Wind Energy Systems

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Wind Energy

1. Now a major source of energy
2. Currently more than 440 GW; expected to exceed 760 GW by 2020.
3. Wind turbines with individual capacities of up to 6–8 MW are now available.
4. Wind farms (onshore and offshore) having overall ratings of hundreds of megawatts are in operation.

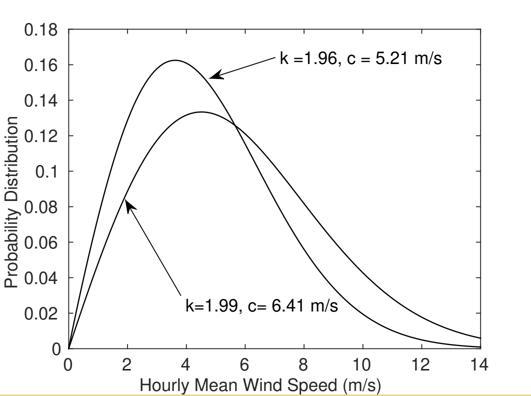
Wind Characteristics

1. The wind speed at a given height varies continuously as a function of time. The wind speed cannot be predicted precisely and can only be analyzed statistically.
2. While wind speed exhibits diurnal and seasonal variations, there may also be turbulent periods caused by gusts of wind in the sub-second to minute range.
3. The probability density distribution of the wind speed at a given location $p(\nu_w)$, gives us the proportion of time spent by the wind within narrow bands of wind speed. This distribution is obtained from measurements of wind speeds taken over a long period of time.
4. Weibull distribution:

$$p(\nu_w) = \frac{k}{c} \left(\frac{\nu_w}{c}\right)^{k-1} e^{\left[-\left(\frac{\nu_w}{c}\right)^k\right]}$$

where c is the scale factor having the unit of speed and k is a dimensionless shape factor.

Wind Characteristics



The probability distributions obtained for $k = 1.96$ and $c = 5.21$ m/s, and $k = 1.99$ and $c = 6.41$ m/s. These correspond to the Weibull curves that fit the hourly mean wind speed measured at two locations in India, Tuticorin and New Kandla.

Wind Turbines: Power Extraction

1. A wind turbine can be thought of as intercepting a moving tube of wind which has a cross-sectional area A_w in m^2. A_w is the area swept by the blades of the turbine and is given by $A_w = \pi \times \mathcal{R}^2$, where $\mathcal{R}$ is the radius of the blades.
2. The mass of air flowing through this cross-section in h seconds is given by,

$$M = A_w \rho \, \nu_w \, h$$

   where ρ is the density of air in $\mathrm{kg/m}^3$ and ν_w is the wind velocity in m/s. The density of air is a function of the height above sea level and the temperature.
3. The kinetic energy contained in this mass of wind is $\frac{1}{2} A_w \rho \nu_w^3 \times h$. If this entire kinetic energy was to be extracted by the wind turbine then its power output would be $\frac{1}{2} A_w \rho \nu_w^3$.

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Wind Turbines: Power Extraction (continued)

1. This is not feasible as the wind has to continuously flow past the turbine, and cannot be abruptly halted. In practice only a fraction $\mathcal{C}_p$ (also called the turbine power coefficient) of this energy can be extracted.
2. The theoretical maximum value of $\mathcal{C}_p$, which is also called the Betz Limit, is approximately 0.59.
3. Thus, the power output of a wind turbine P_m in W, can be expressed as follows:

$$P_m = \frac{1}{2}\rho A_w \mathcal{C}_p \nu_w^3$$

$\mathcal{C}_p$ is a function of the 'tip-speed ratio' λ, and the pitch angle of the turbine blades β. The tip speed ratio is given by $\lambda = \frac{\omega_m' \mathcal{R}}{\nu_w}$, where ω_m' is the speed of the turbine in rad/s.

Wind Turbines: Power Extraction (continued)

1. The following expression may be used for power system studies:

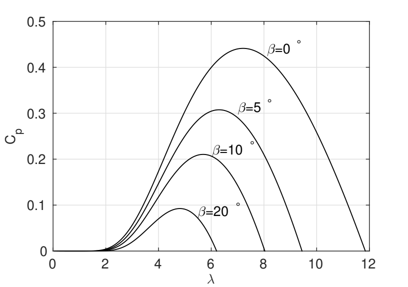
$$\mathcal{C}_p = c_1 \left(\frac{c_2}{\lambda_i} - c_3\beta - c_4\beta^{c_5} - c_6 \right) e^{\frac{-c_7}{\lambda_i}}$$

   where,

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + c_8\beta} - \frac{c_9}{\beta^3 + 1}$$

2. The pitch angle β is expressed in degrees in these equations.
3. The coefficients c_1 to c_9 can be determined by using a numerical optimization procedure which minimizes the error between the power curve obtained from these equations and the one obtained from the manufacturer's documentation.

Wind Turbines



Turbine Parameters

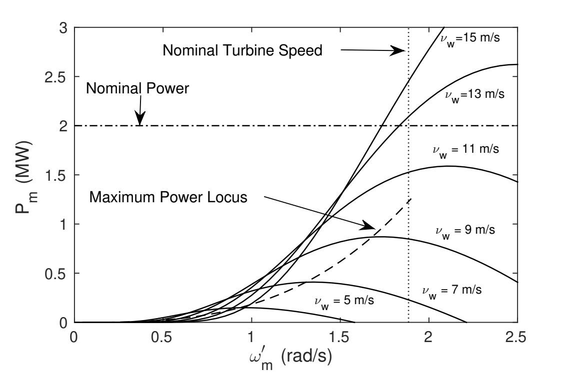
c_1	0.73
c_2	151
c_3	0.58
c_4	0.002
c_5	2.14
c_6	13.2
c_7	18.4
c_8	-0.02
c_9	-0.003

Wind Turbines: Maximum Power Extraction (for various wind speeds)

1. For the turbine parameters given in the previous slide, for $\beta = 0°$, the approximate optimum value of $\mathcal{C}_p = 0.44$ which occurs when $\lambda_{opt} = 7.2$.
2. The maximum power that can be extracted as a function of turbine speed is given by:

$$P_{m_{opt}} = \left[\frac{1}{2} \frac{\rho A_w \mathcal{R}^3 \mathcal{C}_{p_{opt}}}{\lambda_{opt}^3} \right] (\omega_m')^3 = k_{opt} \, (\omega_m')^3$$

Wind Turbines: Power Extracted vs Turbine Speed (for various wind speeds)



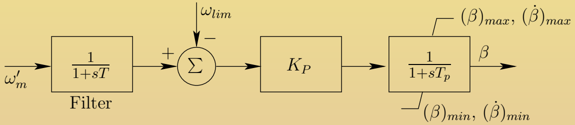
$\beta = 0°$. $\mathcal{R} = 37.5$ m, $\rho = 1.225$ kg/m^3.

Wind Turbines: Control of Power Extraction

1. Below cut-in wind speed (typically around 3 m/s): No power extraction from the wind.
2. Between cut-in wind speed and rated wind speed: The turbine speed and the extracted power depends on the characteristics and/or control of the electrical system (generator, power electronic interfaces and grid). The electrical system may be controlled so that maximum power is extracted from the wind, subject to the power rating of the equipment and the turbine speed limit.
3. Between rated wind speed and cut-out wind speed: The power extracted from the wind is regulated at the rated value or reduced, by pitch angle control or stall control.
4. Above cut-out wind speed (typically 20-25 m/s): No power extraction from the wind (the turbine turns out of the main wind direction.)

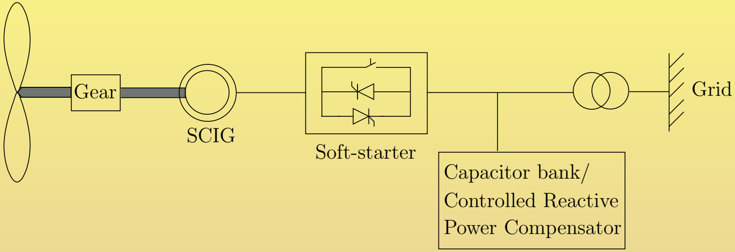
Wind Turbines: Pitch and Stall Control

1. Pitch (β) control involves turning the blades around their longitudinal axis. This reduces $\mathcal{C}_p$, which is a function of β, thereby reducing the power output.
2. The rate of increase in pitch angle is dependent on the blade-drive system. The maximum ramp-up rate of the pitch angle is in the order of 3 to 10° /s and depends on the size of the wind turbine. The speed will exceed the value ω_{lim} during high speed conditions since the rate of change of β is limited (some headroom may be provided).

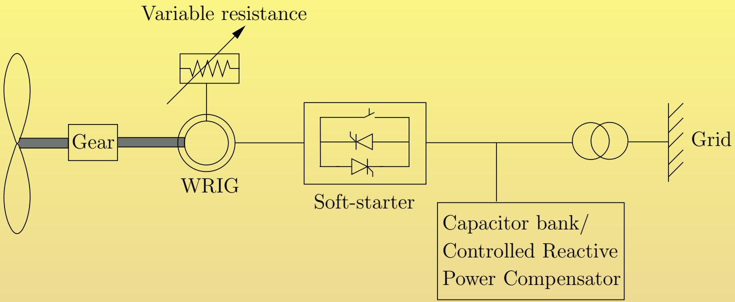


3. Even when the blades of the turbine are bolted to the hub at a fixed angle (no pitch control), the rotor aerodynamics may be designed to stall (lose power) when the wind speed exceeds a certain level. This is known as stall control.

Generator & Power Electronic Configurations - Type I

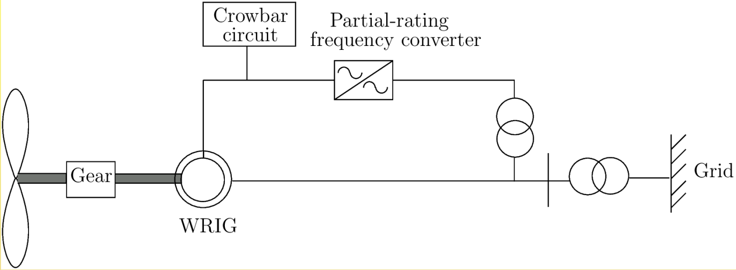


- Capacitor bank needed to supply reactive power to SCIG.
- Soft starter needed to limit the starting current.



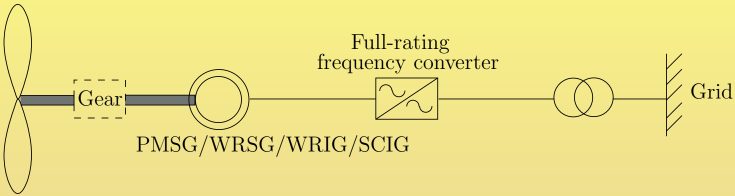
- Capacitor bank needed to supply reactive power to SCIG.
- Soft starter needed to limit the starting current.
- Variable resistance: modifies torque-speed characteristics of the machine.

Generator & Power Electronic Configurations - Type III



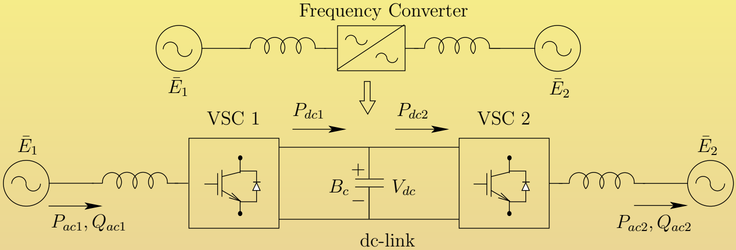
- Capacitor bank not needed: VSC can supply reactive power.
- Crowbar circuit: required for protection of VSC.
- VSC: control rotor voltage and frequency to modify the torque-speed characteristics.

Generator & Power Electronic Configurations - Type IV



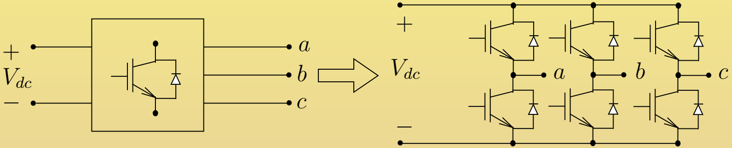
- Capacitor bank not needed: VSC can supply reactive power.
- VSC: control stator frequency and voltage to modify the torque-speed characteristics.

Frequency Conversion using VSCs

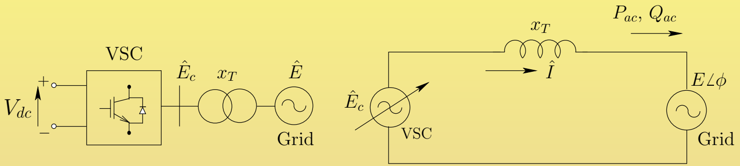


(1) $P_{ac1}=P_{dc1}$, $P_{ac2}=P_{dc2}$ (lossless converter)
(2) $P_{dc1}=P_{dc2}$ in steady state
(3) Q_{ac1}, Q_{ac2} are independently controllable

Frequency Conversion using VSCs



Frequency Conversion using VSCs



(1) $\hat{E}_c = mV_{dc}\angle(\phi + \alpha)$
(2) m and α are independently controllable

- $\bar{E}_c$: fundamental component of inverter output voltage (neglecting harmonics).
- Adjust m and α to control P_{ac} and Q_{ac}.

Wind Farm Configurations

1. Each variable-speed (Wind Turbine-Generator) WTG may have its own frequency converter and they may be paralleled on the grid side. This configuration is suitable for both Type III and IV WTGs.
2. The generators of different Type IV WTGs may be connected in parallel, and a common frequency converter may be used for connection to the grid. With this configuration it may not be possible to operate all turbines in the maximum power extraction mode.
3. Another alternative is to have the generators connected to individual ac-dc converters which are then connected in parallel on the dc side. A common dc-ac converter may then be used to connect to the ac grid. Electrical storage devices like batteries (if present) can be connected in shunt at the dc bus.

Wind Farm Configurations

1. For offshore wind-farms, the output can be pooled on the dc side of the ac-dc converters and dc transmission from the offshore platforms to the mainland can be used for power evacuation. The dc-ac conversion is then done on the mainland.
2. Small WTGs may also be used in stand-alone mode (not connected to a grid; feeding a local load). However, these will require devices to regulate the frequency and voltage magnitude.
3. Small WTGs may also be integrated with other energy sources (solar and/or diesel generators) and storage systems to form micro-grids.