Wind Power Generation Electrical Systems: Technologies, Challenges, and Grid Integration

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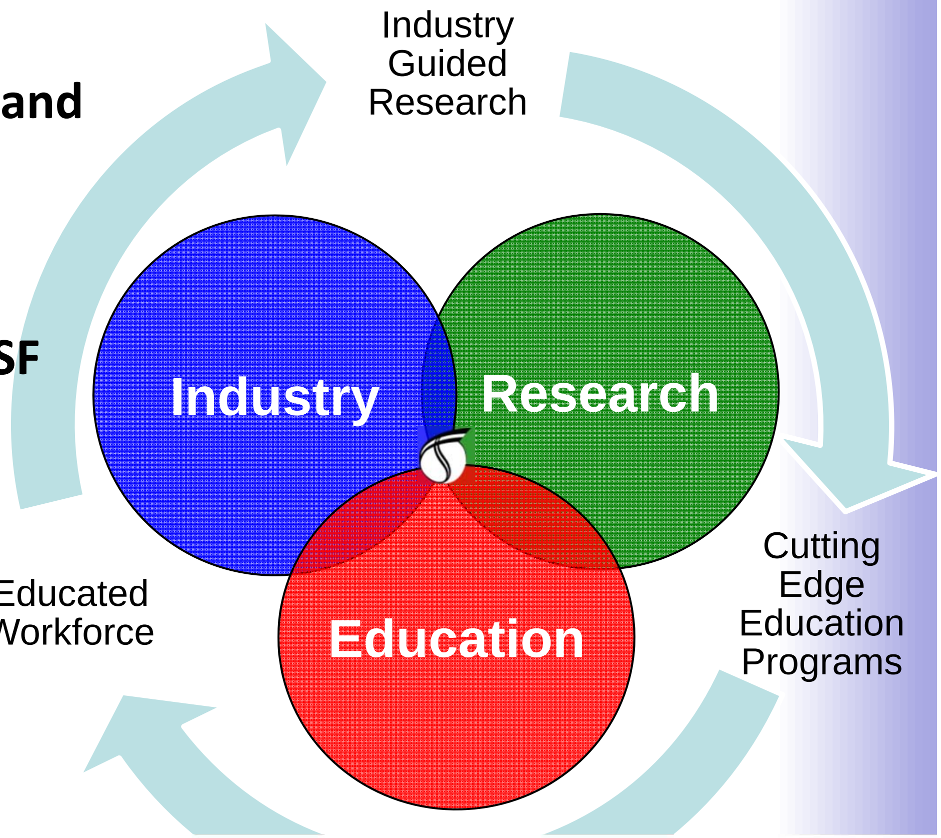
FREEDM ERC

- **Future Renewable Energy Distribution and Managements (FREEDM) Engineering Research Center (ERC) established in 2008**
- **Potentially a ten year investment by NSF**
- **Must address a transformative grand challenge , industry engagement and workforce preparation**
- **FREEDM is an R&D Engine for Grid Modernization**



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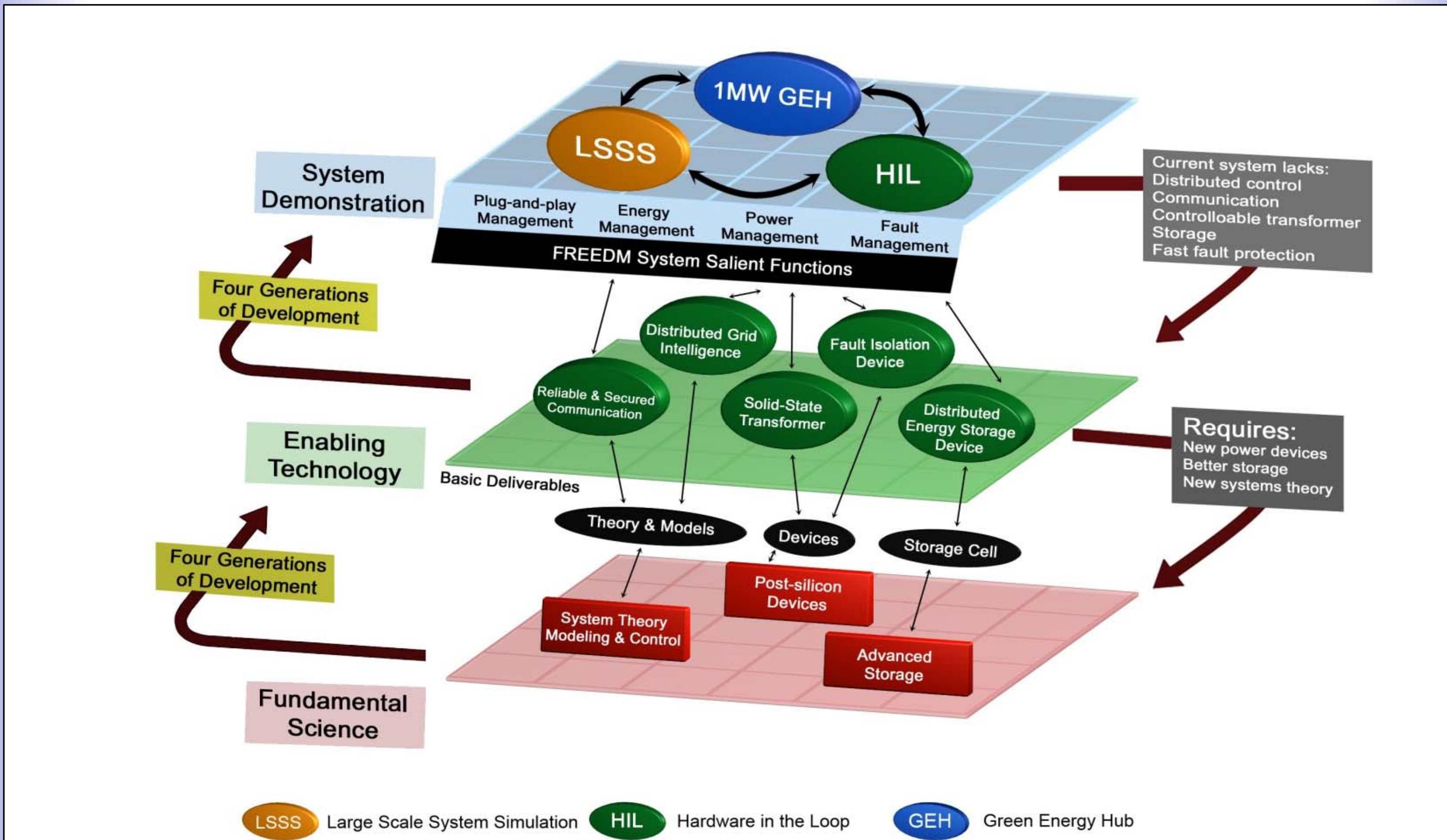
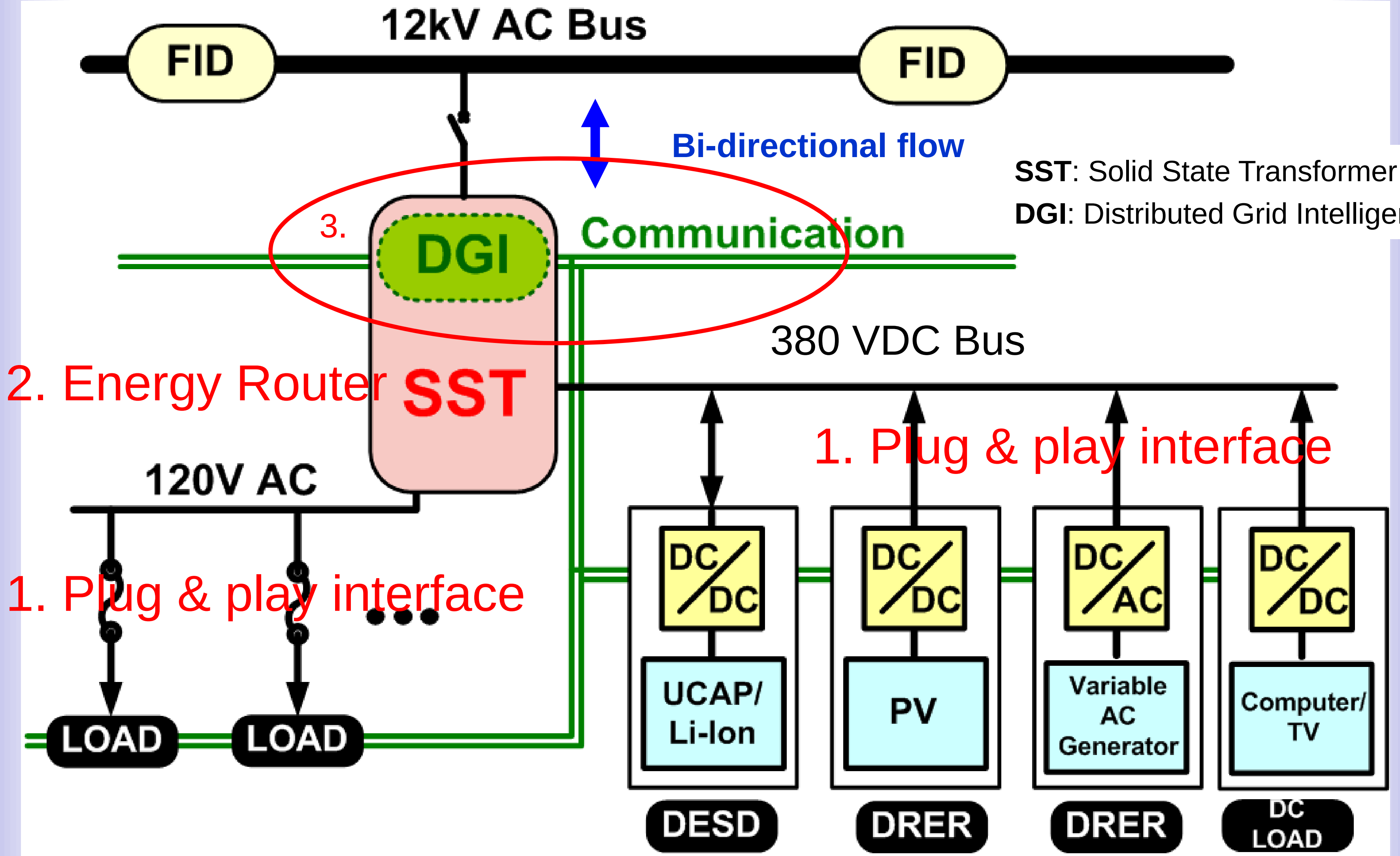
Three-Plane FREEDM



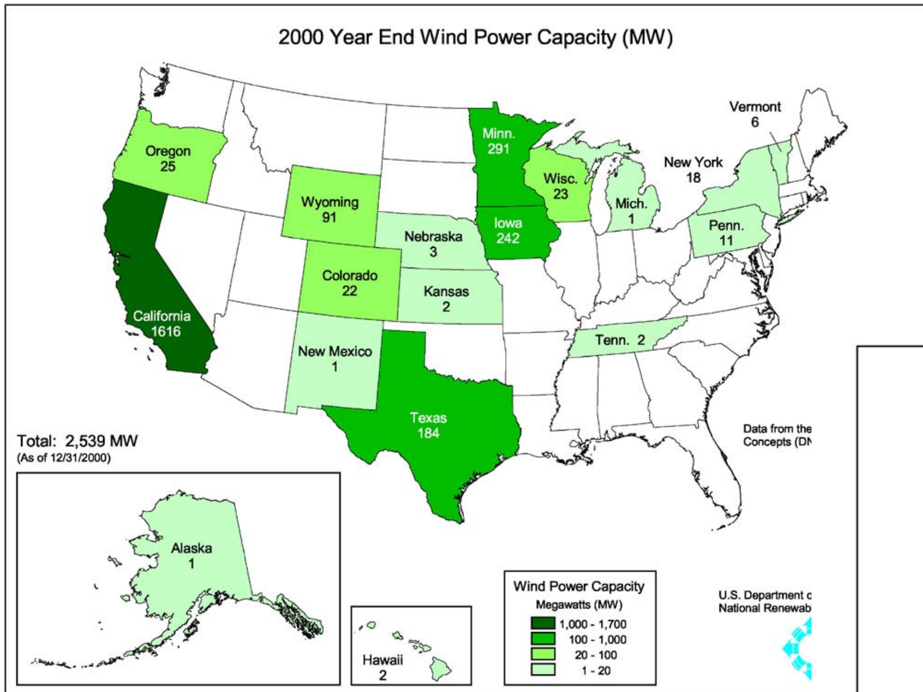
FREEDM System @Home Level

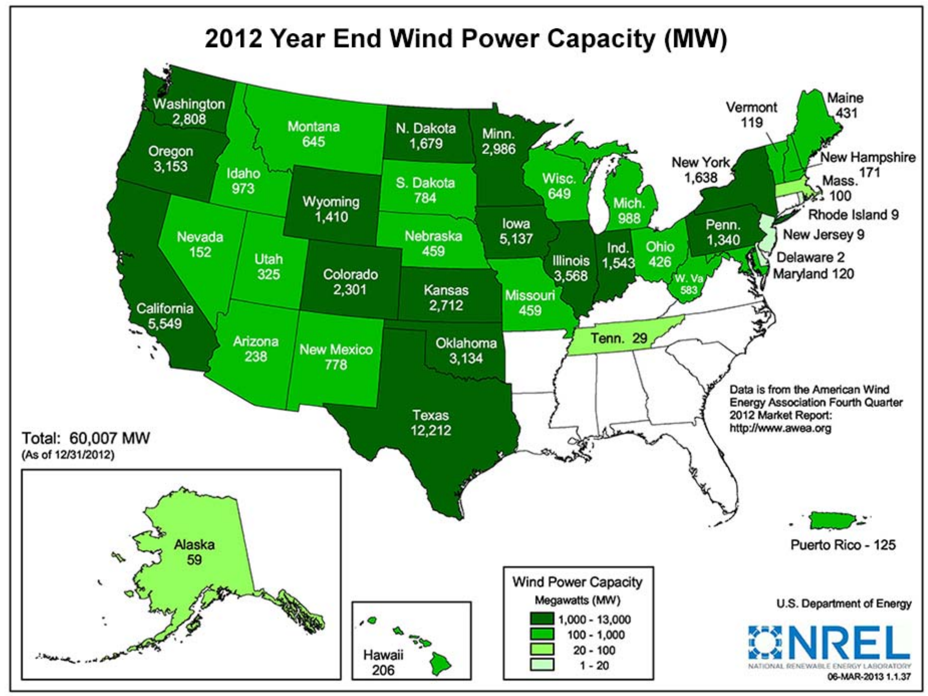


Laboratory with 12kV Voltage

Wind Energy Around the Globe

US Wind Installed Capacity

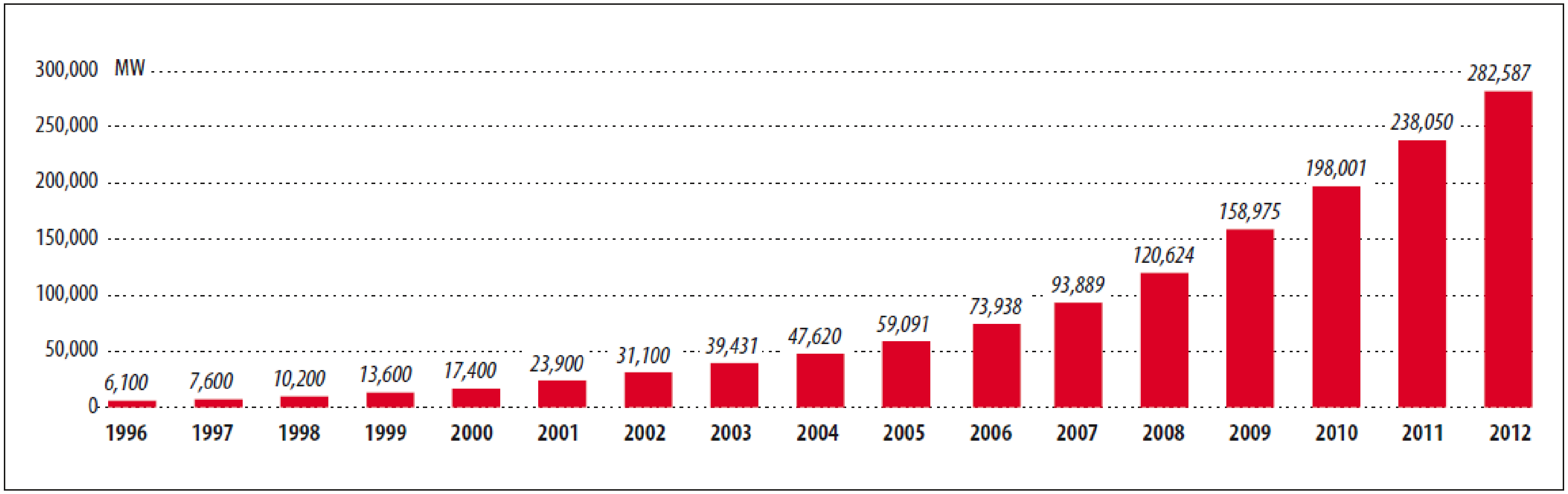




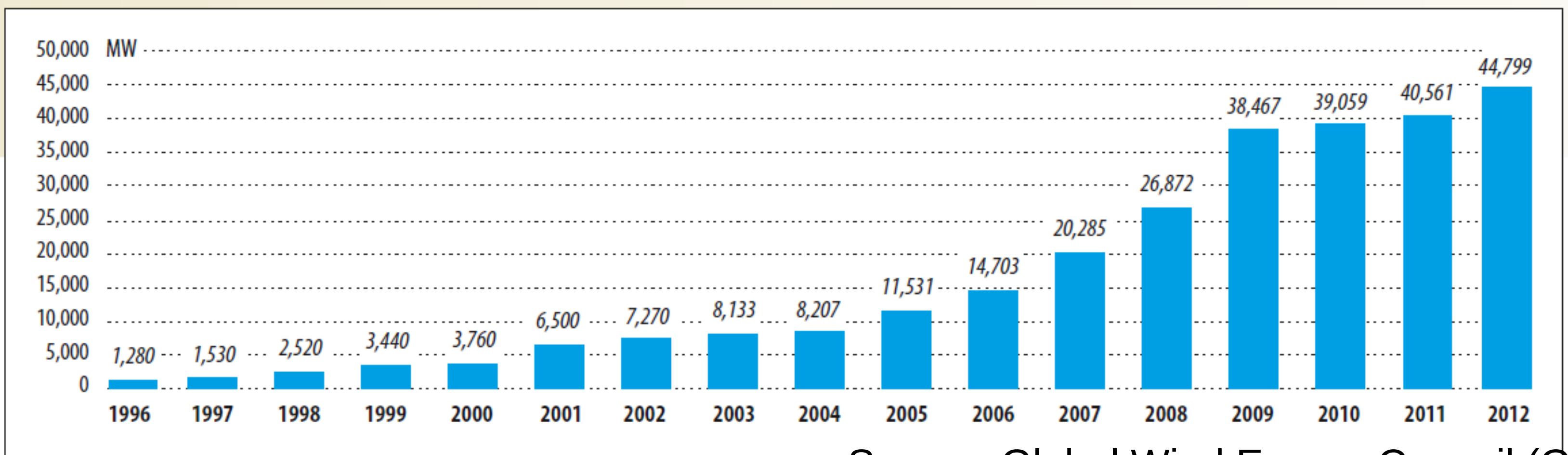
Source: NREL, US Department of Energy

Global Installed Wind Capacity

Global Cumulative Installed Wind Capacity 1996-2012



Global Annual Installed Wind Capacity 1996-2012

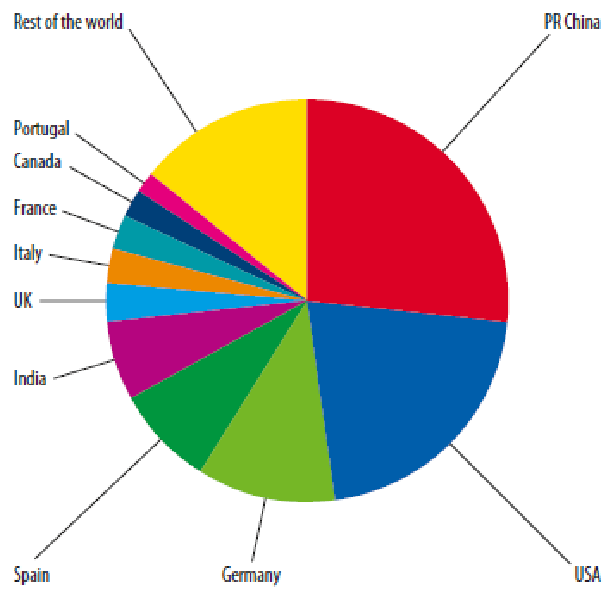


Source: GWEC

Source: Global Wind Energy Council (GWEC)

Installed Capacity Around the Globe

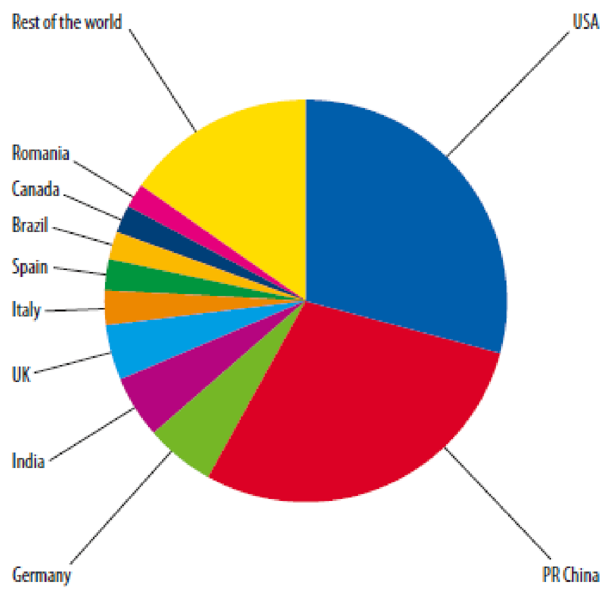
Top 10 Cumulative Capacity (December 2012)



Country	MW	% SHARE
PR China	75,324	26.7
USA	60,007	21.2
Germany	31,308	11.1
Spain	22,796	8.1
India	18,421	6.5
UK	8,445	3.0
Italy	8,144	2.9
France	7,564	2.7
Canada	6,200	2.2
Portugal	4,525	1.6
Rest of the world	39,853	14.1
Total TOP 10	242,734	85.9
World Total	**282,587**	**100.0**

Source: GWEC

Top 10 New Installed Capacity (Jan-Dec 2012)



Country	MW	% SHARE
USA	13,124	29.3
PR China	12,960	28.9
Germany	2,415	5.4
India	2,336	5.2
UK	1,897	4.2
Italy	1,273	2.8
Spain	1,122	2.5
Brazil	1,077	2.4
Canada	935	2.1
Romania	923	2.1
Rest of the world	6,737	15.0
Total TOP 10	38,062	85
World Total	**44,799**	**100.0**

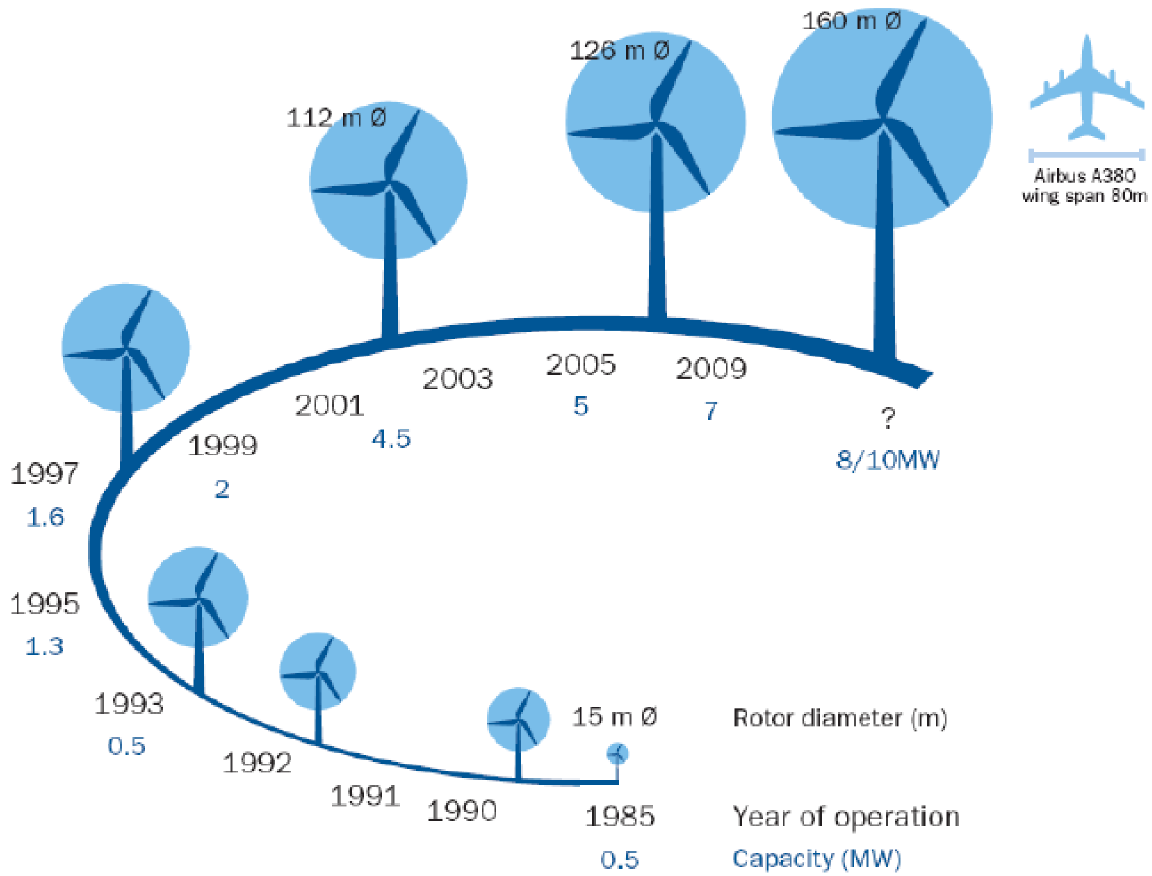
Source: GWEC

- Three main regions
  - Europe
  - Asia
  - North America
- 36% of all new capacity has been installed in China

Offshore Wind Power

- Trend -> Huge offshore wind farms (in GW range) with increased turbine output power
- Offshore Advantage
  - Large areas available
  - Higher and more constant wind speed than onshore
  - Higher energy yield (about 40% more than onshore)
- Challenges
  - High cost of installation and maintenance
  - Cost for grid connection
  - Energy Storage
  - Accessibility of offshore installations
  - Legislative issues

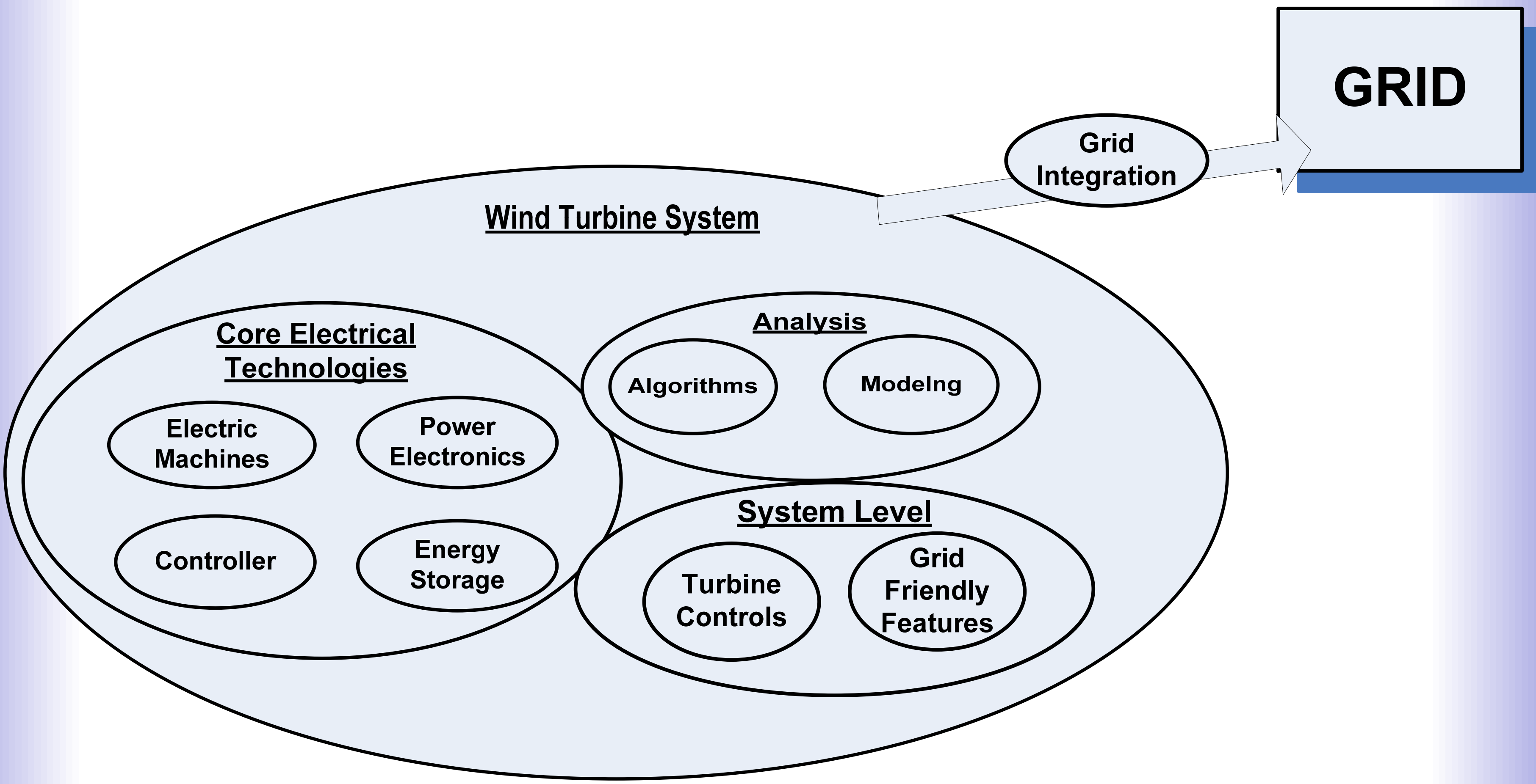
Wind Turbines



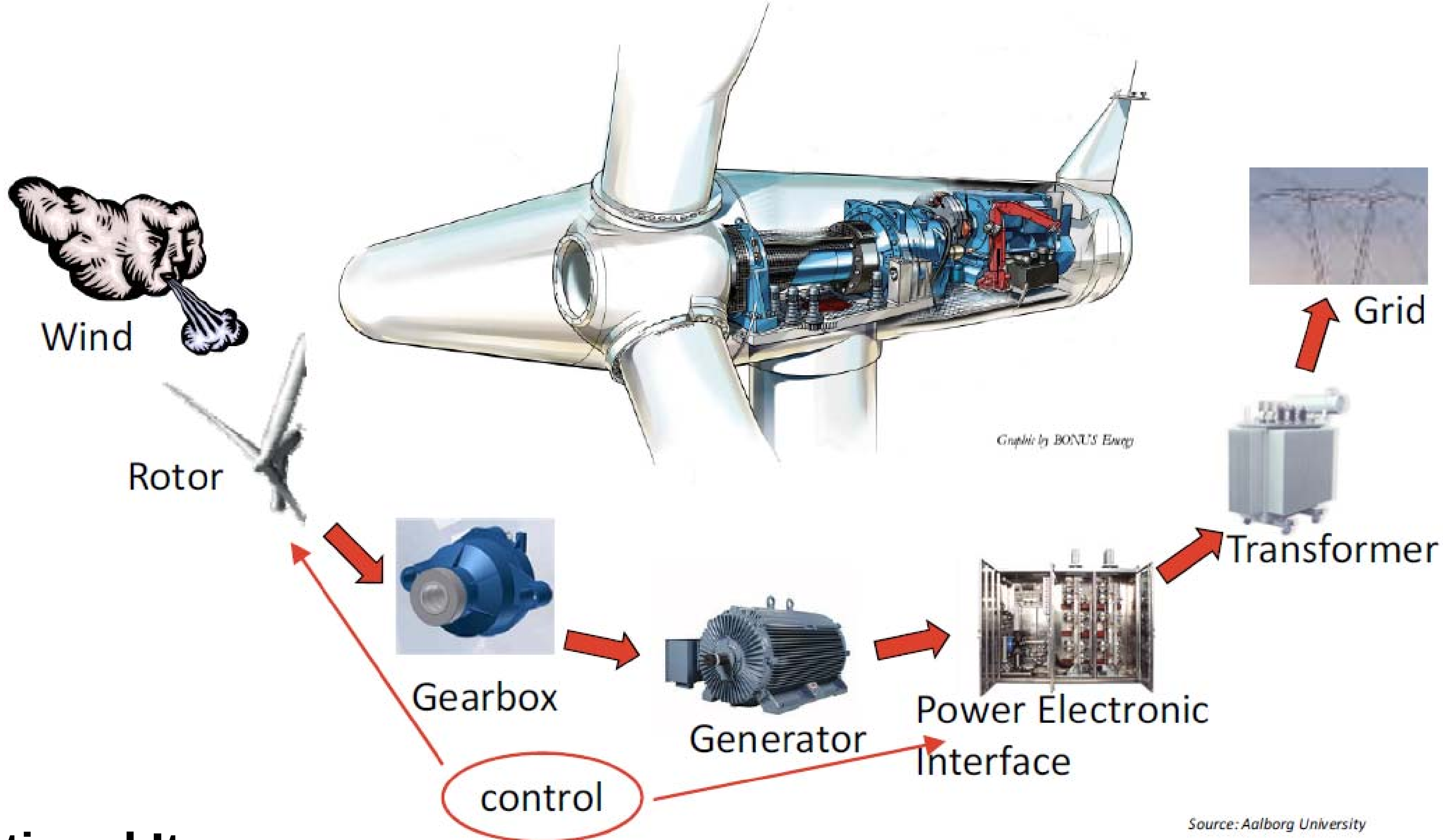
Source: European Wind Energy Association

- Wind turbines gradually becoming larger and more efficient
- Prototypes up to 7 MW running

Wind System Overview



Wind Energy Conversion



Optional Items:

- Battery storage system
- Transmission link to grid

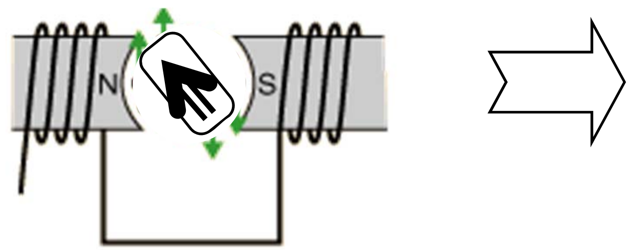
Electric Machines and Generators

Principles of Different Machine Types

- Biot-et-Savart law:
  - Wire and PM

    B_r from PM

    B_s from wire with I

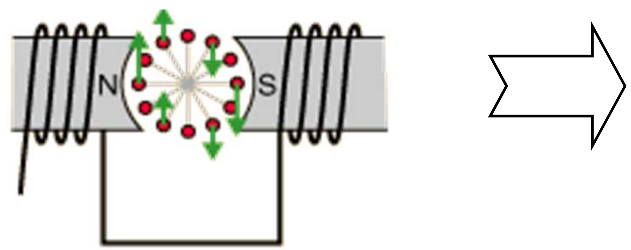


PM

  - Wire and wire

    B_s from one wire

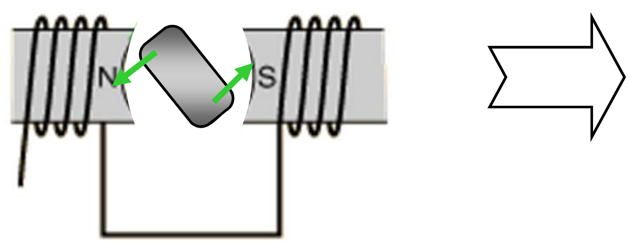
    B_r from other wire



Induction

  - Need for rotating field

- Minimum reluctance law



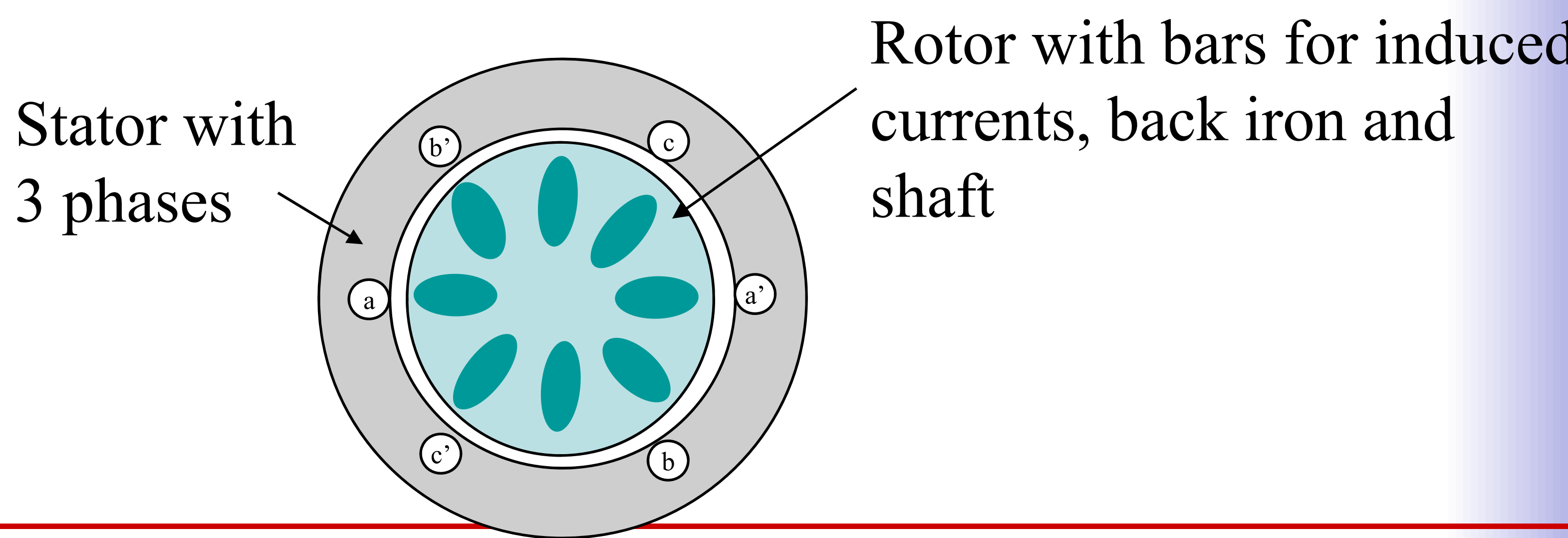
SR

AC Machines and Reluctance Machines

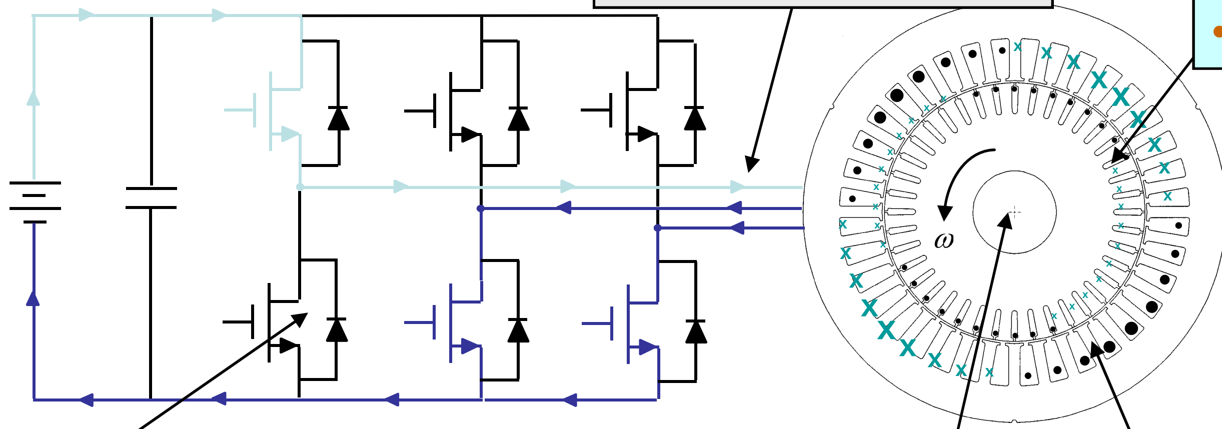
- Armature is stationary as opposed to DC machines
- Field or Excitation
  - Rotor circuit generates excitation or
  - Reluctance principle used (self-excitation)
- AC Machine types
  - Induction
  - Synchronous
  - PM Synchronous
- Reluctance Machines
  - Switched reluctance Machines
  - Synchronous Reluctance Machines
- No commutator or brushes in AC machines

3-Phase System: Induction Type

- 3-phase Balanced sinusoidal currents induce a stator rotating field (Stator mmf)
- Generates its own rotor rotating field field (rotor mmf) by inducing current in rotor bars (makes is own magnets on the fly, provided the speed between stator field and rotor is non-zero)
- Interaction of stator and rotor mmf's produce torque



Induction Machine Drive Implementation



Connection: 3 cables

Rotor currents:
•Generate heat

Inverter:
•Standard 6 switches
•Diodes in parallel with Mosfets/IGBTs
•Power shoot-through if short-circuit

Excitation:
•Comes from stator
•Efficiency (-)
•Small airgap (-)

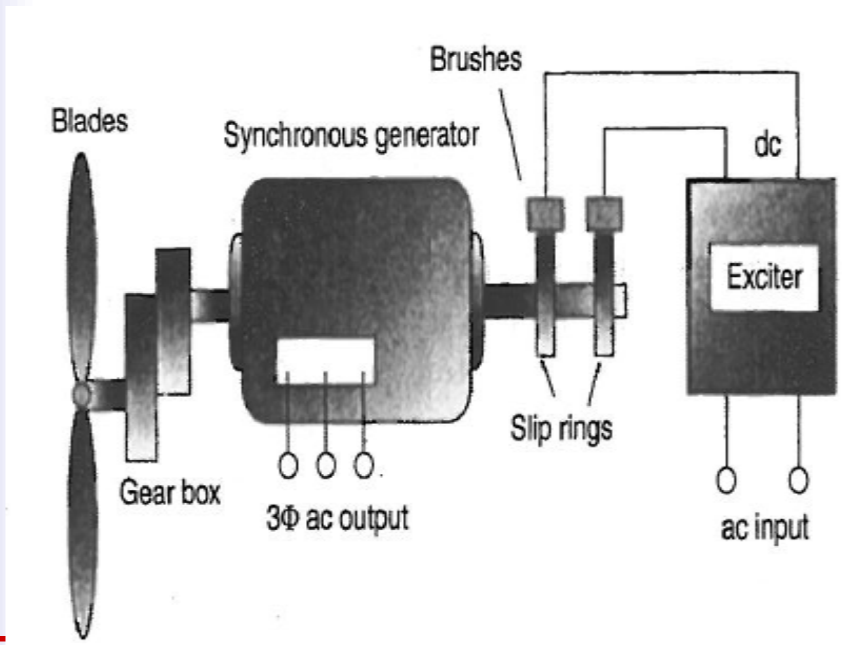
Motor position sensor:
•Incremental, Resolver

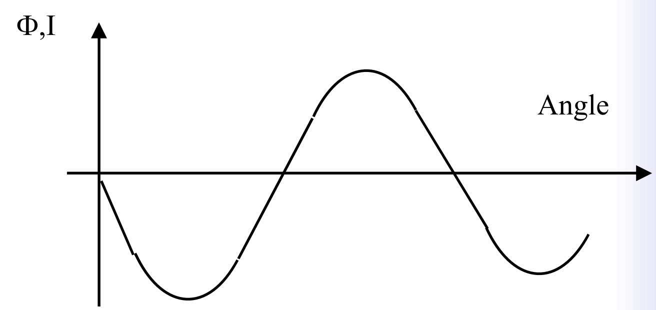
Controller: Well known

- **95% of world motors are induction**
  - **Large body of knowledge**

Synchronous Machines

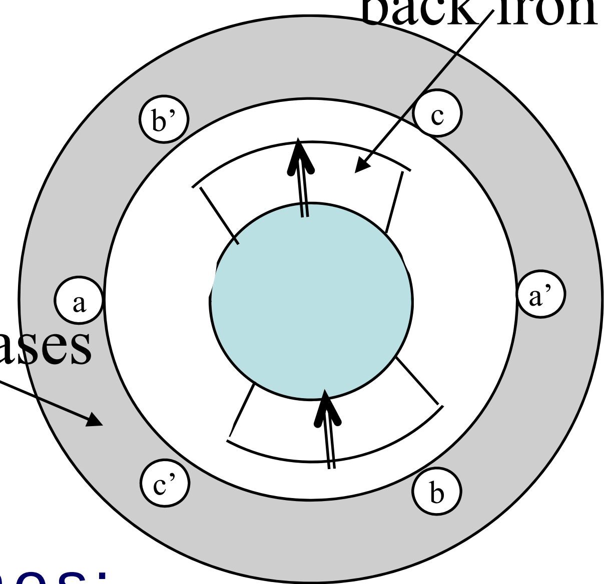
- 3-Phase Stator windings similar to induction machine Stator
- Excitation, i.e. second magnet pole pair, is created in the rotor DC circuit through an exciter
- Traditionally used in utility power generation.





3-Phase Machine: PMSM Type

- Rotating field created by 3 phases
- Magnets follow rotating field

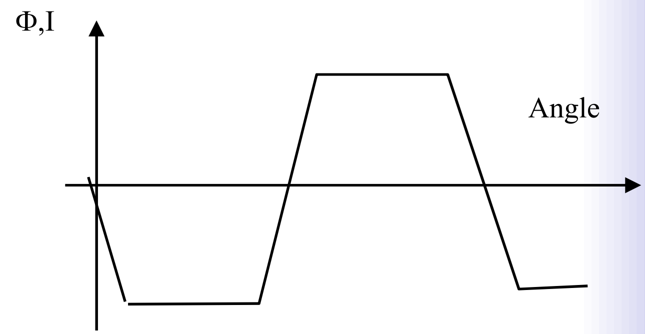


Advantages of PM machines:

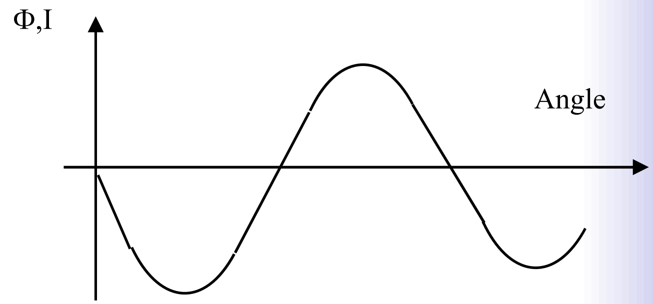
- **Loss-free excitation, useful for small machines**
- **High power density**
- **No brushes and slip rings required**

Permanent Magnet Machines

- Magnetization shape and current excitation:
  - Trapezoidal (PMBLDC): Magnet flux (Φ) trapezoidal; current (I) square
  - No rotating field
    - Simpler
    - Most common
    - EPS, brakes, etc.



  - Sinusoidal (PMSM): Magnet flux (Φ) and current (I) sinusoidal
    - Smoother torque
    - Needs a high resolution sensor
    - Wind Turbine, HEVs, EPS



Permanent Magnet Machine Types

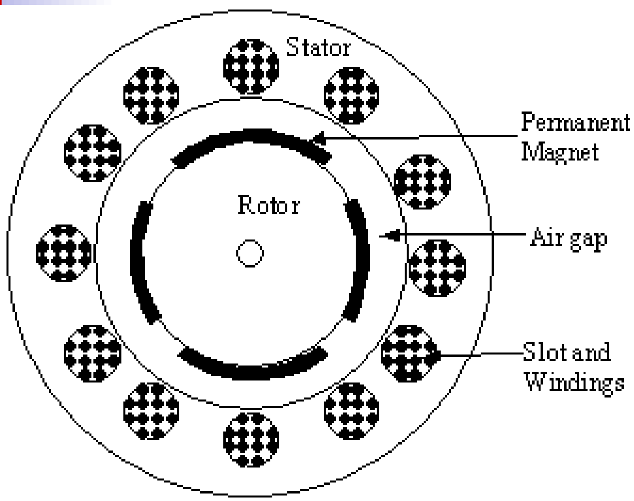
PMSM Based on Magnet Location:

Surface: Most common in automotive applications

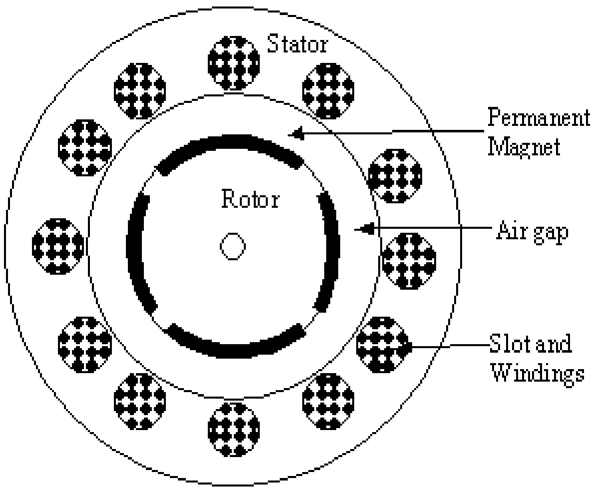
Inset: PM inserted at rotor surface, $L_d \neq L_q$ limited speed range

Interior: Wide constant power speed range, more expensive, requires larger machine (starter-generator, EV, HEV)

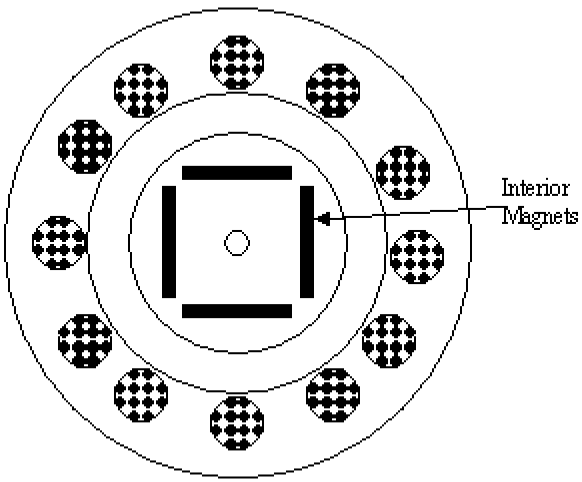
Surface mounted



Inset

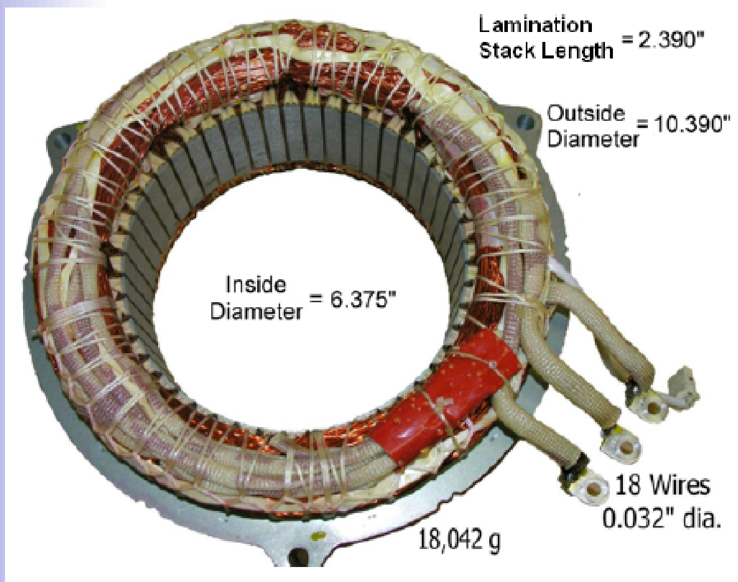


Interior/IPM



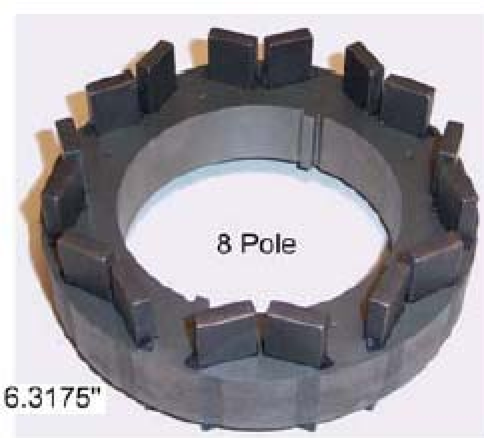
Radial Flux PM Machine

Interior Permanent Magnet (IPM) Machine is the design choice for production hybrid vehicles



Stator

Stator Laminations



Rotor

Source: Evaluation of 2007 Toyota Camry Hybrid Synergy Drive System, DOE Report ORNL/TM-2007/190, 2008.

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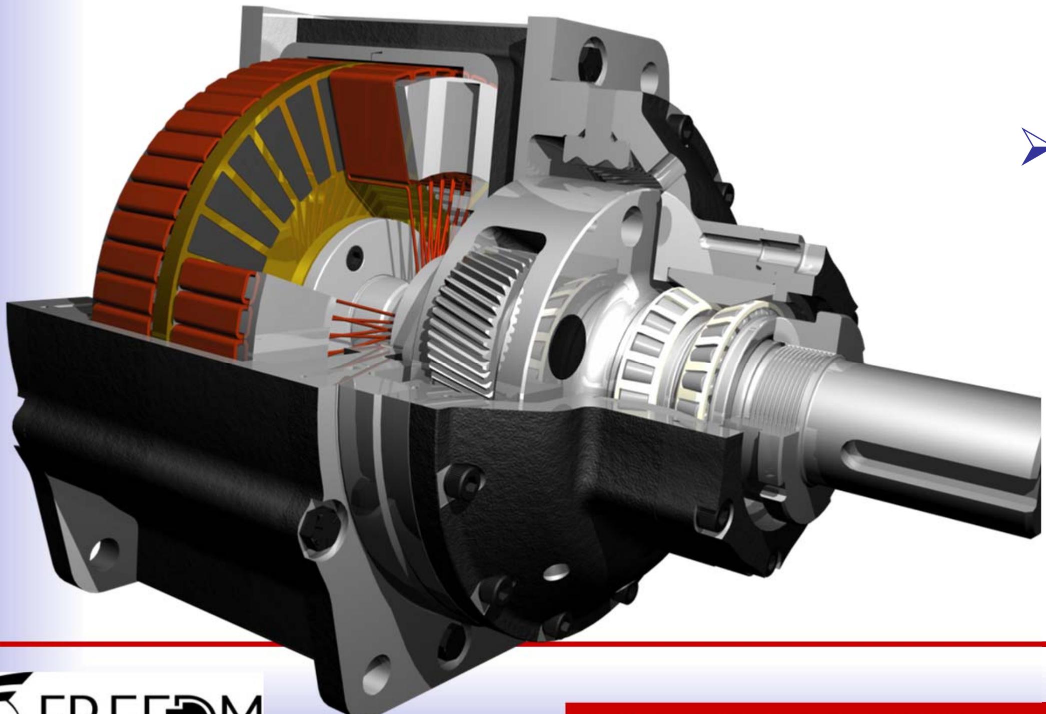
Axial Flux PM Machine

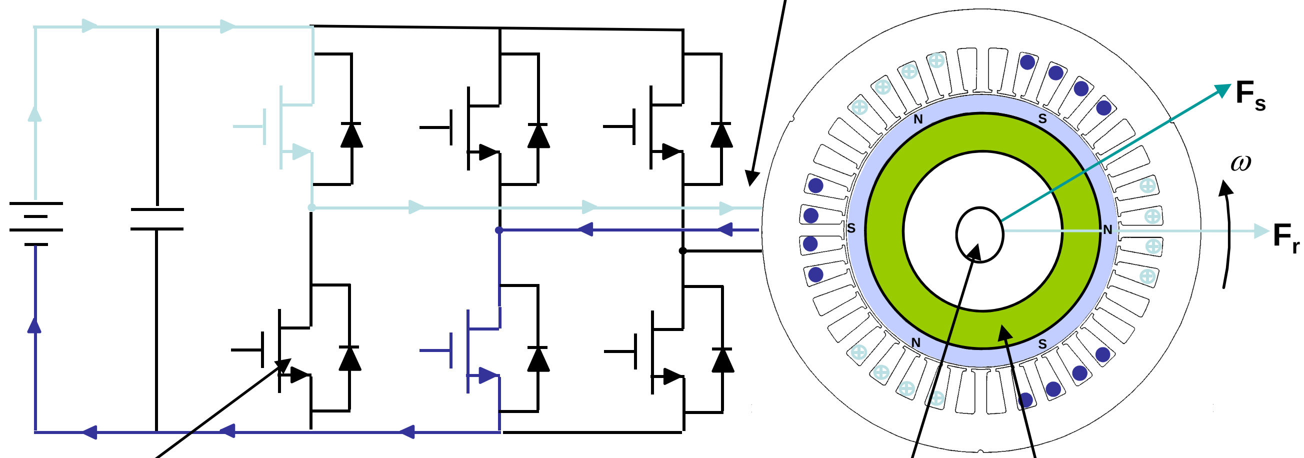
- Torque is a function of shear stress in the air gap times the air gap area times the moment arm
- Torque is produced over a continuum of radii, not a single radius
- Torque density advantage of axial flux increases as pole count increases.
- The utilization factor (specific torque) of the axial flux motor core is approximately twice that of the radial flux.



- Many options exist
  - Single Stator Single Rotor
  - Dual Stator Single Rotor
  - Single Stator Dual Rotor
  - Dual Stator Dual Rotor
  - Multiples of above

PM Drive Implementation

Connection: 3 cables



Inverter:
- Standard 6 switches
- Diodes in parallel with Mosfets/IGBTs
- Power shoot-through if short-circuit

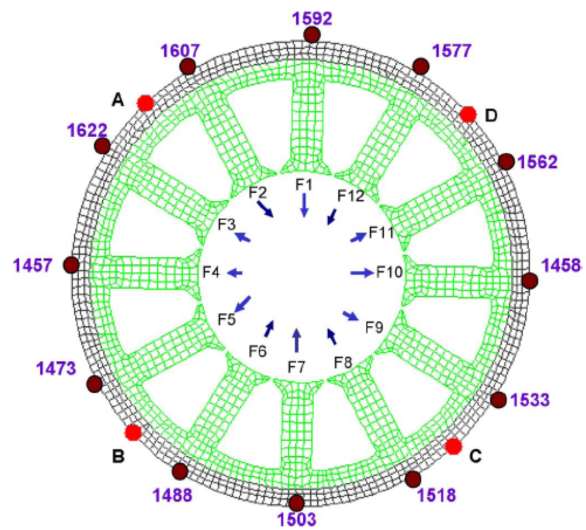
Magnets:
- Material cost (-)
- Motor assembly issues (-)
- Larger airgaps (+)

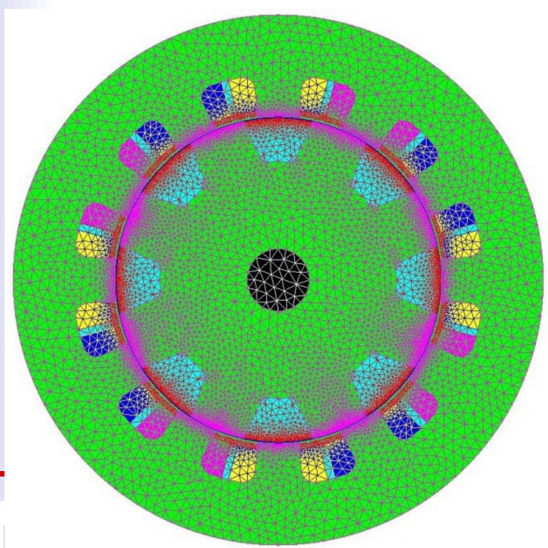
Controller:
- Trapezoidal: Simple switching scheme
- Sinusoidal: Well known
- High Speed Control

Motor position sensor:
- Trapezoidal: Low resolution
- Sinusoidal: High resolution

Machine Design and Analysis

- Analytical Model based Design
- Electromagnetic FEA
- Structural Analysis
- Thermal Analysis

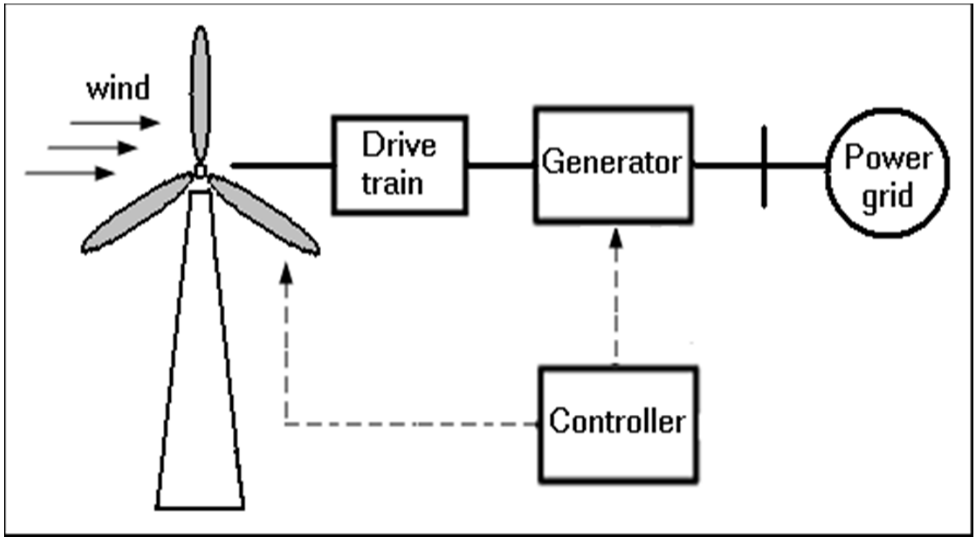




$$\lambda(i,\theta) = A_m(\theta,\xi) + A_f(\theta,\xi) - B_m(\theta,\xi)\sqrt{C_m(\xi) + D_m(i,\xi) + E_m\left(i^2,\xi\right)} - B_f(\theta,\xi)\sqrt{C_f(\xi) + D_f(i,\xi) + E_f\left(i^2,\xi\right)}$$

Wind System Generators and Their Controls

Induction vs. Synchronous Generators

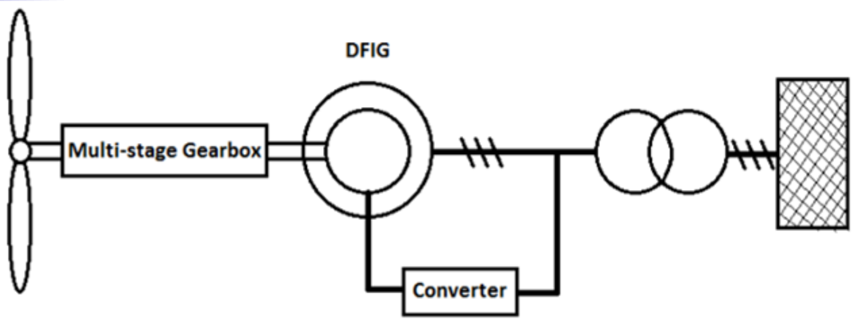


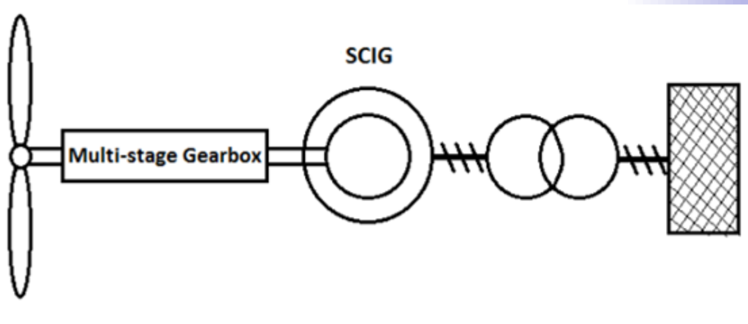
Wind Generation Syster

- Induction Generators widely used on wind power generation systems.
- Advantages of Induction generators over Synchronous generator:
  - Smaller size
  - Lower cost
  - Lower maintenance requirement

Induction Generators

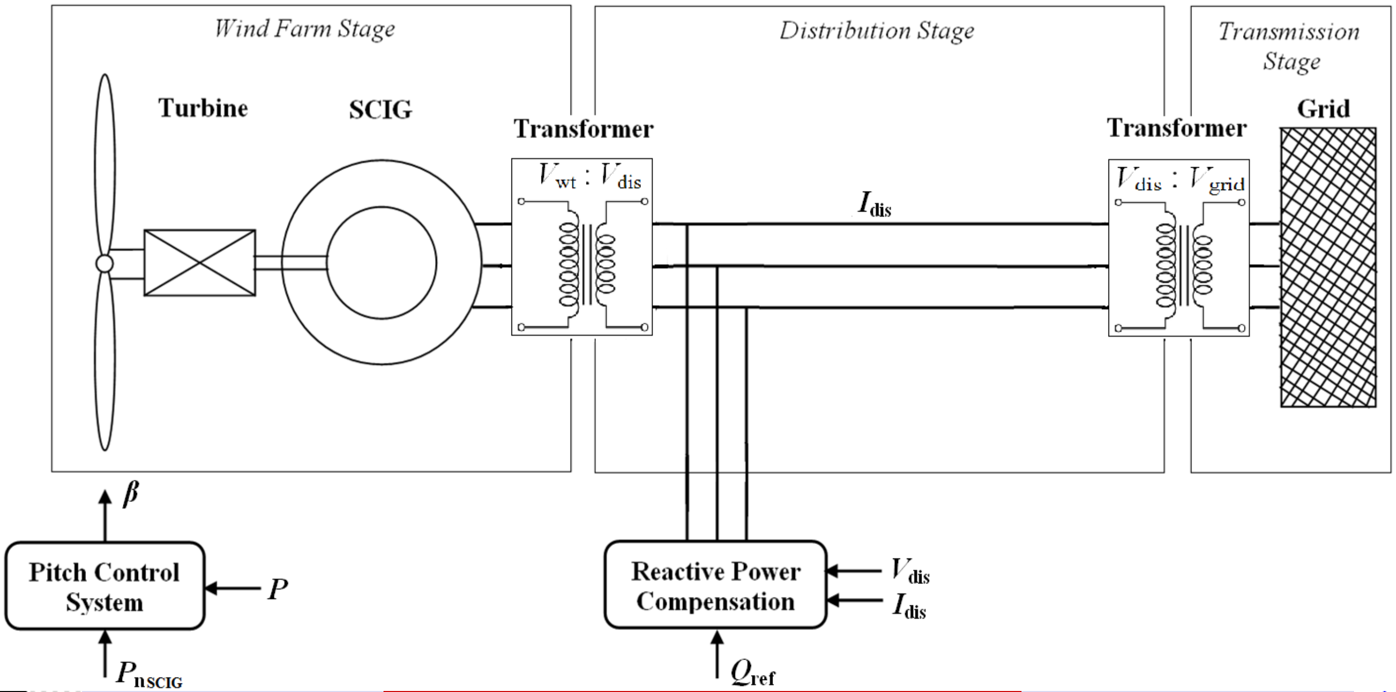
- Two types of induction generators
  - Squirrel-Cage Induction Generator (SCIG)
    - Fixed speed
  - Doubly-Fed Induction Generator (DFIG)
    - Variable speed



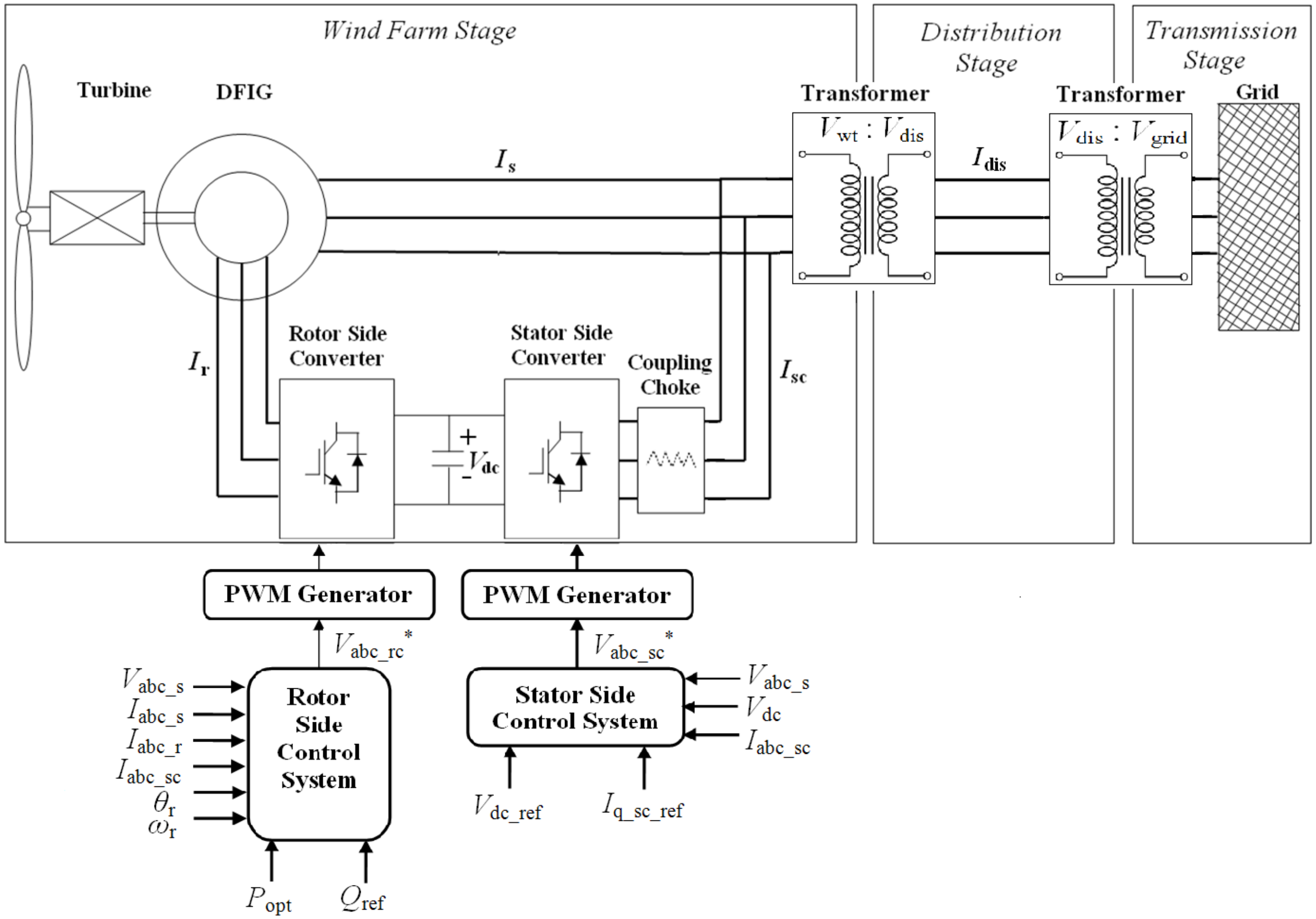


SCIG Wind Farm

- Three stages from wind turbine to power grid
  - Low voltage wind farm stage
  - Medium voltage distribution stage
  - High voltage transmission stage
  - 3-phase transformers couple each of the stages



DFIG Wind Farm



- Wound rotor induction generator
- Back to back converter with DC-link capacitor

Doubly Fed Induction Generator (DFIG)

- Doubly-Fed Induction Generator
  - With variable speed capability has higher energy capture efficiency and improved power quality
  - Back to back converter, which consists of two bidirectional converters and dc-link, acts as an optimal operation tracking interface
  - Field orientation is applied to both stator- and rotor-side converters to achieve desirable control on voltage and power

WT Generator Voltage Levels

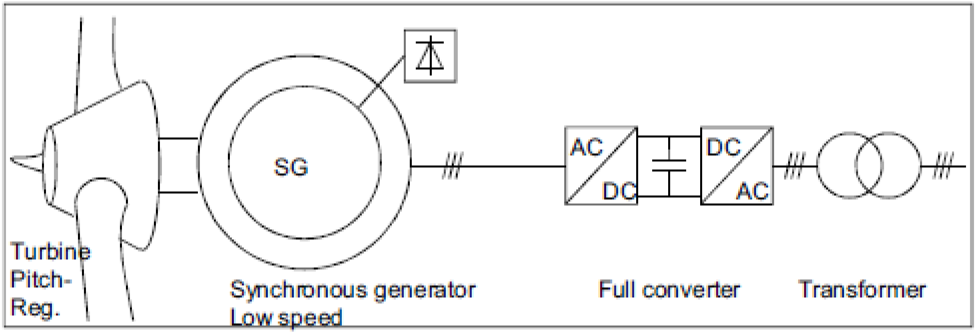
- Typical voltage levels:
  - Low Voltage (LV): 690V
  - Medium Voltage (MV): 3kV to 13.8kV
- MV Advantages
  - Lower loss connection between generator and converter
  - Power electronics can be placed in tower
  - Reduction of volume and weight of nacelle
  - Increased efficiency
- LV Advantages
  - Less expensive generator, since MV insulation is not required
  - MV personnel training not required

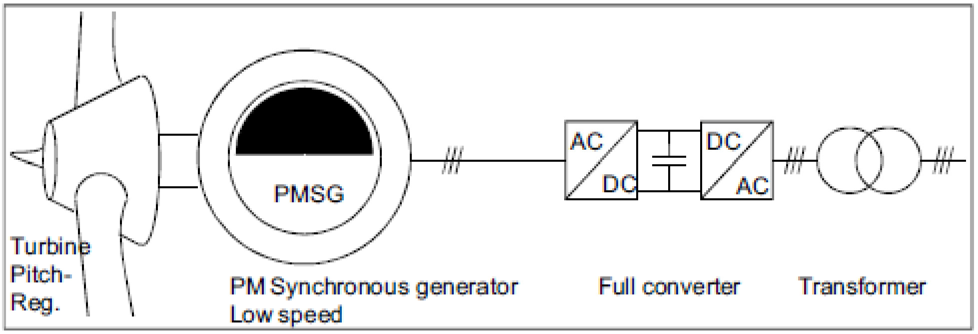
WT Variable Speed Operation

- Advantages:
  - Reduction of mechanical stress due to the weak grid coupling
  - Utilization of synchronous generators possible
  - Turbine acts as intermediate storage of kinetic energy during gusts
  - Less pulsation of output power
  - Ride-through of grid faults
  - Efficiency gain at low wind due to adaptation of turbine speed
  - Less noise at low wind speed
- Drawback:
  - Power Electronics is needed

Wind Turbines at Variable Speeds

- Electrically excited Synchronous Gen.
  - Gearless
  - Low-speed multi-pole generator
  - Large weight of nacelle
  - Power up to 6MW



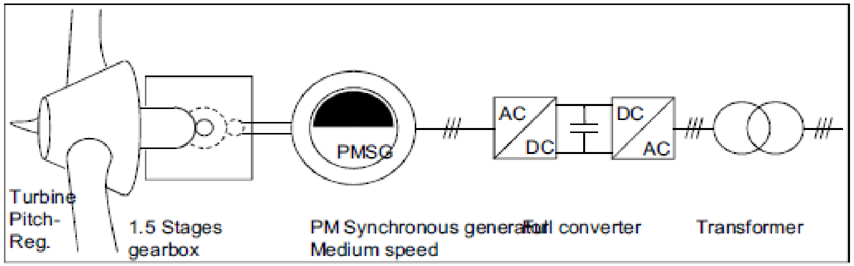


- Direct-drive PMSG
  - Low-speed generator
  - Reduced size and weight
  - Power up to 3.5MW

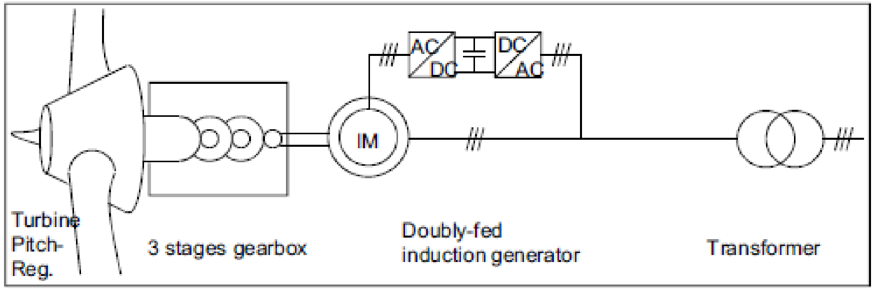
Source: ECCE 2010 Tutorial on Grid Converters for PV and WT Systems by Prof. R. W. De Doncker, RWTH Aachen, Germany

Wind Turbines at Variable Speeds

- 1 to 2 state gearbox PMSG
  - Medium speed generator
  - Compact Design
  - Power up to 5 MW



- Doubly-Fed Induction Generator (DFIG)
  - Variable speed operation without full-rated converter
  - Converter designed for about 30% of rated power
  - Market introduction since 1996
  - Today's most commonly used concept
  - Power up to 6MW



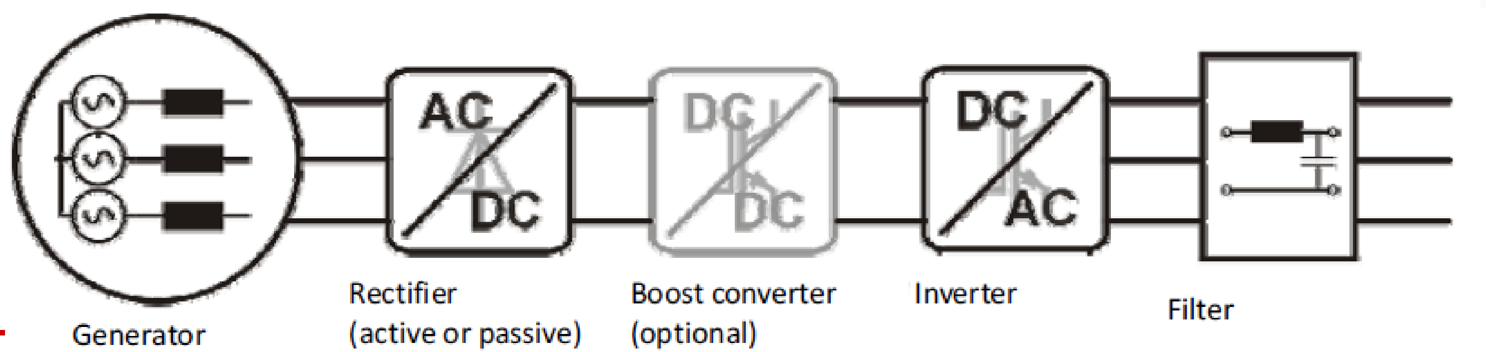
Source: ECCE 2010 Tutorial on Grid Converters for PV and WT Systems by Prof. R. W. De Doncker, RWTH Aachen, Germany

Partial Converter vs. Full Converter

- Partial Converter with DFIG
  - Small inverter needed in theory
  - Reduction of power electronic losses
  - Not fully decoupled generator from the grid
- Full converter
  - Increased power quality and very flexible reactive power control
  - Converter needs to be designed for full power
  - Higher efficiency of generator
- Grid interconnection rules in the future will govern the choice

Full Converter

- Connection between generator and grid
- Voltage source converter using Pulse Width Modulation (PWM)
- Back-to-Back converter with intermediate DC-link
  - Decouples turbine speed and grid frequency
  - Enables variable speed operation
- Converter rating needs to be higher than rated turbine output power
  - Fulfillment of grid code requirements
  - Overload capability



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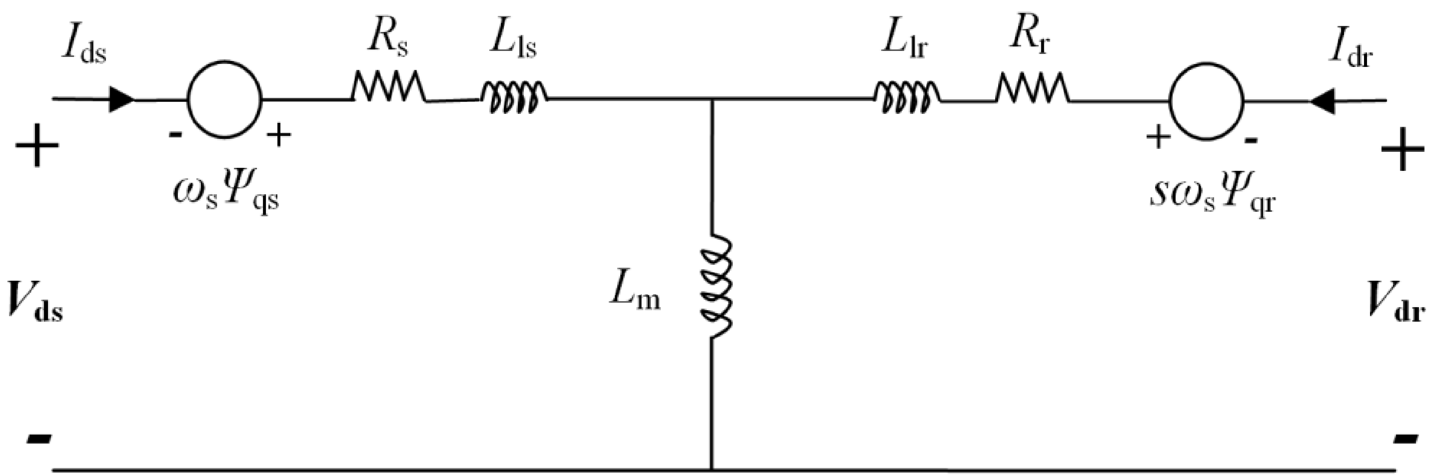
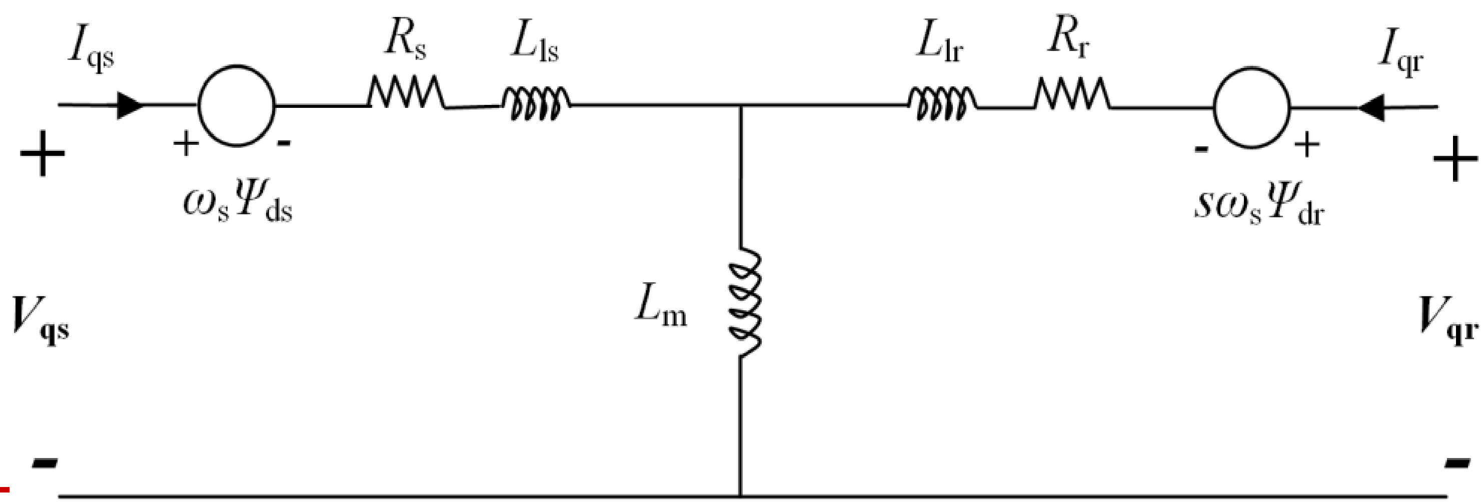
DFIG Equivalent Circuit



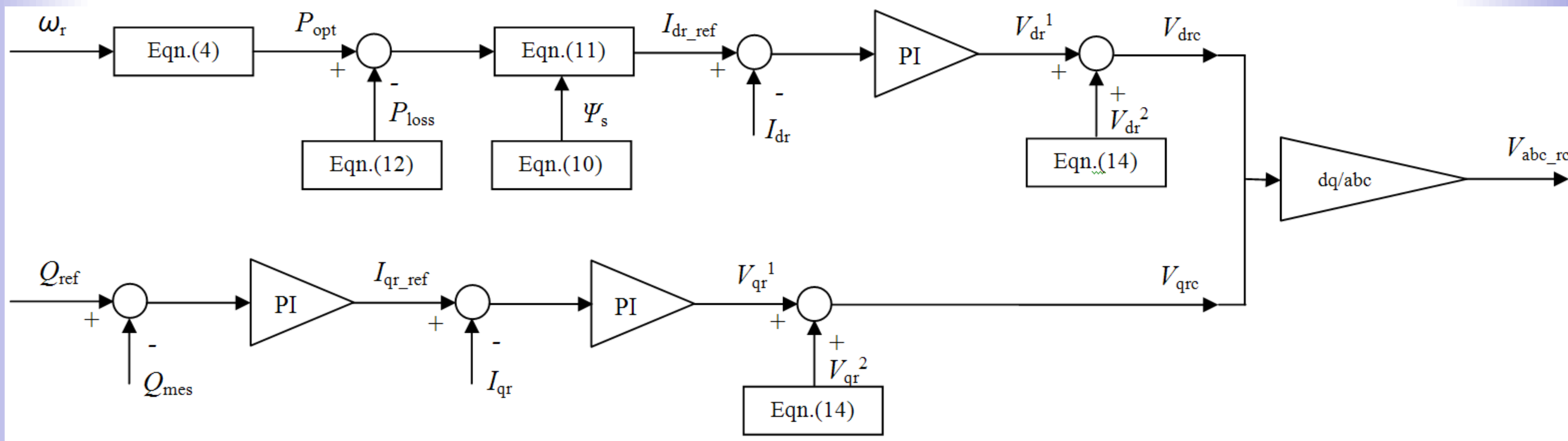
d-axis model



q-axis model

Rotor-Side Converter Control

- Rotor side responsible for regulation of active and reactive power

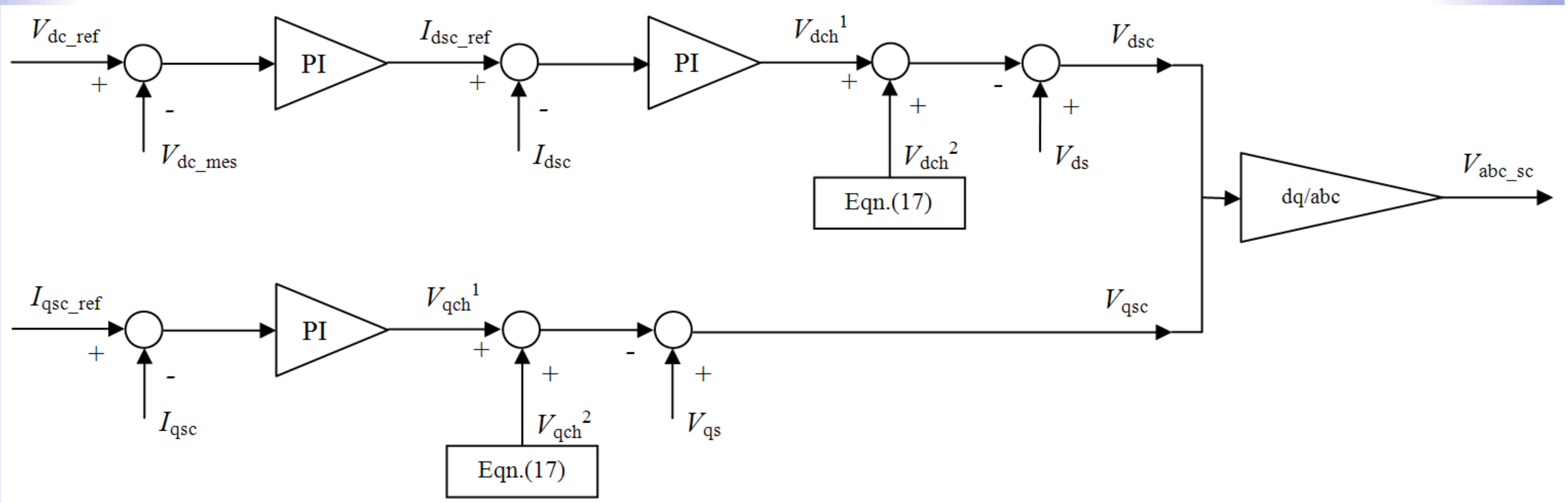


Reference:

Y. Zou, M. Elbuluk and Y. Sozer, "A Complete Modeling and Simulation of Induction Generator Wind Power Systems," IEEE-IAS Annual Meeting Conference Proceedings, 2010.

Stator-Side Converter Control

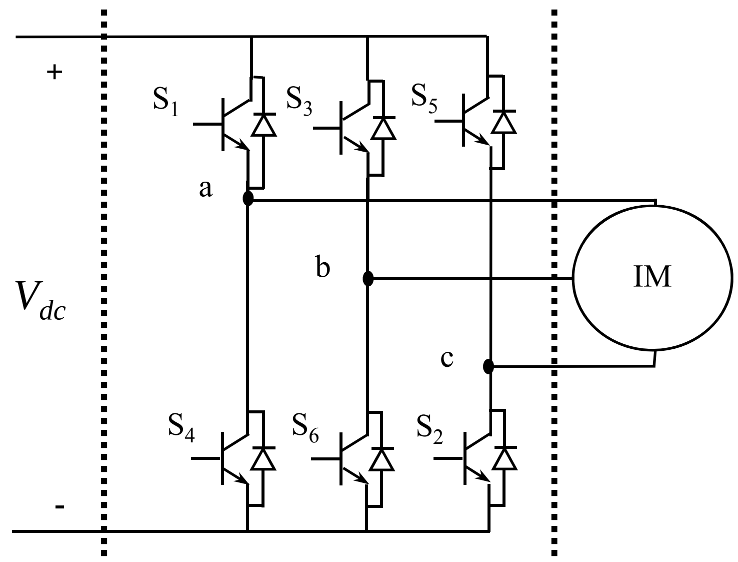
- Stator side responsible for regulation of dc-link voltage



Power Electronics

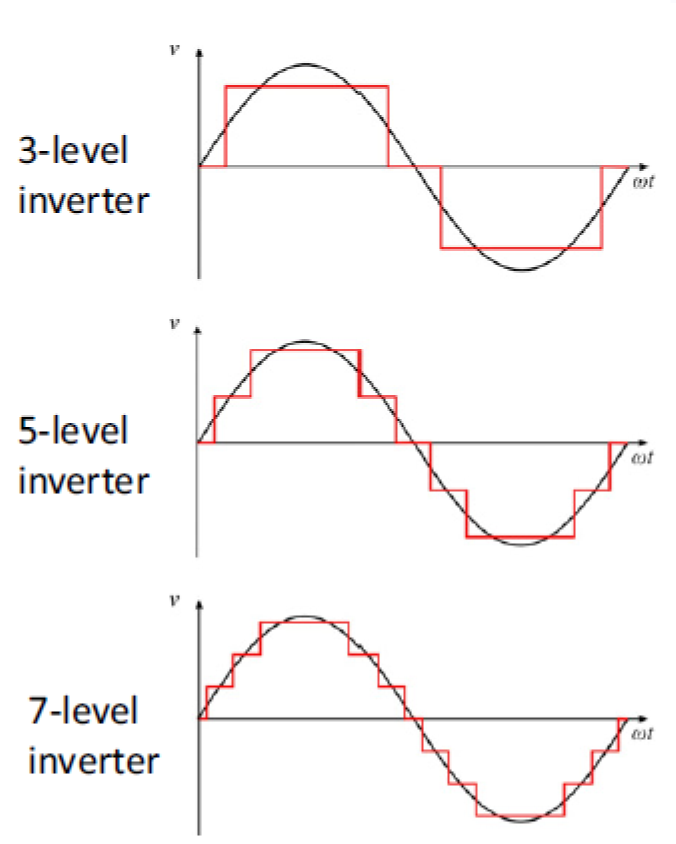
Two-Level Power Converter

- Two-level converter
  - Standard topology for low voltages and low power
  - IGBT and Freewheeling diodes



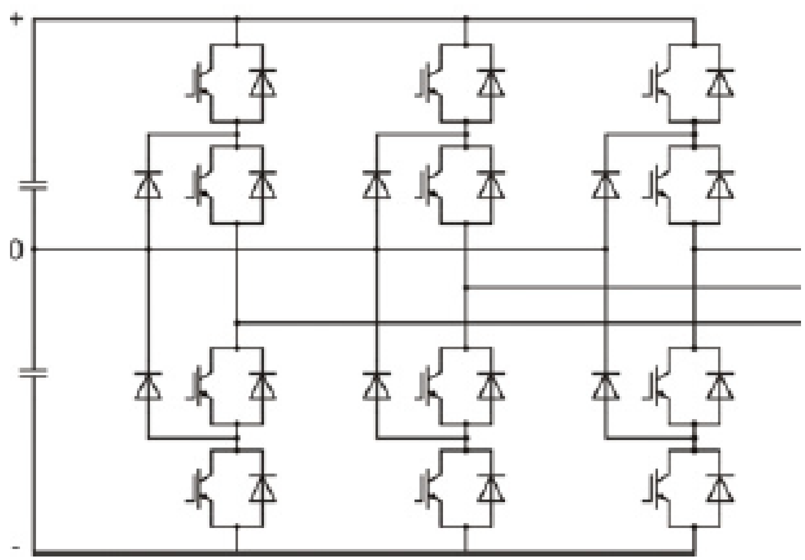
Multilevel Power Converter

- Medium output voltage: level >2
- Better approximation of sine wave with increasing number of levels
- Advantages
  - Lower harmonic distortion
  - Smaller filter



Three-level Power Converter

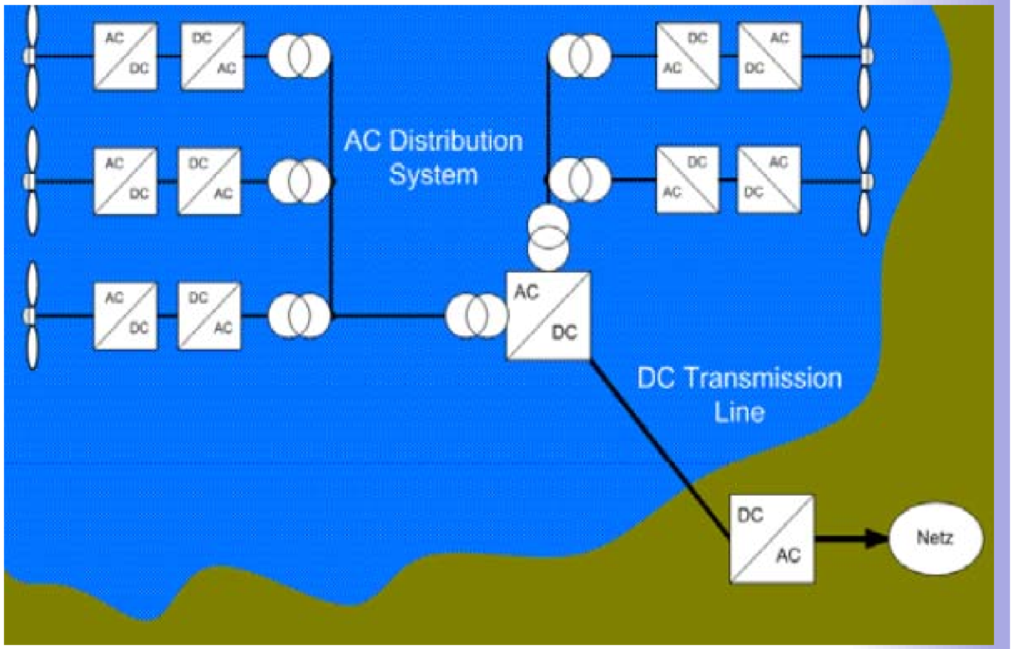
- Three-level converter
  - Used in medium voltage converters
  - Increased efficiency at high power
  - Low-loss connection between generator in nacelle and tower based converter



Source: ECCE 2010 Tutorial on Grid Converters for PV and WT Systems by Prof. R. W. De Doncker, RWTH Aachen, Germany

Grid Topologies for Off-shore Wind Farms

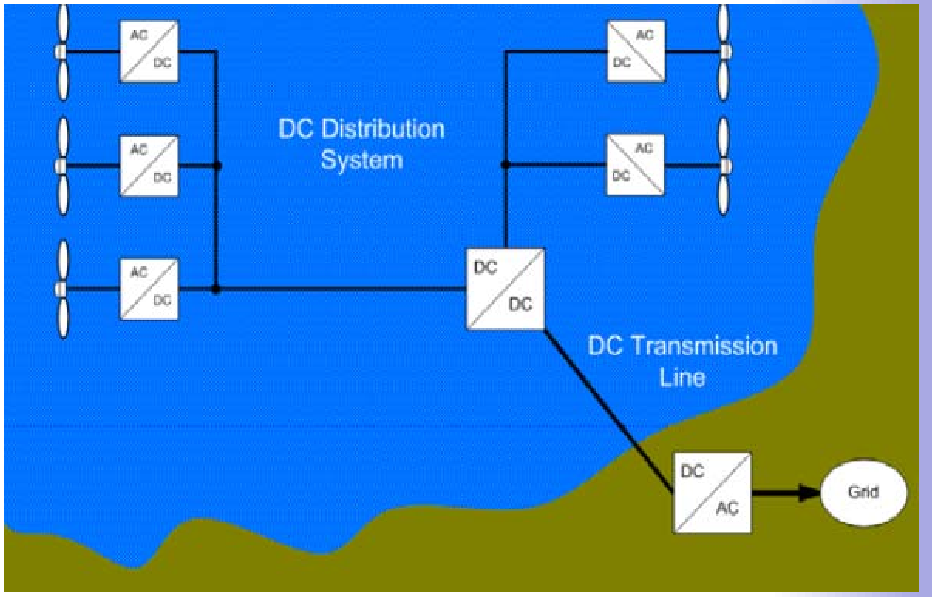
- Full converter concept > 5MW
  - Active front end rectifier
  - Dc-link
  - PWM grid inverter
- 50/60 Hz transformers
  - Turbine: AC collector field
  - Collector field: Transmission
- DC Transmission
  - Sea cable, long distance
  - Active rectifiers, VAR control
  - VSC IGBT HVDC



- Disadvantages
  - High cost of power electronic components
  - High losses due to PWM operating mode of IGBT inverters
  - Low reliability of wind turbine (complex inverters and communications)
  - Large 60 Hz (or 50 Hz) transformers

Source: ECCE 2010 Tutorial on Grid Converters for PV and WT Systems by Prof. R. W. De Doncker, RWTH Aachen, Germany

MV Collector of Off-shore Wind Farms



- Increased efficiency
  - 2% higher energy output
  - Better partial load efficiency
- Smaller and lighter transformers
  - 30% weight reduction
- Reduced costs, higher reliability of individual turbines
  - Smaller off-shore platforms
  - Reduced maintenance, higher reliability
  - Reduced installation, transportation and investment cost
  - Improved reliability

- New Technology Challenges
  - Protection devices
  - Electronic transformer (DC-DC converters)
- Offers development platform for future DC distribution systems

Source: ECCE 2010 Tutorial on Grid Converters for PV and WT Systems by Prof. R. W. De Doncker, RWTH Aachen, Germany

Wind Turbine Controls

Power In the Wind (Cont.)

- Power extracted from the wind

$$P_o = \frac{1}{2} \times (mass\ flow\ rate) \times \{V^2 - V_o{}^2\}$$

V = upstream wind velocity

V_o = downstream wind velocity

- Mass flow rate $= \rho A \frac{V+V_o}{2}$
- $P_o = \frac{1}{2}\left[\rho \cdot A \cdot \frac{V+V_o}{2}\right]\left(V^2 - V_o{}^2\right)$
- $P_o = \frac{1}{2}[\rho \cdot A \cdot V^3] \underbrace{\frac{\left(1+\frac{V_o}{V}\right)\cdot\left(1-\frac{V_o{}^2}{V^2}\right)}{2}}_{C_p}$

Power In the Wind (Cont.)

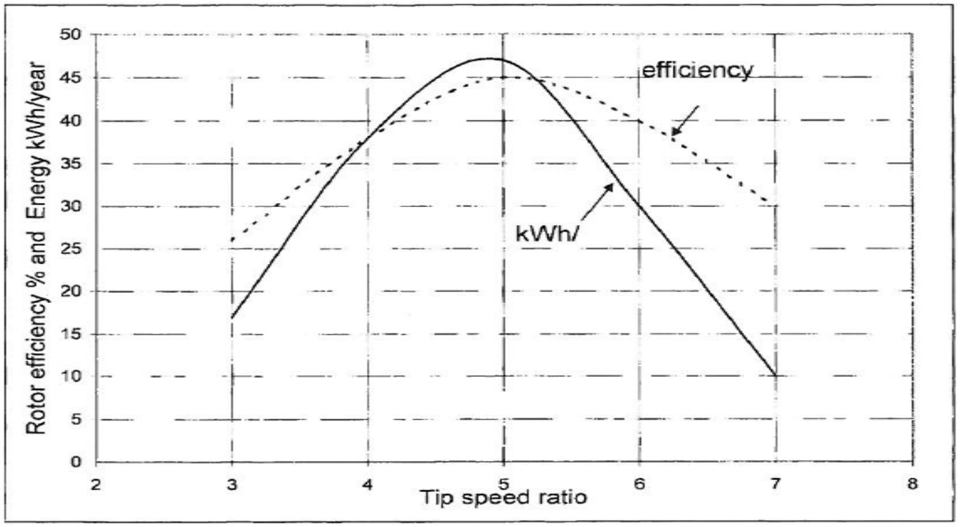
- C_p is the fraction of the upstream windpower which is captured by the wind turbine
- C_p is the **rotor efficiency**
  - $C_p = 0.59$ is the maximum rotor efficiency
  - $C_{p,max} = 0.5$ for 2 blade turbines
  - C_p varies between 0.2-0.4 for slow speed turbines with more than 2 blades
- $P_{max} = \frac{1}{2}\rho A V^3 \cdot 0.59$
  - ρ is the density of air and A is the swept area.

Tip-Speed Ratio (TSR)

- Tip Speed Ratio

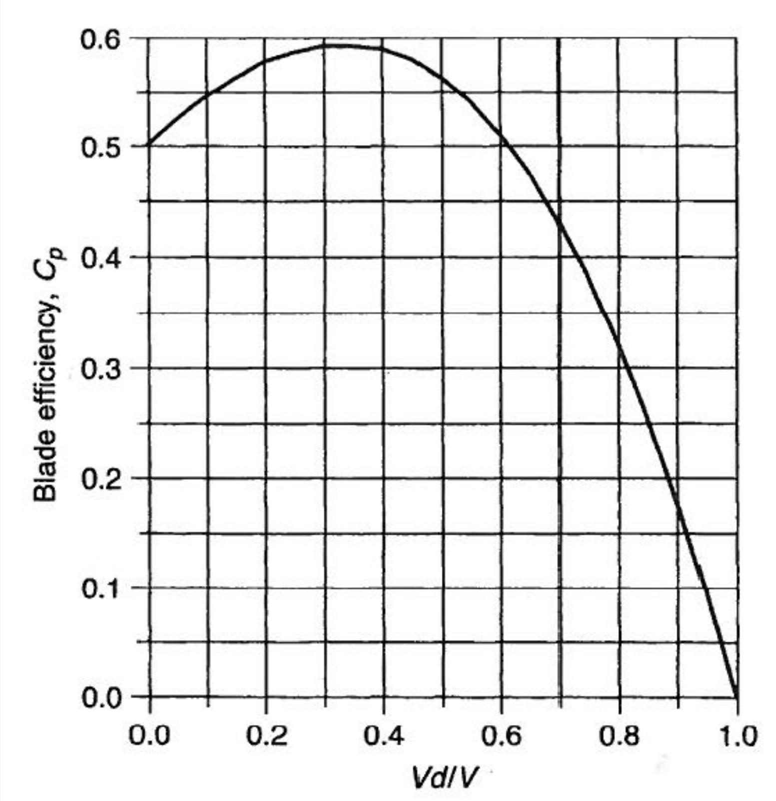
$$TSR = \frac{Linear\ speed\ of\ the\ blade\ outer\ most\ tip}{Free\ upstream\ wind\ velocity} = \frac{\omega R}{V}$$

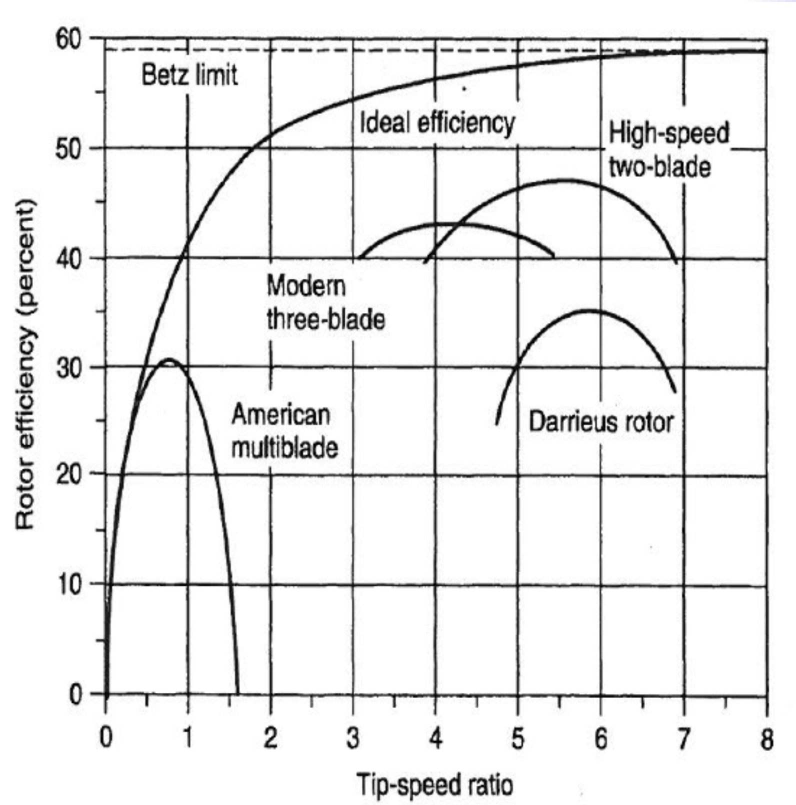
  - The machine working at higher TSR will be stressed more.
  - For the same power machine, higher TSR operating machine will have smaller blades.
  - Higher TSR means starting torque capability would decrease
  - TSR for $C_{p,max}$ is close to 1 for slow speed machine and nearly up to 6 for high speed turbines



Source: *Wind and Solar Power Systems*, Mukund R. Patel CRC Press, Boca Raton, FL, , USA

Rotor Efficiency





- Rotor efficiency reaches its maximum when the wind velocity is slowed down to one-third of its upstream value.
- Rotors with fewer blades reach their maximum efficiency at higher rotational speeds.

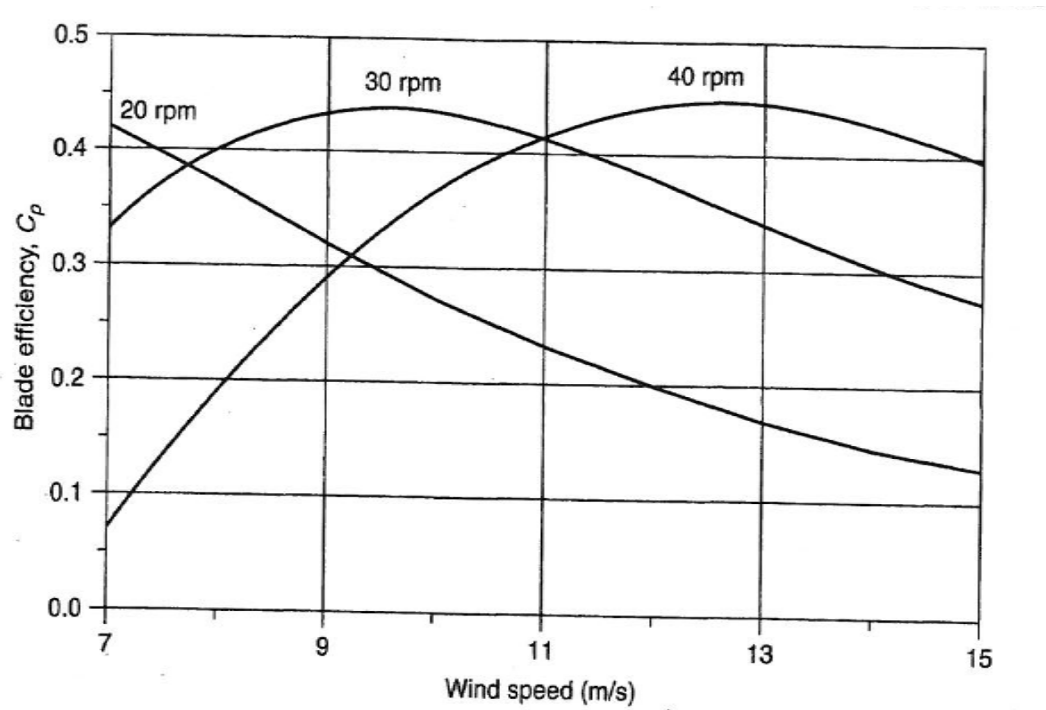
Source: *Renewable and Efficient Electric Power Systems,* Gilbert Masters, John Wiley, NJ, USA

Turbine Controls

- **Yaw Control:** Continuously orients the rotor in the direction of the wind
- **Pitch Control:** Changes the pitch of the blade with the changing wind speed to regulate the rotor speed
- **Stall Control:** When the wind speed exceeds the safe limit it stalls the blades

Variable Rotor Speed Operation

- Modern turbines operate with a TSR of 4-6
- *Cp* changes with wind-speed
  - ⇒ Turbine blades should change their speed as wind-speed changes
  - ⇒ *Cp* becomes a function of TSR and pitch angle
- Rotor efficiency improves if rotational speed changes with wind velocity
- *Cp* is relatively flat near its peaks



Blade efficiency for a hypothetical rotor at three different speeds

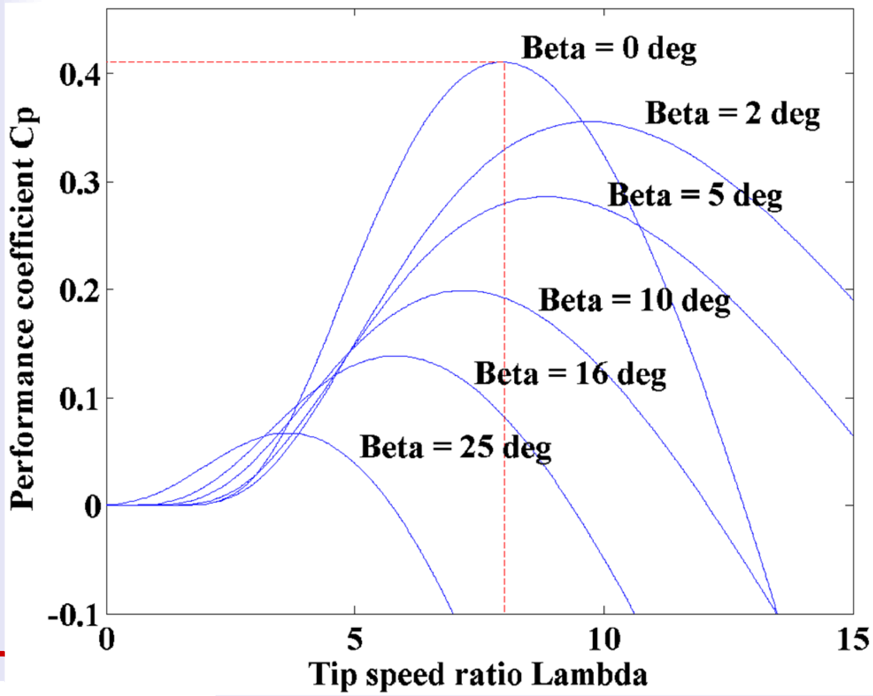
Source: *Renewable and Efficient Electric Power Systems*, Gilbert Masters, John Wiley, NJ, USA

Turbine Control

- Wind systems can produce power only above a minimum wind speed.
- Power output

$$P_o = \frac{1}{2}\rho V^3 \cdot C_p(\lambda, \beta)$$ [λ is the TSR; β is he pitch angle]

- Turbines with a fixed geometry will have fixed $C_p - \lambda$ characteristics
- The controller maintains maximum *Cp* until the rated power level is reached
- The maximum C_p for a given wind-speed *V* is maintained using λ control



A non-linear *Cp* model [Heier]:

$$C_p(\lambda, \beta) = c_1(c_2 - c_3\beta - c_4\beta^2 - c_5)e^{-c_6}$$

where

$c_1=0.5$, $c_2=116/\lambda_i$, $c_3=0.4$, $c_4=0$, $c_5=5$, $c_6=21/\lambda_i$

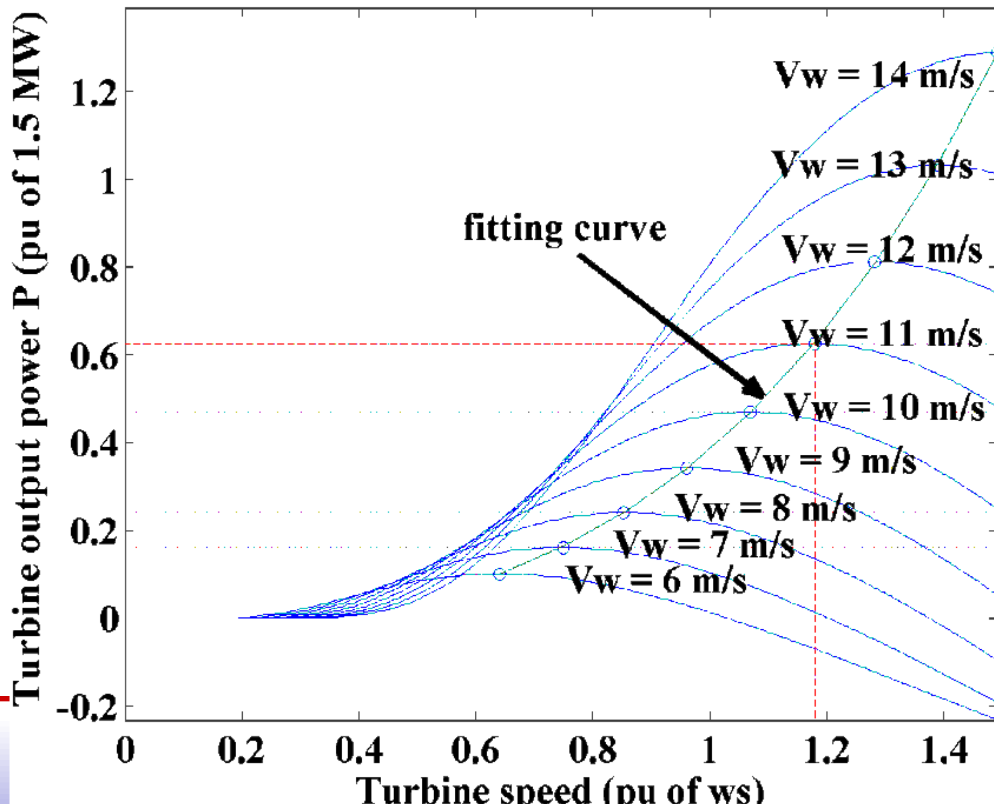
$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1}$$

Maximum Power Operation

Maximum Power Point Line

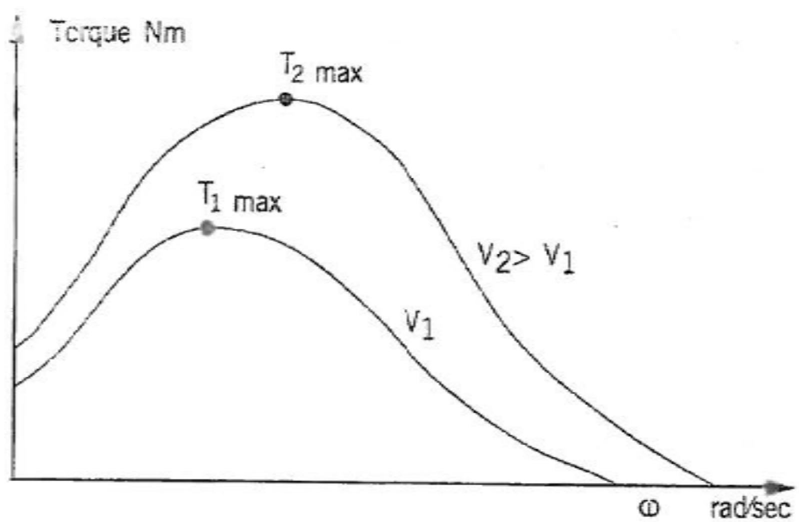
- Turbine blade power output for λ = 8 and β =0 degrees is plotted
- The maximum power point line equation obtained through curve fitting as follows:

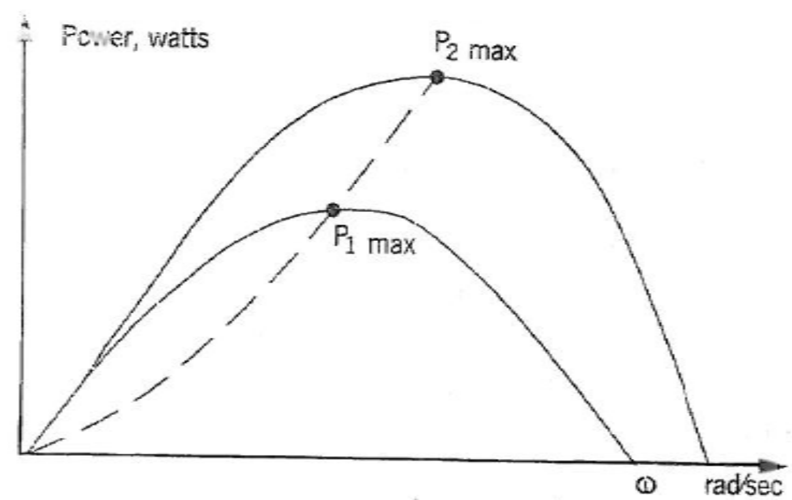
$$P_{opt} = 0.5572\omega_r^3 - 0.5081\omega_r^2 + 0.4792\omega_r - 0.1449$$



Electrical Load Matching

- Turbine output torque and power varies with rotor speed
- Speed at the maximum power is not the same at which torque is maximum.
- **Control Strategy:** Match the load on the Electric Generator so that the rotor continuously operates at speeds close to P_{max}

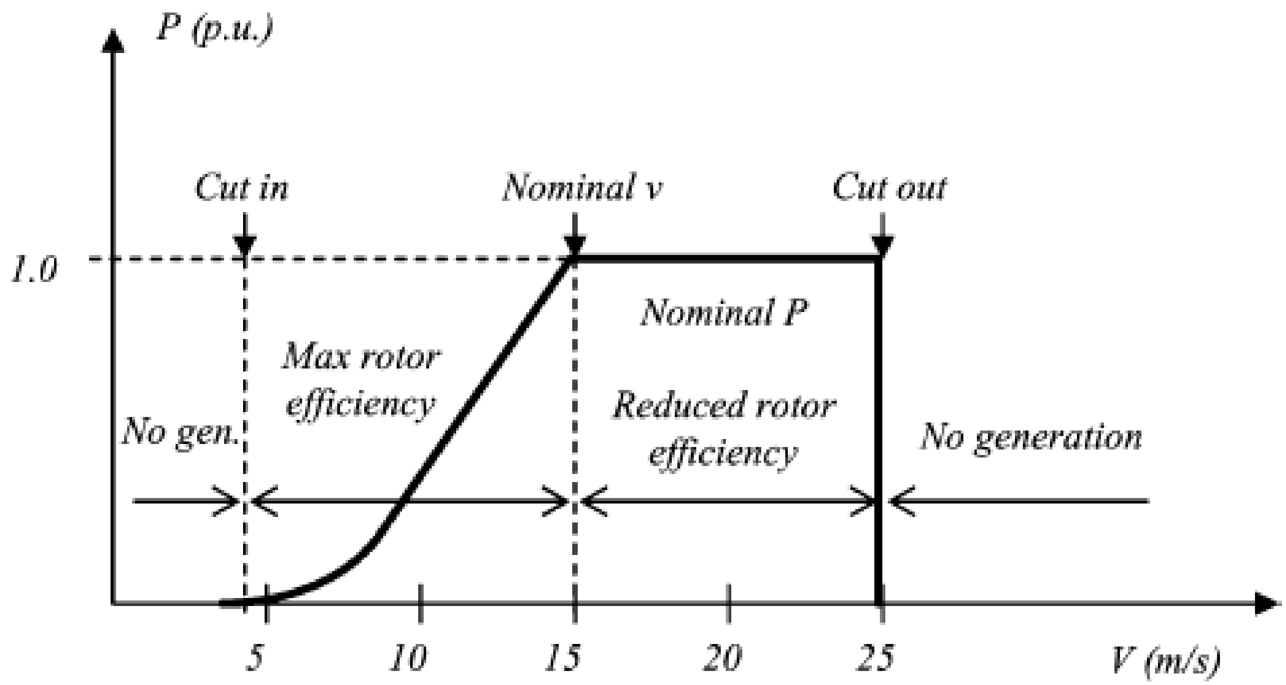




Source: *Wind and Solar Power Systems*, Mukund R. Patel CRC Press, Boca Raton, FL, , USA

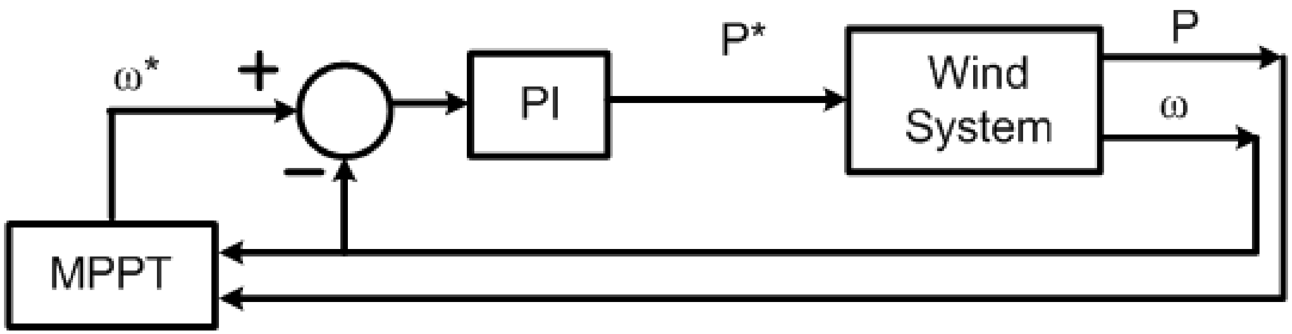
Turbine Control (Cont.)

- Power generation is disabled below a cut-in speed
- Between cut-in and nominal speed (when turbine rated power level is reached), maximum power point tracking (MPPT) algorithms used
- MPPT is disabled once turbine rated power is reached,
- Rated power limit for the turbine is maintained above nominal speed with reduced rotor efficiency



Wind Maximum Power Point Tracking

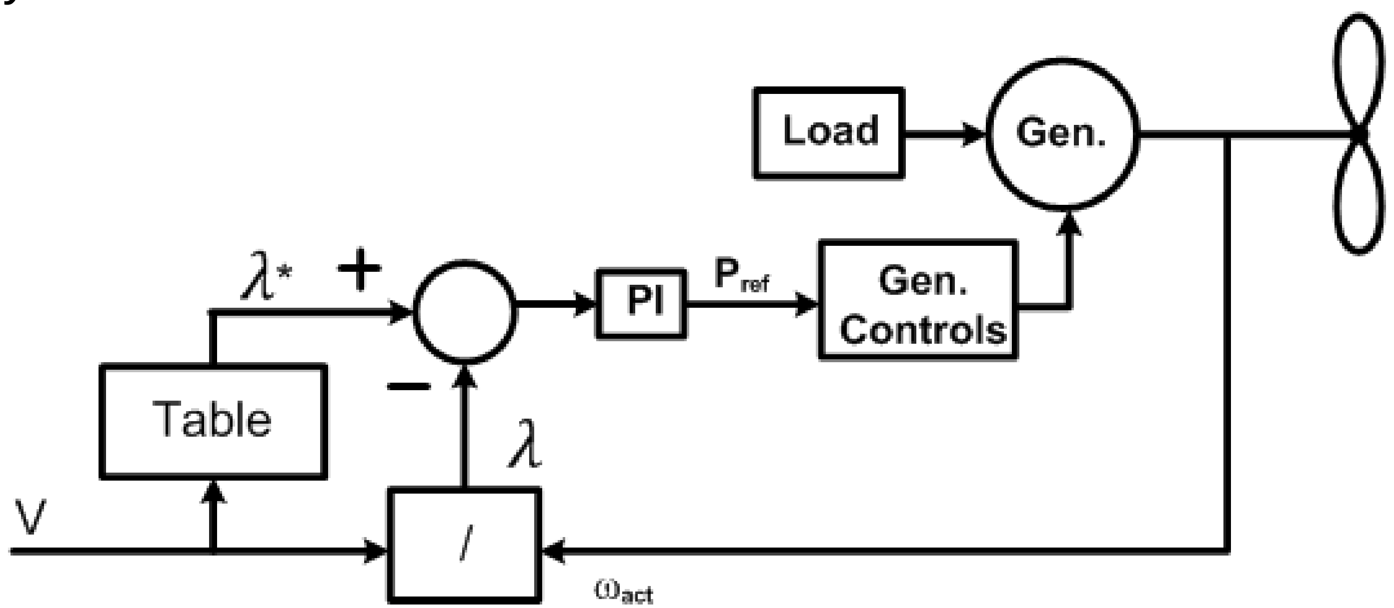
- MPPT Methods
  - Method relying on wind-speed (TSR control)
  - Method relying on output power measurement and calculation (Power Signal Feedback Control)
  - Method relying on characteristic power curve (Hill Climbing search)



TSR Control

TSR Control

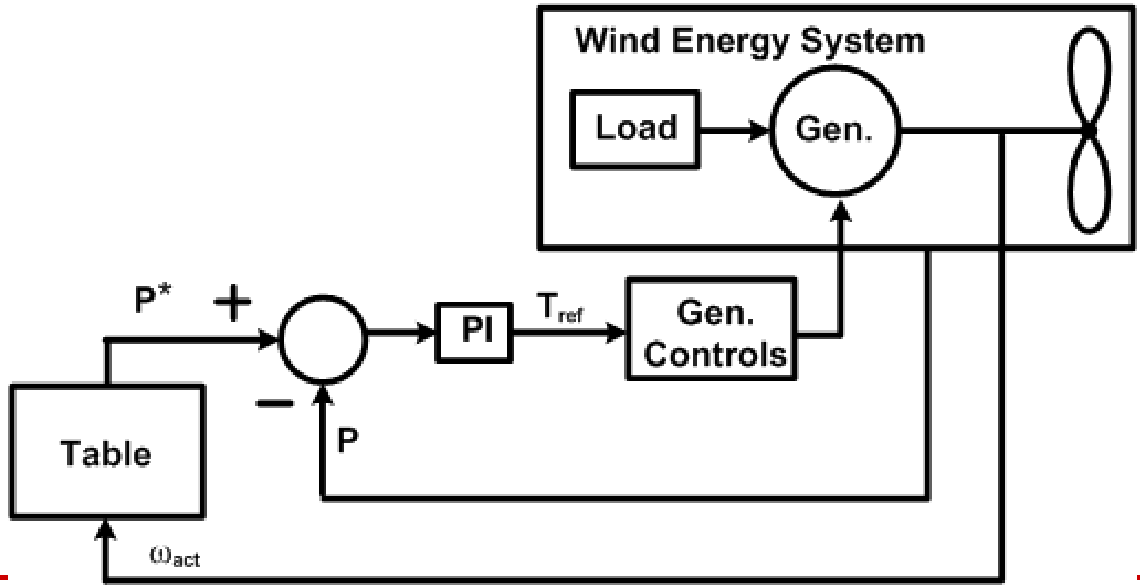
- Used for maximum power point tracking
- Controller regulates wind turbine speed to maintain an optimal TSR
- Accurate wind-speed may be difficult to obtain
- Use of external anemometer increases complexity and cost of the system



Power Signal Feedback (PSF) Control

Power Signal Feedback Control

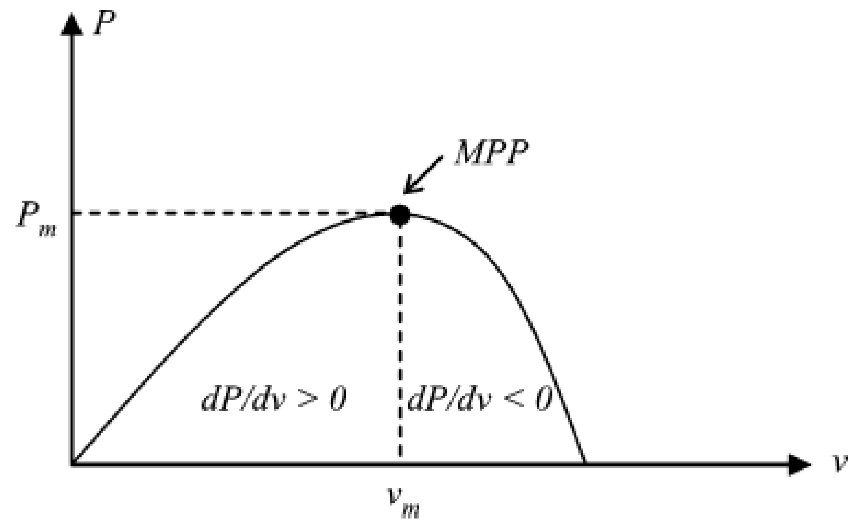
- Requires the knowledge of the turbine maximum power curves
- These curves can be obtained from simulation or practical tests
- Wind-speed used to select the power curve which gives the target power to be tracked by the system
- In many cases, this power curve can be substituted by the wind-speed as function of the power and the wind-turbine speed



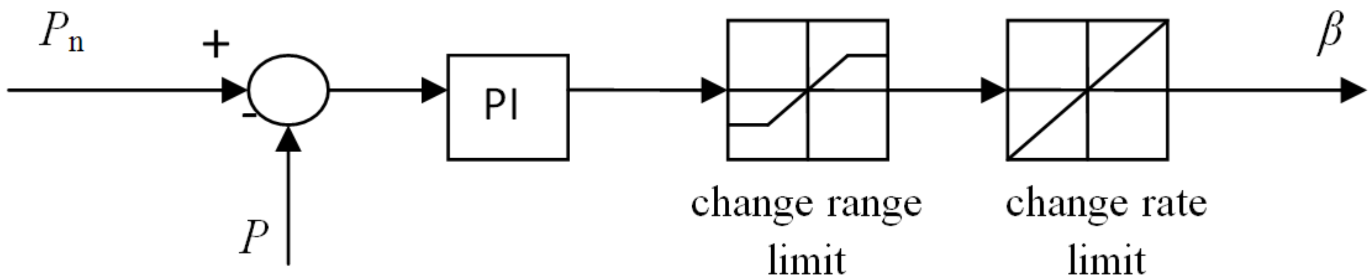
Hill Climbing Search (HCS) Control

HSS Control

- When wind-turbine speed is increased, output power should normally increase, otherwise the speed should be decreased
- Similar method is used in photovoltaic systems
- The method is somewhat ineffective in large turbines, since it is difficult to adjust speeds quickly in large turbines

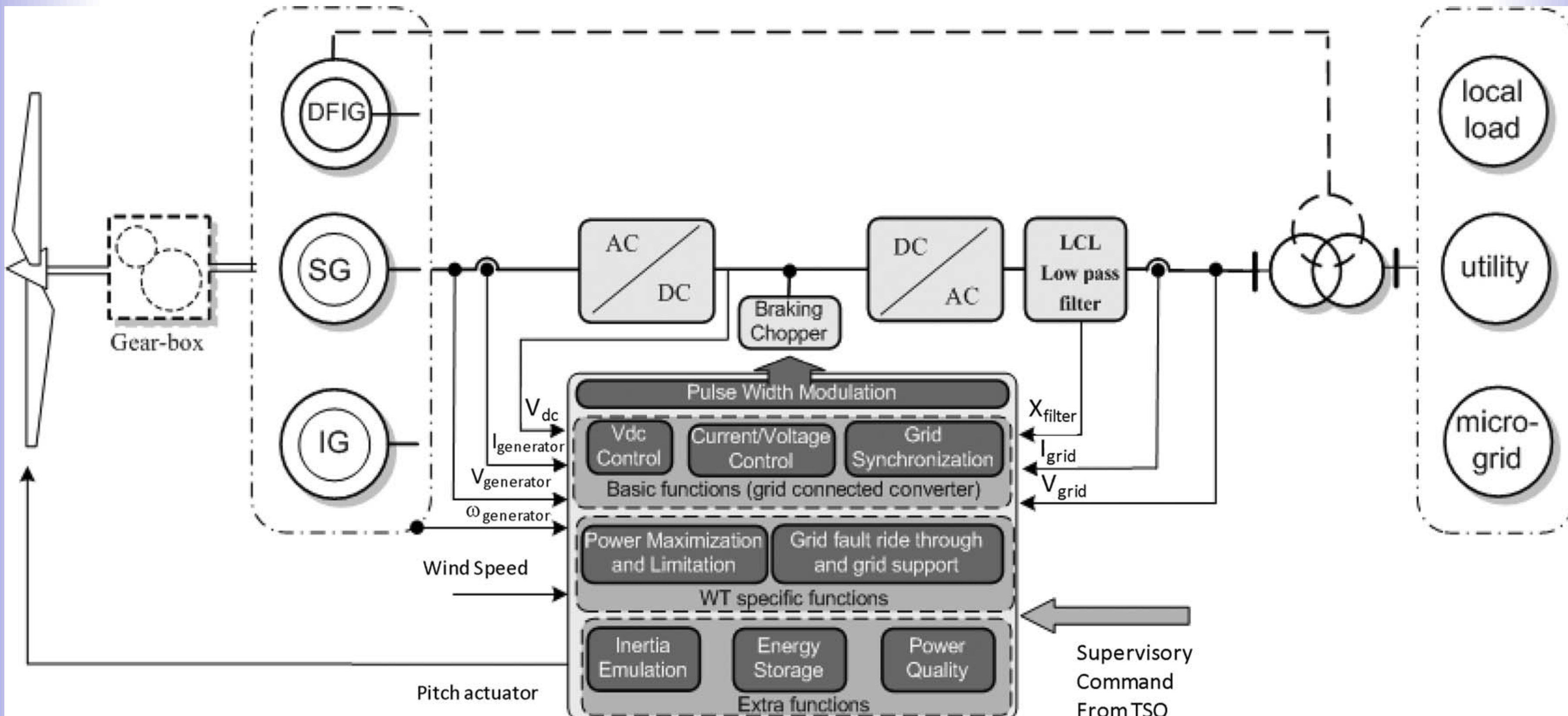


Pitch Angle Control



- Turbine blade pitch angle generated from active power control loop
- Due to huge size and inertia of blades, pitch angle has to change at slow rate within a reasonable range.
- Pitch angle controller will limit the generated power by changing the pitch angle and will not trigger the system until nominal speed is reached.

Wind Turbine Operation



Ref: [1] M Liserre, R Cárdenas, M Molinas, and J Rodríguez, “Overview of Multi-MW Wind Turbines and Wind Parks”, IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, VOL. 58, NO. 4, APRIL 2011

Wind Turbine Operation

Generator side (AC/DC)

- DC-Link voltage control or
- Active and reactive Power Control
- Generator speed control (in the outer loop)

Grid side (DC/AC)

- DC-Link Voltage and Grid reactive power control or
- Grid active and reactive power control

Grid Friendly Features:

- Generator speed regulation could achieve both maximum power point operation or power curtailment
- Grid support through real and reactive power control.
- With generator side DC-Link voltage control, grid support through low-voltage ride through (LVRT) is possible.

Grid Integration and MicroGrid

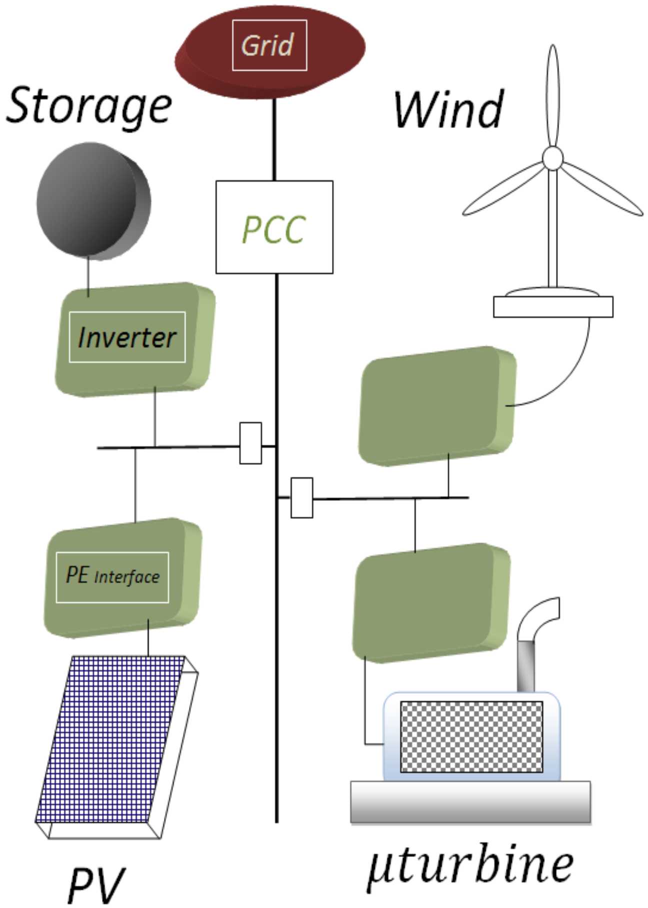
Grid Integration Challenges

- Variability in power generation with renewable energy sources
- Adding energy storage eliminates the variability, but increases cost
- Control of power flow to grid and to/from the storage system depending on the wind situation and grid demand.
- Grid connection and synchronization in the presence of impurity (harmonics, voltage unbalance).
- Fast delivery of reactive power to the HV transmission network overcoming high cable impedances.

Grid Integrated Local Energy Network (Microgrid)

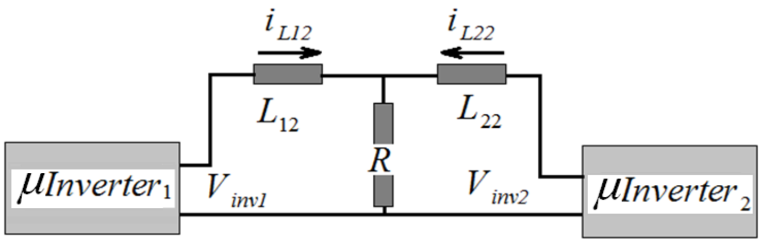
Microgrid :

- A small scale grid comprising of small number of power sources.
- Very effective for integrating renewable energy sources.
- Can connect to the grid or run in islanding mode.
- Provides a high quality power.
- Simplifies grid expansion.



Microinverter Based Microgrid

- High penetration of Renewable Energy Sources (RES) jeopardizes the grid stability and reliability.
- Microgrids can allow more RESs to be integrated with grid without affecting its stability through:
  - Balancing the local power production and consumption.
  - Isolating itself from the grid when disturbance occurs in either side.
- Low cost and low rated power microinverters (µinverters) allow the integration of more alternative energy sources with the grid.



- The transient dynamics in the µinverters are fast due to their low capacitances and inductances. To insure the microgrid stability, appropriate controllers are needed.

Conclusions

- Wind Systems have a lot of potentials, but there are also a number of challenges
- Systems level perspective is essential in all projects
- Theoretical analysis based on the fundamentals leading to modeling
- Analytical models to be verified or complemented with computational tools
- Experimental verification desired when feasible