Solar Energy Systems

Anil Kulkarni

Introduction

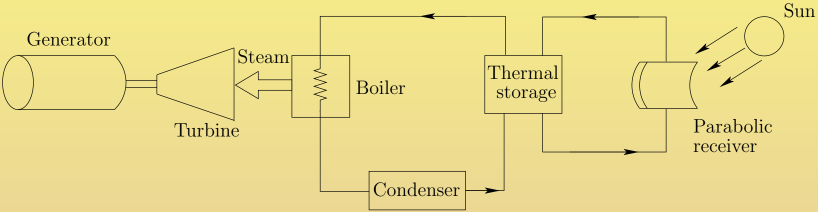
- **Solar Thermal Power Conversion**: Solar radiation (photons) interacts with a material to increase the kinetic energy of atoms (heat). This heat is used to produce steam, which is then used to drive a turbine. The turbine is coupled with an electrical generator, which produces electricity.
- **Solar Photo Voltaic (PV) Conversion**: Photons falling on a semiconductor P-N junction cause a voltage to be generated across the junction (photovoltaic effect). This can drive current into an external circuit and deliver power to it.

The global installed capacity of solar PV in 2015 was about 220 GW, while for solar thermal conversion systems it was less than 5 GW.

Introduction

- The size of solar PV plants may vary from a few kilowatts (for example, roof-top solar plants) to large farms of hundreds of megawatts.
- Depending on their capacity, the plants may be connected to the low or medium voltage distribution grid or the high voltage grid.
- They may also be operated in the stand-alone mode (no grid connection).
- The largest solar PV plant in 2015 had a total power rating of 579 MW, but plants much larger than this are now being installed. A significant proportion of solar PV generation is in the form of a large number of smaller capacity units connected close to the points of consumption (distributed generation).
- The most significant dynamics are due to the control of the power-electronic converters, which are needed to interface the solar panels to the grid.

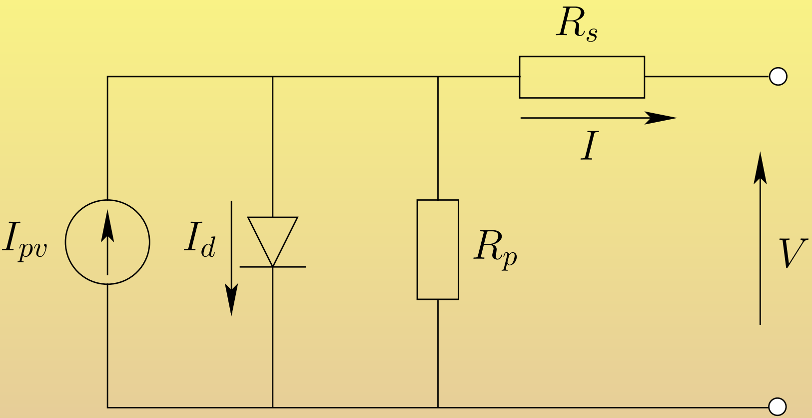
Solar Thermal Generation



Solar Photovoltaic Generation

- Crystalline silicon cells (mono-crystalline and multi-crystalline) - most prevalent
- Thin-film based solar cells (Amorphous Silicon - a-Si, Cadmium Telluride - Cd-Te and Copper Indium Gallium Selenide - CIGS)
- The efficiency of average commercially available wafer-based modules has increased from 12% to 17%, while it has increased from 9% to 16% for Cd-Te thin-film modules
- Solar PV **modules** are made up of many solar cells which are connected in series and parallel in order to reach convenient values of dc voltage and power.
- The typical power output of a solar cell is around 3-4 W, a module may be available from 3 W to 300 W (peak power).
- Several modules may then be connected in series and parallel to form solar PV arrays. Several such arrays may be used in a solar power plant.

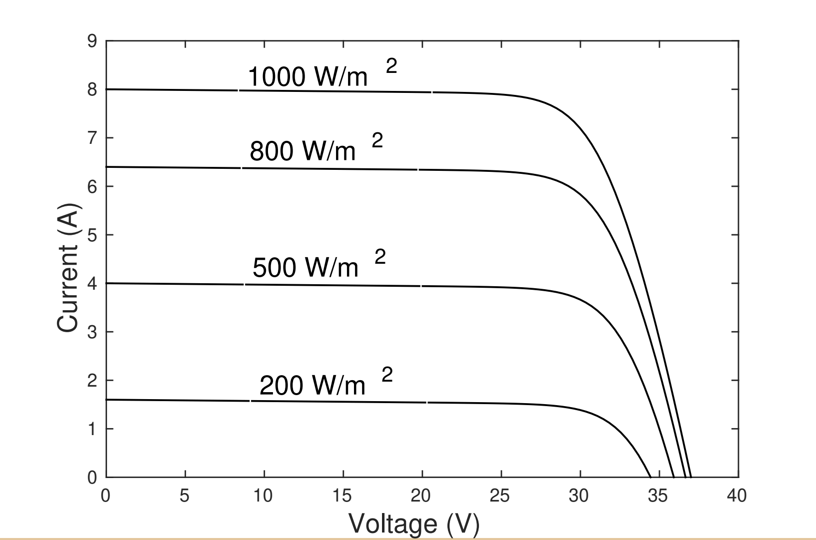
Solar Module I-V Characteristics



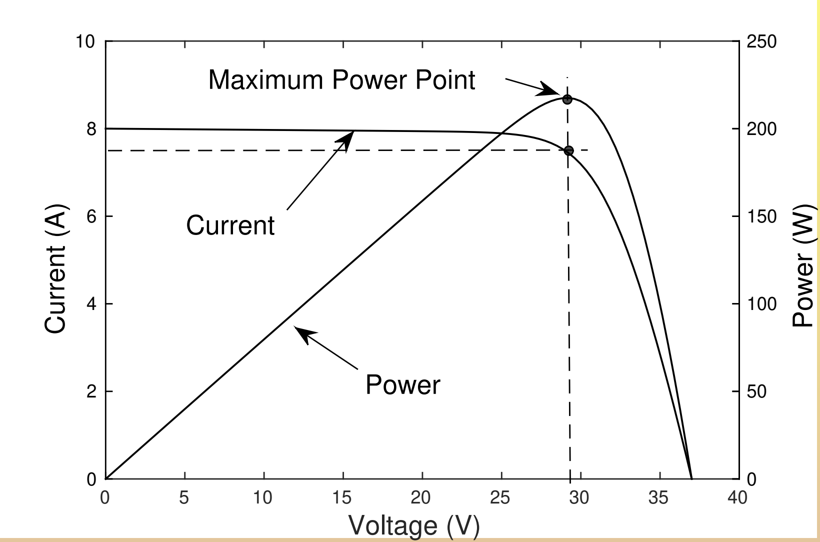
Solar Module I-V Characteristics

- Current-voltage (I-V) curves depend on the amount of solar radiation falling over a unit area (irradiance) and the temperature.
- A manufacturer generally specifies the peak output power under Standard Test Conditions (1000 W/m^2 solar irradiance with the specified spectral characteristics, and 25°C module temperature).
- The characteristics may be obtained from the information given in the datasheets of the the module:
  [M. G. Villalva, J. R. Gazoli and E. R. Filho, "Comprehensive Approach to Modeling and Simulation of Photovoltaic Arrays," in IEEE Transactions on Power Electronics, vol. 24, no. 5, pp. 1198-1208, May 2009.]

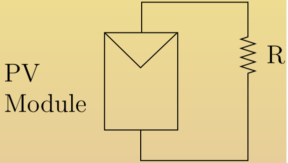
Solar Module I-V Characteristics

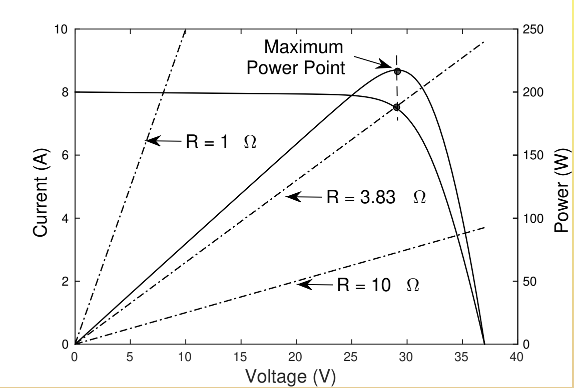


Solar Module I-V Characteristics



Power Extraction





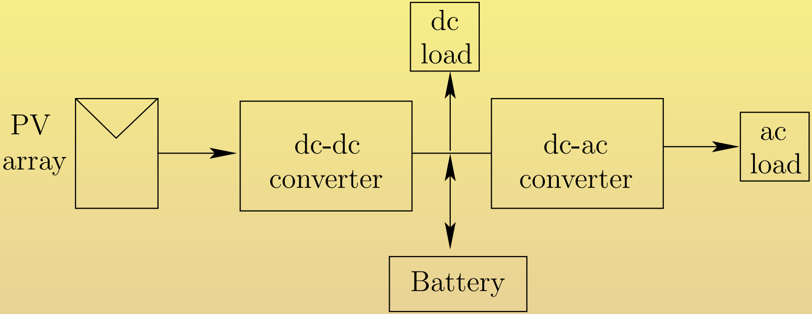
Maximum Power Extracted if $R = 3.83\Omega$.

Power Extraction

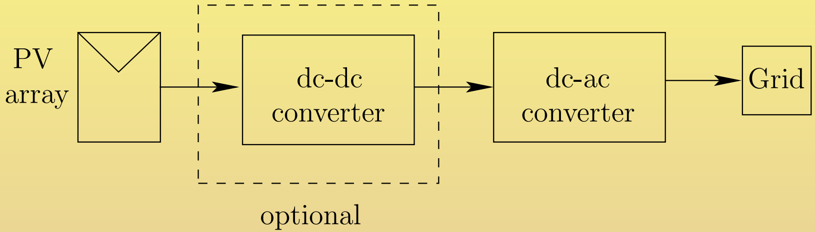
- In PV arrays, where several modules are connected in series and parallel to achieve higher power ratings, the overall I-V characteristic and the load characteristic determines the output power.

- A mismatch in the parameters of the modules and/or non-identical operating conditions (for example, partial shading of modules) may result in sub-optimal power extraction and may cause *hot-spots* in the modules.

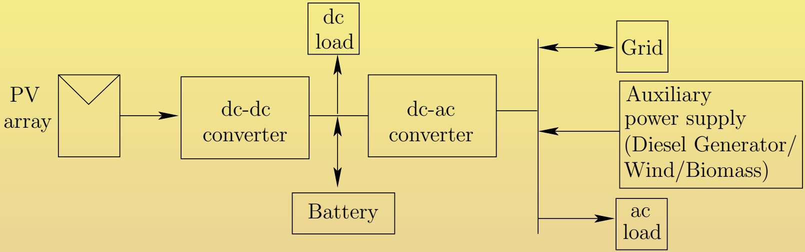
Solar PV Connections

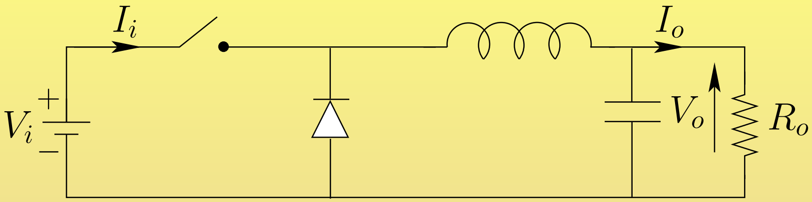


Solar PV Connections



Solar PV Connections



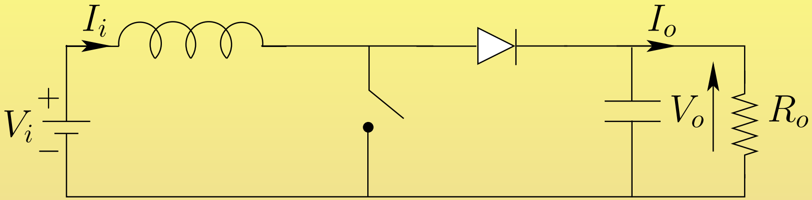


$$\frac{V_o}{V_i} = D$$

$$\frac{I_o}{I_i} = \frac{1}{D}$$

$$R_i = \frac{R_o}{D^2}$$

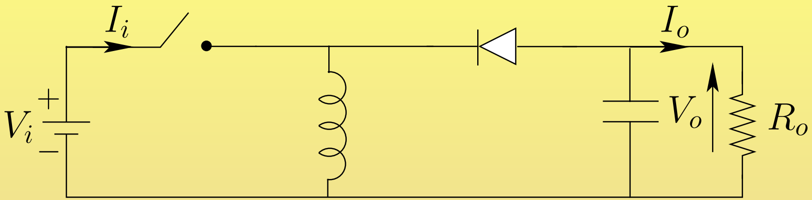
DC-DC Converters: Boost Converter



$$\frac{V_o}{V_i} = \frac{1}{1 - D}$$

$$\frac{I_o}{I_i} = 1 - D$$

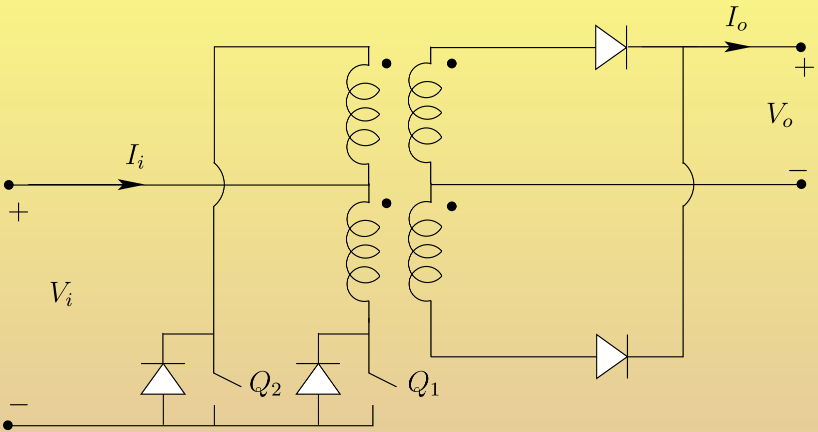
$$R_i = (1 - D)^2 \times R_o$$



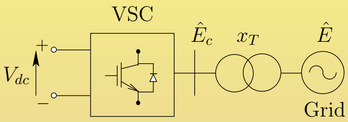
$$\frac{V_o}{V_i} = \frac{-D}{1-D}$$

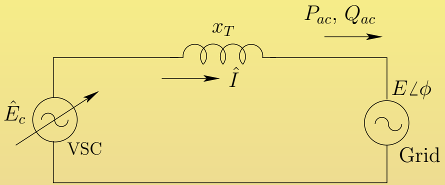
$$\frac{I_o}{I_i} = -\frac{1-D}{D}$$

$$R_i = \left(\frac{1-D}{D}\right)^2 \times R_o$$

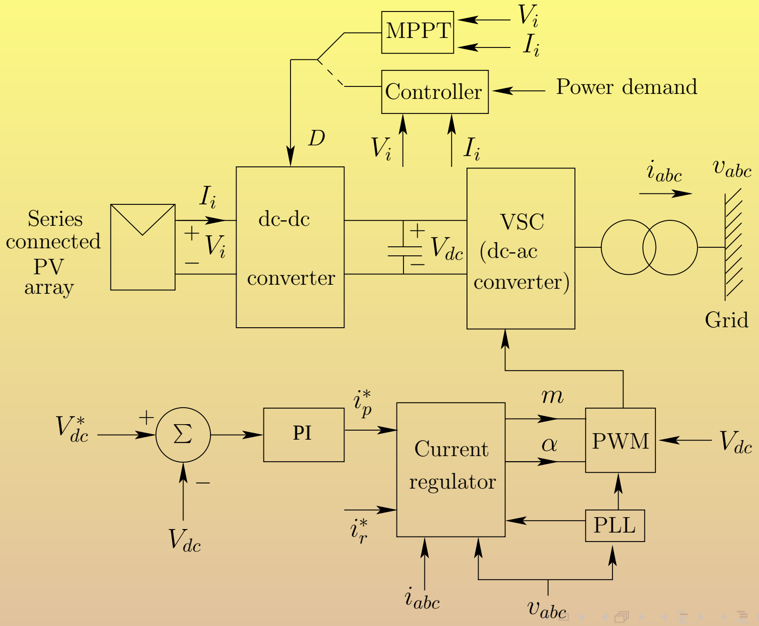

I_o
$+$
V_o
$-$
I_i
$+$
V_i
$-$
Q_2
Q_1

DC-AC Converters

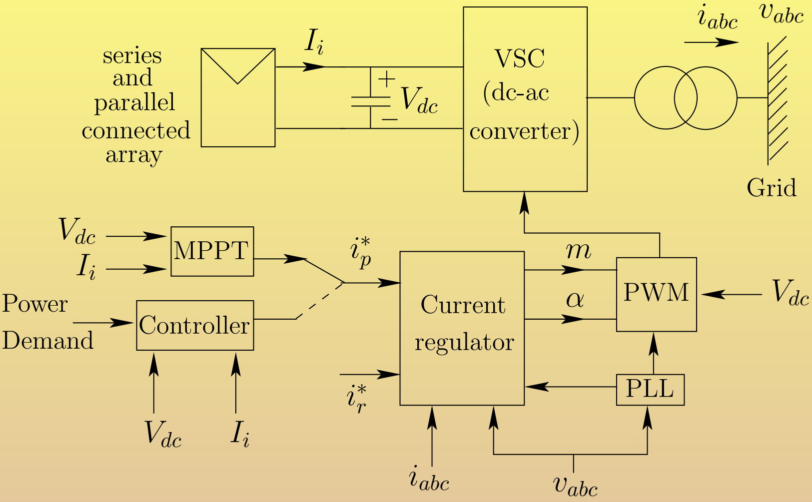




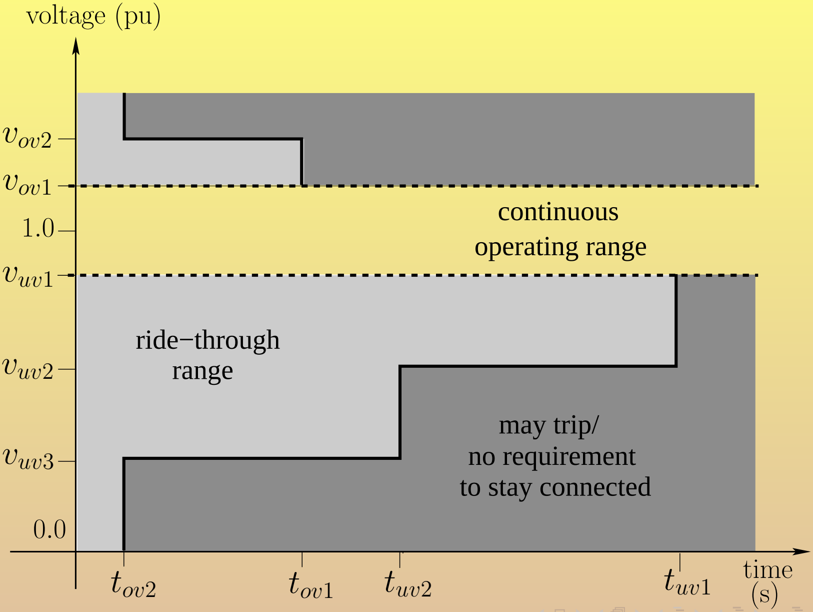
(1) $\hat{E}_c = mV_{dc}\angle(\phi + \alpha)$
(2) m and α are independently controllable


MPPT
V_i
I_i
Controller
Power demand
D
V_i
I_i
Series connected PV array
I_i
+
V_i
−
dc-dc converter
+
V_{dc}
−
VSC (dc-ac converter)
i_{abc}
v_{abc}
Grid
V_{dc}^*
+
Σ
−
V_{dc}
PI
i_p^*
i_r^*
Current regulator
m
α
PWM
V_{dc}
PLL
i_{abc}
v_{abc}

Grid-connected High-Power Solar Plants

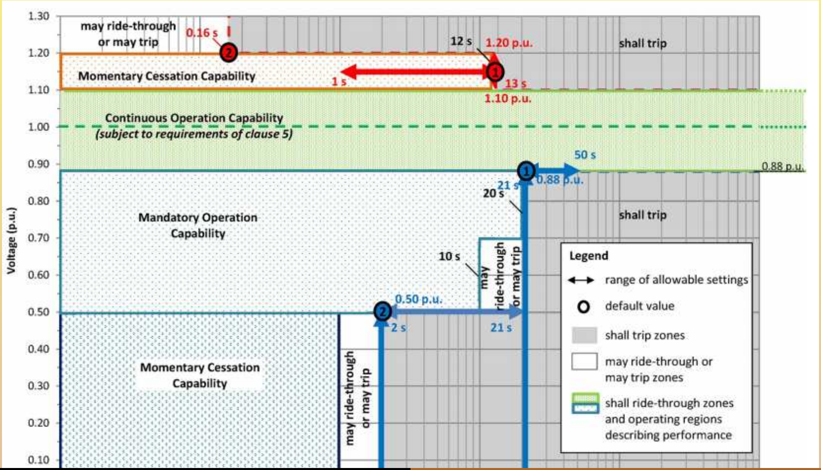


Low-Voltage Ride Through

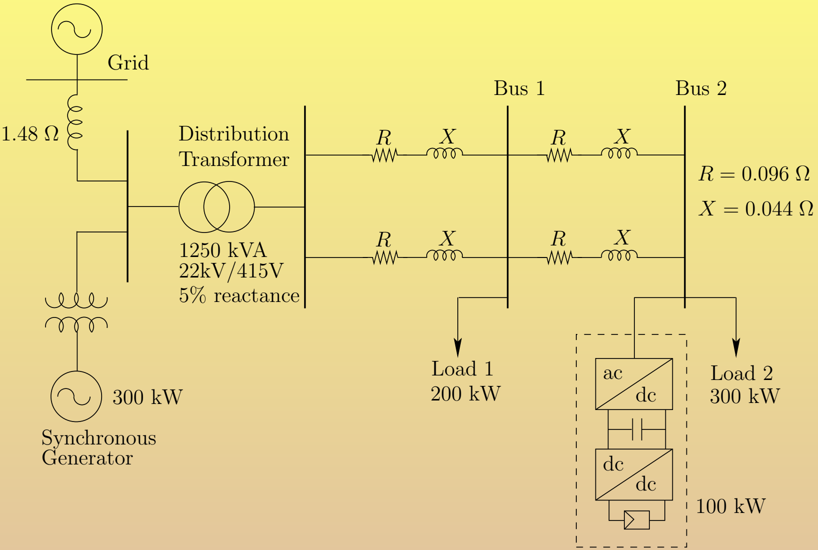


Low-Voltage Ride Through: IEEE Std 1547-2018 (Revision of IEEE Std 1547-2003)

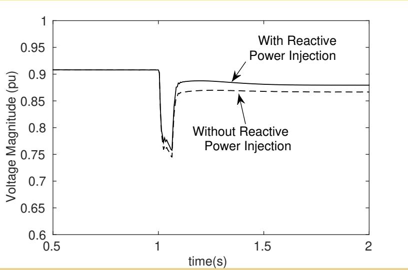
IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces

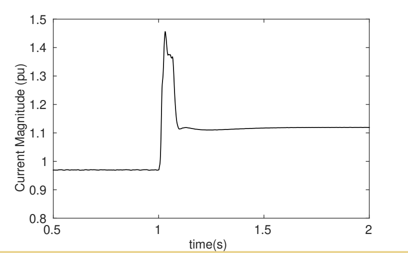


Voltage Support Capability

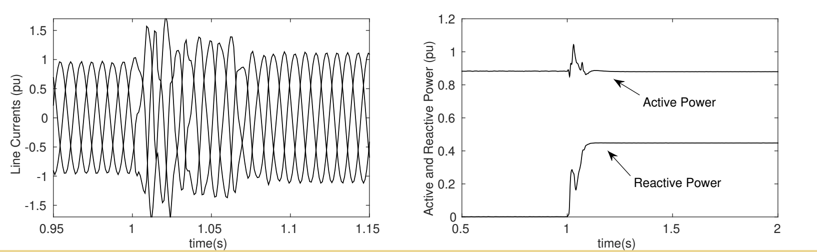


Voltage Support Capability

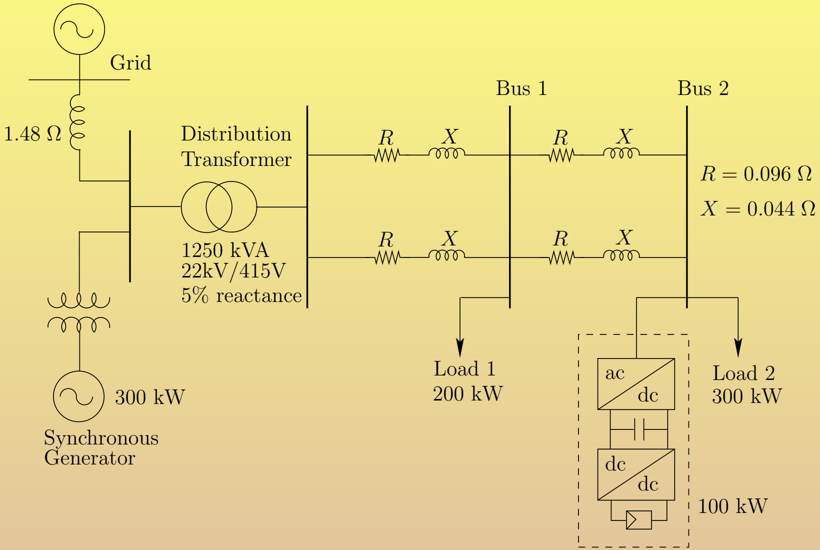




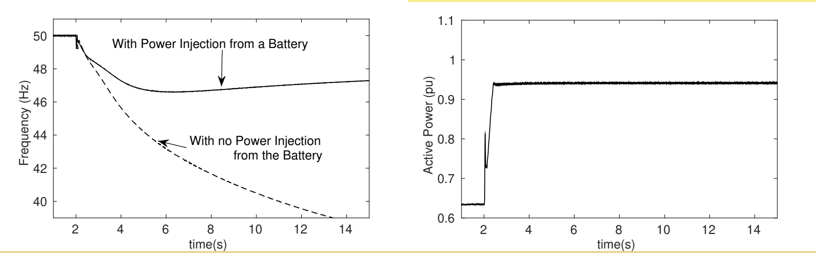
Voltage Support Capability

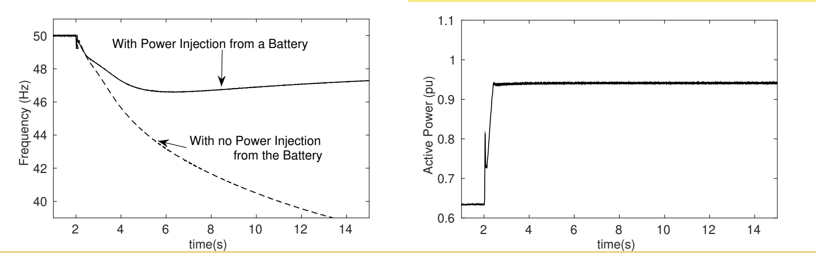


Frequency Support Capability (Battery)



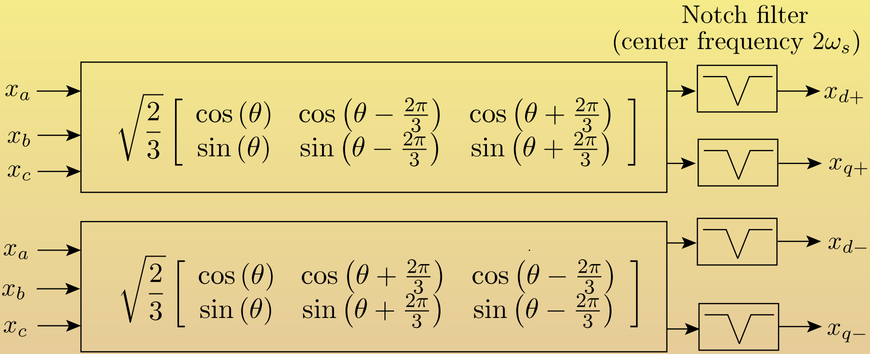
Frequency Support Capability (Battery)



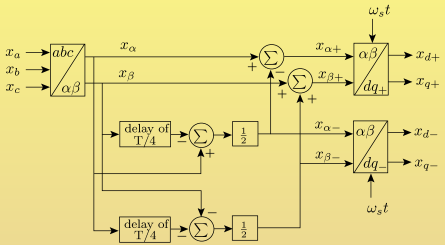


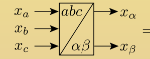
With Power Injection from a Battery
With no Power Injection from the Battery
Frequency (Hz)
50
48
46
44
42
40
2
4
6
8
10
12
14
time(s)
Active Power (pu)
1.1
1
0.9
0.8
0.7
0.6
time(s)

VSC Control under Unbalanced Conditions: Sequence Extraction

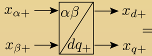


VSC Control under Unbalanced Conditions: Sequence Extraction

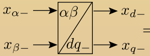




$$\Longrightarrow \begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -0.5 & -0.5 \\ 0 & -\frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix}$$

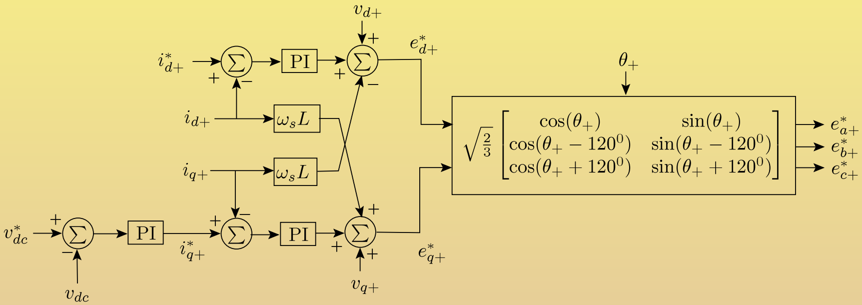


$$\Longrightarrow \begin{bmatrix} x_{d+} \\ x_{q+} \end{bmatrix} = \begin{bmatrix} \cos\omega_s t & -\sin\omega_s t \\ \sin\omega_s t & \cos\omega_s t \end{bmatrix} \begin{bmatrix} x_{\alpha+} \\ x_{\beta+} \end{bmatrix}$$

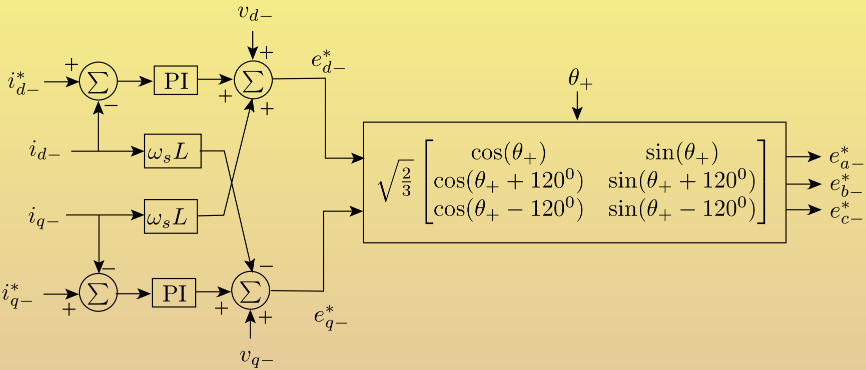


$$\Longrightarrow \begin{bmatrix} x_{d-} \\ x_{q-} \end{bmatrix} = \begin{bmatrix} \cos\omega_s t & -\sin\omega_s t \\ \sin\omega_s t & \cos\omega_s t \end{bmatrix} \begin{bmatrix} x_{\alpha-} \\ x_{\beta-} \end{bmatrix}$$

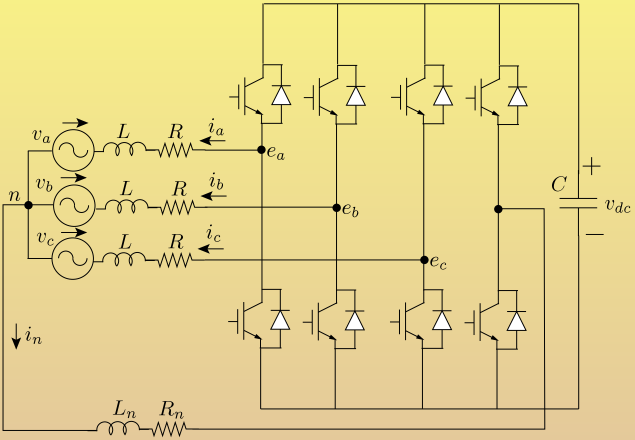
VSC Control under Unbalanced Conditions: Positive Sequence Control



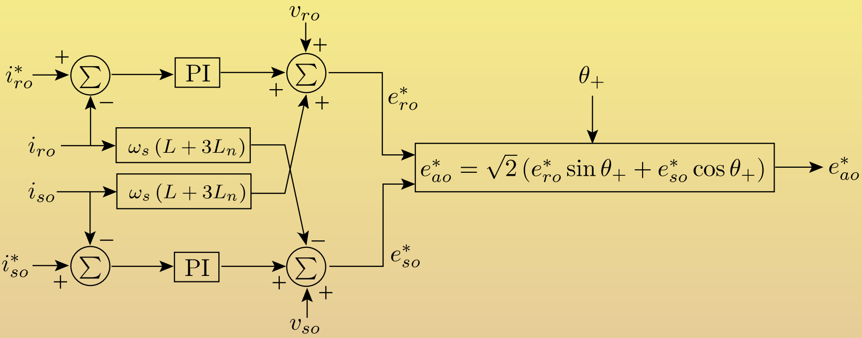
VSC Control under Unbalanced Conditions: Negative Sequence Control



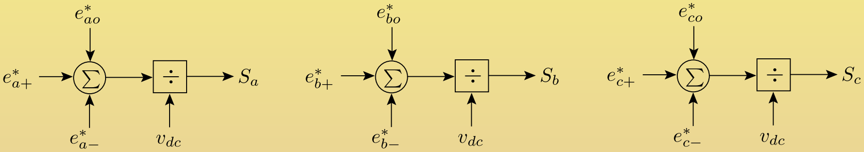
VSC Control under Unbalanced Conditions: Four-Leg STATCOM



VSC Control under Unbalanced Conditions: Zero Sequence Control (Four Leg STATCOM)



VSC Control under Unbalanced Conditions: Switching Function Generation



VSC Control under Unbalanced Conditions: Switching Function Generation