EE2029 Introduction to Electrical Energy Systems

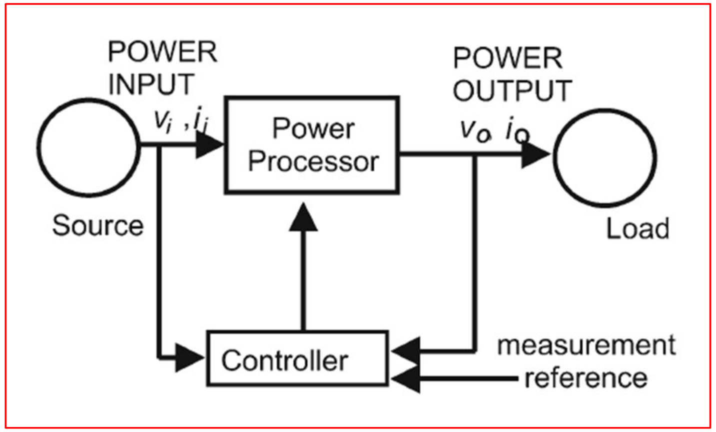
Power converters and Renewable Energy Sources

Learning objectives

- Explain principles of common Power converters
- Explain principles of solar PV generation
- Explain principles of Wind power generation
- Describe power converters used in integration of these renewables
- Describe Harmonics in power systems and mitigation techniques
- Simulate various power converter using PLECS

Fundamentals of Power Converters

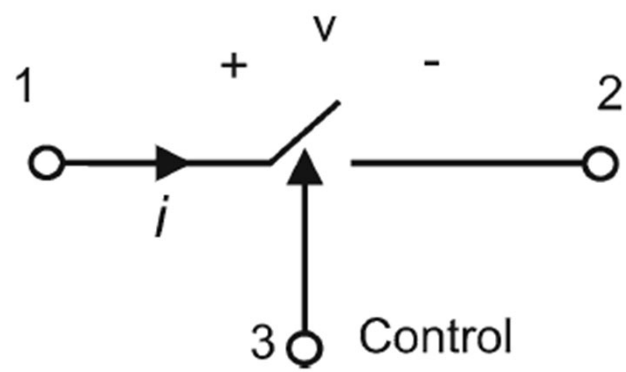
- Converter circuits that process energy
  - from one DC level to another DC level,
  - rectify AC input voltage to uncontrolled DC output voltage
  - rectify AC to controlled DC
  - from DC (inverters) to AC
- It consists of a power processor and a controller.



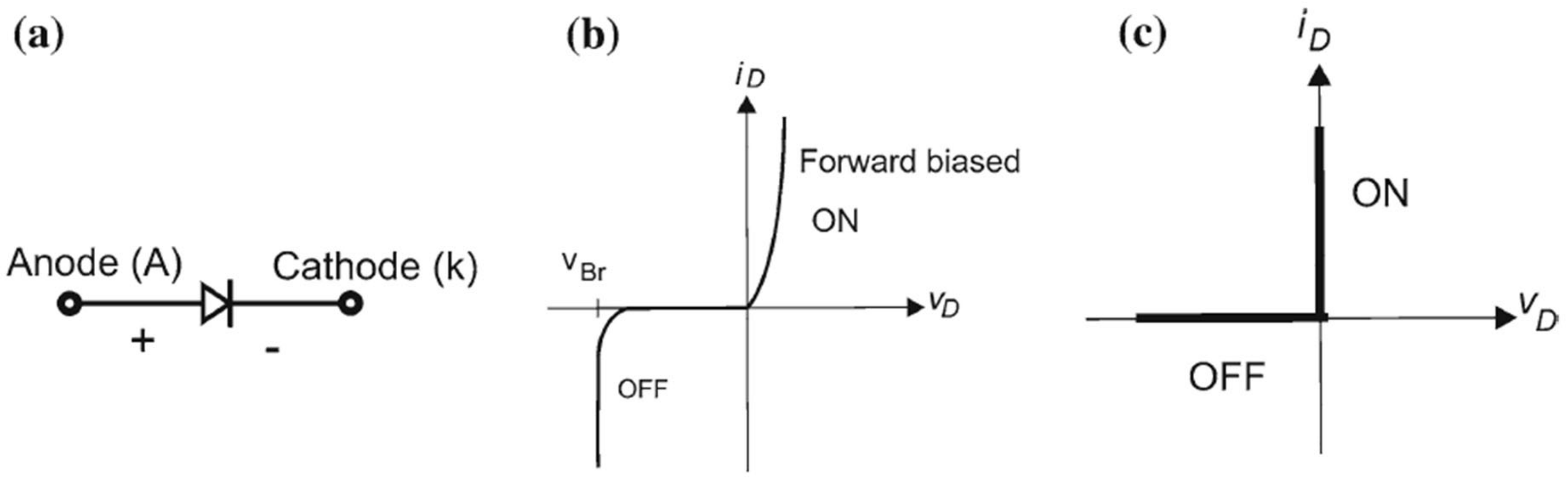
- The power processor is built from power semiconductor switches and passive elements like inductor and capacitor.
- The controller provides the necessary control signals to the switches so as to ensure the desired voltage, current and power as desired.

Power Semiconductor Devices

- Power semiconductor devices can be used as electronic switches capable of handling high voltage and current operations at high frequency.
- An ideal power electronic switch can be represented as a three terminals device.
- The ideal switch has
  - zero-voltage drop,
  - zero-leakage current, and
  - instantaneous transitions
- Diode is an uncontrolled switch
- Transistors are controlled switches

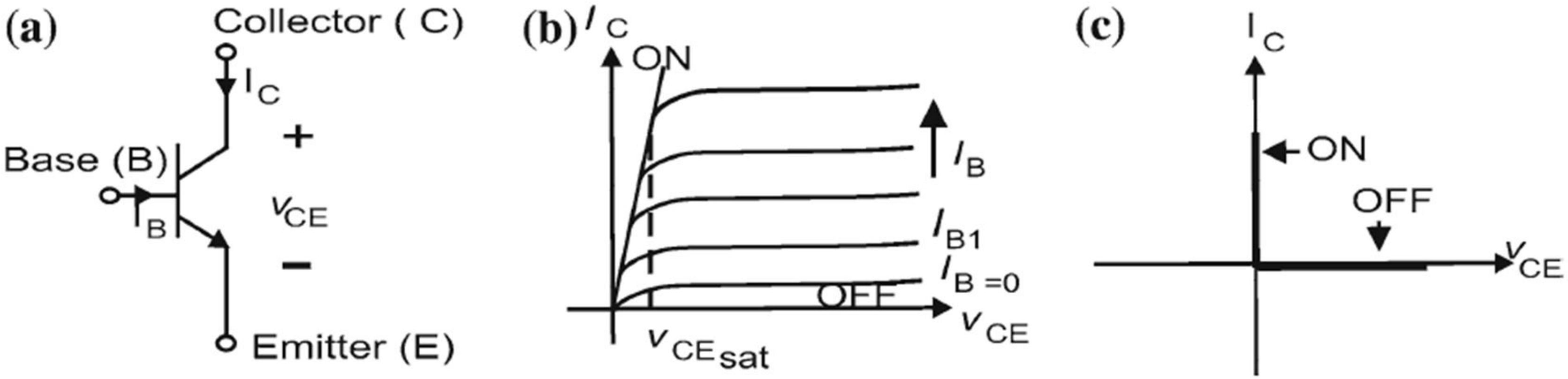


Diode



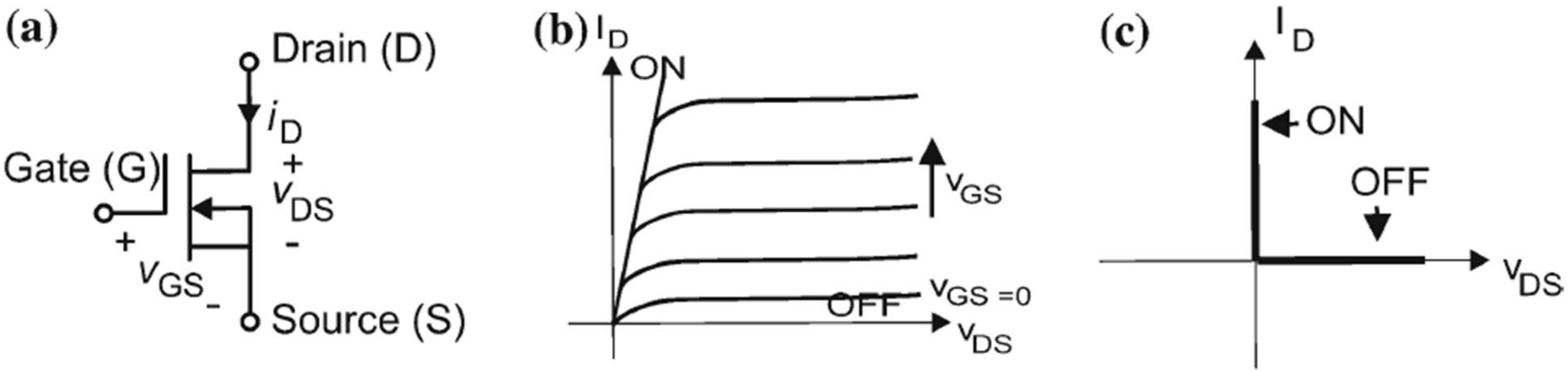
Diode: (a) symbol, (b) i-v characteristics, and (c) idealized characteristics

Bipolar Junction Transistor (BJT)



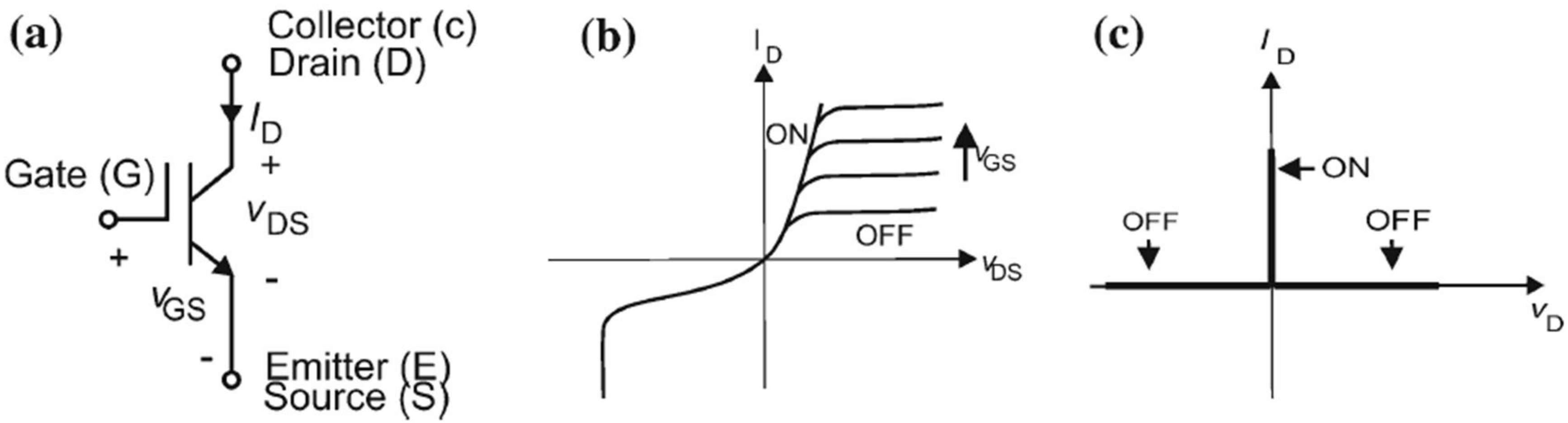
The BJT: (a) symbol, (b) i-v characteristics, and (c) idealized characteristics

Metal Oxide Semiconductor Field Effect Transistor (MOSFET)



The MOSFET: (a) symbol, (b) i-v characteristics, and © idealized characteristics

Insulated Gate Bipolar Transistor (IGBT)

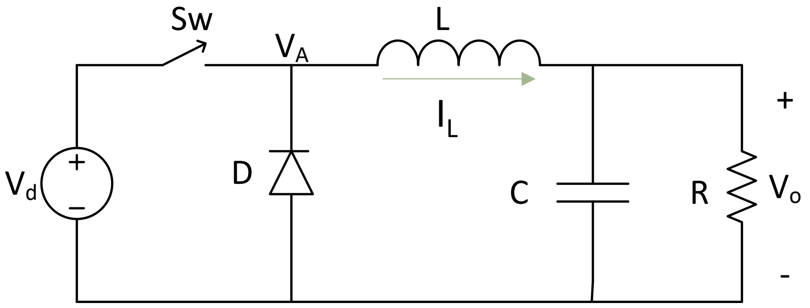


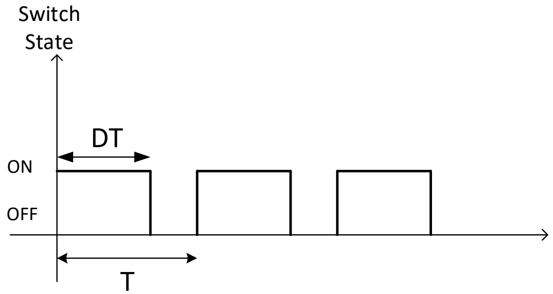
The IGBT: (a) symbol, (b) i-v characteristics, and (c) idealized characteristics

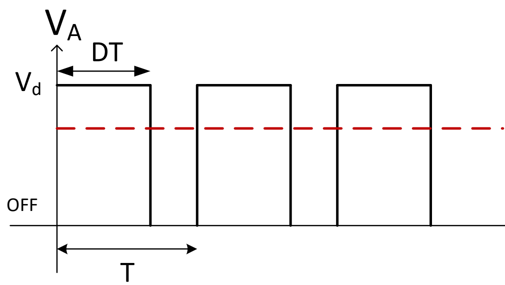
Power Electronic Converter Topologies

1. DC/DC Converter
2. DC/AC Converter
3. AC/DC Converter
4. AC/AC Converter

DC/DC Converters :
Non-isolated Buck converter

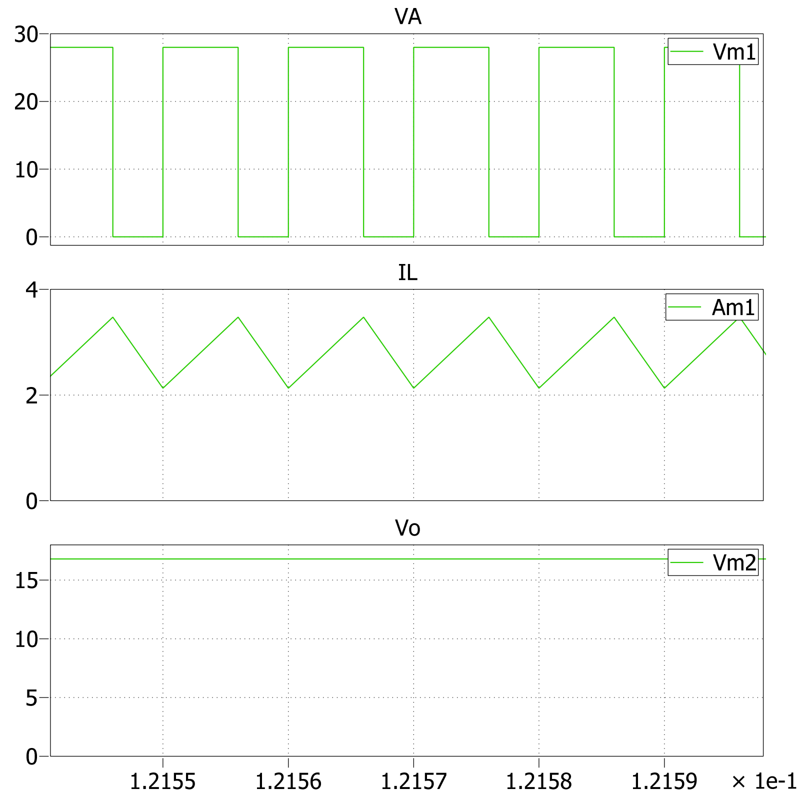




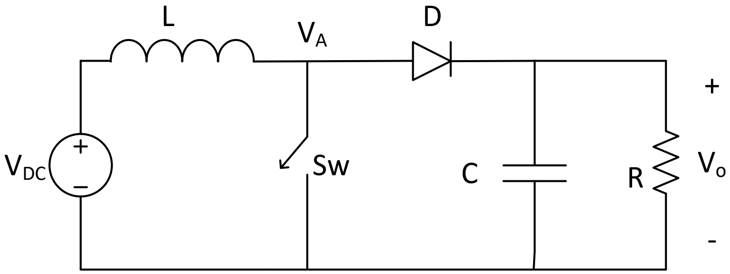


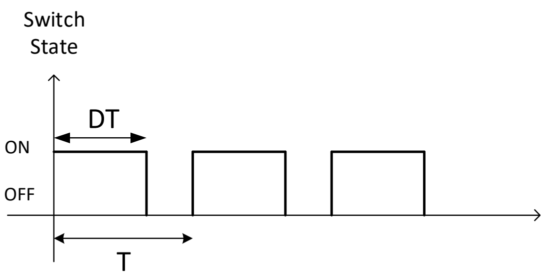
$$V_{o,avg} = V_d \times D$$

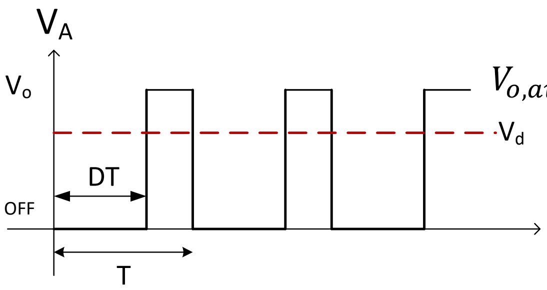
$$V_d = 28V, D = 0.6, V_o = 16.8V$$



DC/DC Converters: Non-Isolated Boost Converter

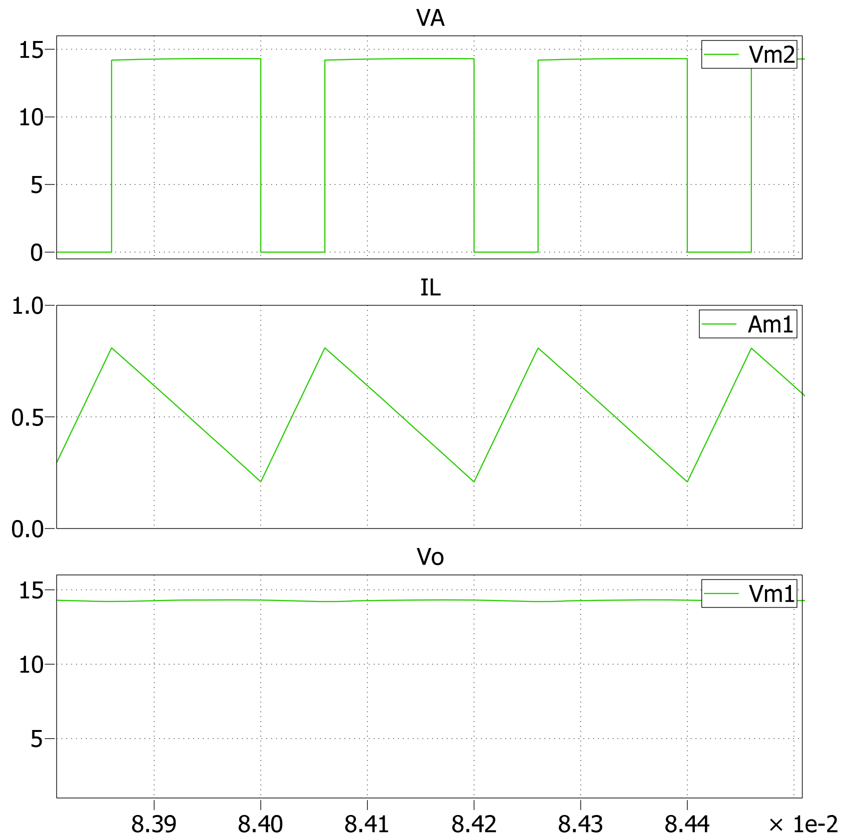






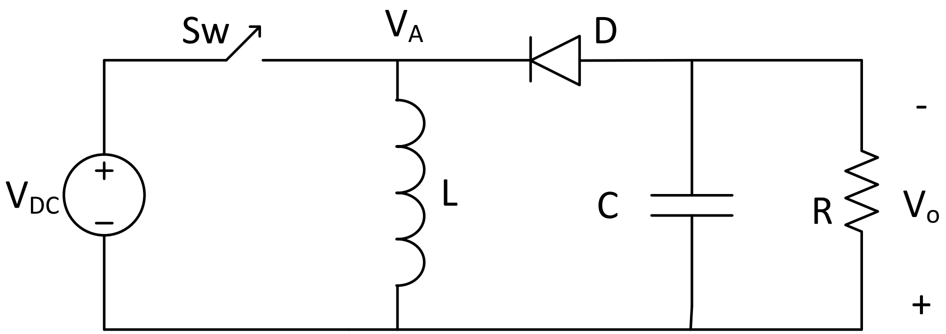
$$V_{o,avg} = V_d \times \frac{1}{1-D}$$

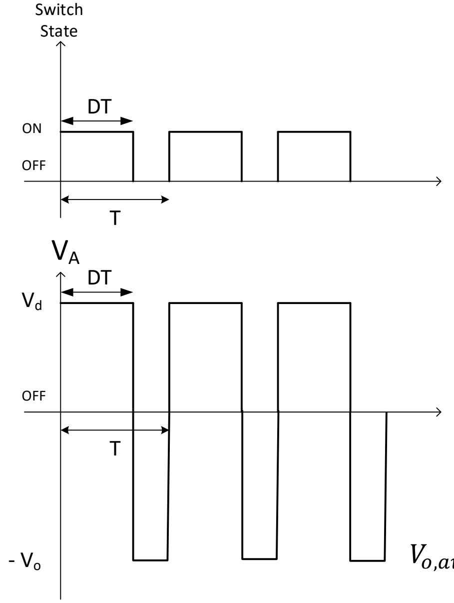
$V_d = 10V, D = 0.3, V_o = 14.3\ V$



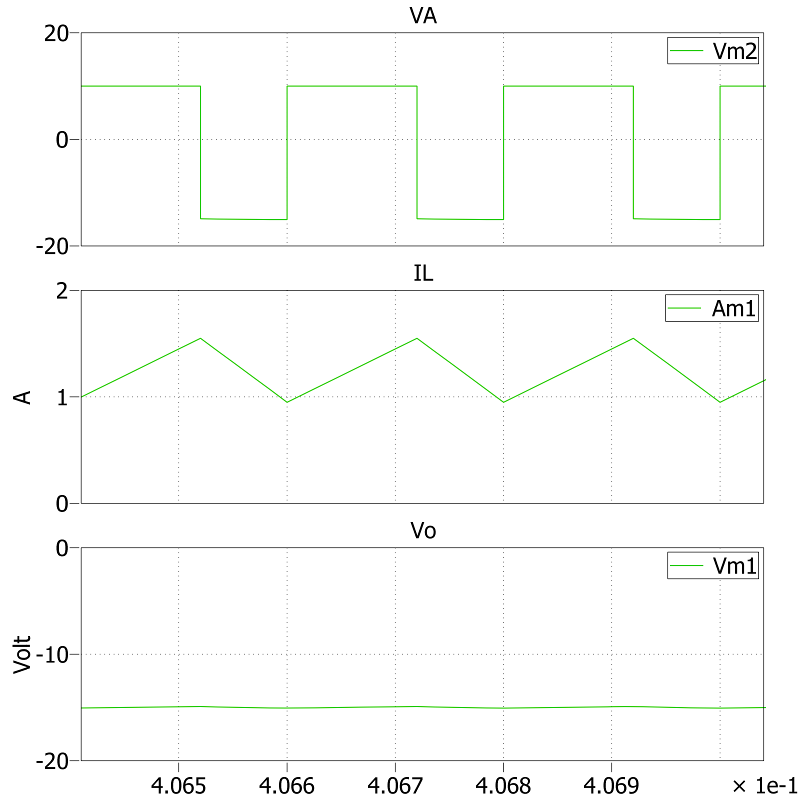
DC/DC Converters : Non-isolated Buck-boost converter

$$V_d = 10V, D = 0.6, V_o = -15\ V$$

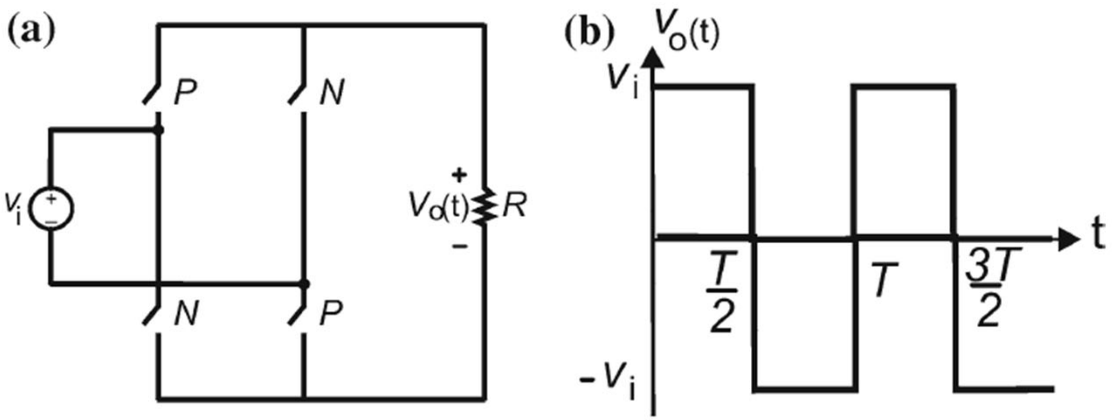




$$V_{o,avg} = V_d \times \frac{D}{1-D}$$



DC/AC Converters (Inverters): Single phase full-bridge inverter

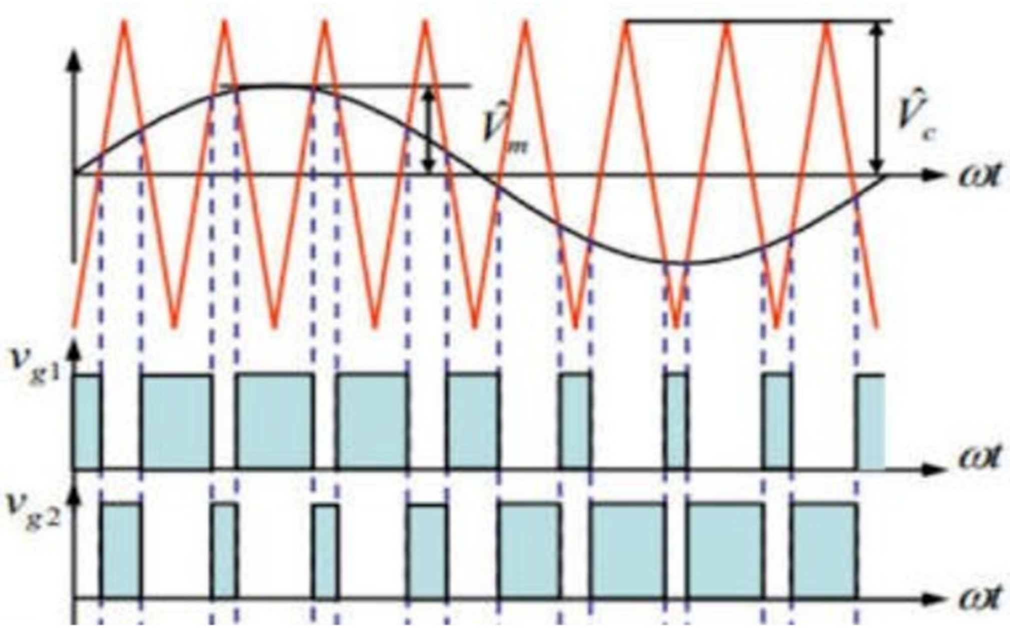


Full bridge (FB) DC/AC converter: (a) circuit, and (b) waveforms

PWM gating pulse generation

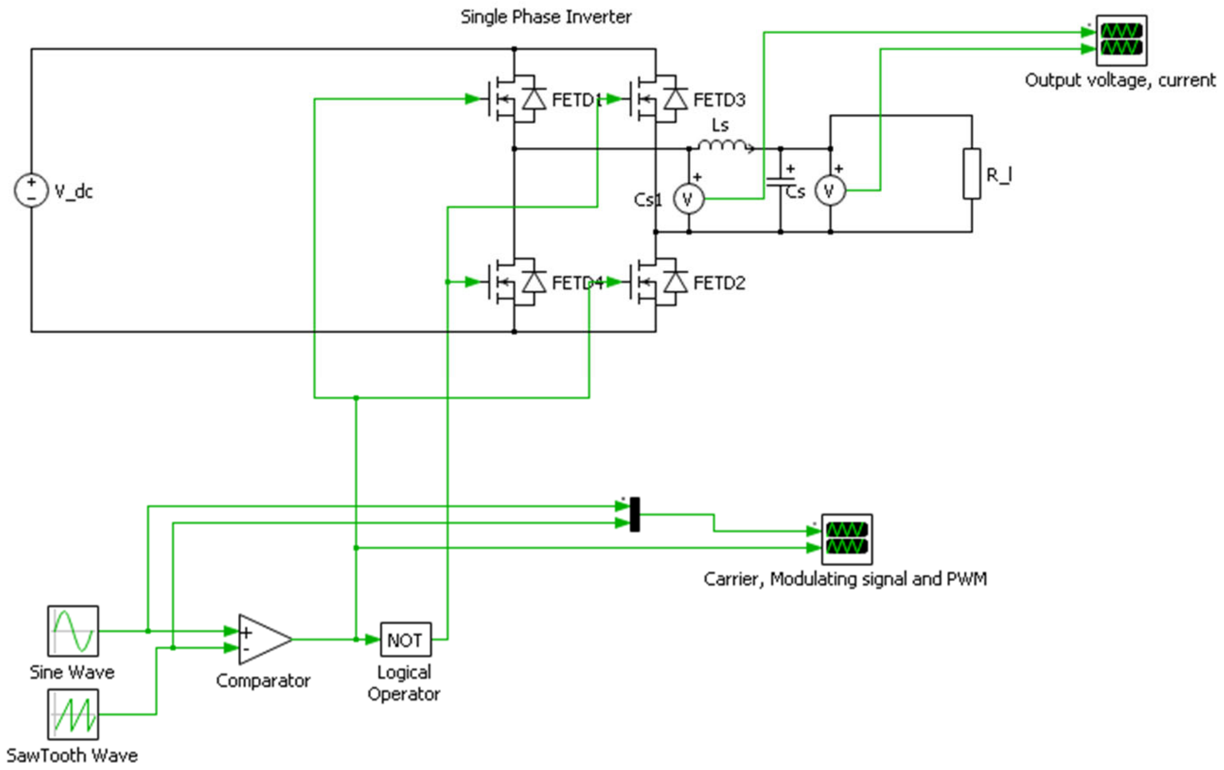
Control signal
and
Carrier Signal

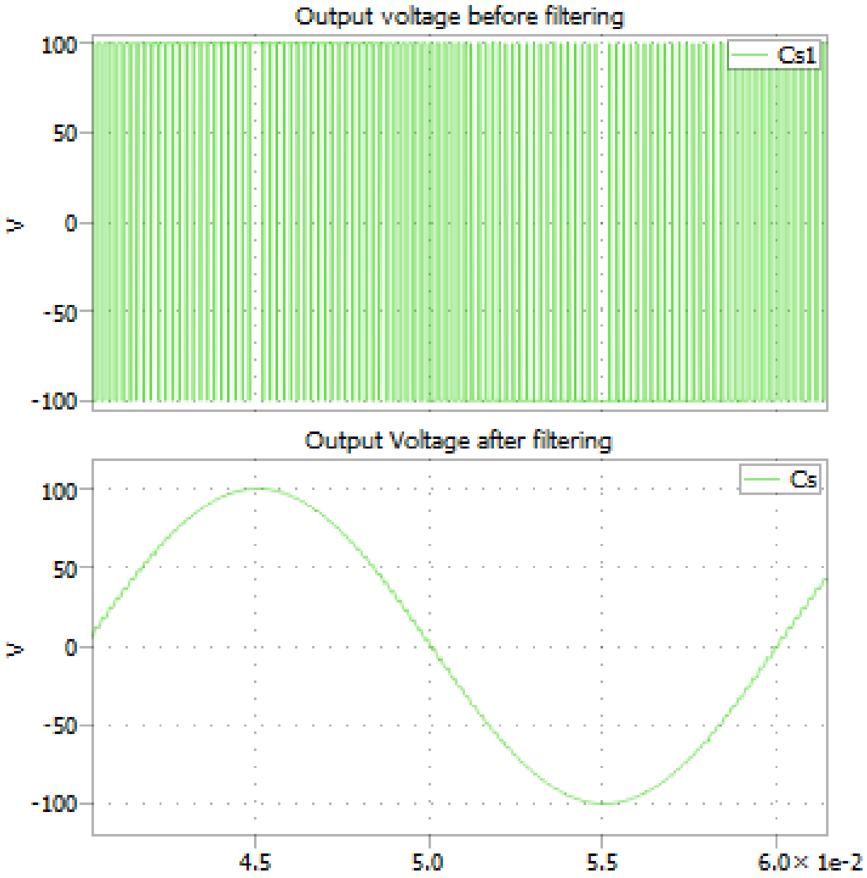
Gating
Pulse



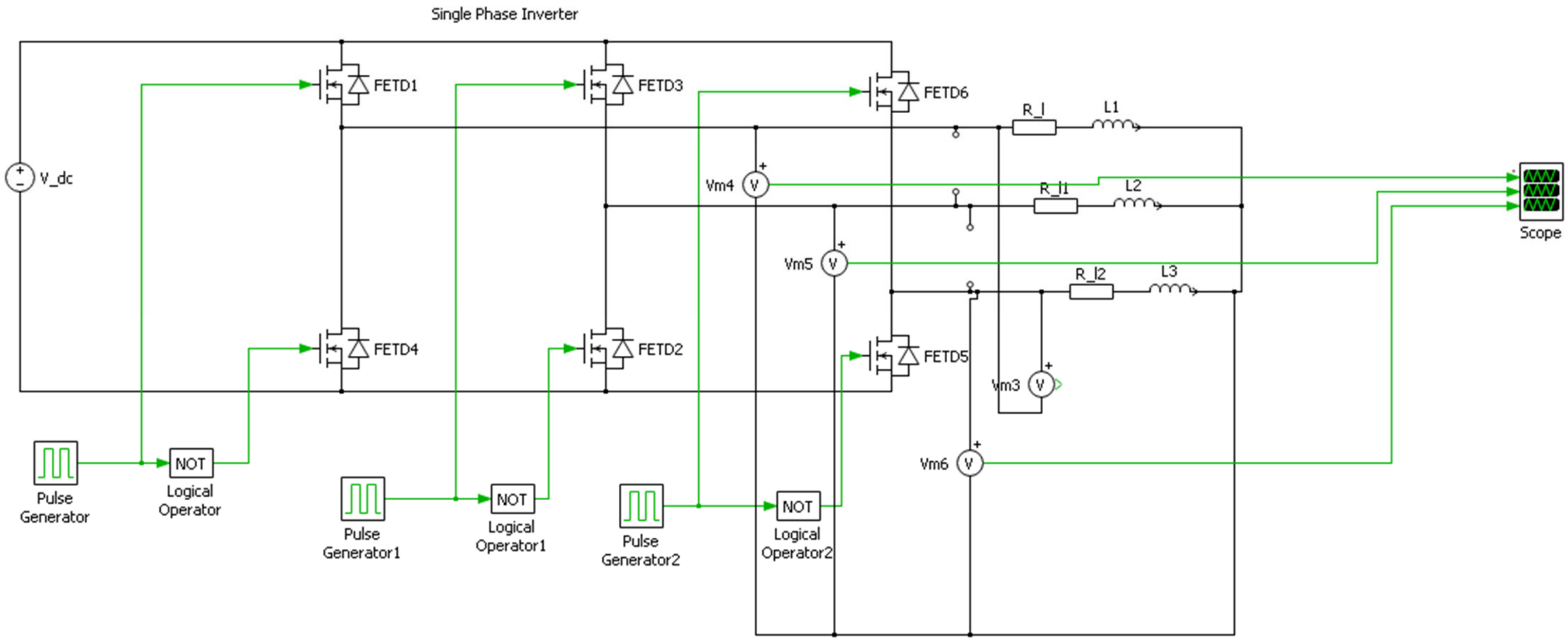
Source: https://electronics.stackexchange.com

Single-phase PWM Inverter Simulation

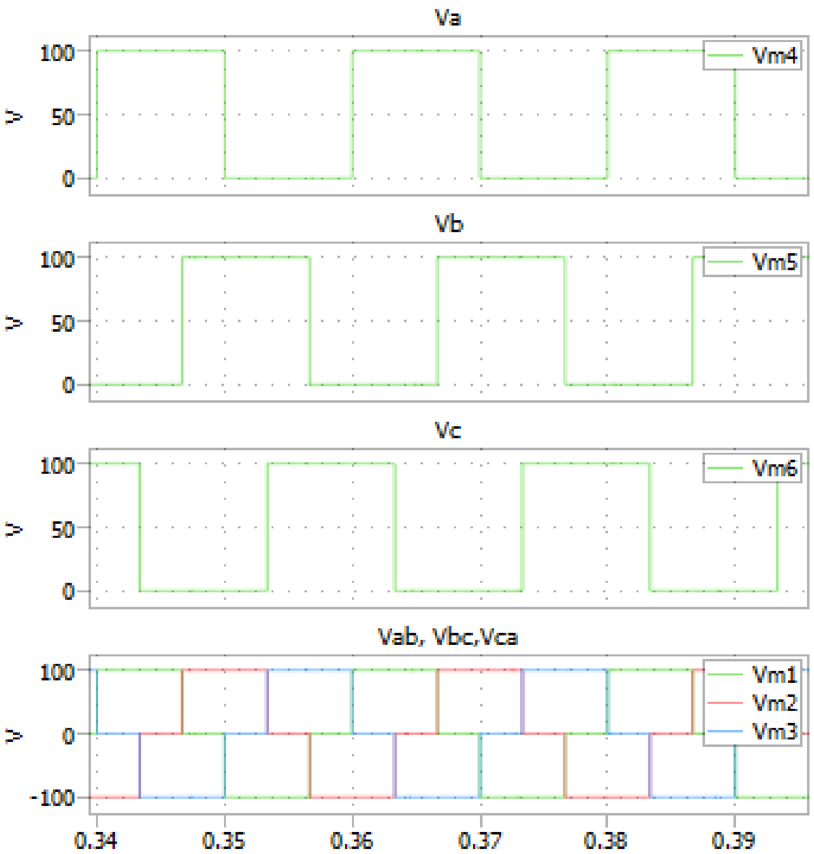


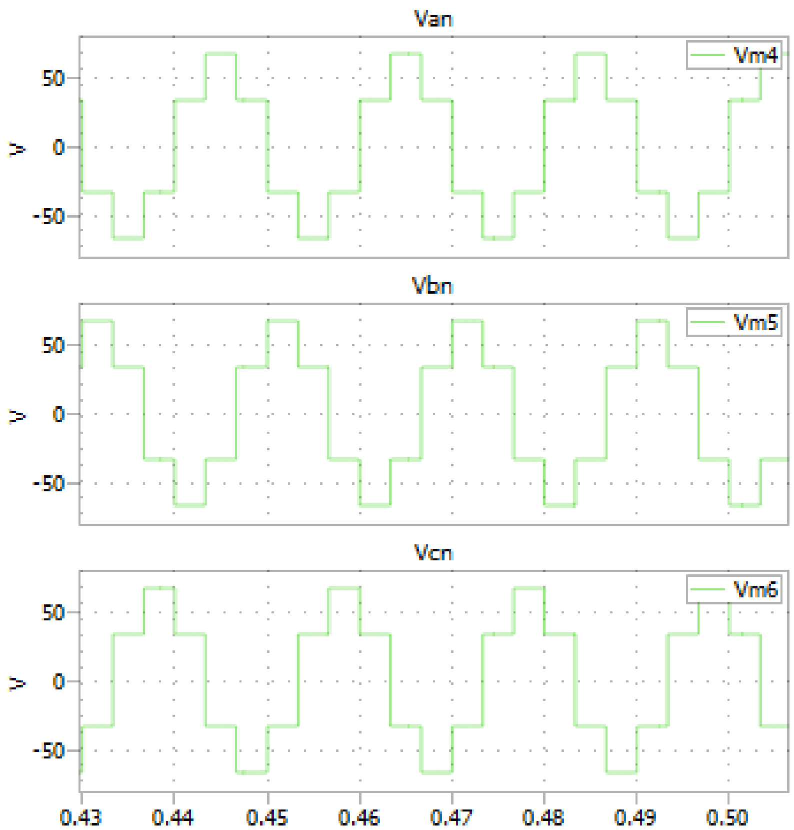


Three-phase inverter

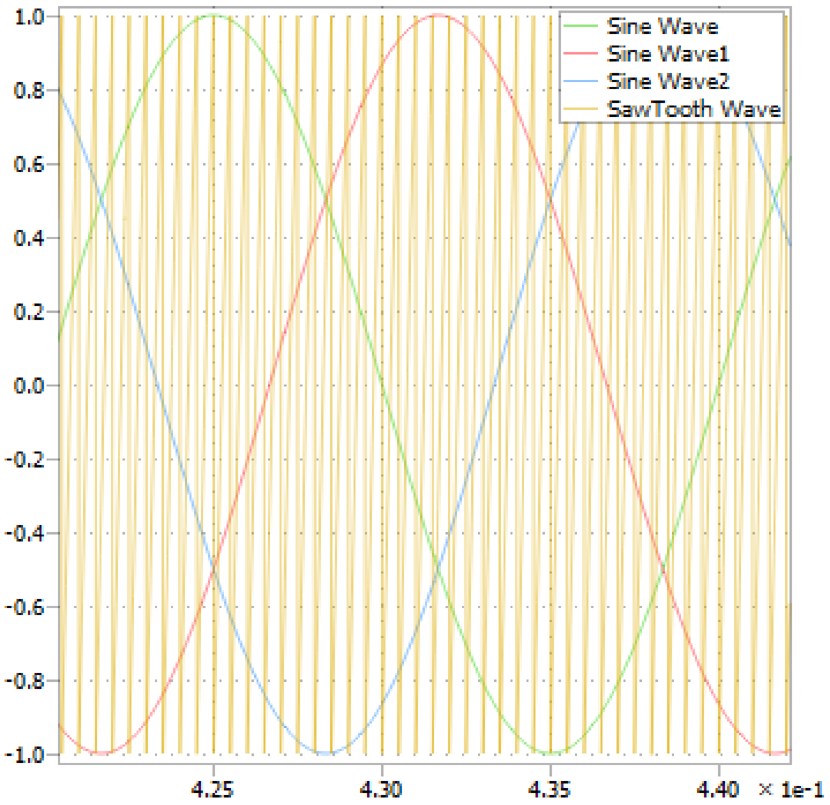


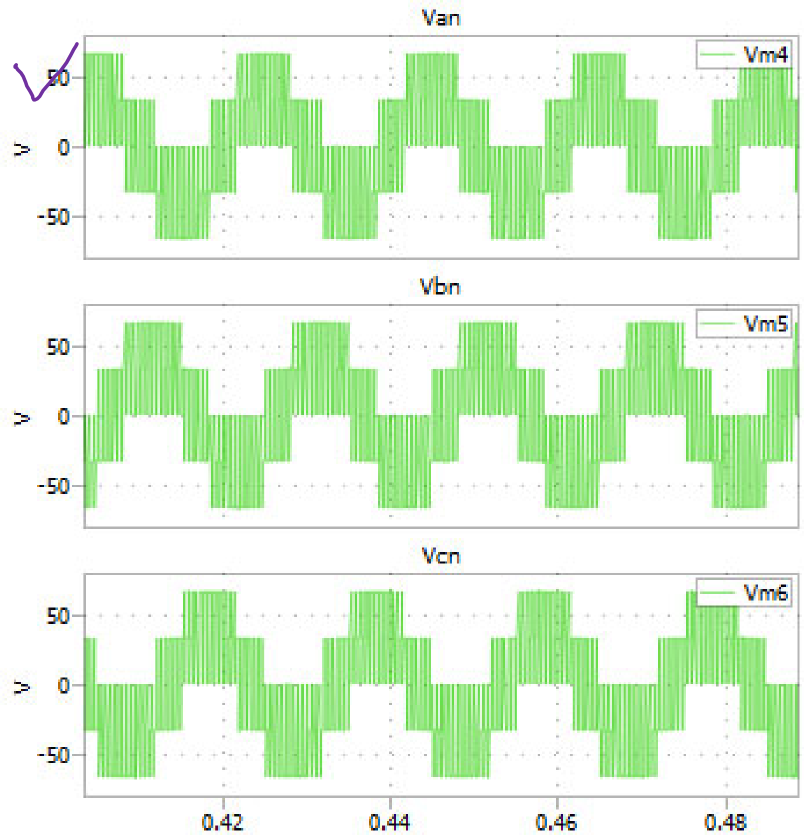
Three-phase inverter with Square-wave gating pulses, six-step phase voltages



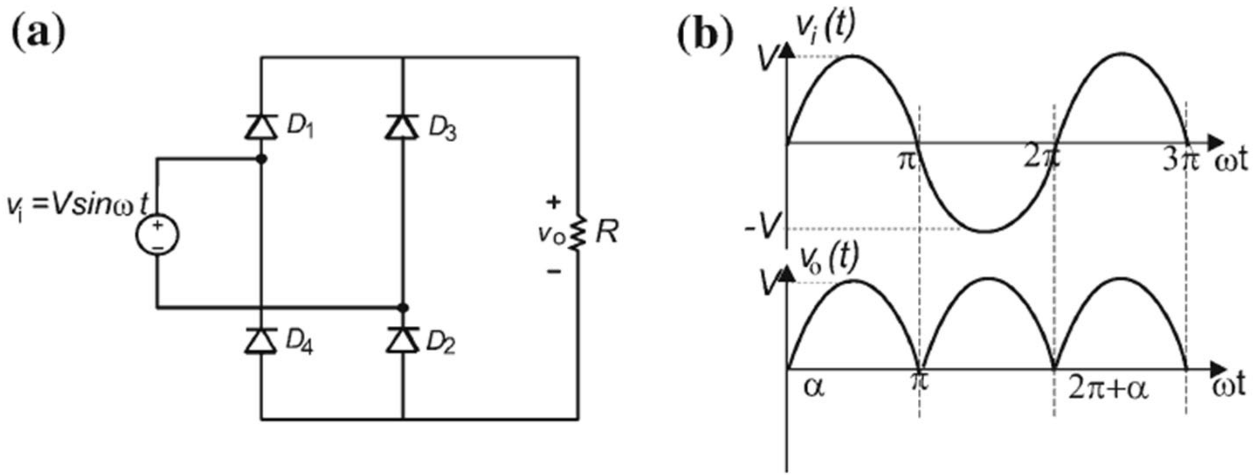


Three Phase PWM Inverter output





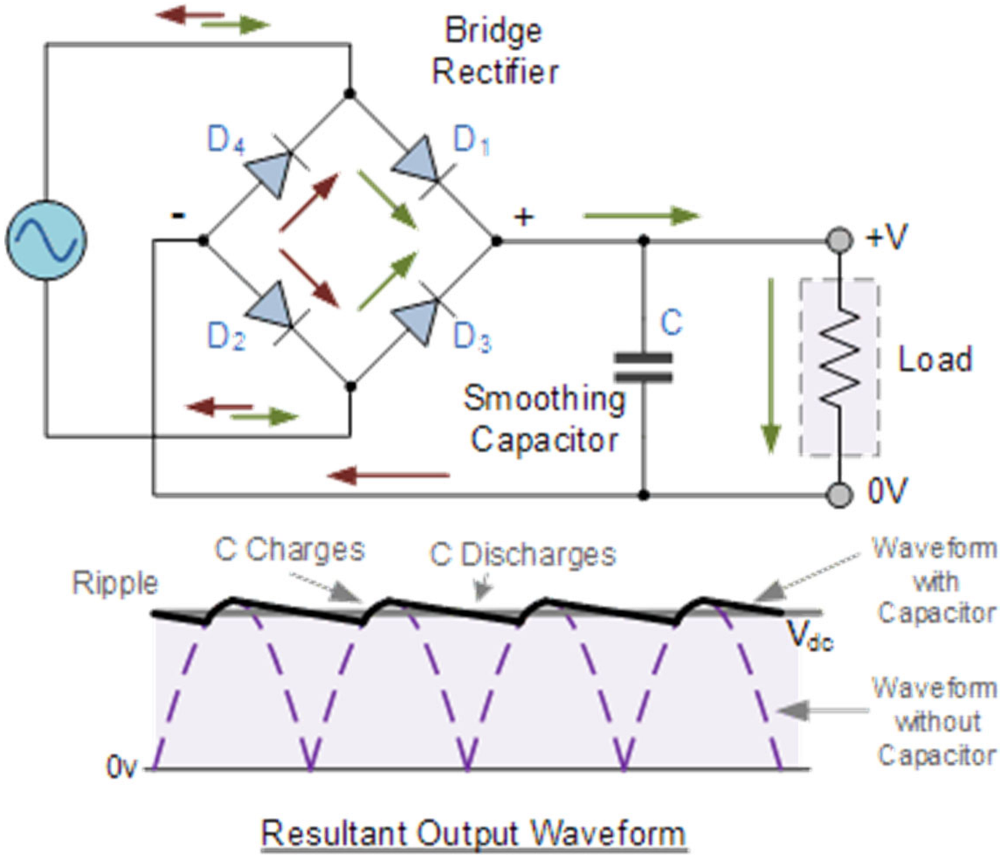
AC/DC Converter:
Single-Phase Diode Bridge Rectifiers



Diode bridgerectifiers: (a) full-bridge (FB), and (b) waveforms

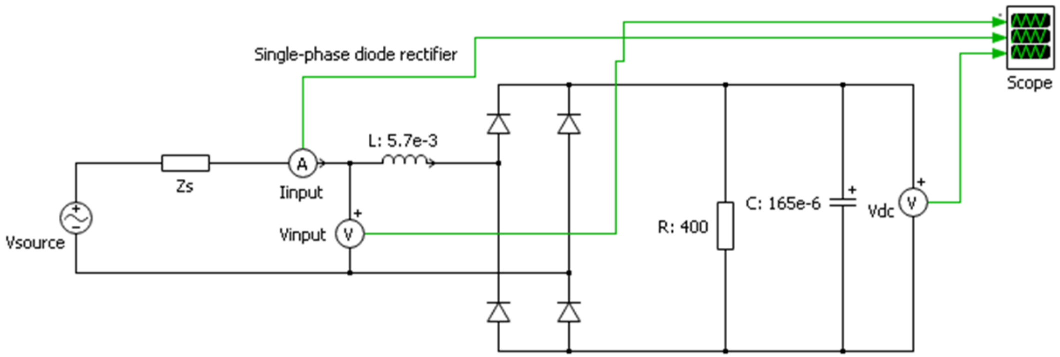
$$V_{avg} = \frac{1}{2\pi}\int_0^{\pi} V \sin \omega t \, \mathrm{d}(\omega t) = \frac{V}{\pi}$$

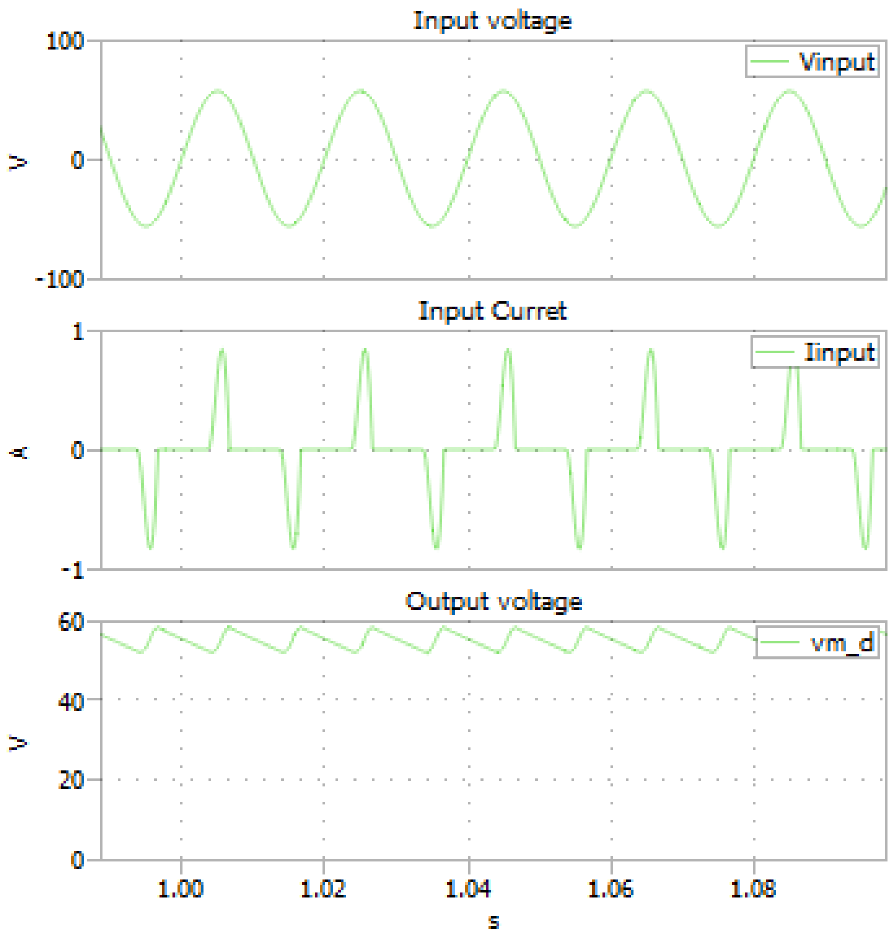
Diode bridge rectifier with capacitor filter



https://www.electronics-tutorials.ws/diode/diode_6.html

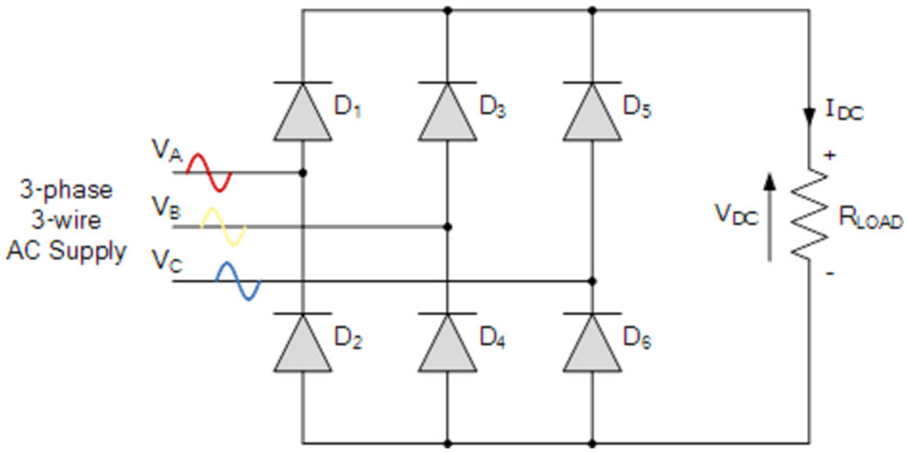
Diode bridge rectifier with capacitor filter
Simulation



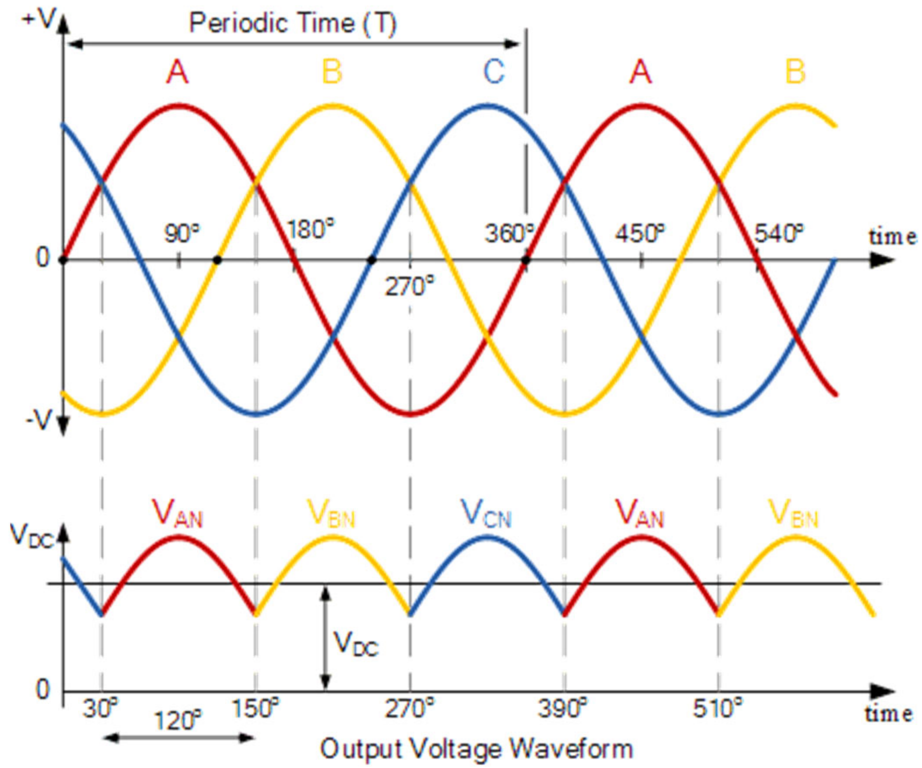


AC/DC Converter:

Three-Phase Diode Bridge Rectifiers

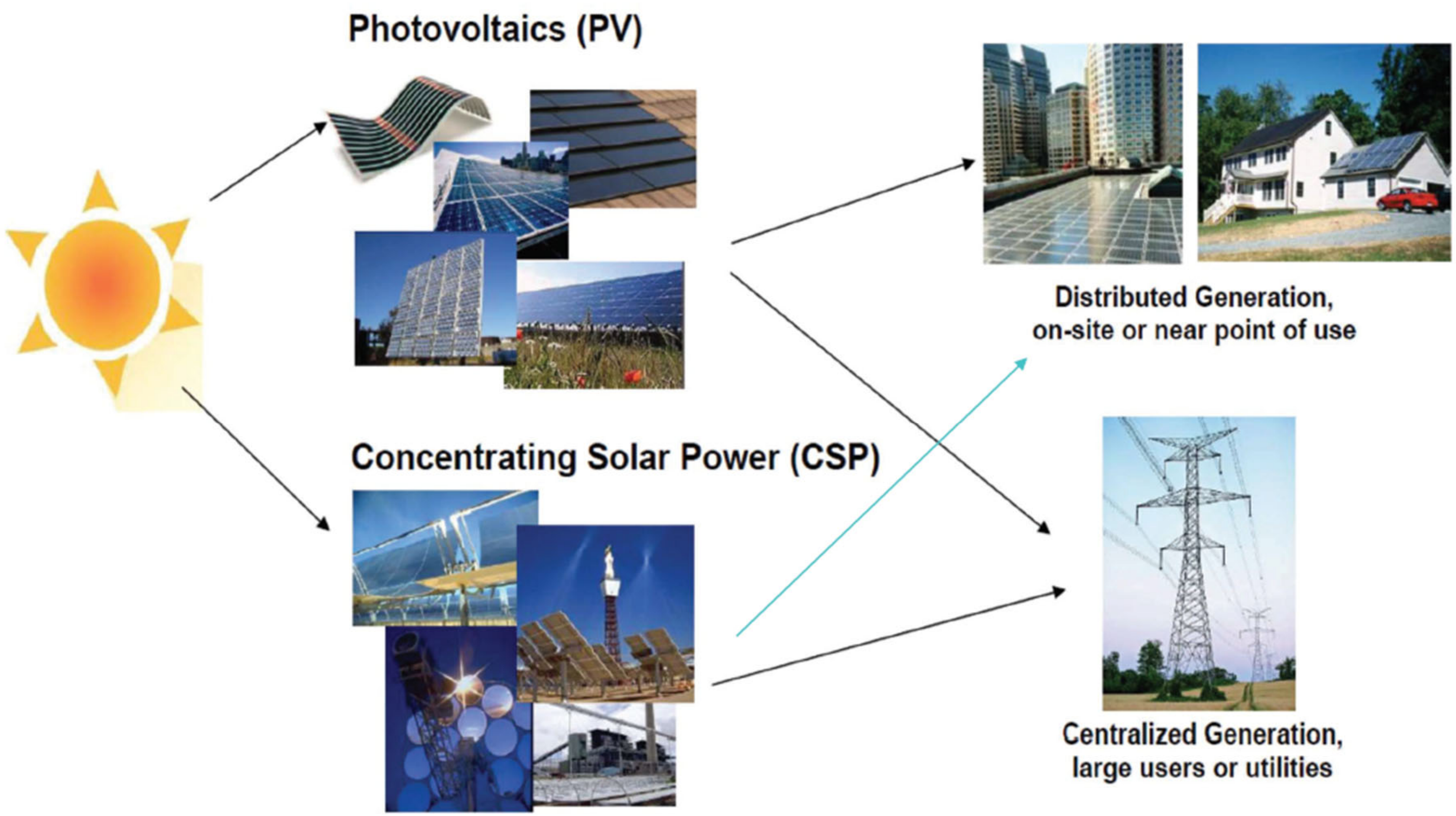


$$V_{avg} = \frac{1}{(2\pi/3)} \int_{\frac{\pi}{6}}^{\frac{5\pi}{6}} V \sin \omega t \, d(\omega t) = \frac{3\sqrt{3}V}{2\pi}$$



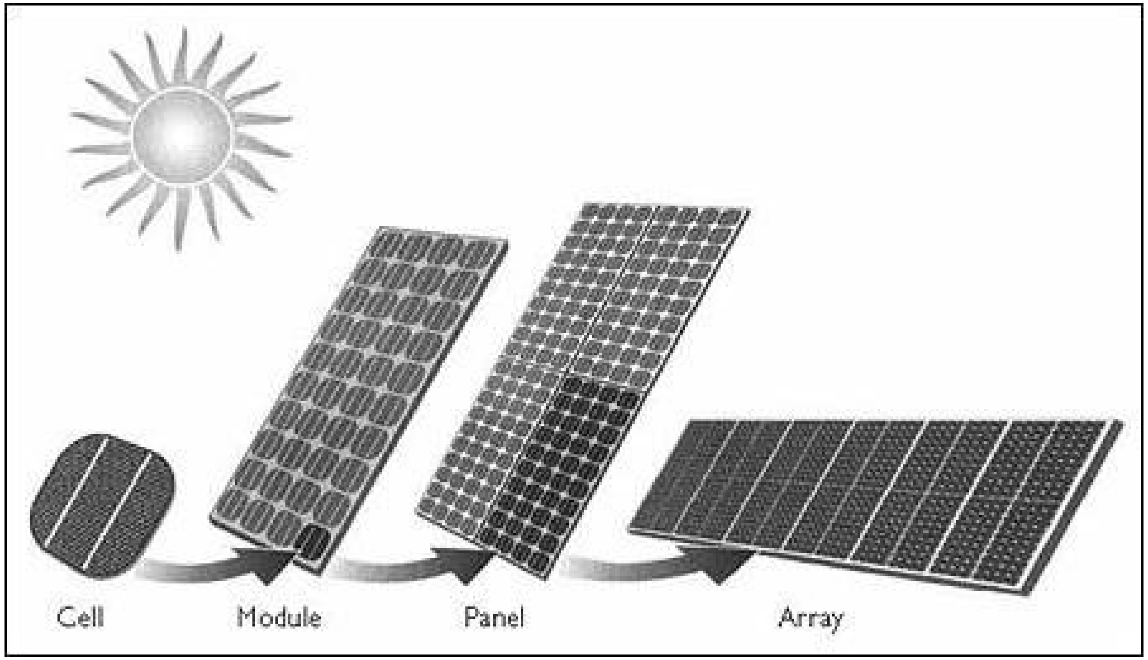
Source : https://www.electronics-tutorials.ws

Solar Energy



Solar PV Energy Generation

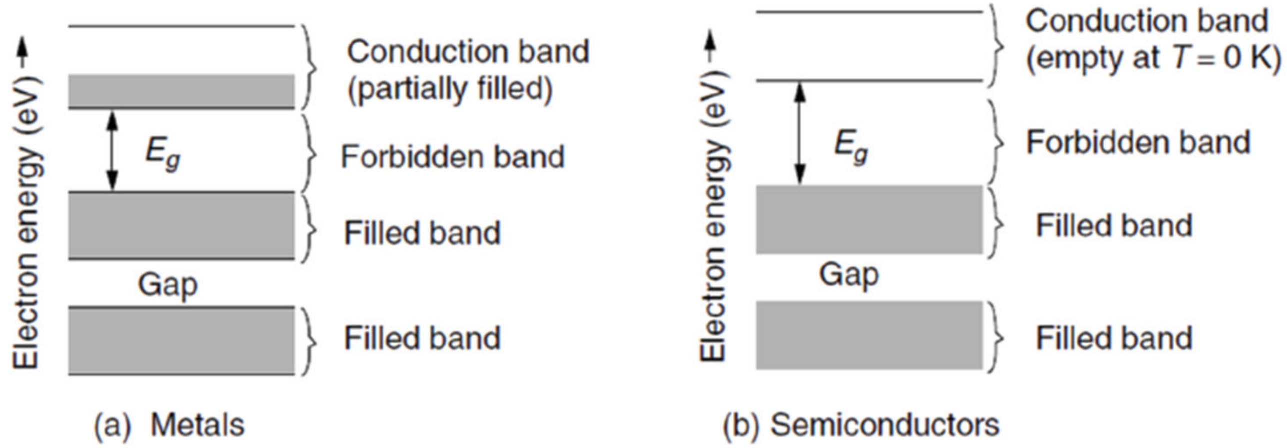
The generation of photovoltaic electrical power with modules is constituted of many photovoltaic solar cells arranged in modules and arrays of modules.



Photovoltaic (PV)

A material that can convert the energy in photons of light into an electrical voltage and current is a photovoltaic.

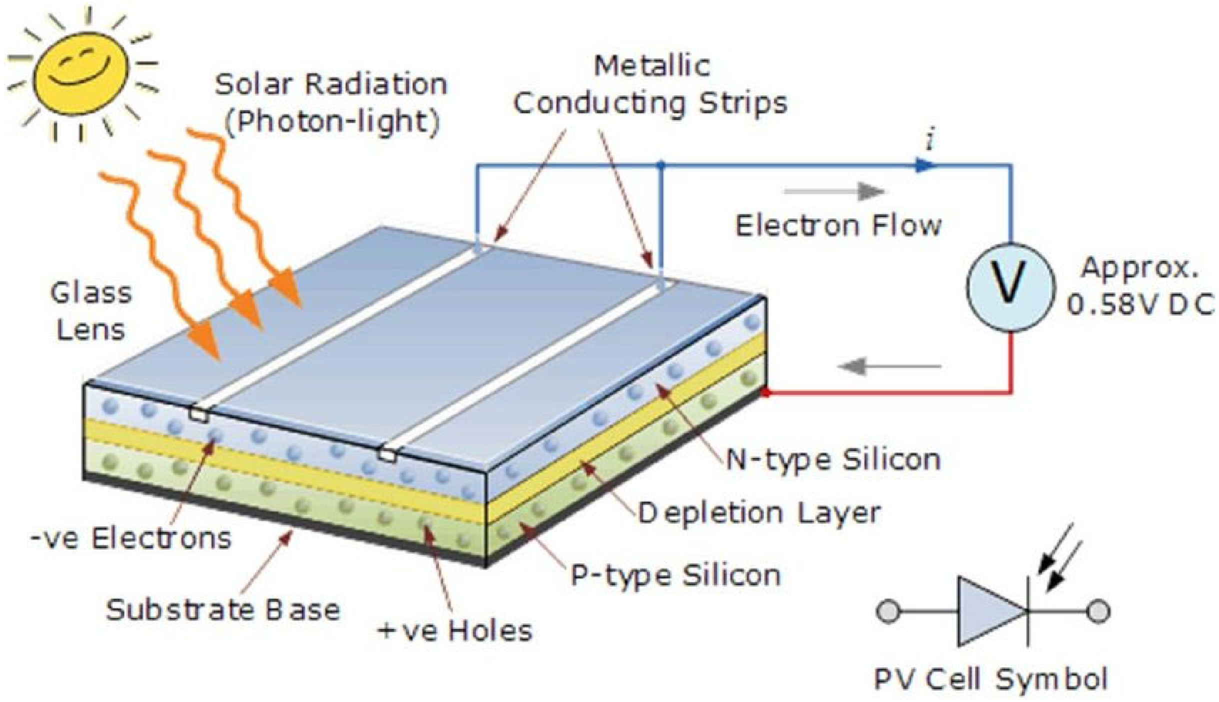
- Photovoltaics use semiconductor material, typically Silicon

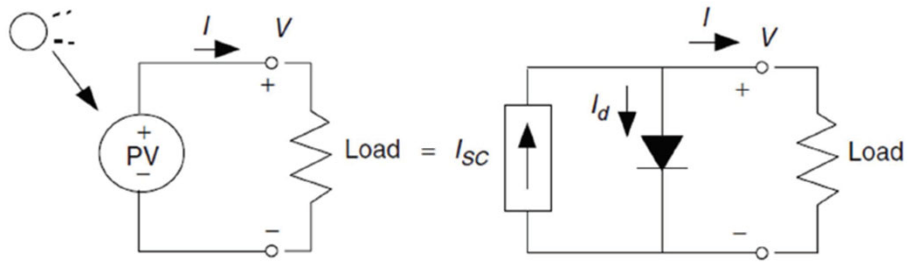


Energy bands for metals and semiconductors

Band gap energy for silicon is 1.12 eV, i.e. the energy required to jump to conduction band

Model of PV Cells





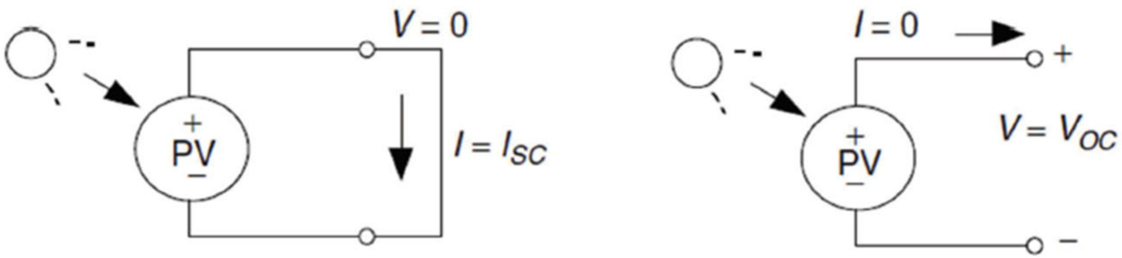
I_{SC}: Short-circuit current depends on the solar irradiance

I_d: Diode current is given as $I_d = I_0 \times \left(e^{qV/nkT} - 1\right)$

I_0: Diode reverse saturation current
q : electron charge 1.6×10^{-19} C
V: Voltage across the diode
k: Boltzmann constant $1.381 \times 10^{-23}\ J/K$
T: Temperature of the junction in Kelvin
n: 1 for Ge and 2 for Si

https://www.researchgate.net/figure/Construction-Diagram-of-PV-Cell_fig7_334697623

Voltage and current equations for the PV cell



(a) Short-circuit current (b) Open-circuit voltage

Current I: $I = I_{SC} - I_d$

From the diode characteristics, substituting for I_d: $I = I_{SC} - I_0\left(e^{qV/kT} - 1\right)$

Current I:Open circuit voltage (when I = 0): $V_{OC} = \frac{kT}{q} \ln\left(\frac{I_{SC}}{I_0} + 1\right)$

At 25^0 C, the equations become:

$\boxed{I = I_{SC} - I_0(e^{38.9\ V} - 1)}$

$\boxed{V_{OC} = 0.0257 \ln\left(\frac{I_{SC}}{I_0} + 1\right)}$

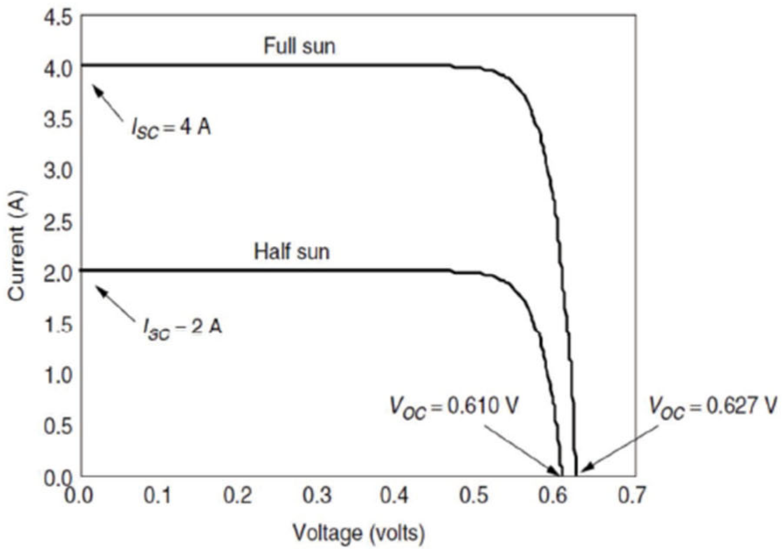
Example **The $I-V$ Curve for a Photovoltaic Cell.** Consider a 100-cm^2 photovoltaic cell with reverse saturation current $I_0 = 10^{-12}$ A/cm^2. In full sun, it produces a short-circuit current of 40 mA/cm^2 at 25°C. Find the open-circuit voltage at full sun and again for 50% sunlight. Plot the results.

Solution. The reverse saturation current I_0 is 10^{-12} A/cm^2 $\times$ 100 cm^2 = 1 $\times$ 10^{-10} A. At full sun I_{SC} is 0.040 A/cm^2 $\times$ 100 cm^2 = 4.0 A. From (8.11) the

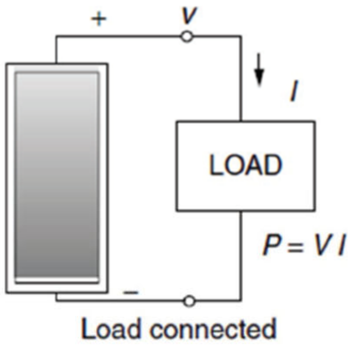
$$V_{OC} = 0.0257 \ \ln\left(\frac{I_{SC}}{I_0} + 1\right) = 0.0257 \ln\left(\frac{4.0}{10^{-10}} + 1\right) = 0.627 \text{ V}$$

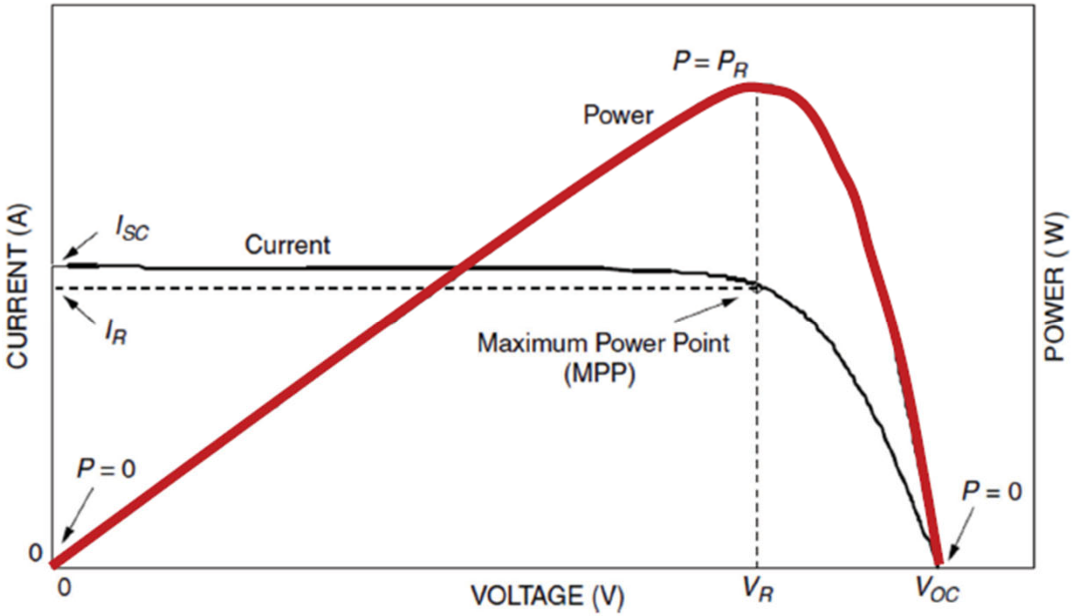
Since short-circuit current is proportional to solar intensity, at half sun $I_{SC} = 2$ A and the open-circuit voltage is

$$V_{OC} = 0.0257 \ln\left(\frac{2}{10^{-10}} + 1\right) = 0.610 \text{ V}$$



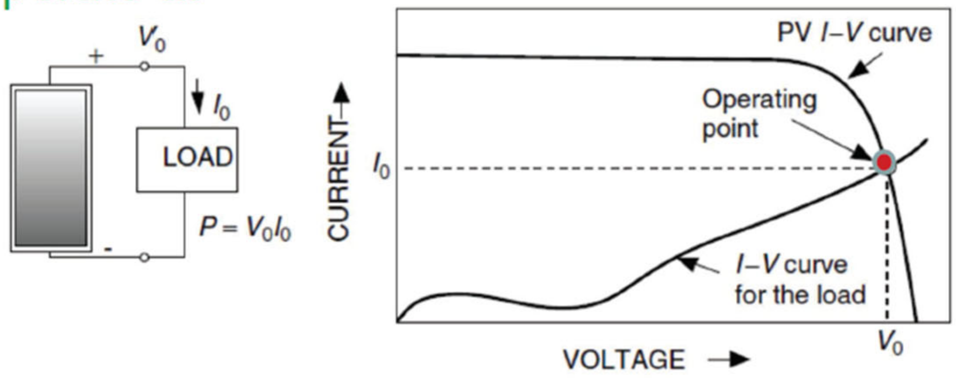
Voltage, Current and Power Curves





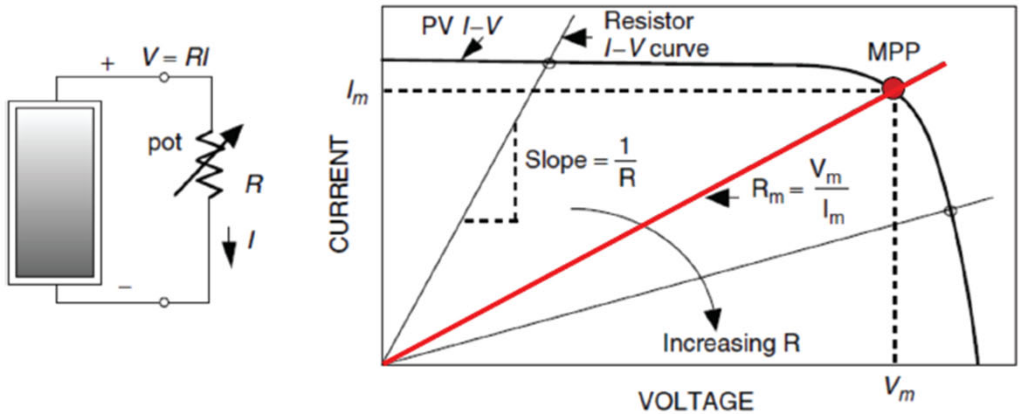
Current-Voltage Curve for Load

- **Operating point** – intersection of curves where the system will finally operate at



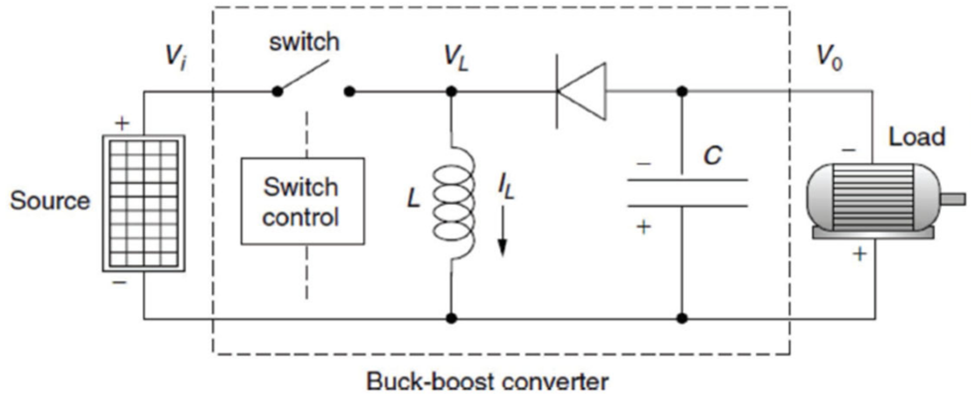
Resistance corresponding to maximum power:

$$R_m = \frac{V_m}{I_m}$$



Maximum Power Point Trackers (MPPT)

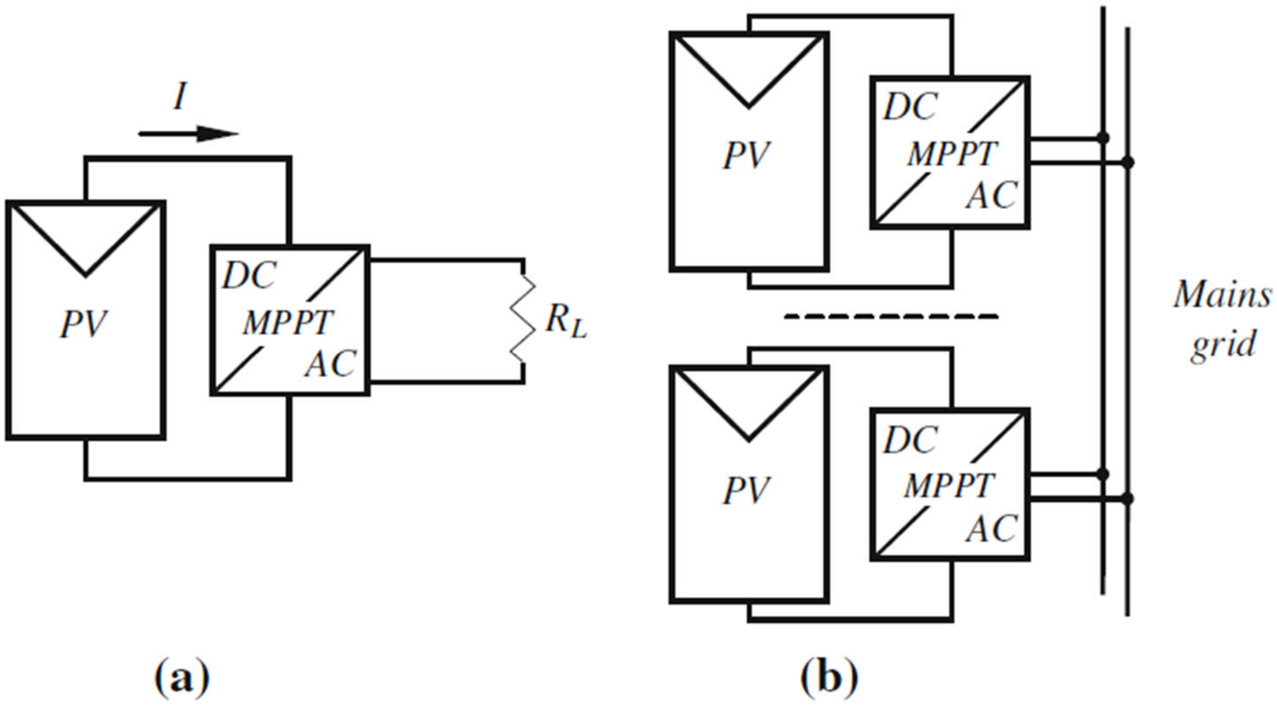
- Standard part of most grid-connected systems
- Commonly use a buck-boost converter (also used in linear current boosters)
    - Raises or lowers the voltage to the desired value needed by load
    - When switch is CLOSE: energy supplied to inductor, and I_L builds up
    - When switch is OPEN: Inductor current flows through C, load and diode
    - With fast switching, inductor current and output voltage are CONSTANT
    - Typically, the on-off switch in this switched-mode dc-dc converter is an IGBT transistor



Maximum Power Point Tracking (MPPT)

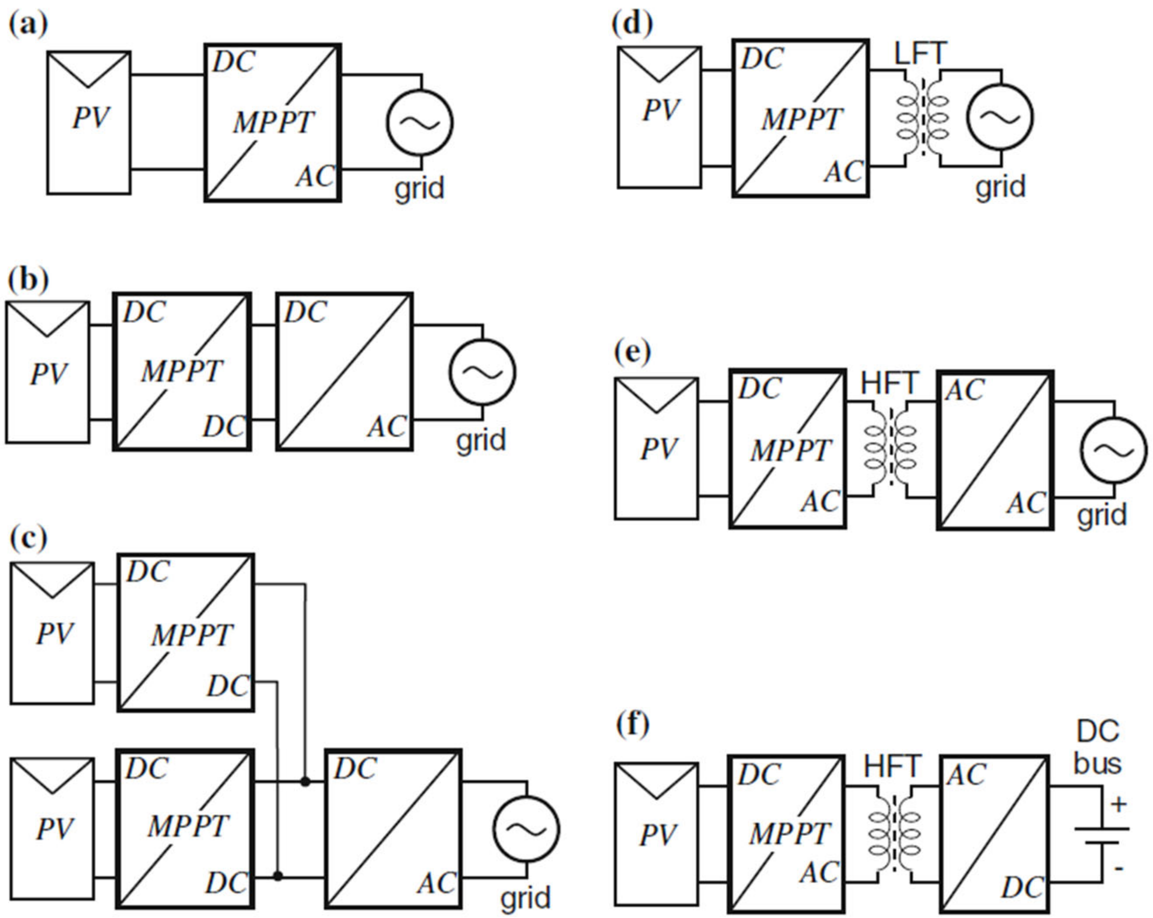
- When dealing with alternative sources of energy, operating at point of maximum power is important.
- Various algorithms are to search for the MPP
  - Hill climbing
  - Constant Voltage
  - Perturb and Observe
  - Incremental Conductance

Module Inverter



Module PV inverter. (a) Module inverter connected to an AC load. (b) Module inverter connected to the grid

Grid-Connected PV Systems



(a) single-stage inverter
(b) double-stage inverter
(c) dual-stage processing for parallel connections
(d) connection through low frequency transformer
(e) connection through high-frequency transformer
(f) connection to a DC bus through high-frequency transformer

Advantage of Solar PV

Photovoltaic electrical power generation is a very attractive means to produce energy for several reasons:

- As it is modular, it is quick to install.
- The solar energy that is produced can match well with daylight loads.
- It has no moving parts.
- The systems do not produce noise or pollution
- Low maintenance.
- Highly reliable and can produce power for a long period of time.

Solar PV installation

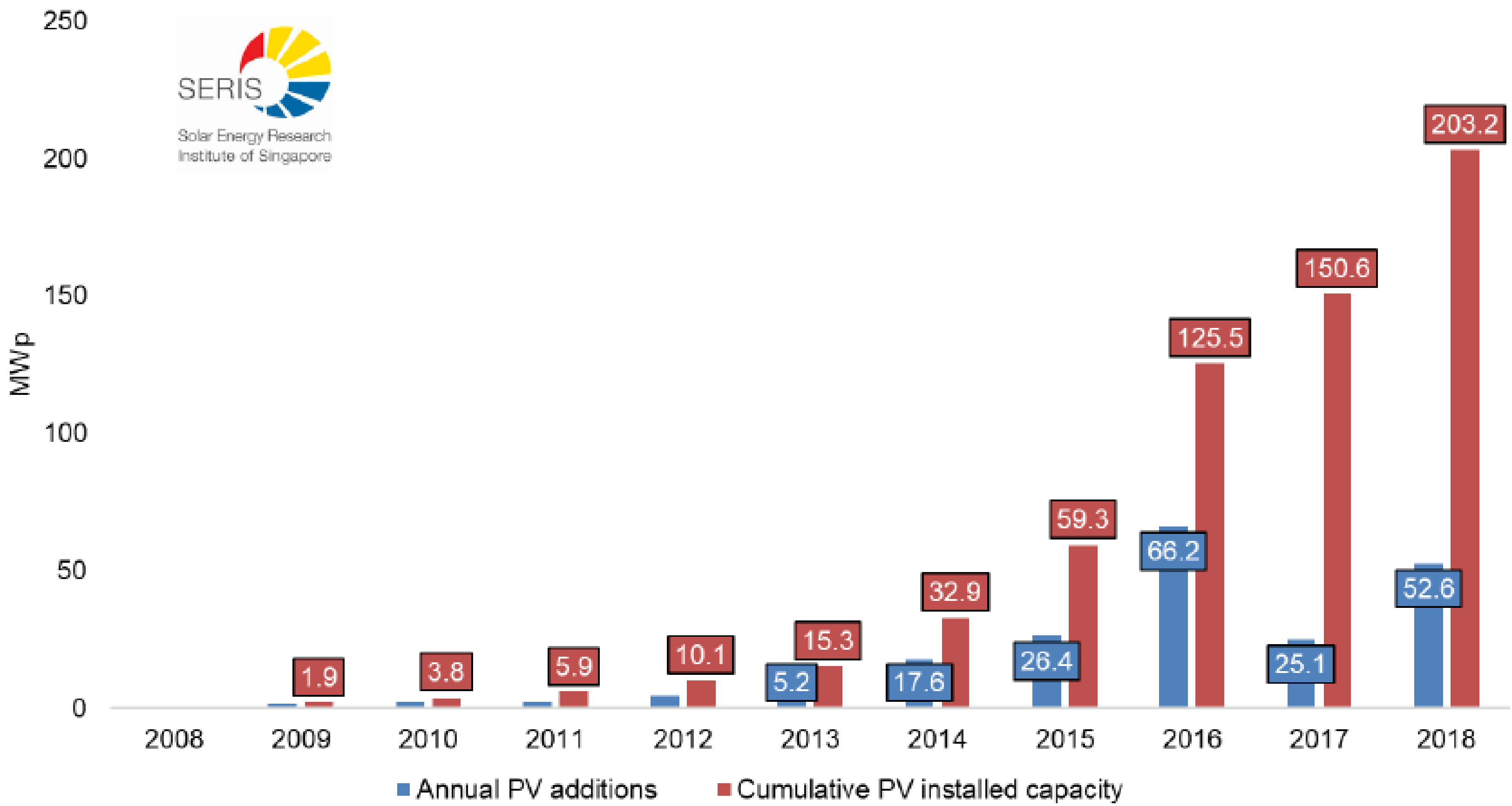
- The sunlight energy produces an average of 1,372 W/m2 on the earth's outer atmosphere.
- On their way to the Earth surface the sunrays go through air layers, clouds, and haze, reducing the received surface energy.
- At earth's surface it is about 1,000 W/m2 or less.
- The PV panels should be so installed so that the sun rays hit the panels at right angle
- A two axis tracking system can be used to track the movement of the sun during the day as well during the year.
- With a good sun tracker it is possible to increase the electricity production from about 15 to 30 %.

Solar PV system on an HDB building

The floating solar photovoltaic testbed at Tengeh Reservoir

In October 2016, the largest ever floating solar photovoltaic system in Singapore formally completed the grid connection and went into operation. The installed capacity was 204kW, using SRP-315-6PA modules.

Singapore annual and cumulative PV installed capacity (2008-2018).

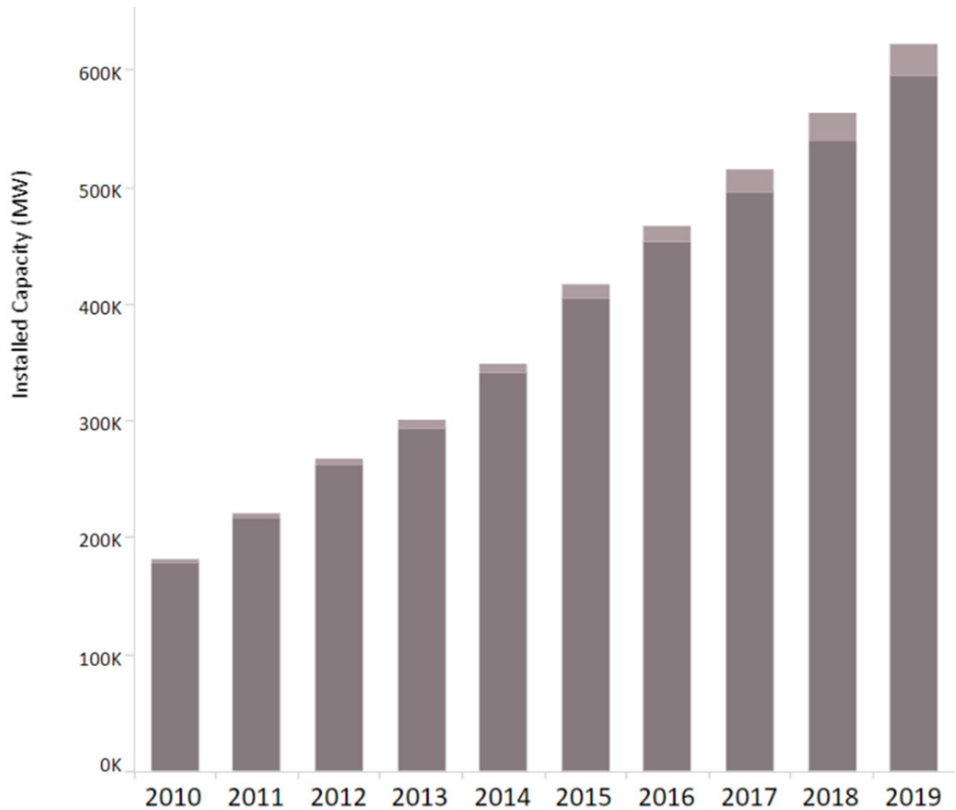


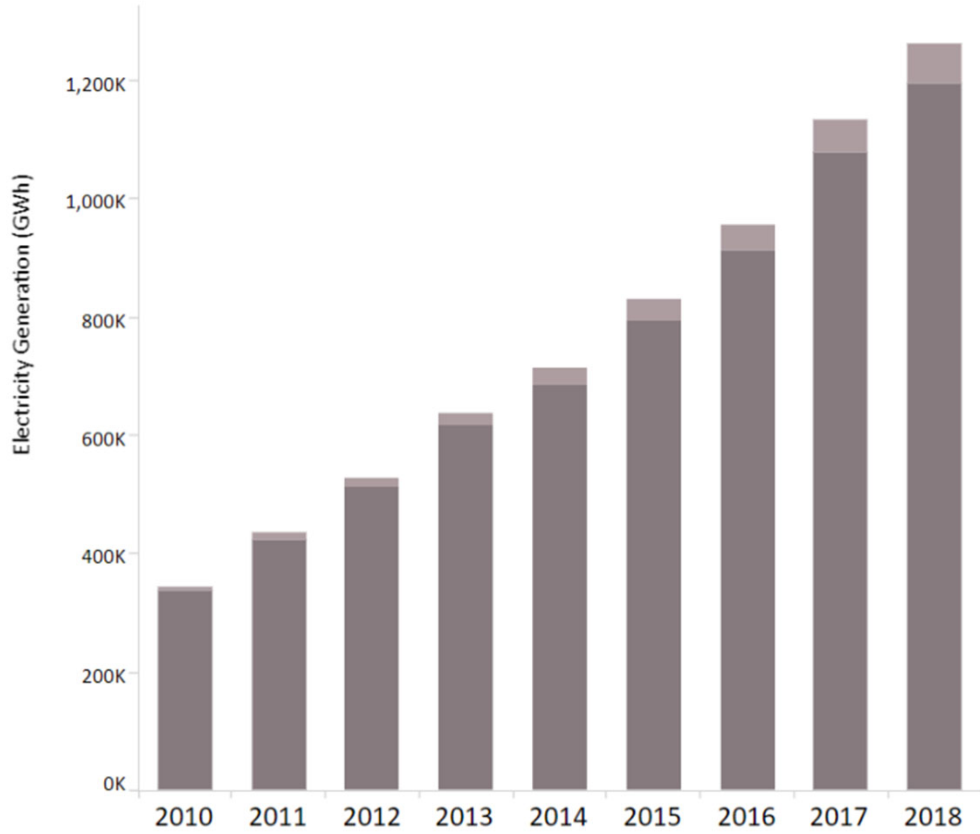
Wind Energy

Wind Energy

- The wind is a free, clean, and renewable energy source on our planet.
- The kinetic energy inherent in the wind is converted to electrical energy
- Wind turbines and wind power plants (WPPs) rely on electrical machinery and power converters work together to achieve this purpose in an optimal and stable fashion.
- The US continued to see growth and remains on top in total installed capacity followed by China and Germany.
- Singapore does not have much potential for wind energy.

Wind Energy Data





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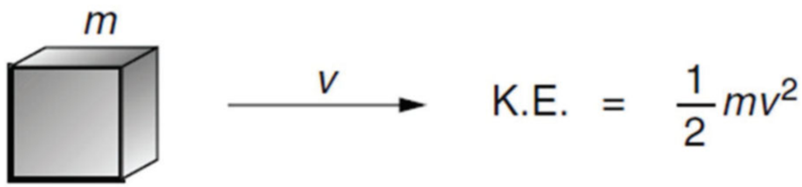
Wind Energy Basics

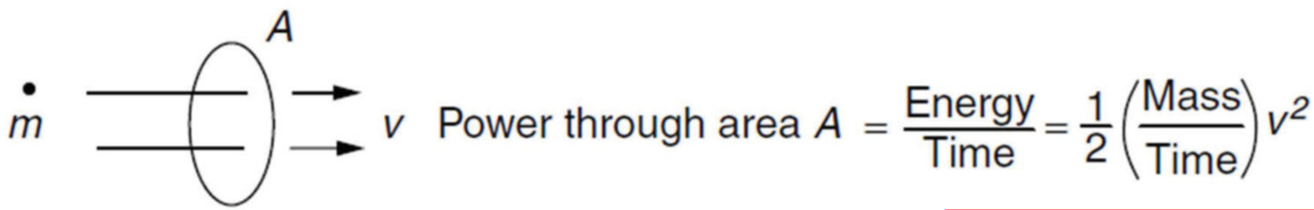
- The atmosphere receives heat energy from the sun.
- In the process, regions of lower and higher pressure are developed in the air.
- This pressure differences cause winds to blow.
- Factors like solar radiation, surface cooling, humidity, complexity of terrain, rotation of the earth, etc. also affect the wind.
- Accurate estimation of wind energy potential is the most important element in selecting a site for a future winder power plant.

Power In The Wind

- Consider a "packet" of air with mass 'm' moving at a speed 'v'.
- Its kinetic energy K.E., is given by the familiar relationship



- Since power is energy per unit time, the power represented by a mass of air moving at velocity *v through area A will be*



$$P_w = \frac{1}{2}\dot{m}v^2 = \frac{1}{2} \times \rho A v \times v^2 = \frac{1}{2}\rho A v^3$$

ρ – Density of air
A – Cross section area
v – Velocity of wind

Observations from the Equation for Power

- Power in the wind depends on
  - Density of air
  - Swept area of the wind turbine rotor
  - Wind Speed

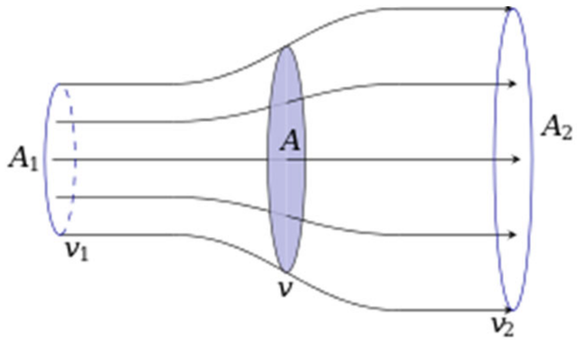
$$\boxed{P_w = \frac{1}{2}\rho A v^3}$$

- Power increases at cube of wind speed. Small increase in wind speed results in large change in power output.
- Average wind speed cannot be used to calculate the average power output of a wind turbine.

Power Extracted From Wind:

Albert Betz's Formulation

- Betz derivation explains the constraint that limits the ability of a wind turbine to convert kinetic energy in the wind to mechanical power.
- Turbine blades remove energy from wind, hence wind is slowed down as a portion of its kinetic energy is extracted.
- The wind leaving the turbine is of lower pressure than the incident wind, and therefore its volume.
- The power extracted depends on ratio of the exit speed to inlet speed.



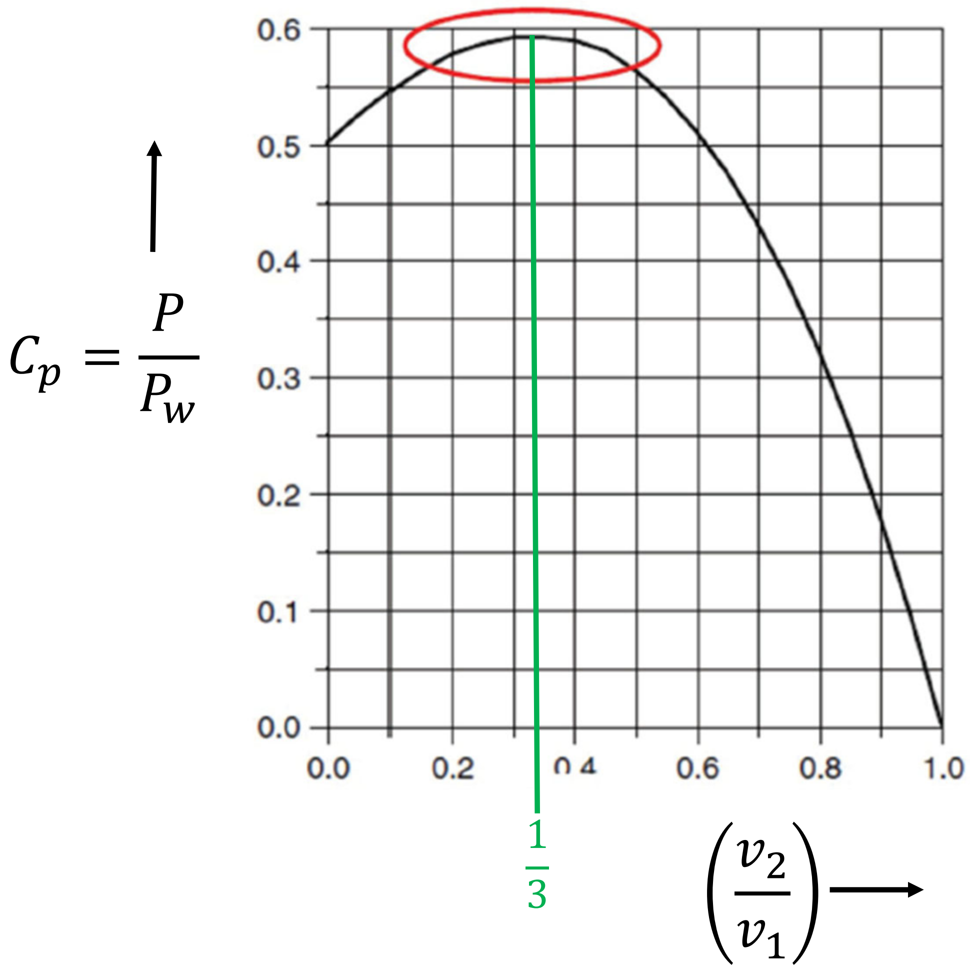
$$A_1 v_1 = A_2 v_2 = Av$$

$$P = \frac{1}{2}\rho \mathrm{A} \frac{v_1 + v_2}{2}(v_1^2 - v_2^2)$$

With $\lambda = \frac{v_2}{v_1}$, $P = \frac{1}{2}\rho A v_1^3 \frac{1+\lambda}{2}(1 - \lambda^2)$

$$P = \frac{1}{2}\rho A v_1^3 \cdot C_P$$

Rotor Efficiency, C_P

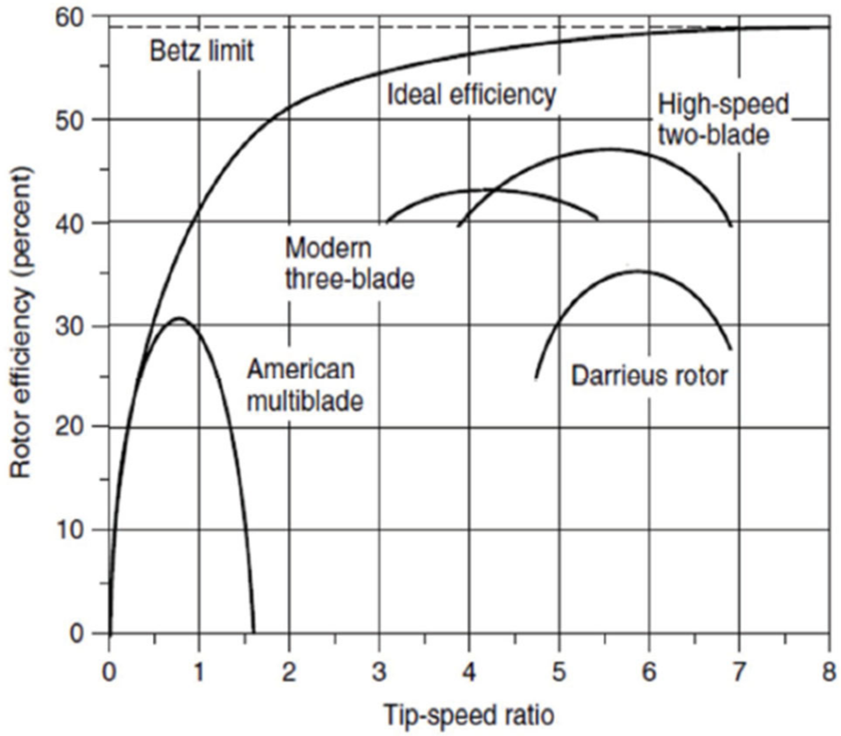


- Maximum theoretical efficiency of a rotor is 59.3%.
- This is known as the Betz efficiency or Betz's law.

Tip Speed Ratio (TSR)

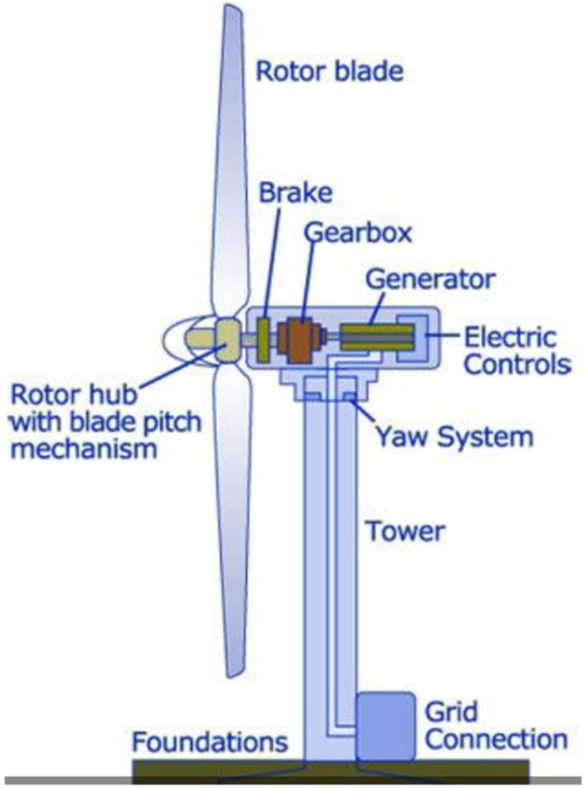
$$TSR = \frac{rotor\ speed}{wind\ speed} = \frac{rpm\ \times\ \pi D}{v}$$

- If TSR is high, it means that the blade spins too fast, and that the blade will experience turbulent wind.
- If TSR is low, it means that the blade spins too slowly, and it can not efficiently capture wind energy.

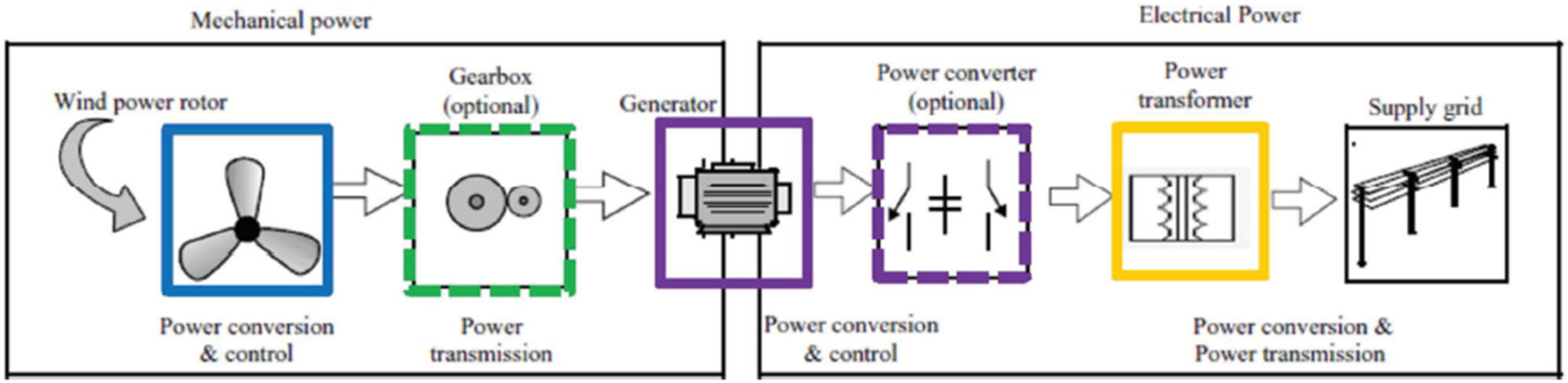


Wind Turbines

- Wind turbines produce electrical power by converting the kinetic energy of wind into mechanical power with subsequent conversion into electrical power by means of an electrical generator.
- Gearboxes are used to increase the speed of rotating shaft to a level appropriate for generator to operate.
- Power electronic converters are used in variable-speed wind turbines to convert generator varying voltage and frequency to the constant level required by the utilities.
- The power output then goes to a transformer, which converts voltage to a collection level (usually 35 kV).



Wind Energy Conversion Systems (WECS)



Power extracted by the rotor at low rotational speed, typically at 10-15 rpm.

Gearbox is used to increase rotational speed to a higher rpm to generate 50/60Hz electricity.

Generators and power converters are the main components to make sure that WECS produce high quality voltage supplies.

Transformers are used to step-up the voltage to connect the generator to the grid.