Lecture#05

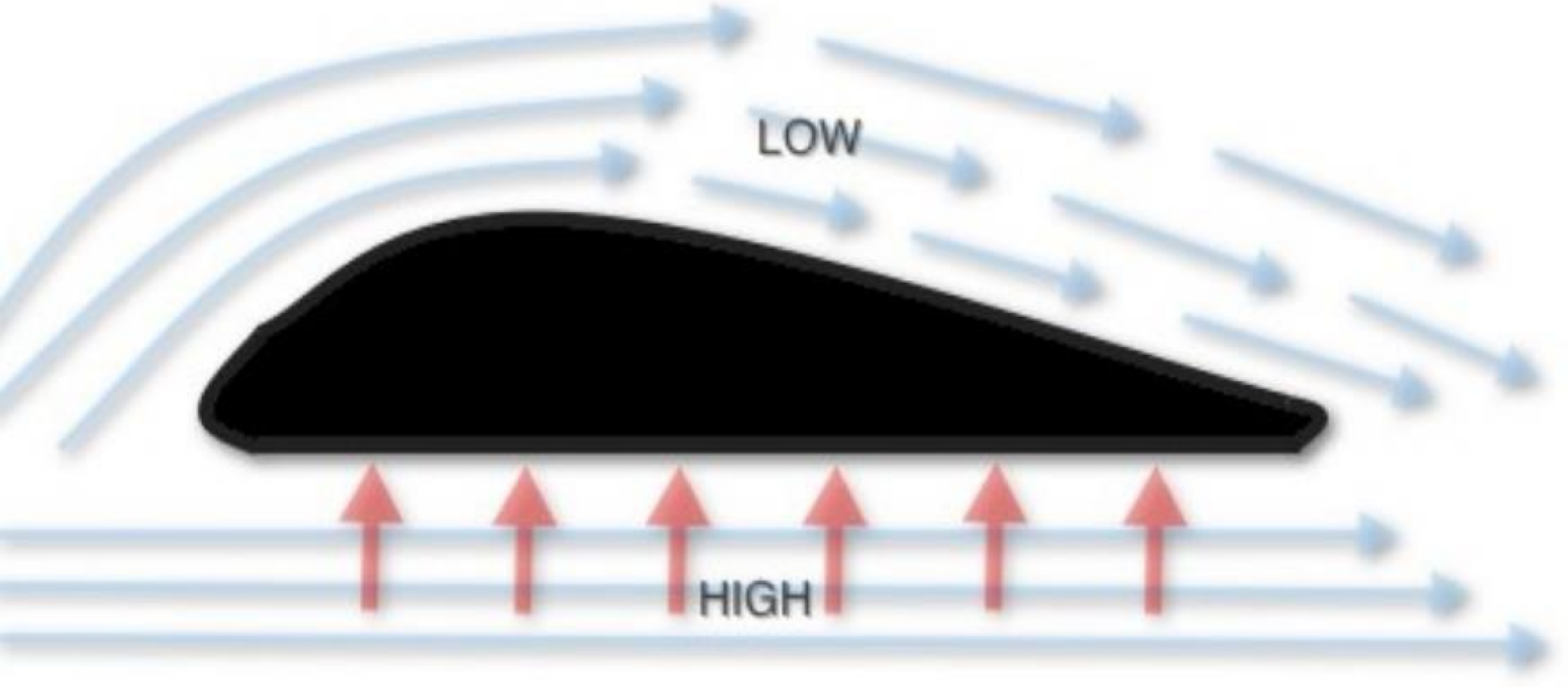
2.3 Wind Turbine Aerodynamics

- 2.3.1 Power Characteristic of Wind Turbine
- 2.3.2 Aerodynamic Power Control: Passive Stall, Active Stall & Pitch Control

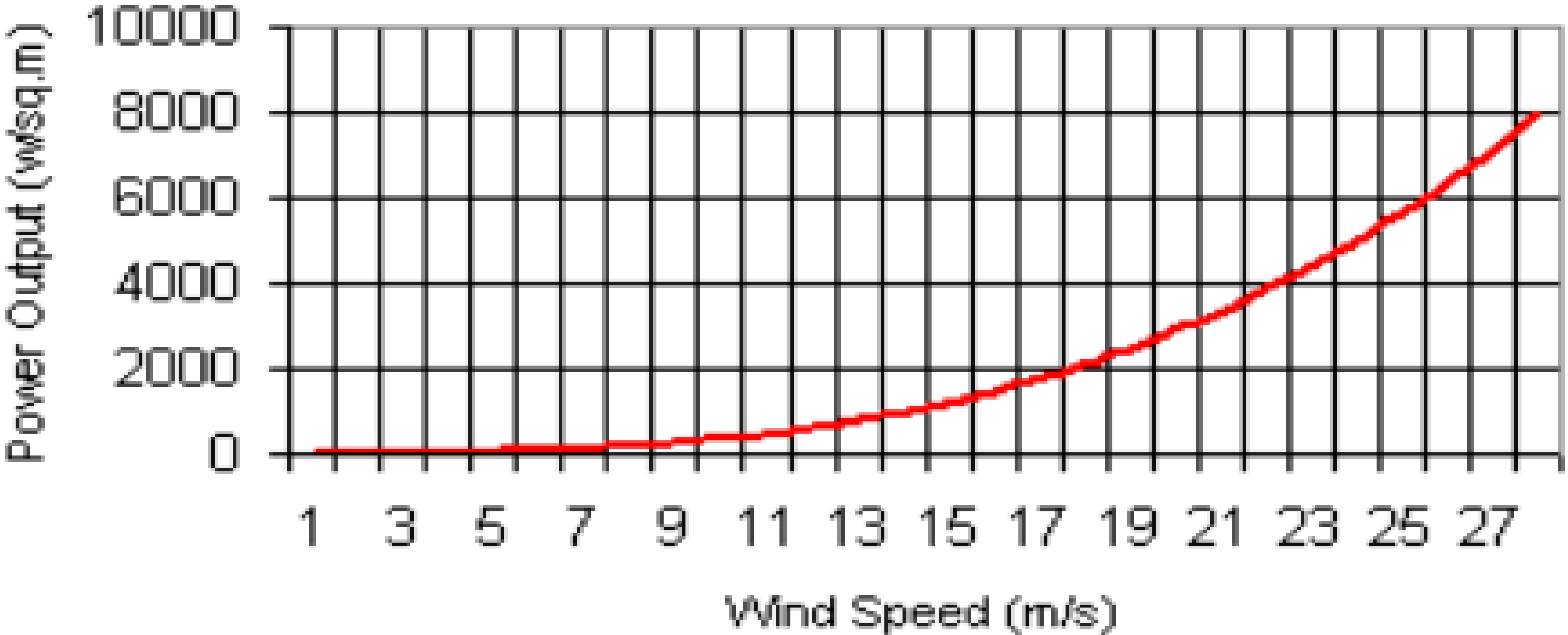
2.4 Maximum Power Point Tracking (MPPT)

- 2.4.1 MPPT with Turbine Power Profile
- 2.4.2 MPPT with Optimal Tip Speed Ratio
- 2.4.3 MPPT with Optimal Torque Control

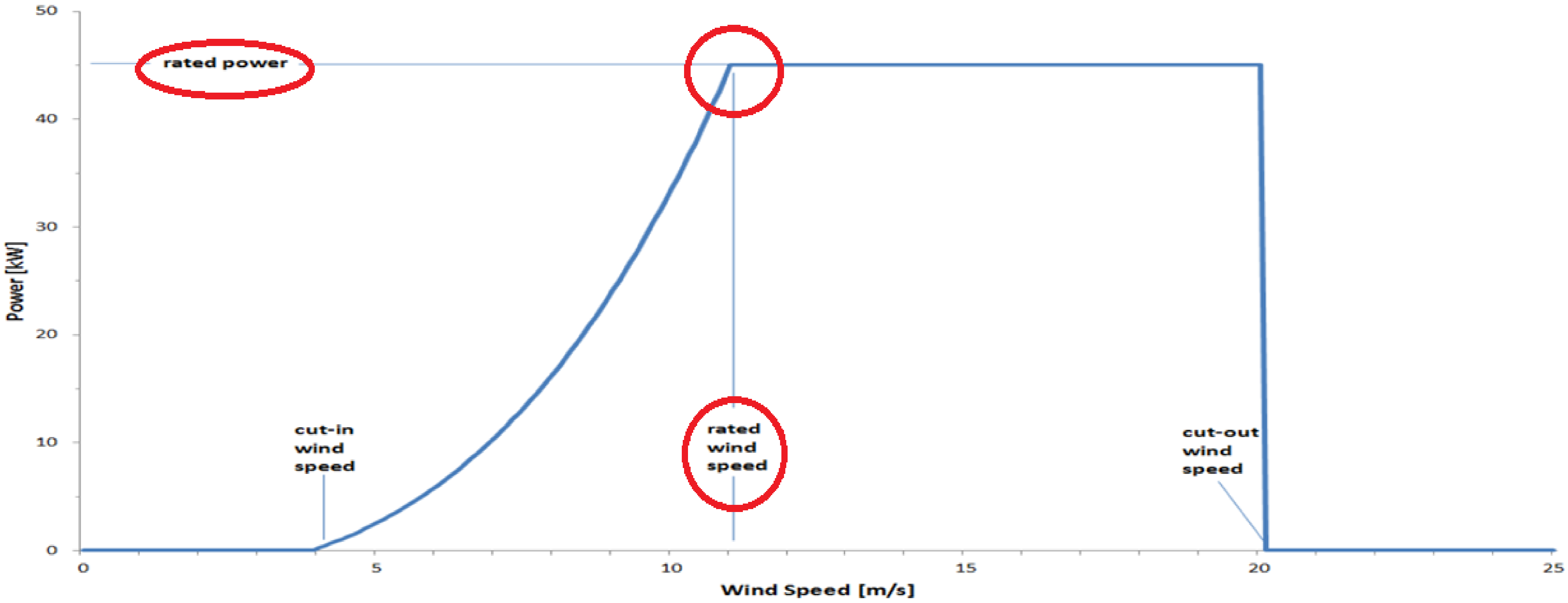
2.3 Wind Turbine Aerodynamics



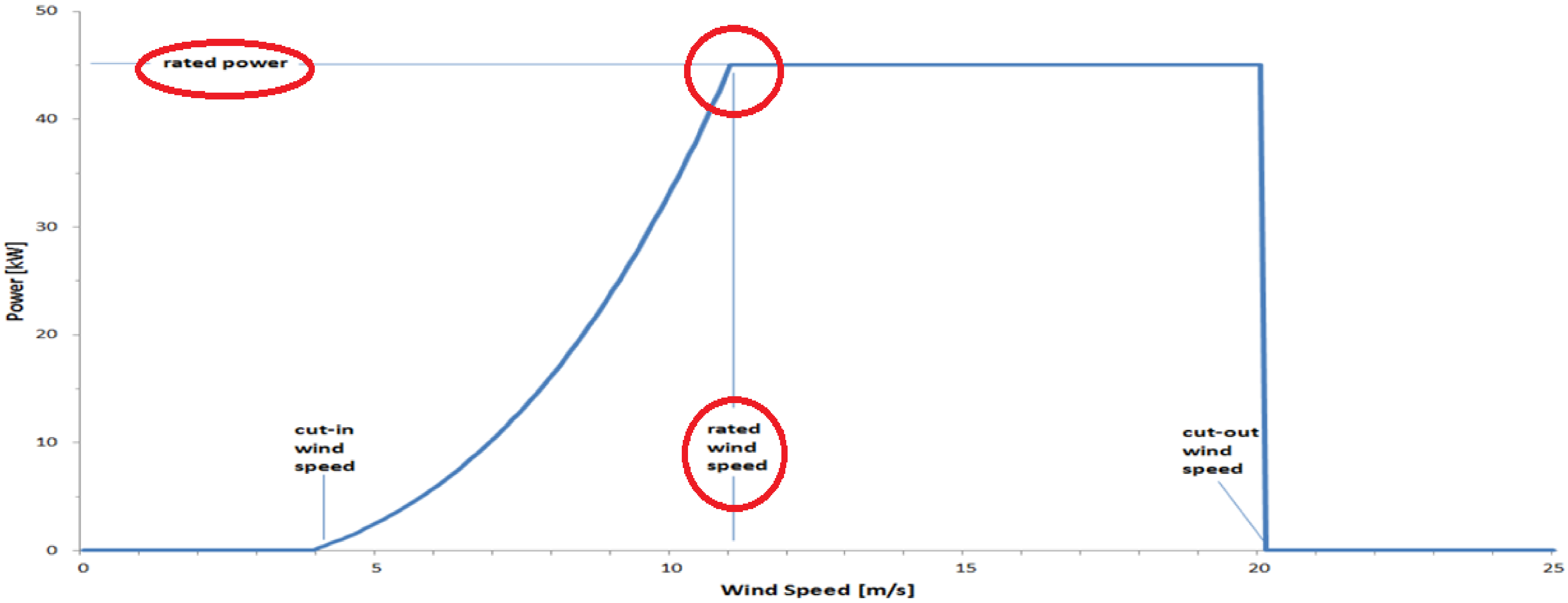
Aerodynamic design of turbine blade has a significant influence on amount of energy captured from wind. Indeed we can capture more power with good aerodynamic design.



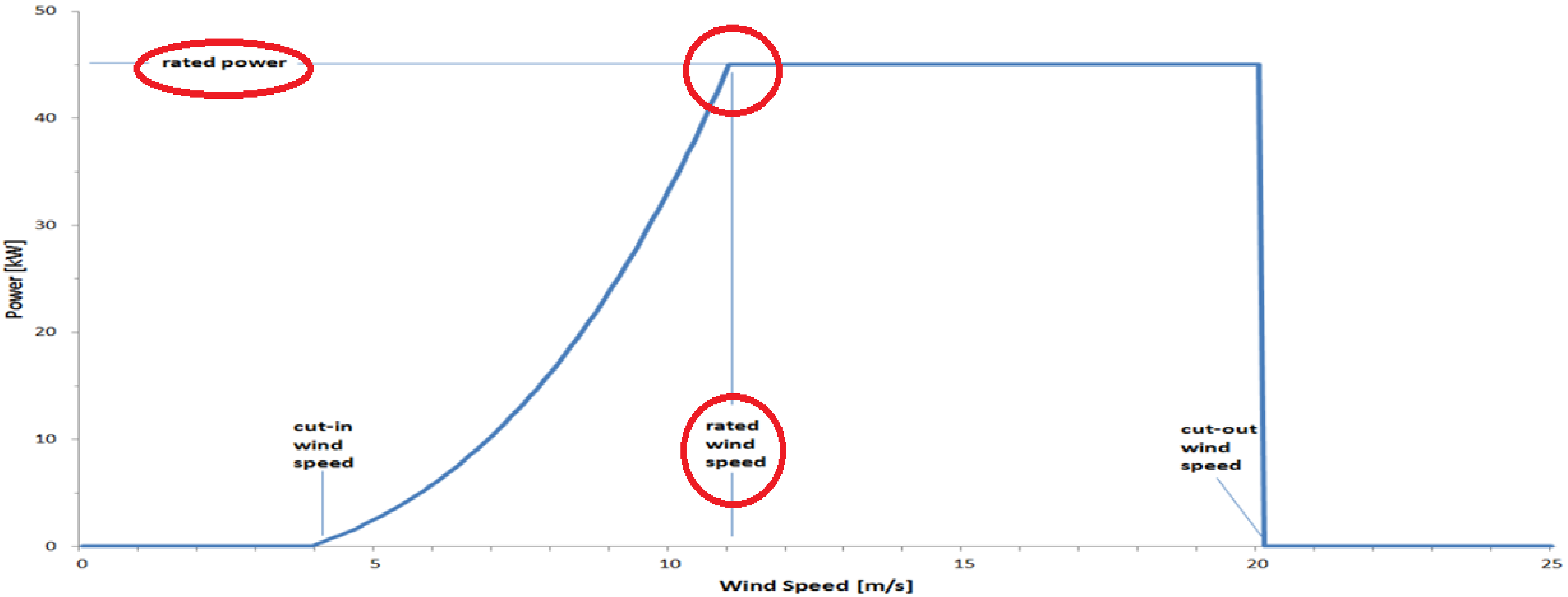
We have to limit (i) power & (ii)rotating speed of turbine rotor for wind speeds_________?



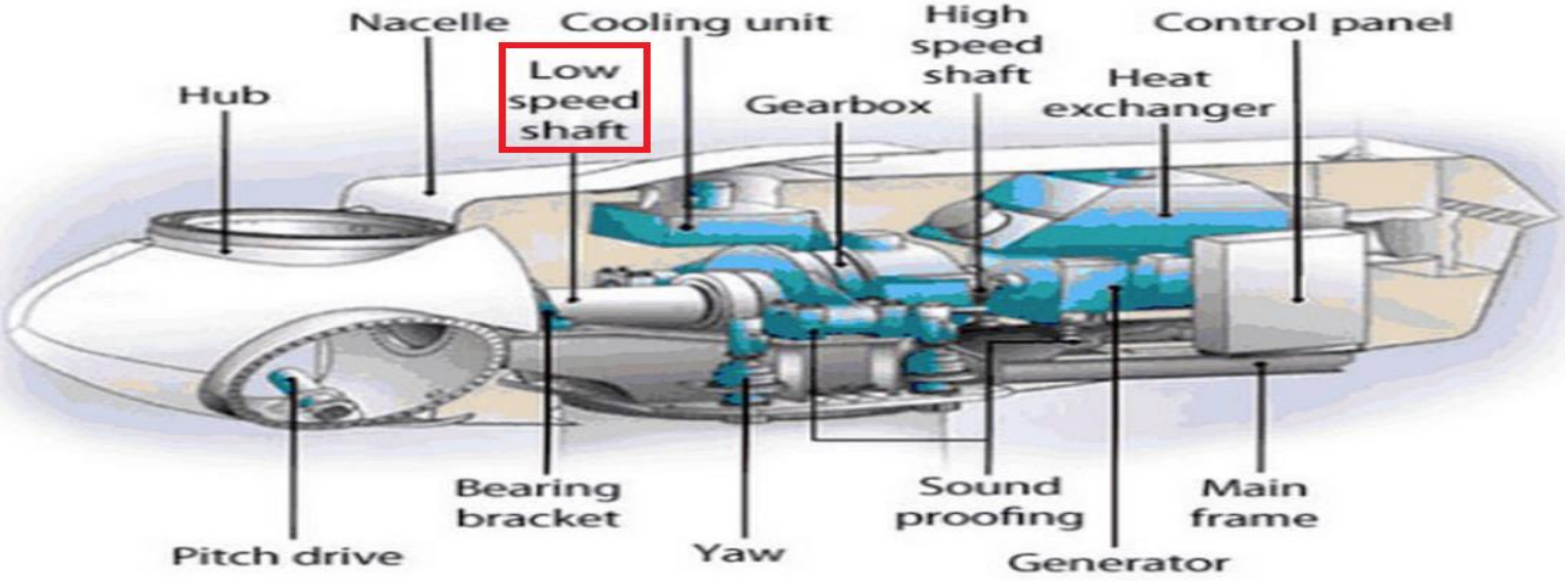
We limit (i) power & (ii)rotating speed of turbine rotor for wind speeds above rated value.



Why we limit (i) power & (ii)rotating speed of turbine rotor for wind speeds above rated value?

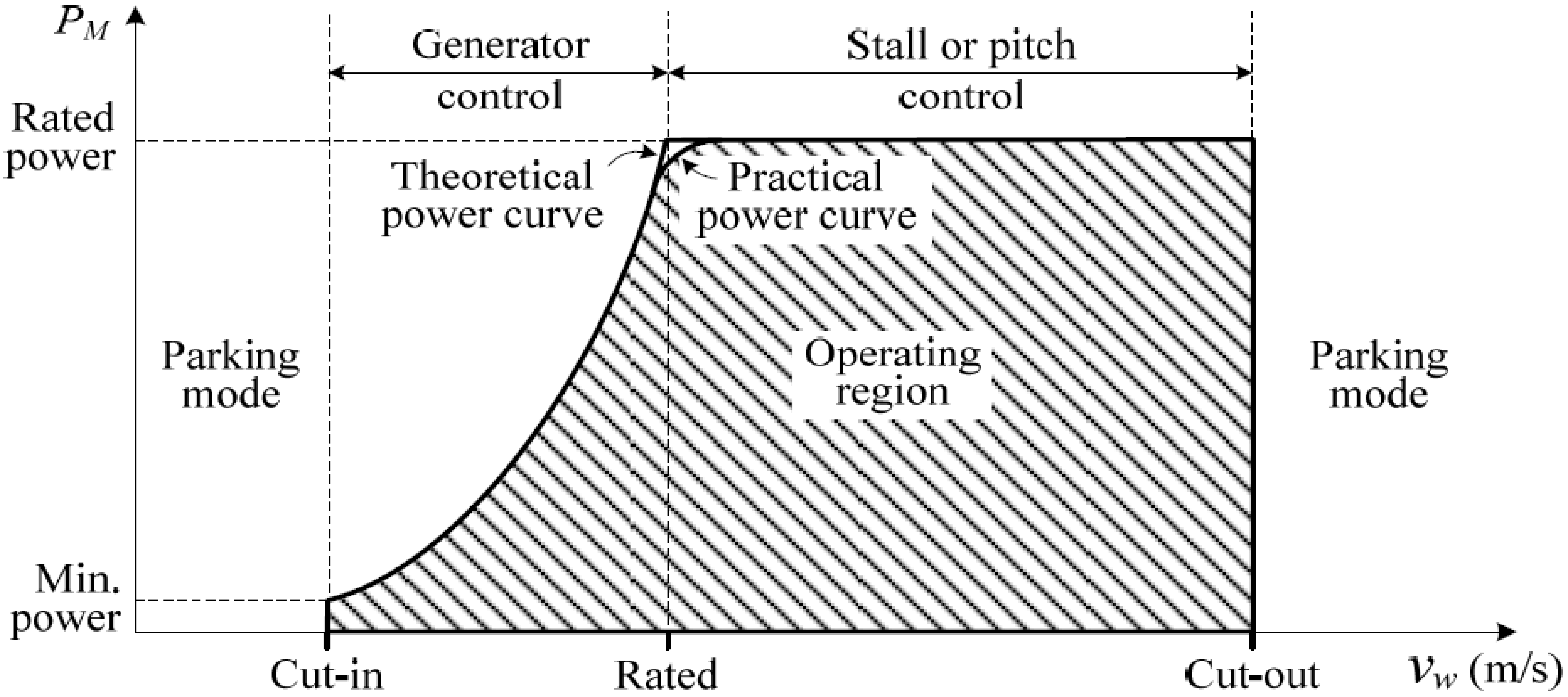


In order to keep forces on mechanical components (blade, gearbox, shaft, etc.) & output power of generator within safety margins.

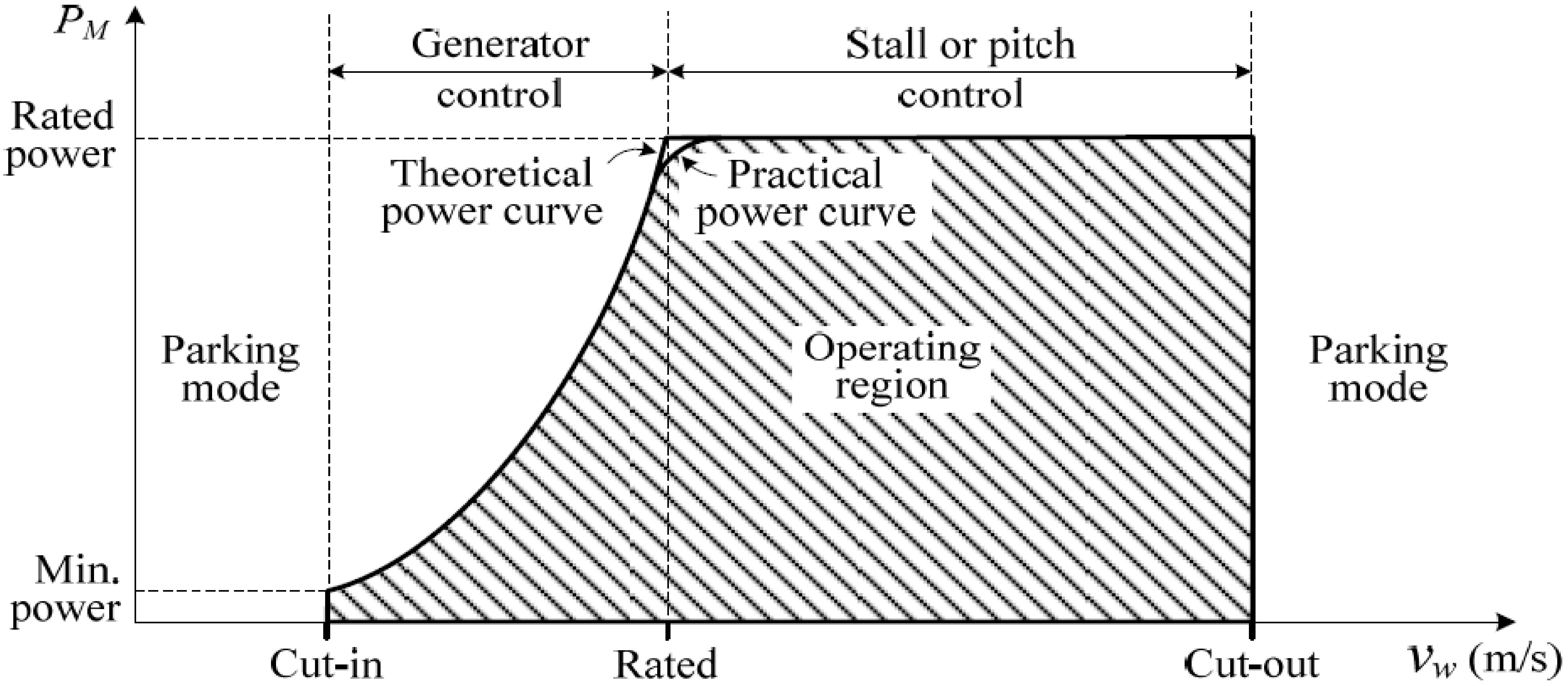


Larger turbines have narrower safety margins due to (i) cost & (ii)size constraints.

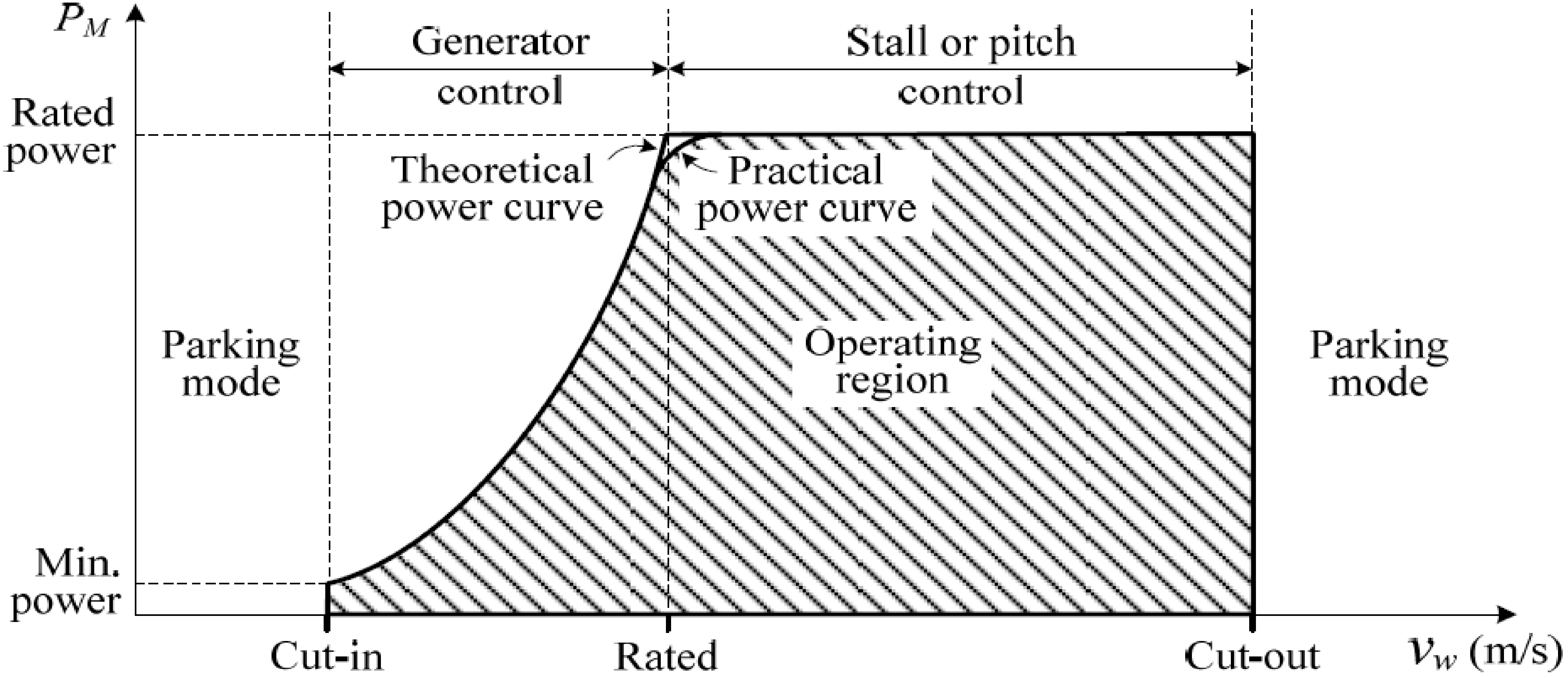
2.3.1 Power Characteristic of Wind Turbine



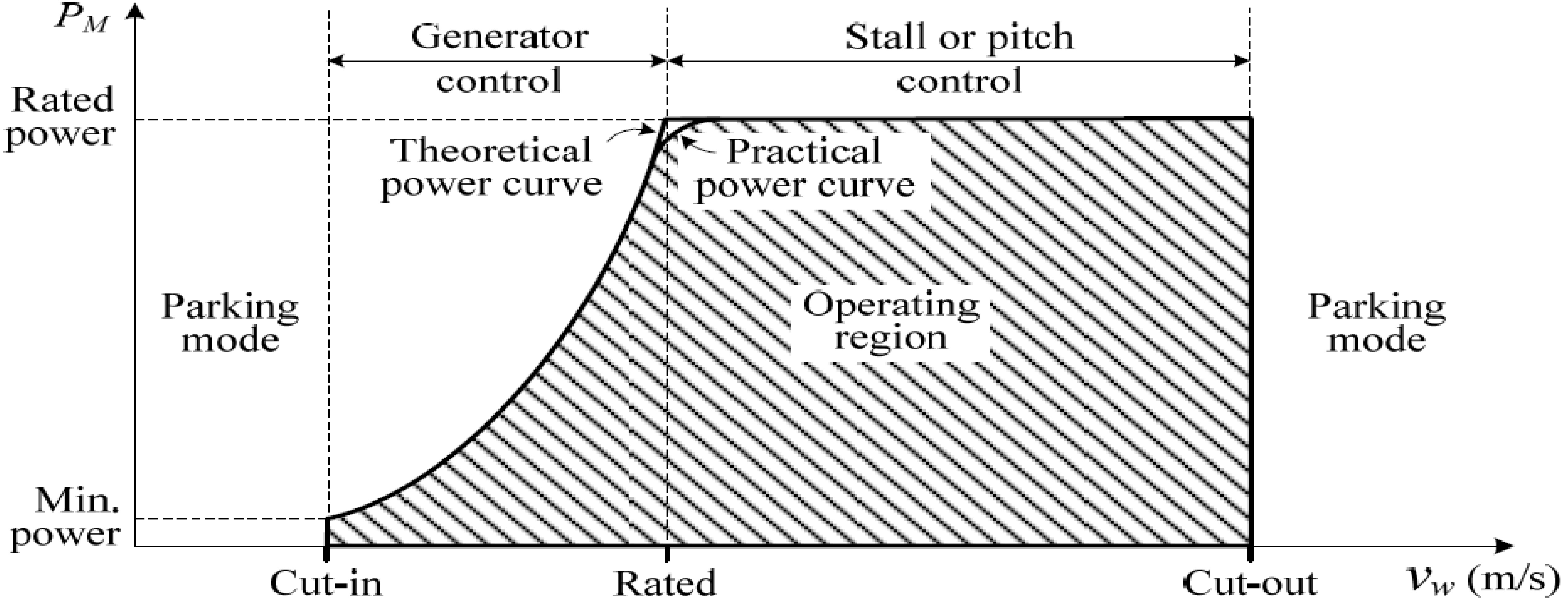
Power curve is very important that relates mechanical power(P_M) of turbine to wind speed(v_w).



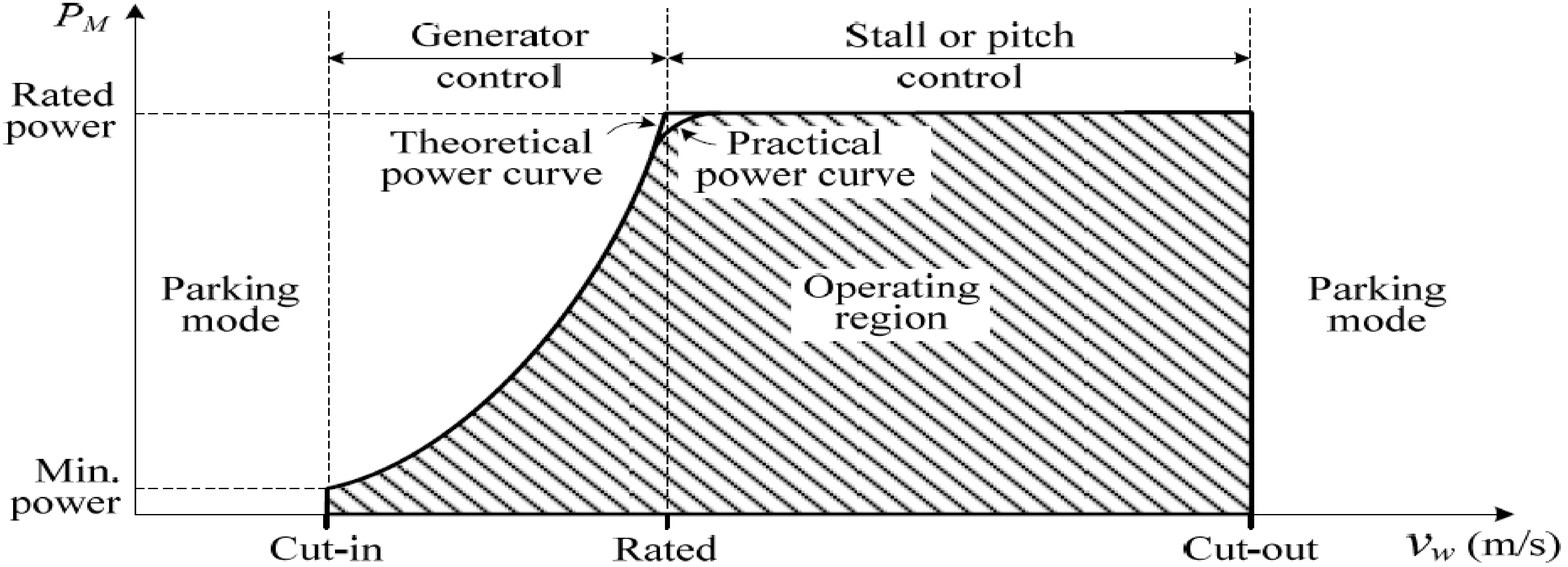
Power curve is a wind turbine’s certificate of performance that is guaranteed by manufacturer.



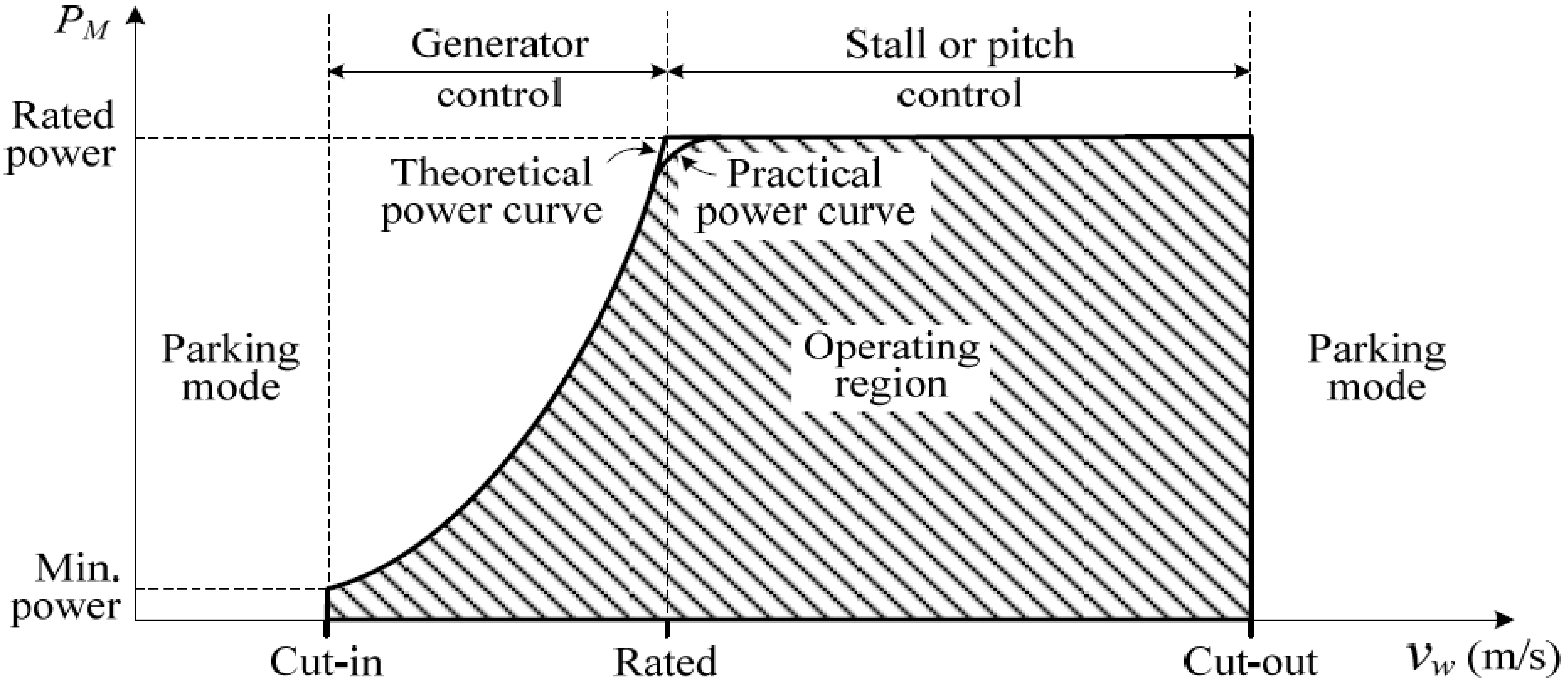
International Energy Association (IEA) developed power curve & after improvement, adopted by International Electrotechnical Commission (IEC).



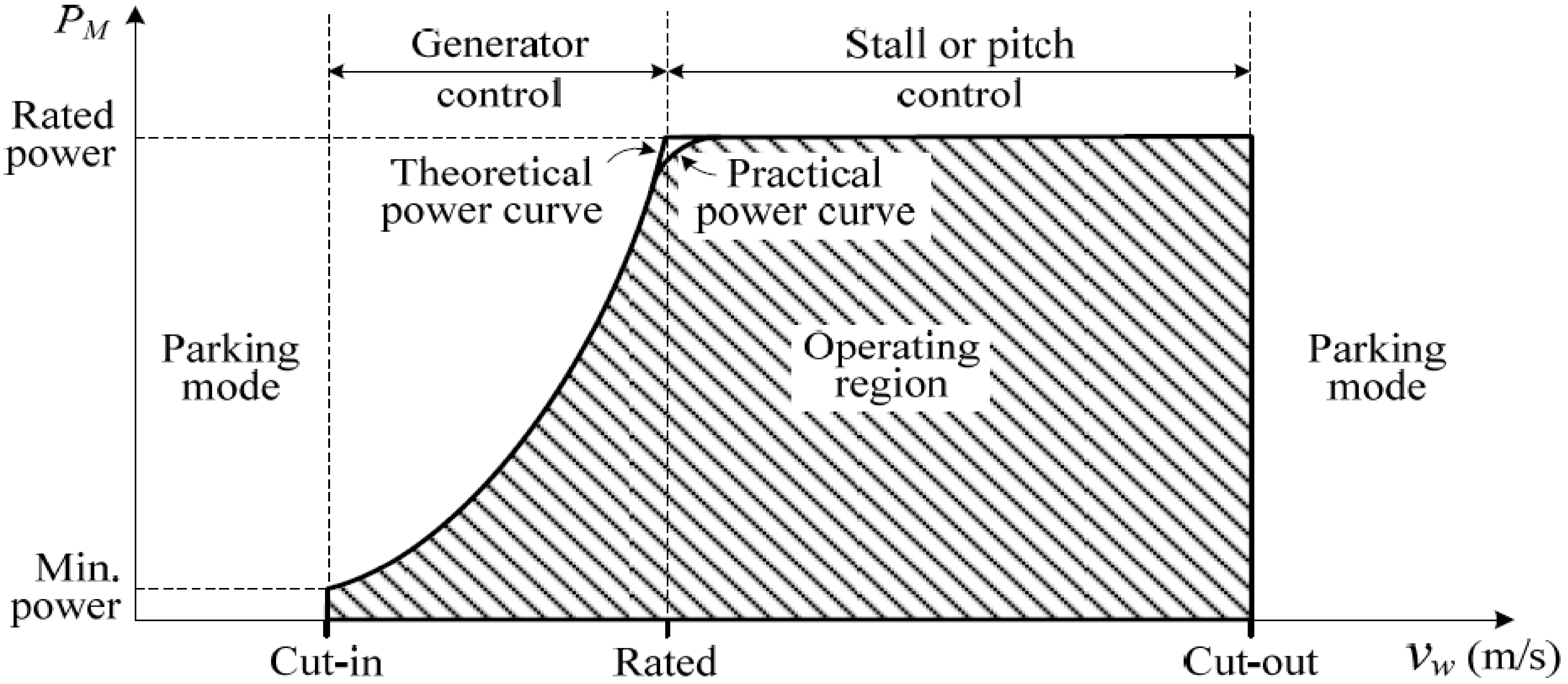
Standard, IEC61400-12, is generally accepted as a basis for defining & measuring power curve. We follow this standard in power curve.



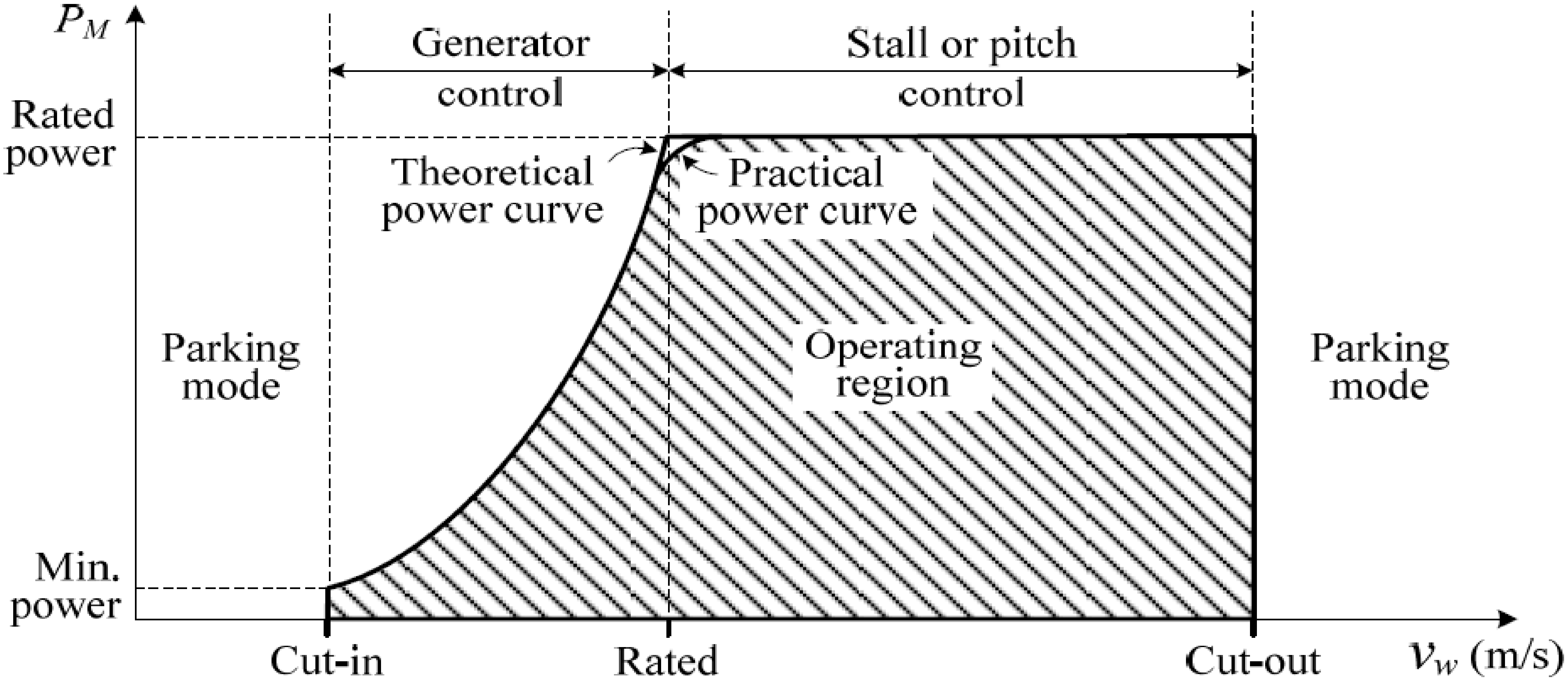
Power curve comprises of:



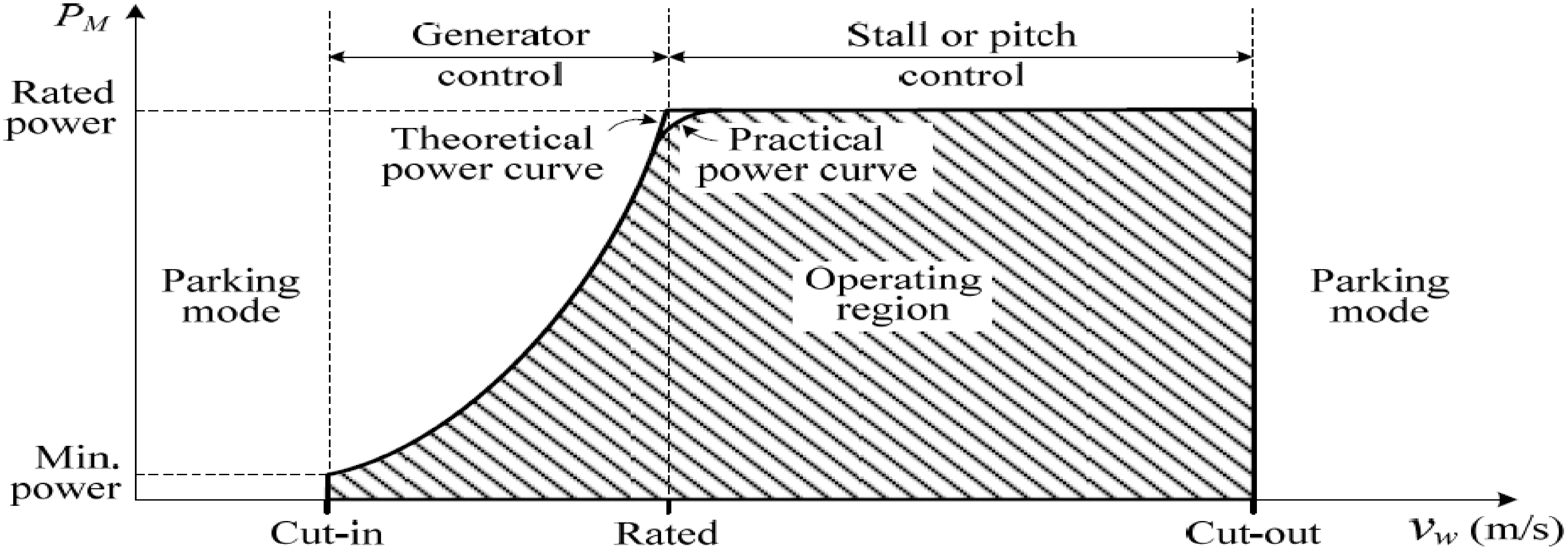
(i) Cut-in wind speed



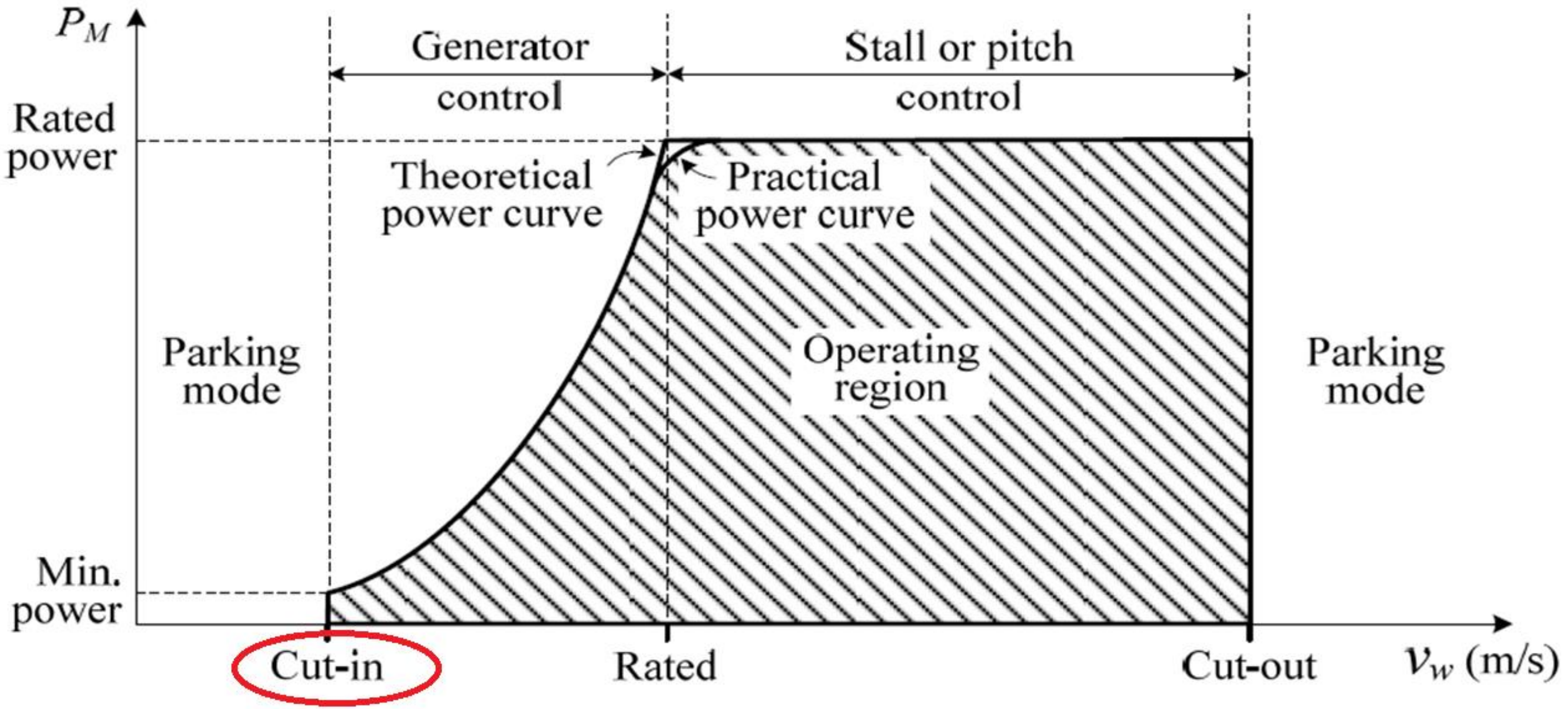
(ii) Rated wind speed



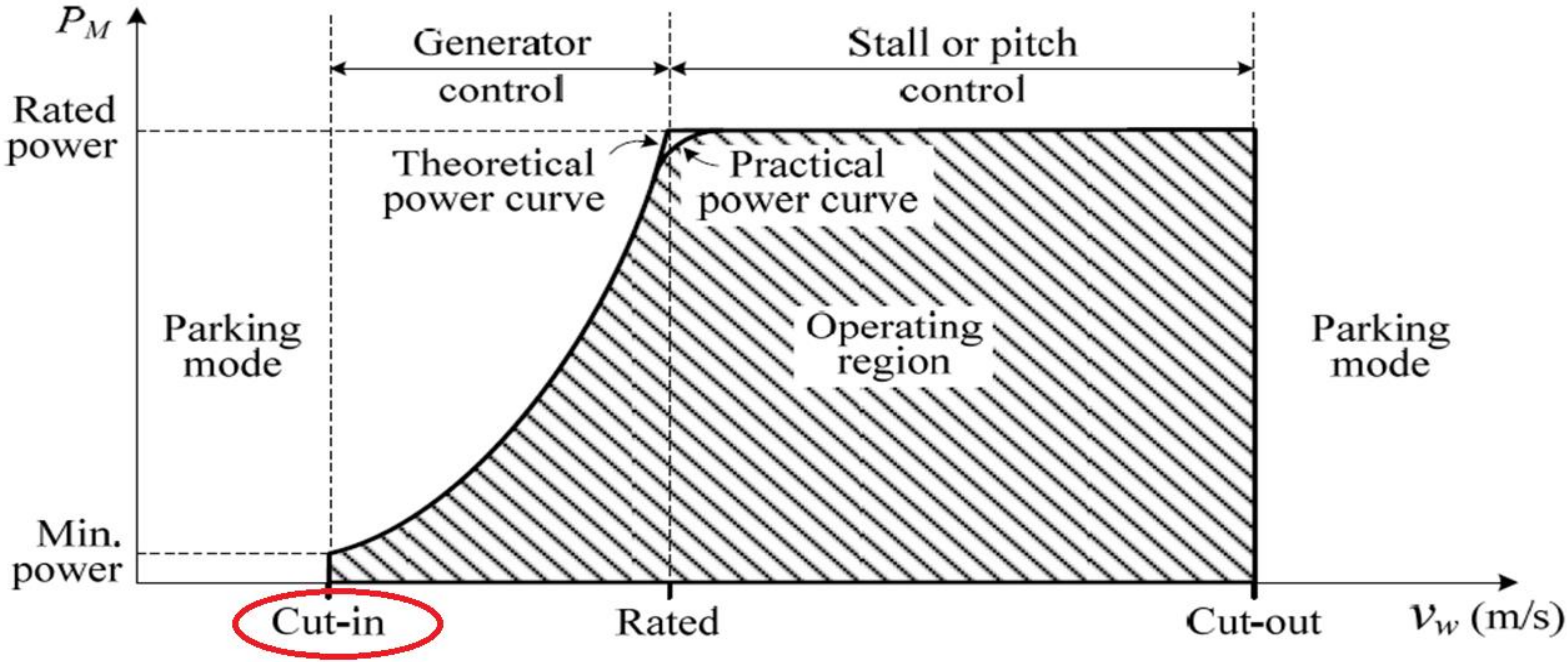
(iii) Cut-out wind speed



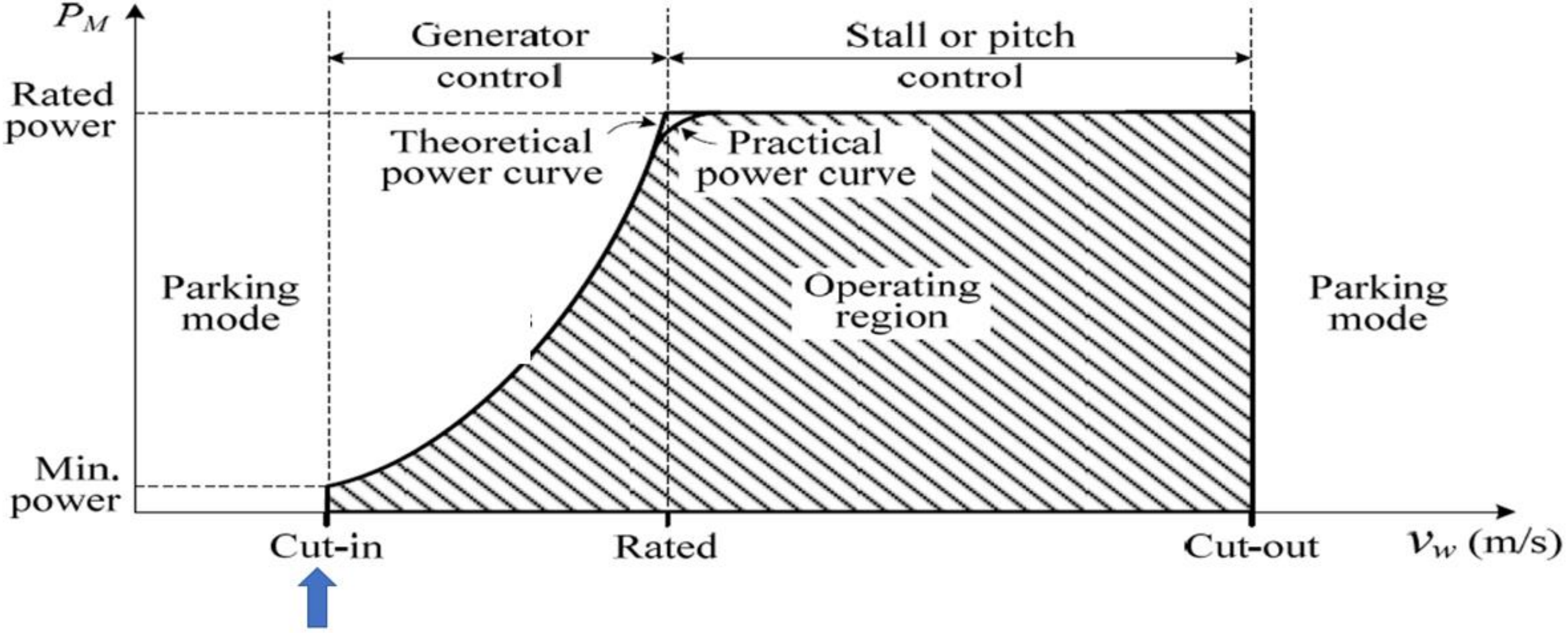
Define Cut-in wind speed?



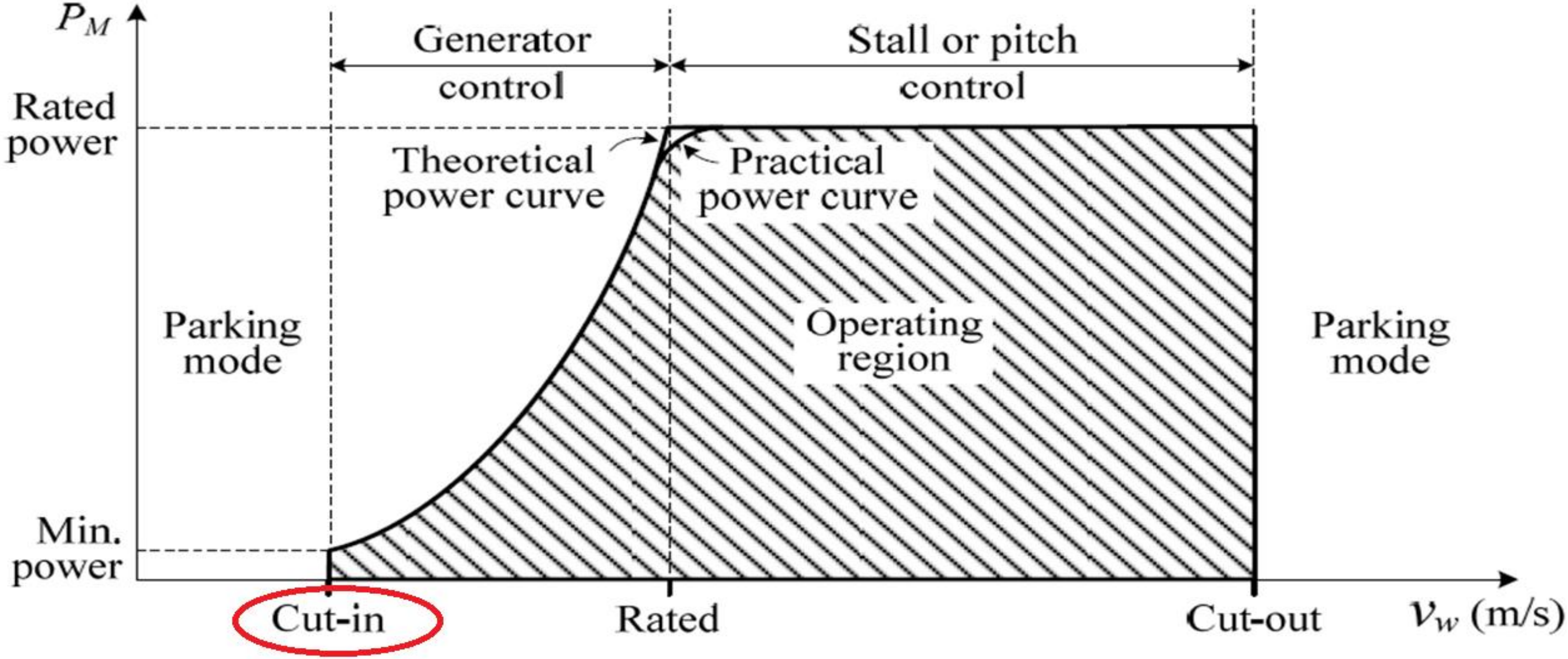
Cut-in wind speed: is the wind speed at which turbine starts to operate & deliver power.



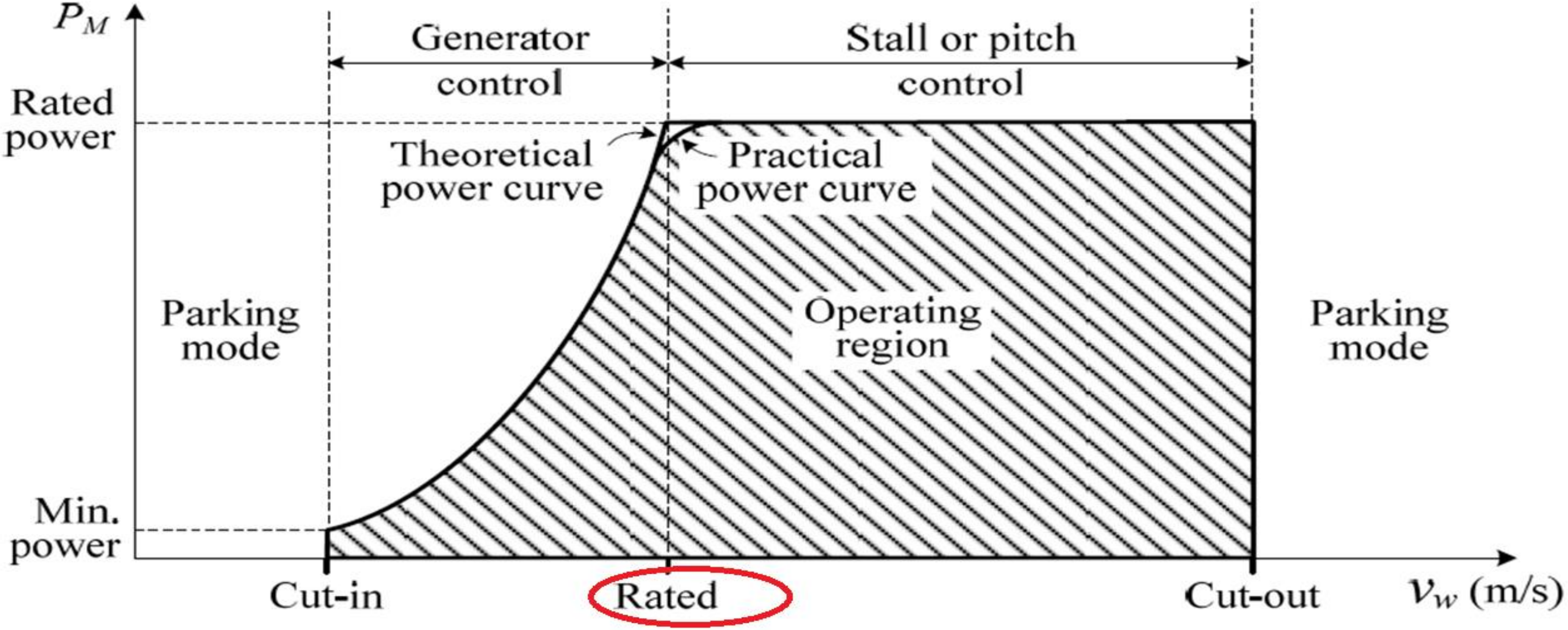
Wind turbine starts to capture power at cut-in wind speed.



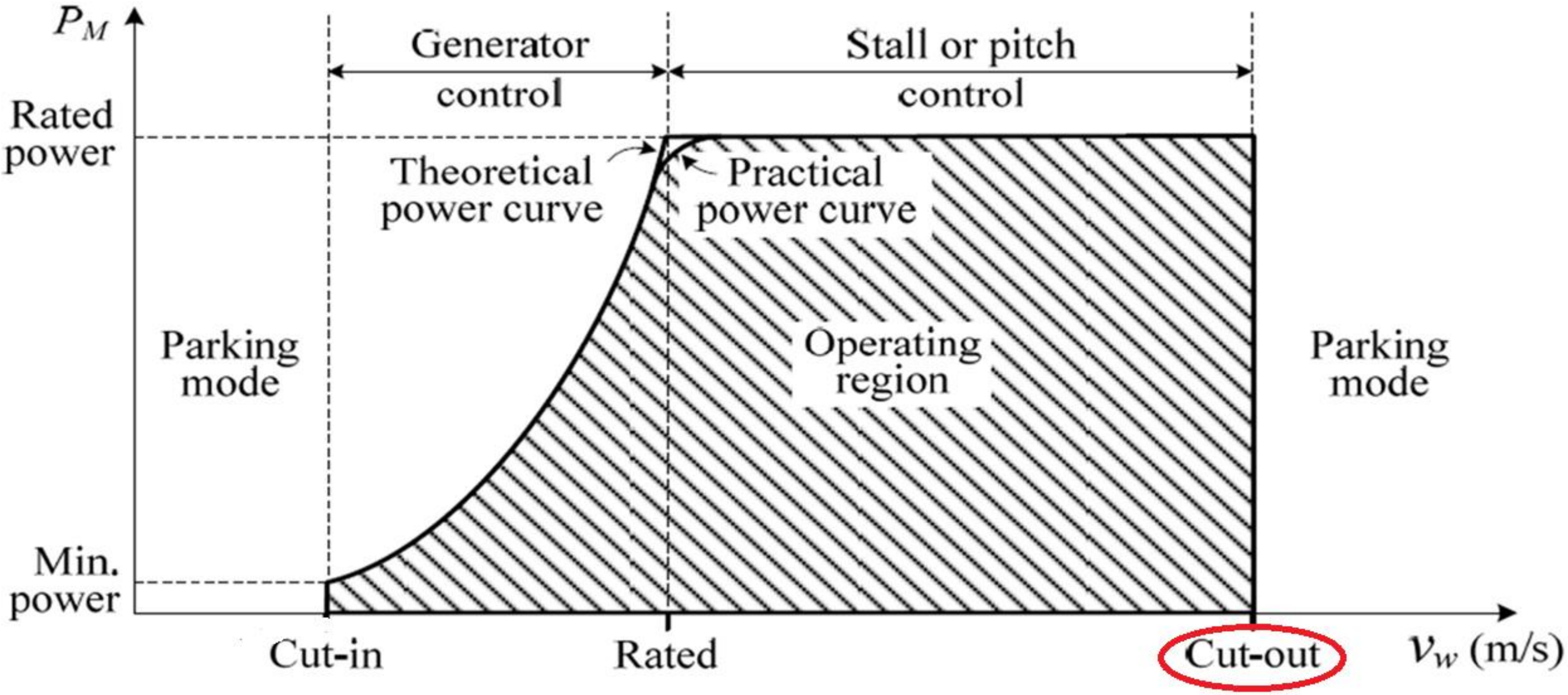
At cut-in wind speed: Blades should be able to capture enough power for compensation of turbine power losses.



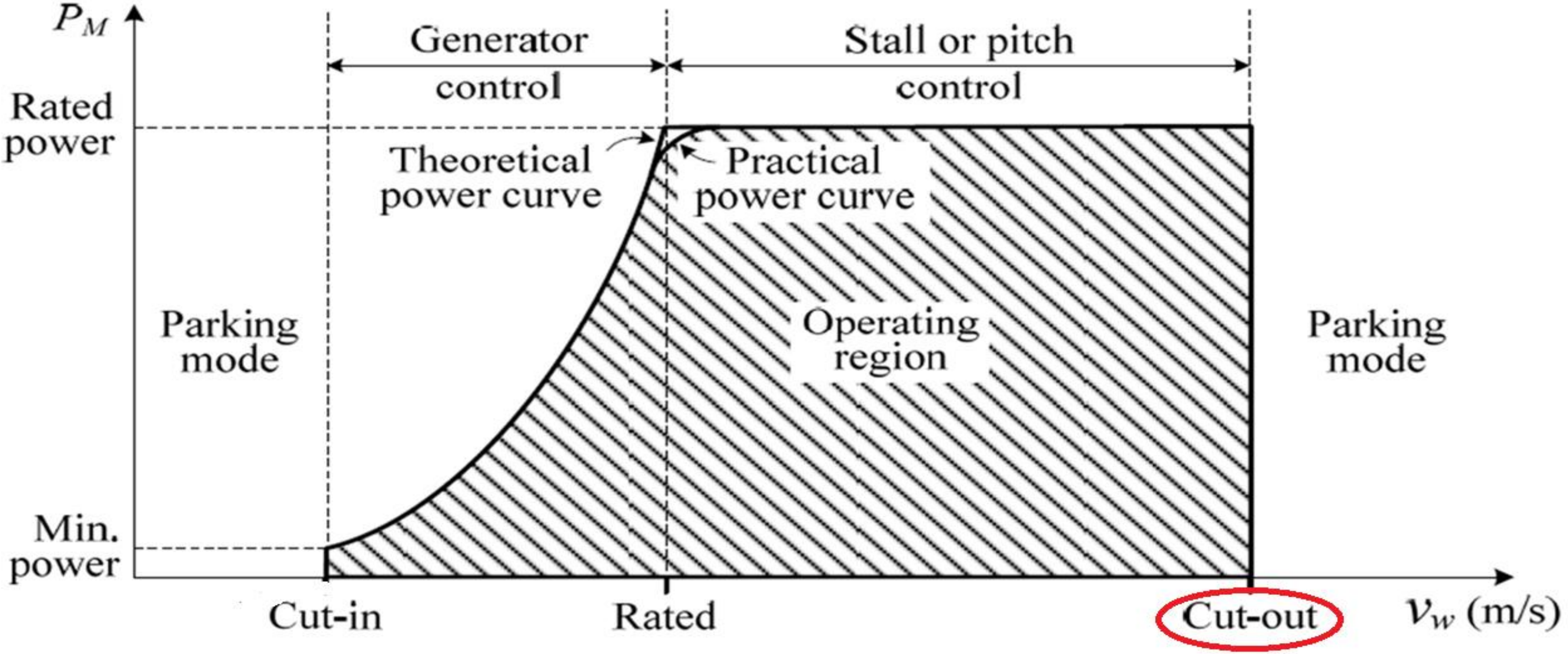
At rated wind speed: System produces nominal power, which is also the rated output power of generator.



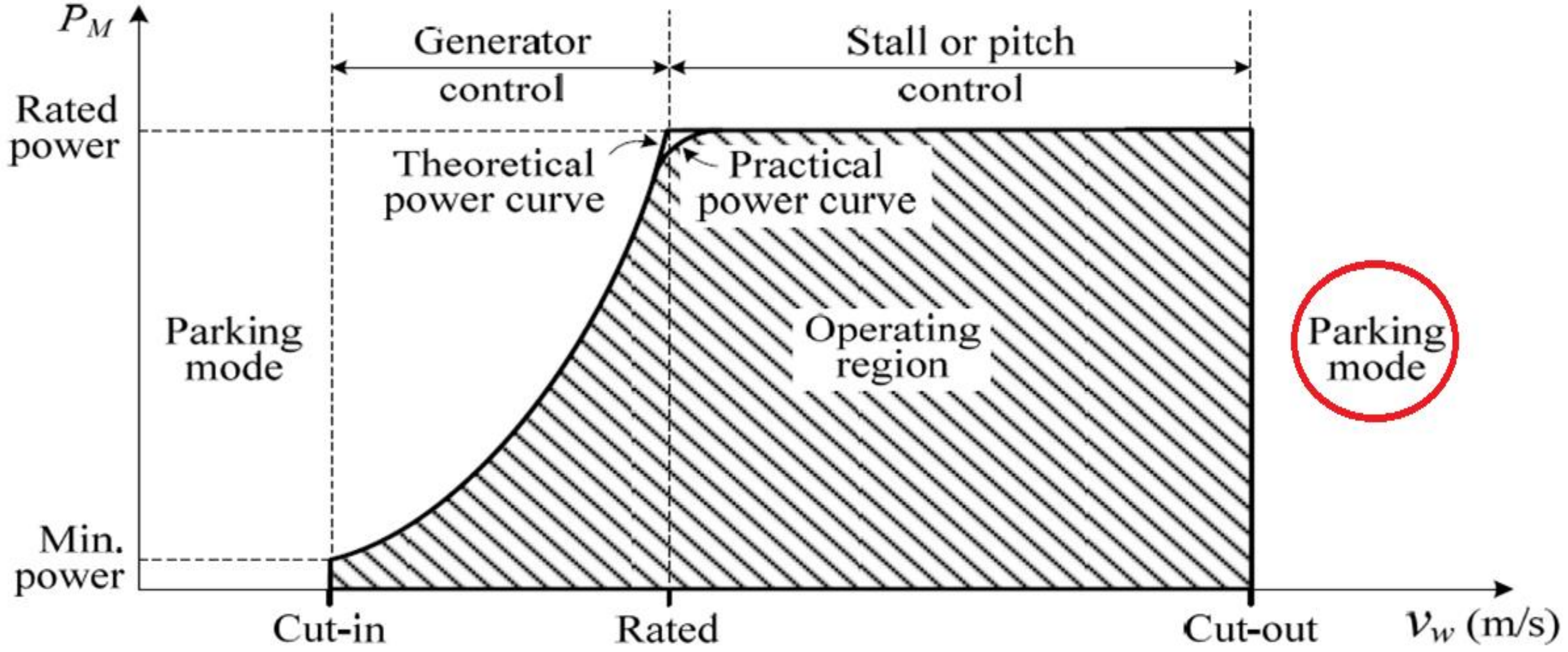
Define Cut-out wind speed?



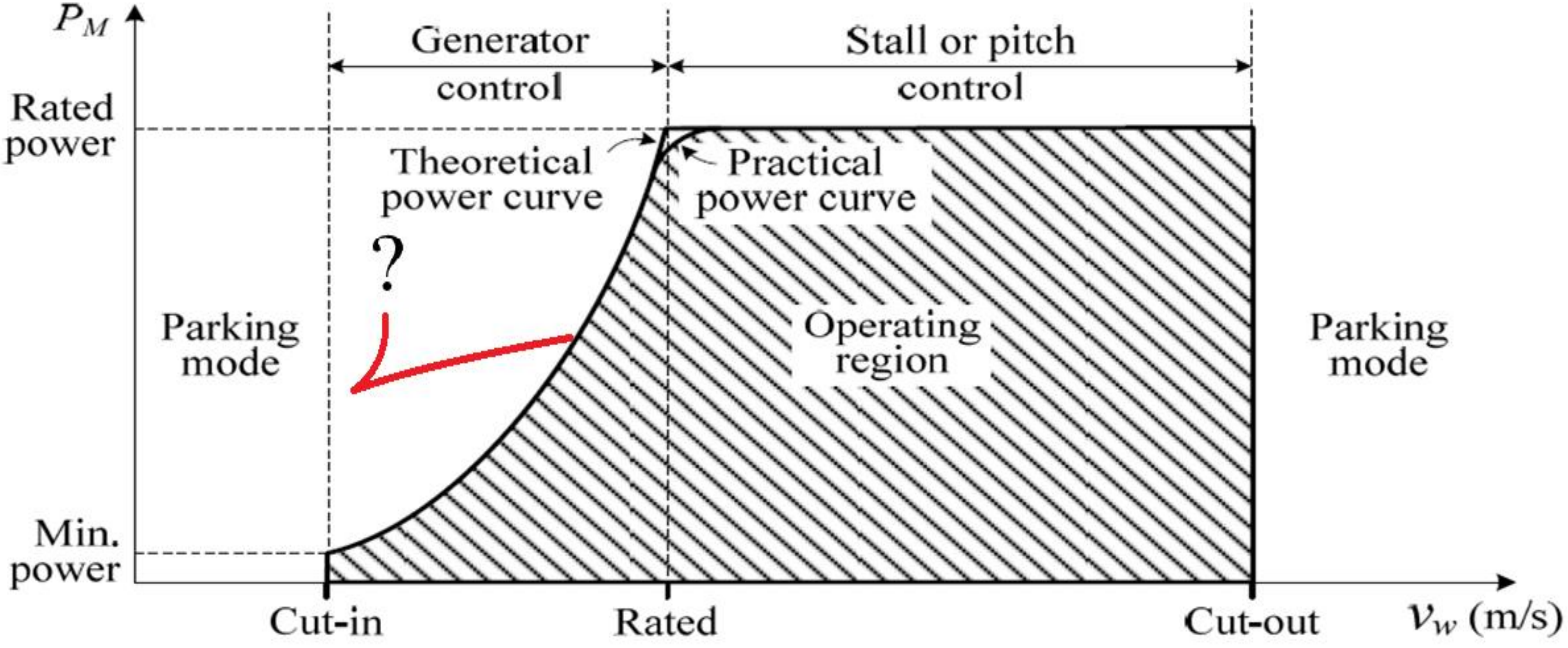
Cut-out wind speed is the highest wind speed at which the turbine is allowed to operate before it is shut down.



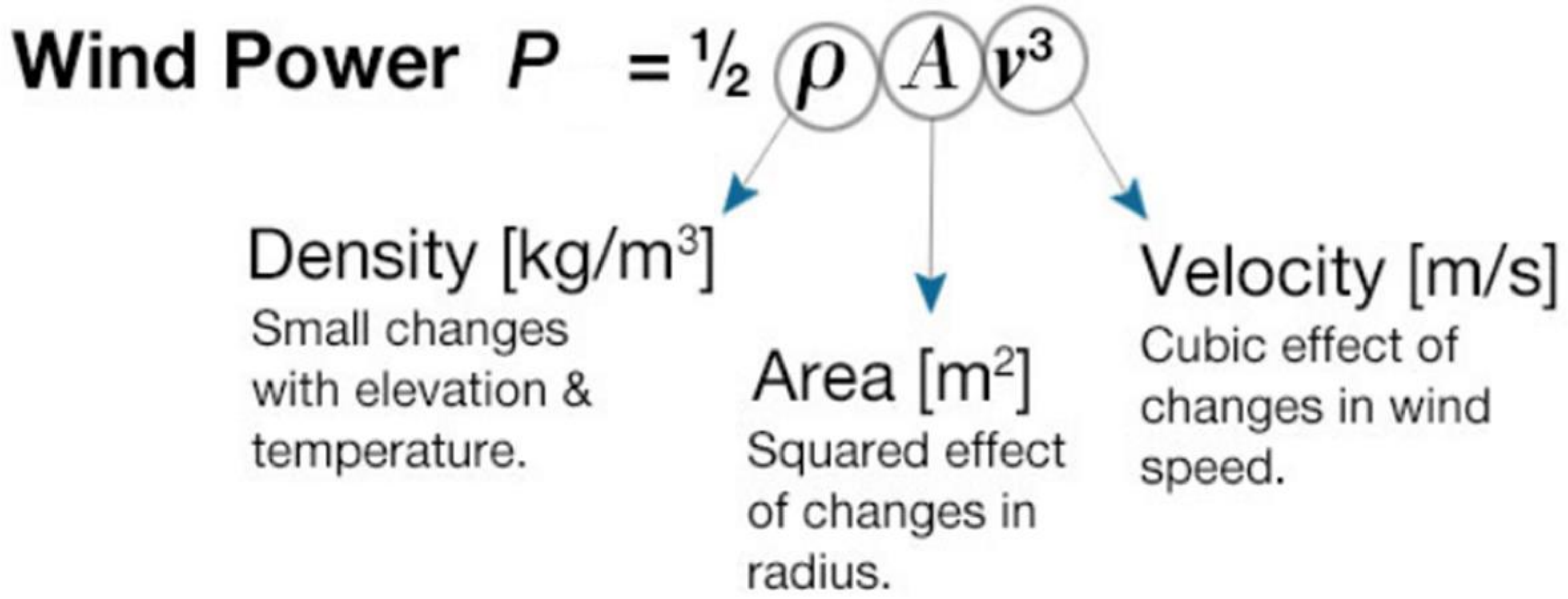
For wind speeds>cut-out speed turbine must be stopped, preventing damage from the excessive wind.



What should be the function between power captured by blades & wind speed?

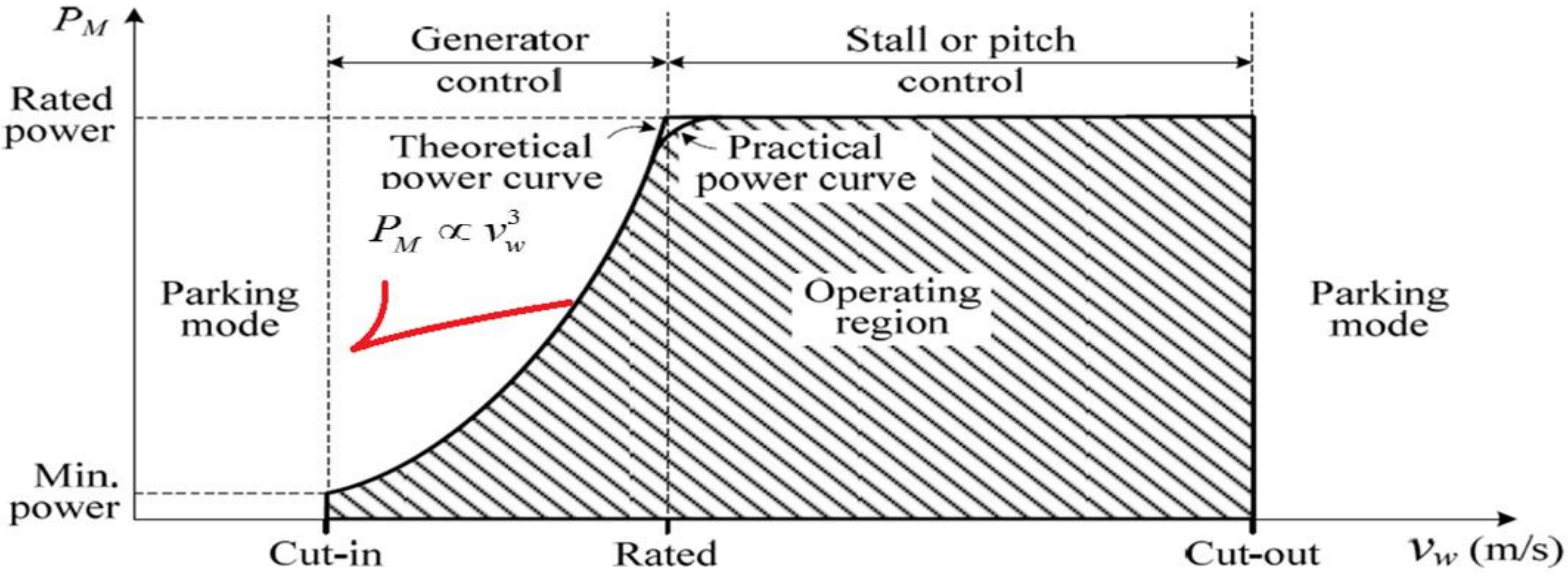


Power of an air mass flowing at speed v_w through an area A can be calculated by:

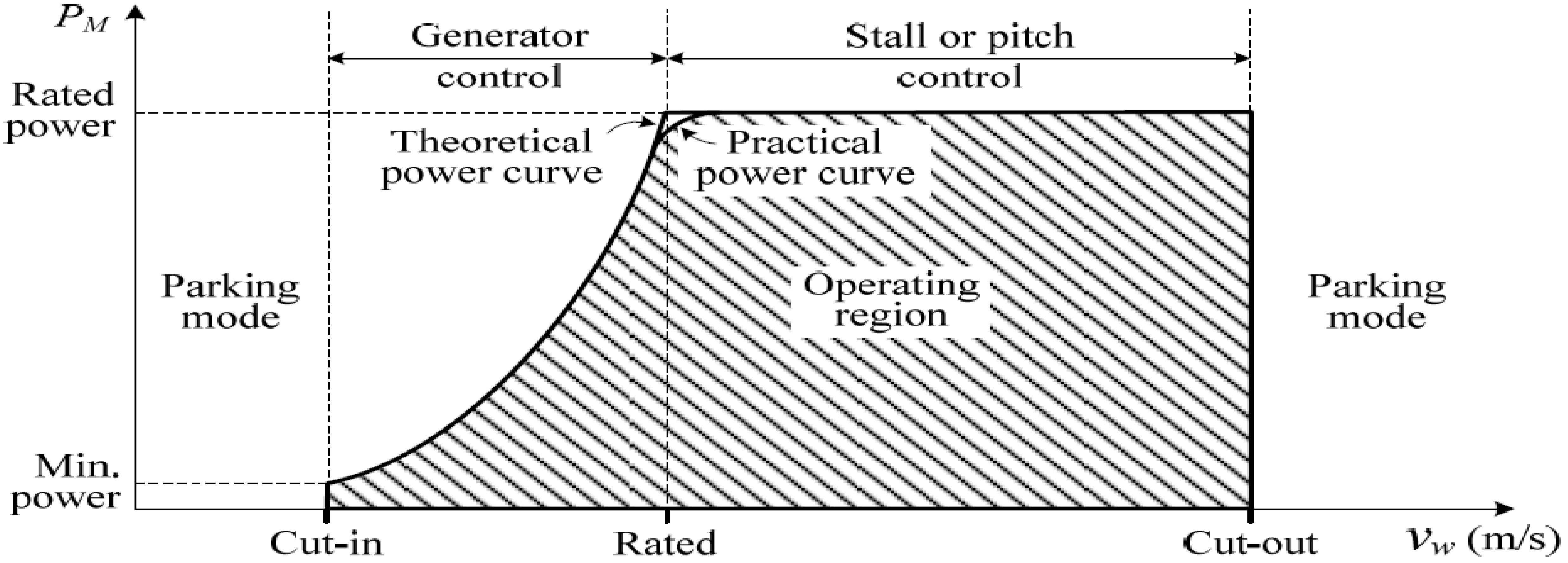


Power captured by blades is a cubic function of wind speed until wind speed reaches its rated value.

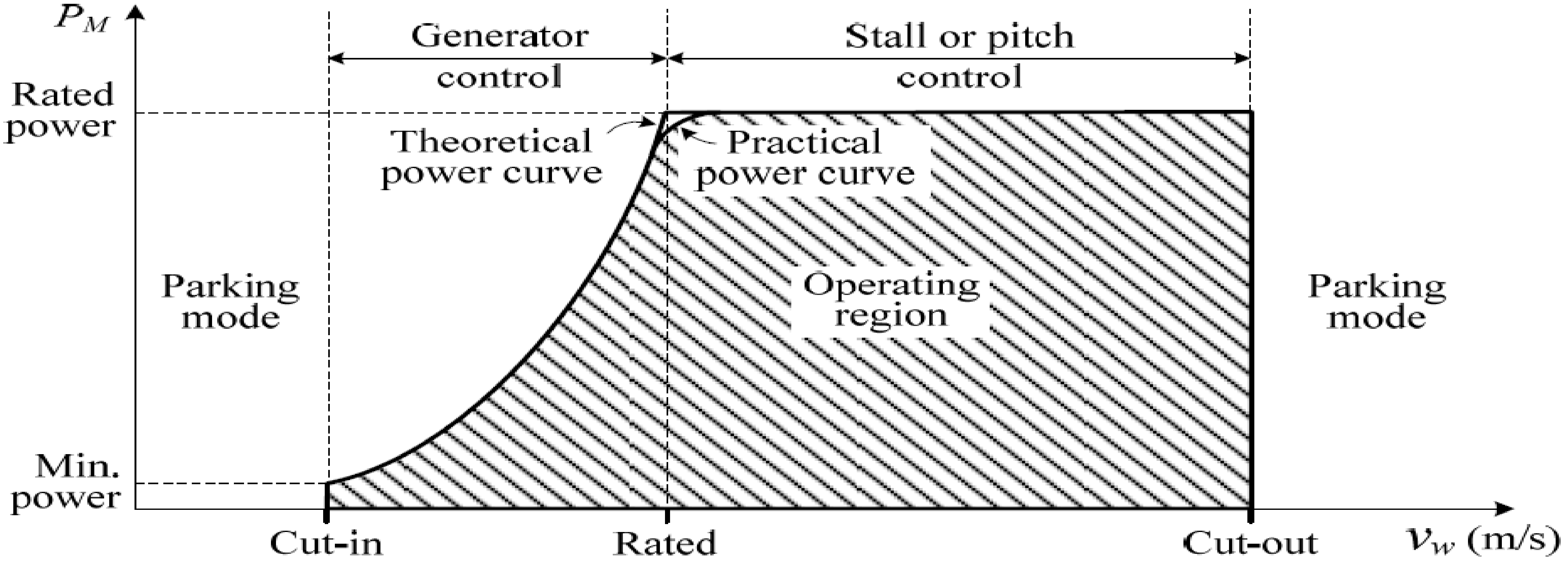
$$P = \boxed{\tfrac{1}{2}\,\rho\,A}\,v^3 \qquad\qquad P_M \propto v_w^3$$



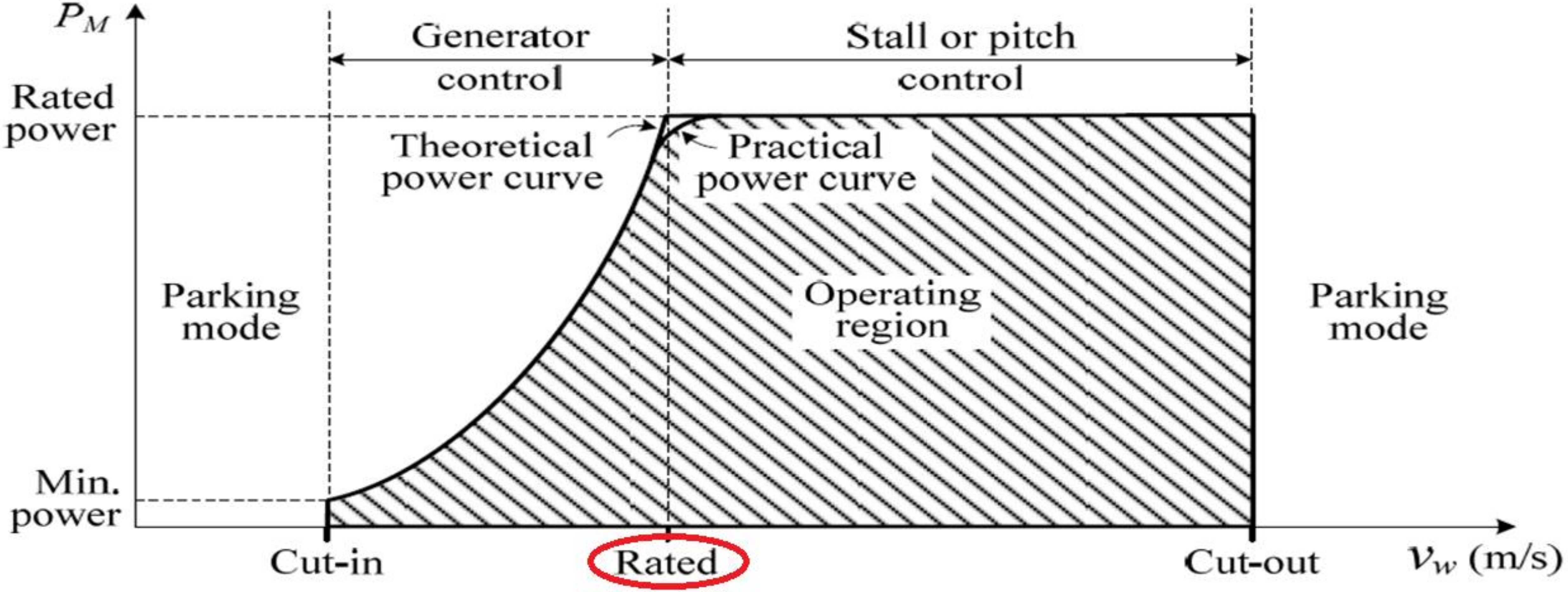
To deliver captured power to grid at different wind speeds: Wind generator should be properly controlled with variable speed operation.



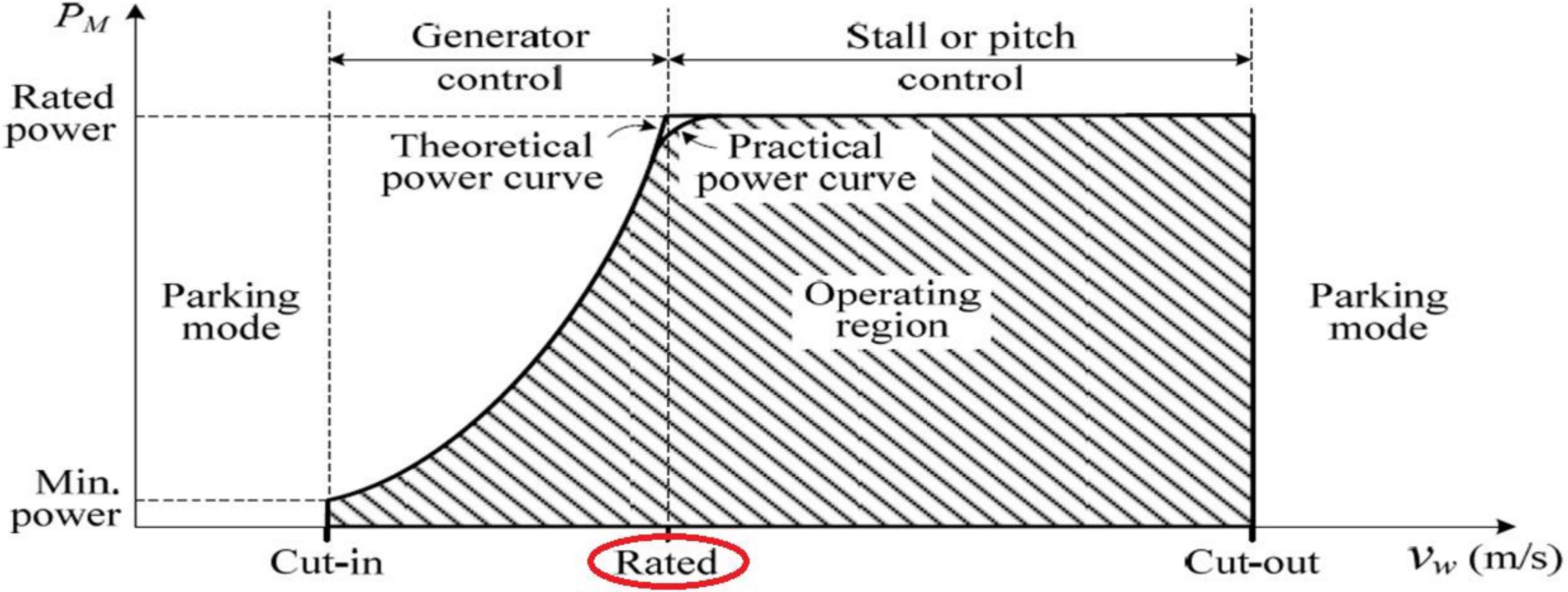
1.When wind speed is less, then increase generator speed
2.When wind speed is higher then decrease generator speed
It can be possible only with the variable speed operation.



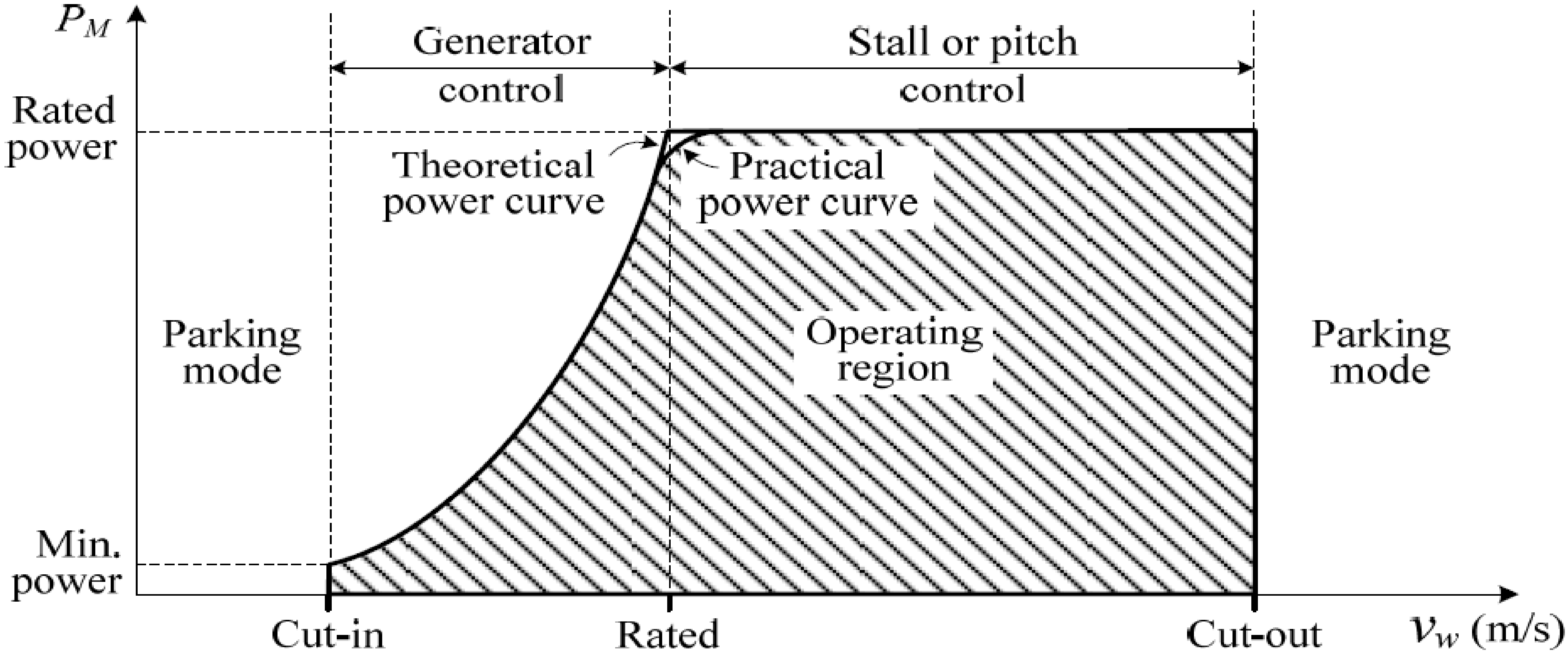
When wind speed increases beyond **rated speed:** What should we do?



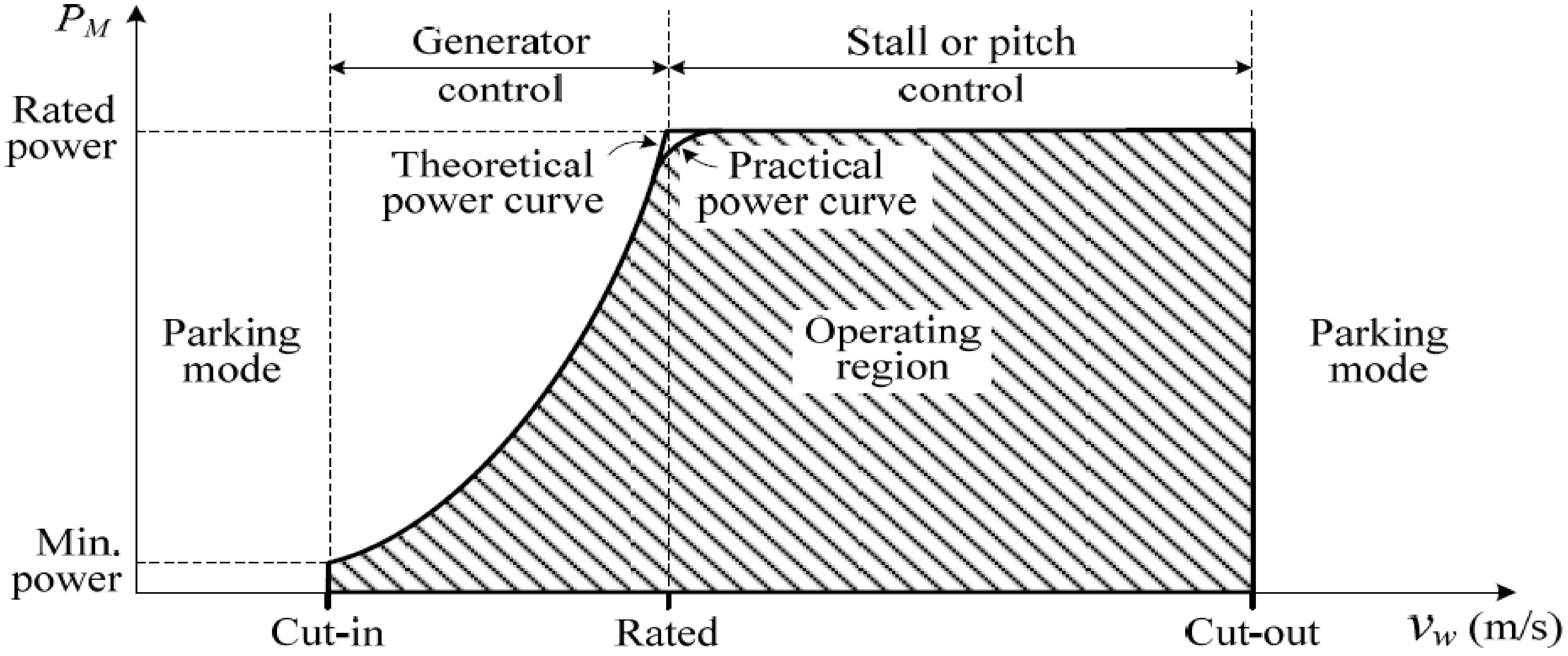
Apply Aerodynamic power control of blades that keeps power at rated value.



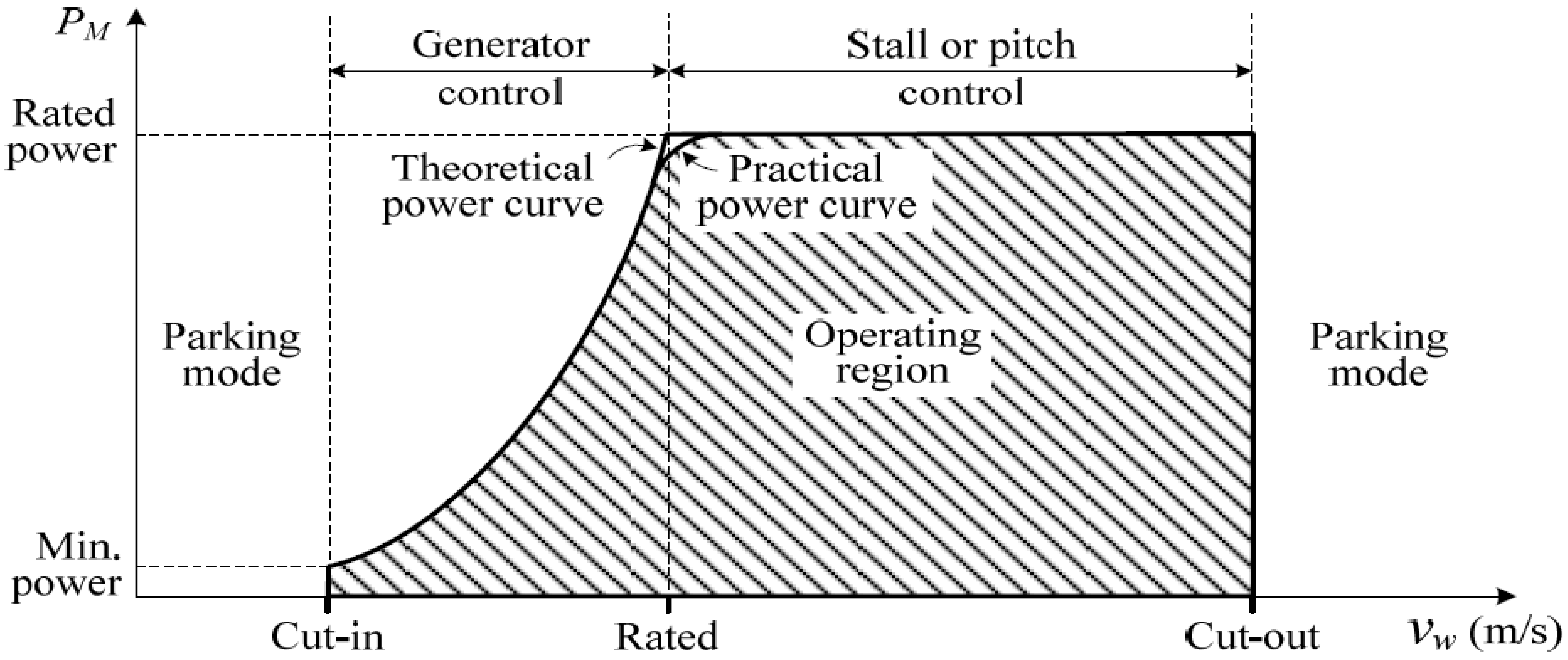
Aerodynamic power control is performed by 3 main techniques:



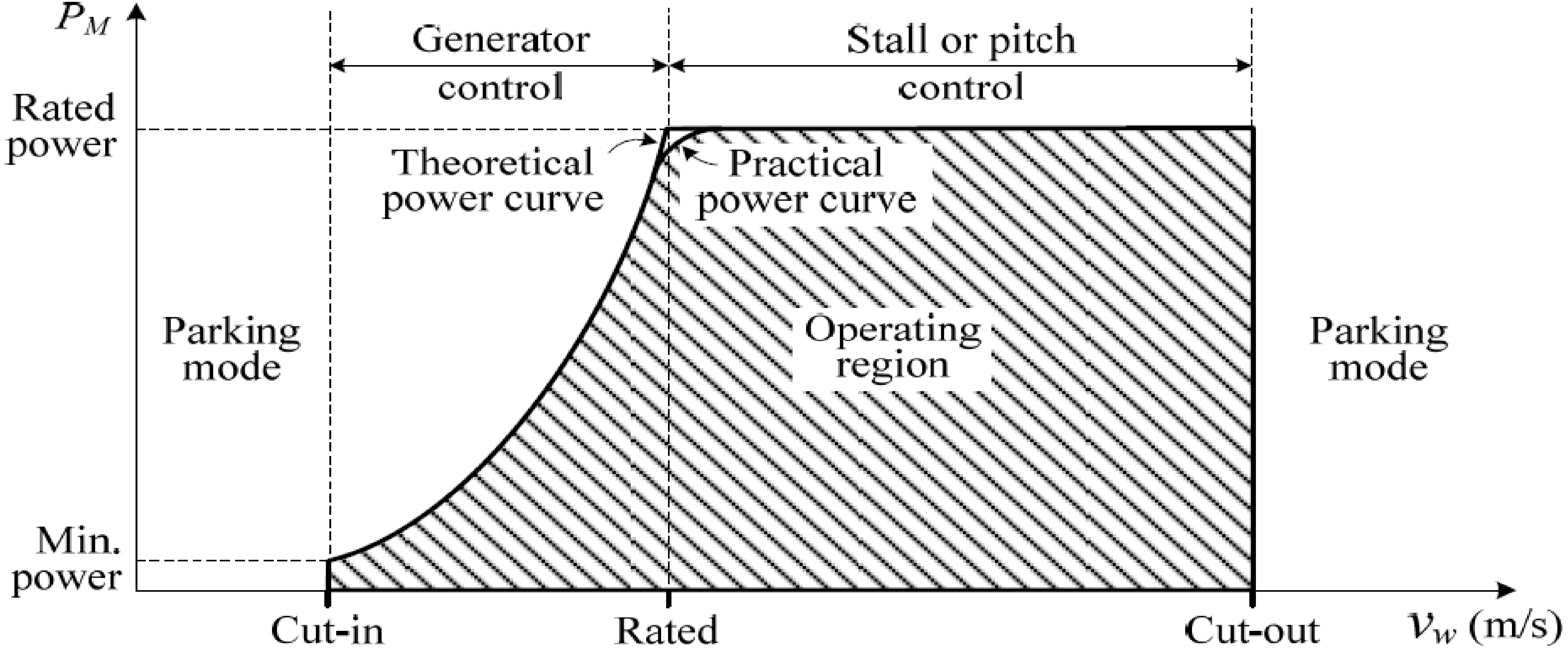
(i)Passive-stall



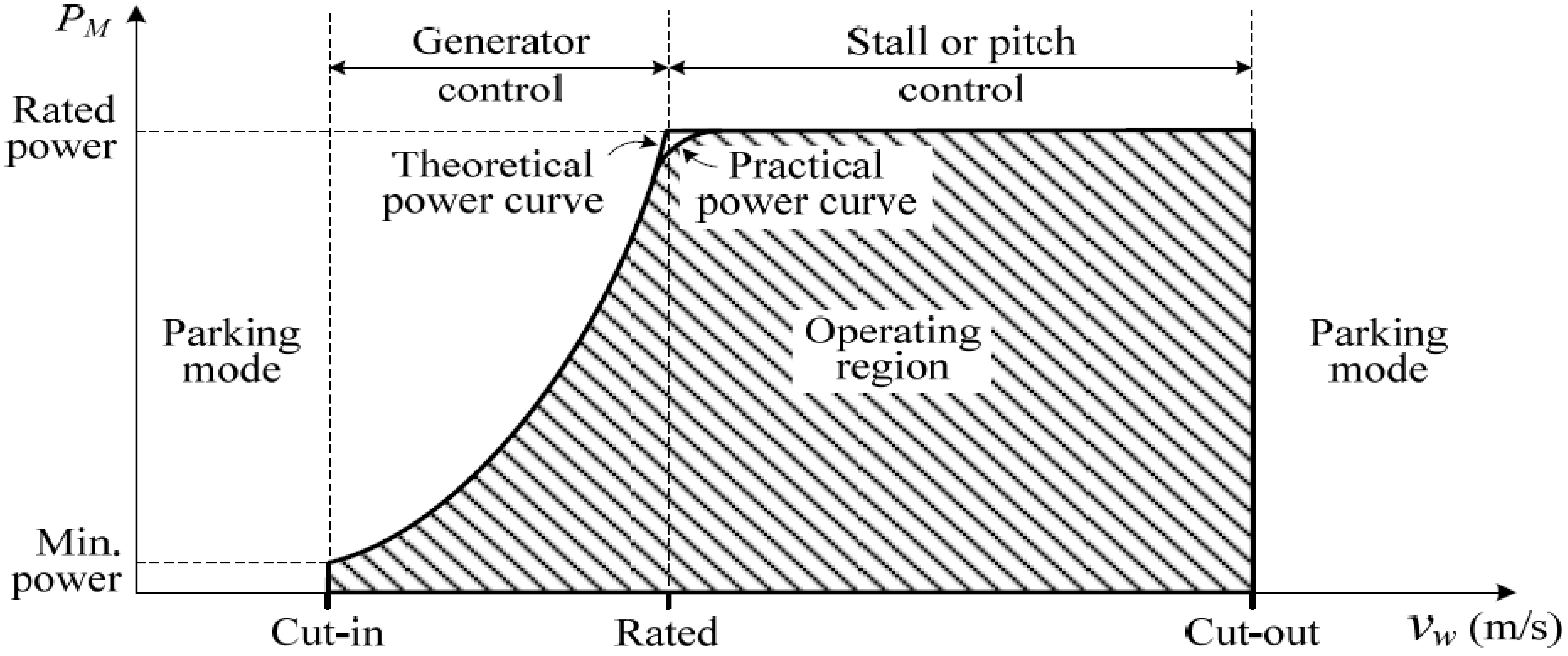
(ii)Active-stall



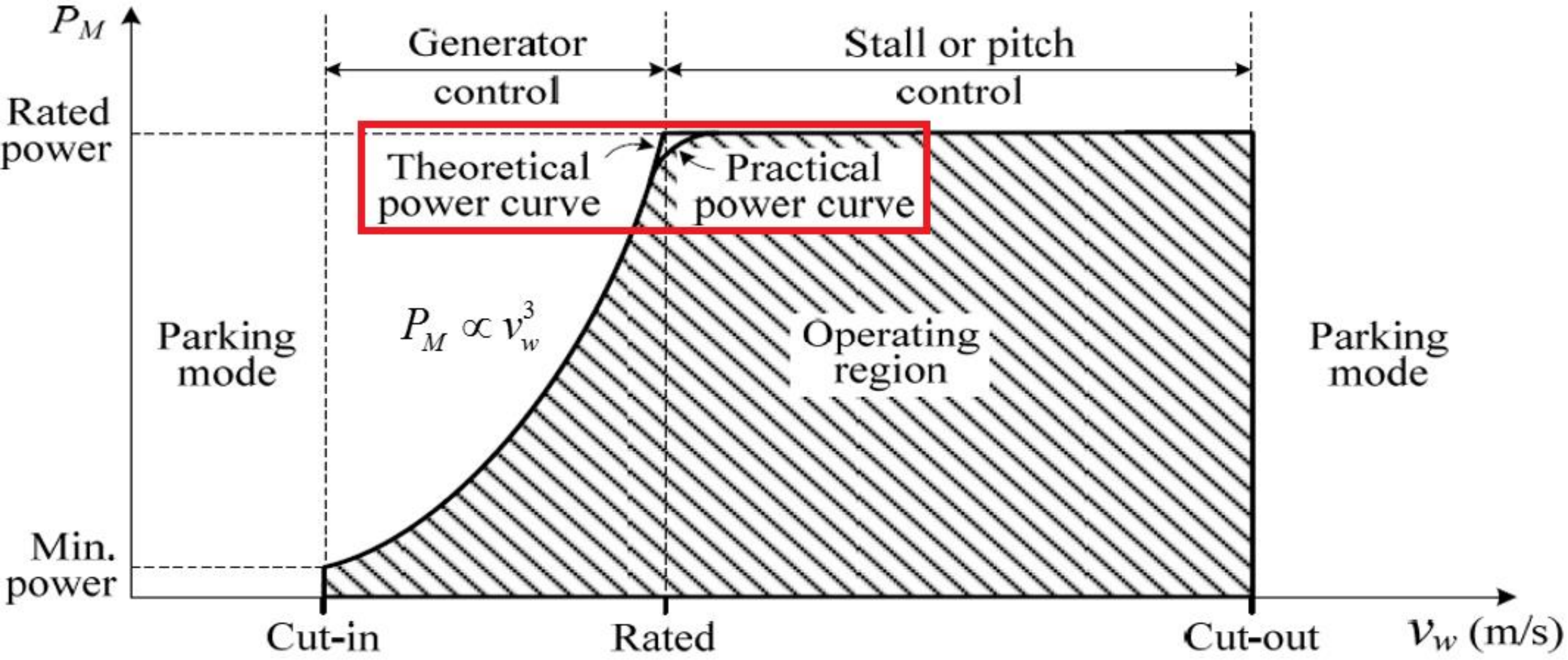
(iii)Pitch control



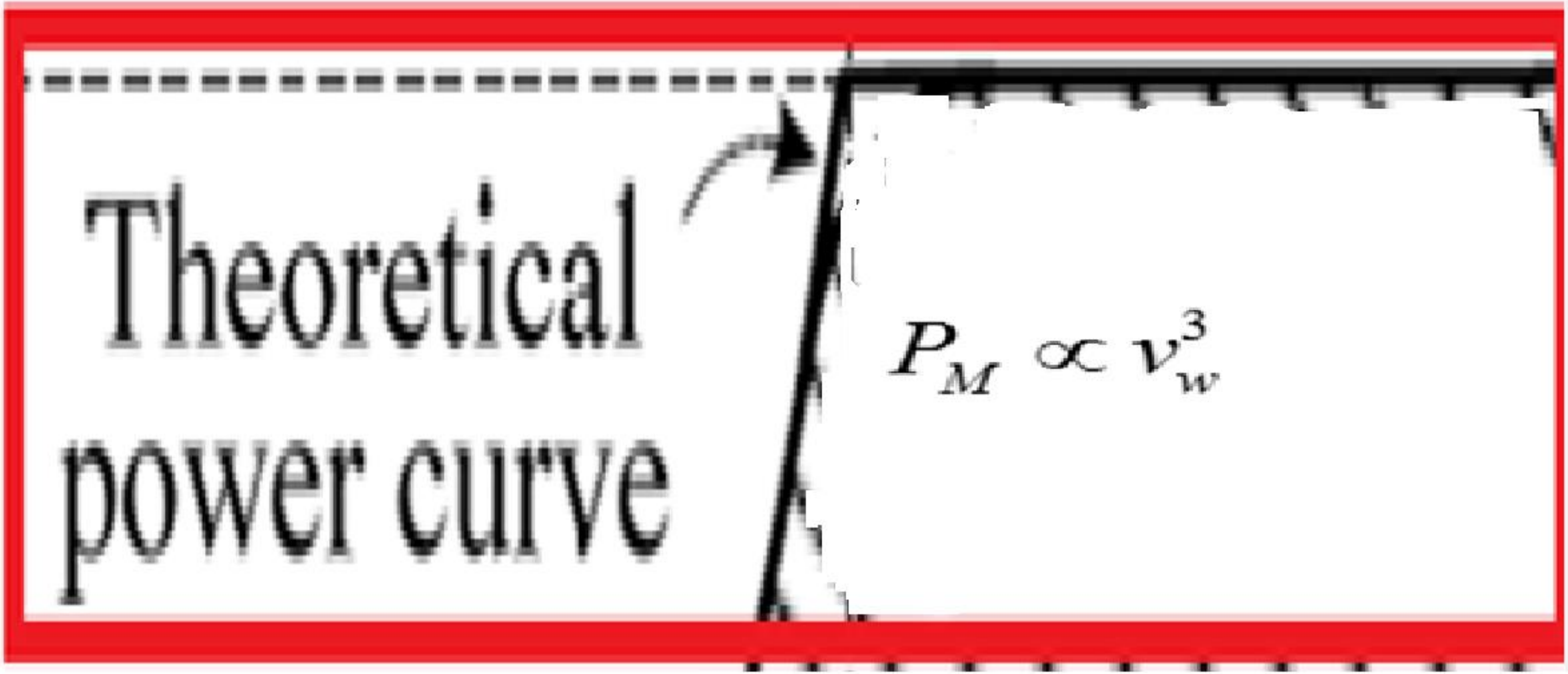
Wind turbine should stop generating power & be shut down when speed is > cut-out wind speed.



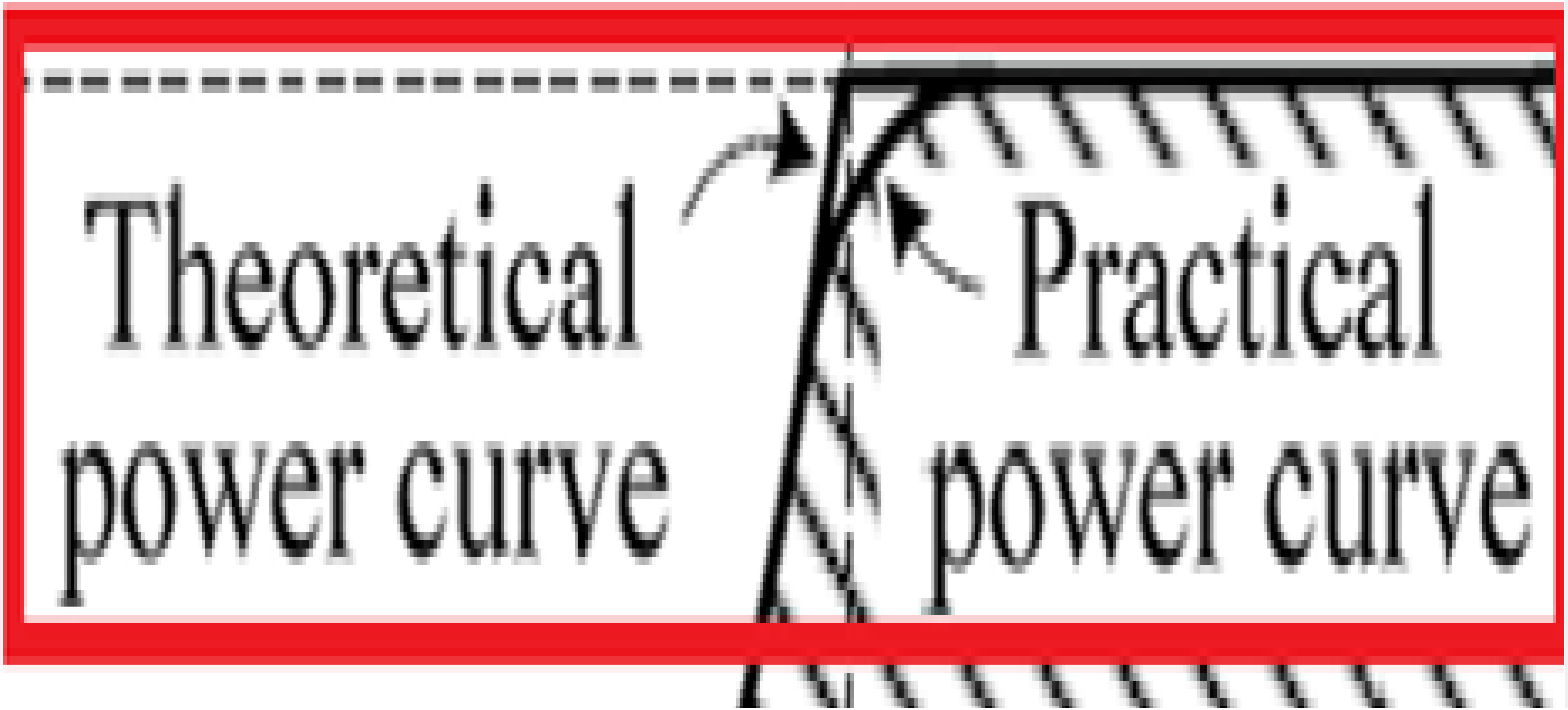
At higher speeds define behaviour of theoretical curve?



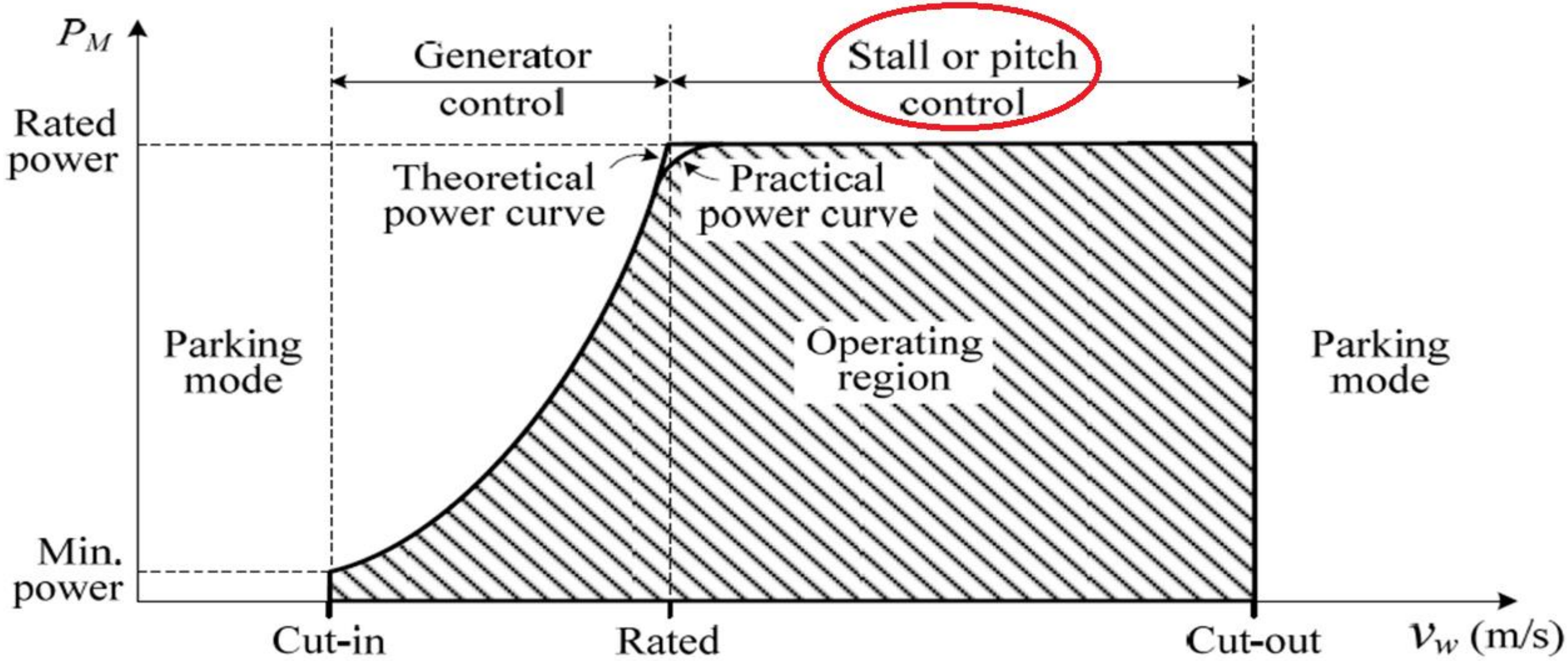
At higher speeds theoretical curve has an abrupt transition from cubic characteristic to constant power operation



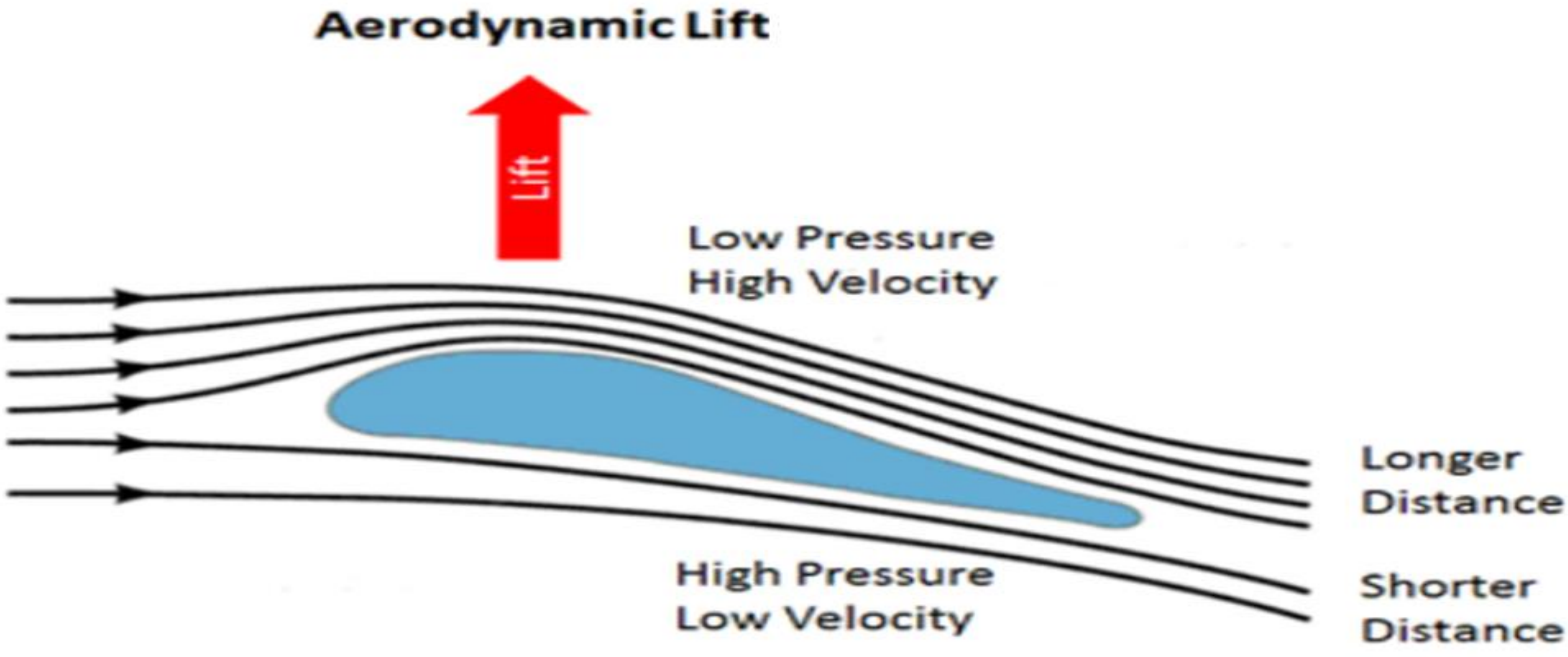
Practical turbines do not exhibit this behaviour, & transition is smoother .



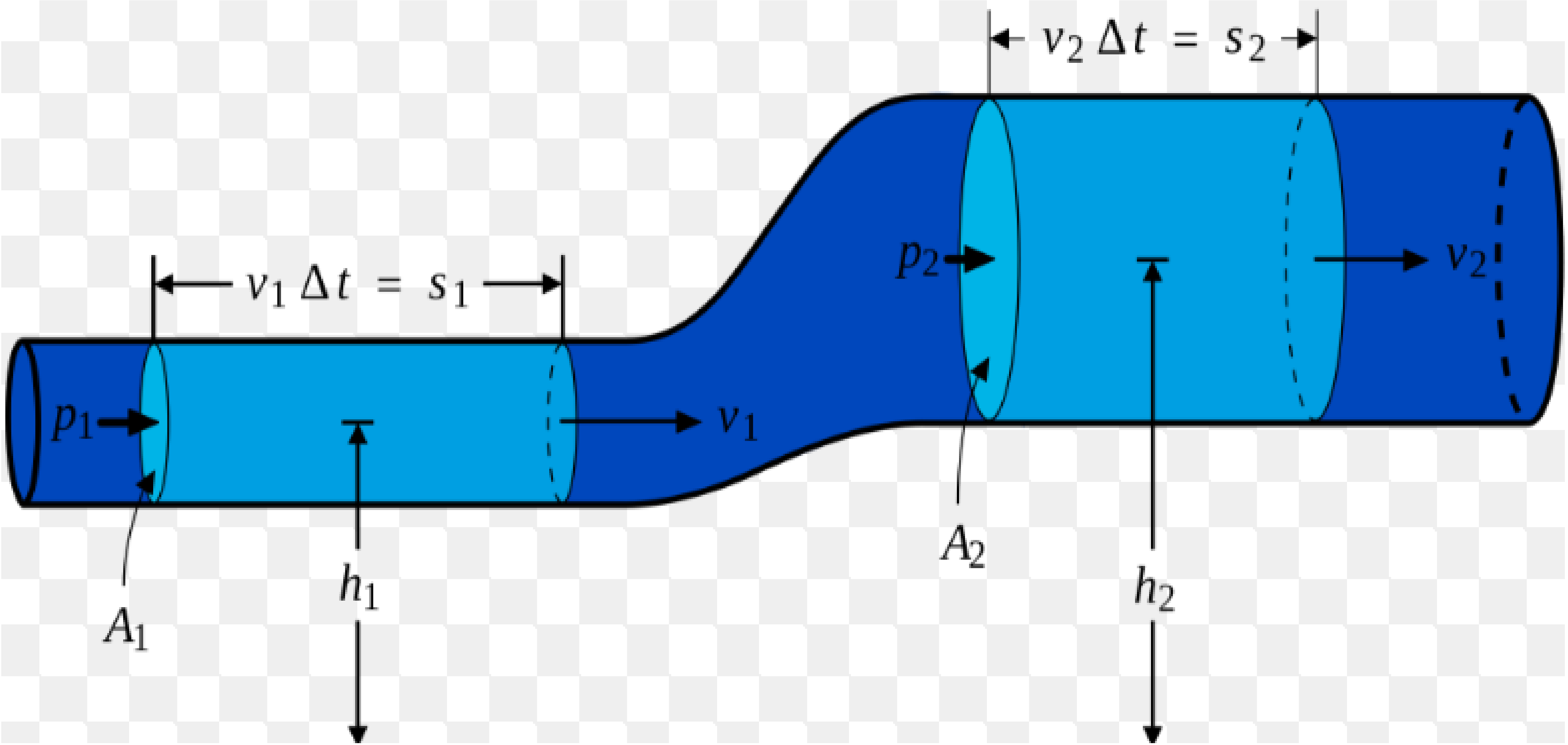
2.3.2 Aerodynamic Power Control: Passive Stall, Active Stall & Pitch Control



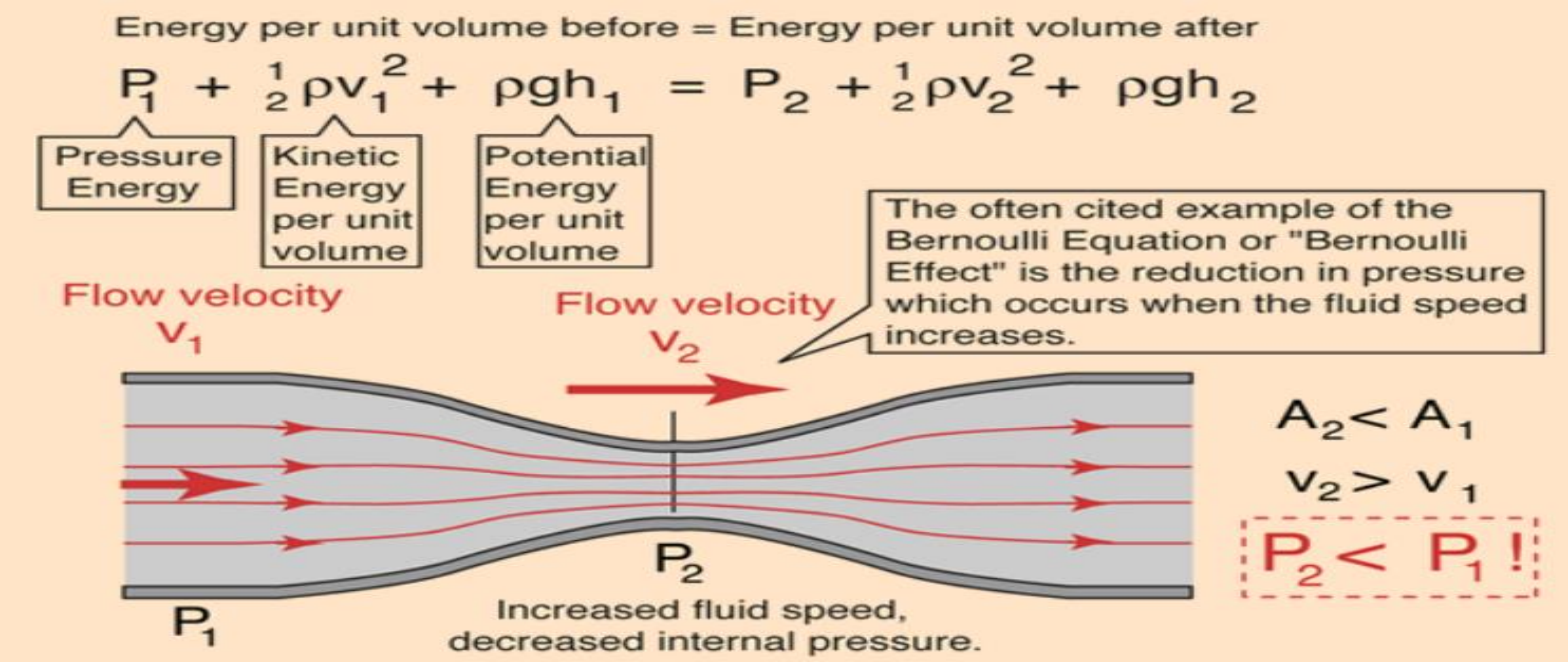
How wing/blade is pushed(lift) up-ward?



What is Bernoulli's principle?



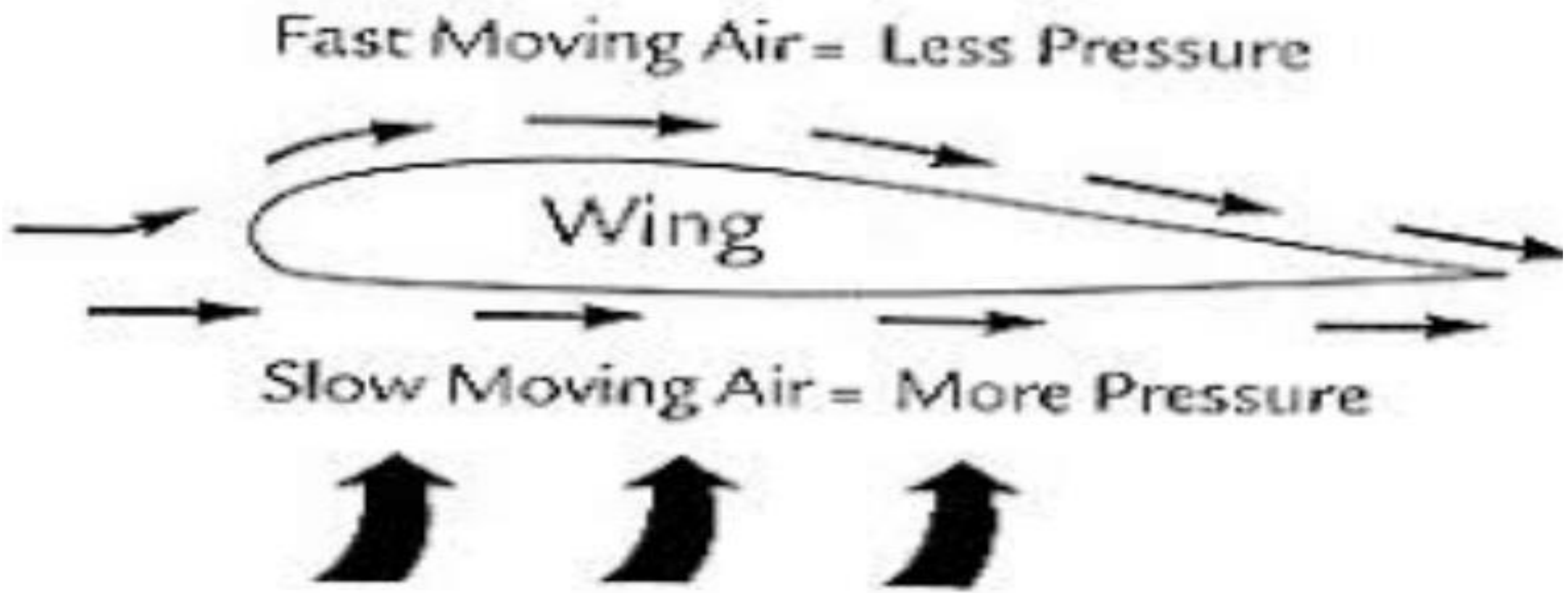
Bernoulli's principle: **"As speed of a moving fluid (liquid or gas) increases, pressure within fluid decreases".**



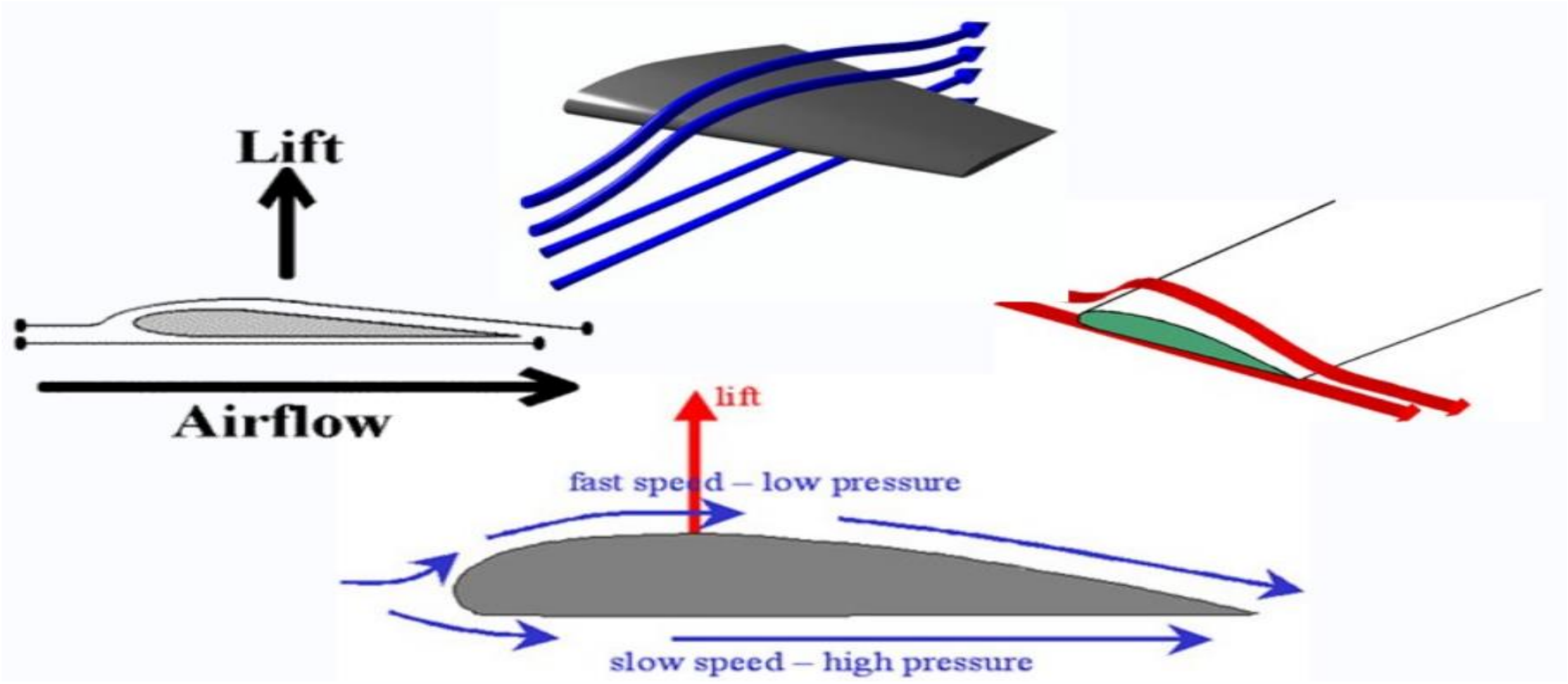
The top of the wing is?

The top of the wing is curved

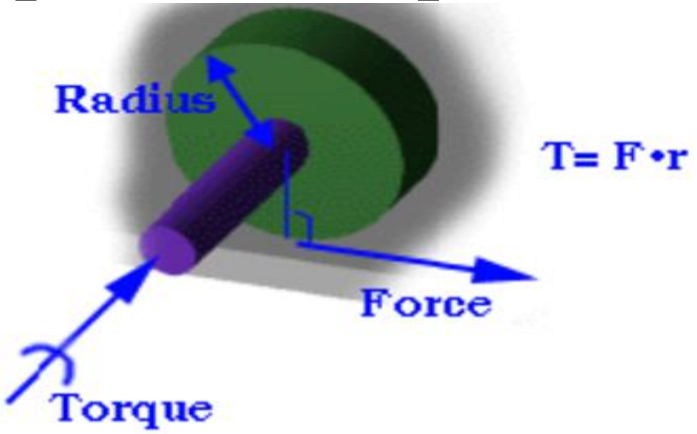
The top of the wing is curved

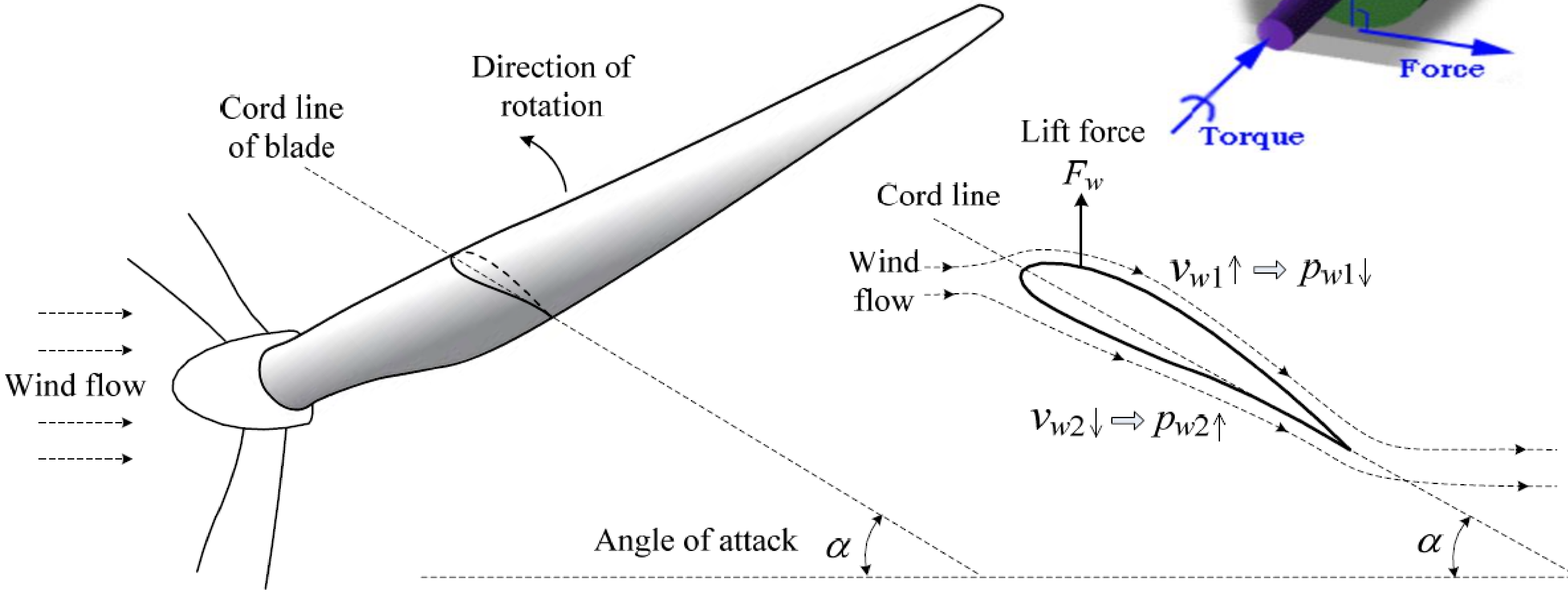


Air moves quickly over the curved blade with low Pressure. On lower part of blade, wind speed is slow with high pressure. Hence wing is pushed(lift) up-ward.

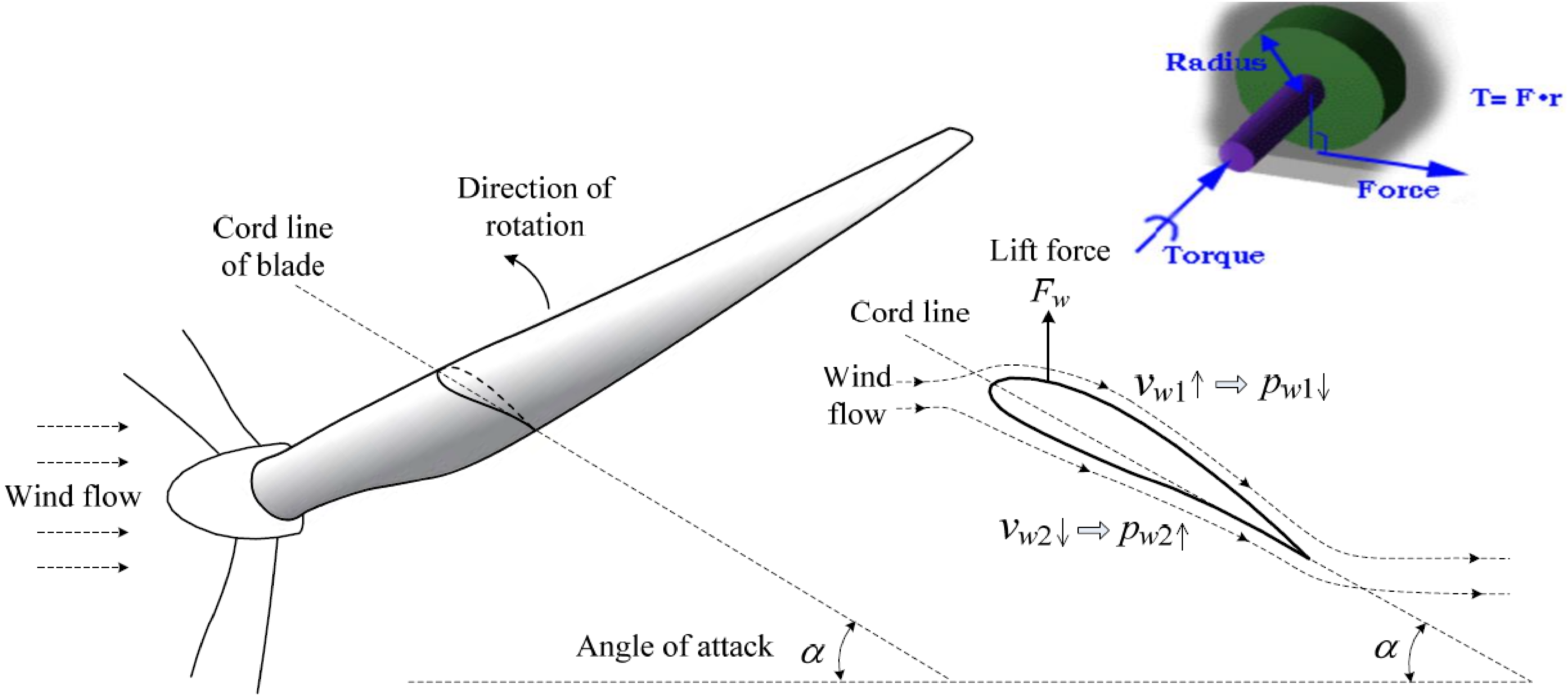


Angle of attack of blade (α)is responsible for force & torque. Thus it controls amount of captured power.

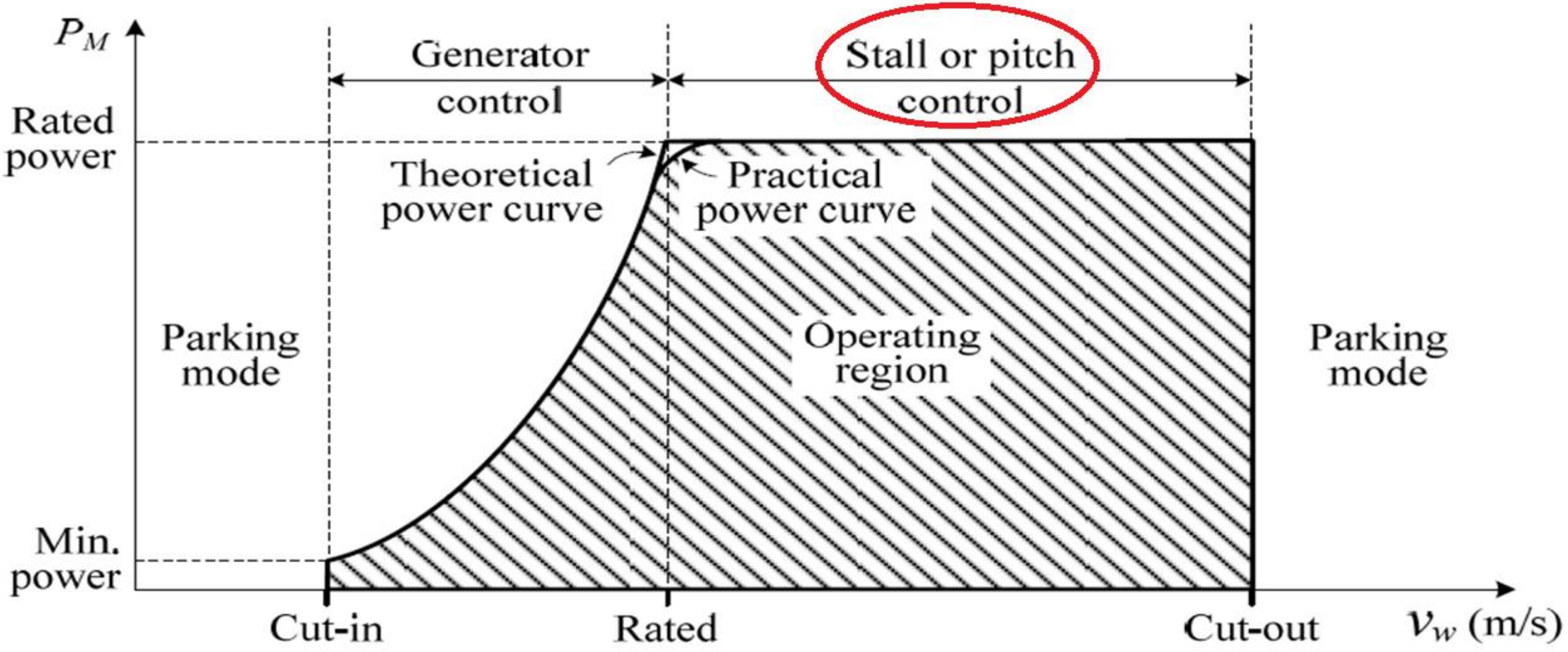




When α=0, no lift force or torque will be produced

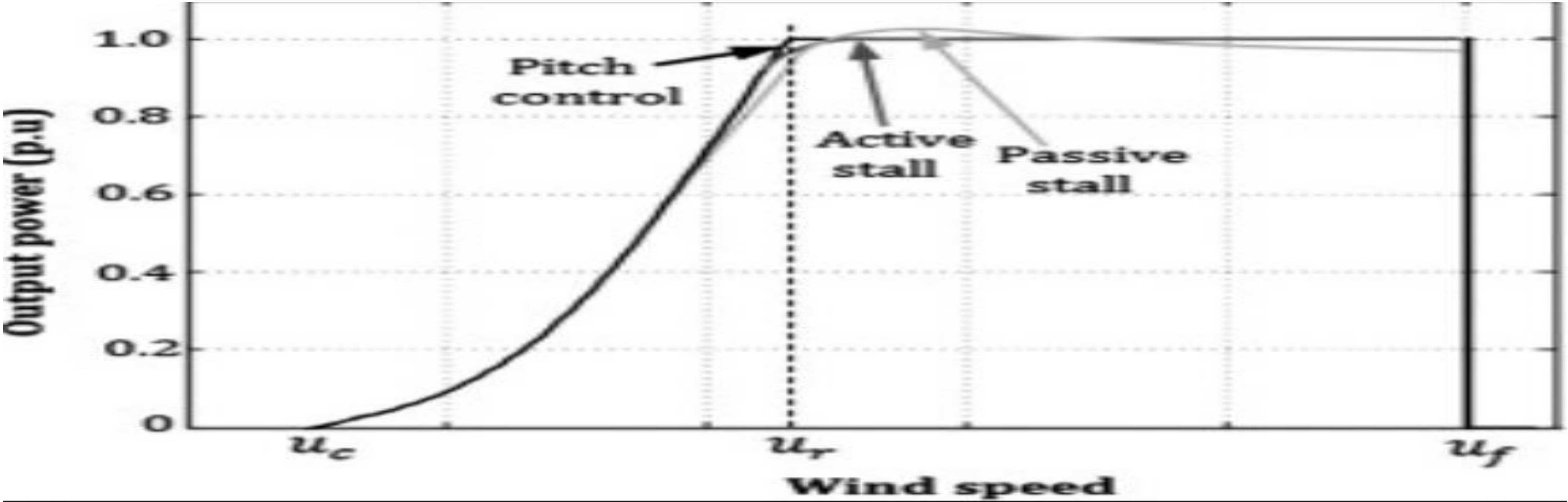


There are 3 aerodynamic methods to control captured power for large wind turbines

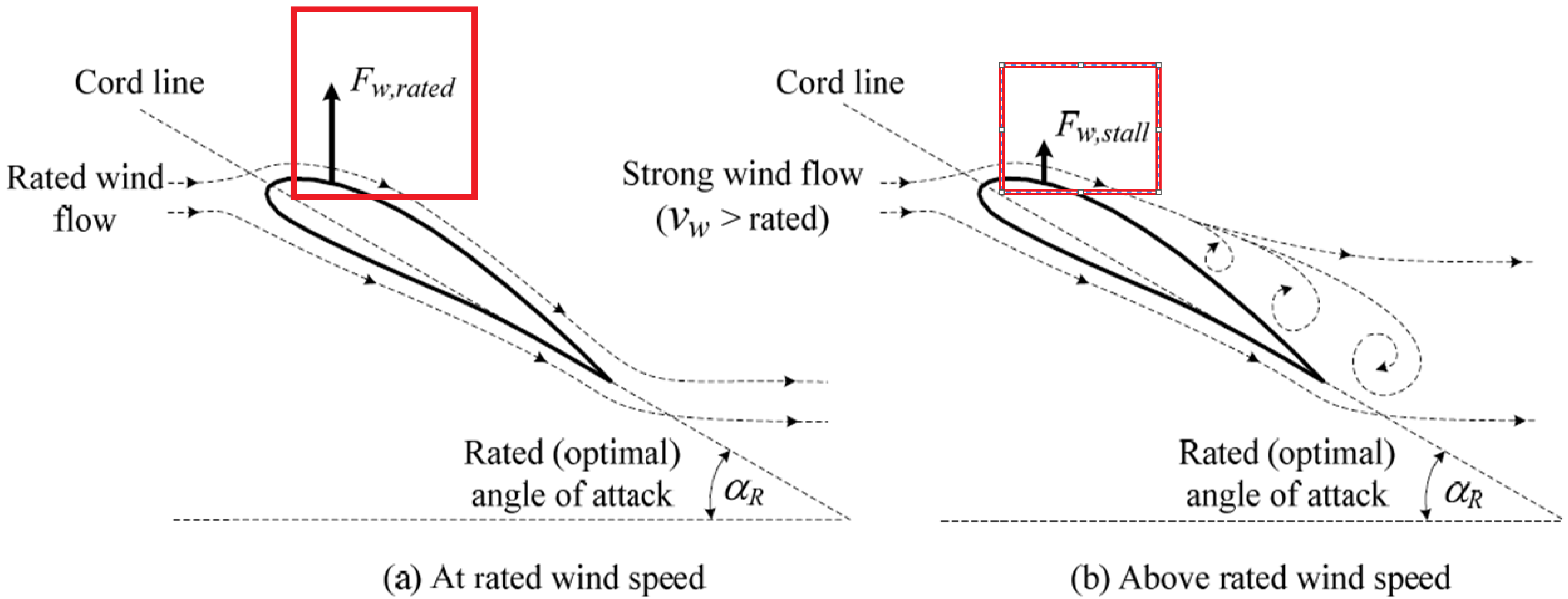


Passive-stall Control

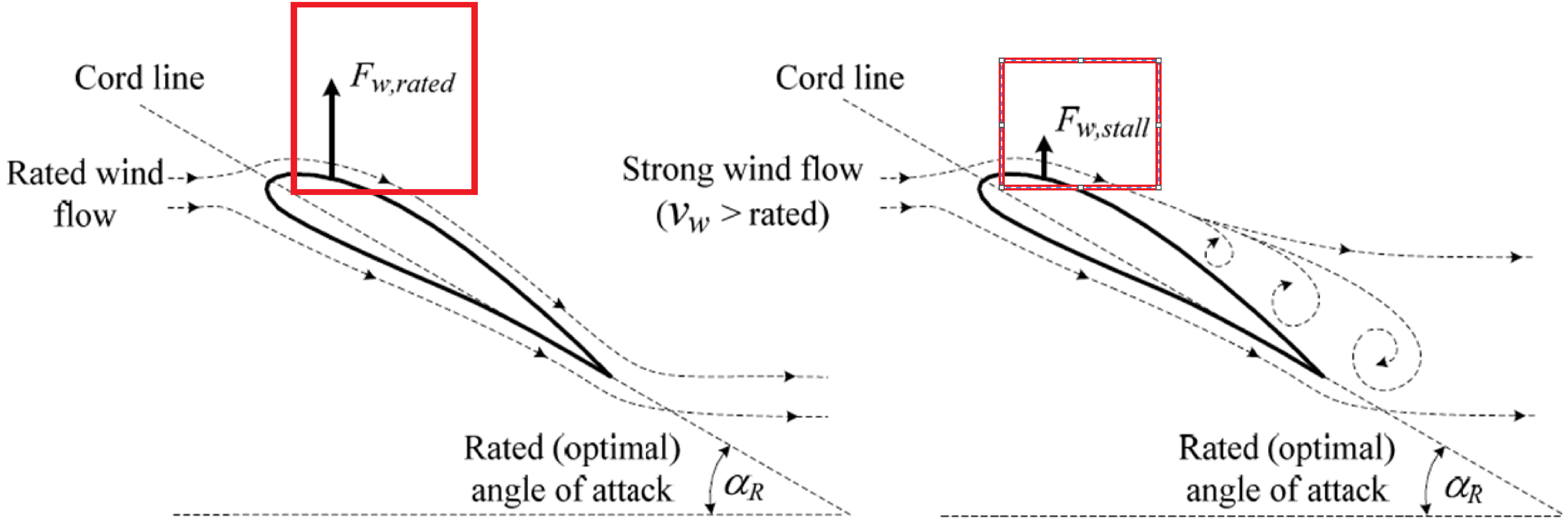
- In a passive-stall controlled wind turbines, blade is fixed onto rotor hub at an optimal (rated) angle of attack.



Operating principle of passive-stall control



Lift force produced by higher wind, (called stall lifting force $F_{w,stall}$) < rated force $F_{w,rated}$.

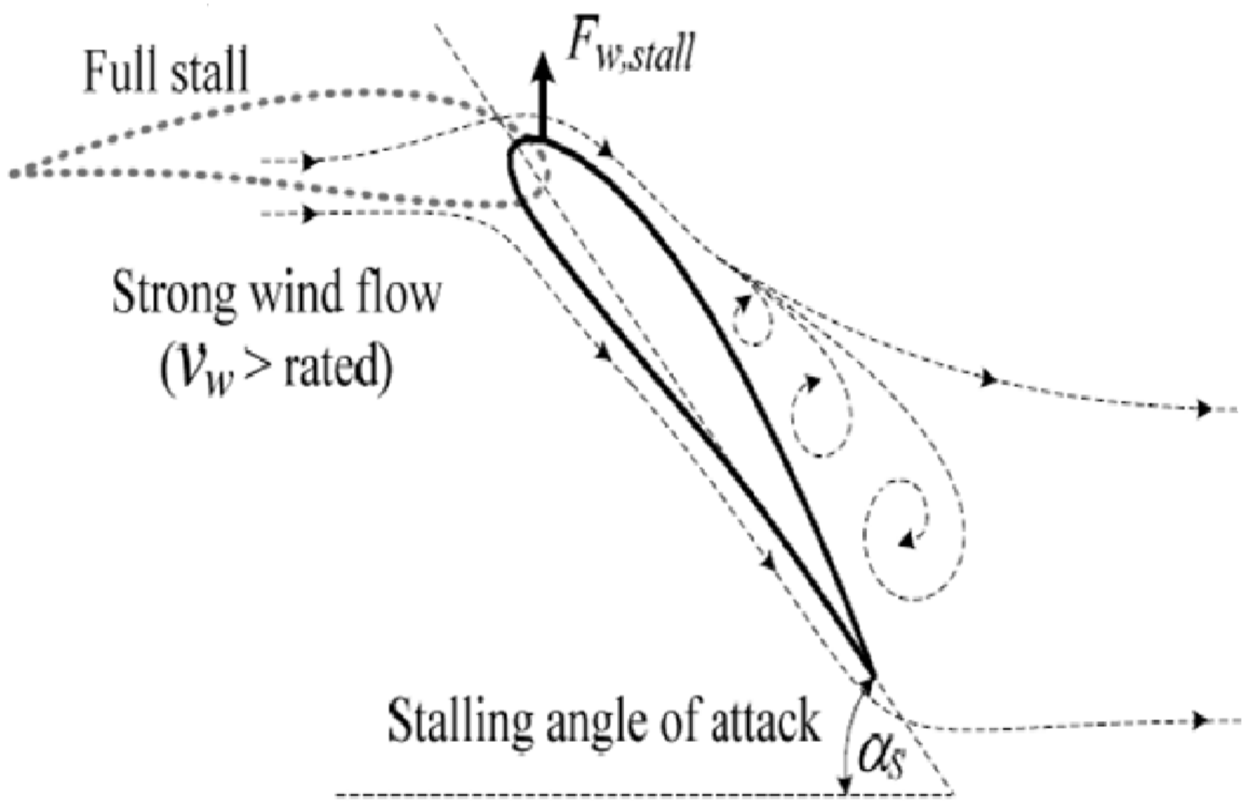


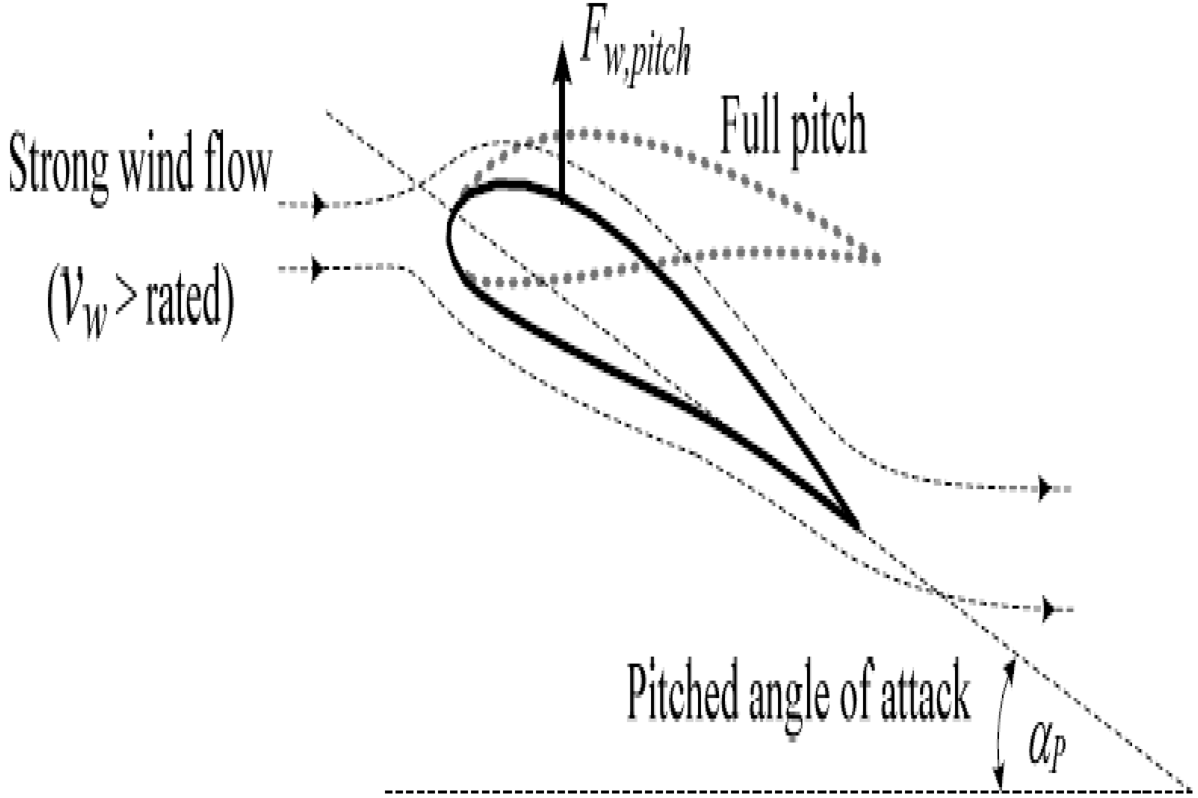
(a) At rated wind speed (b) Above rated wind speed

Both pitch & active-stall controls are based on rotating actions on blade

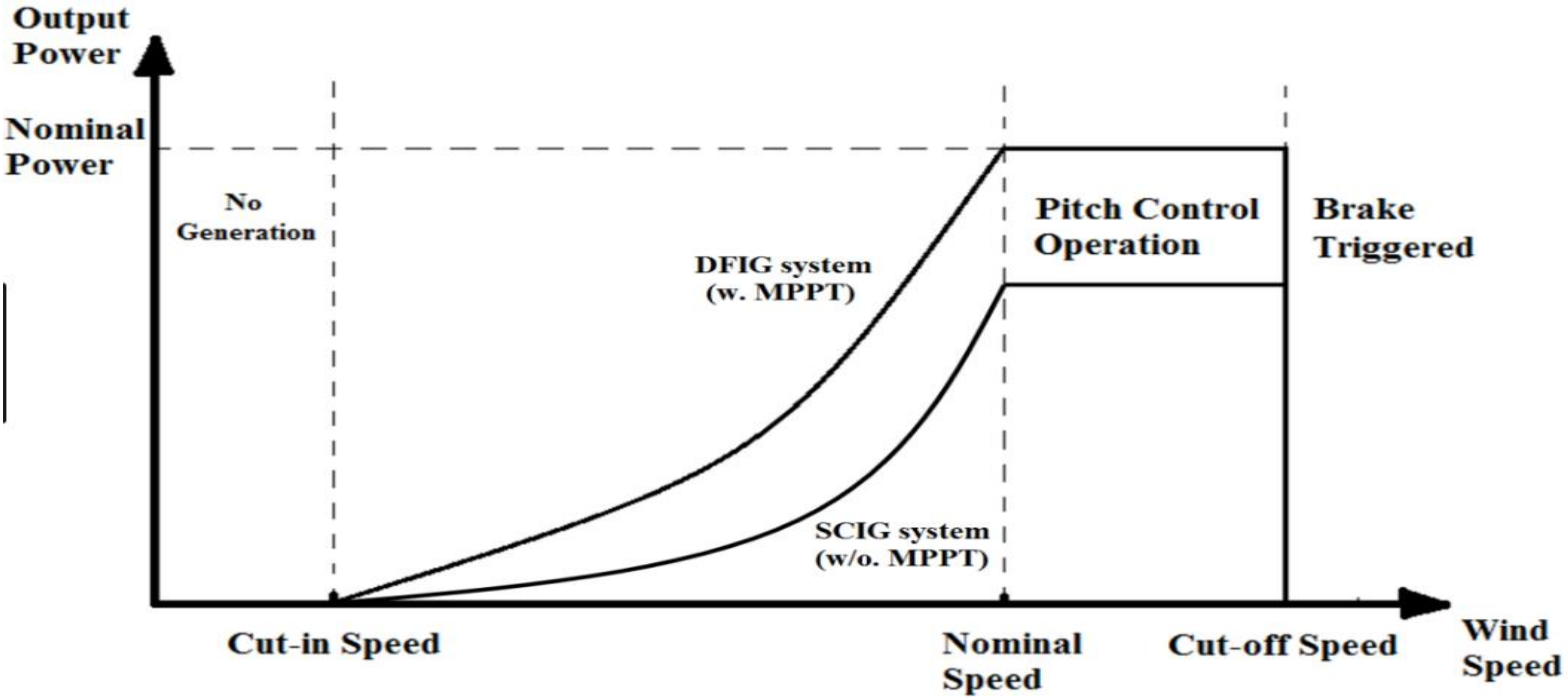
Active-stall control turns blades into wind causing turbulences to reduce lift force.

Pitch control turns blade out of wind leading to a reduction in lift force

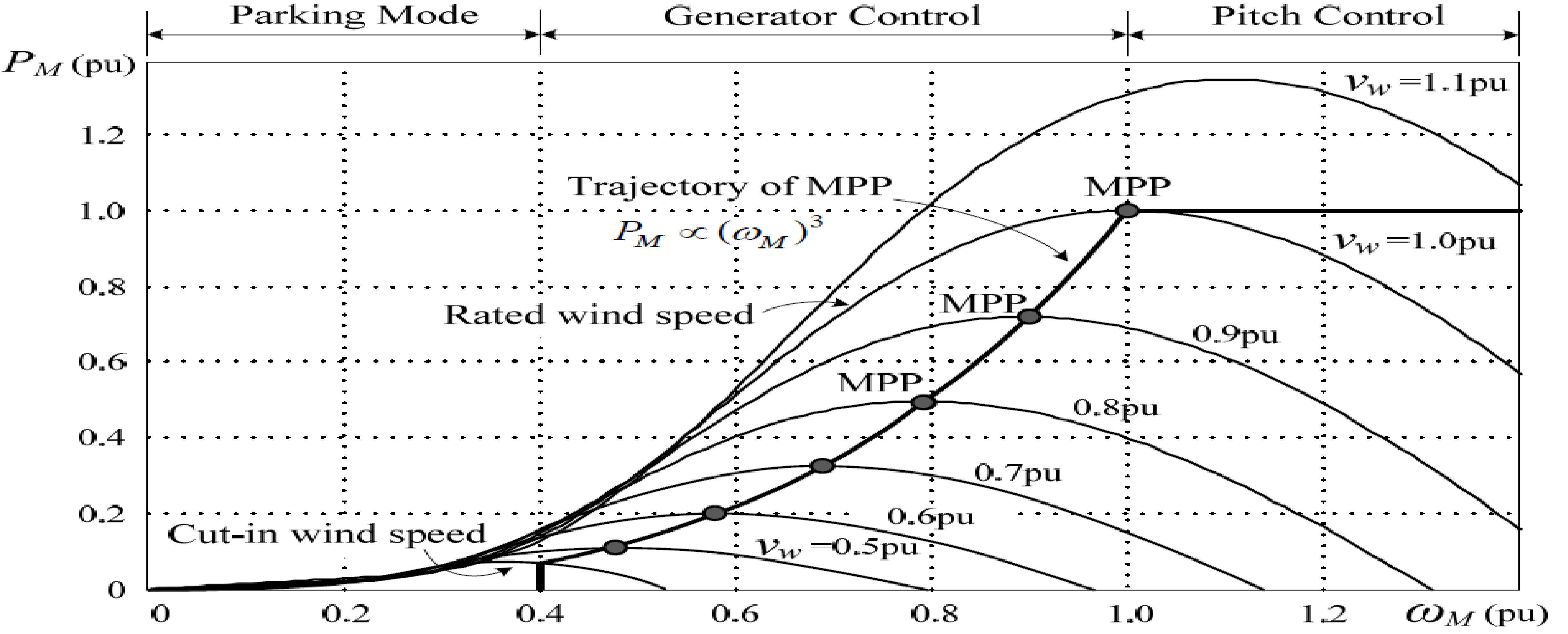




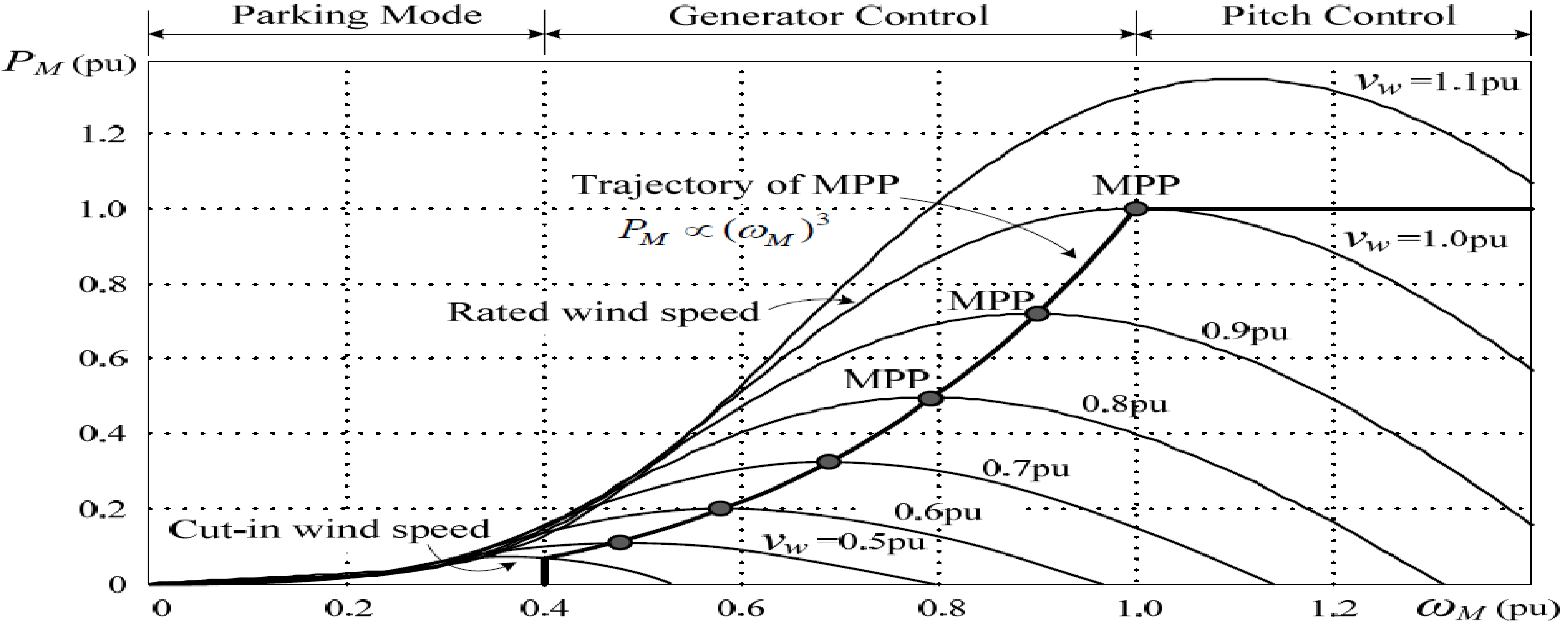
2.4 Maximum Power Point Tracking (MPPT) Control



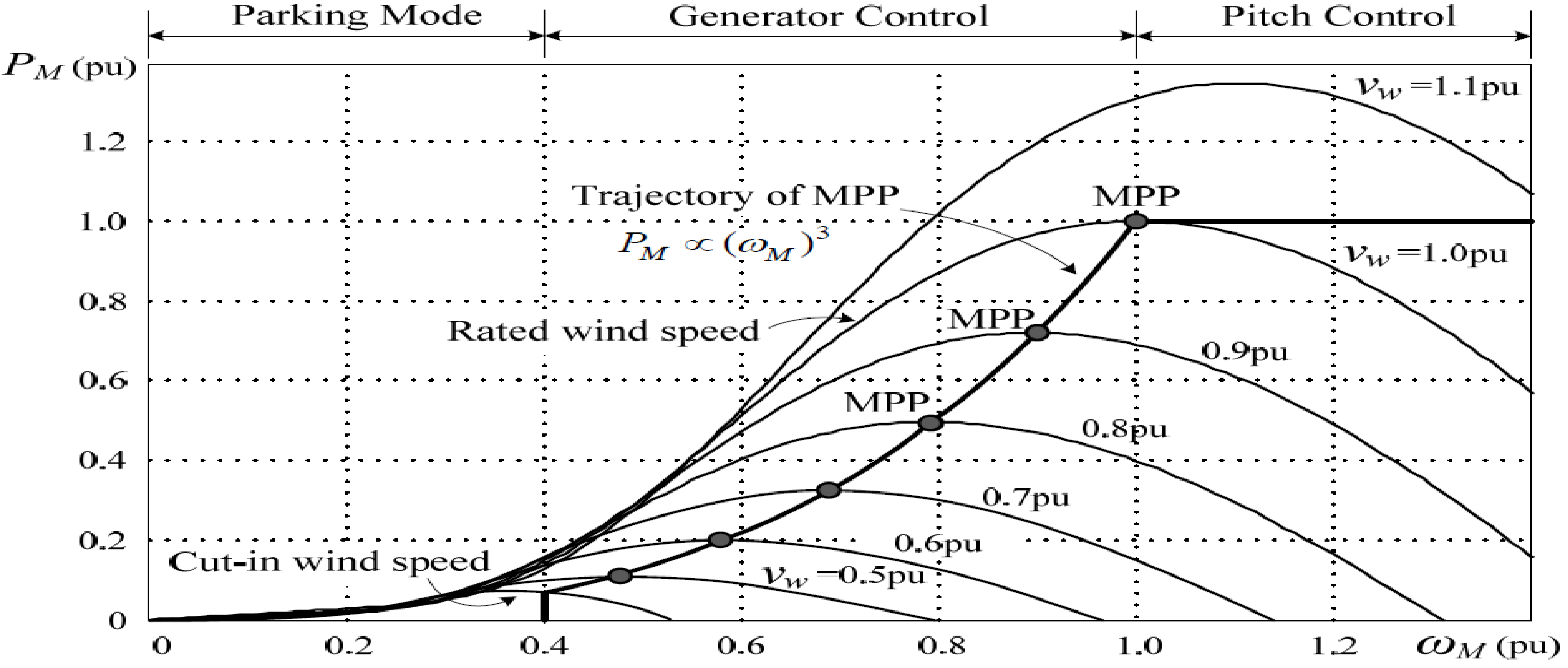
Control of a variable-speed wind turbine **below rated wind speed** is achieved by controlling generator.



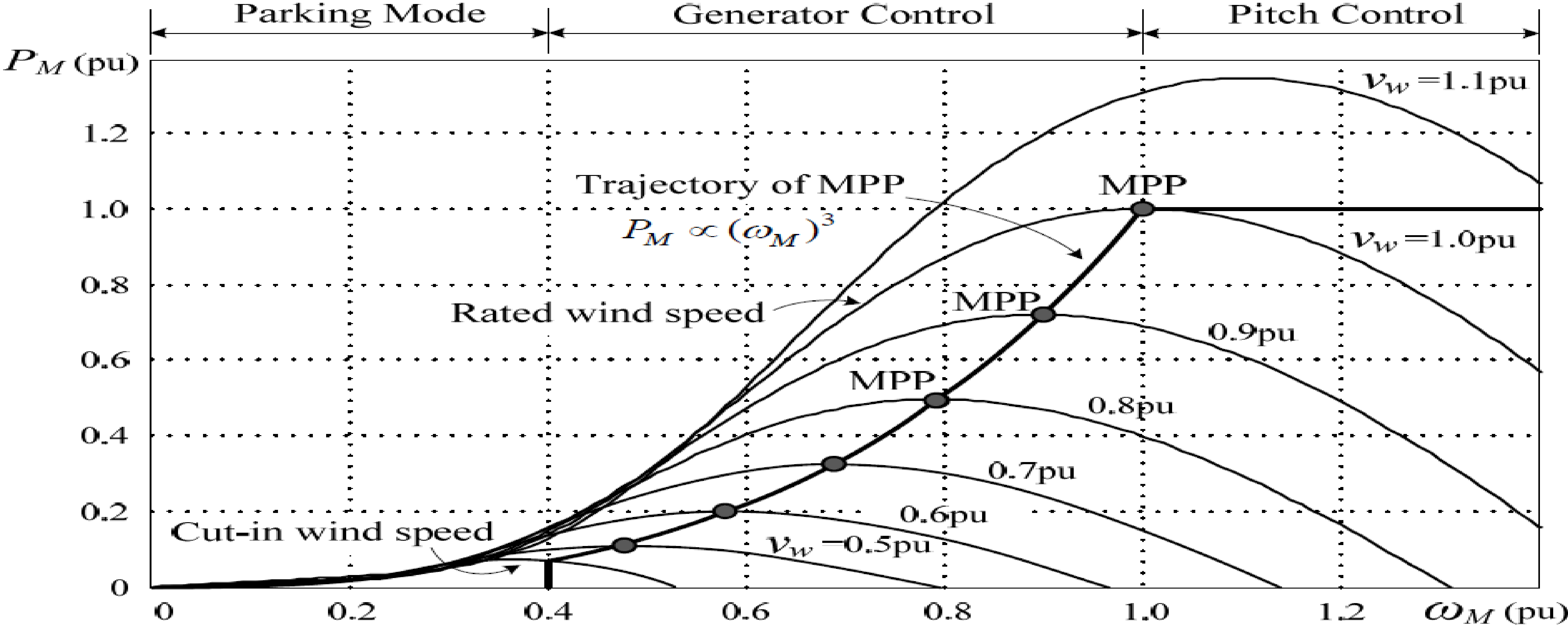
Main goal is to maximize wind power captured at different wind speeds, which can achieved by adjusting turbine speed in such a way that optimal tip speed ratio λ_{Topt} is maintained.



P_M versus ω_M curves are obtained with blade angle of attack set to its optimal value.



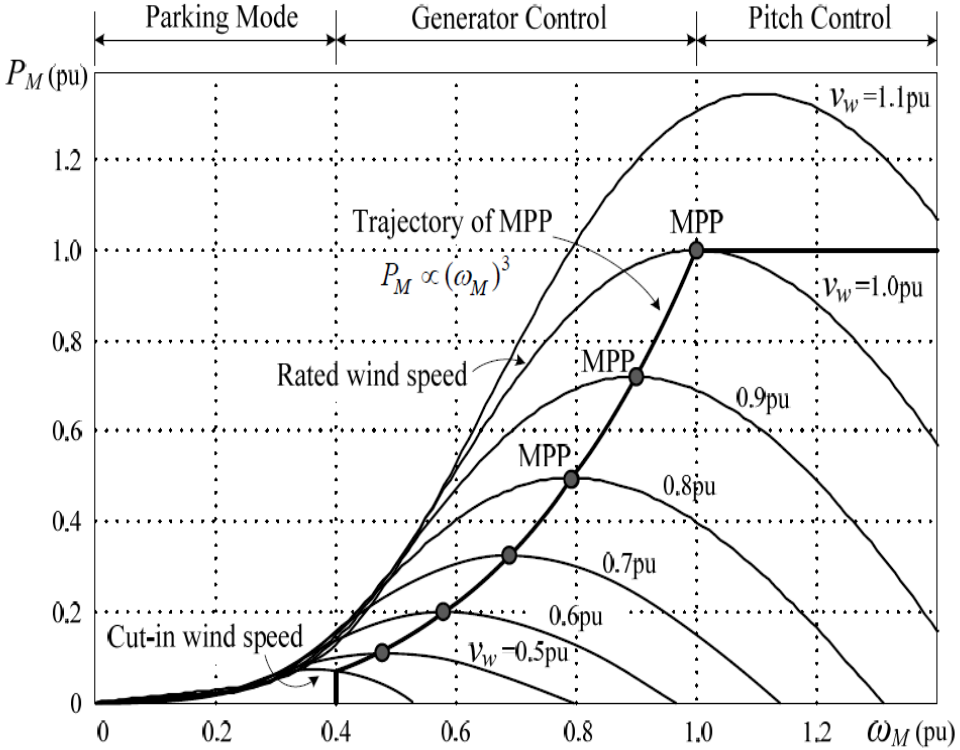
Wind turbine power-speed characteristics & maximum power point (MPP) operation.



For a given wind speed, each power curve has a maximum power point (MPP), at which the optimal tip speed ratio λ_{Topt} is achieved.

- To obtain maximum available power from wind at different wind speeds, turbine speed must adjusted to ensure its operation at all MPPs.
- Trajectory of MPPs represents a power curve, which can be described by:

$$P_M \propto \omega_M^3$$



Mechanical power captured by turbine can also be expressed in terms of the torque: $P_M = T_M \omega_M$

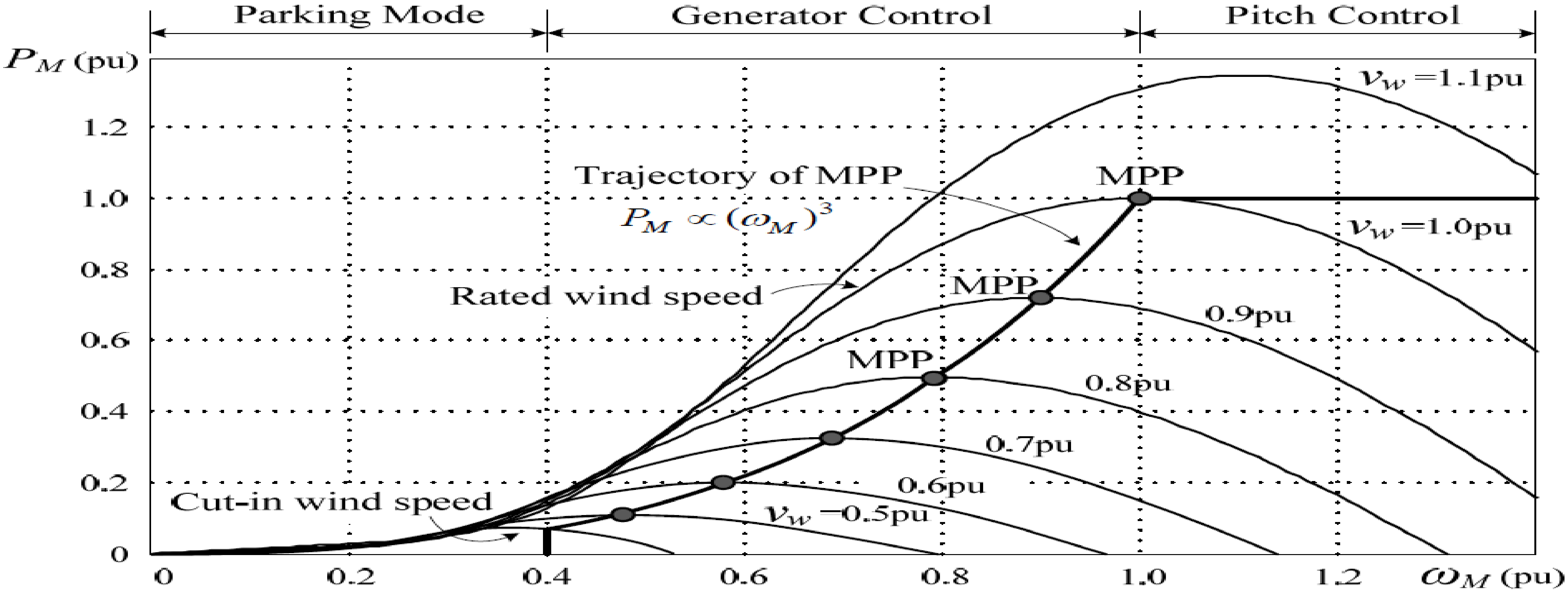
- where T_M is turbine mechanical torque.

By Substituting above equation into $P_M \propto \omega_M^3$

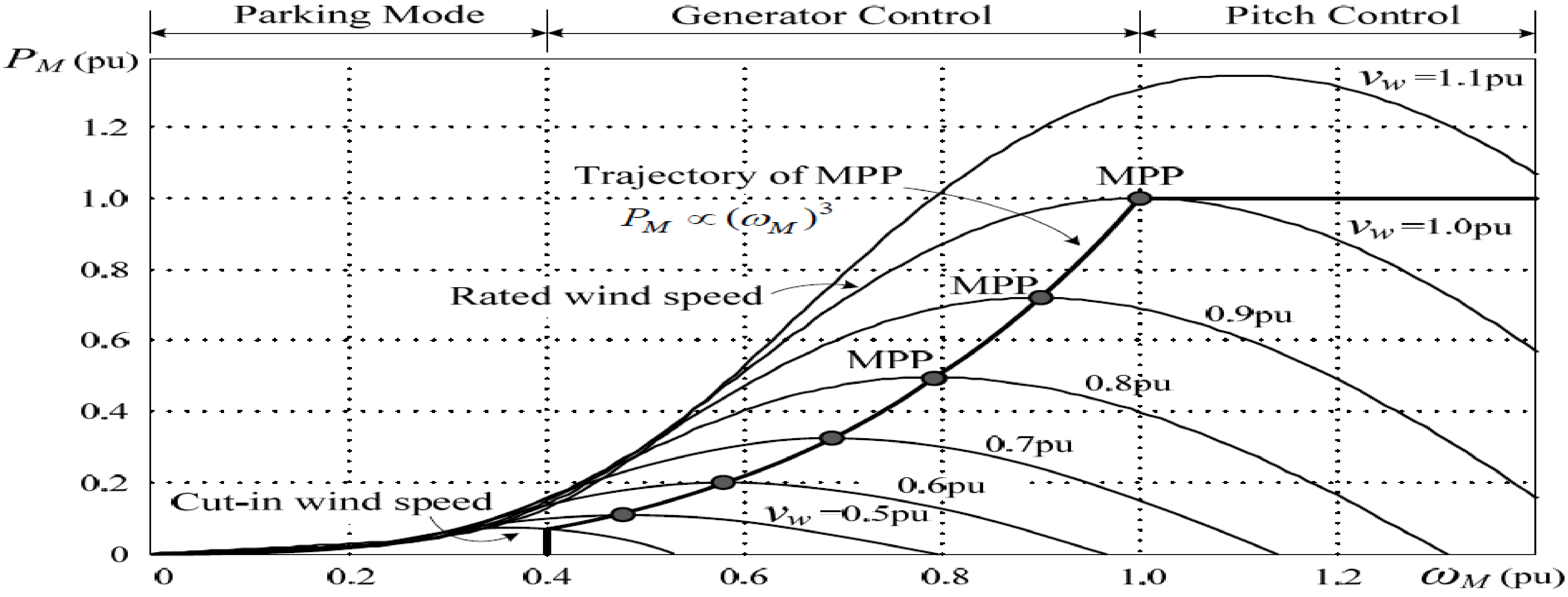
$$T_M \propto \omega_M^2$$

i.e turbine mechanical torque T_M is a quadratic function of turbine speed ω_M.

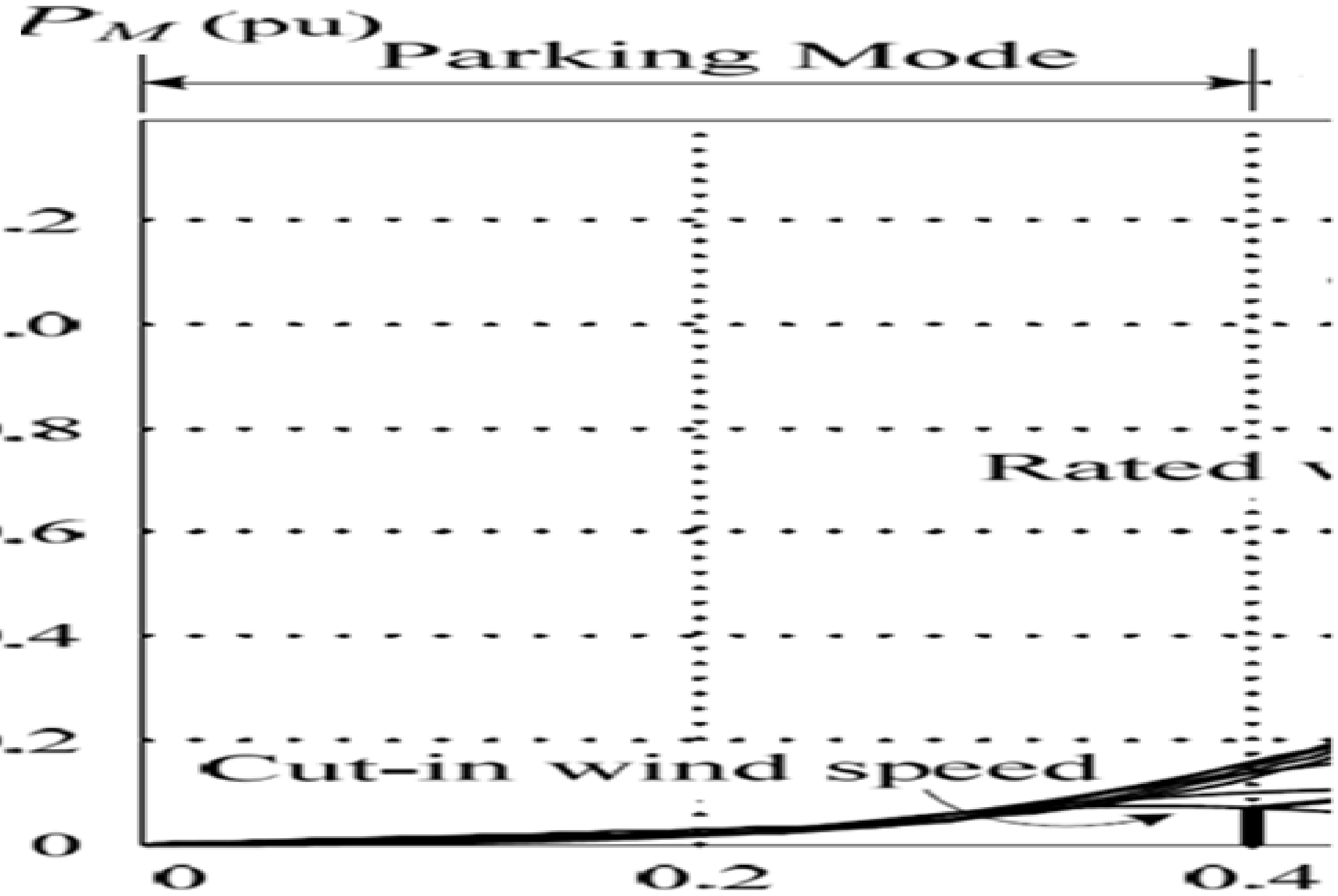
Relations between mechanical power, speed, & torque of a wind turbine can be used to determine optimal speed or torque reference to control generator & achieve MPP operation.



Operation of wind turbine can be divided into 3 modes: 1.parking mode, 2.generator control mode 3.pitch control mode.

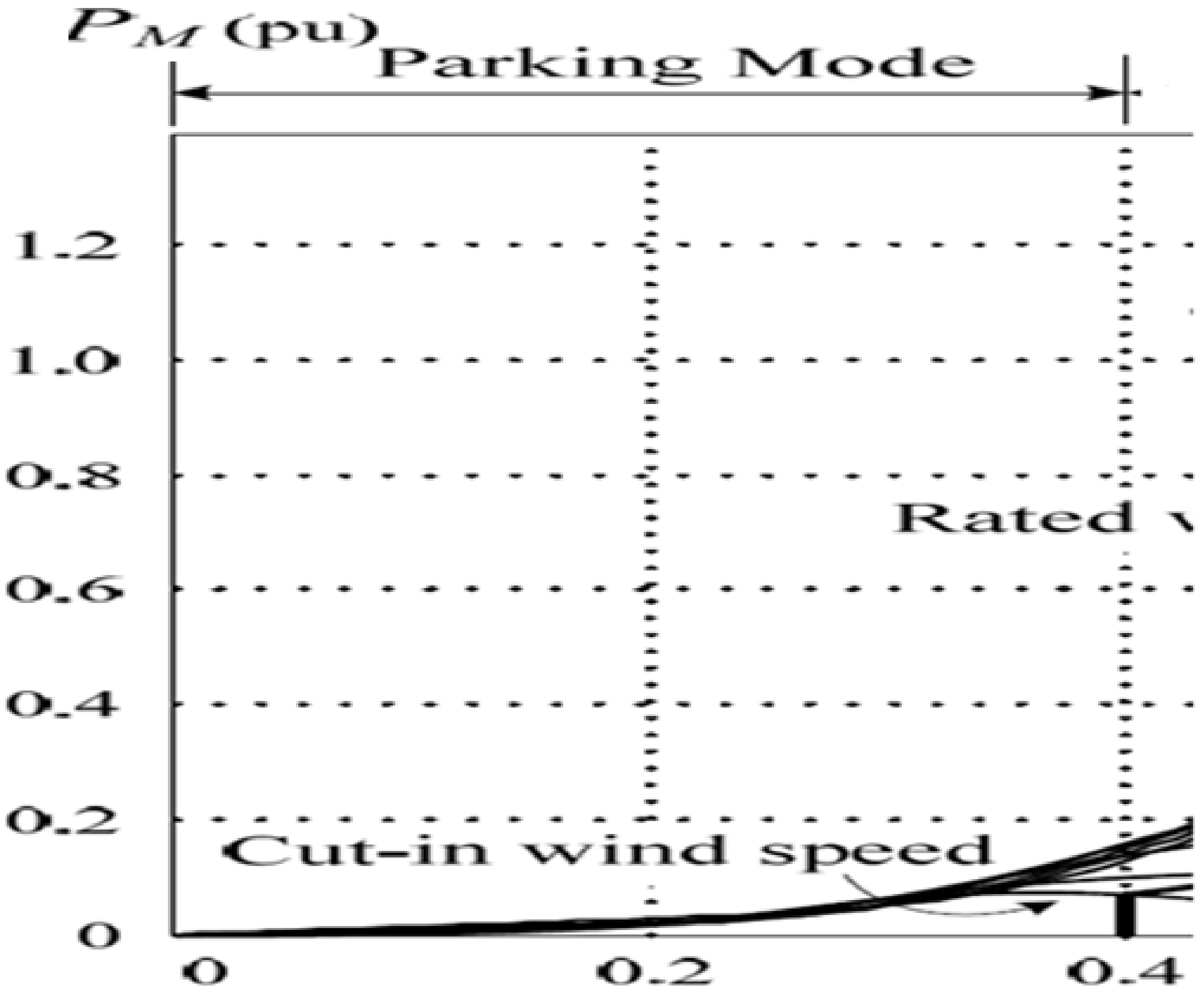


Parking mode.

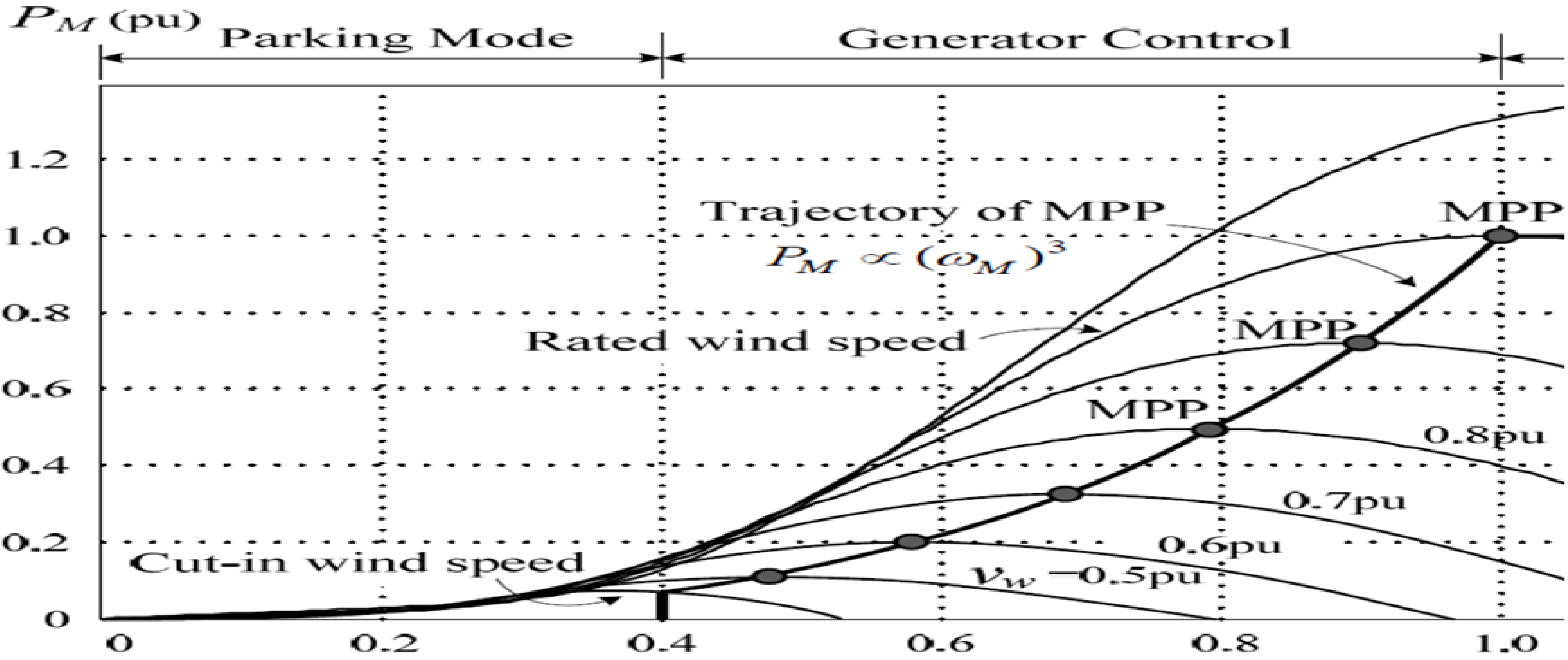


When wind speed is below cut-in speed, turbine system generates less power than its internal consumption,

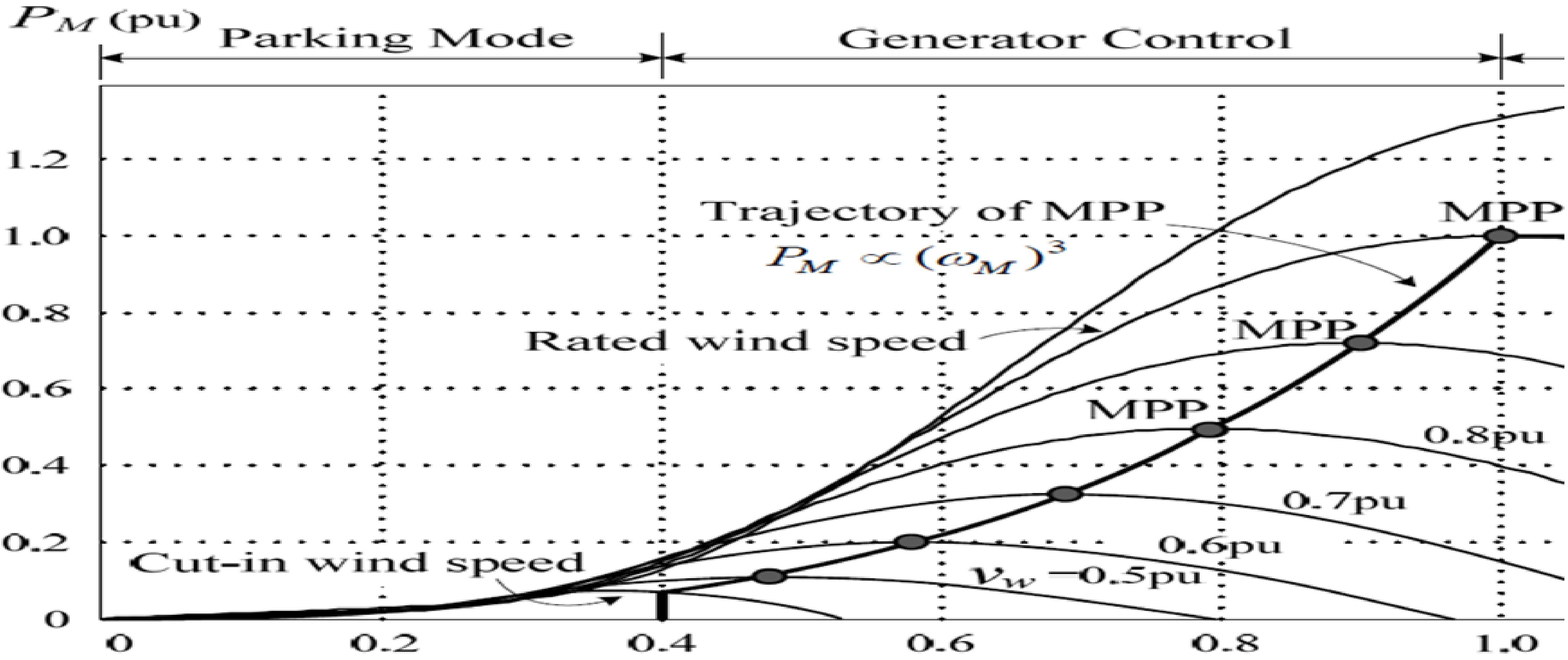
- Therefore turbine is kept in parking mode.
- Blades are completely pitched out of wind, & mechanical brake is on.



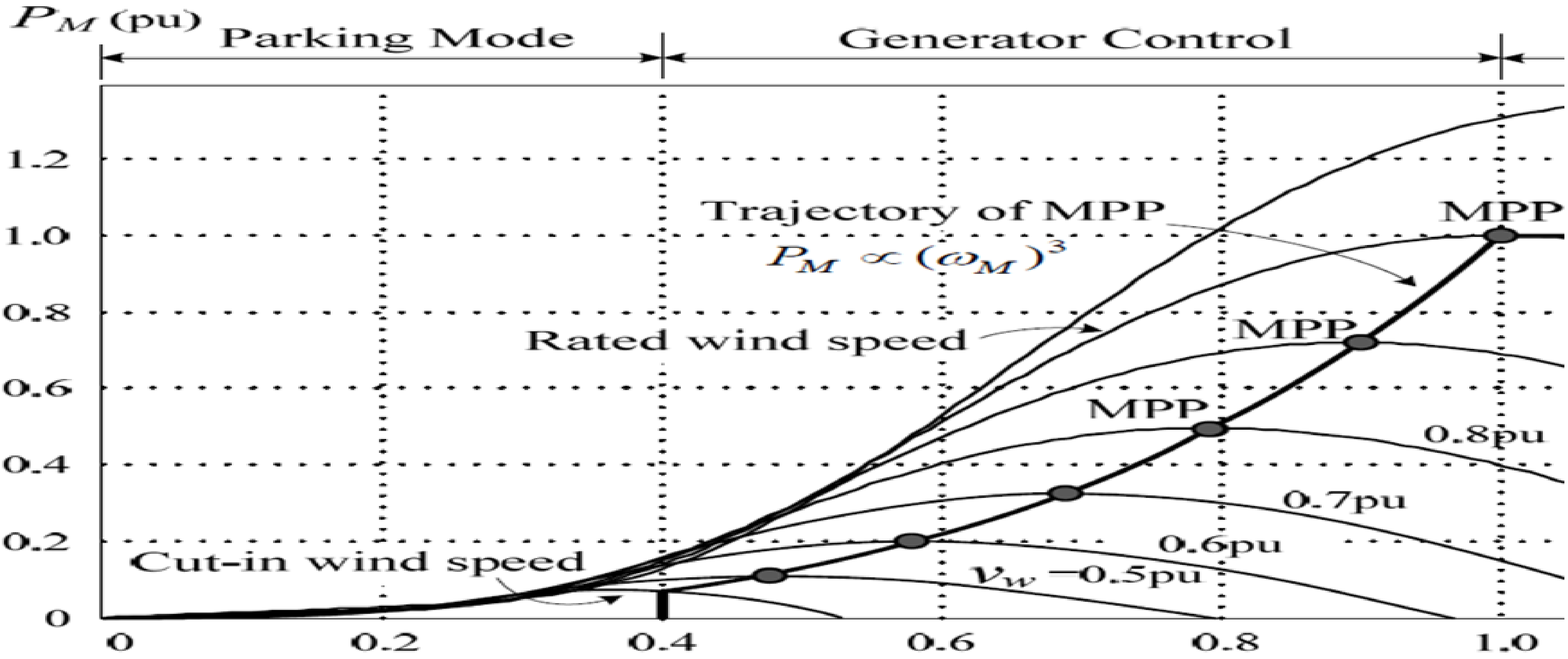
Generator control mode.



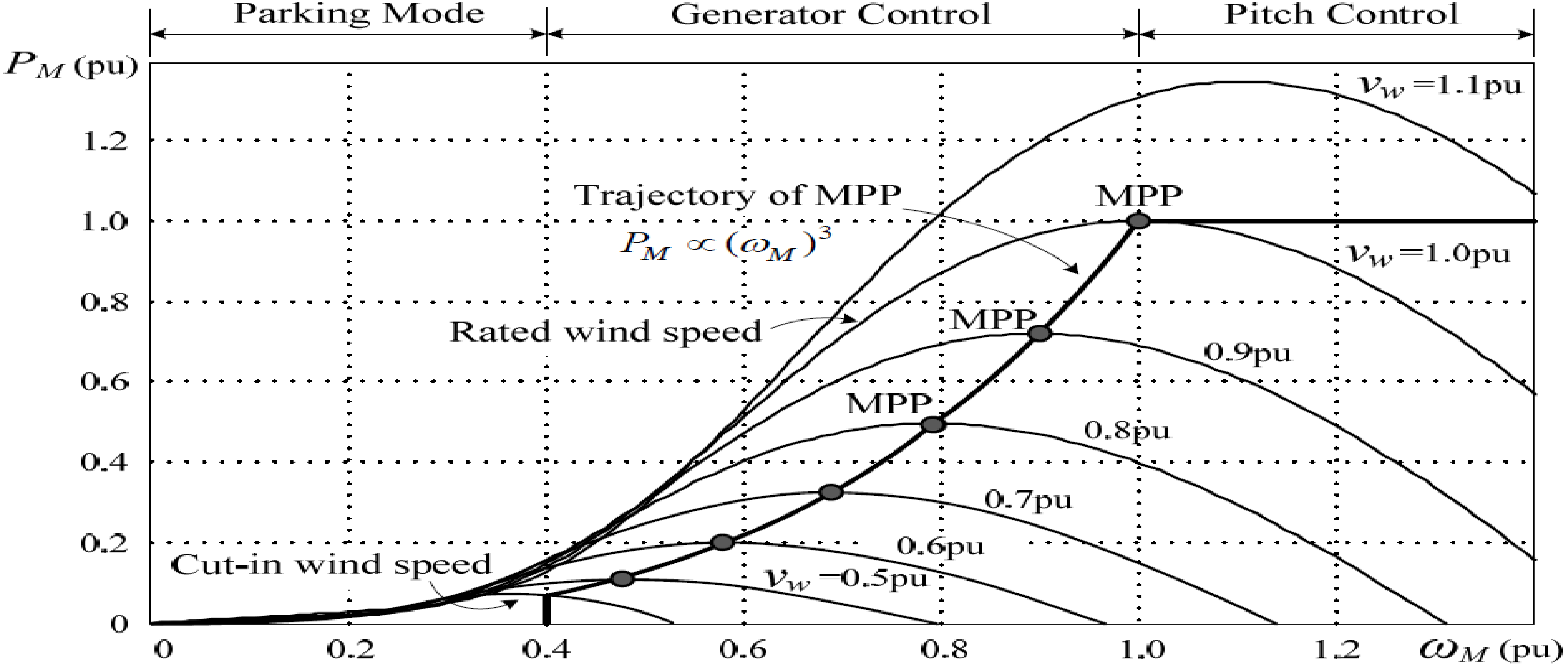
When wind speed is between cut-in & rated speed, blades are pitched into wind with its optimal angle of attack.



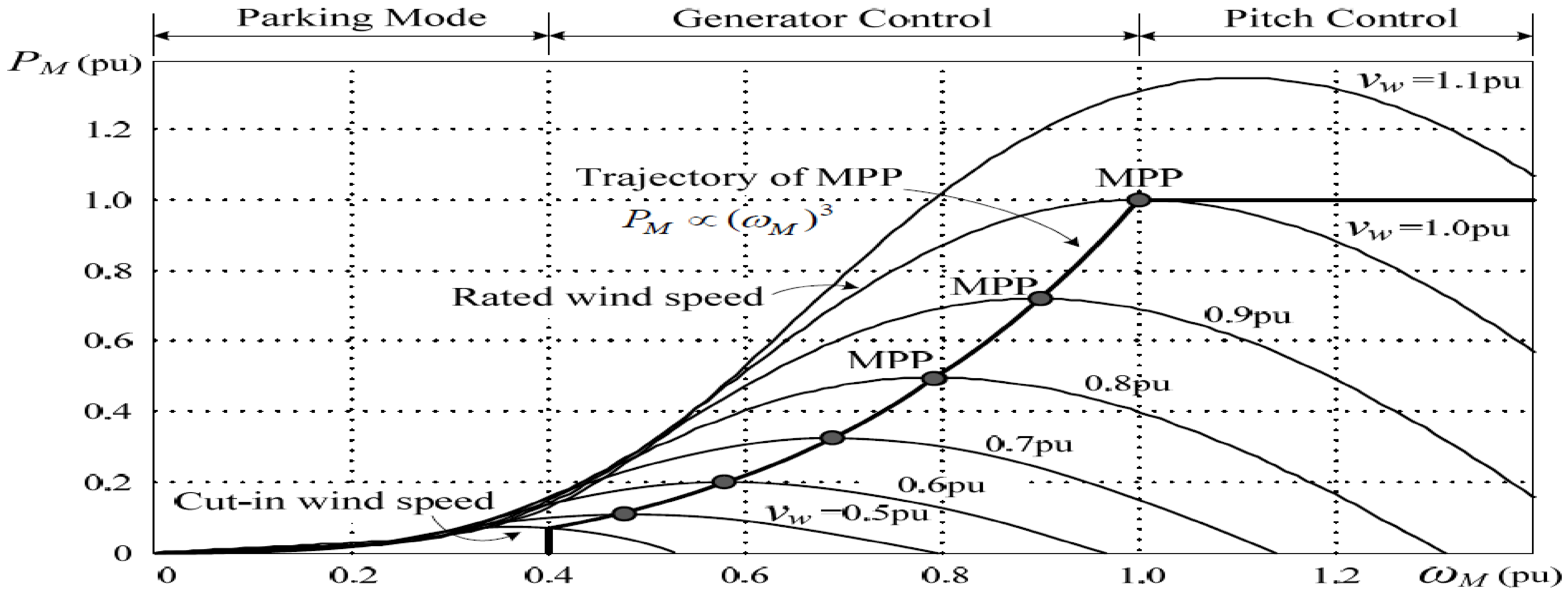
Turbine operates with variable rotational speeds in order to track MPP at different wind speeds. This is achieved by proper control of generator.



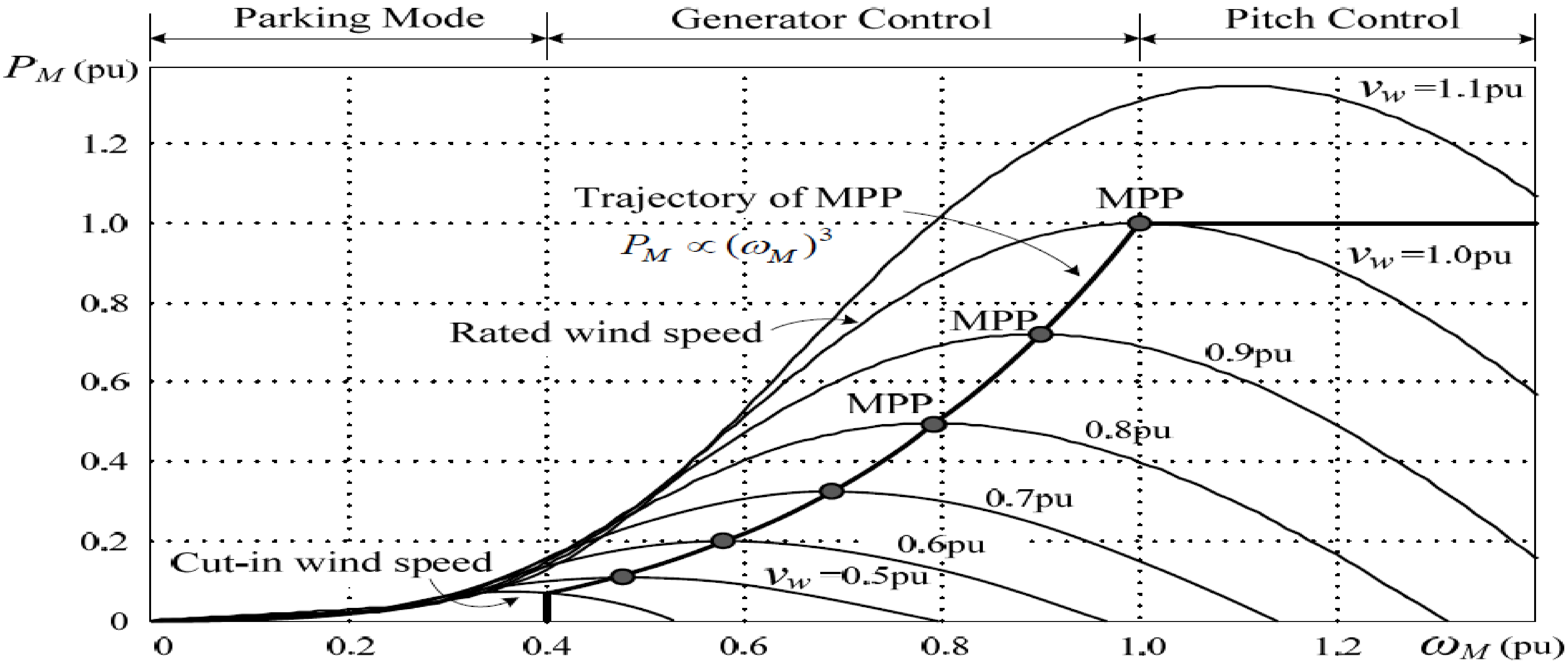
Pitch control mode



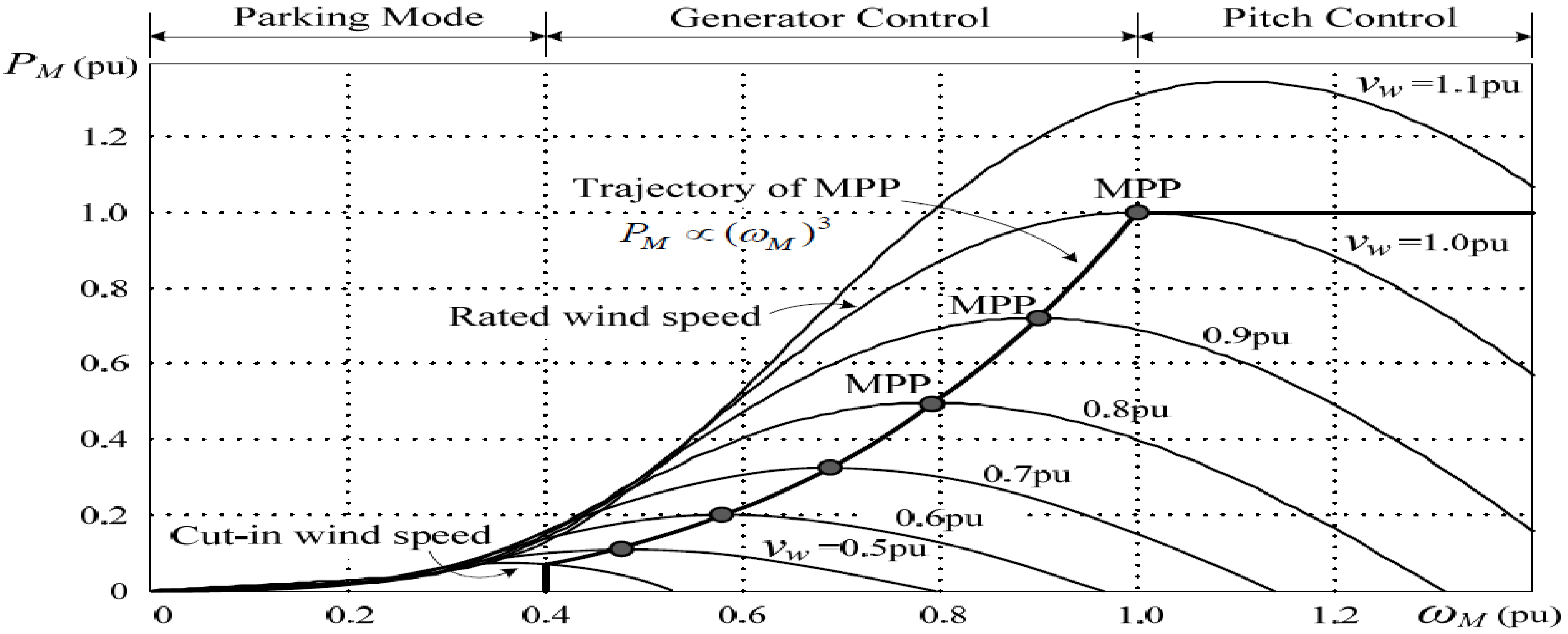
For higher than rated wind speeds but below cut-out limit, captured power is kept constant by pitch mechanism to protect turbine from damage while system generates & delivers rated power to grid.



When wind speed reaches or exceeds cut-out speed, blades are pitched completely out of wind

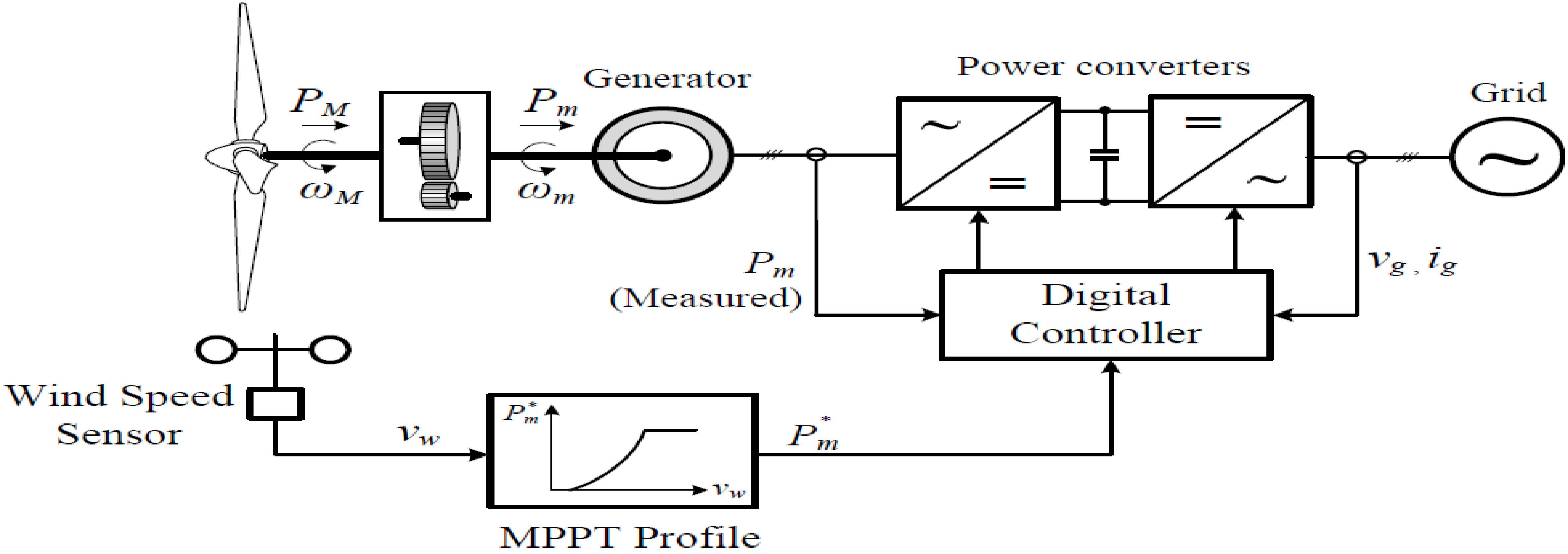


No power is captured, & turbine speed is reduced to 0. Turbine will be locked into parking mode to prevent damage from strong wind.

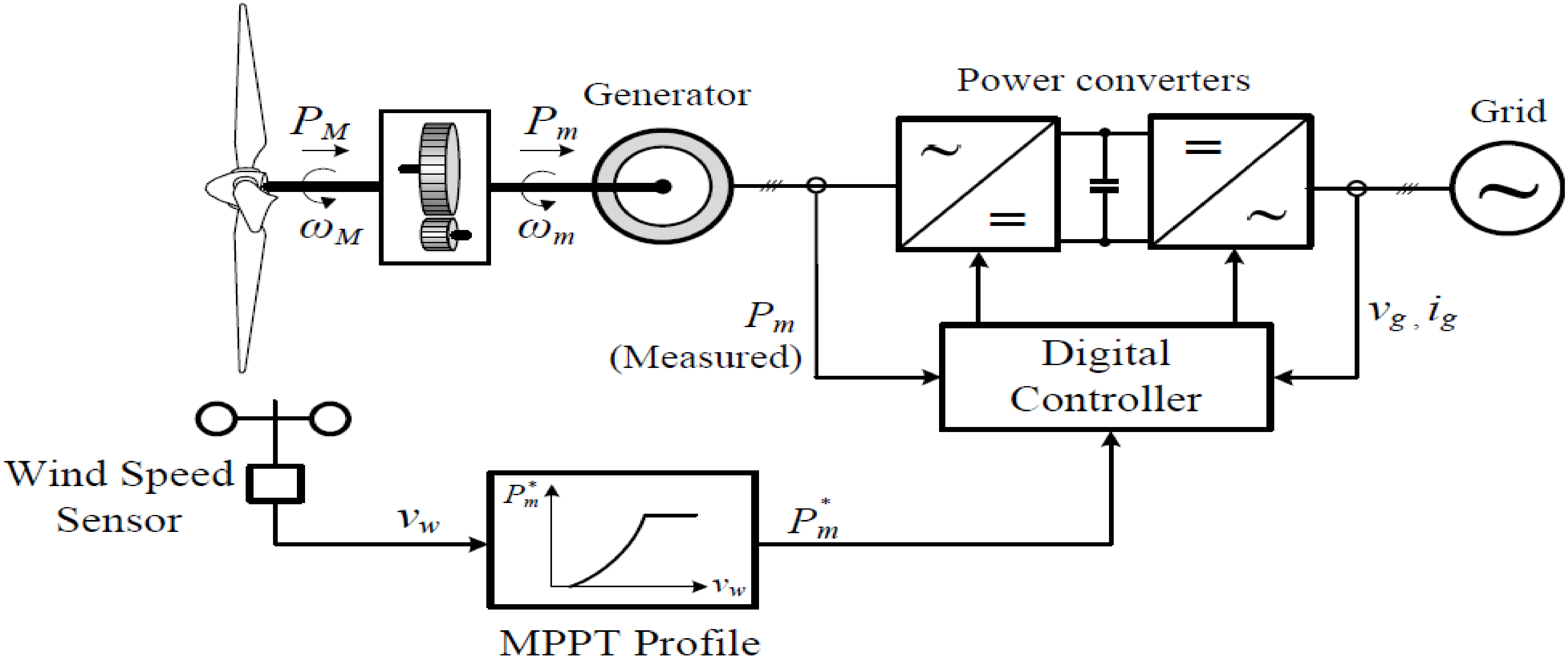


2.4.1 MPPT with Turbine Power Profile

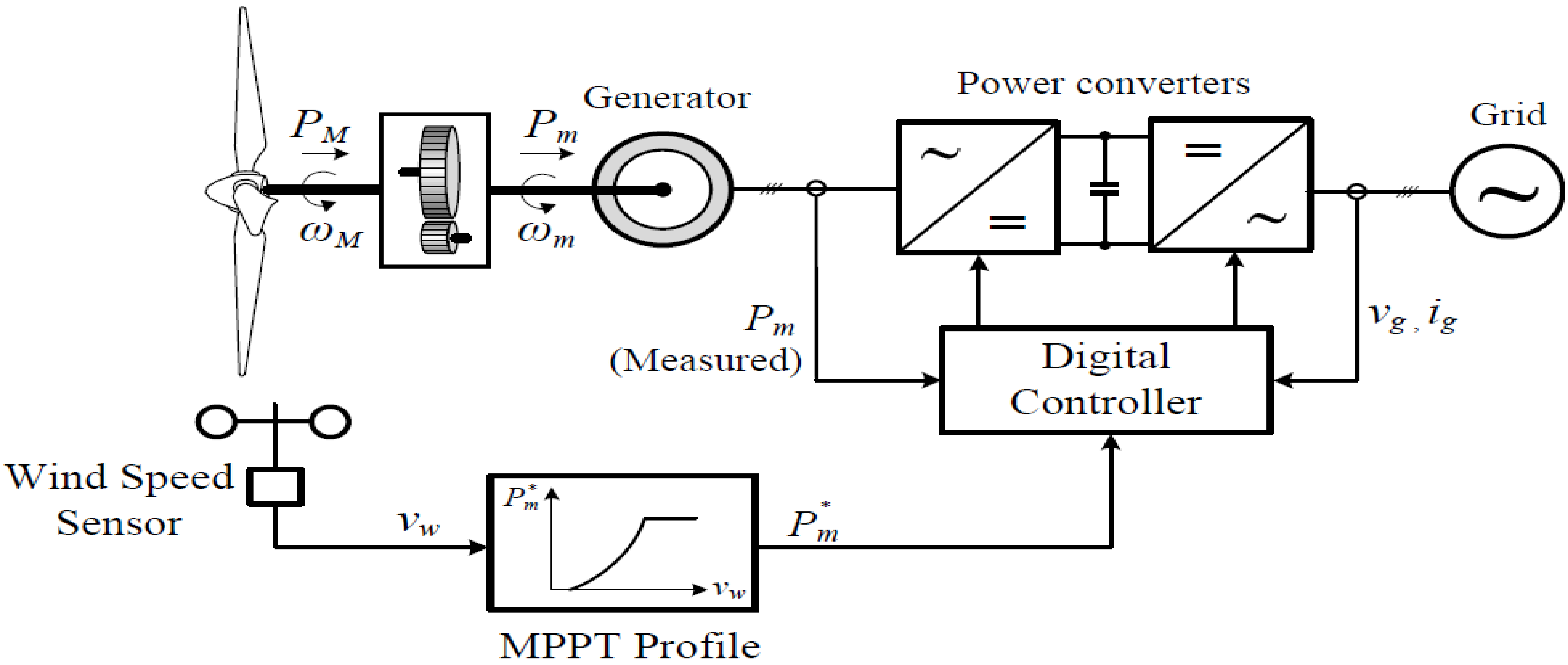
- One of maximum power point tracking methods is based on power versus wind speed curve provided by manufacturer for a given wind turbine.



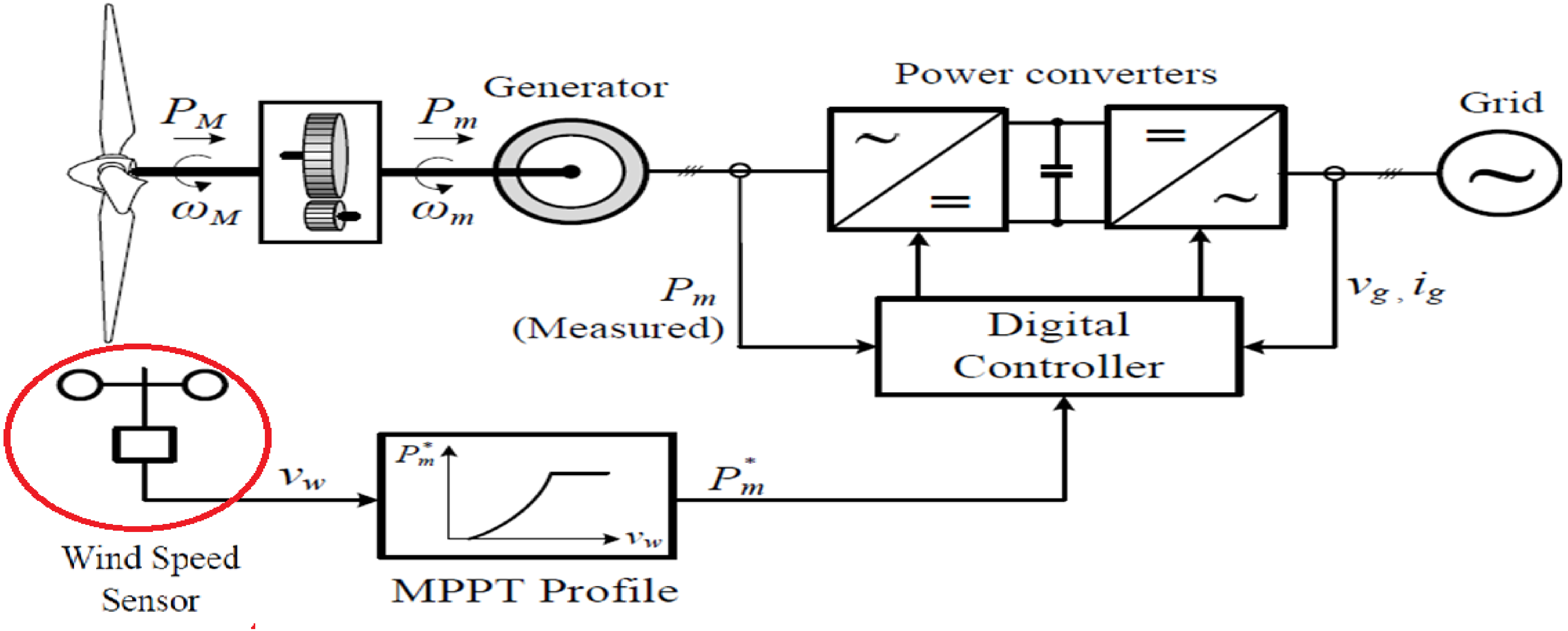
Power curve defines?



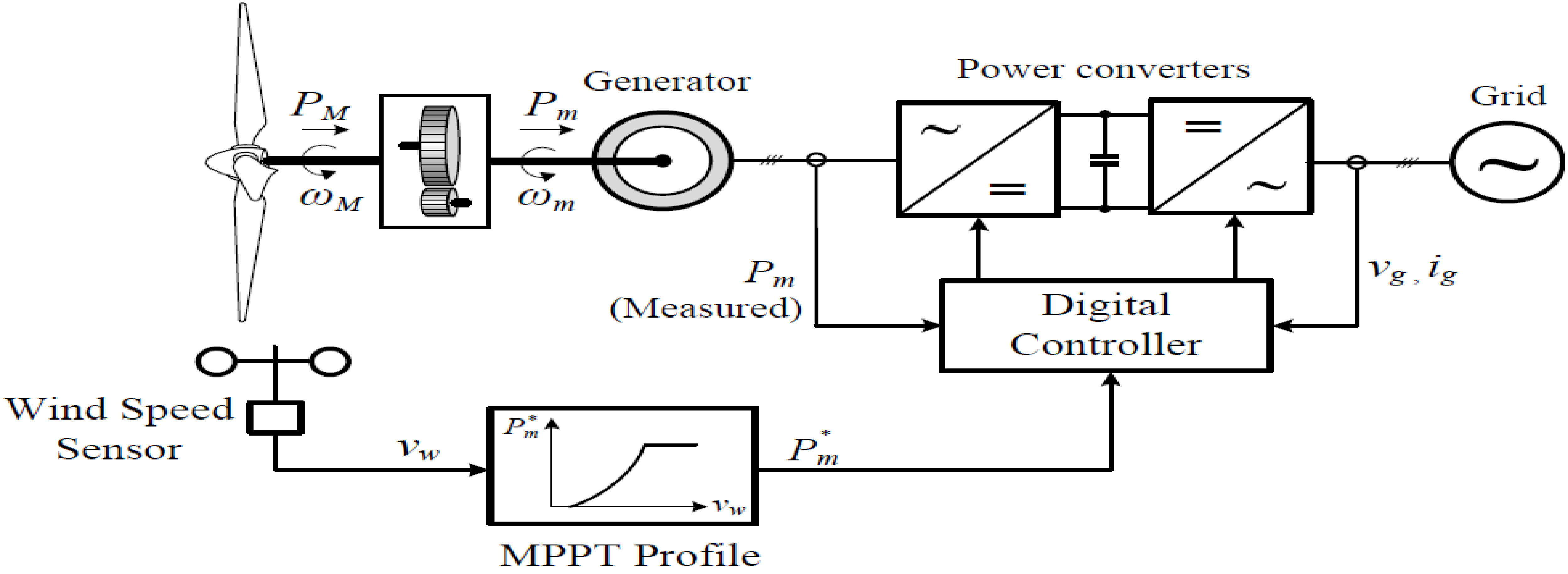
Power curve defines maximum power that can be produced by turbine at different wind speeds.



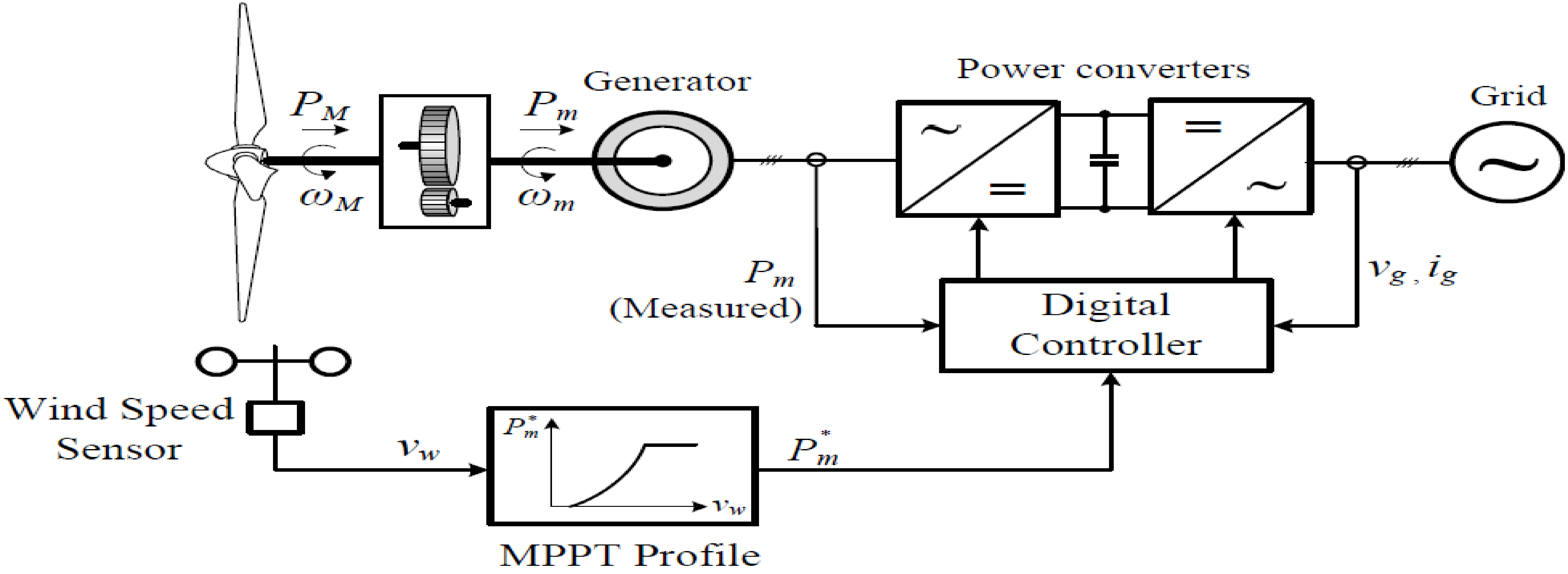
Wind speed is measured in real time by a wind speed sensor.



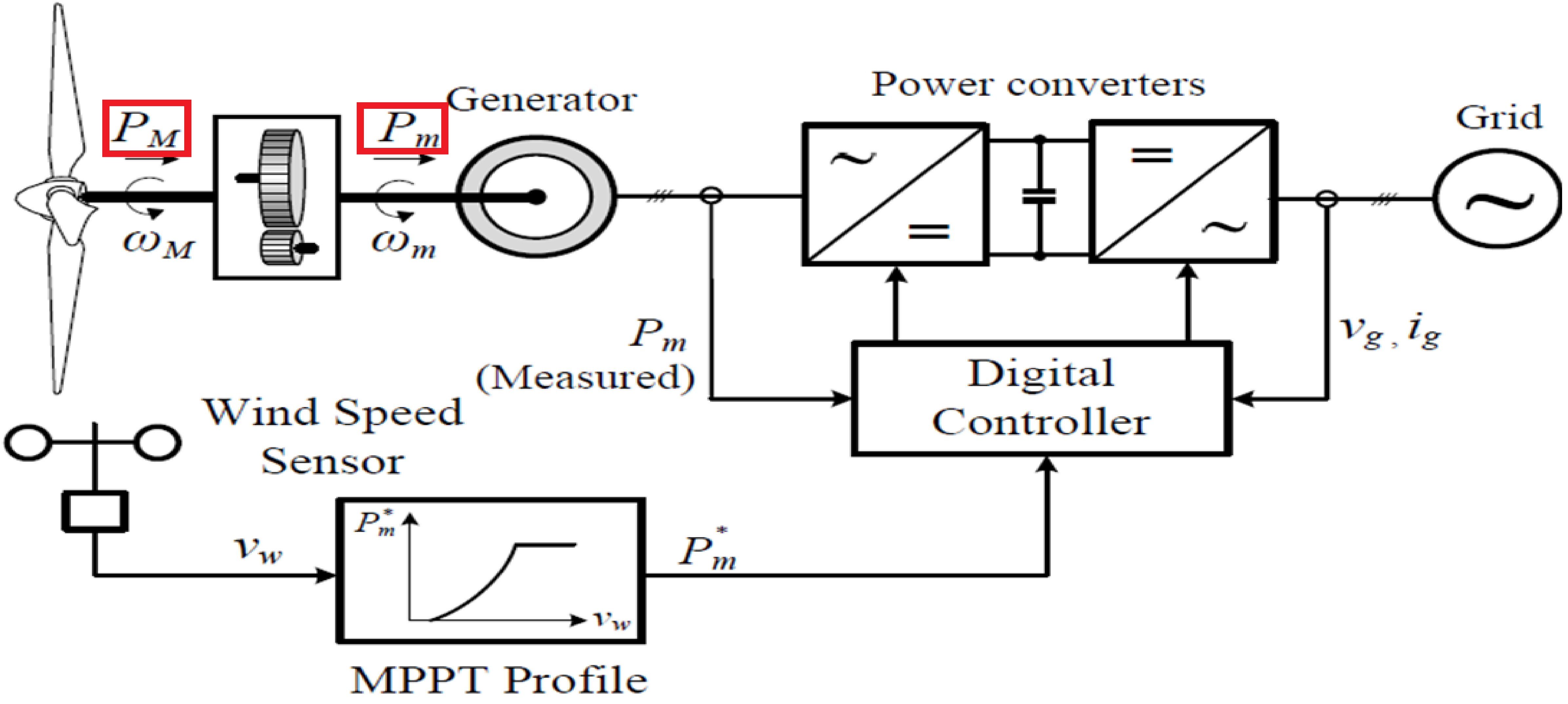
Power reference *Pm** is generated & sent to generator control system, which compares power reference with measured power *Pm* from generator to produce control signals for power converters.



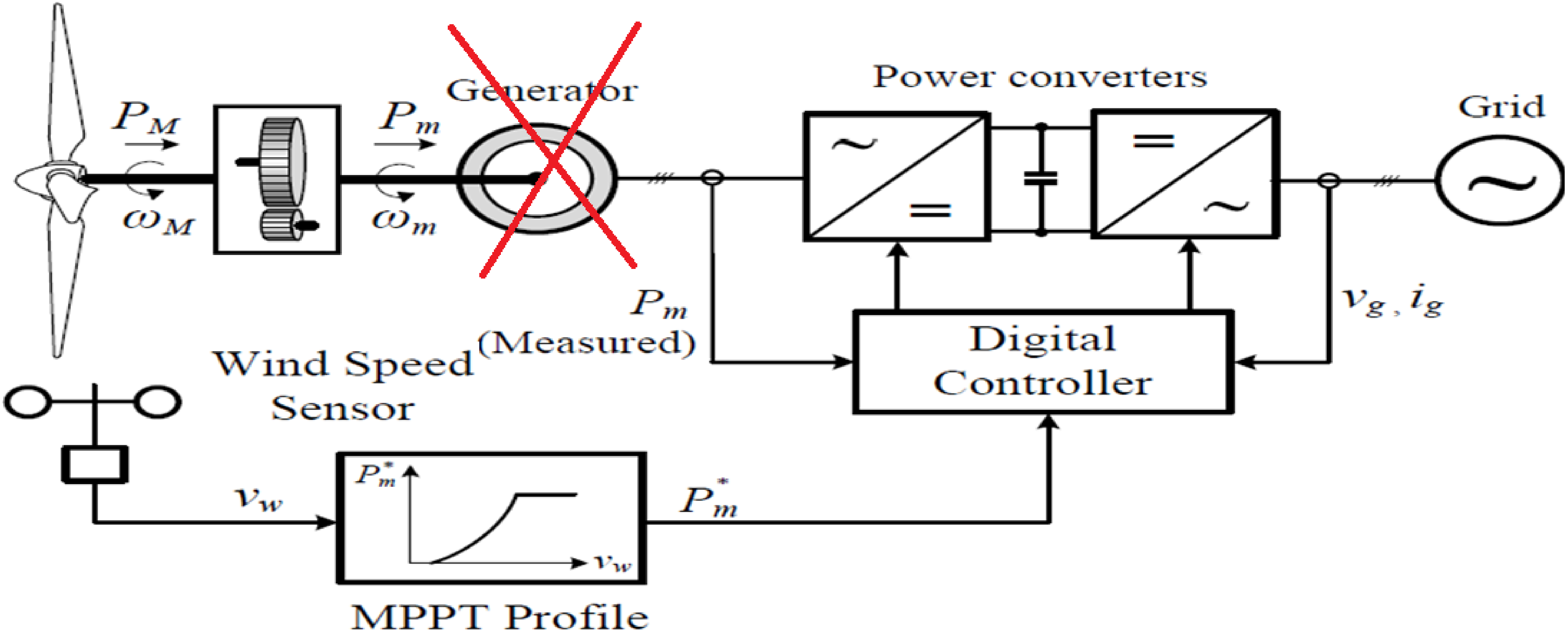
Through control of power converters & generator, mechanical power *Pm* of generator will be equal to its reference in steady state *(Pm=Pm*)*, at which maximum power operation is achieved.



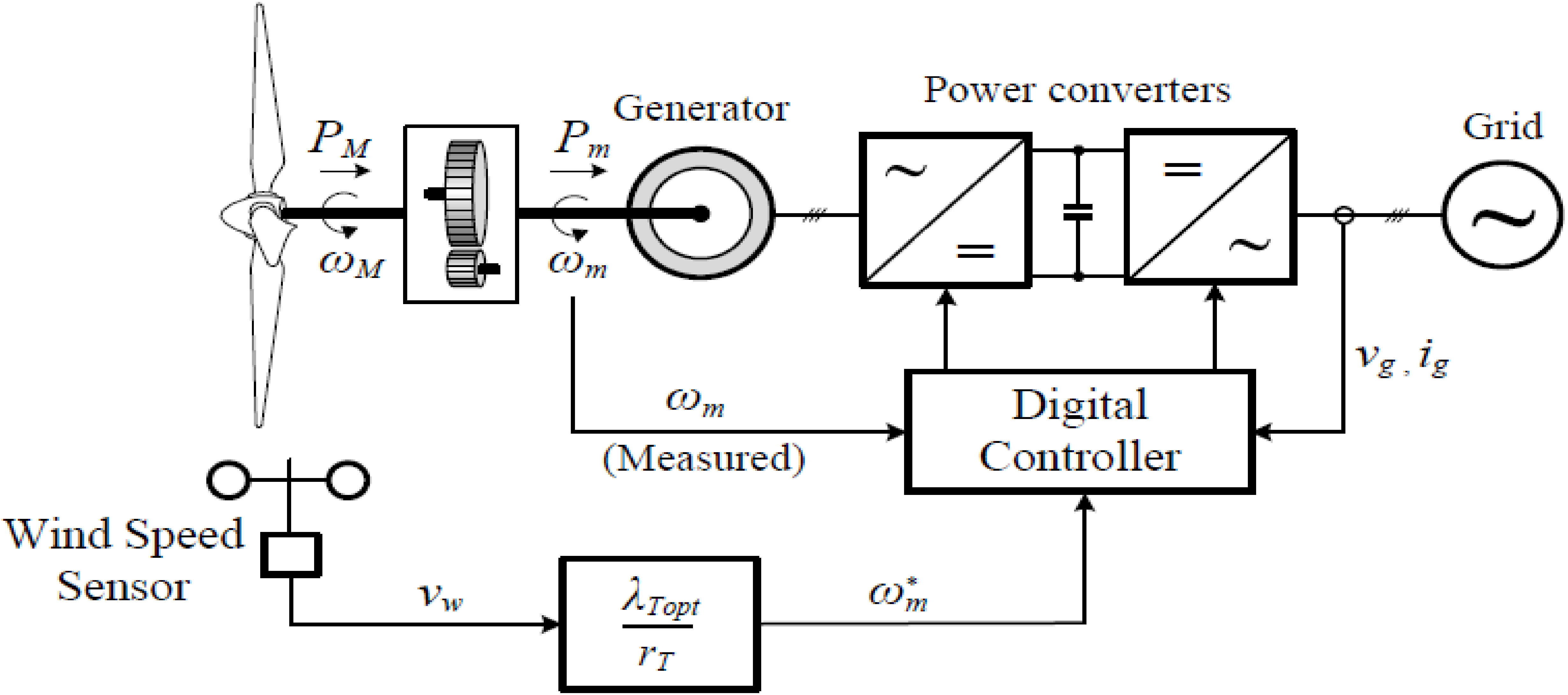
How to equate mechanical power of generator Pm to mechanical power P_M produced by turbine? i.e $Pm=P_M$



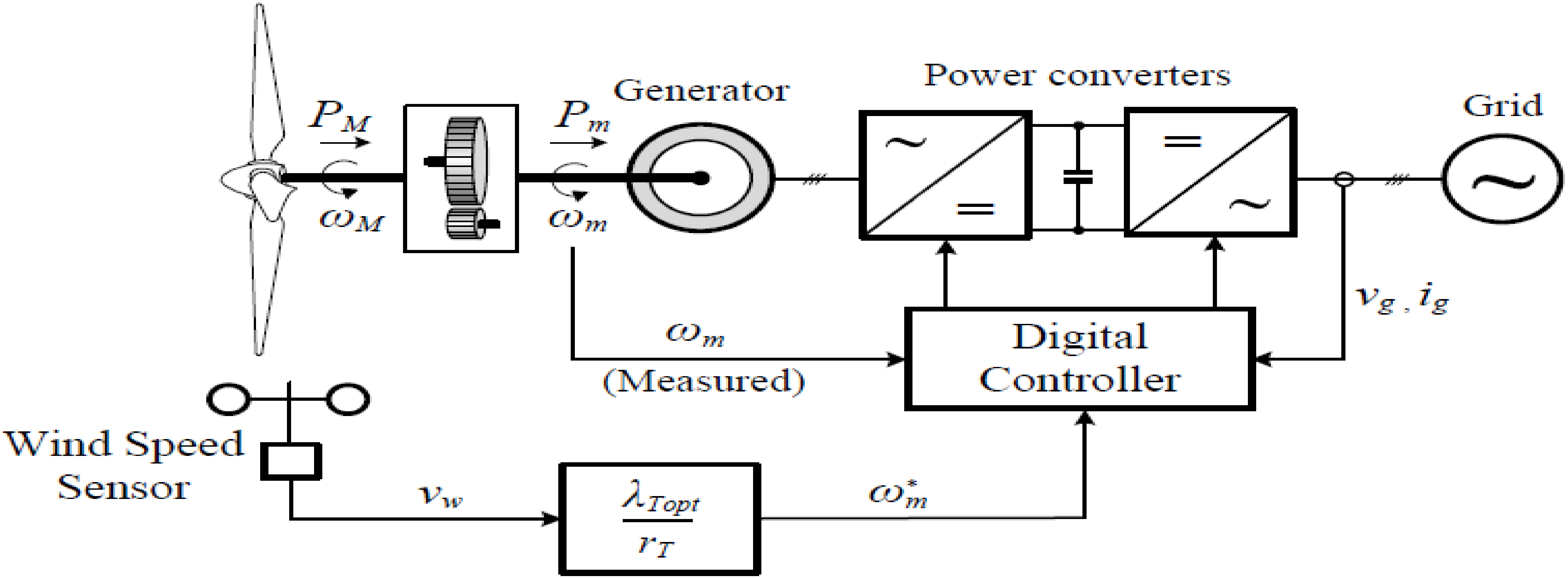
Power losses of gearbox & drive train should be neglected then mechanical power of generator *Pm* is equal to mechanical power P_M produced by turbine i.e $Pm = P_M$.



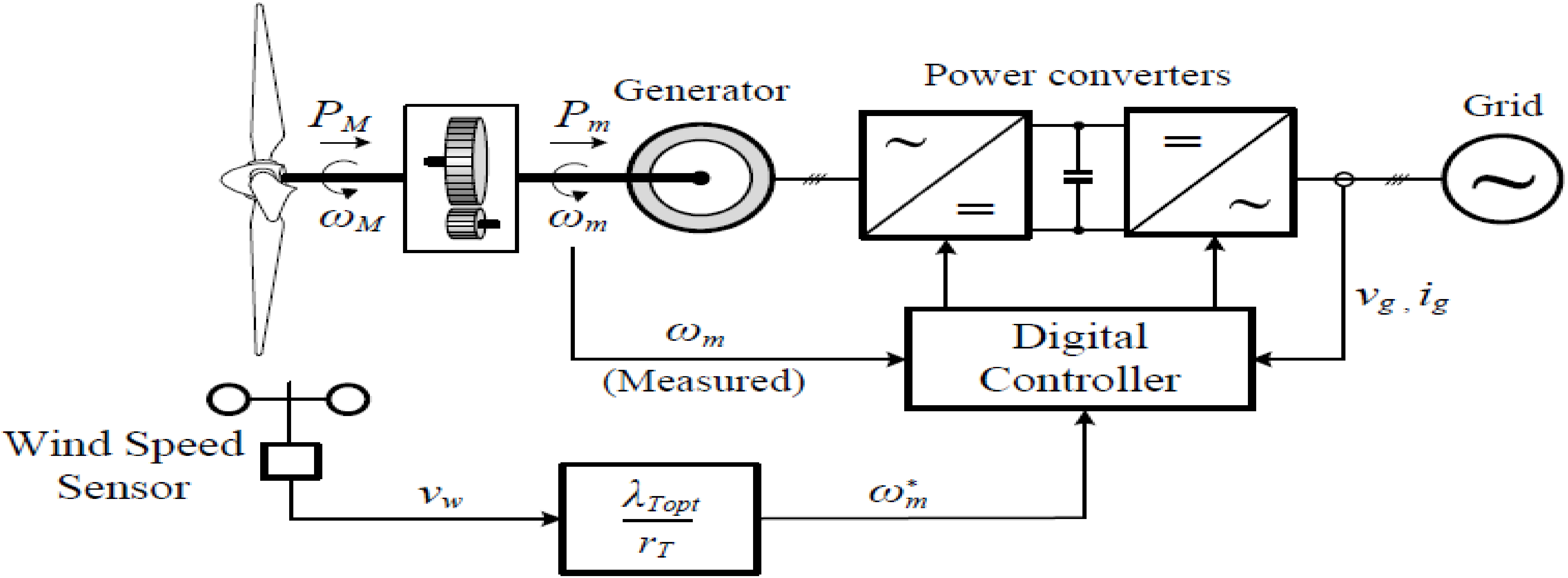
2.4.2 MPPT with Optimal Tip Speed Ratio



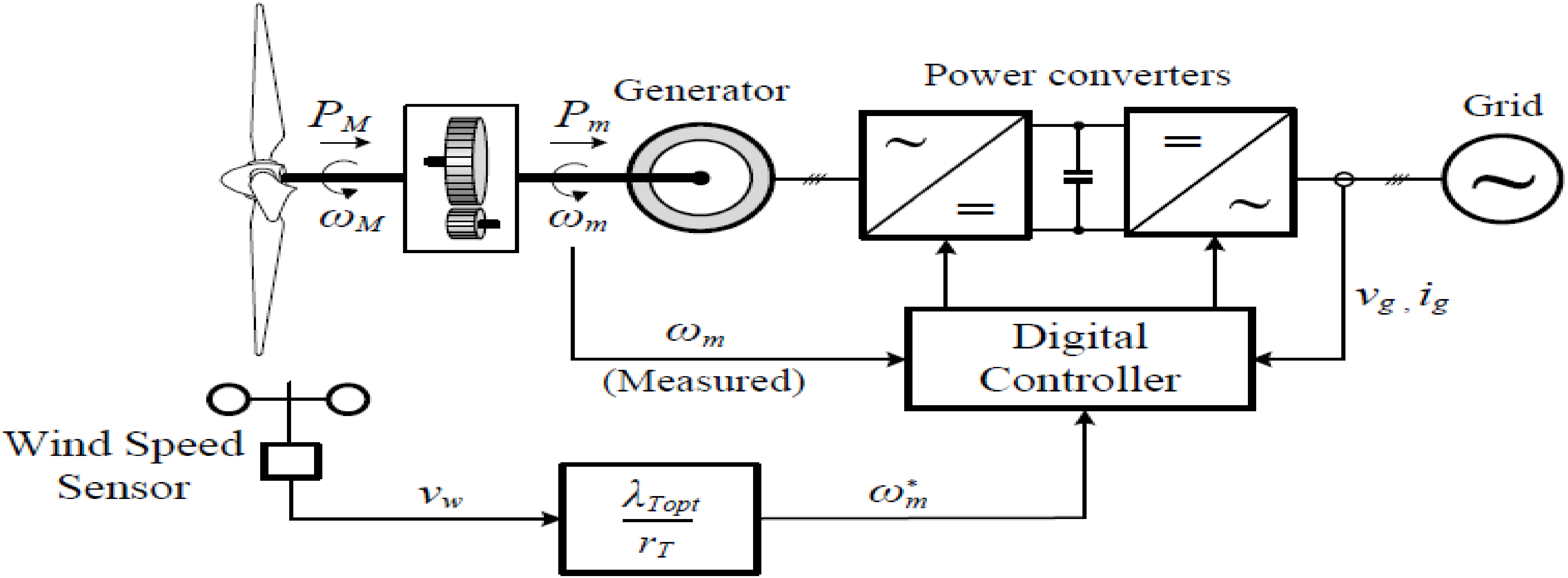
In this method, maximum power operation of wind turbine is achieved by keeping tip speed ratio to its optimal value λ_{Topt}.



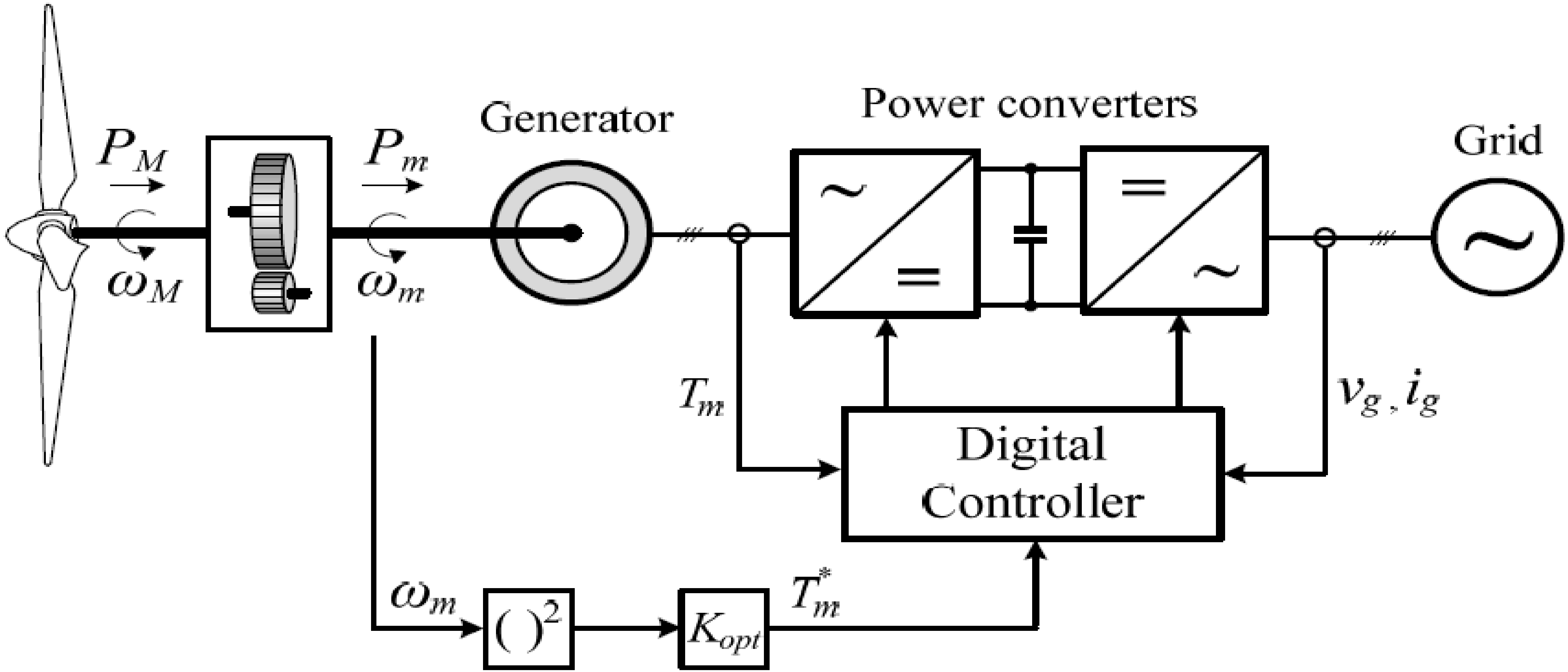
Measured wind speed *vw* is used to produce generator speed reference ω*m** according to optimal tip speed ratio λ*Topt*.



Generator speed ωm is controlled by power converters & will be equal to its reference in steady state, at which MPPT is achieved.



2.4.3 MPPT with Optimal Torque Control



Mechanical power captured by turbine can also be expressed in terms of the torque: $P_M = T_M \omega_M$

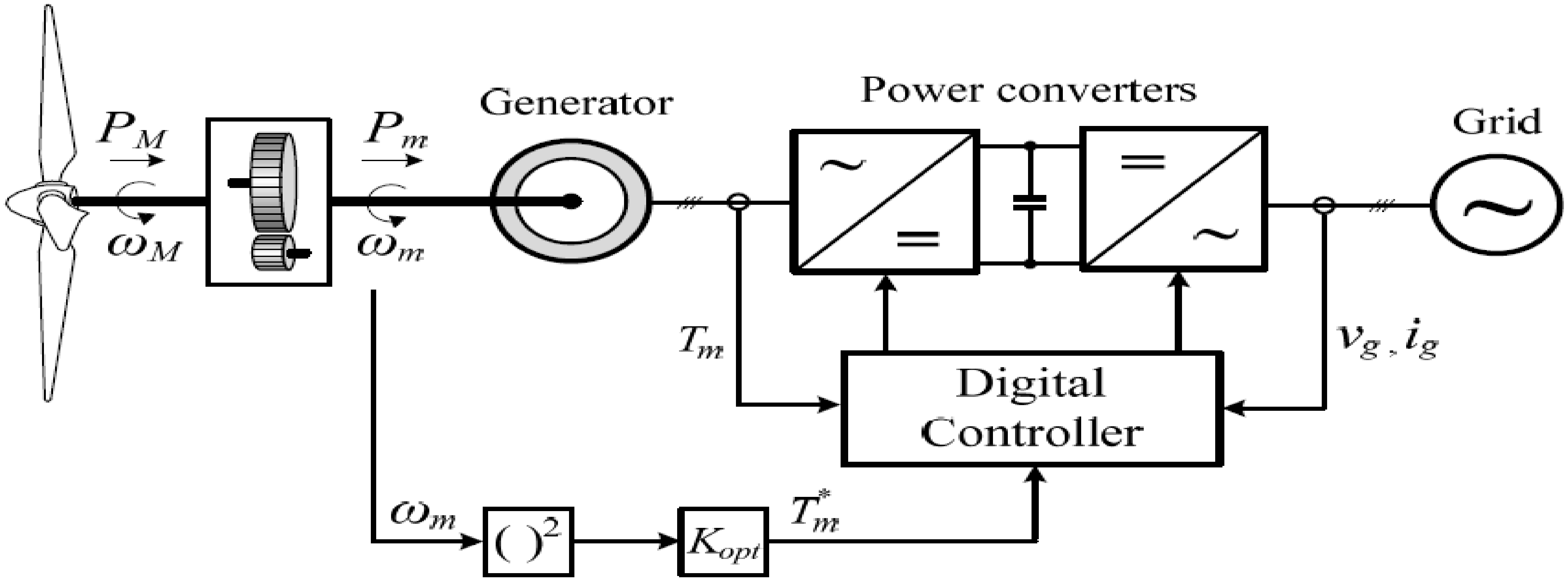
- where T_M is turbine mechanical torque.

By Substituting above equation into $P_M \propto \omega_M^3$

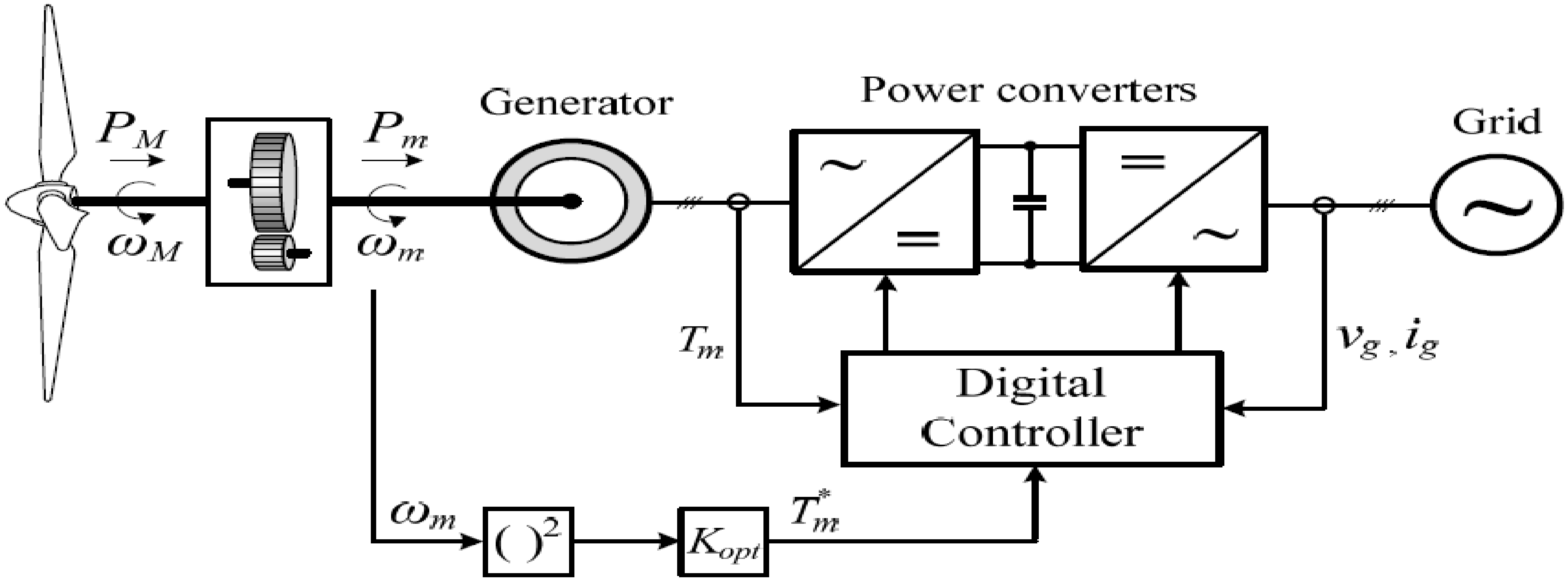
$$T_M \propto \omega_M^2$$

i.e turbine mechanical torque T_M is a quadratic function of turbine speed ω_M.

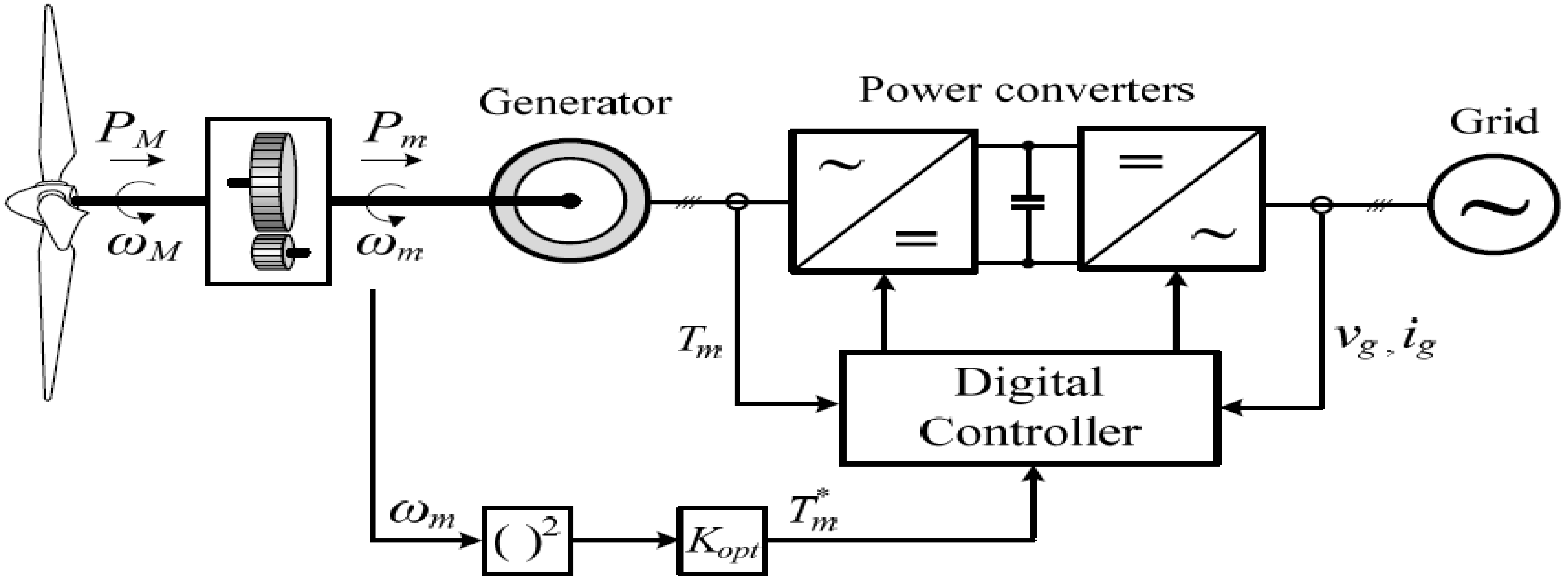
Maximum power operation can also be achieved with optimal torque control , where turbine mechanical torque T_M is a quadratic function of turbine speed ω_M. $T_M \propto \omega_M^2$



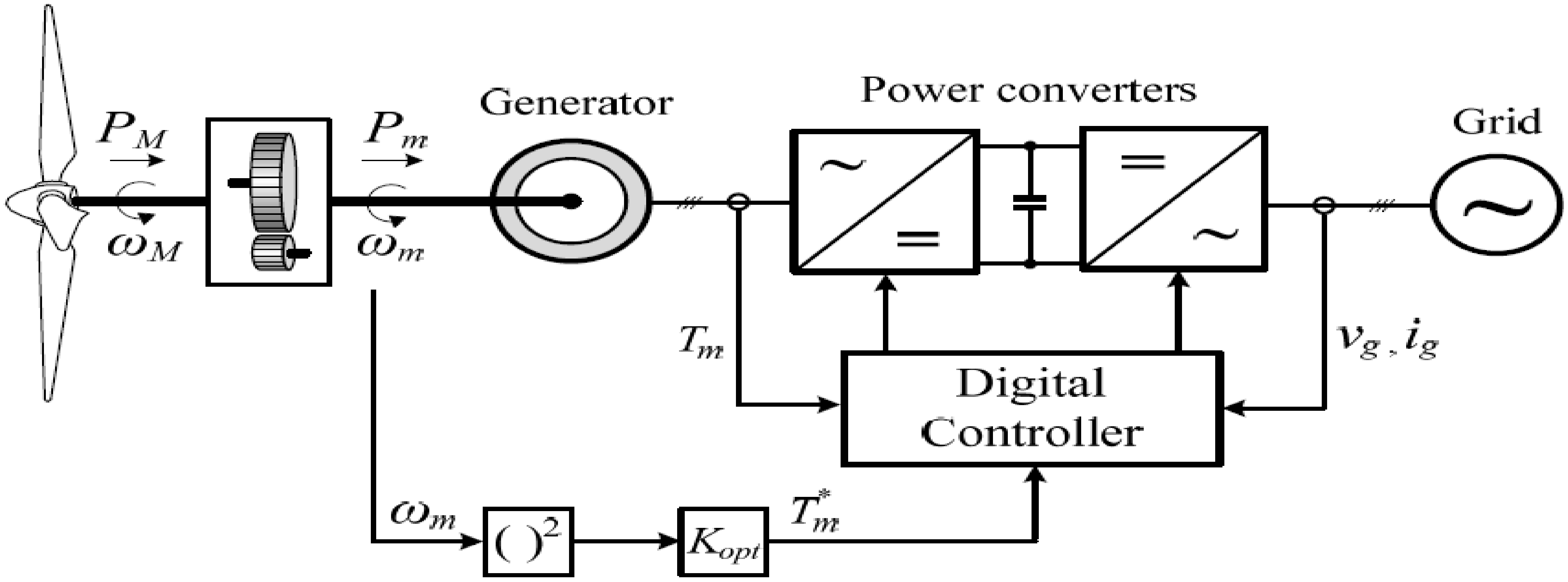
For a given gear ratio & with mechanical power losses of gearbox & drive train neglected.



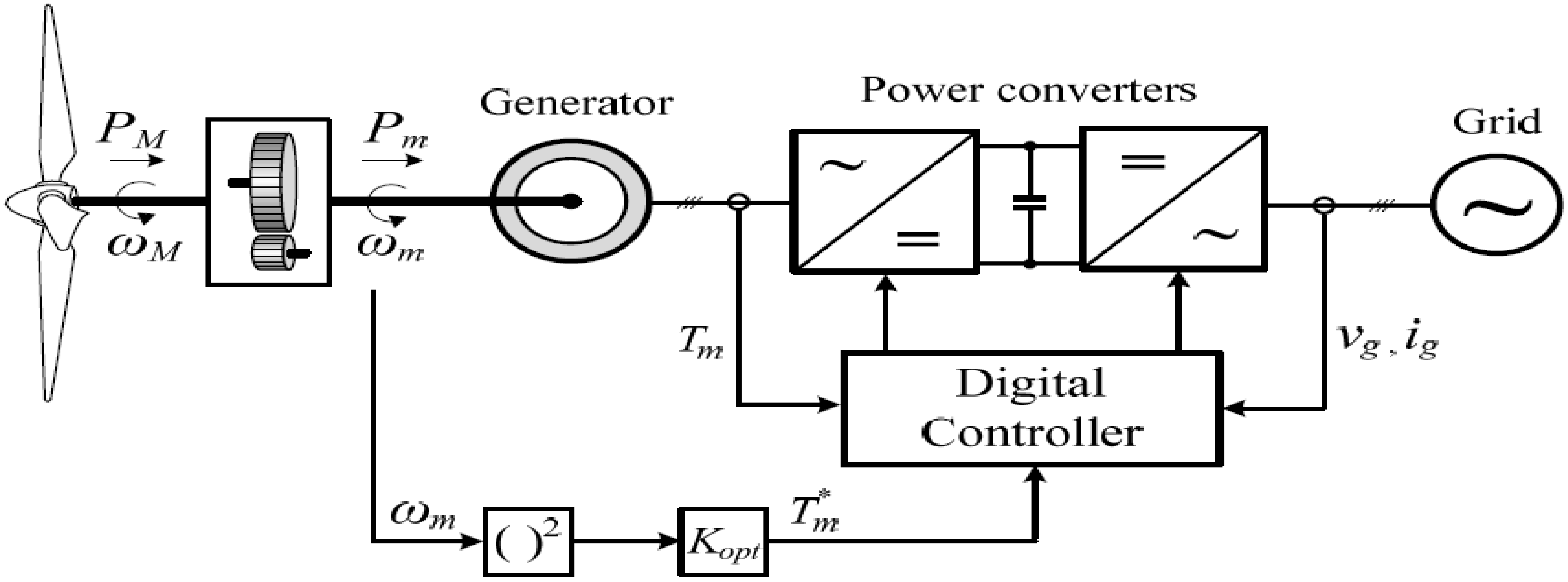
For a given gear ratio,turbine mechanical torque T_M & speed ω_M can be easily converted to generator mechanical torque T_m & speed ω_m, respectively.



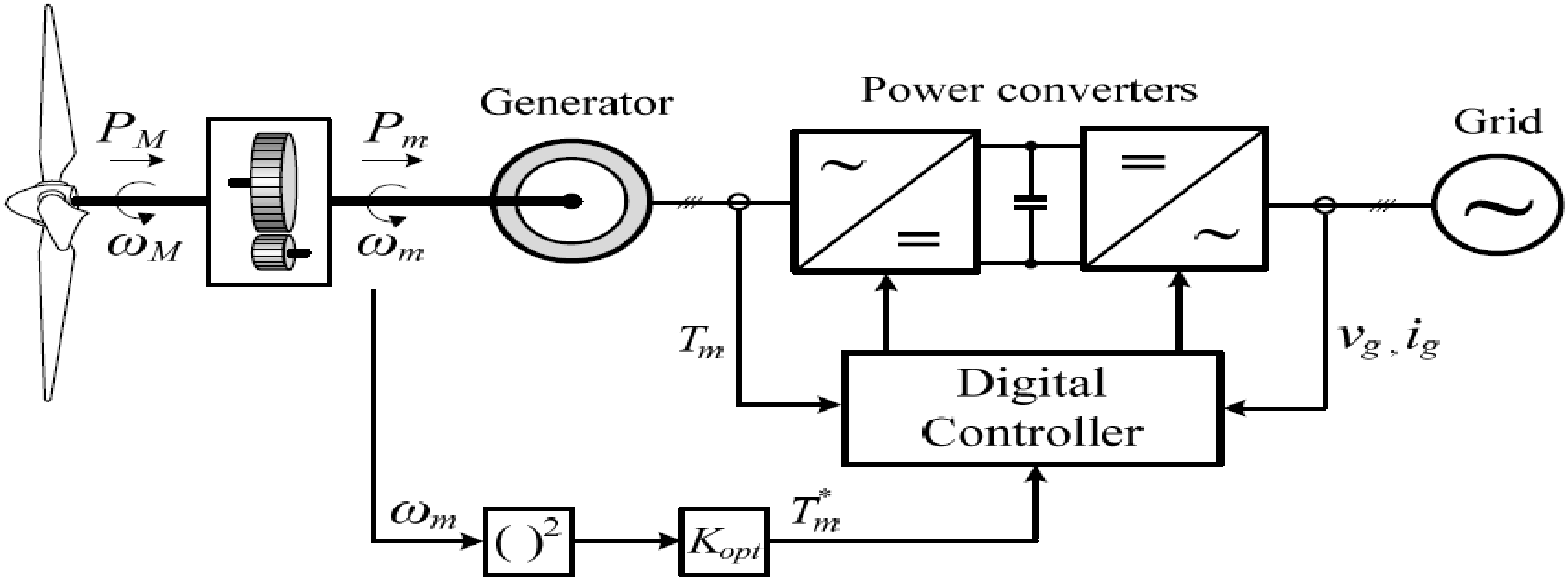
Principle of MPPT scheme with optimal torque control, where generator speed ω_m is measured & used to compute desired torque reference T_m*



Coefficient for optimal torque *Kopt* can be calculated according to rated parameters of generator.



Through feedback control, generator torque *Tm* will be equal to its reference *Tm** in steady state, & MPPT is realized.



It is noted that there is no need to use wind speed sensors in this scheme.