17-Stand Alone Wind Energy Systems

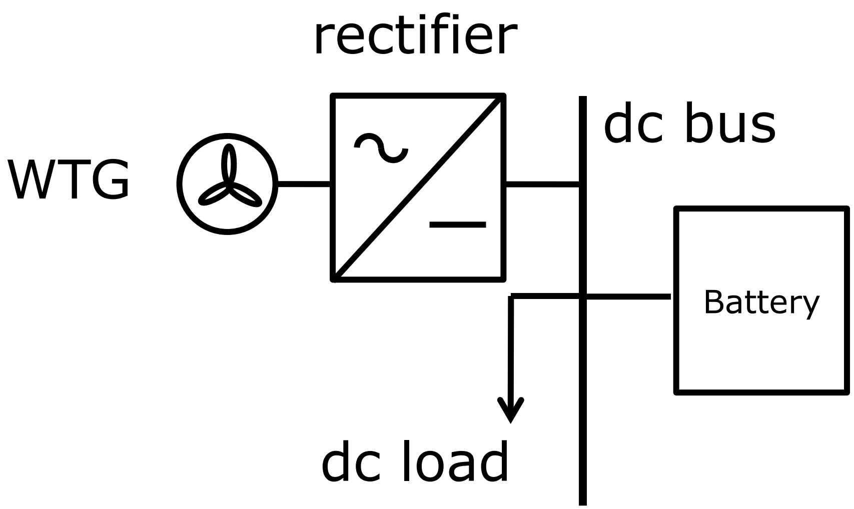
ECEGR 452

Renewable Energy Systems

Overview

- Topology
- Modeling
- Power Output
- Rotational Dynamics

Basic System Topology



*rectifier may be included in WTG
*controls not shown
*inverter and ac load not shown

Stand Alone Wind Turbines

- Almost always less than 100kW
  - Typically < 10kW
- Permanent Magnet Synchronous Generators (PMSG)
  - Direct drive (no gearing)
  - AC output (assume three phase)
  - Rectifier
  - Battery

Farday's Law

- PMSG: voltage induced according to Lenz's Law

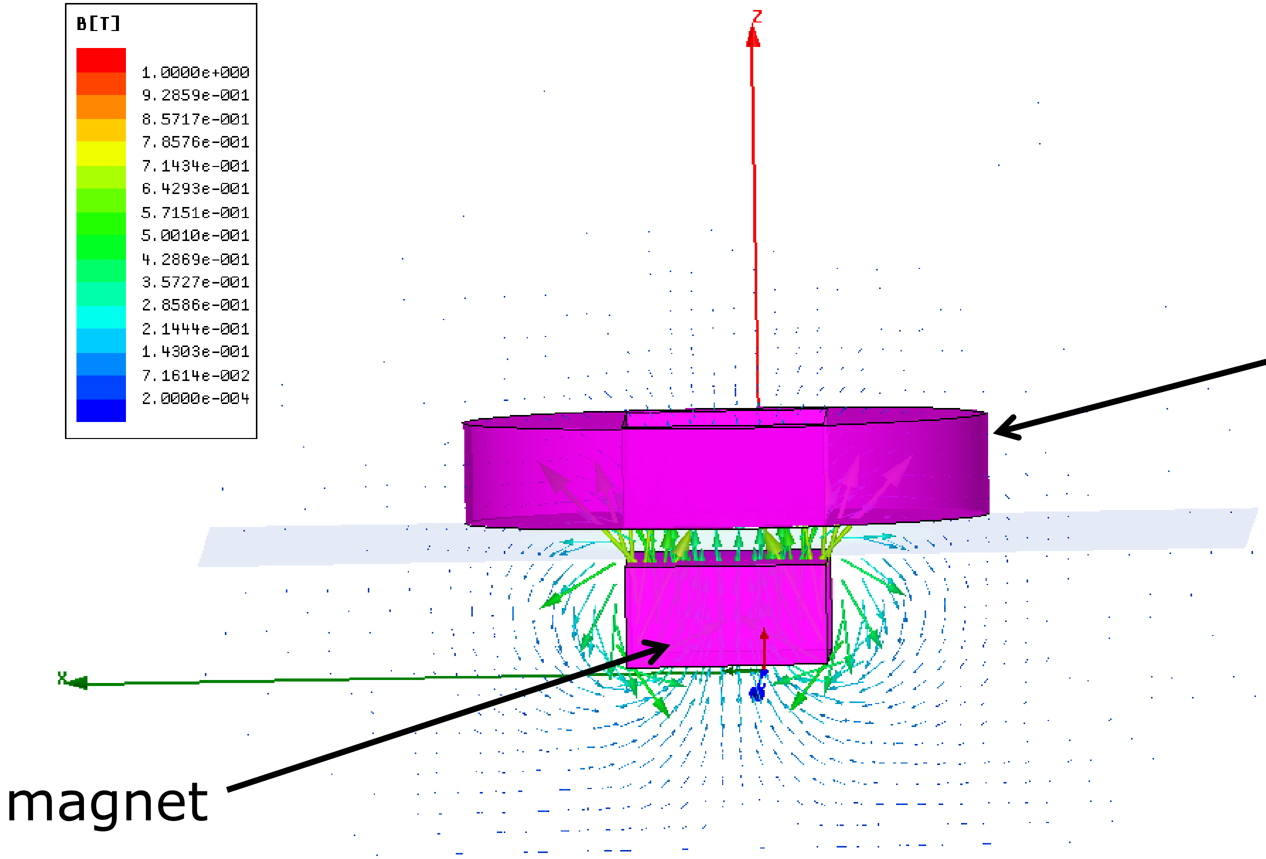
$$\oint_C \boldsymbol{E} \bullet d\ell = -\int_s \frac{\partial \boldsymbol{B}}{\partial t} \bullet d\boldsymbol{s}$$

$$e = -\int_s \frac{\partial \boldsymbol{B}}{\partial t} \bullet d\boldsymbol{s} = -\frac{d\Phi}{dt}$$

- Where e is the induced electromotive force (emf)
- For multiple turns (N)

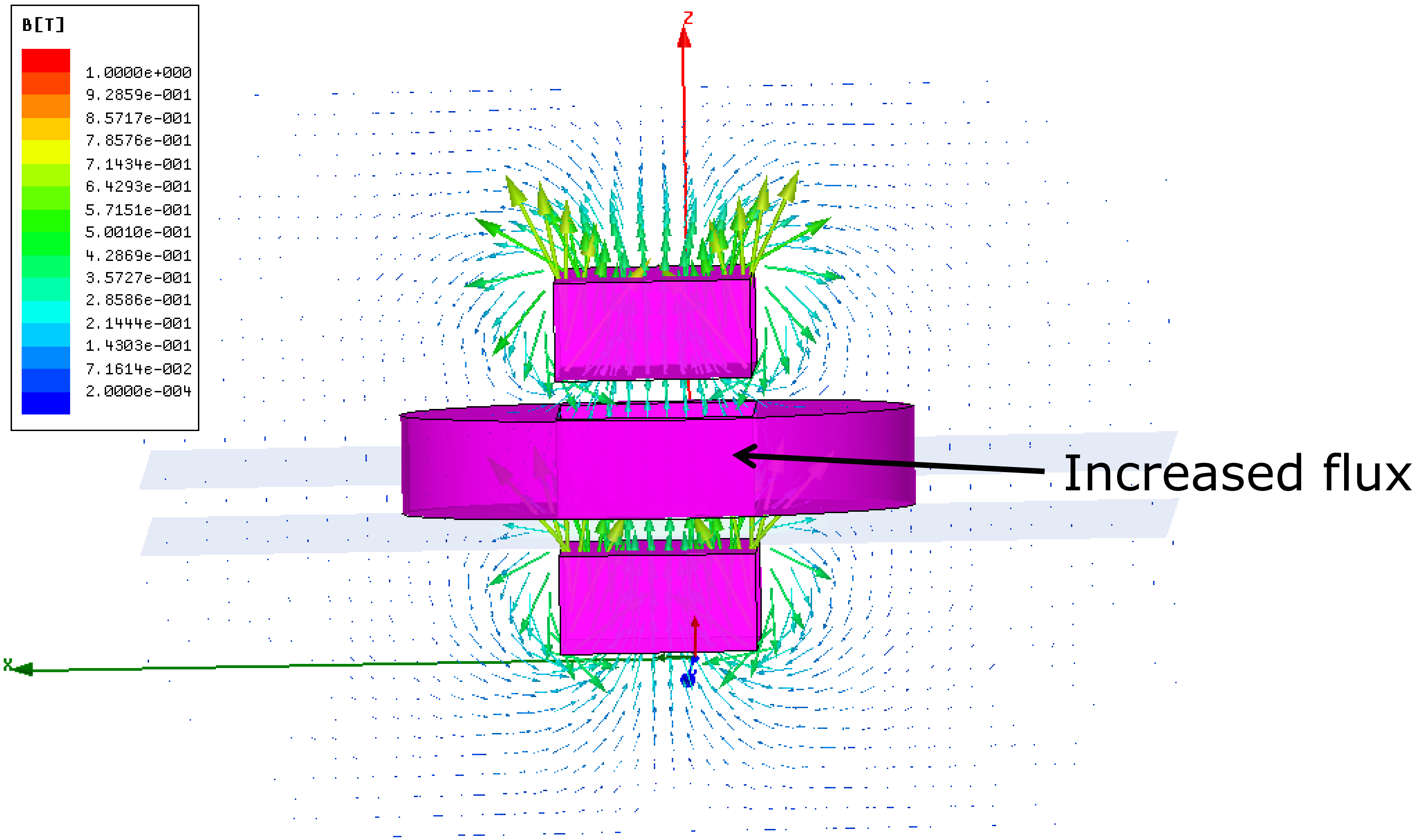
$$e = -N\frac{d\Phi}{dt}$$ ← Need time-varying magnetic flux

PMSG

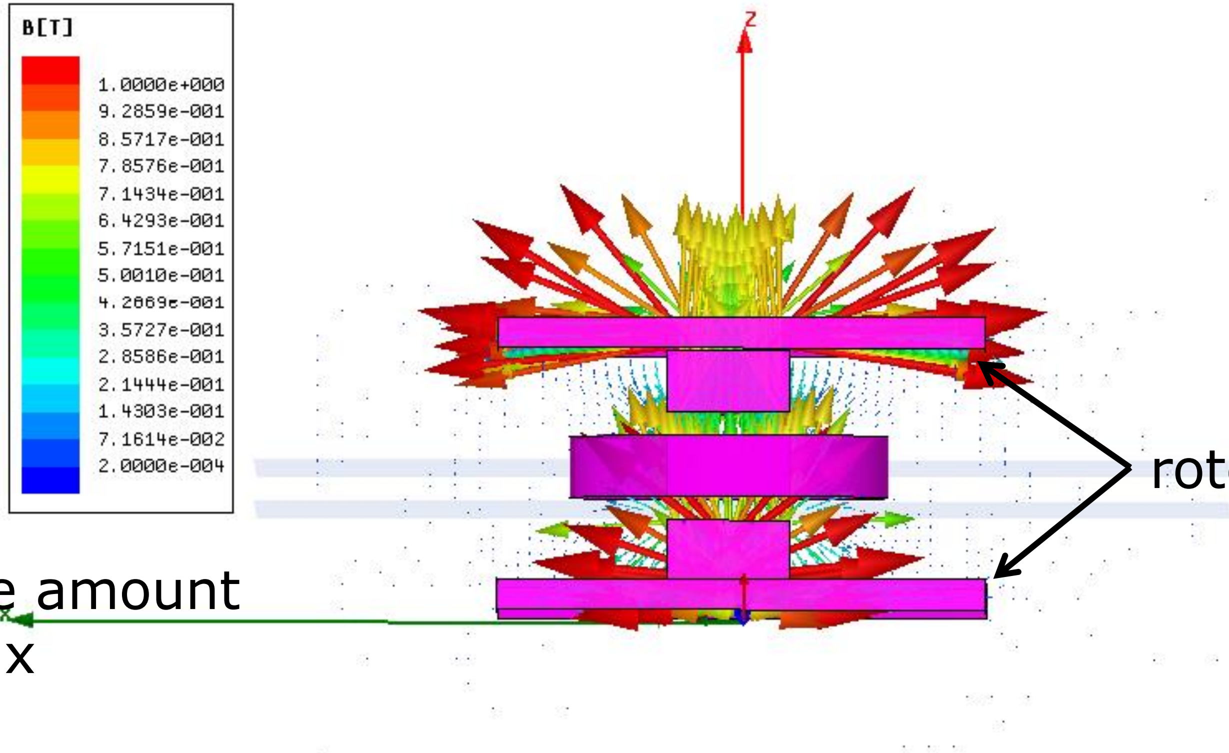


B[T]
1.0000e+000
9.2859e-001
8.5717e-001
7.8576e-001
7.1434e-001
6.4293e-001
5.7151e-001
5.0010e-001
4.2869e-001
3.5727e-001
2.8586e-001
2.1444e-001
1.4303e-001
7.1614e-002
2.0000e-004
Z
X
coil
magnet

PMSG (two magnets per pole)



PMSG (with rotor disks)

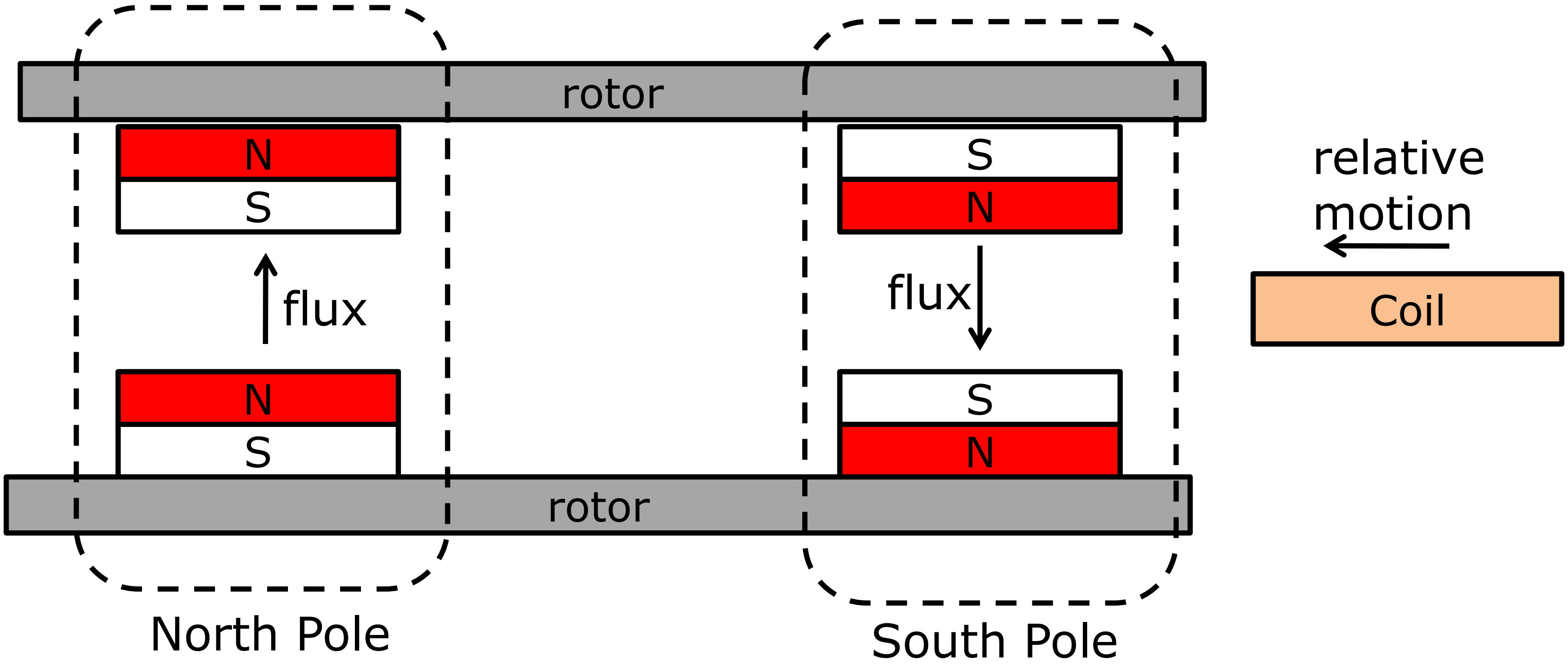


rotor disks

Large amount of flux

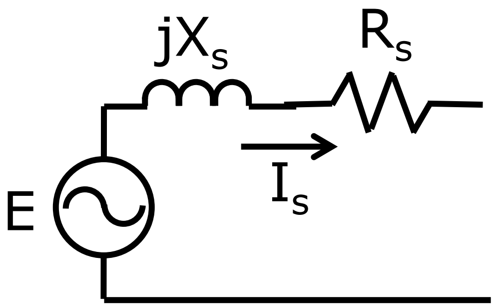
PMSG (multi-pole)

- For every <u>pair of poles</u>, that the coil passes by, one sinewave is induced



Wind Turbine Generator (WTG)

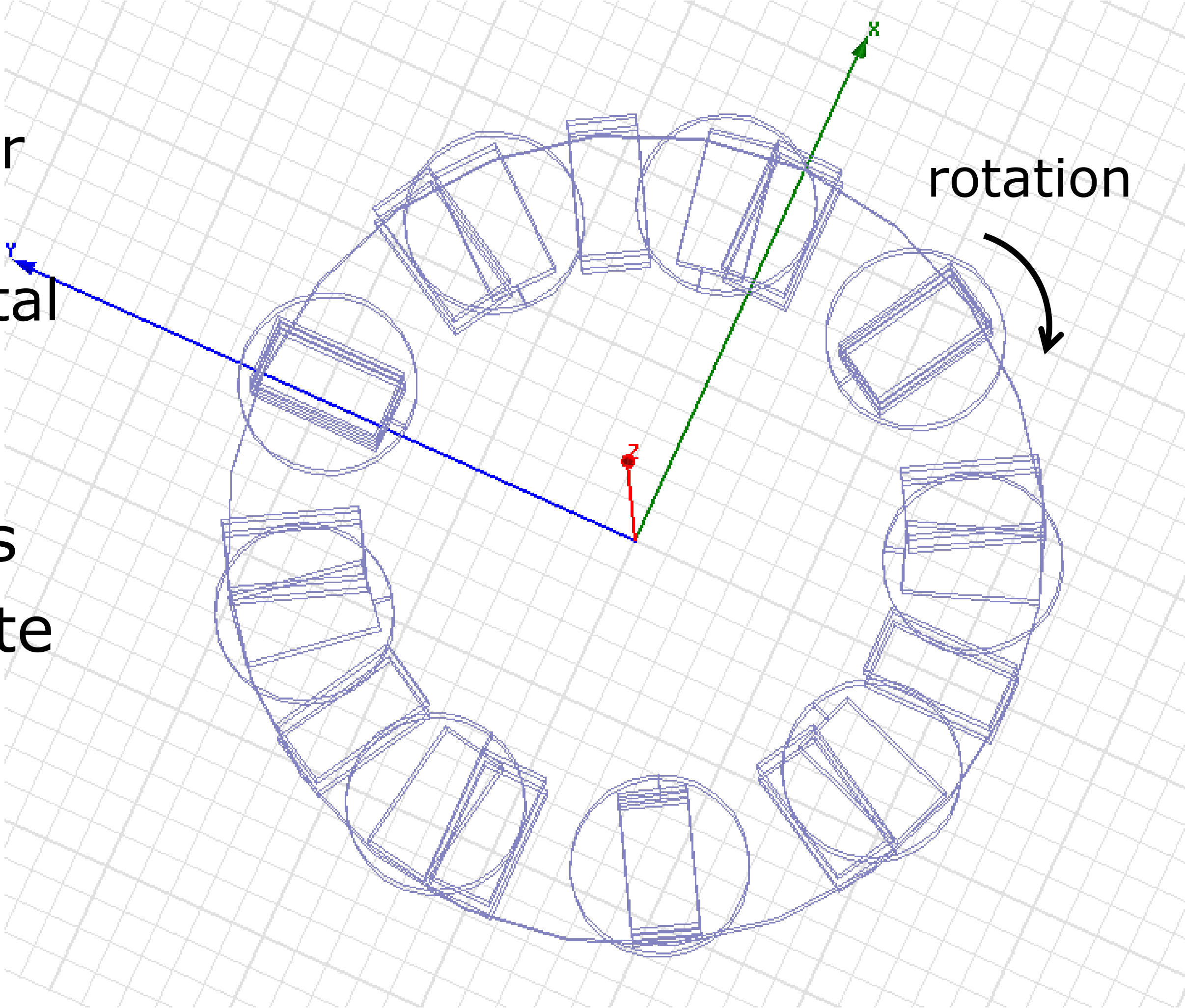
- $E = \omega_m \times A \times C \times N \times P \times B$
  - E: induced emf (V RMS)
  - ω_m : rotor shaft speed (rad/s)
  - A: cross-sectional area of stator coils (m^2)
  - C: number of series-connected coils
  - N: number of turns in each coil
  - P: number of pole pairs
  - B: flux density (Tesla RMS)
- L_s: Series synchronous inductance (H)
- R_s: Series resistance (Ohm)



per-phase equivalent

Wind Turbine

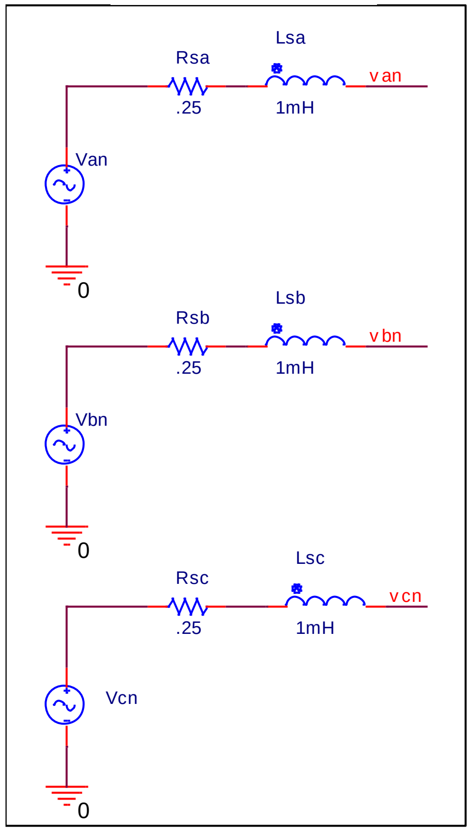
- 6 pole pairs
  - 12 magnets per rotor
  - 24 magnets total
- 1 mechanical period = 6 electrical periods
- Magnets alternate N-S around face



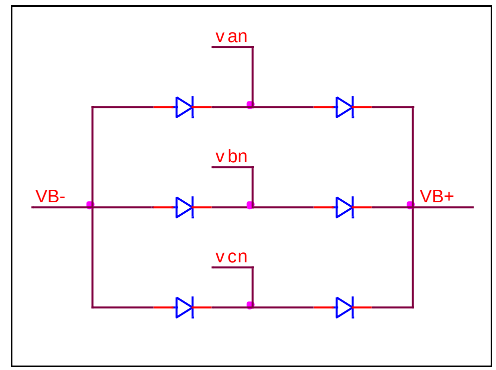
Basic System Topology

3-phase generator

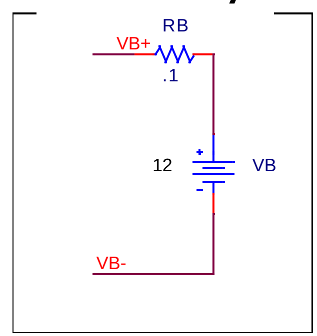
WTG



Rectifier



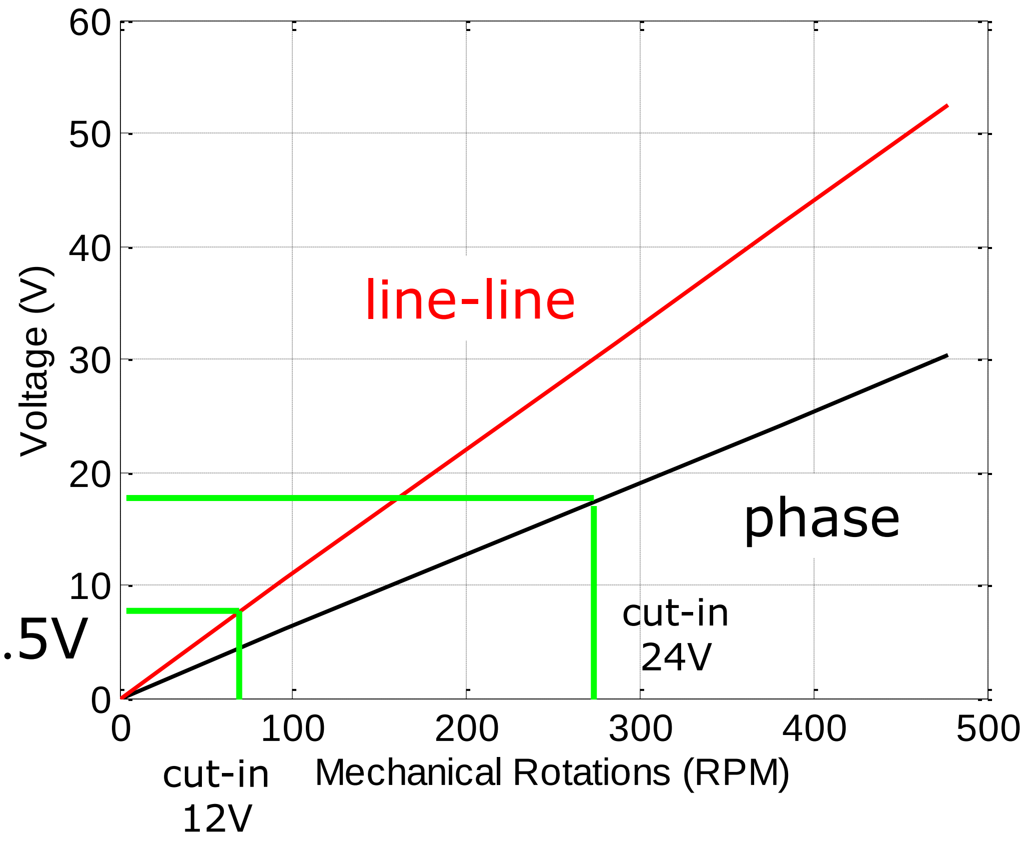
Battery



Operation

- Let $E = \omega_m \times A \times C \times N \times P \times B = E = \omega_m \times K_m$
  - A: 0.0013 m^2
  - C: 3 series-connected coils
  - N: 70 turns
  - P: 6 pole pairs
  - B: 0.37 Tesla
- Therefore: $K_m = 0.6\ V_{rms}/rad/s$
- X_s: 0.001 H
- R_s = 0 Ohm (lossless)

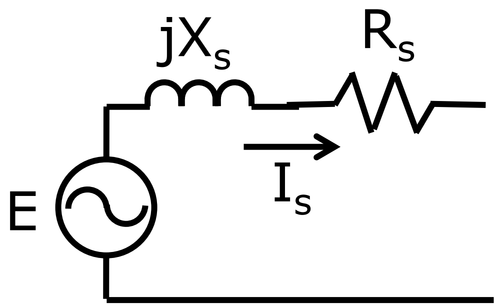
Open Circuit Terminal Voltage (RMS)



Note: $\frac{12}{\sqrt{2}} \approx 8.5V$

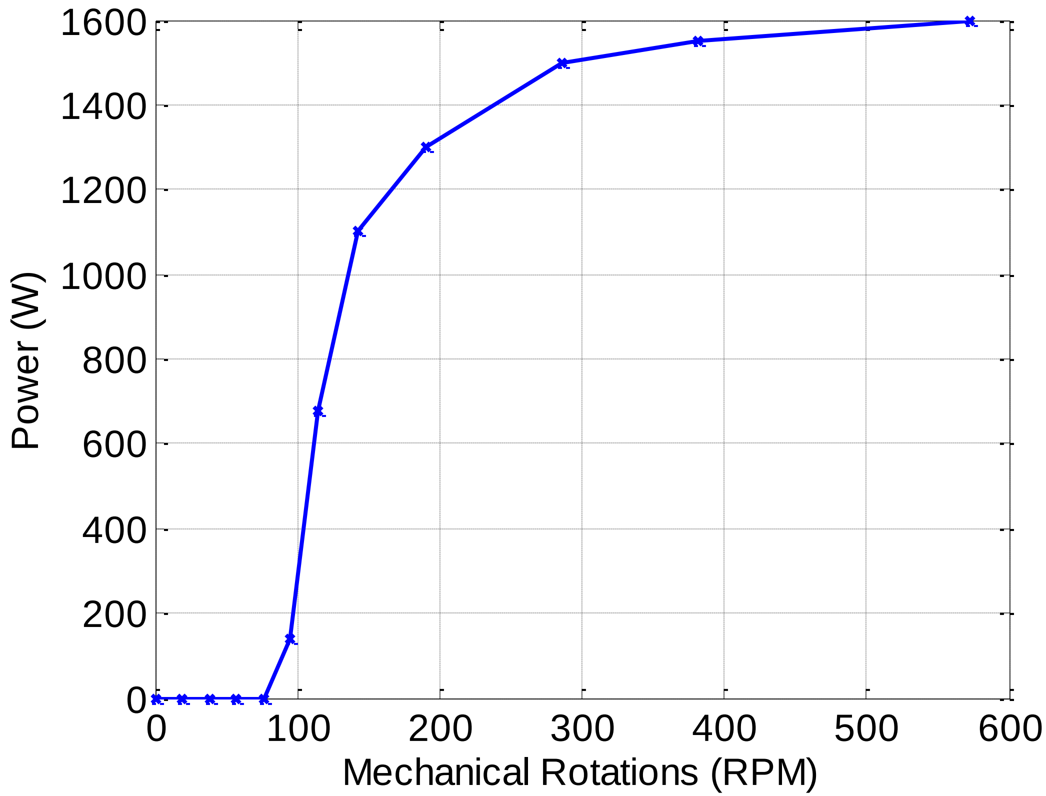
Operation

- If voltage (E) increases linearly with RPM, how does the power to the battery increase?
  - Non-linear
  - As E increases, so does jX_s



per-phase equivalent

Power to Battery (12V)



Rotational Dynamics

- Recall
  - Power = torque x angular velocity
- How do we determine the rotor speed and net torque of a wind turbine?

Rotational Dynamics

- Assume
  - Direct coupling of generator and rotor
  - No rotor friction
- From rotational dynamics:

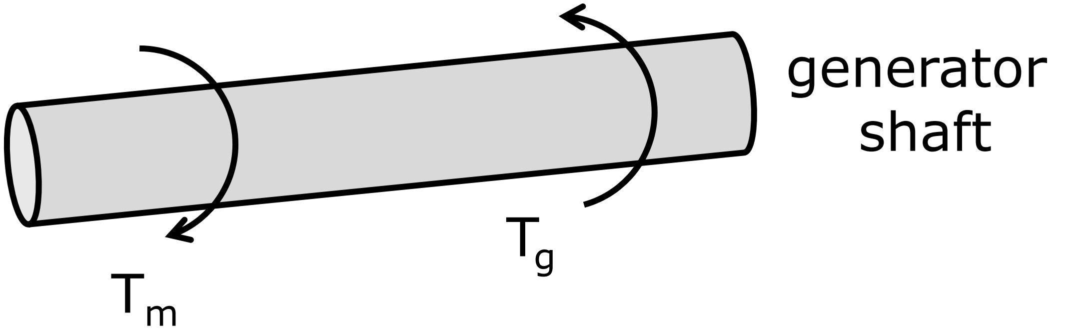
$$T_m - T_g = J\frac{d\Omega}{dt}$$

  - Where:
  - T_m: torque on shaft caused by wind (Nm)
  - T_g: torque on shaft caused by electrical load, electromagnetic in nature (Nm)
  - J: wind turbine moment of inertia
  - Ω: rotor angular velocity (rad/s)

Rotational Dynamics

- $T_m = T_g$
  - No change in rotor speed
- $T_m > T_g$
  - rotor speed increases
- $T_m < T_g$
  - rotor speed decreases

$$T_m - T_g = J\frac{d\Omega}{dt}$$

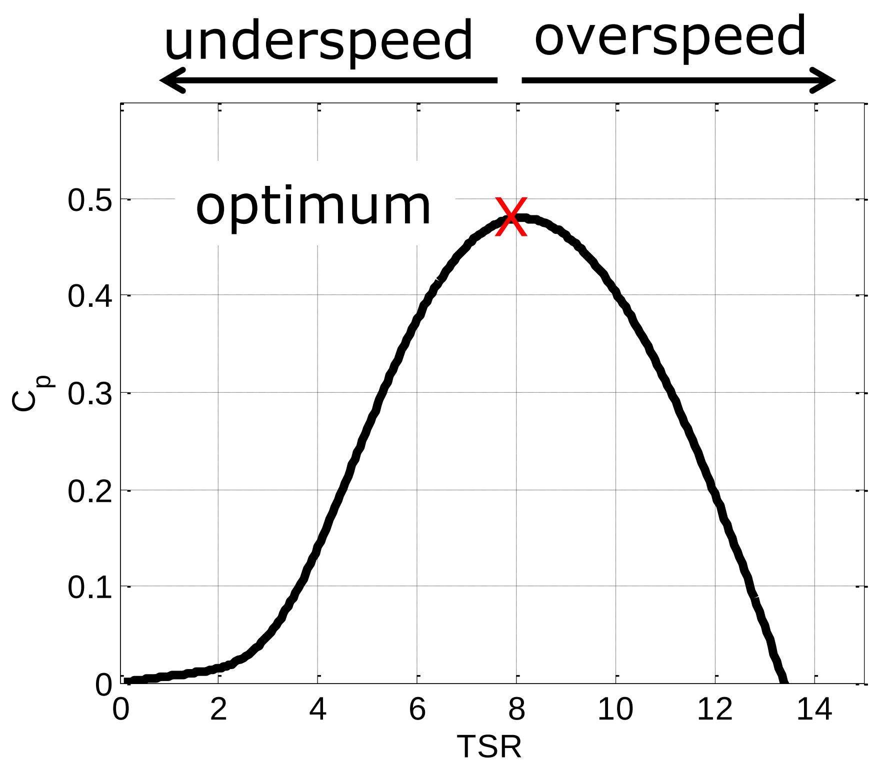


Rotational Dynamics

- Mechanical power from the wind turbine:

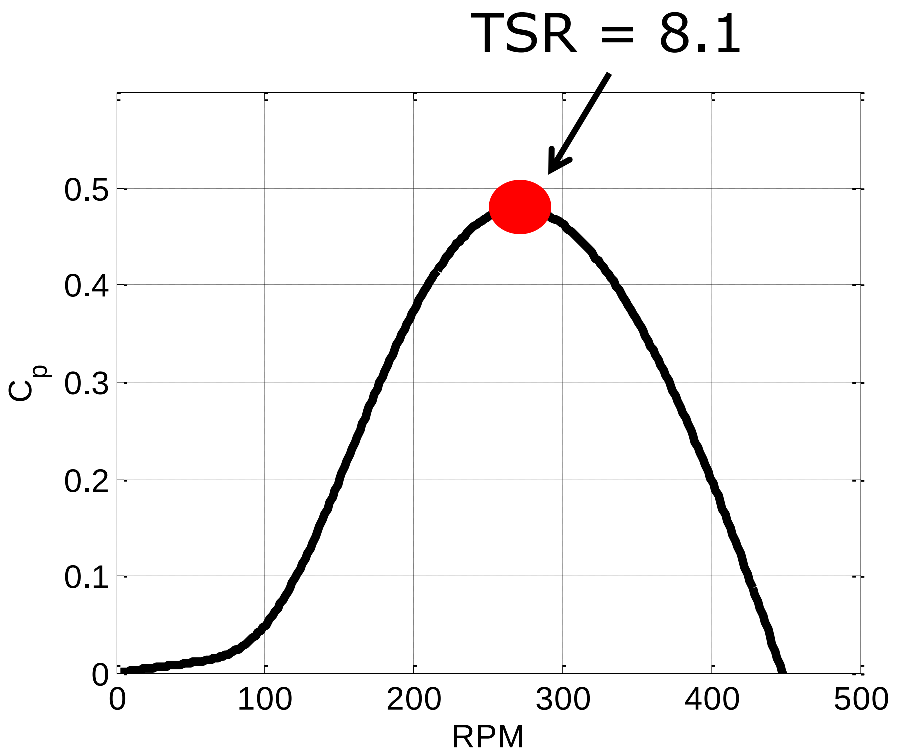
$$P_m = \frac{1}{2} C_p(\lambda, \beta) A \rho v^3$$

  - λ: tip seed ratio
  - β: blade pitch (degrees)



Rotational Dynamics

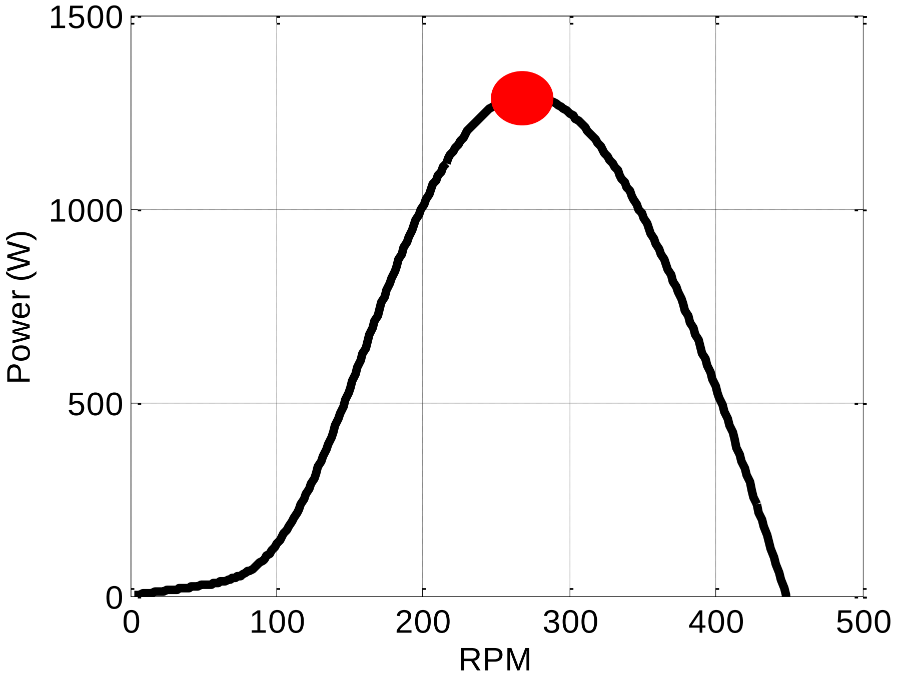
- Let v = 7m/s and r = 2m (rotor radius)
- Assume turbine is operating at optimal TSR

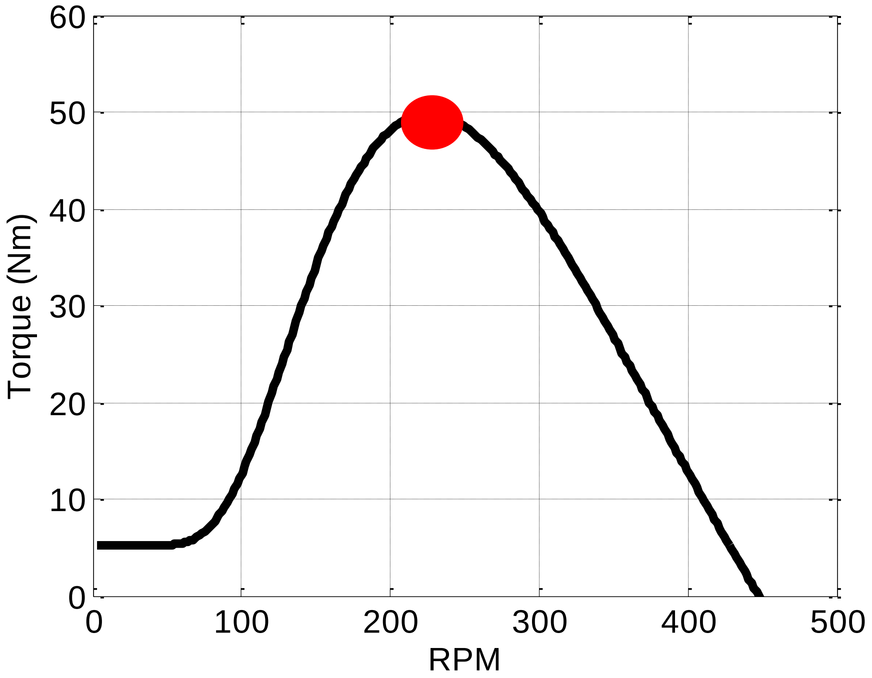


Rotational Dynamics

Operating point does not change if $T_g = T_m$,

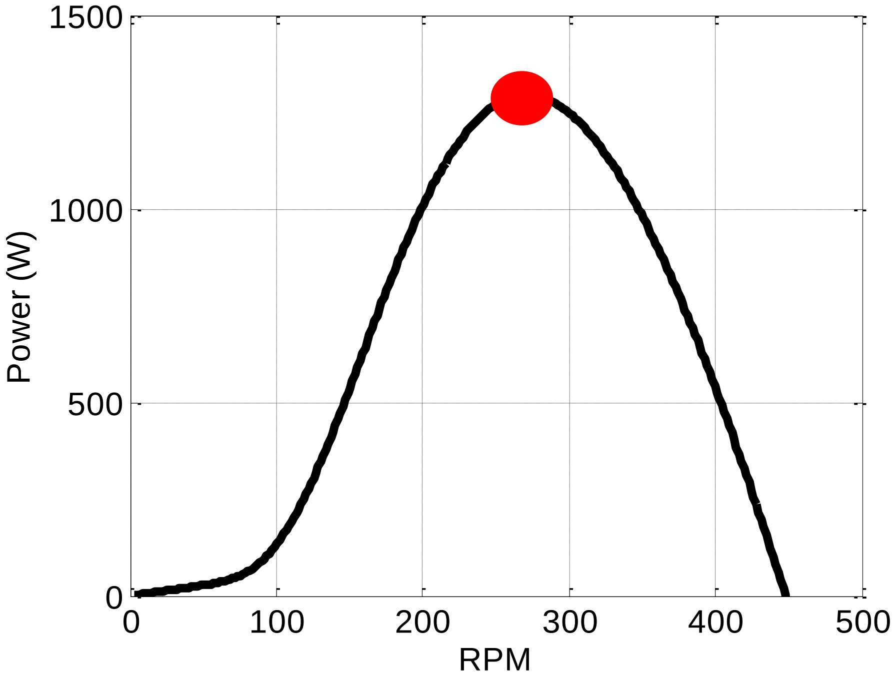
but T_g is determined by the generator and its load

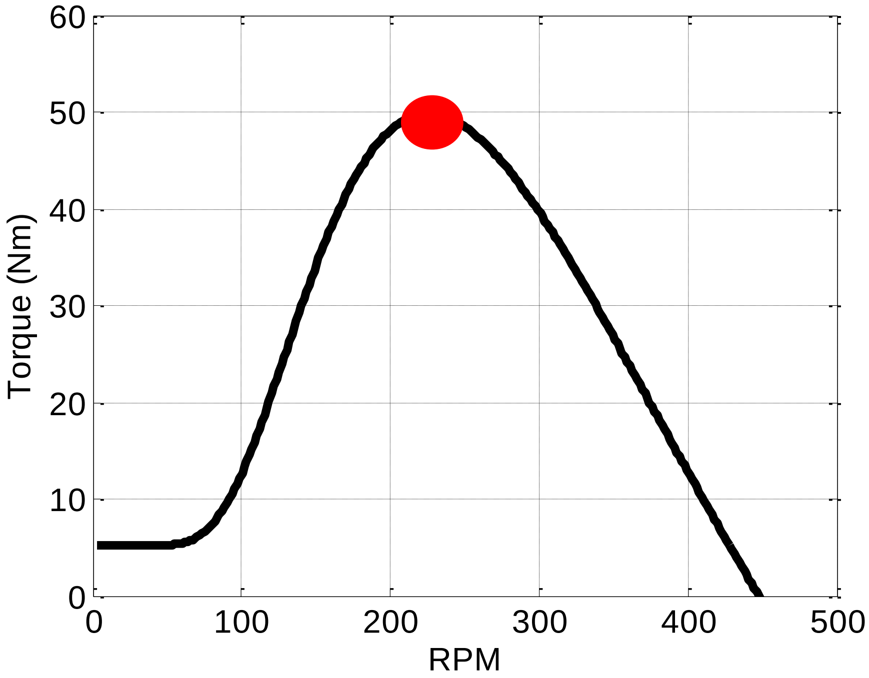




Rotational Dynamics

What happens if generator torque suddenly increases to 55 Nm?

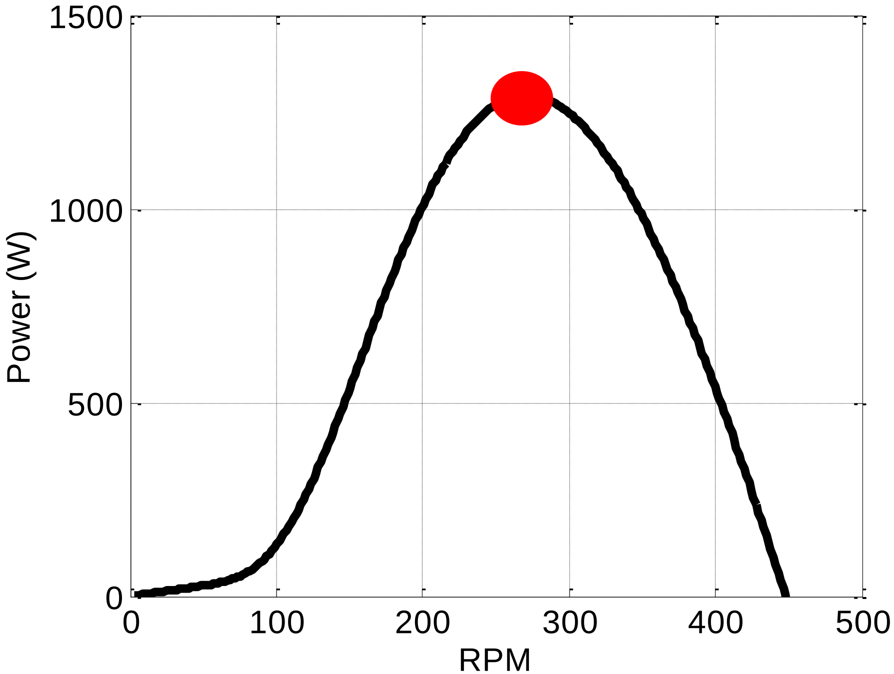


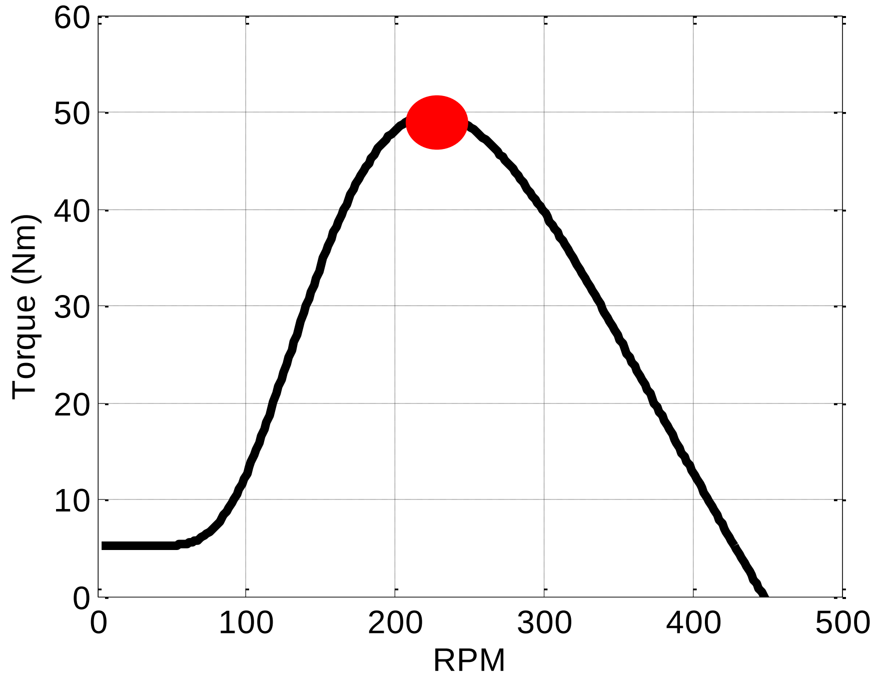


Rotational Dynamics

$T_g > T_m$, so generator slows down

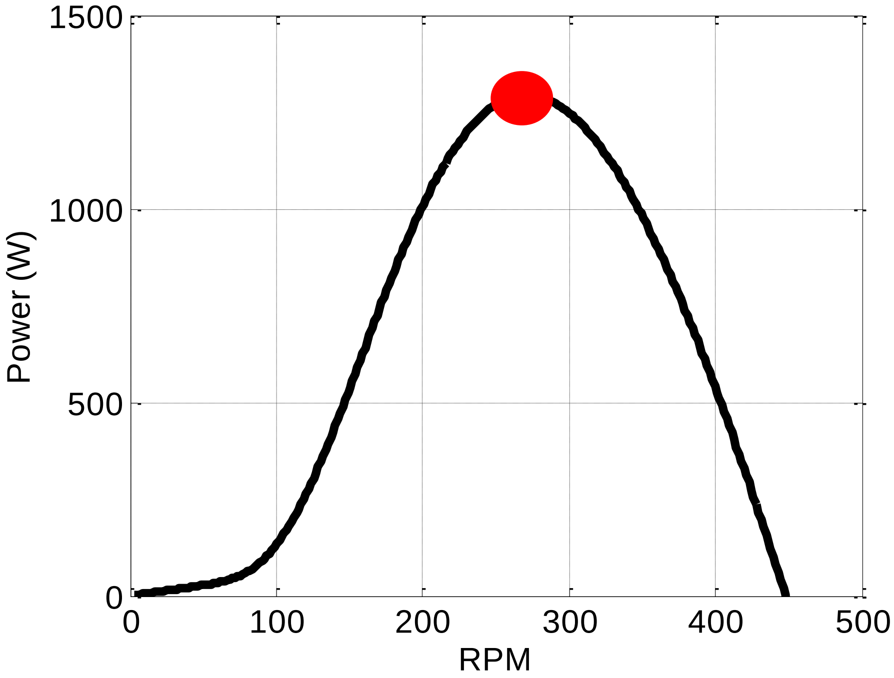
If generator load is constant torque, wind turbine will eventually stop

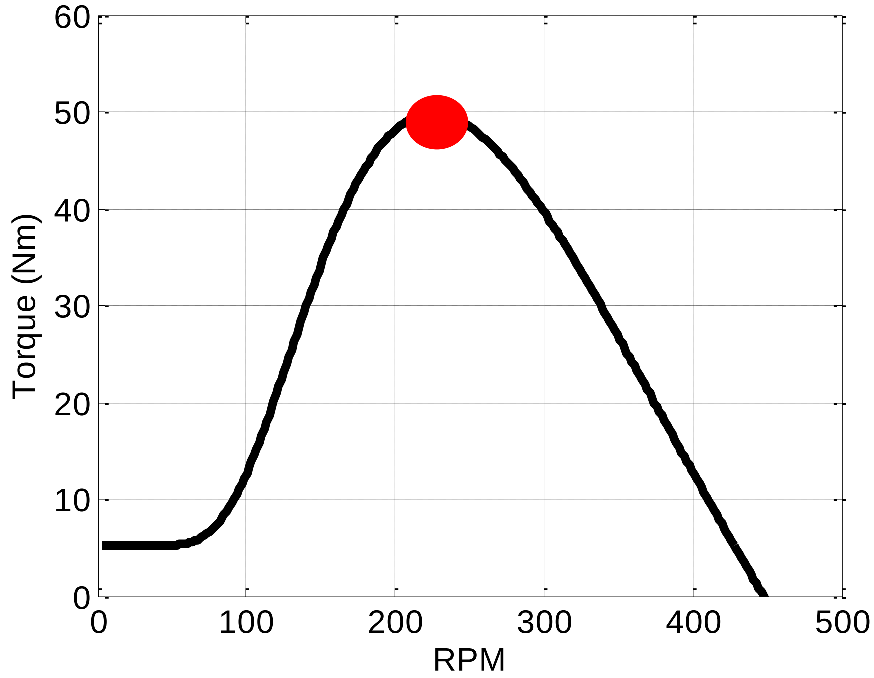




Rotational Dynamics

What happens if generator torque suddenly decreases to 20 Nm?

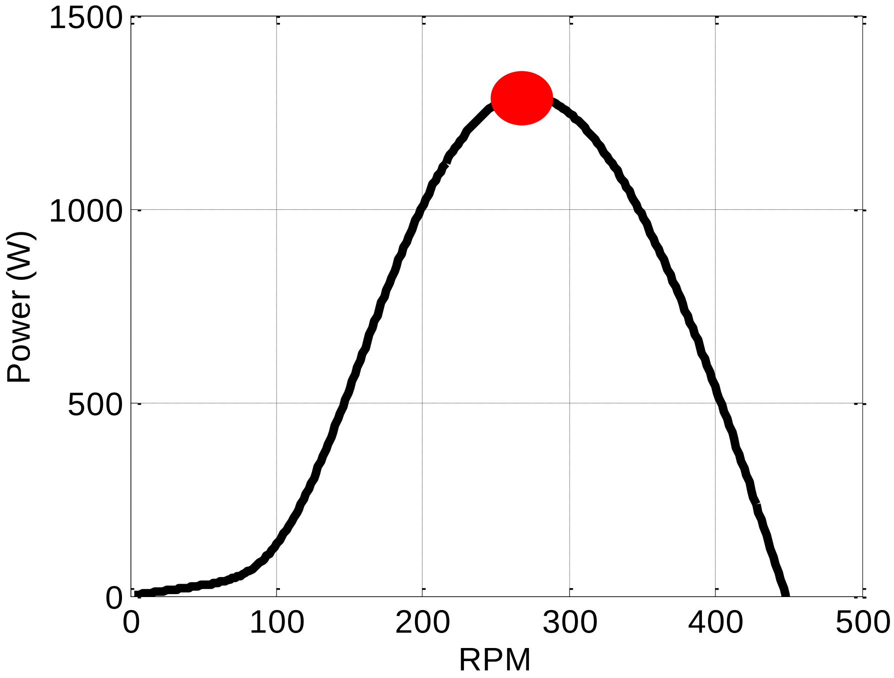


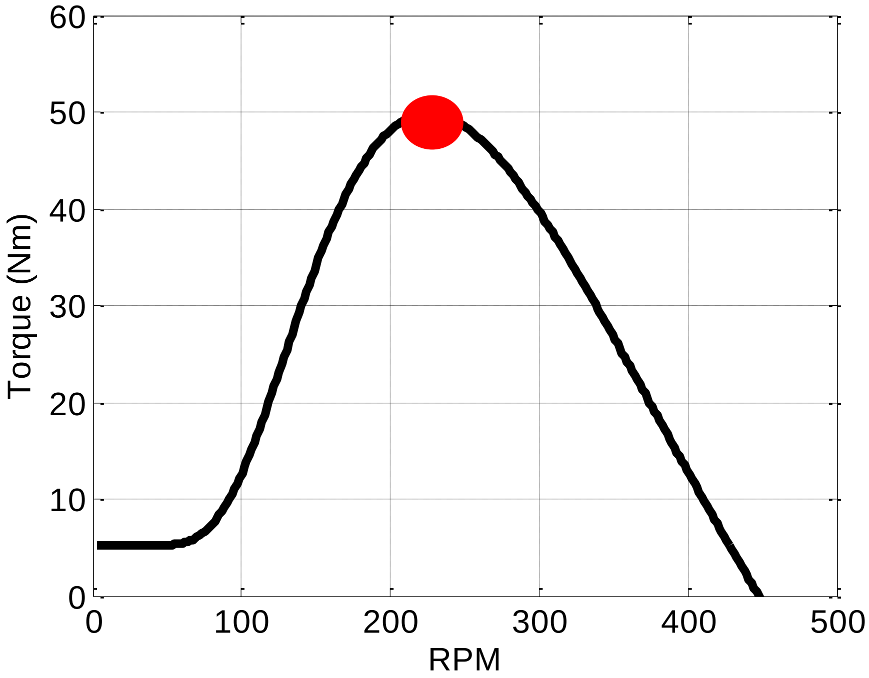


Rotational Dynamics

$T_g < T_m$, so generator speeds up

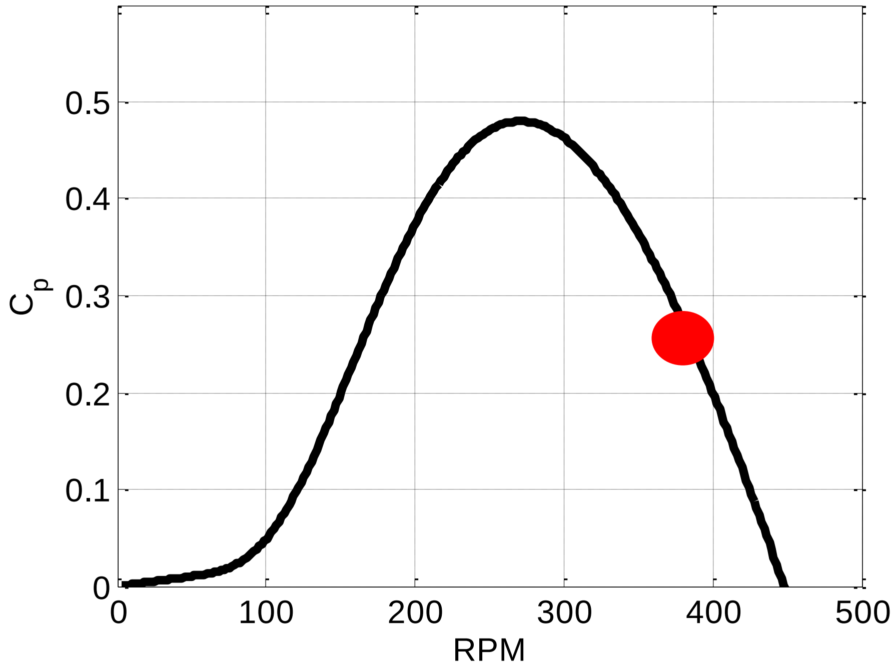
If generator load is constant torque, wind turbine will reach equilibrium point (but is operating inefficiently)





Rotational Dynamics

Operating point is sub-optimal (overspeed)



Generator Characteristics

- Battery loads are not constant torque
- Need to match wind turbine blades with generator characteristics