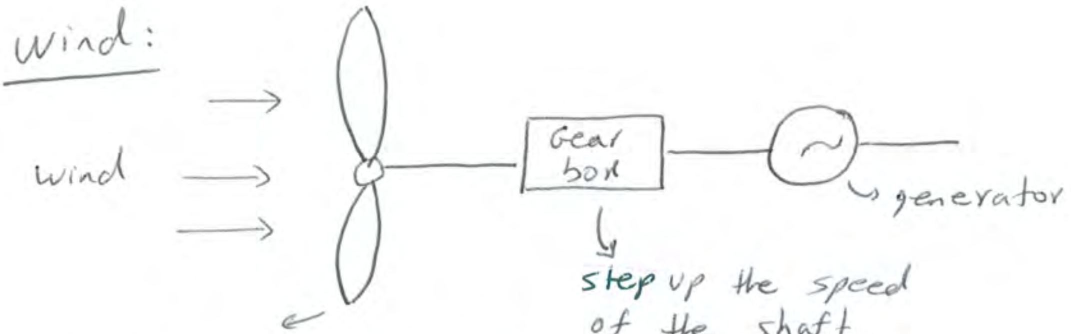
- Renewable energy:

wind:



step up the speed of the shaft

Turbine: Convert wind enery into mechanical energy

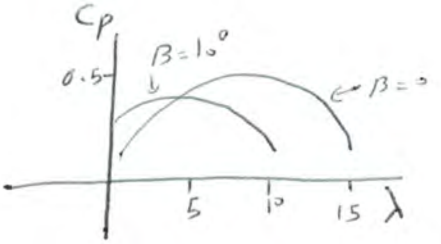
$P_{aero} = \frac{1}{2} \underbrace{C_p(\lambda, \beta)}_{\text{power coefficient}} \rho A V^3$ ↳ wind velocity

↙ power captured from wind

ρ = air density
A = rotor swept area
β = Blade pitch angle
λ = tip speed ratio
$= \frac{WR}{V}$ → speed at blade's tip

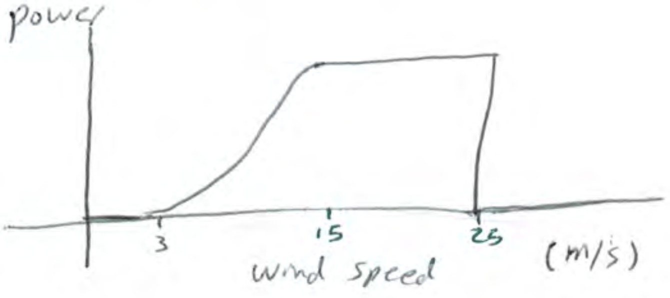
$P_{available} = \frac{1}{2} \rho A V^3$

$\Rightarrow C_p(\lambda, \beta) = \frac{P_{aero}}{P_{avai}} < 0.59$



- V changes in real time and is highly variable

max efficieny → max $C_p(\lambda, \beta)$ → 1 - pitch control for β
2 - torque control for λ
(thru generator)



- $P_{out} = \alpha V^3$

$\Rightarrow$ a little change in V makes a lot of change in P_{elec}.

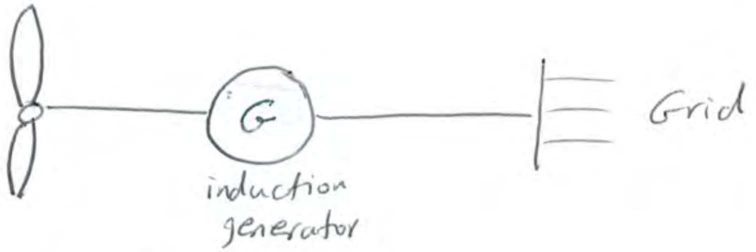
- wind Turbine:

1- fixed speed : simple, reliable, low-efficiency, stress,
power fluctuatio

2- variable speed : high-efficiency energy conversion,
reduced stress, improved power quality,
complex design, high cost for convertor.

($\lambda = \frac{WR}{V}$ $\Rightarrow$ w should be variable to optimize efficiency).

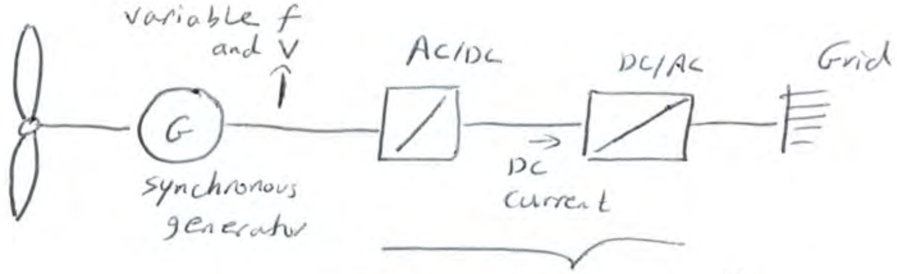
- fixed speed:
(singly-fed)



the grid makes the rotor of generator and then turbine turn at a constant speed (stress on mechanical components

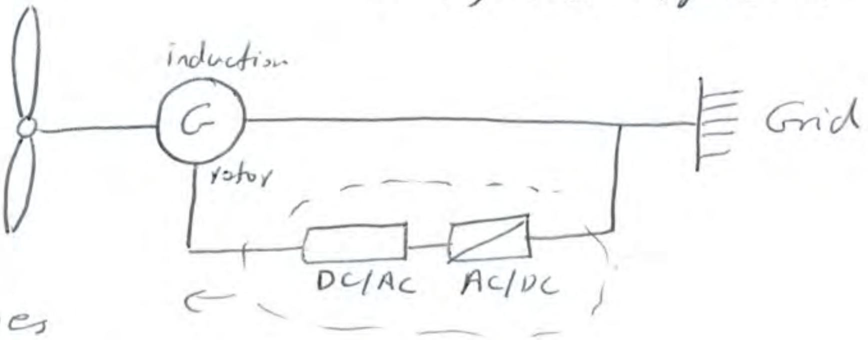
- Variable speed:

  - Decoupled:



all power goes thru convertor. so, the device is big and expensive.

  - Doubly-fed induction gen: (DFIG)



30% of power goes

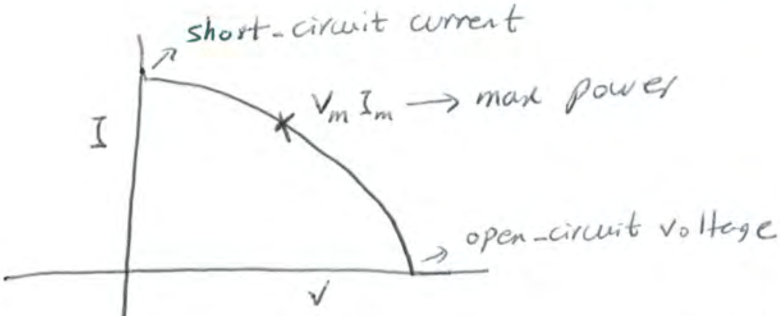
singly-fed: $f_{Net} = \dfrac{\overset{\nearrow \text{speed of rotor}}{n_r} \times N_{pole}}{120}$

dubly-fed: $f_{net} = \dfrac{n_r \times N_{pole}}{120} \underset{\swarrow \text{direction of magnetic field}}{\boxed{\pm}} \underbrace{f_{rotor}}_{\text{frequency of current injected to rotor}}$

⇒ charge f and V for rotor to keep f and V of grid constant despite variable wind.

<u>solar enery:</u> photovoltics (PV) = convert solar radiation into DC current

(highest efficiency available = 43.5%)



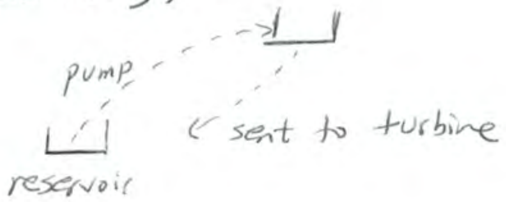
solar inverter:
- ↗ convert DC to AC for grid purpose
- ↘ maximum power point tracking (variable resistance)

PV → increase voltage magnitude (voltage rise) → Control reactive power via PV inverter.

solar and wind:
- $\underbrace{\text{intermittent}}_{\text{unintentionally stopped or unavailable}}$ energy source
- high $\underbrace{\text{variability}}_{\text{undesired or uncontrolled changes}}$

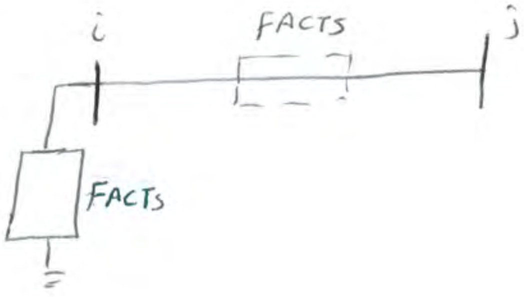
How to cope with intermittency and variability:

- storage:
  - Batteries: expensive, limited lifespan
  - Electric vehicle: vehicle-to-grid
  - Compressed air: compress air → heat it later.
  - flywheel: Use the mechanical inertia in a heavy rotating disc. (good for improving power quality).
  - pumped hydro: pumped-storage hydroelectricity (high dispatchability).



Advanced power-electronic devices:

1 - FACTS (flexible AC Transmission system):



- shunt: capacitor / inductor, control reactive power
- series: reduce inductance

$$P_{tranfer} = \frac{|V_1||V_2|}{X_{ij}} \sin(\theta_1 - \theta_2)$$

⇒ Control active power

FACTS is adjustable in a continuous or discrete way.

2 - phase shifter: relieve congestion and route power.

3 - phasor measurement unit (PMU) or synchrophasor.

- To monitor the health of the network and take preventive or corrective actions, we need to know the state of the network.

- State estimation: Given measurement, find state.

- Traditional way: measurements $P, Q, |V|$
  - issue 1: measurement is slow, asynchronous and without time stamp.
  - issue 2: $P, Q, |V|$ have nonlinear relationship.

- PMU: Based on GPS with accuracy of $1\mu s$, get 10-30 samples every second (synchronous report).
  1- measurements are V, I (complex)
  2. relationship between V and I is linear.

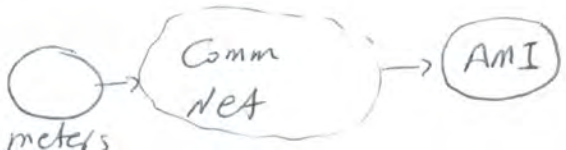
Smart grid : (modernized grid)

1 - Renewable and storage

2 - Advanced sensing and measurement

3 - smart meter: Replace electromechanical meter with digital meter than can establish a two-way communication with data centers and smart devices.

Advanced metering Infrastructure (AMI): a system for measuring, collecting, and analyzing energy usage and for communication with metering devices.



Issue: privacy of information

meter's signal can be disaggregated to find out what device has been used and monitor activities (no activity good for robbery).

Issue: security of information

grid operation relies on data. Its manipulation (financial incentive or malicious activity) could increase the price in the market to the advantage of some party or bring the grid down by requesting too much power.

4 - Advanced Control:

current practice: - Decentralization
Take Local actions without any theoretical quarantee
(e.g. what speed governor does)
- use PID controller as opposed to observer-based controller.

Future trend: Use distributed controller (talking between neighboring devices), which are designed to be robust and optimal (control theory)

why should the control architecture change?

renewable is highly uncertain and variable and traditional controllers don't allow a high penetration of renewable energy.

5 - Reliability: fault-detection and self-healing

what's the traditional way of guaranteeing a secure operation?

- Imagine a set of contingencies $C_1, C_2, \dots, C_k$ (C_i corresponds to a component failure).
- Find a solution to OPF in such a way that if any of these contingencies happens, the network still survives.

Security-constrained OPF (SCOPF):

$$\min f(X_0, U_0)$$

$$g(X_i, U_i) = 0 \qquad i = 0, \dots, k$$

$$h(X_i, U_i) \le 0 \qquad i = 0, \dots, k$$

$$|U_i - U_0| \le \alpha_i \qquad i = 1, \dots, k$$

($k=0$ is the base case)

X_i : state for C_i

U_i : Control for C_i

$\alpha_i = 0$ preventive action

$\alpha_i > 0$ corrective action

- In a smart grid, faults may not be deterministic. (e.g., wind speed drops in a continuous way or there is too much fluctuation).

$\Rightarrow$ SCOPF should account for probabilistic events. (worst case, expectation, etc.)

6- Efficiency: improve algorithms and protocols (less approximation for OPF, state estimation, SCOPF, UC ...)

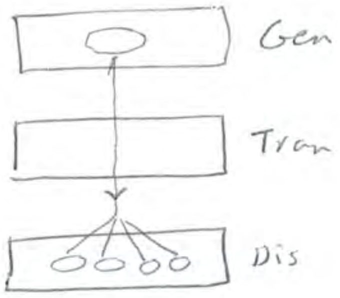
Unit commitment: $\sum_i f_i(p_i)$

s.t. Constraints of OPF

$$\alpha_i p_i^{min} \le p_i \le \alpha_i p_i^{max}$$

$\alpha_i = 0, 1 \Rightarrow$ should the generator be used at all?

7 - Distributed generation (DG):



Replace big generators at generation level with many small distributed generator at distribution level.

- Loss is lower.
- Robustness is enhanced.

8 - Integrated communication:

Use communication for real-time control and information/ data exchange to optimize reliability, utilization and security.

9 - Electric vehicle (EV):

allow charging of EVs in large scale

- vehicle-to-grid (V2G): sell power back to the network if necessary.

10 - Demand-response: Instead of using reserve generators (costly get help from consumers.

real-time price can be given to a consumer so they decide when would be the right time for using power.

loads: curtailable, deferrable....

shed load   shift load

Demand response ⟶ reduce electricity price ⟶ incentive, stability issues ...