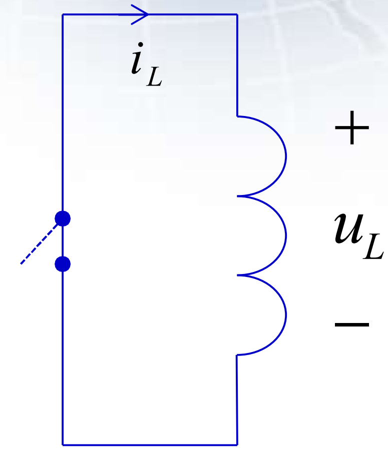
$$\frac{di_L}{dt} = \frac{1}{L} \cdot u_L$$



Never break an inductive current
Never short a capacitive voltage



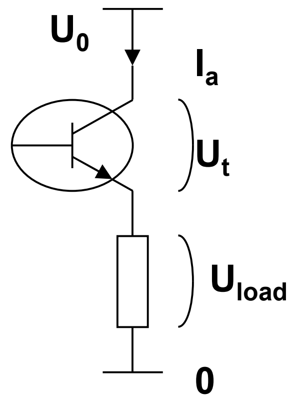
$$\frac{du_c}{dt} = \frac{1}{C} \cdot i_c$$



$$\frac{di_L}{dt} = \frac{1}{L} \cdot u_L$$

Basic Switching

Fundamentals of Switching



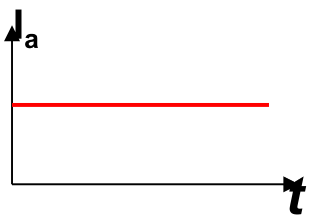
Analogue

$P_{load} = U_{load} * I_a$

$P_{loss} = U_t * I_a$

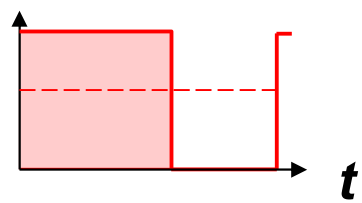
$U_t \approx U_{load}$

$P_{loss} \approx P_{load}$



Switched

On	Off
$U_t \approx 0$	$U_t = U_0$
$I_a = I_{load}$	$I_s = 0$
$P_{loss} = 0$	$P_{loss} = 0$

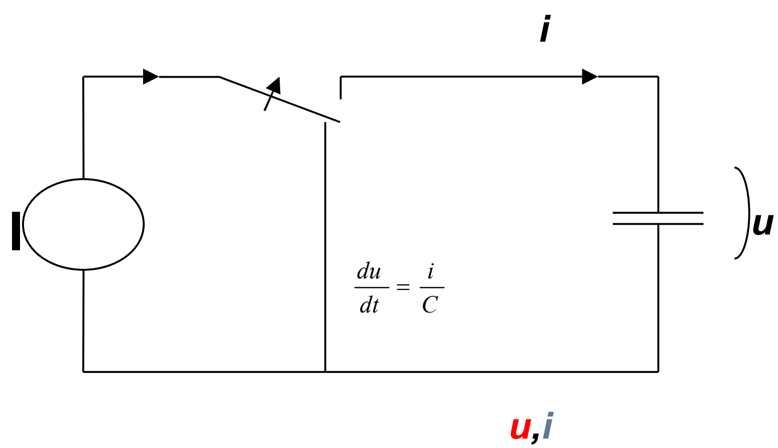


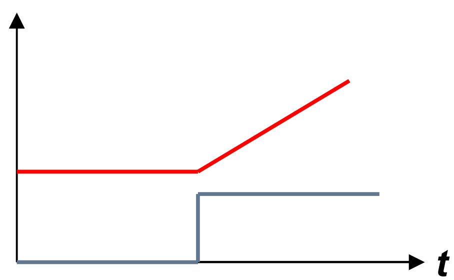
Never break an inductive current
Never short a capacitive voltage

BASIC

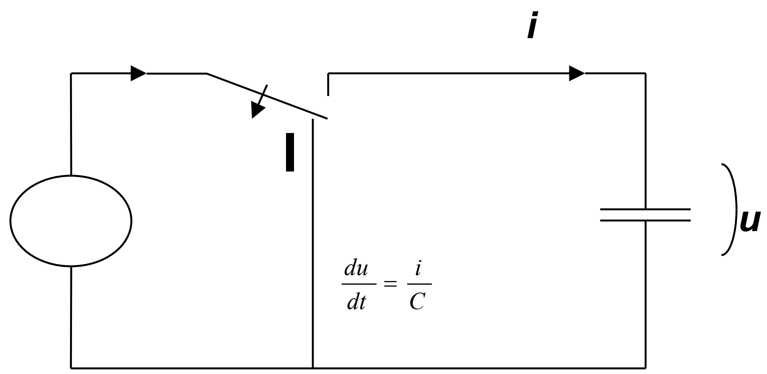
turn on current step, capacitive load.

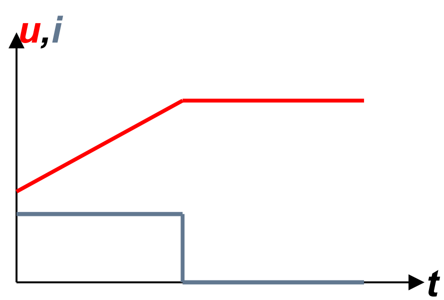
No problem





BASIC
turn off current step, capacitive load.
No problem



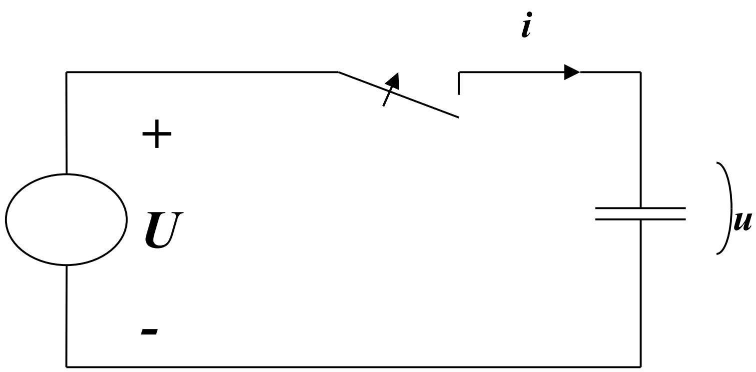


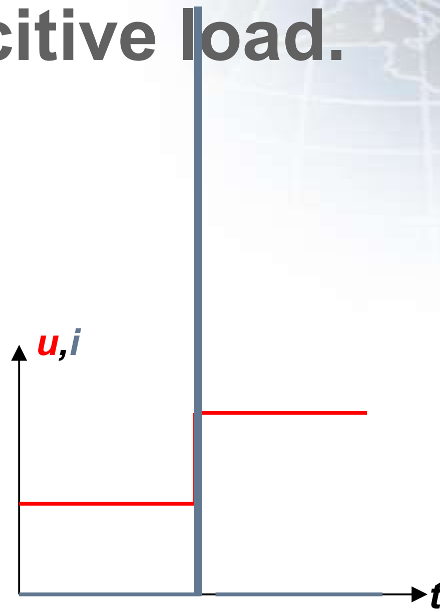
BASIC

turn on voltage step with capacitive load.

Problem!

$$i = C \cdot \frac{du}{dt}$$

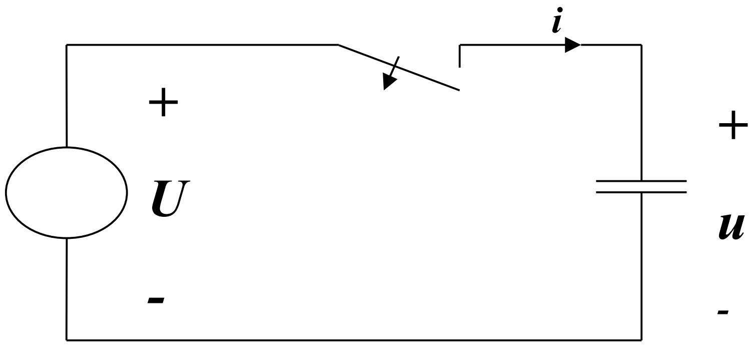


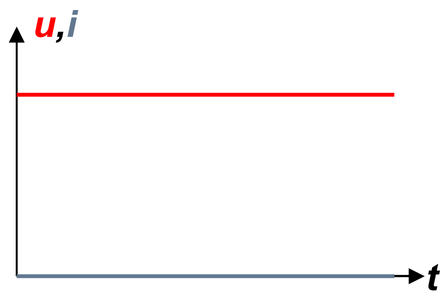


$$U \neq u$$

BASIC
turn off voltage step, capacitive load.
No problem

$$i = C \cdot \frac{du}{dt}$$

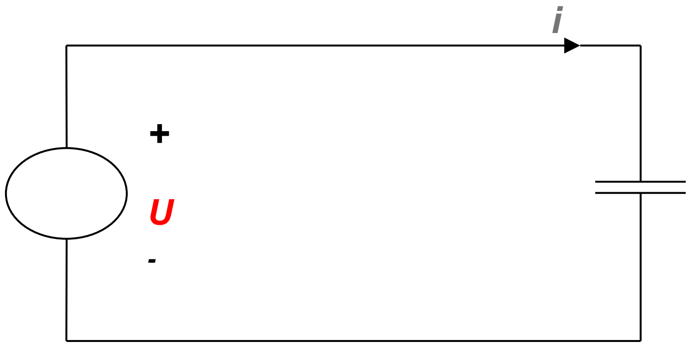


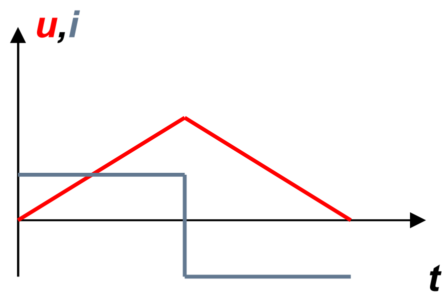


$$U = u$$

BASIC
voltage ramp, capacitive load.
No problem

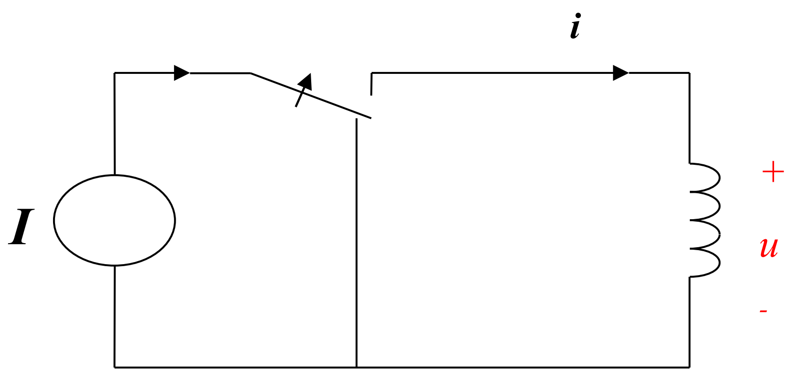
$$i = C \cdot \frac{du}{dt}$$





BASIC
turn on current step, inductive load.
Problem

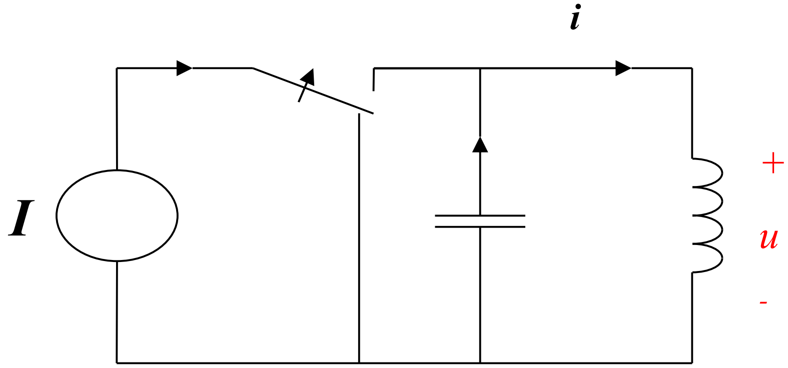
$$u = L \cdot \frac{di}{dt}$$



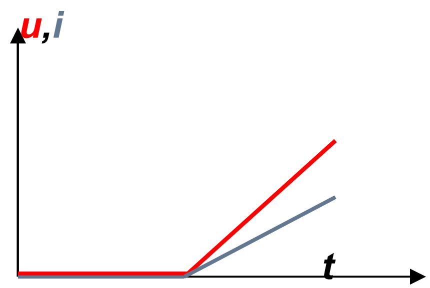
$$I > i$$

BASIC
turn on current step, inductive load. Counter measure with capacitor

$$u = L \cdot \frac{di}{dt}$$



$I > i$

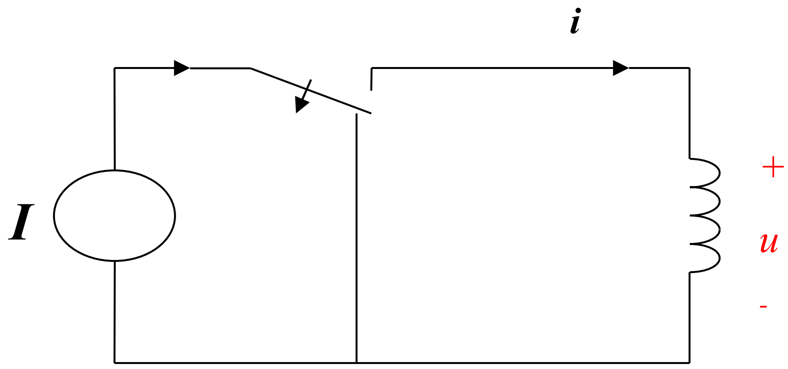


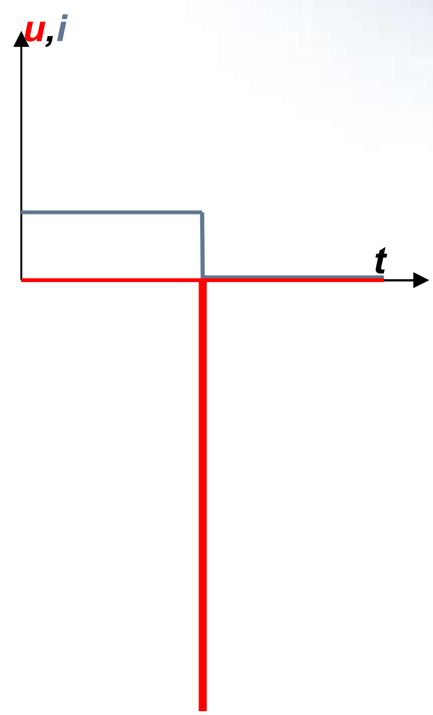
BASIC

turn off current step, inductive load.

Problem

$$u = L \cdot \frac{di}{dt}$$





BASIC
turn off current step, inductive load. Counter measure with freewheeling diode