SECTION 2: ENERGY STORAGE FUNDAMENTALS

ESE 471 – Energy Storage Systems

Performance Characteristics

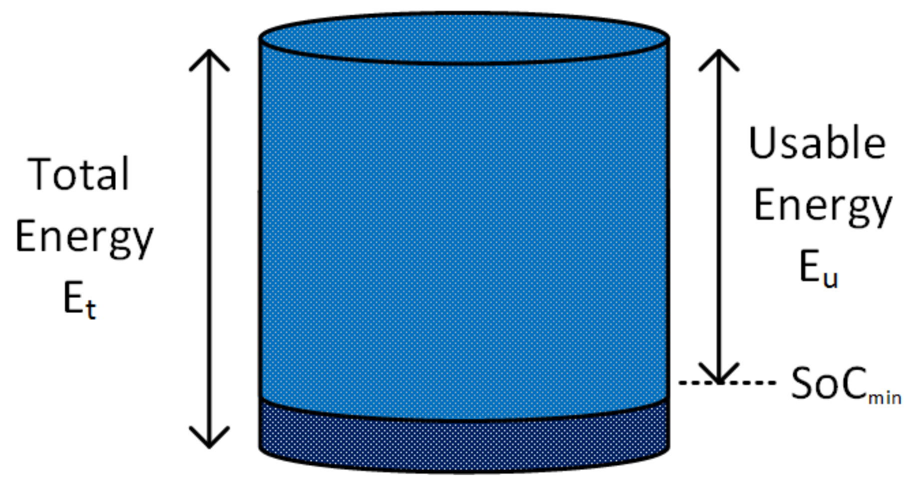
Energy Storage Performance Characteristics

- Defining performance characteristics of energy storage mechanisms
  - ***Capacity***
  - ***Power***
  - ***Efficiency***

Capacity

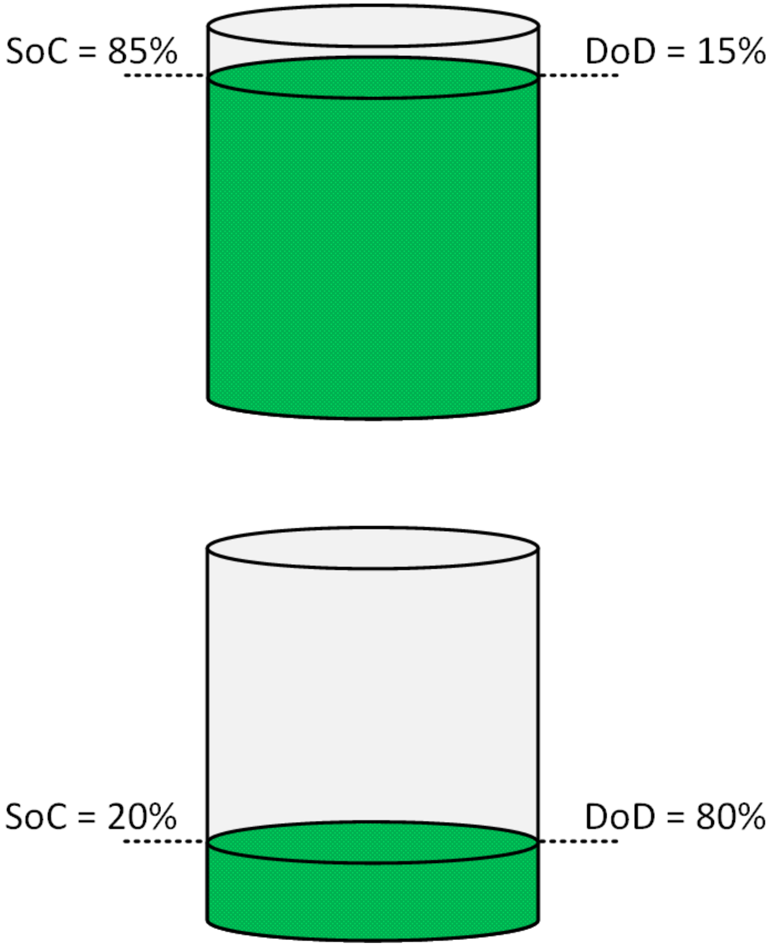
- **Capacity**
  - The amount of ***energy*** that a device can store
- ***Total energy capacity***, E_t
  - Total energy stored in a device when fully charged
- ***Usable energy capacity***, E_u
  - The total energy that can be extracted from a device for use
  - Difference between stored energy at maximum state of charge (SoC) and minimum SoC
  - In general, storage devices are not fully discharged, so typically

$$E_u < E_t$$



Capacity

- Units of capacity:
  - Watt-hours (Wh)
  - (Ampere-hours, Ah, for batteries)
- ***State of charge*** (SoC)
  - The amount of energy stored in a device as a percentage of its total energy capacity
    - Fully discharged: SoC = 0%
    - Fully charged: SoC = 100%
- ***Depth of discharge*** (DoD)
  - The amount of energy that has been removed from a device as a percentage of the total energy capacity



Capacity

- We can also characterize storage devices in terms of size or mass required for a given capacity
- ***Specific energy***
  - Usable energy capacity per unit ***mass***
  - Units: Wh/kg

$$e_m = \frac{E_u}{m}$$

- ***Energy density***
  - Usable energy capacity per unit ***volume***
  - Units: Wh/m^3 or Wh/L

$$e_v = \frac{E_u}{V}$$

- These are very often used (incorrectly) interchangeably

Power

- ***Power*** is an important metric for a storage system
  - Rate at which energy can be stored or extracted for use
    - Charge/discharge rate
  - Limited by loss mechanisms
- ***Specific power***
  - Power available from a storage device per unit mass
  - Units: W/kg

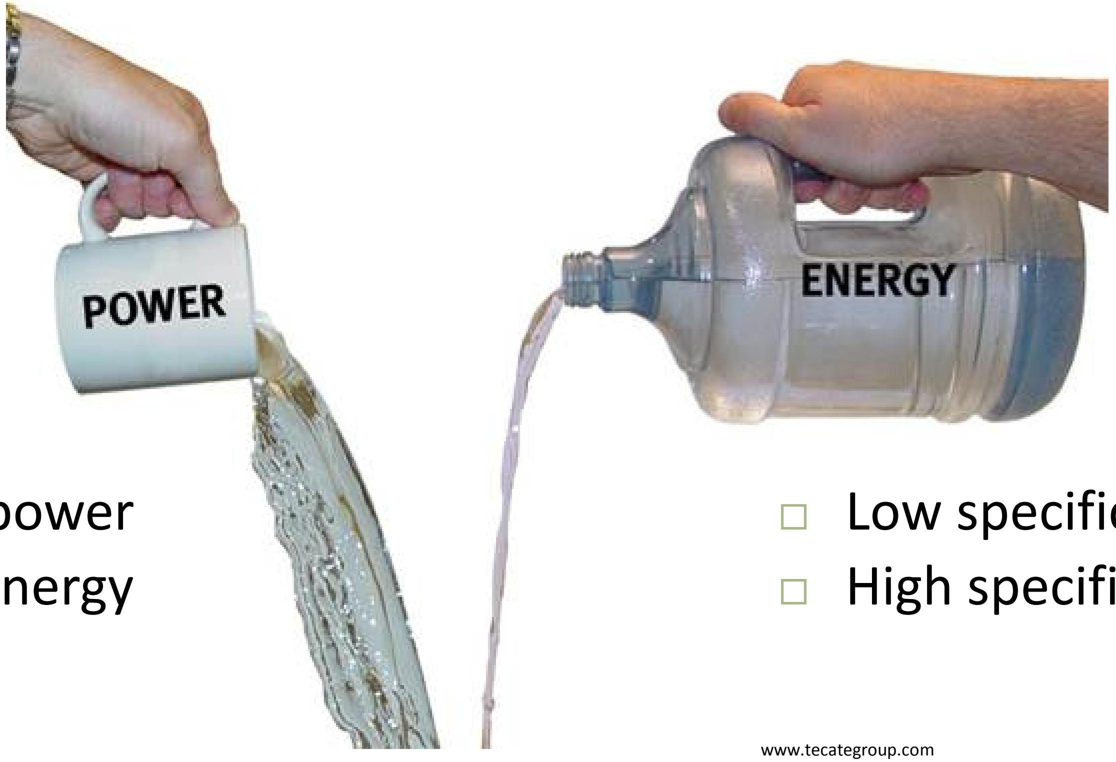
$$p_m = \frac{P}{m}$$

- ***Power density***
  - Power available from a storage device per unit volume
  - Units: W/m^3 or W/L

$$p_v = \frac{P}{V}$$

Power vs. Energy

- Capacity and the rate at which energy can be stored or extracted are different characteristics
  - Applications determine which is most important



- High specific power
- Low specific energy

- Low specific power
- High specific energy

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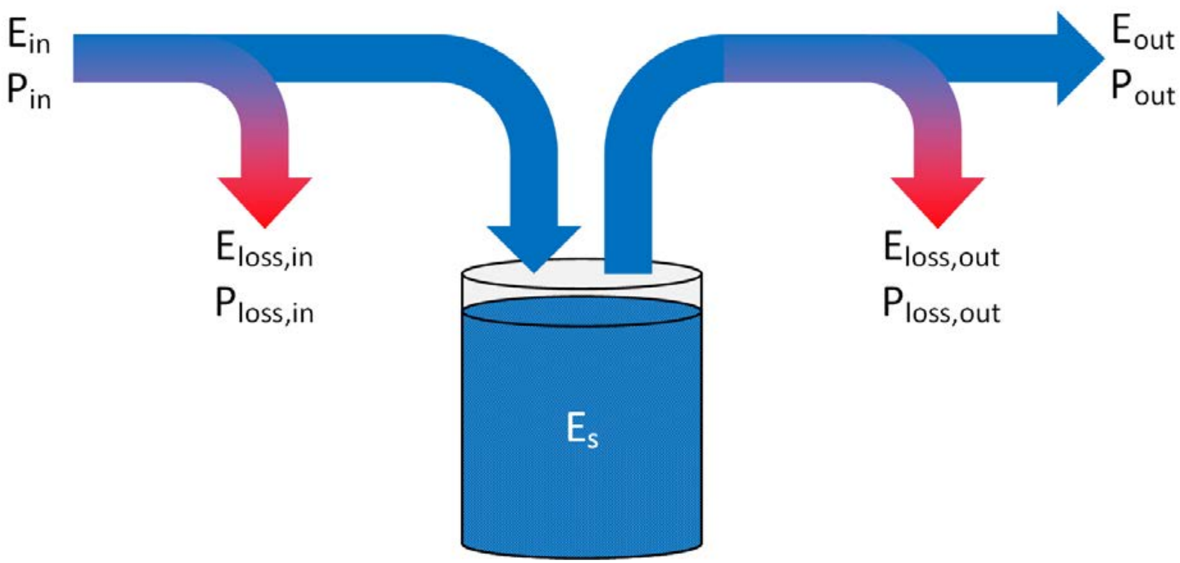
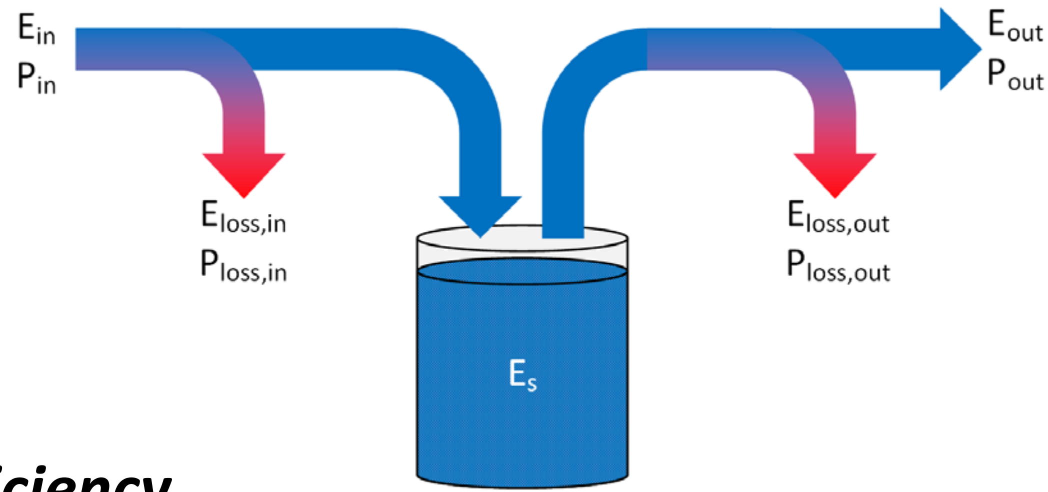
Efficiency

- Another important performance characteristic is efficiency
  - The percentage of energy put into storage that can later be extracted for use
- All storage systems suffer from losses
  - Losses as energy flows into storage
  - Losses as energy is extracted from storage



Round-Trip Efficiency



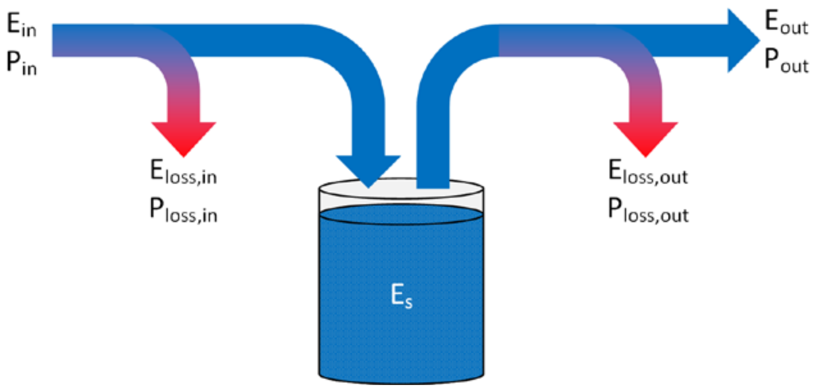
- ***Round-trip efficiency***
  - Energy extracted from a storage system as a percentage of the energy put into the system

$$\eta_{rt} = \frac{E_{out}}{E_{in}}$$

$$\eta_{rt} = \frac{E_{in} - E_{loss,in} - E_{loss,out}}{E_{in}}$$

Round-Trip Efficiency

- We can define a ***charging efficiency***
  - Amount of energy stored as a percentage of the energy input



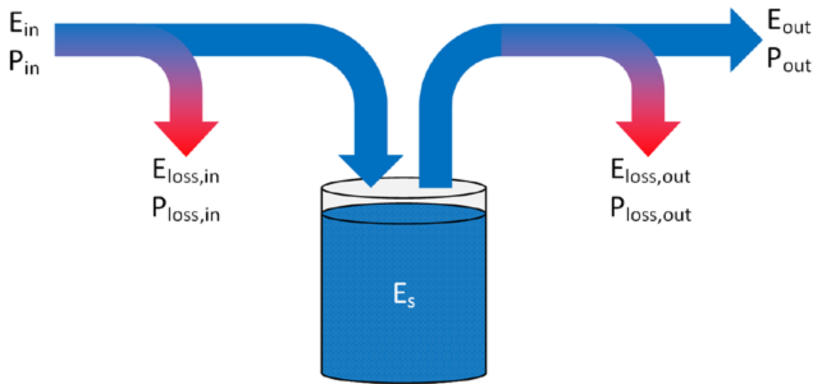
$$\eta_{in} = \frac{E_s}{E_{in}} = \frac{E_{in} - E_{loss,in}}{E_{in}}$$

- And a ***discharging efficiency***
  - Amount of energy output as a percentage of the energy stored

$$\eta_{out} = \frac{E_{out}}{E_s} = \frac{E_s - E_{loss,out}}{E_s}$$

$$\eta_{out} = \frac{E_{in} - E_{loss,in} - E_{loss,out}}{E_{in} - E_{loss,in}}$$

Round-Trip Efficiency



- The round trip for energy in a storage system is a cascade of the ***charge*** and ***discharge*** processes
  - Round trip efficiency given by:

$$\eta_{rt} = \eta_{in} \cdot \eta_{out}$$

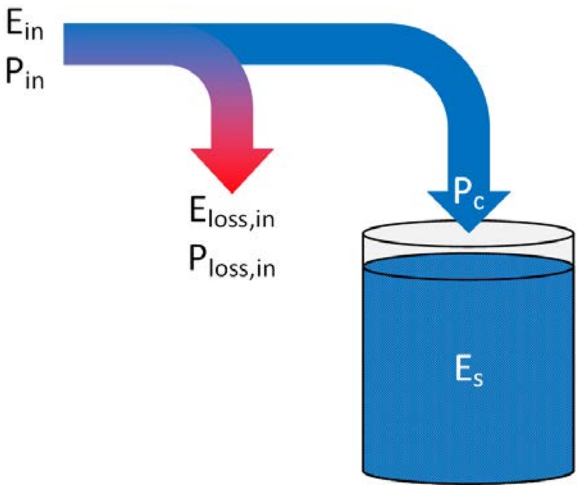
- In general, efficiency is a function of:
  - Charging/discharging power, P_{in} and P_{out}
  - State of charge

Charging Time

- Typically, what is needed is a certain power for a certain time
- ***Charging time***
  - The time it takes to go from minimum SoC to maximum SoC at a given power input
  - The time it takes to store the usable energy, E_u

$$t_c = \frac{E_u}{P_c}$$

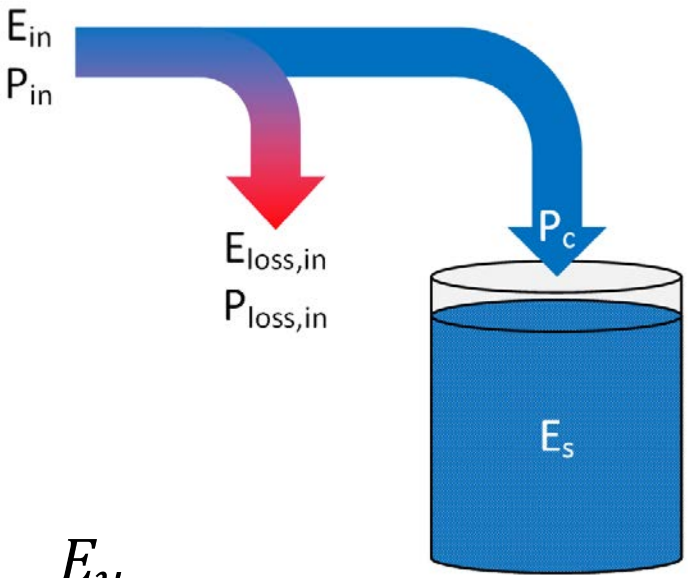
where P_c is the rate of energy storage



- Note that, due to losses, the rate of energy storage, P_c, is ***less*** than the input power, P_{in}

Charging Time

- The power we have direct control over is the input power, P_{in}
  - The charging time in terms of input power is

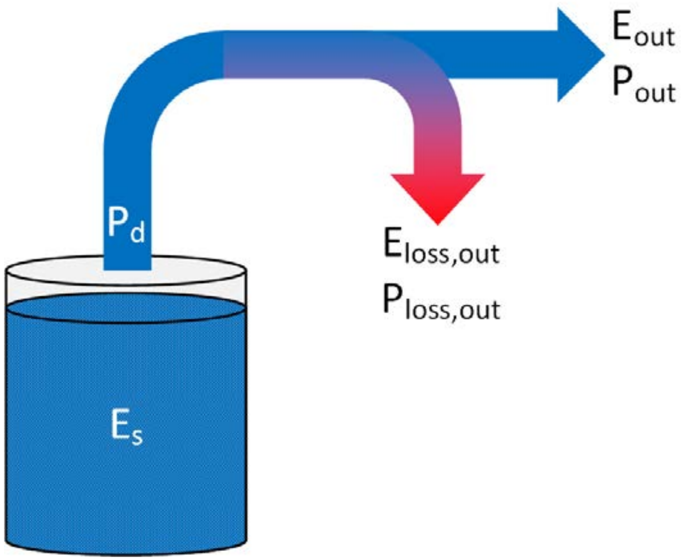


$$t_c = \frac{E_u}{P_{in} - P_{loss,in}} = \frac{E_u}{P_{in} \cdot \eta_{in}}$$

Discharge Time

- ***Discharge time***
  - The time required to go from maximum SoC to minimum SoC at a given output power
  - Due to losses, the rate of discharge, P_d, is ***greater*** than the output power, P_{out}

$$t_d = \frac{E_u}{P_d}$$



- Again, the power of interest is the power we have direct control over, the output power, P_{out}, so

$$t_d = \frac{E_u}{P_{out} + P_{loss,out}} = \frac{E_u}{P_{out}/\eta_{out}} = \frac{E_u}{P_{out}} \cdot \eta_{out}$$

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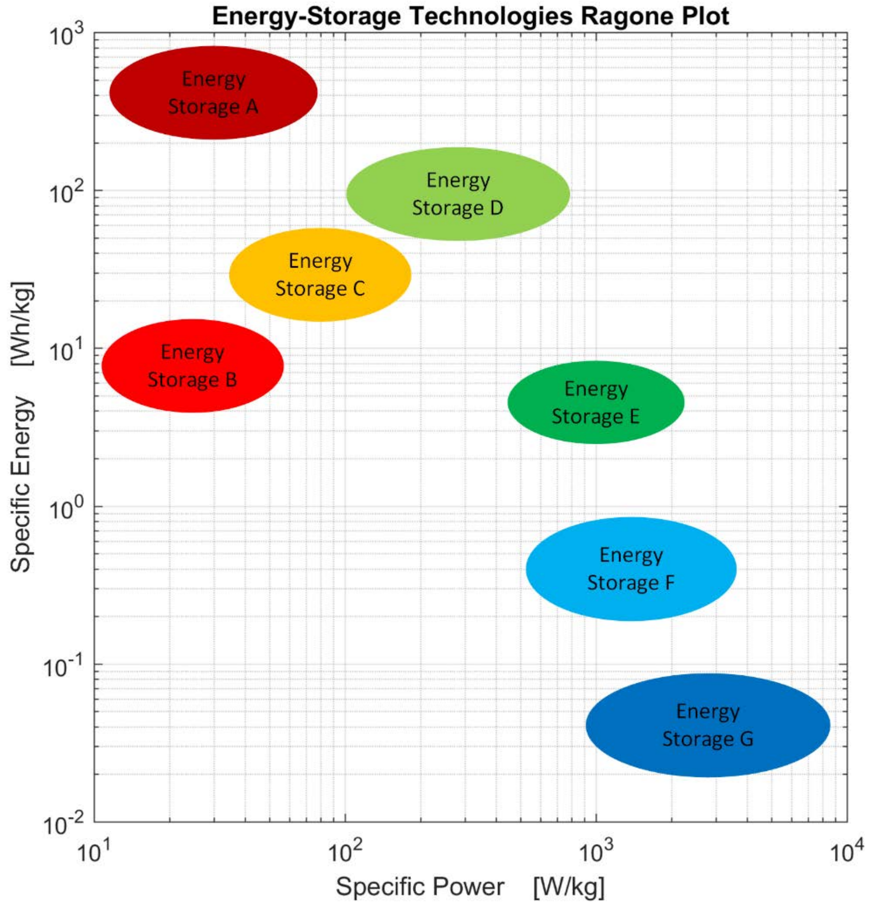
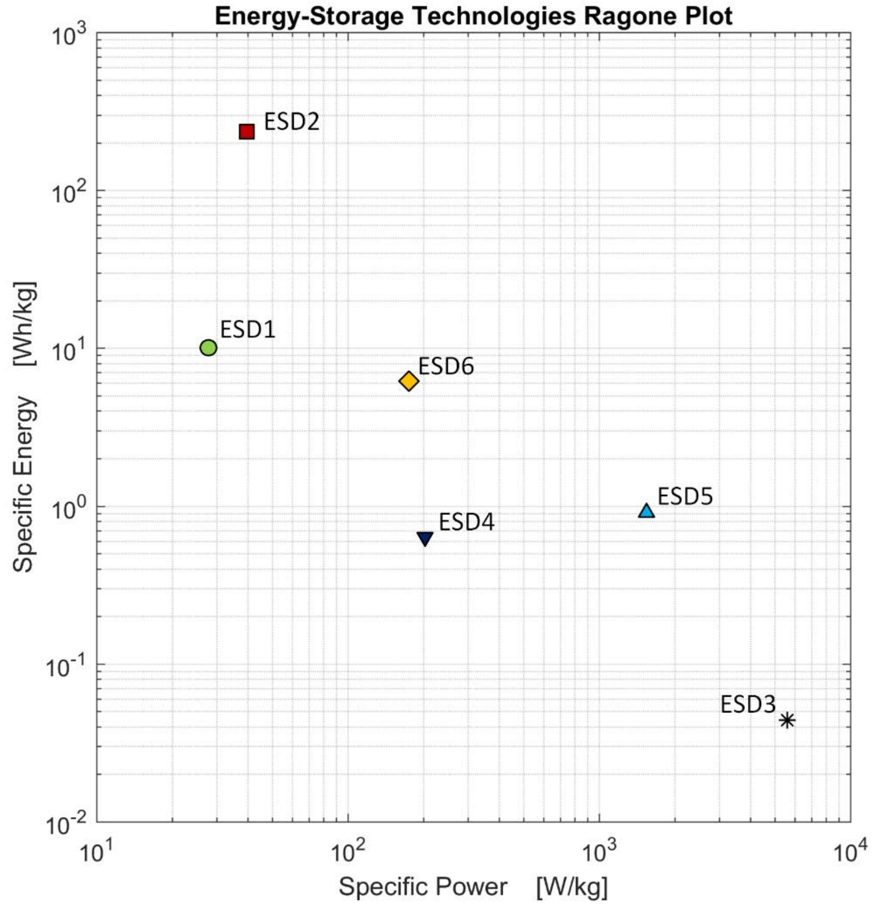
Ragone Plots

Ragone Plots

- Two primary figures of merit for energy storage systems:
  - ***Specific energy***
  - ***Specific power***
- Often a tradeoff between the two
  - Different storage technologies best suited to different applications depending on power/energy requirements
- Storage technologies can be compared graphically on a ***Ragone plot***
  - Specific energy vs. specific power
  - Specific storage devices plotted as points on the plot, or
  - Categories of devices plotted as regions in the Ragone plane

Ragone Plots



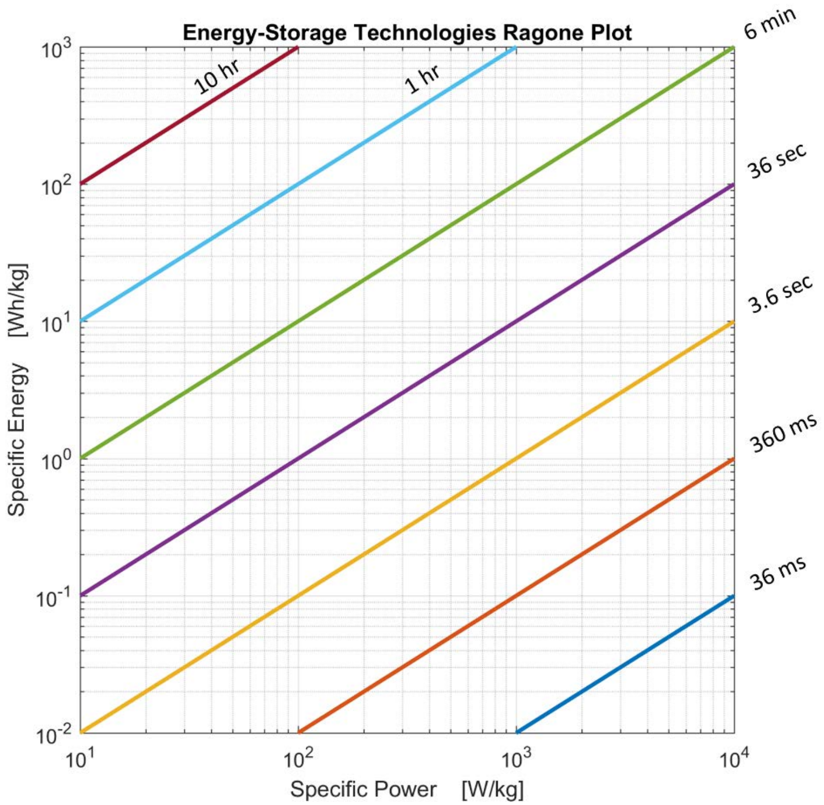


Discharge Time

- Any given storage system will have a specific energy capacity and a specific power rating
  - A point in the Ragone plane, (p_m, e_m)
  - Discharge time at rated power for that point (neglecting losses):

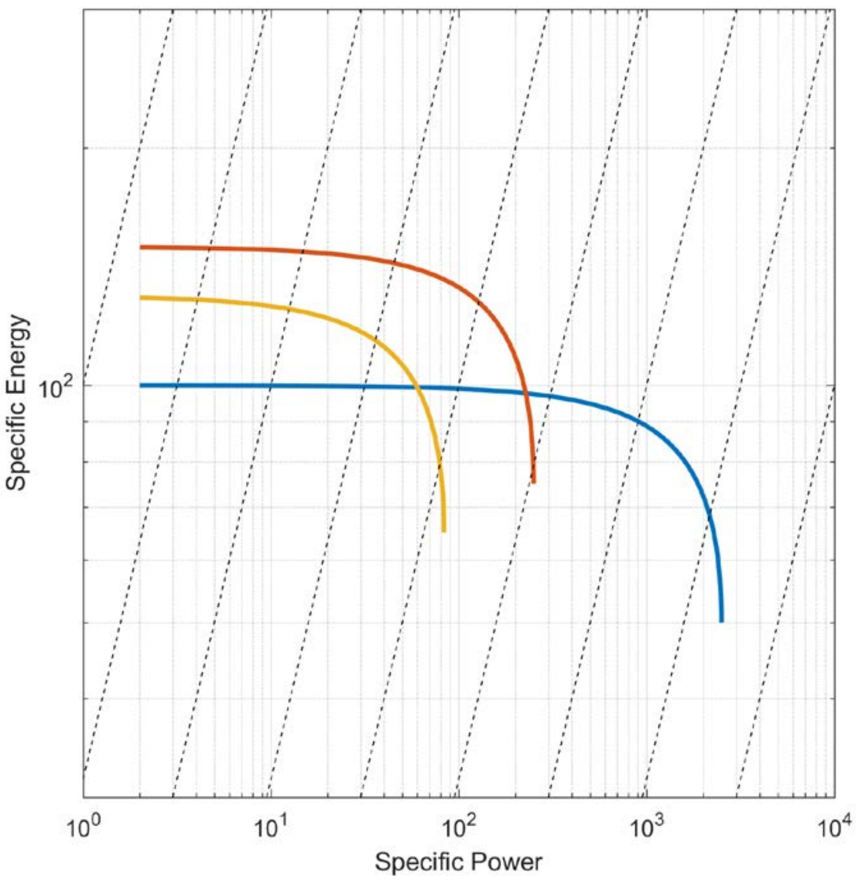
$$t_d = \frac{e_m}{p_m}$$

  - Constant discharge time maps to lines with unity slope on a Ragone plot
  - Storage systems that lie on the same line have equal discharge times at rated power



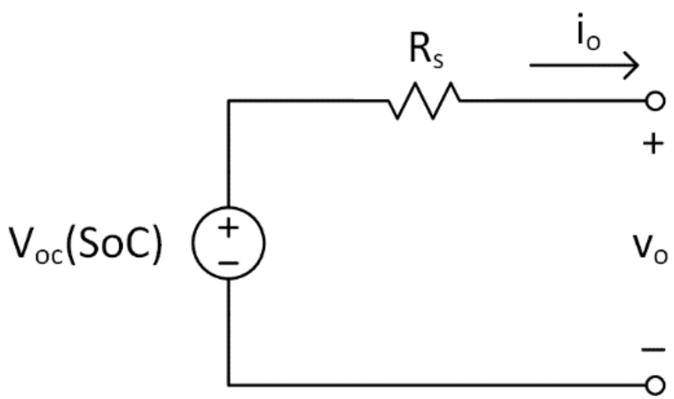
Ragone Curves

- Ragone plots we've seen so far plot a storage device at one operating point
  - Maximum or rated power
- Can also depict a device's energy capacity over a range of power
  - A Ragone curve
- Most curves share a similar characteristic shape
  - Available energy decreases at higher power
  - Fraction of energy lost as heat increases

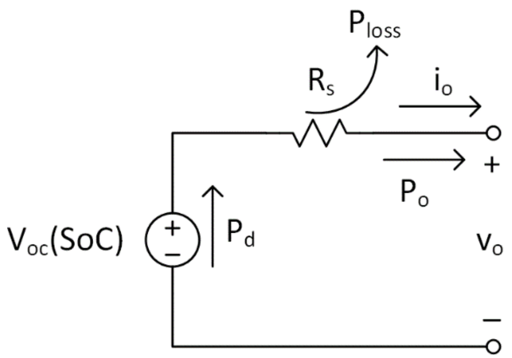


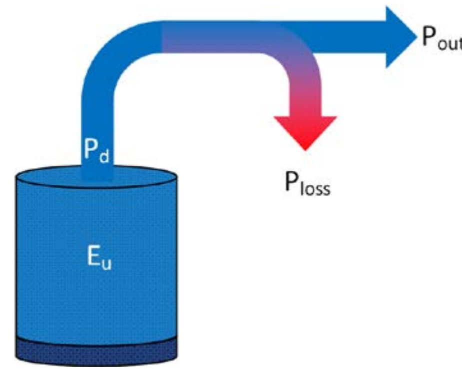
Thévenin Equivalent Model

- What is the reason for the characteristic shape of Ragone curves?
- Consider that we could model a storage device with as an electrical ***Thévenin equivalent***
  - Need not be an electrical storage device
- Open-circuit voltage is some function of SoC
  - Possibly linear
  - May be highly nonlinear
  - Or, could be constant



Thévenin Equivalent Model

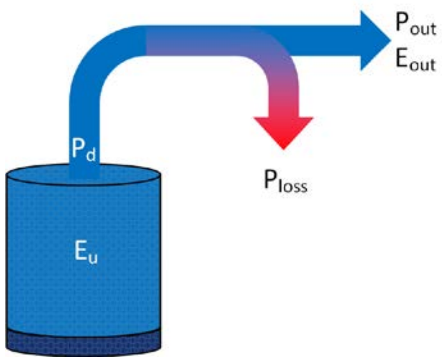


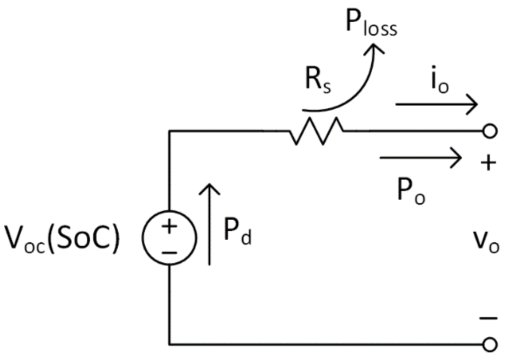


- Three power components associated with discharge
  - P_d: discharge power
    - The rate at which energy leaves storage: $P_d = V_{oc} i_o$
  - P_{loss}: power lost during discharge
    - Modeled as heat dissipation in the Thévenin resistance: $P_{loss} = i_o^2 R_s$
  - P_{out}: output power flowing to the external system

$$P_{out} = v_o i_o = (V_{oc} - i_o R_s) i_o$$
$$P_{out} = V_{oc} i_o - i_o^2 R_s = P_d - P_{loss}$$

Thévenin Equivalent Model





- Discharge time:

$$t_d = \frac{E_u}{P_d}$$

- Amount of energy extracted from the storage system:

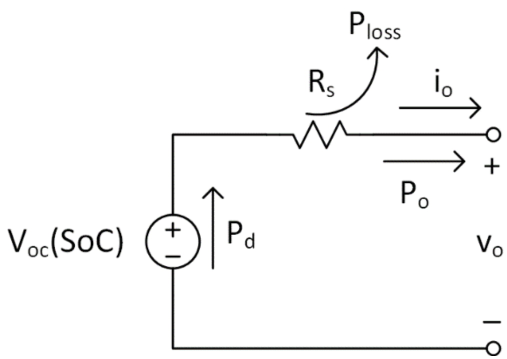
$$E_{out} = P_{out} \cdot t_d = E_u \frac{P_{out}}{P_d}$$

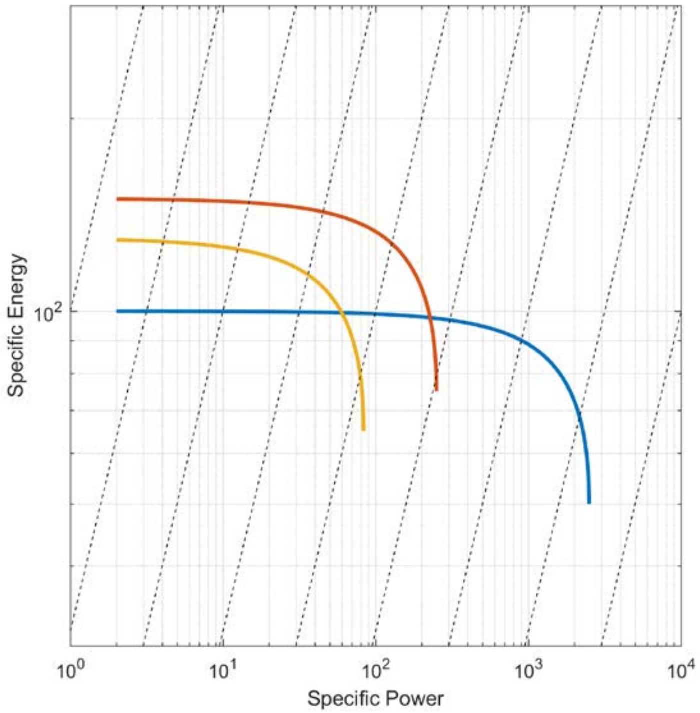
- Substituting in expressions for P_{out} and P_d, we have

$$E_{out} = E_u \left[\frac{V_{oc} i_o - i_o^2 R_s}{V_{oc} i_o} \right]$$

$$E_{out} = E_u \left[1 - i_o \frac{R_s}{V_{oc}} \right]$$

Available Energy vs. Output Power





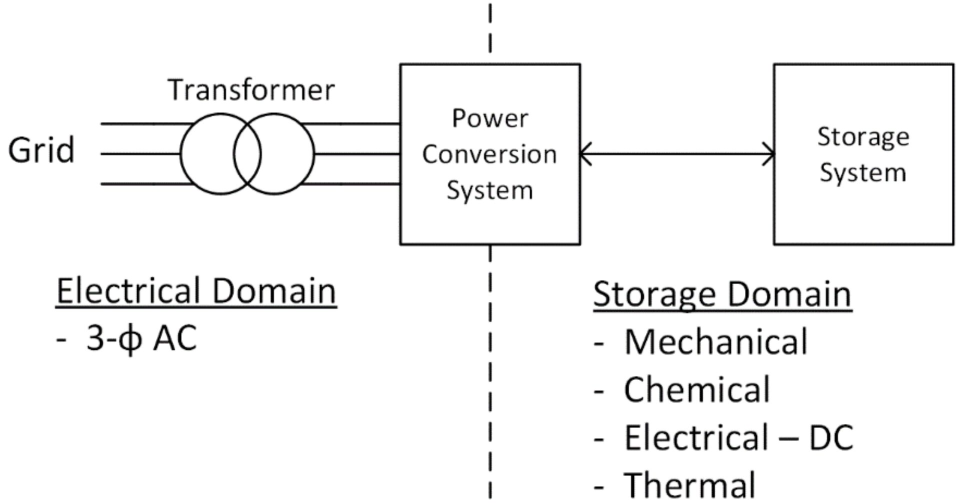
$$E_{out} = E_u \left[1 - i_o \frac{R_s}{V_{oc}}\right]$$

- We can see that the available energy decreases as i_o increases
  - ***Available energy decreases as output power increases***
  - Illustrated by the characteristic shape of Ragone plots

Storage System Configurations

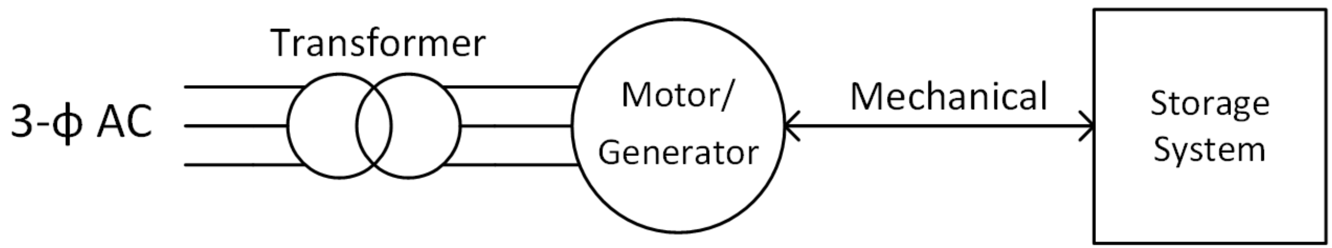
Storage System Configurations

- Our focus is grid-connected energy storage
  - Energy stored in many different domains
  - Input and output energy is electrical
    - Three-phase AC power
- Conversion is required between the storage domain and the electrical domain
  - Transformer
  - Power conversion system (PCS)



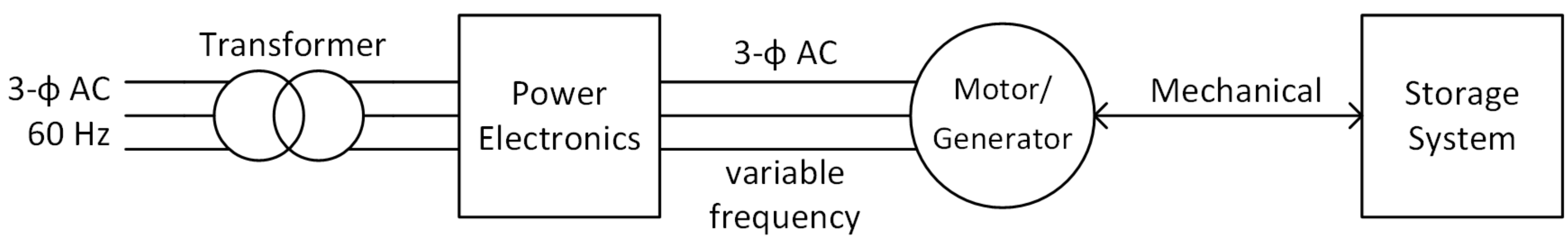
System Configurations – Mechanical

- ***Mechanical storage***
  - Pumped hydro, flywheels, compressed air
  - PCS includes a ***motor/generator***
    - Possibly driven by a turbine
  - Motor/generator may be connected directly to the grid
    - ***Synchronous*** with the grid
    - Runs at ***fixed speed***



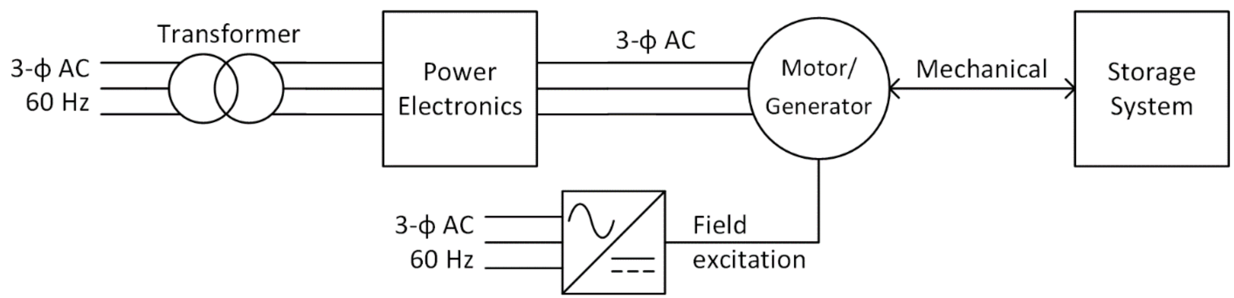
System Configurations – Mechanical

- Alternatively, motor/generator can be run at ***variable speed***
  - Maximize efficiency
  - Interface to grid through power electronic converter
- Two options for variable-speed operation:
  - Singly-fed motor/generator
  - Doubly-fed motor/generator



System Configurations – Mechanical

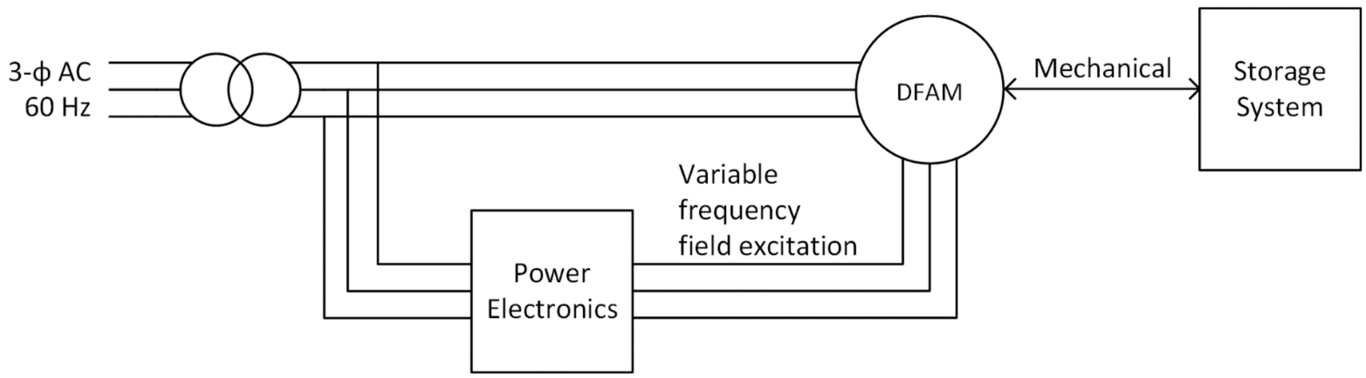
- ***Singly-fed motor/generator***
  - Synchronous machine
  - Stator driven with variable-frequency AC from power electronic converter
  - Field windings on rotor supplied with DC excitation voltage
    - Same as for fixed-speed synchronous machine



  - Converter must be rated for full motor/generator power
    - Large, expensive

System Configurations – Mechanical

- ***Doubly-fed motor/generator***
  - Doubly-fed asynchronous machine (DFAM)
  - Stator connected to grid-frequency AC
  - Field windings on rotor supplied with variable-frequency excitation voltage



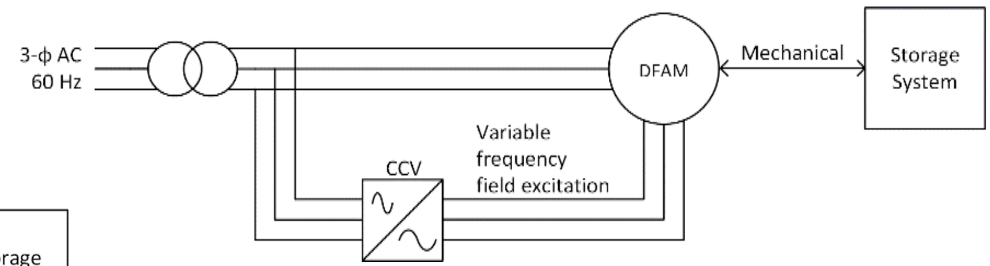
  - Converters need not be sized for rated motor/generator power
    - Only supply lower-power excitation to the rotor

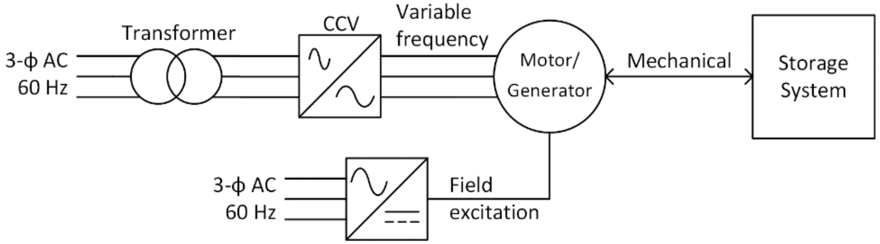
Power Electronic Converters

- Variable-speed motors/generators require a ***static frequency converter*** (SFC)
  - Both for singly- and doubly-fed configurations
  - Power electronic switching converter
  - Convert between grid-frequency to other frequencies
- Common SFC topologies
  - ***Cycloconverter*** (CCV)
    - AC-AC converter
  - ***Voltage-source converter*** (VSC)
    - AC-DC-AC converter

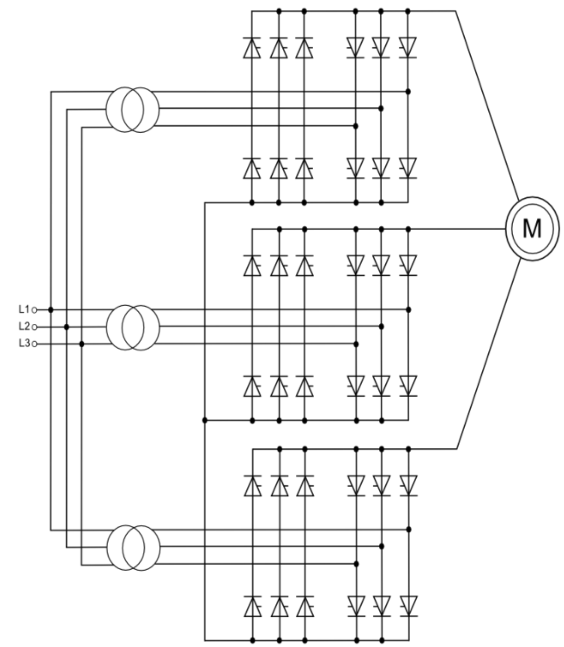
Cycloconverter

- Cycloconverter
  - AC-to-AC frequency converter





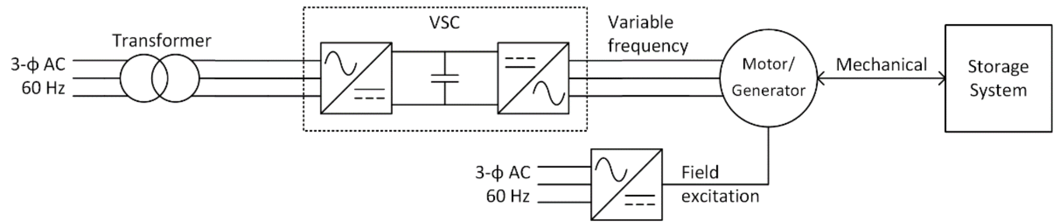
- Direct conversion between grid and variable frequency AC
  - No intermediate DC link
- Switching thyristor bridge circuits
  - Controllable connections between all input and output phases

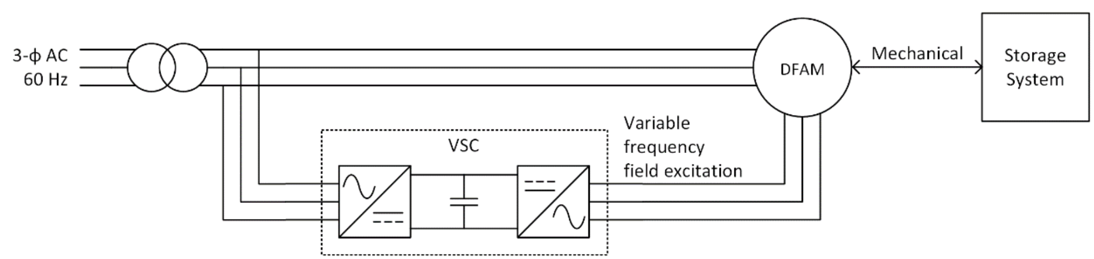


Voltage Source Converter

- Voltage source converter (VSC)
  - Back-to-back AC/DC converters
  - DC link between converters
  - Variable frequency AC on motor/generator side

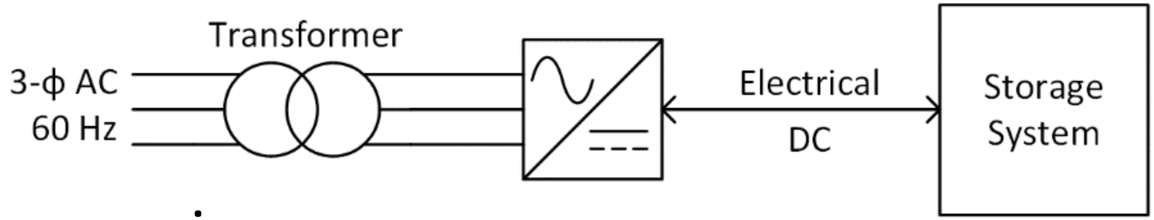
- VSC topologies include:
  - Two-level PWM
  - Multi-level PWM
  - Multi-level modular converter (MMC)





System Configurations – Electrical/Electrochemical

- ***Electrical and electrochemical storage***
  - Ultracapacitors, batteries
- Output from storage device is already in the ***electrical*** domain, but it is ***DC***
  - Need AC/DC conversion to interface with the grid



- AC/DC conversion
  - Charging: AC-to-DC – ***rectification***
  - Discharging: DC-to-AC – ***inversion***
- Voltage source converter is a common choice here
  - Independent control of real and reactive power control
  - Allows storage to provide black start capability