EE 459/559: Control and Applications of Power Electronics

Topic 1: Course Information and Overview

Dr. Luis Herrera
Dept. of Electrical Engineering
University at Buffalo

Spring 2023

University at Buffalo

Course Information

- **Instructor:** Luis Herrera
- **Contact Info:** 224 Davis Hall, lcherrer@buffalo.edu , 716 645-1150
- **Class Times:** Tu/Th 12:30 pm – 1:50 pm
- **Class Location:** Cooke 127A
- **Office Hours*:** TBA (will send email when decided)
- **TAs/SAs:** Lalit Marepalli
- **Website:** UBLearns blackboard (will upload blank notes prior to class), **please use them to follow along**

2

Course Information

- **Course Information:**
  - ✓ This course will discuss advanced topics in power electronics including:
  - ✓ Advanced converter topologies
  - ✓ modeling and control of power converters in various applications, including utility, renewable energy integration, and microgrids.
  - ✓ Prepare students for research activity, such as literature review, advanced computer simulation, and technical report writing.

Grading Policy

- **Homework (35%)**
  - The homework can be considered small projects (3-5 total)
  - Most will use Matlab Simulink/Simpower Systems
  - Project report may be required: formal in MSWord or Latex (extra credit will be given for Latex use)

    overleaf.com

- **Quizzes (15%):** approximately 7-10, 20 mins quizzes (either at beginning or end of class)

- **Midterm (25%):** will be in person

- **Final Project (25%)**

Course Materials

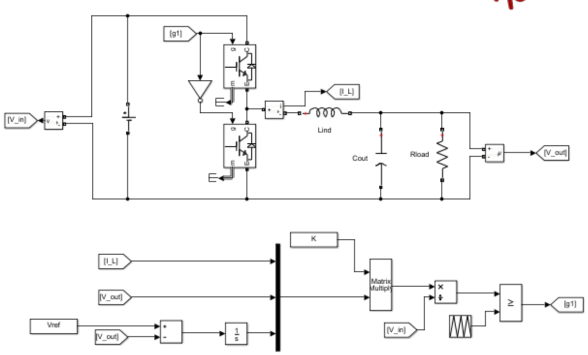
Davis 240

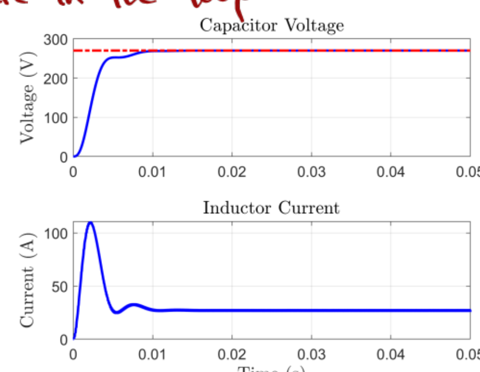
- **Textbook (optional):**
  - R. Erickson and D. Maksimovic, Fundamentals of Power Electronics, 2nd Ed., Springer, 2001 → frequency domain transfer functions
  - N. Mohan, T. Undeland, W. Robbins, Power Electronics: Converters, Applications and Design, 3rd ed., Wiley, 2003 → State Space techniques.
- **Software**
  - Matlab Simulink with Simpower Systems toolbox (free through UB) Furnas 214*
  - Typhoon HIL (free, instructions will be provided) ↳ Hardware in the loop.

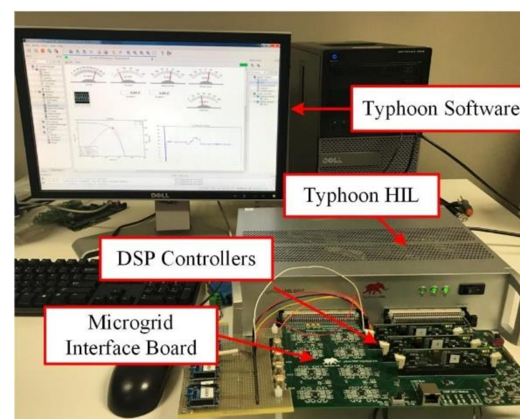
Lucas Nuelle Stand

Typhoon HIL

Typhoon Real Time Simulator







https://research.ece.ncsu.edu/bhattacharya/lab-facilities/typhoon/

Tentative Topics

- **Introduction**
  - Overview of power electronics applications
  - Review of fundamental concepts of power electronics
- **DC/DC converter modeling and control**
  - State space modeling/control
  - Power electronics averaging - State Space Averaging.
  - Feedback control, state feedback, and integrator control
  - Voltage and current controller design (cascaded control)
- **DC/AC inverter modeling and control**
  - Review of three phase inverter and PWM
  - Modeling of DC/AC inverter
  - Close loop controller design

  HVDC, Renewable energy, Motor Drives.
- **Advanced power electronics**
  - Modular Multilevel Converters (MMCs)
  - Multilevel converters
- **Microgrid design and operation**
  - AC microgrids and control strategies
  - DC microgrids and control strategies
  - Optimal operation of energy sources

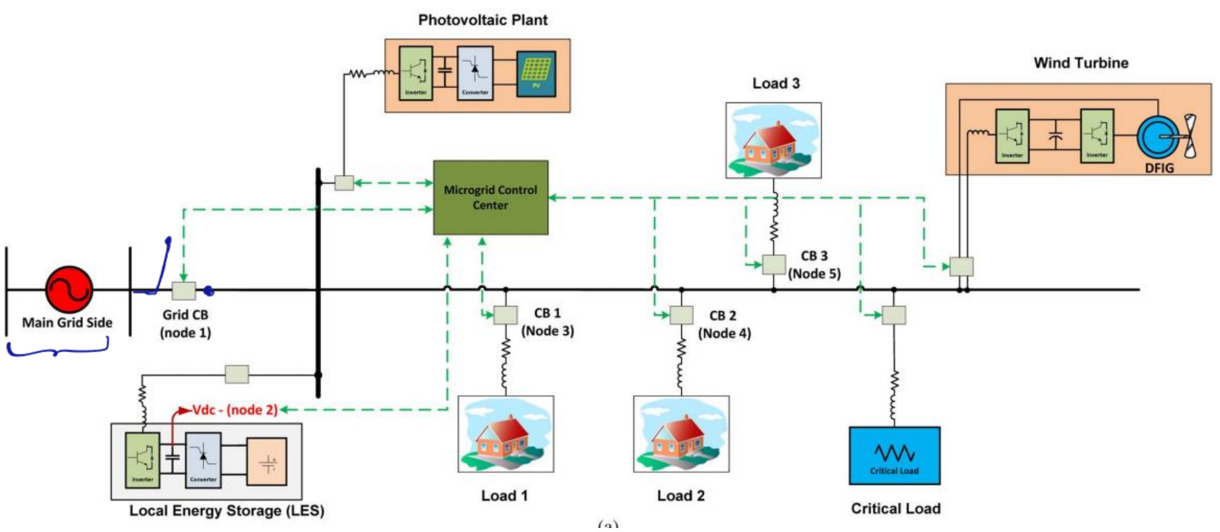
Today

- We will look at an overview of the topics we will cover in class
- Different applications will be discussed
- Start review of power electronics (dc/dc, ac/dc, and dc/ac)

7

Power Electronics

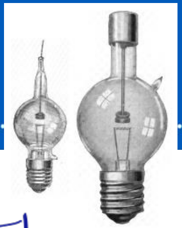
- Power electronics is a technical field to study, analyze, construct, and maintain electronic circuits capable of controlling electric energy flow
- Power systems advancements have been enabled by power electronics
- Static Applications:
  - Energy storage, renewable integration
  - Microgrids
  - Power supplies
- Dynamic/mobile applications
  - Industrial motor drives
  - Electric and hybrid vehicles



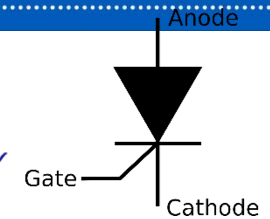
787 - Dreamliner.
DC Microgrids.

History

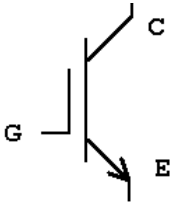
- Year 1928:
  Development of controlled rectifier with gas and vapor filled tubes



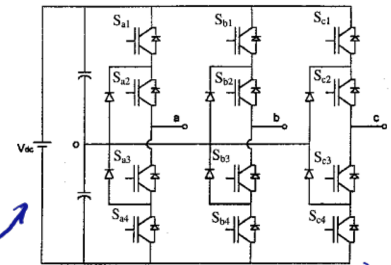
Thyristor



- Year 1957:
  First introduction of semiconductor based thyristor

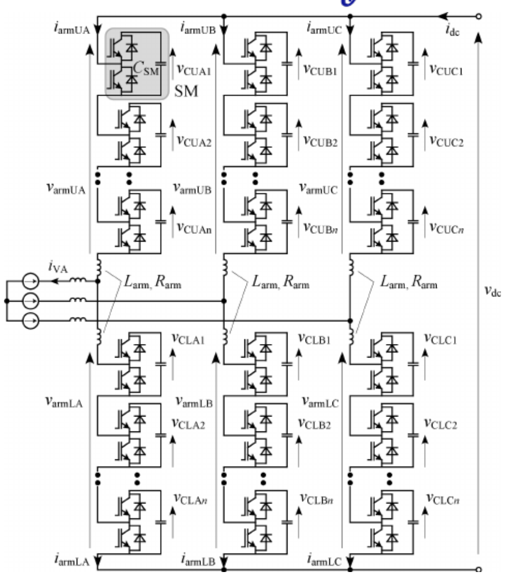


- Years 1959-1970s:
  MOSFETs invented at Bell Labs and IGBT in Mitsubishi, practical IGBTs were developed by J. Baliga (GE) around 1970



- Year 1981:
  Nabae introduced the first multilevel inverter: three level diode clamped inverter

- Since then:
  Three major types of multilevel converters and many other circuit topology and associated pulse width modulation and control strategies are introduced.



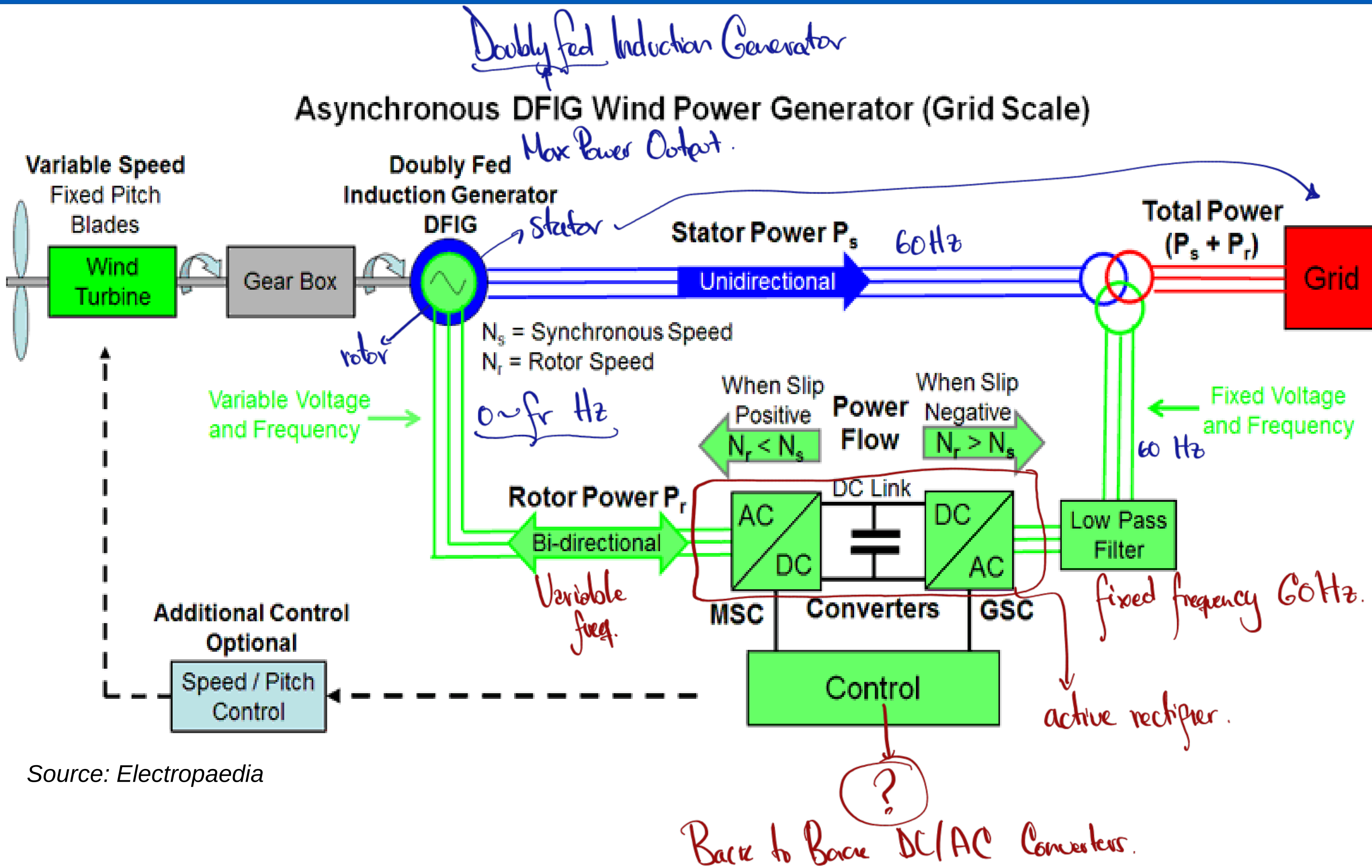
MMC

Power Sources Manufacturers Association (PSMA): Report on Future Trend on Power Electronics

Application Trends	Technology Trends	2015-2017 Trend tables
• Automotive • Communications • Computing • Consumer • Industrial • Lighting • Medical • Military	• DC distribution • Digital power • Nanotechnology • Power supply on chip • Wireless power transfer	• AC/DC front end • AC/DC external • Isolated DC/DC • Non-isolated DC/DC • Non-isolated DC/DC power supply in a package (PSiP)

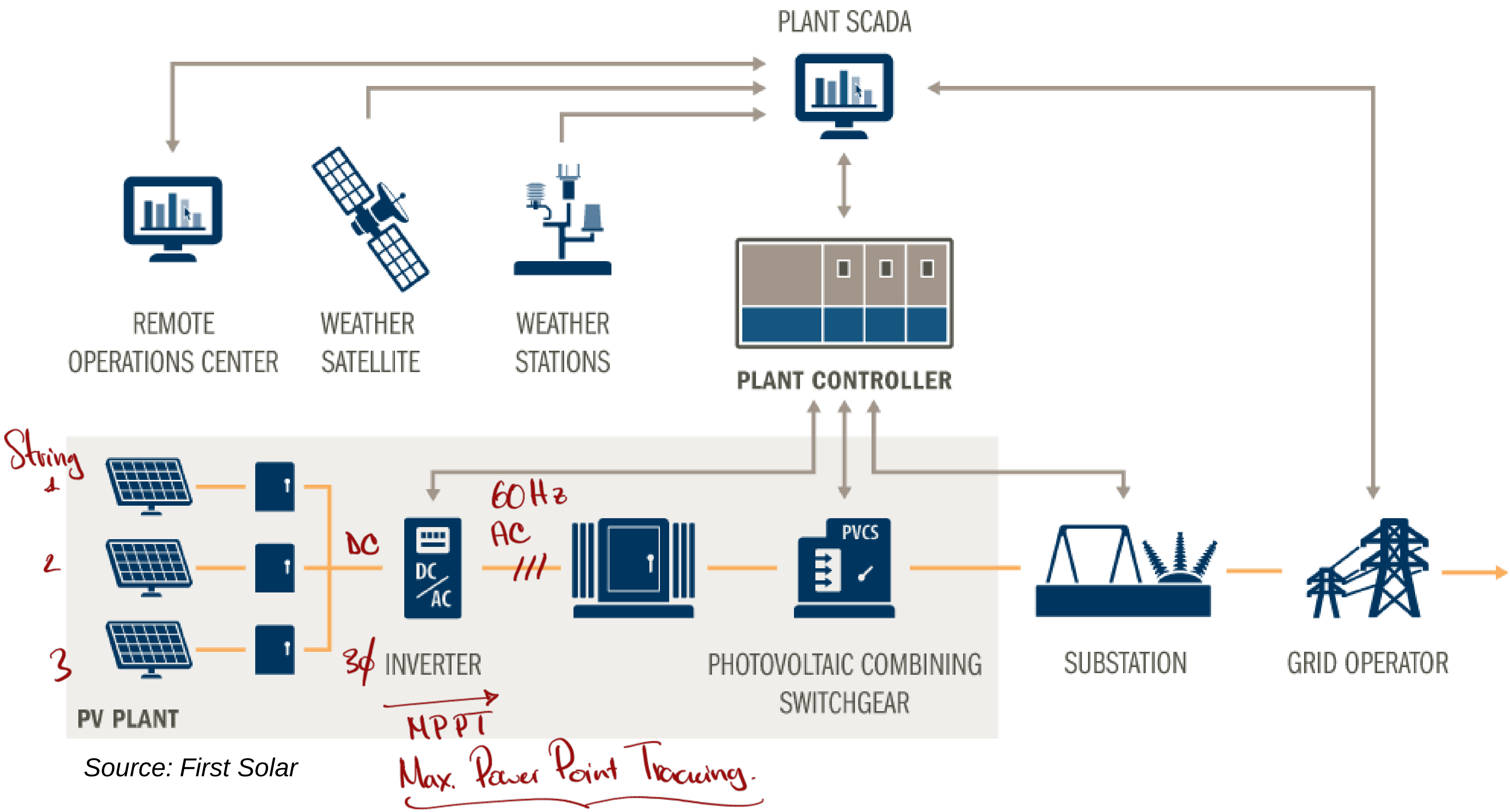
Smaller, more efficient.

Renewable Integration Examples: Wind



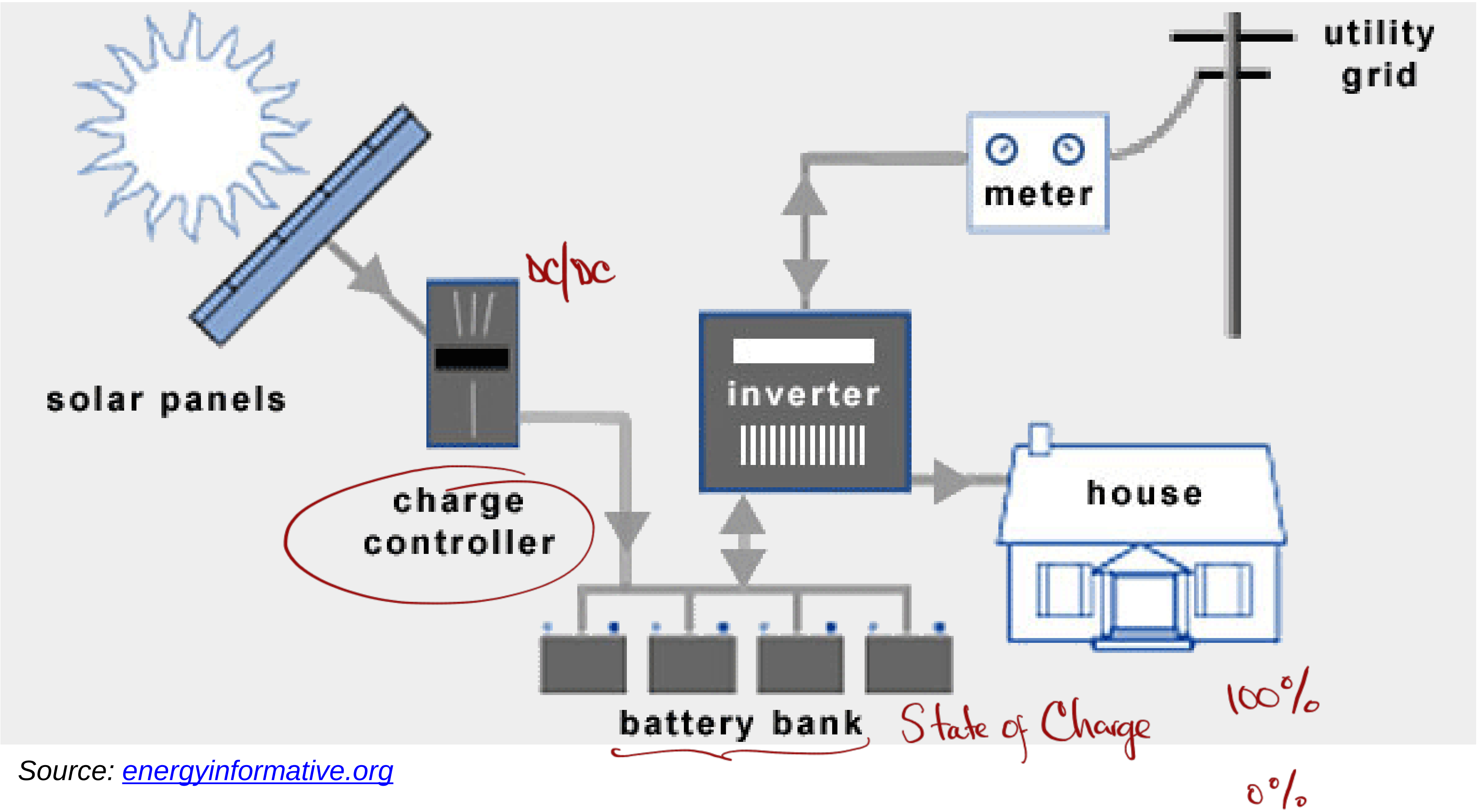
Source: Electropaedia

Grid Scale PV Power Integration



Source: First Solar

Residential PV Power Integration



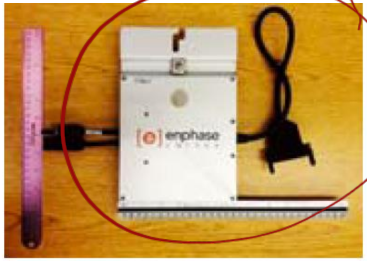
Source: energyinformative.org

Roof top solar panel
Tesla solar roof

PV Integration

Microinverter: a dc/ac inverter that connects a single PV panel to the power grid

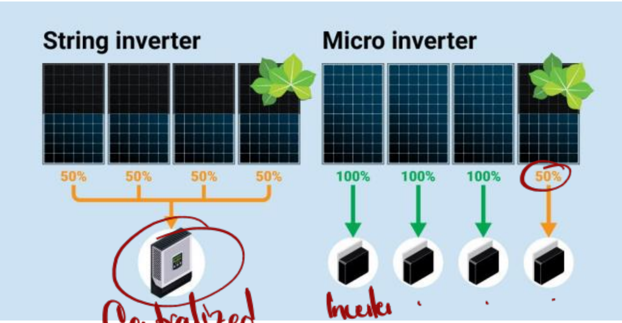
Summary of Micro-inverters from Four Leading Manufacturers		
Specifications		**Models**
The Maximum efficiency	96%	Enphase M215(208/240VAC)
The minimum size (cm^3)	718.7366 27	Enphase M215(208/240VAC)
The highest power density (W/cm^3) (Based on Nom.Output power)	0.216968 011	Enphase M215(208/240VAC)
The minimum weight	3.5 lbs	Enphase M215(208/240VAC)
The Maximum power rating	460W	Direct Grid DGM-460
The Maximum Peak Power Tracking Voltage	DGA Series	Direct Grid



Power density (kW/Area)

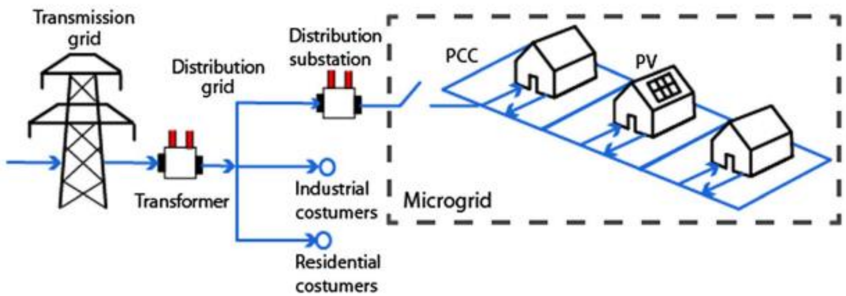
Enphase M215

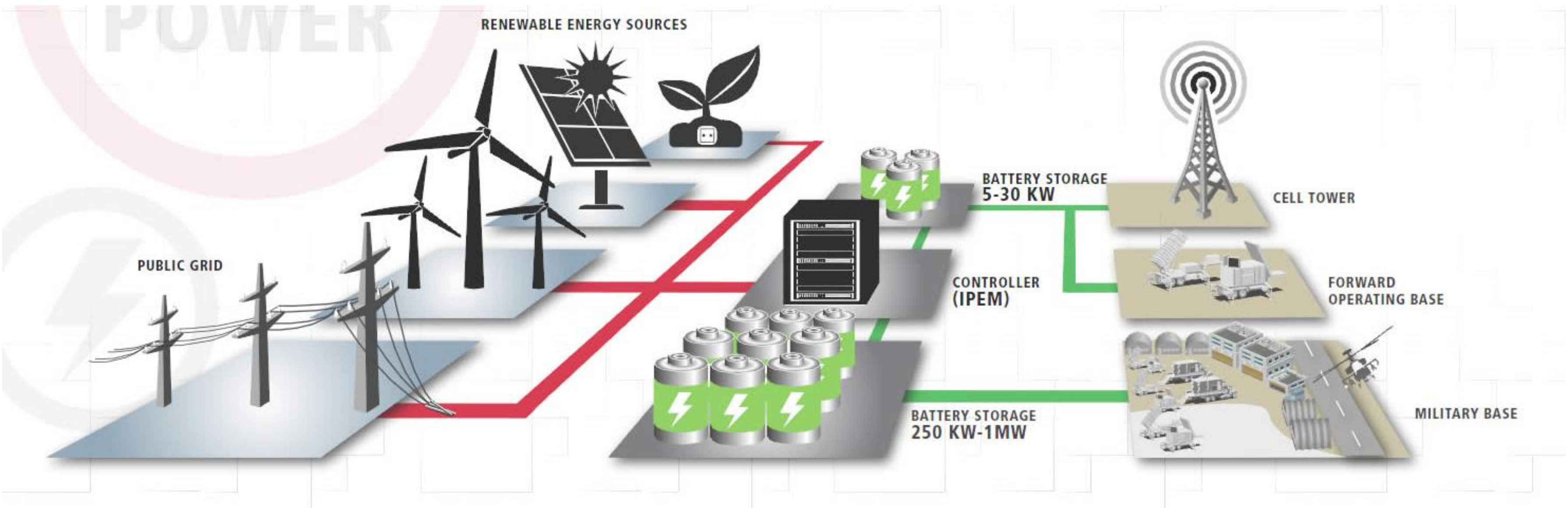
Solar Bridge Panteon Microinverter



Microgrids

- **What is a microgrid?**
  A microgrid is a **local** energy grid with control capability, which means it can disconnect from the traditional grid and operate autonomously. (energy.gov)



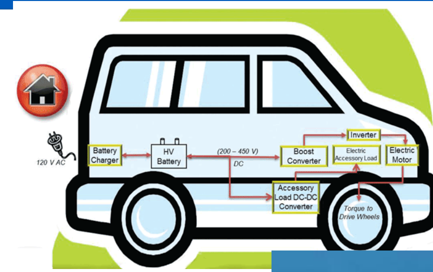


Source: [Raytheon]

Raytheon
Customer Success Is Our Mission

DC Microgrids

- **Electric Vehicles (EV)**
  - Power electronics, electric motors, electronic loads
  - DC bus voltage: 200-800 Vdc



http://powerelectronics.…
electronics-systems/inve…

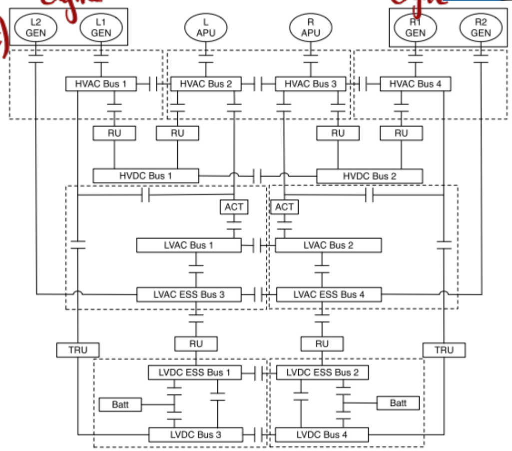
- **(More) Electric Aircraft**
  - Increased power demand (up to MW), complexity
  - Weight, size, constraints
  - DC bus voltage: 270 Vdc, +/- 270 Vdc

Bipolar DC

…www.dvidshub.net/image/935698/aerial…
…ng-f-35-lightning-ii-joint-strike-fighters-…
…b-fla#.UZyEMrVU8QY

787 Boeing.

(540 Vdc)



R. Michalko. "Electrical starting, generation, conversion and distribution system architec… vehicle." U.S. Patent No. 7,439,…

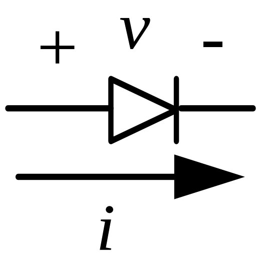
- **Electric Ships**
  - High power, complex networks
  - Variety of energy sources
  - DC bus voltage: ~1000 Vdc

- **Others:** utility, spacecraft, mobile networks (army), HVDC/MTDC, etc.

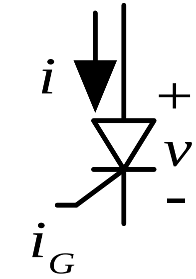
https://defense-update.com/20160522_zumwalt-4.html

Power Electronics Switching Devices

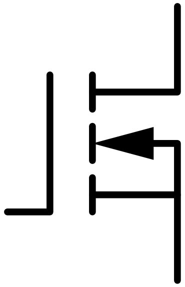
- **Semiconductor switches**
  - Diodes
  - MOSFET
  - IGBTs
  - Thyristors
- **Passive components**
  - Inductor
  - Capacitor
  - Transformer
  - Resistor
- **Peripheral components**
  - Control circuit
  - Gate drive
  - Snubber circuit
  - Protection



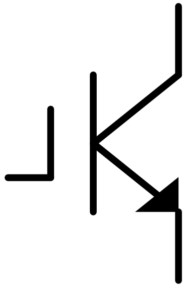
Diode



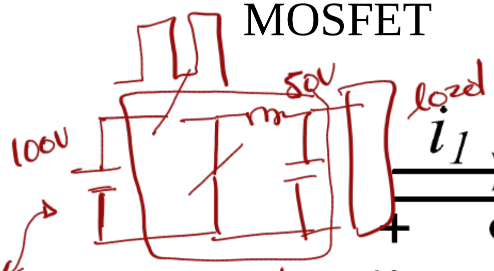
Thyristor

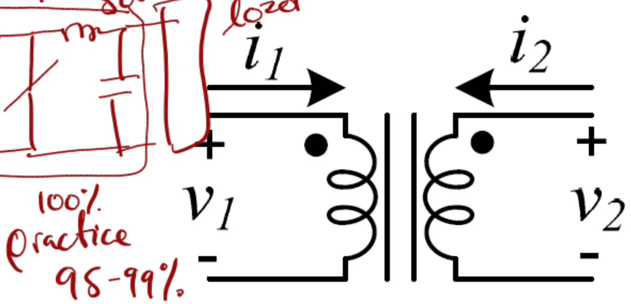


MOSFET



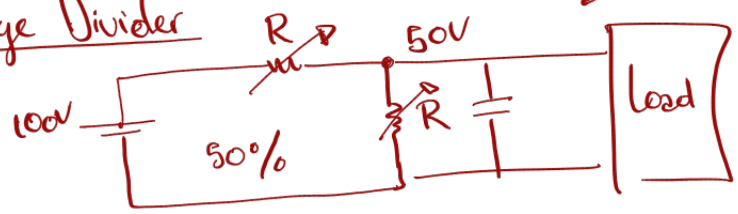
IGBT





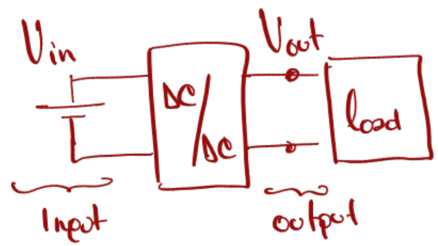
Transformer
(isolation)

Voltage Divider (Step-down Circuit)



Four Types of Power Conversion:

DC/DC: Voltage/current level change

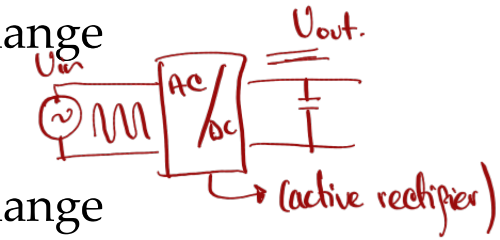


if Vin > Vout
Step-down

Input
Output.

AC/DC: Voltage/current waveform format change

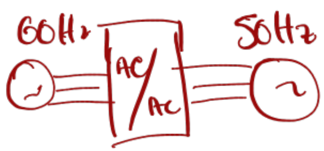
(Rectifiers)
active

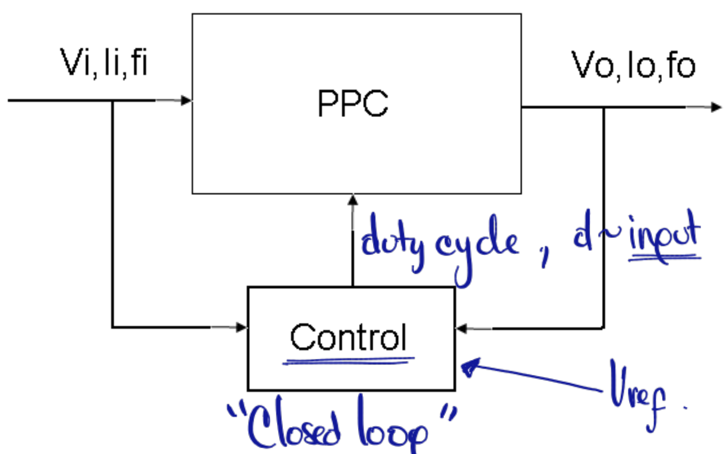


DC/AC: Voltage/current waveform format change

(Inverter)

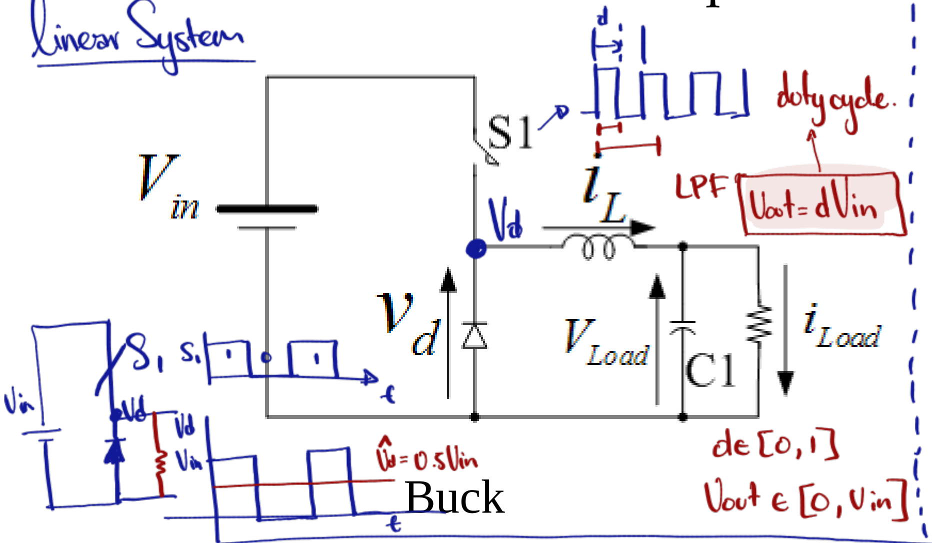
AC/AC: Voltage/current frequency and amplitude change





- DC/DC Converter examples

Linear System



Buck

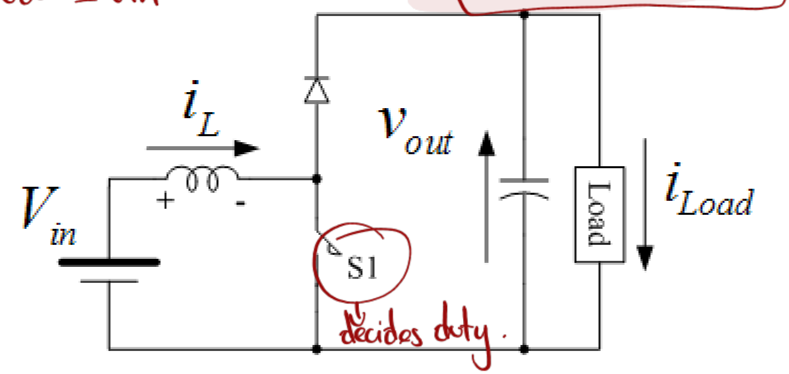
$d \in [0,1]$

$V_{out} \in [0, V_{in}]$

$d \in [0,1)$

$V_{out} \geq V_{in}$

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



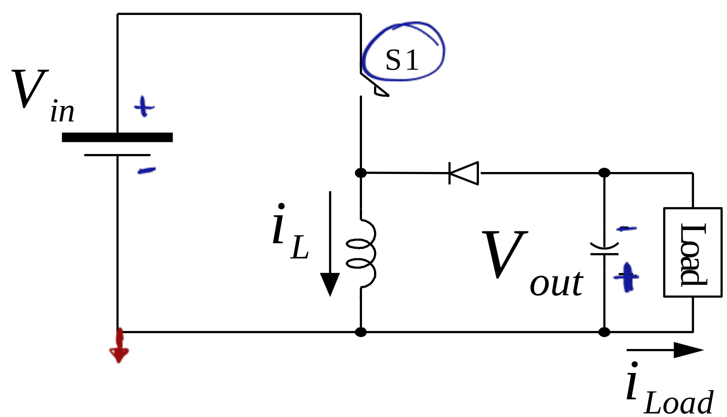
Nonlinear

Boost (Step-up Converter)

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

if $d = 0$ $V_{out} = 0$

if $d \to 1$ $V_{out} \to \infty$



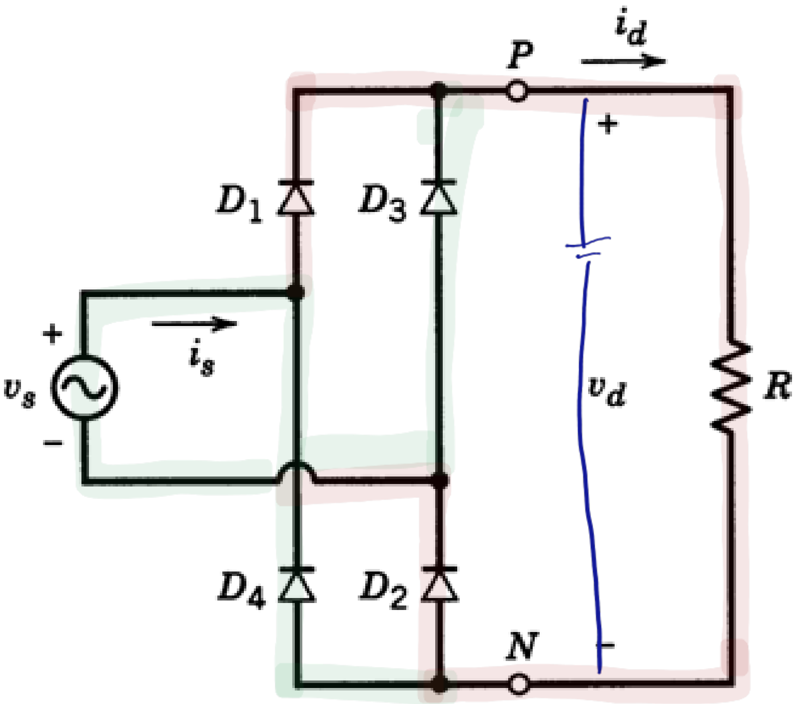
inverting DC/DC converter

Buck/Boost

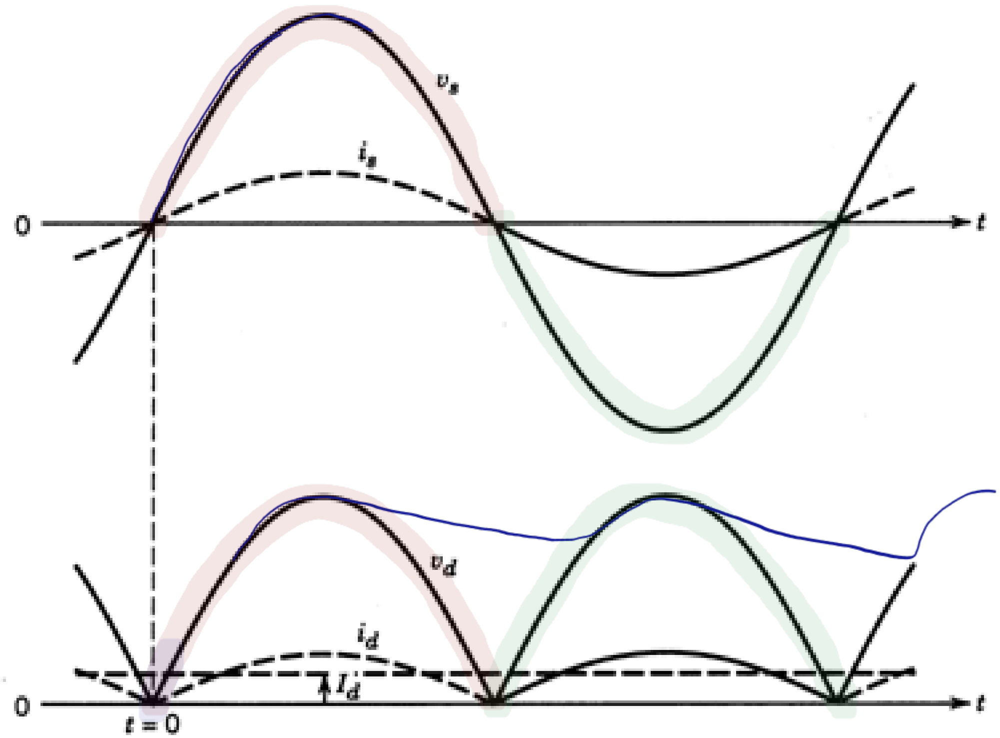
Step up/down (Cuk,)

- AC/DC – passive rectification (drawback: no control *)

full-wave rectifier



(a)

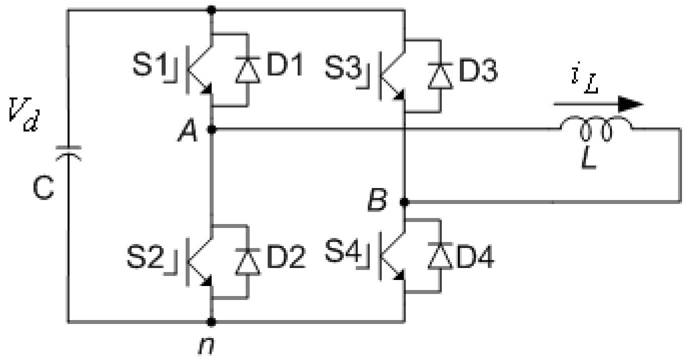


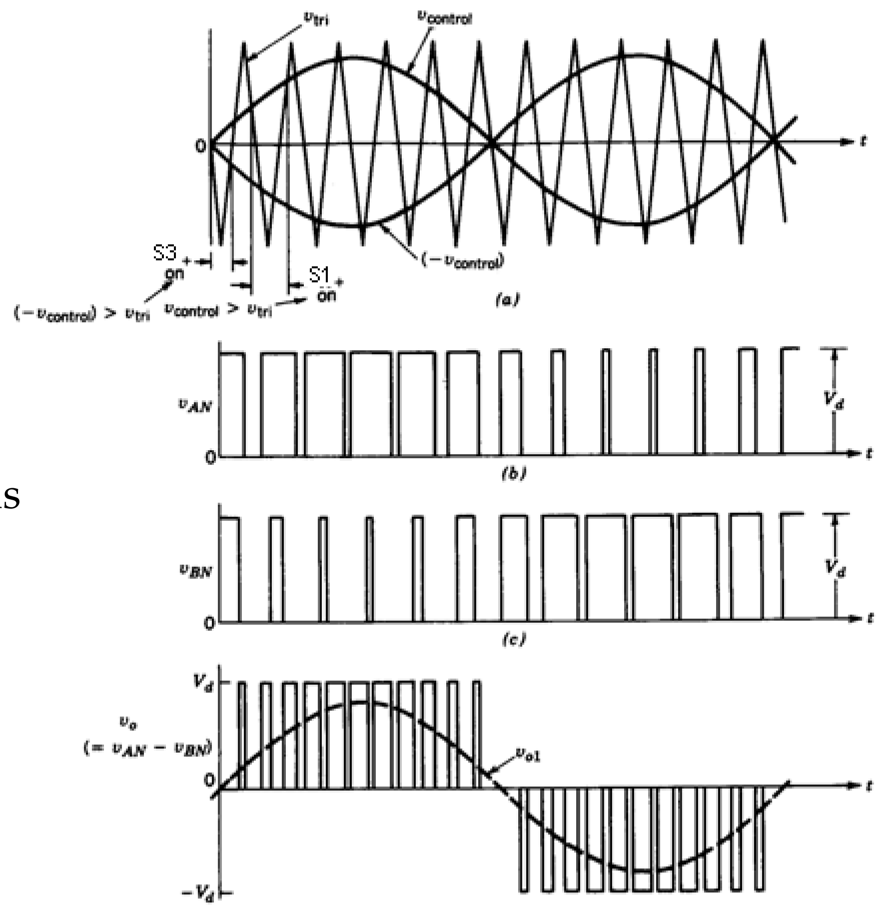
(a)

Source: Text Book

DC/AC Inverters

DC/AC – Inverter examples - H-bridge Full



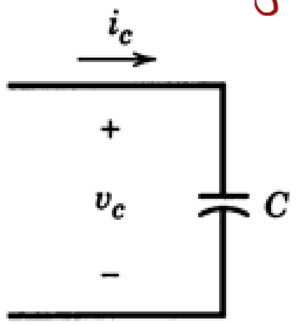


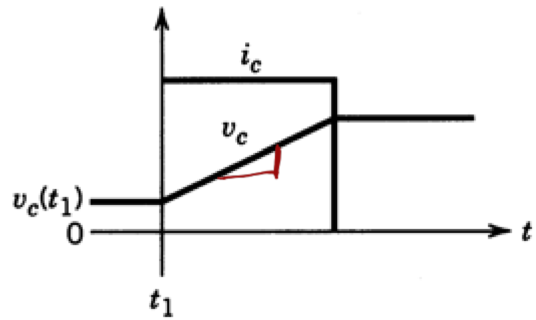
- Simplest modulation: square wave such as deadband, phase shift
- Most commonly used: Pulse-Width-Modulation(PWM)
- More advanced: Space Vector PWM

Source: *Text Book*

Passive Elements in Power Electronics Circuit

- Capacitors (Dynamic)

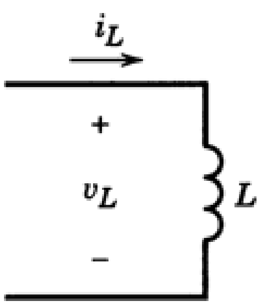


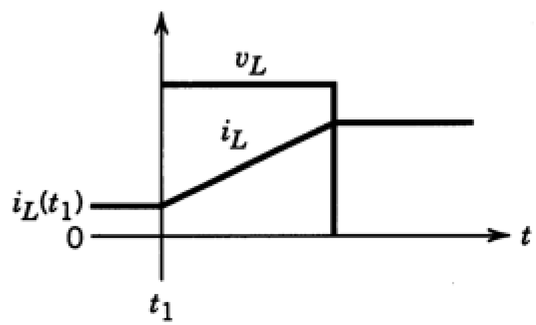


* $$i_C = C\frac{dv_C}{dt}$$

$$W_C = \frac{1}{2}Cv_C^2$$

- Inductors (Dynamic)





* $$v_L = L\frac{di_L}{dt}$$

$$W_L = \frac{1}{2}Li_L^2$$

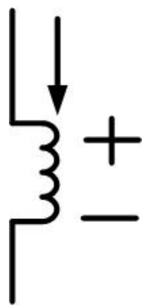
- Resistor (Static)

$V_R = I_R R$

Voltage and Current Balance

- The average voltage across an inductor operating in periodic steady state is zero.

(Voltage-second balance)



$$v_L = L\frac{di_L}{dt}$$

$$W_L = \frac{1}{2}Li_L^2 \quad \Rightarrow \quad i(T) = i(0)$$

$$\langle v_L(t)\rangle = \frac{1}{T}\int_0^T v_L(t)dt = \frac{1}{T}\int_0^T L\frac{di}{dt}dt$$

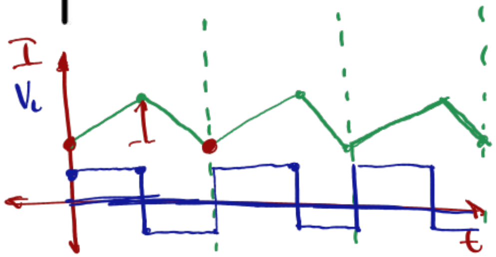
$$= \frac{L}{T}\left(i(T) - i(0)\right) = 0$$

$$\langle v_L(t)\rangle = 0$$

average

$= \frac{1}{T} L\,i(t)\Big]_0^T$

$i(T) = i(0)$ — steady state



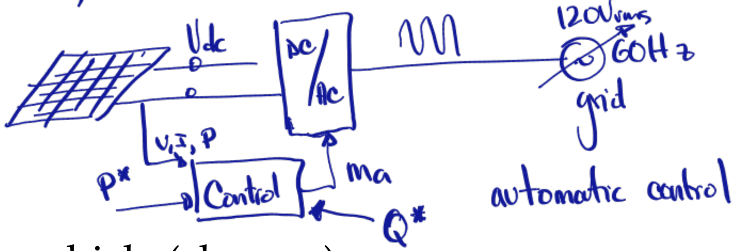
- The average current through a capacitor operating in periodic steady state is zero.

(Ampere-second balance)

$i_C = C\frac{dV_C}{dt}$

Power Converters in Applications

- Consider the typical operation/goals of power converters in:
    - PV (MPPT)



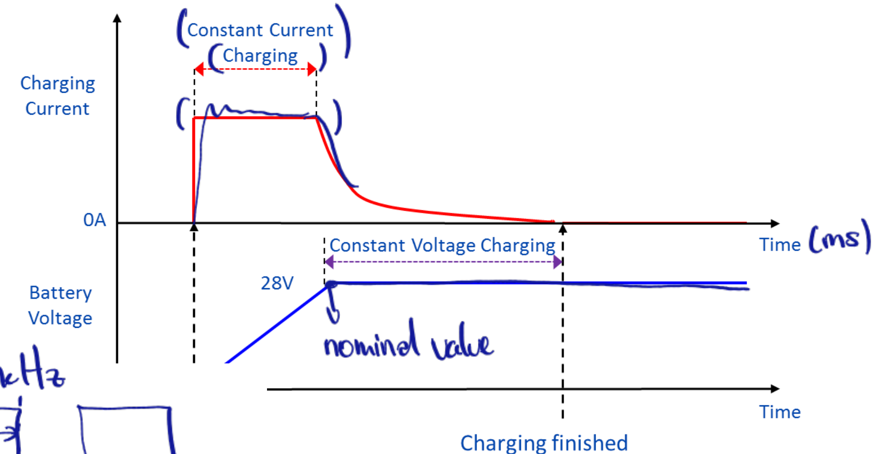
    - Electric vehicle (charger)
    - Electric vehicle (motor drive)

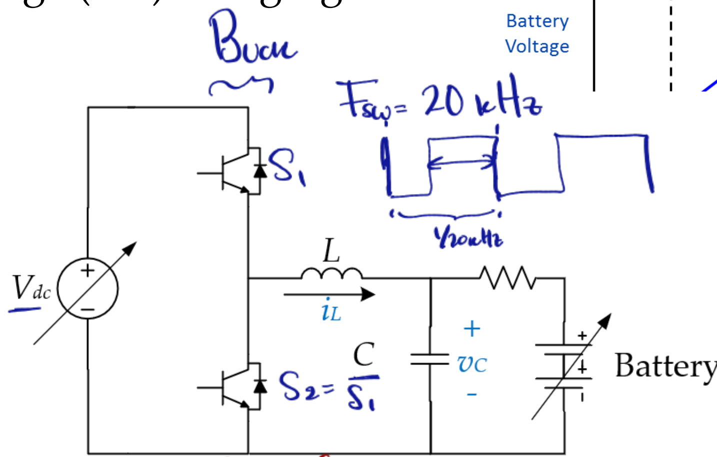
- How do we ensure these converters will maintain their required goal?
- How quickly can they adapt to changes?

Need to develop the necessary controls!

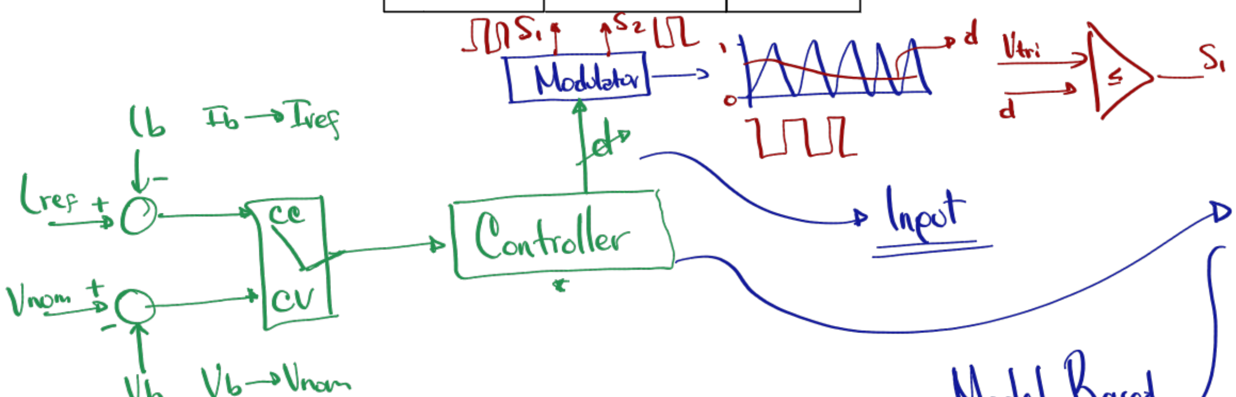
Example 1: Battery Charger

- A common charging strategy for batteries is composed of two steps:
  - Constant current (CC) charging
  - Constant voltage (CV) charging





duty cycle = d = % of time S1 is on during one $T_{sw} = \frac{1}{F_{sw}}$



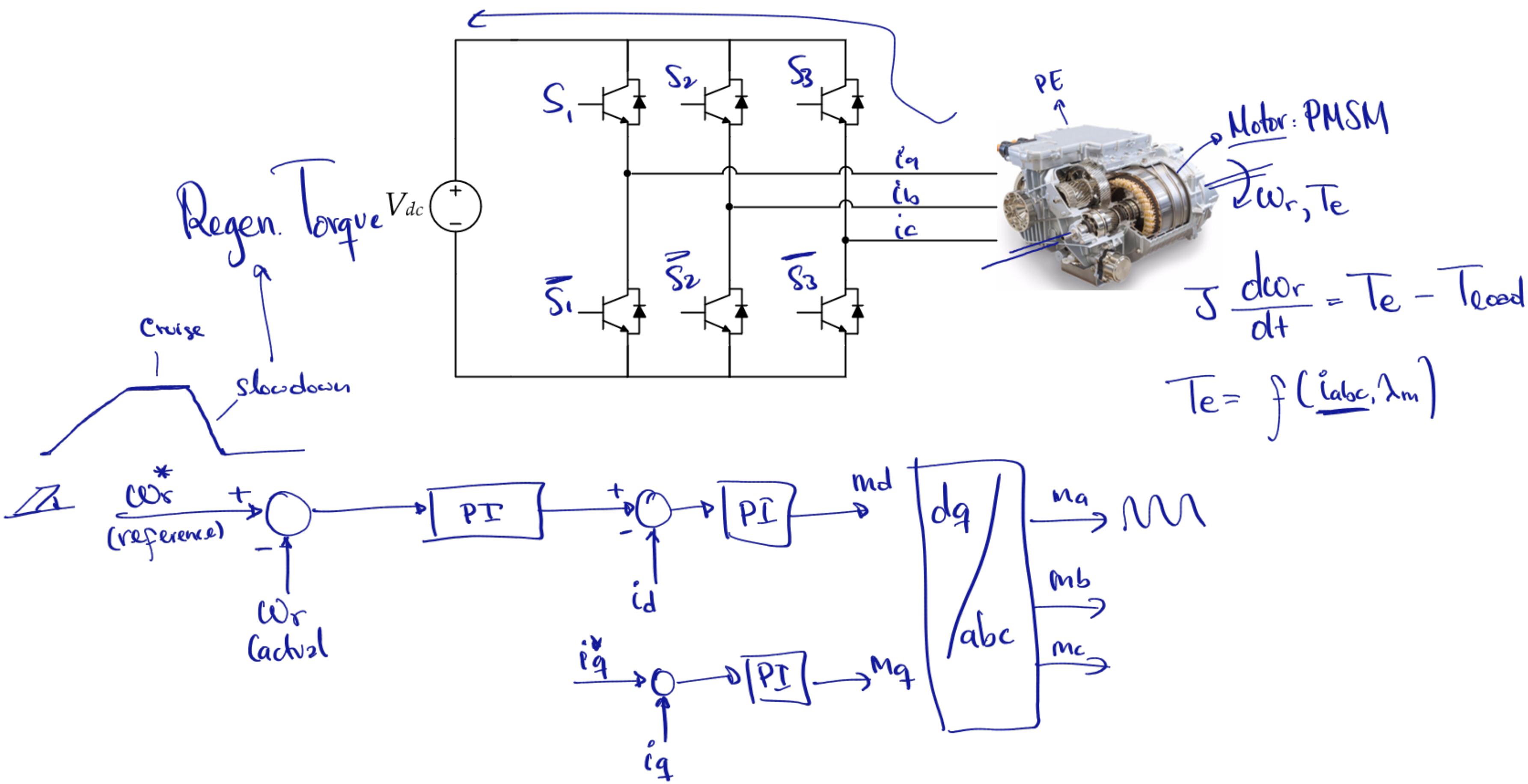
What type of control?

Model Based Control

- PI control (prop. + integral)
- State feedback + Integral
- LQR
- Model Predictive Control

Example 2: Motor Drive

- Now consider a motor drive system such as for electric vehicles, actuators, etc.
- It may be necessary to control the rotor speed:



Tentative Topics

- **Introduction**
- **DC/DC converter modeling and control**
  - State space modeling/control
  - Power electronics averaging — State Space Average — Topic 2
  - Feedback control, state feedback, and integrator control
  - Voltage and current controller design — Topic 3
- **DC/AC inverter modeling and control**
- **Advanced power electronics**
- **Microgrid design and operation**

27