Lecture#02 (Section 1.3 to 1.5)

1.3 Wind Turbine Technology
- 1.3.1 Horizontal- and Vertical-Axis Wind Turbines
- 1.3.2 Fixed- and Variable-speed Turbines
- 1.3.3 Stall and Pitch Aerodynamic Power Controls

1.4 Wind Energy Conversion System Configurations
- 1.4.1 Fixed-speed WECS without Power Converter Interface
- 1.4.2 Variable-speed Systems with Reduced-Capacity Converters
- 1.4.3 Variable-speed Systems with Full-capacity Power Converters

1.5 Grid Code
- 1.5.1 Fault Ride-through Requirements
- 1.5.2 Reactive Power Control

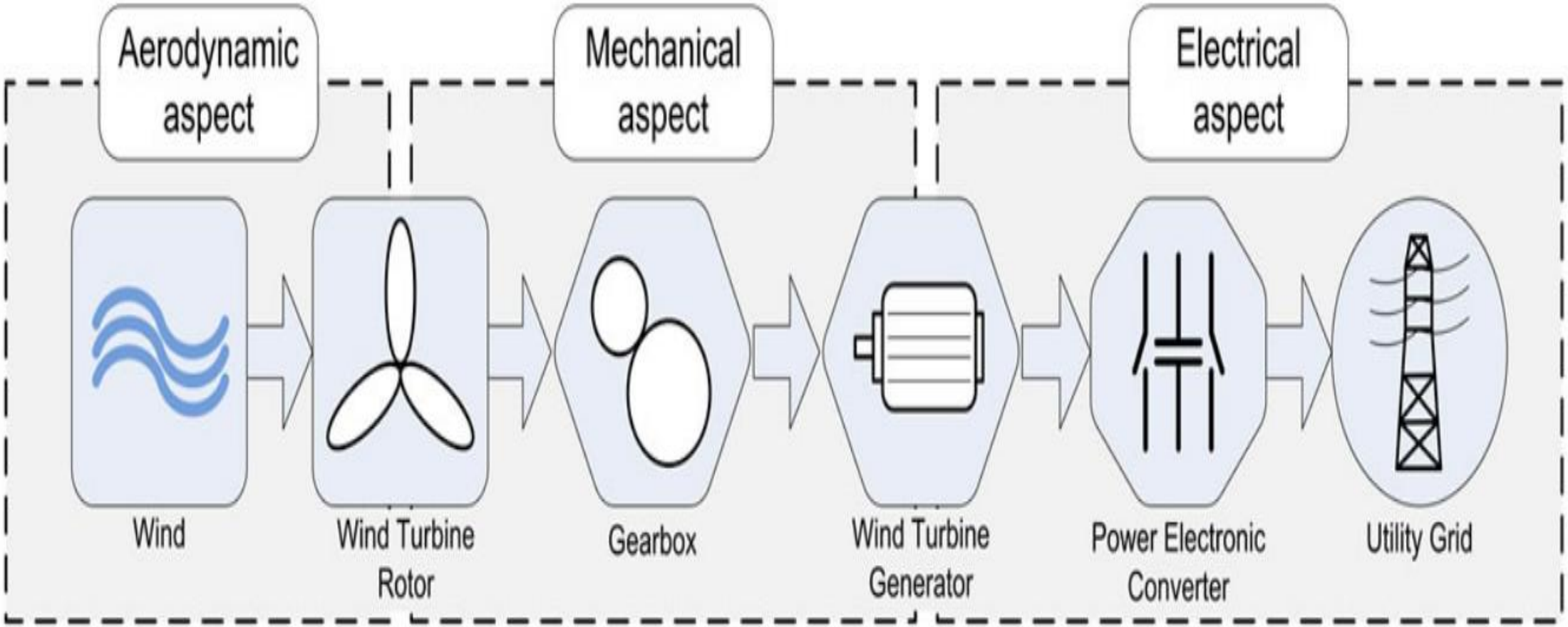
1.3 Wind Turbine Technology

1.3.1 Horizontal- and Vertical-Axis Wind Turbines

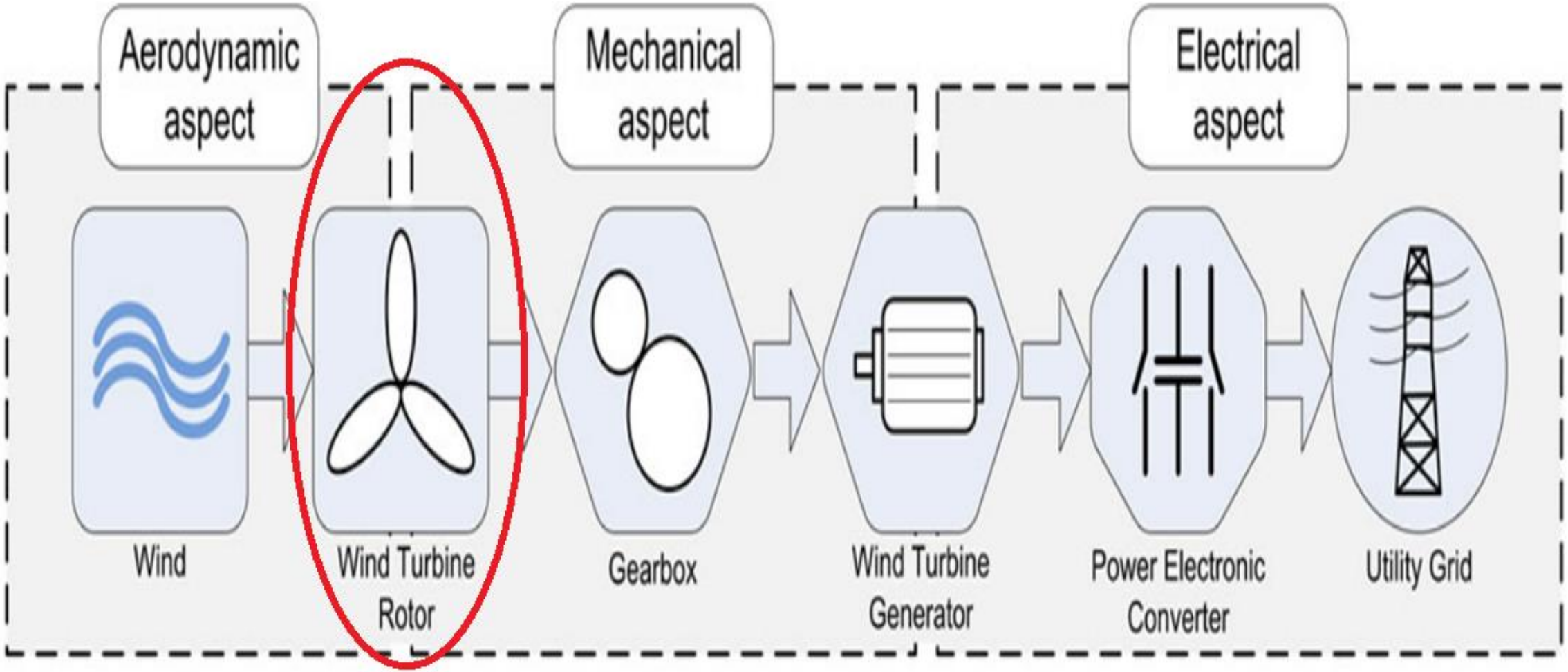
1.3.2 Fixed- and Variable-speed Turbines

1.3.3 Stall and Pitch Aerodynamic Power Controls…Shall study in Chapter.2

Q. What is the most important elements in wind energy conversion systems?



Wind turbine is one of the most important elements in wind energy conversion systems.



Over the years different types of wind turbines have been developed.

1.3.1 Horizontal- & Vertical-Axis Wind Turbines

Lets watch a video on Vertical-Axis Wind Turbine

Lets watch a video on Horizontal-Axis Wind Turbine


WIND TURBINE
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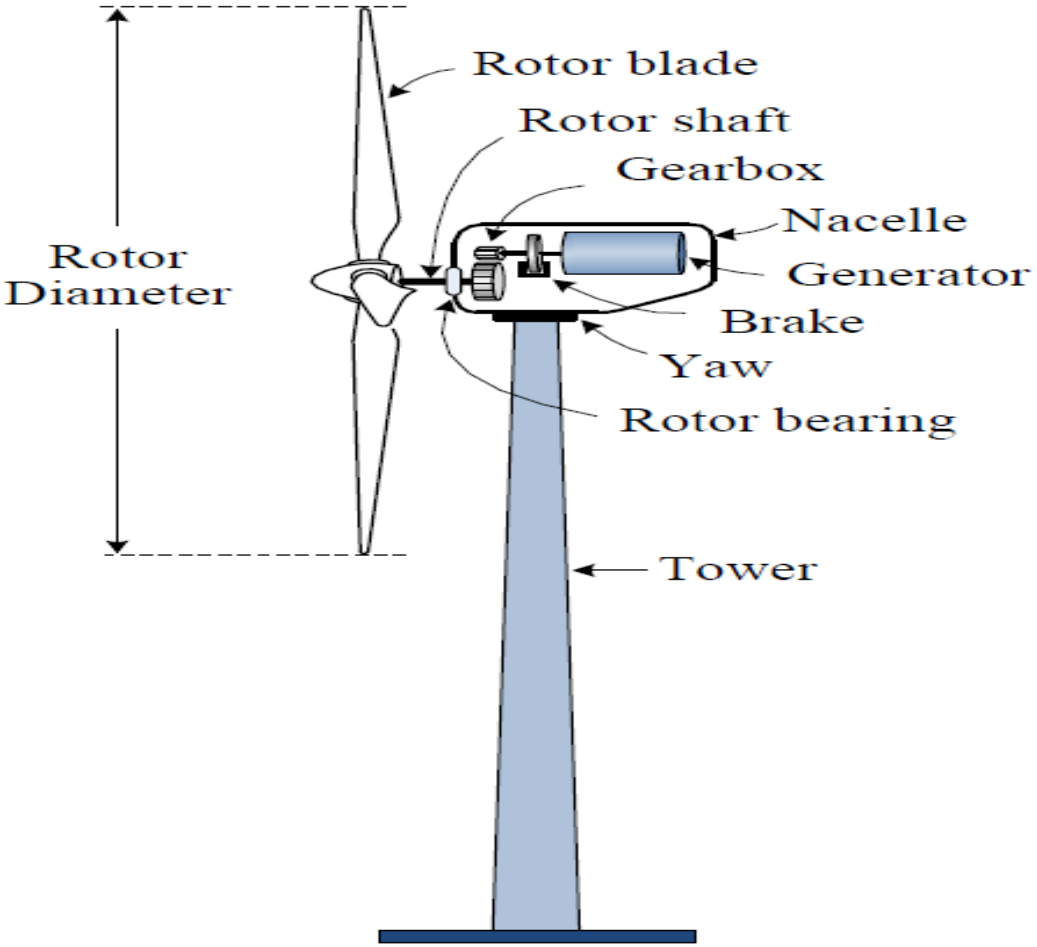
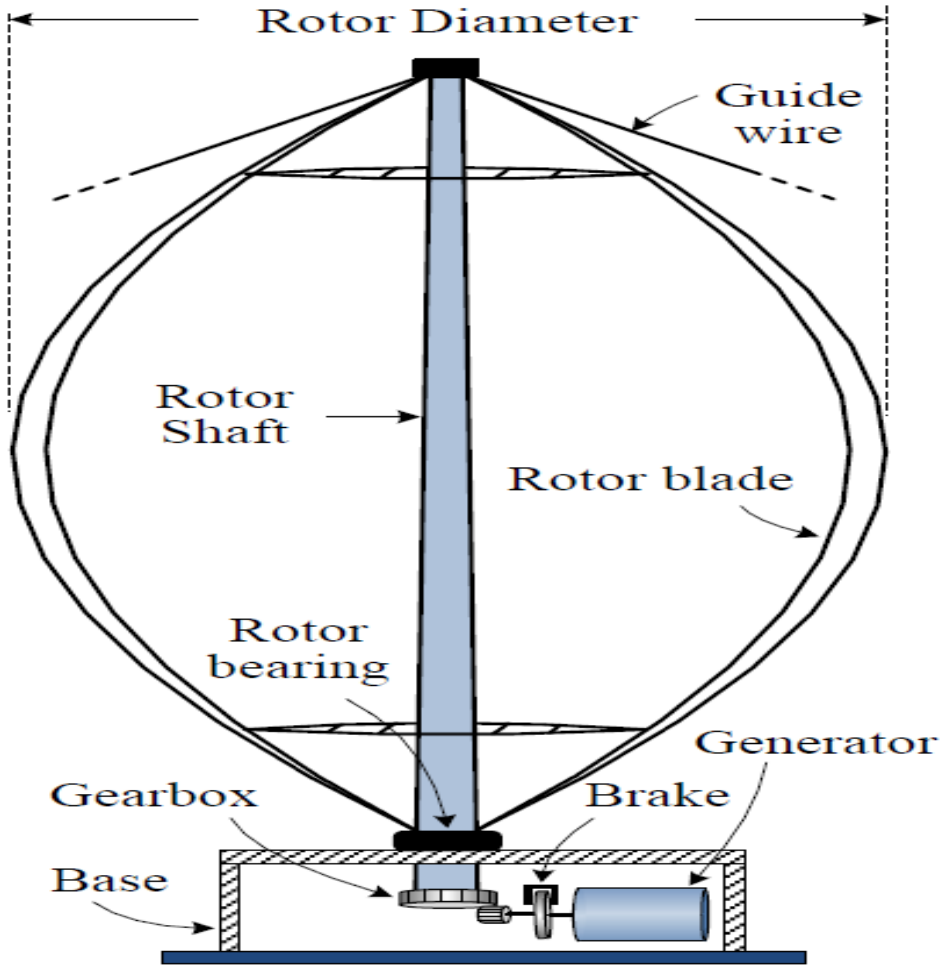
Classifications of Wind turbines



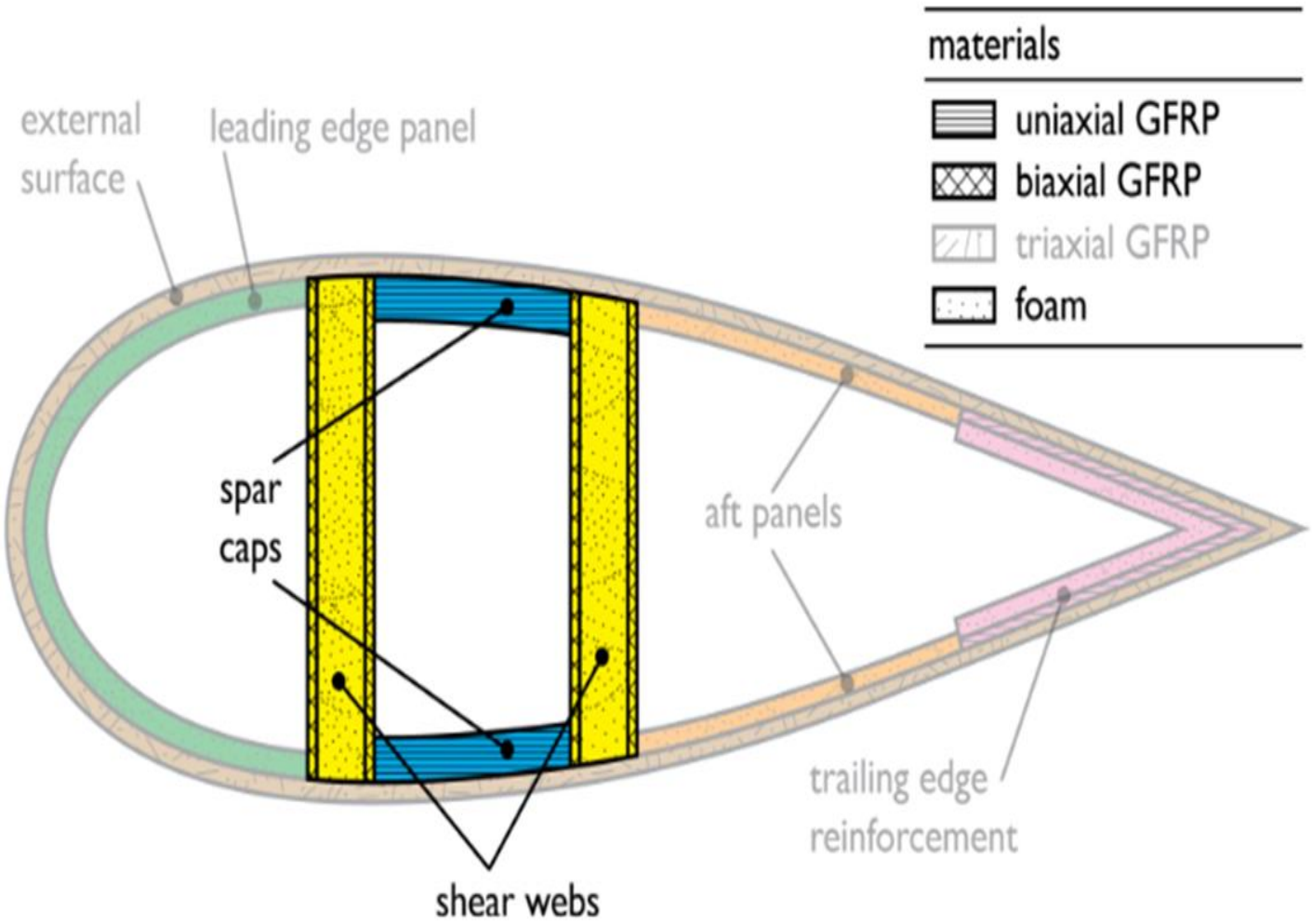
(a) Horizontal-axis turbine

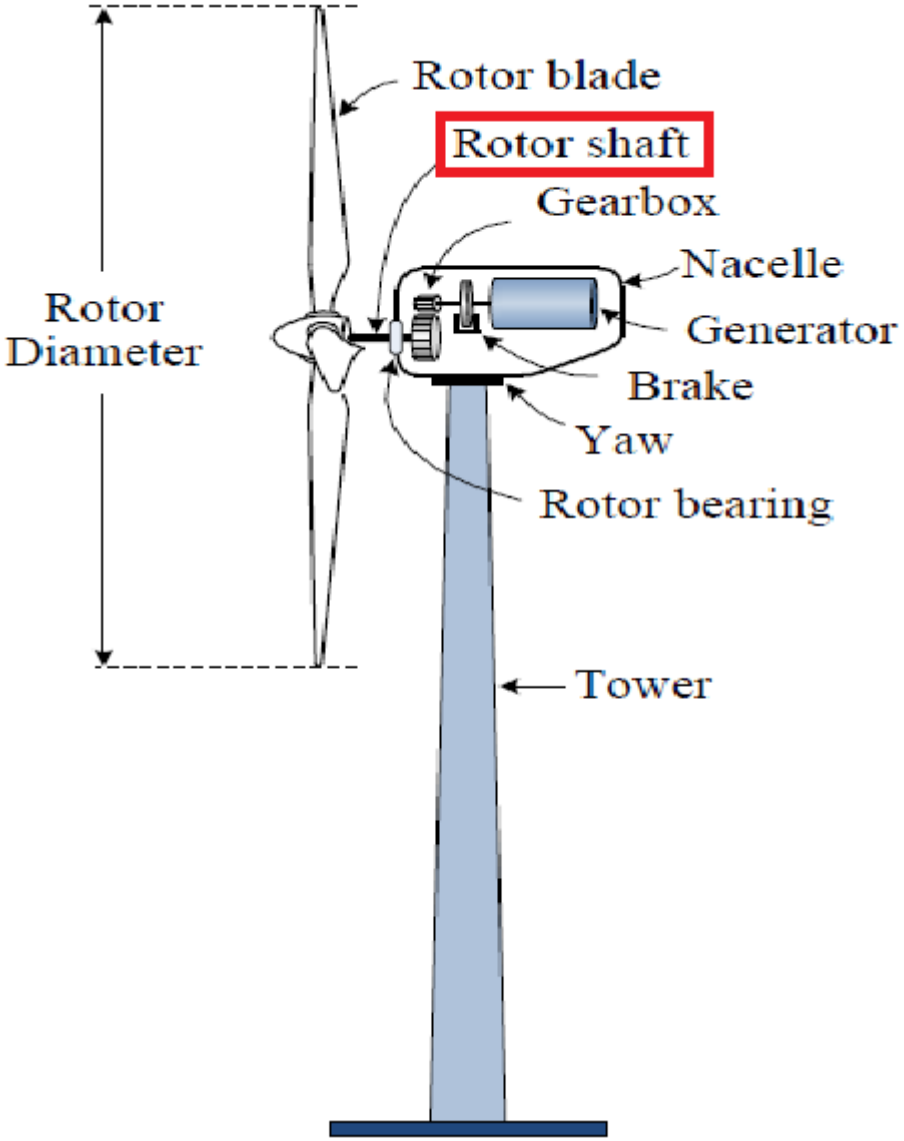


(b) Vertical-axis turbine

Pros & cons of Horizontal-Axis Wind Turbines(HAWT)

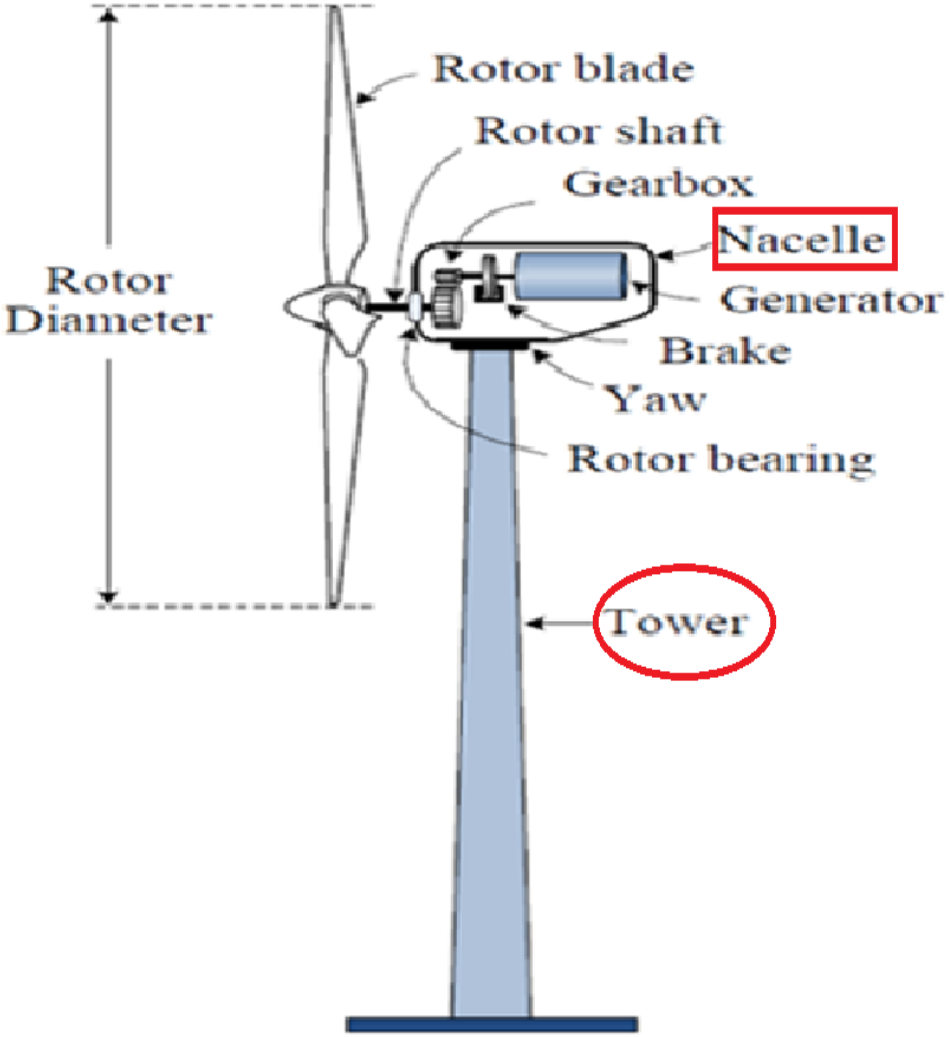
1-HAWT have higher efficiency due to blade design.





2.Access to stronger wind as wind velocities increase at higher altitudes. e.g

Indiana had been rated as having a wind capacity of 30,000 MW, but by raising the expected turbine height from 50 m to 70 m, the wind capacity estimate was raised to 40,000 MW, and could be double that at 100 m.



3.Needs **stronger tower + foundation** to support heavy weight of nacelle

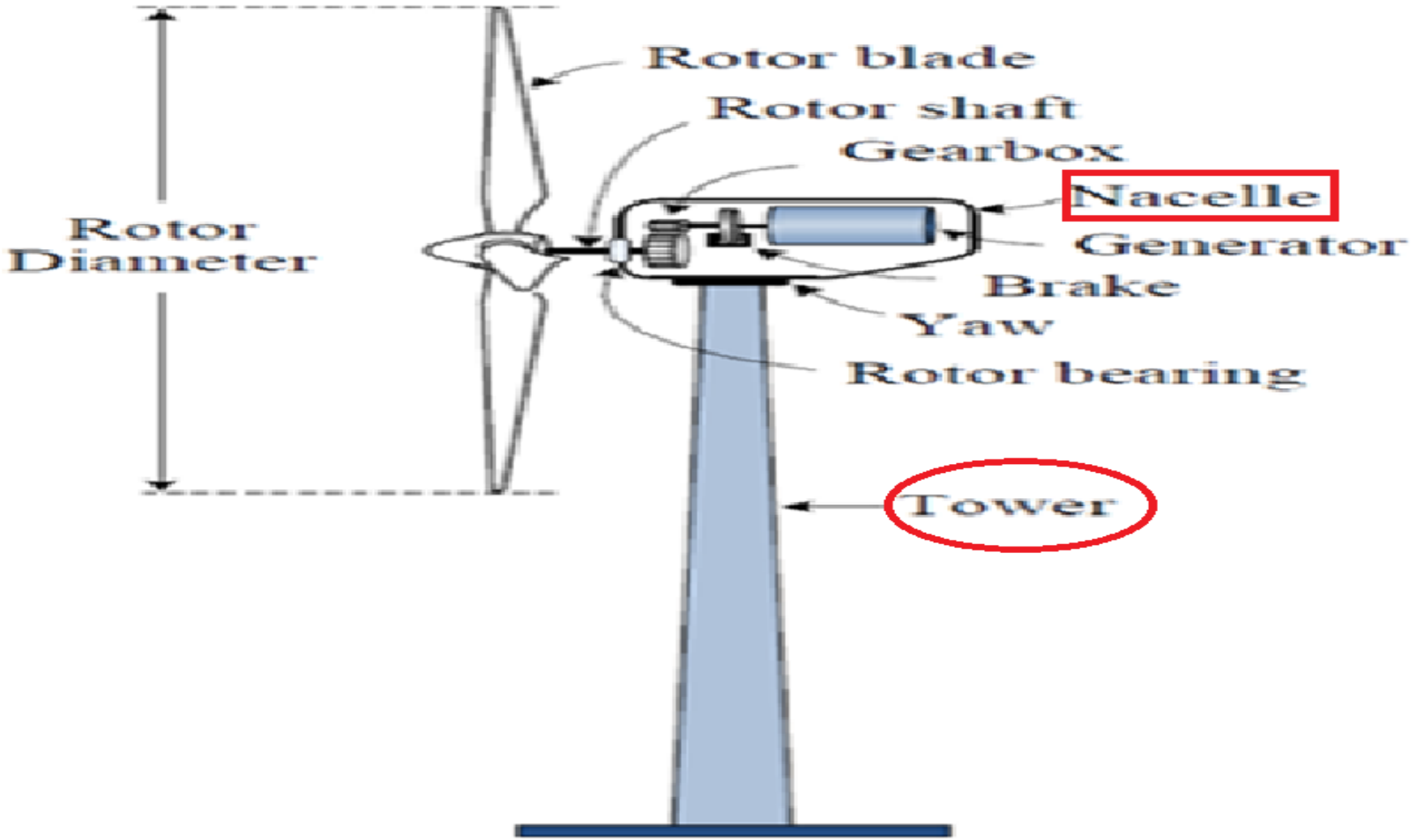
Heavy weight of nacelle

Guess the weight of nacelle ?

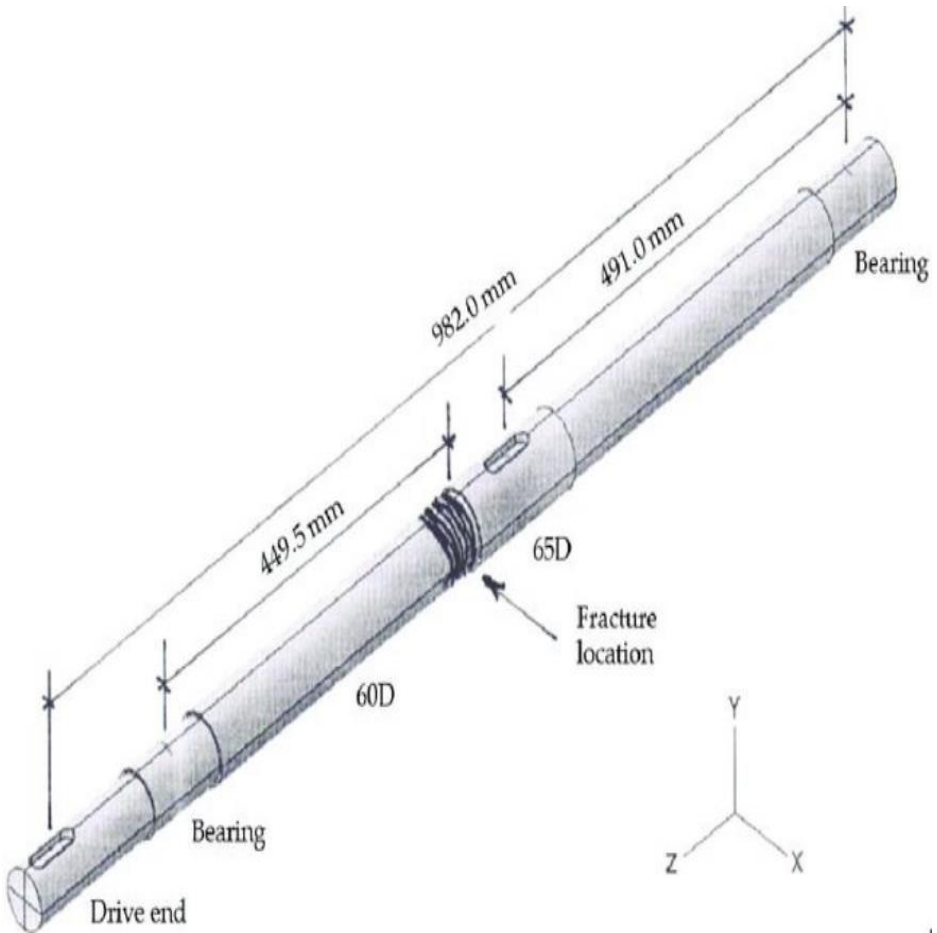
70Tonne

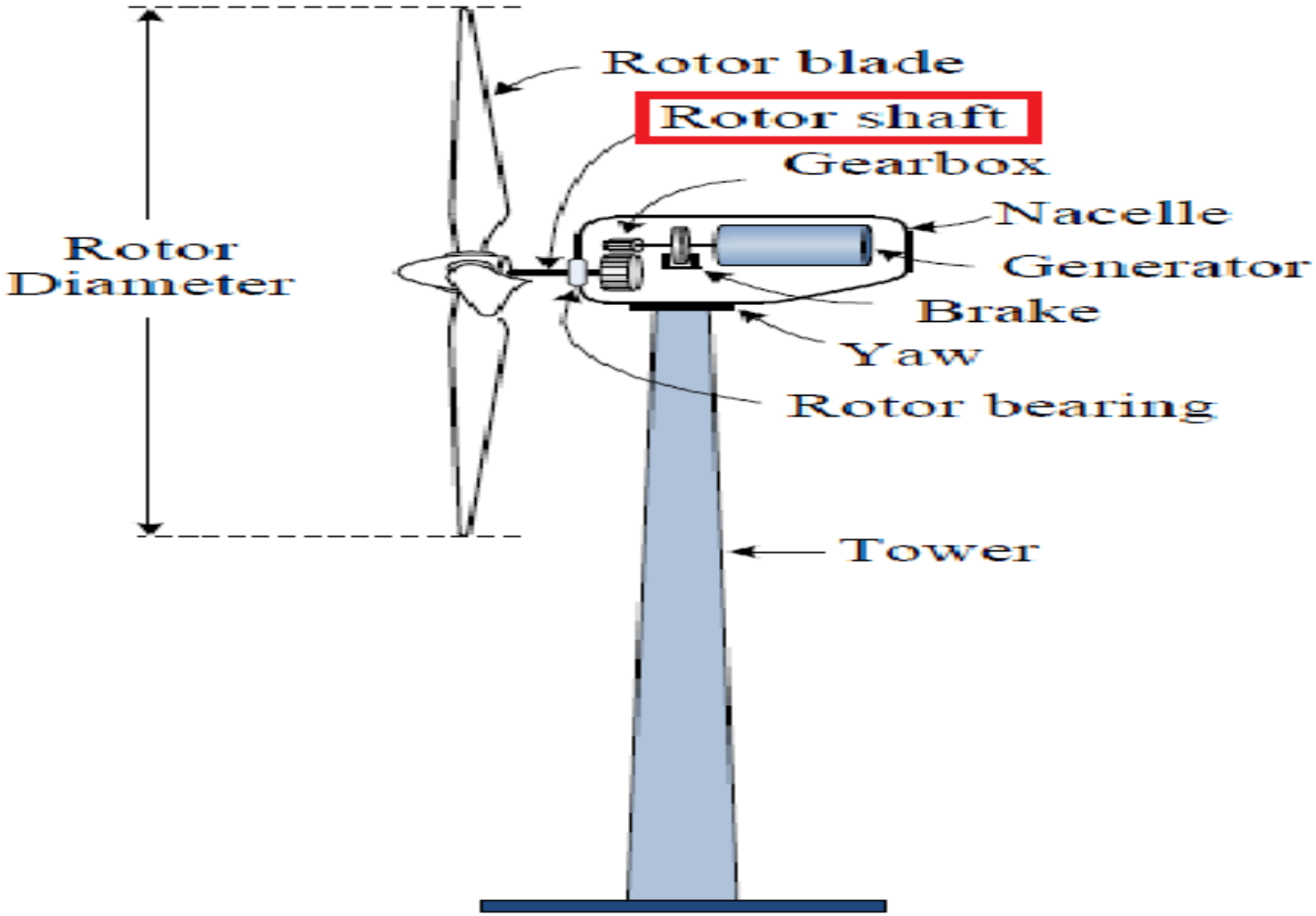
Vestas V90 3MW nacelle

4. Installation cost is higher.



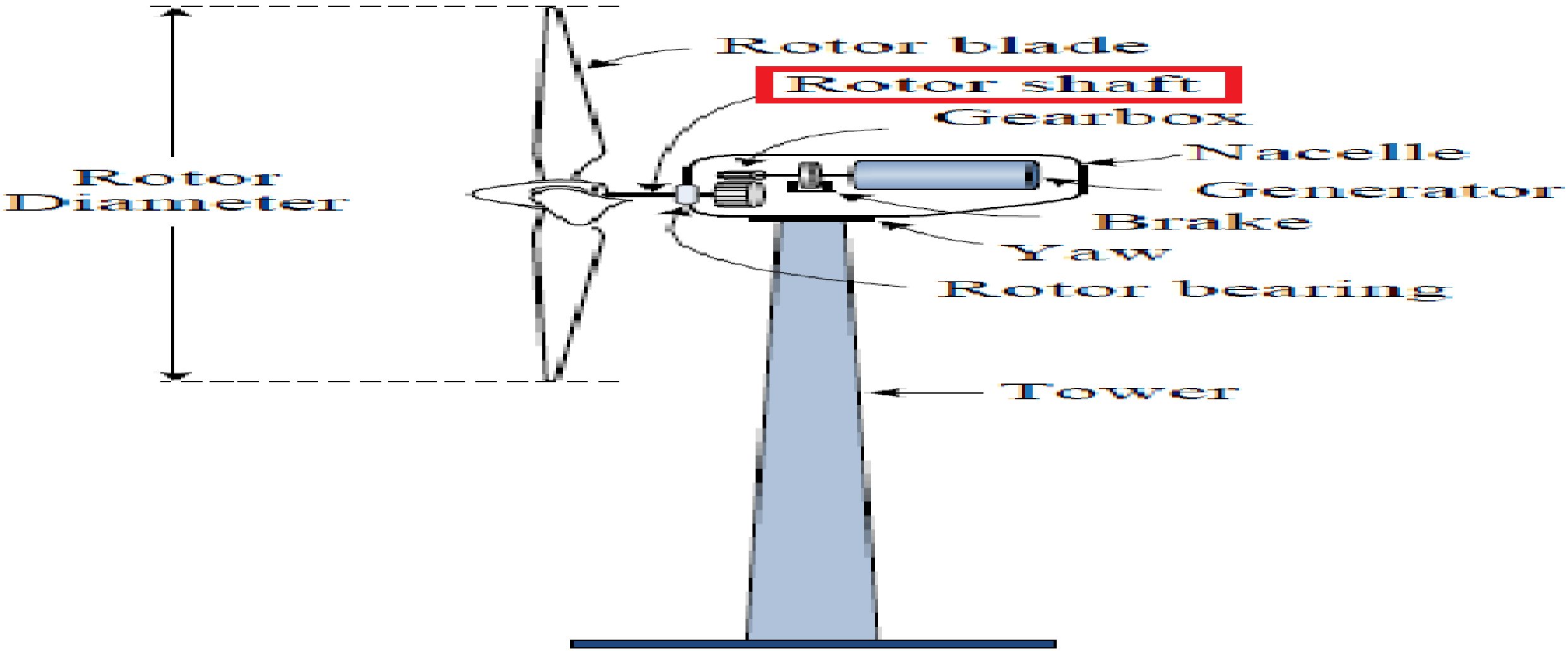
5. Rotor shaft is not so long, so less prone to mechanical vibrations.



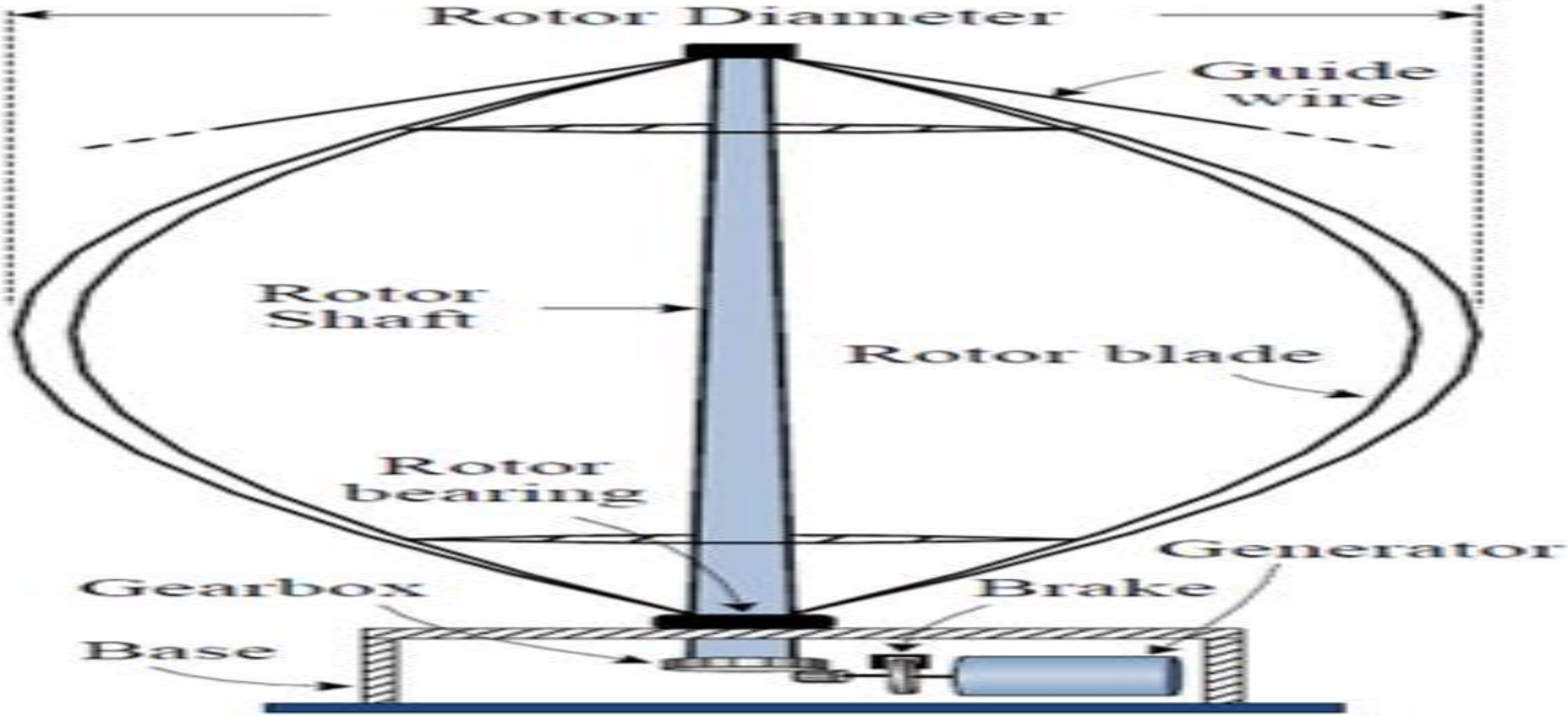


6-Difficulty in maintenance as gearbox & generator are not at ground level

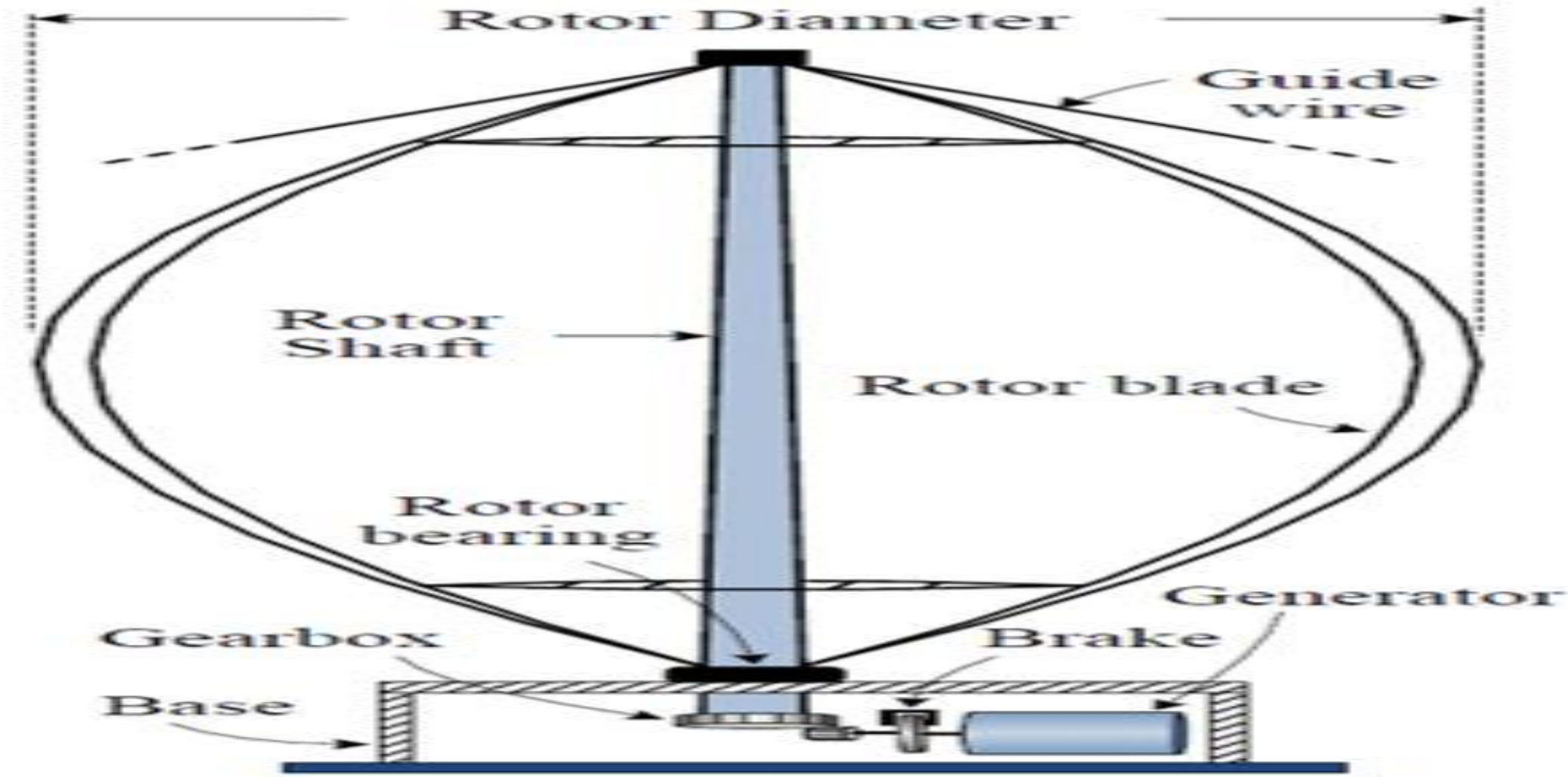
7. Both the Efficiency & installation cost are higher with difficulty in maintenance.



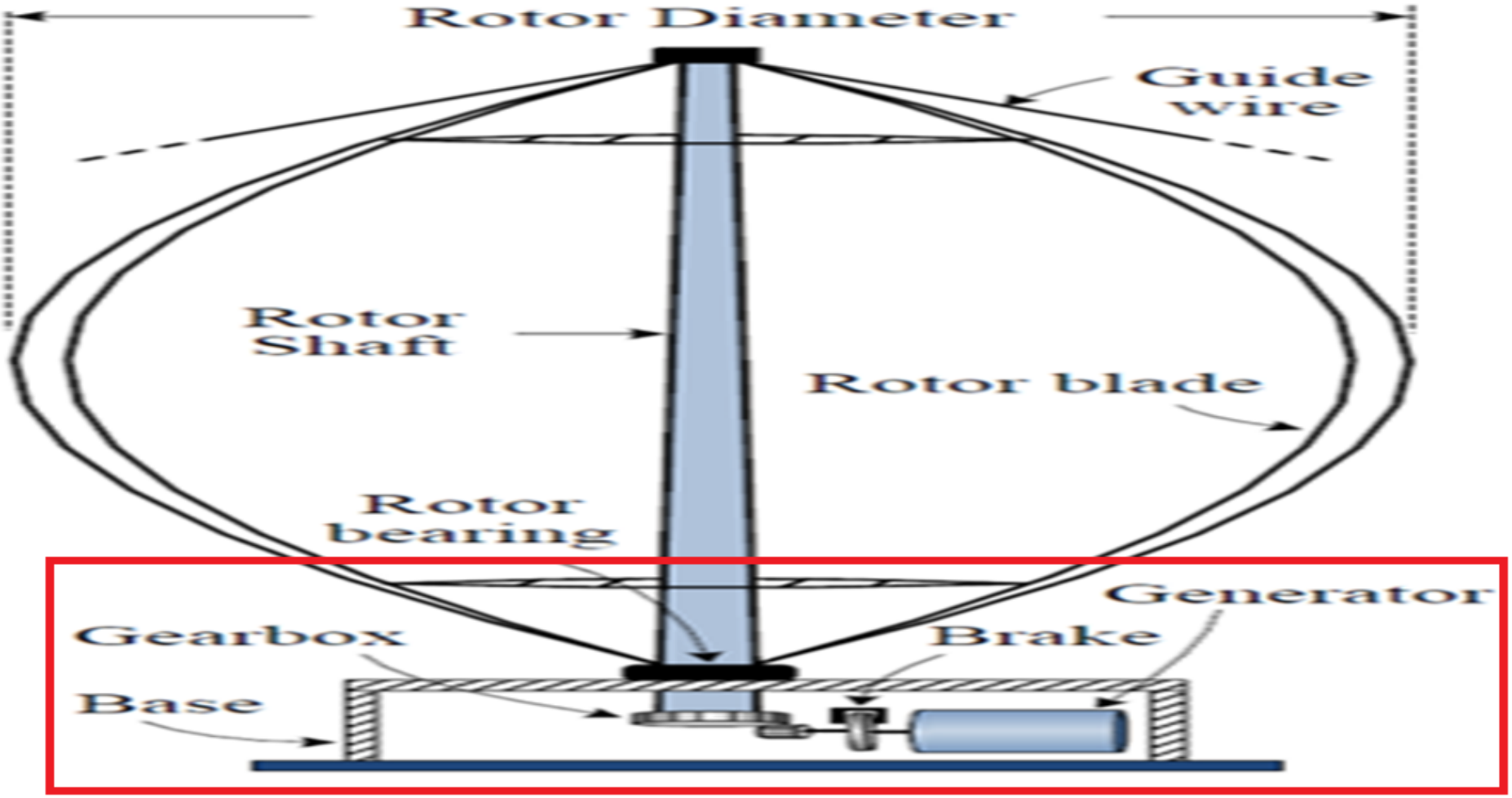
Pros & cons of Vertical-Axis Wind Turbines (VAWT)



1. Have advantage of lower installation costs

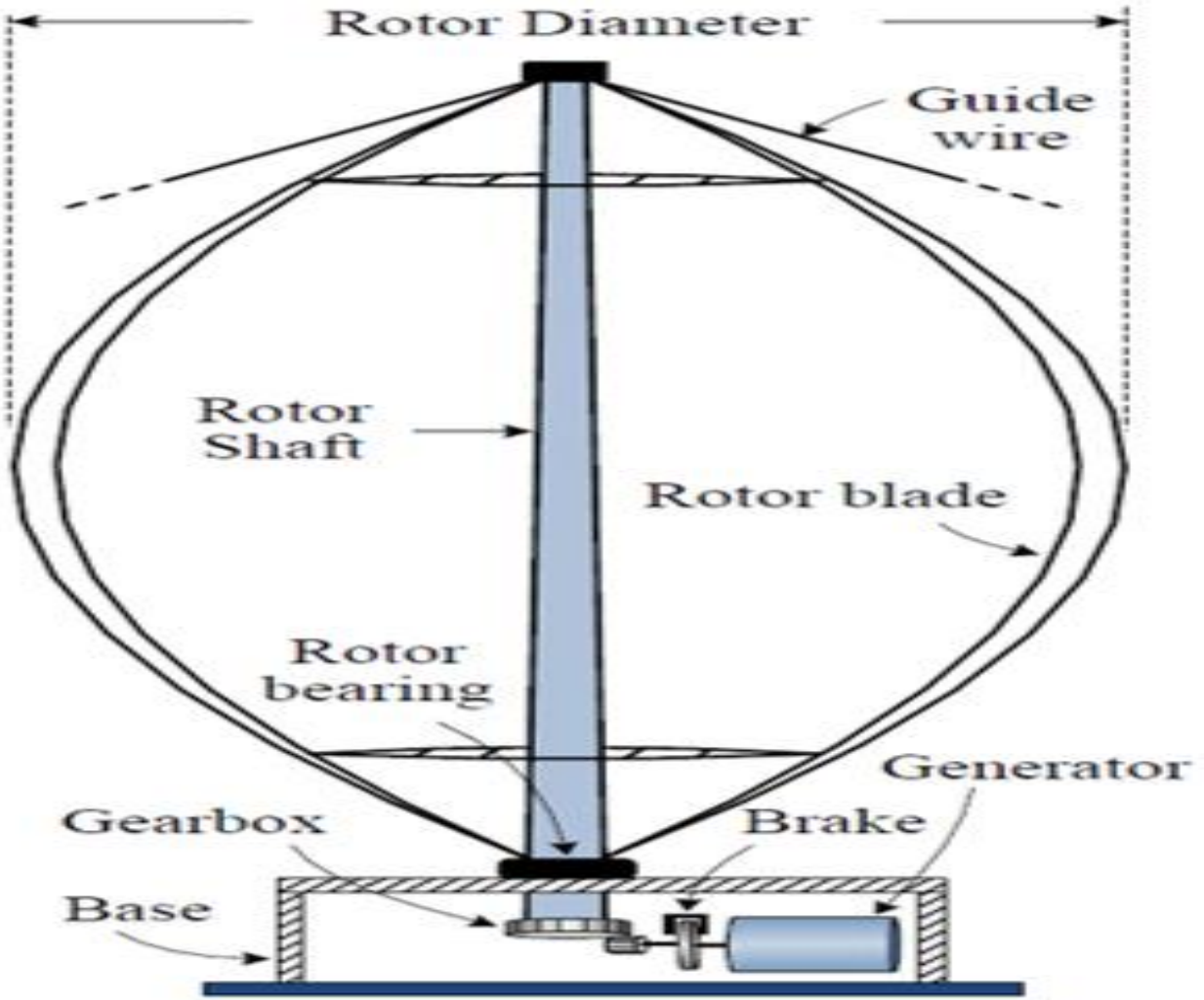


2.Easier maintenance due to ground level gearbox and generator installation,

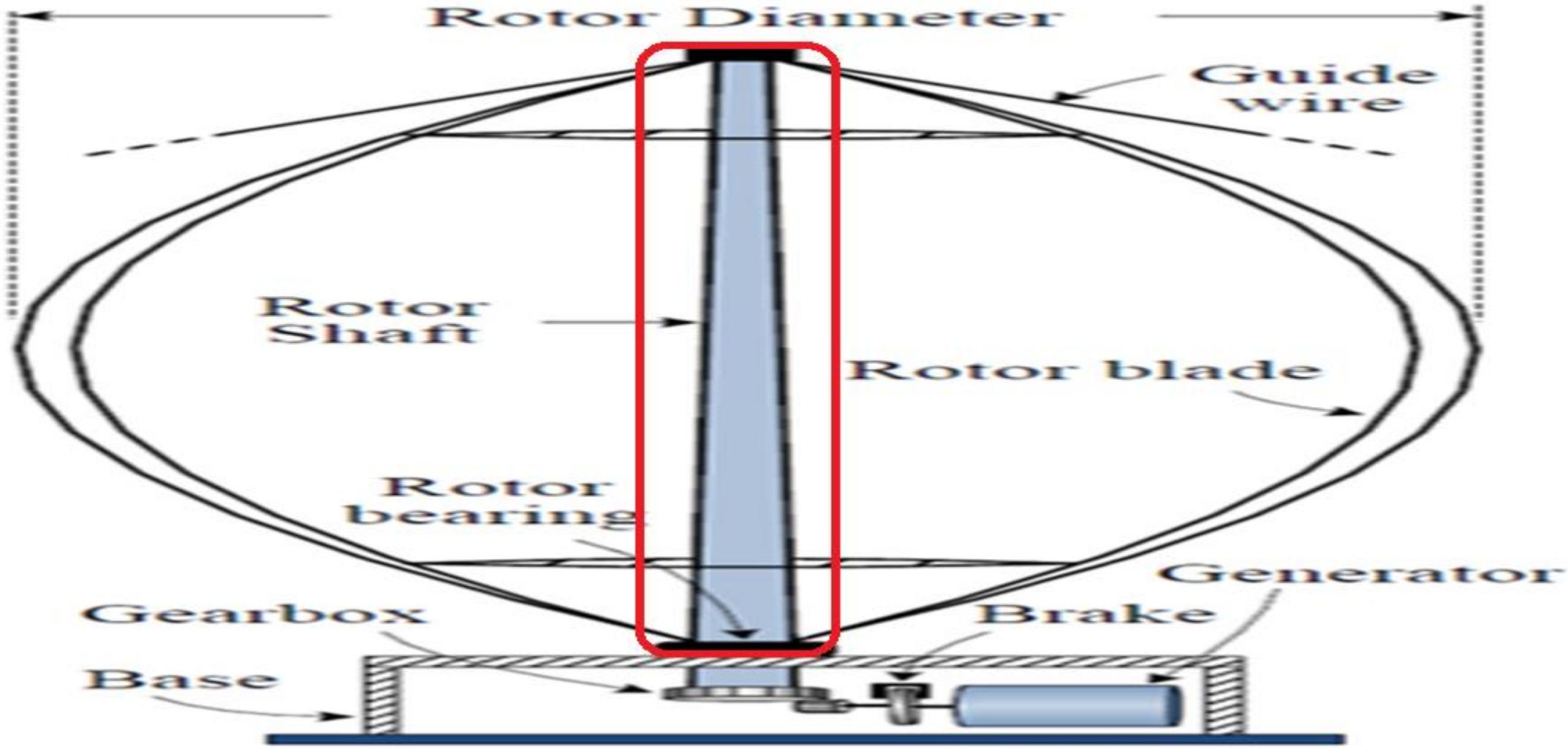


3. Wind energy conversion efficiency is lower

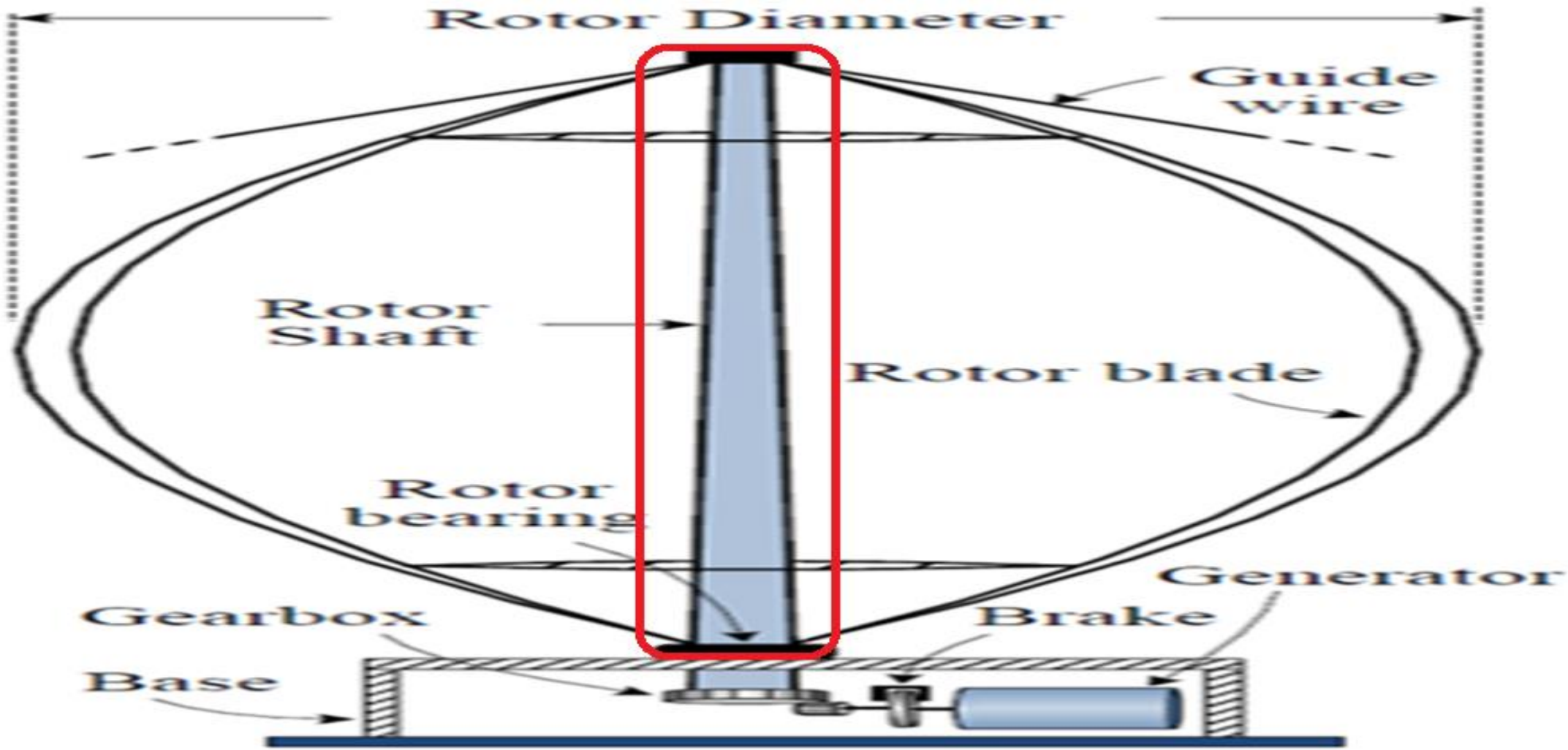
- Due to the weaker wind on lower portion of blades &
- limited aerodynamic performance of the blades.



4.Rotor shaft is long, which is prone to mechanical vibrations

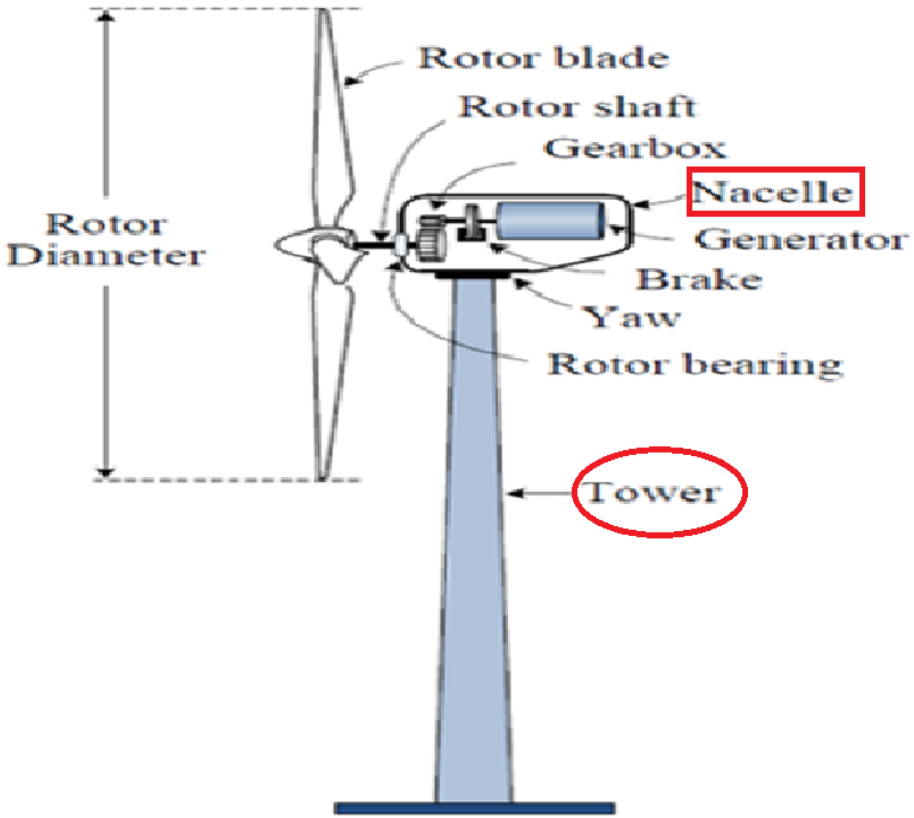


5. Both the Efficiency & installation cost are lower with easy maintenance

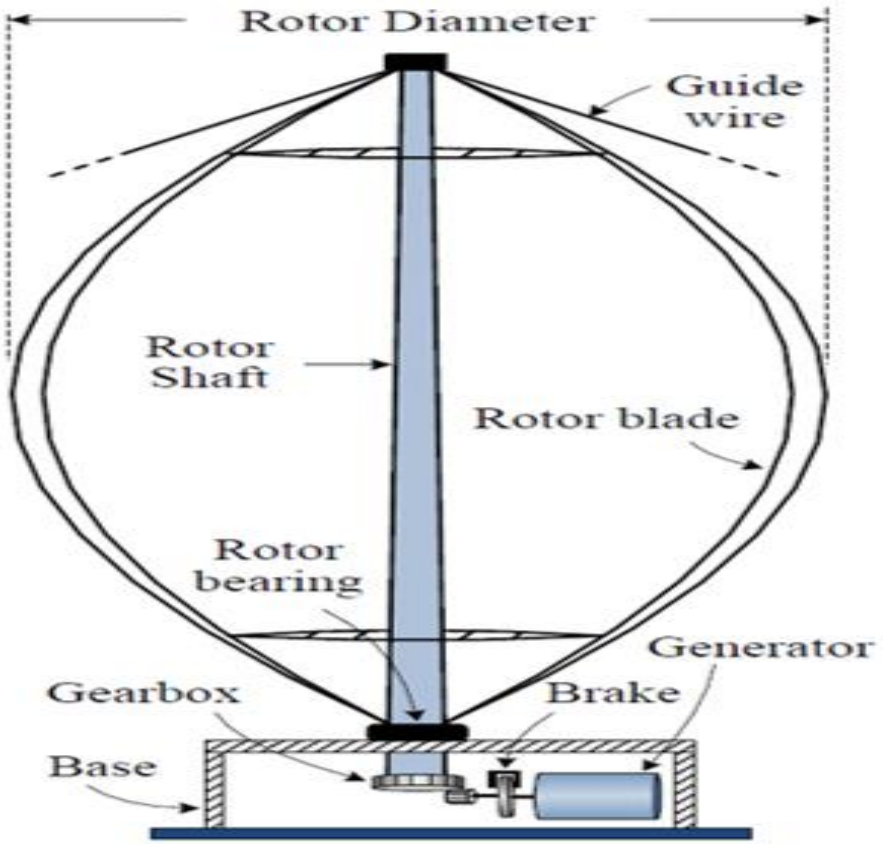


Which one should be used for Practical application?

Horizontal-Axis Wind Turbines (HAWT)

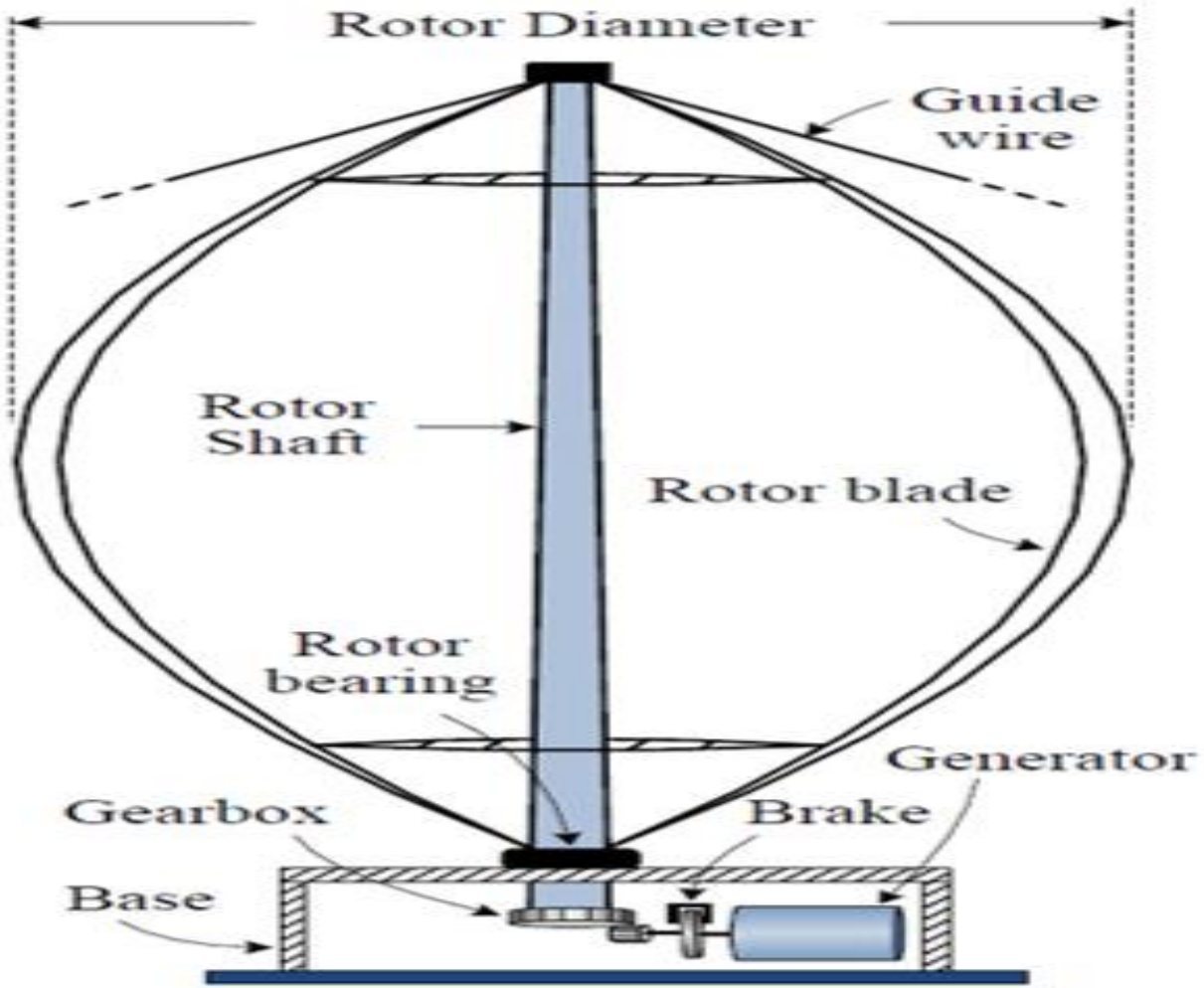


Vertical-Axis Wind Turbines (VAWT)



For large-scale wind energy conversion, vertical-axis turbines are not practical

- Horizontal-axis turbines dominate today's wind market,
- especially in large commercial wind farms.



Advantages of Horizontal Versus Vertical-Axis Wind Turbines

HAWT

1. Higher wind energy conversion efficiency.
2. Access to stronger wind due to high tower.
3. Power regulation by stall and pitch angle control at high wind speeds.

VAWT

1. Lower installation cost and easier maintenance due to ground level gearbox and generator.
2. Operation independent of wind direction
3. Suitable for roof tops(stronger wind without need of tower).

Disadvantages of Horizontal Versus Vertical-Axis Wind Turbines

HAWT

1. Higher installation cost, stronger tower to support heavy weight of nacelle.
2. Longer cable from the top of tower to ground
3. Orientation required (yaw control)

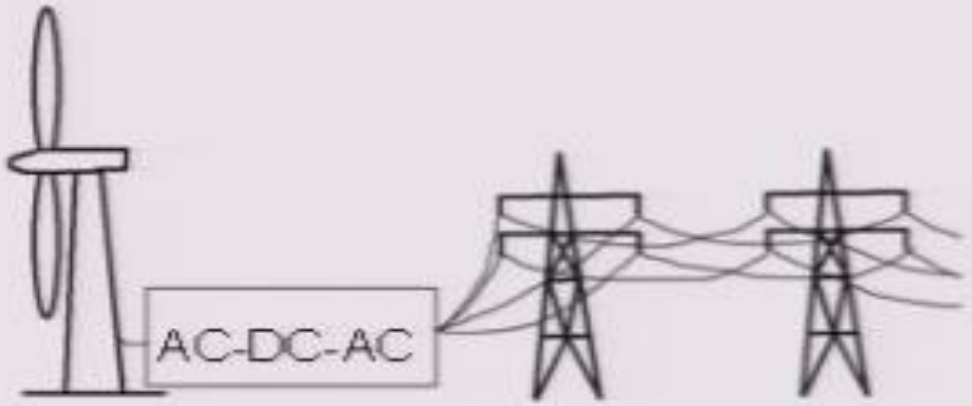
VAWT

1. Lower wind energy conversion efficiency.
2. Higher torque fluctuations & prone to mechanical vibrations.
3. Limited options for power regulation at high wind speeds

1.3.2 Fixed &Variable-speed Turbines

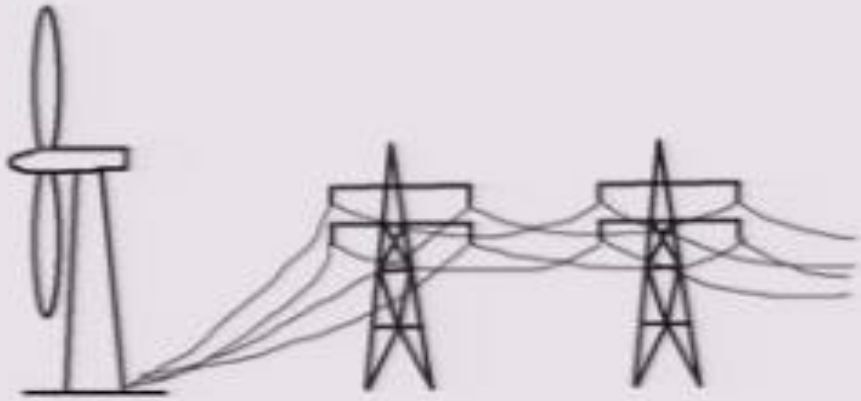
variable speed

- requires power electronics between generator and grid, with controllable grid connection
- rotor acts as flywheel to peak-shave load variations



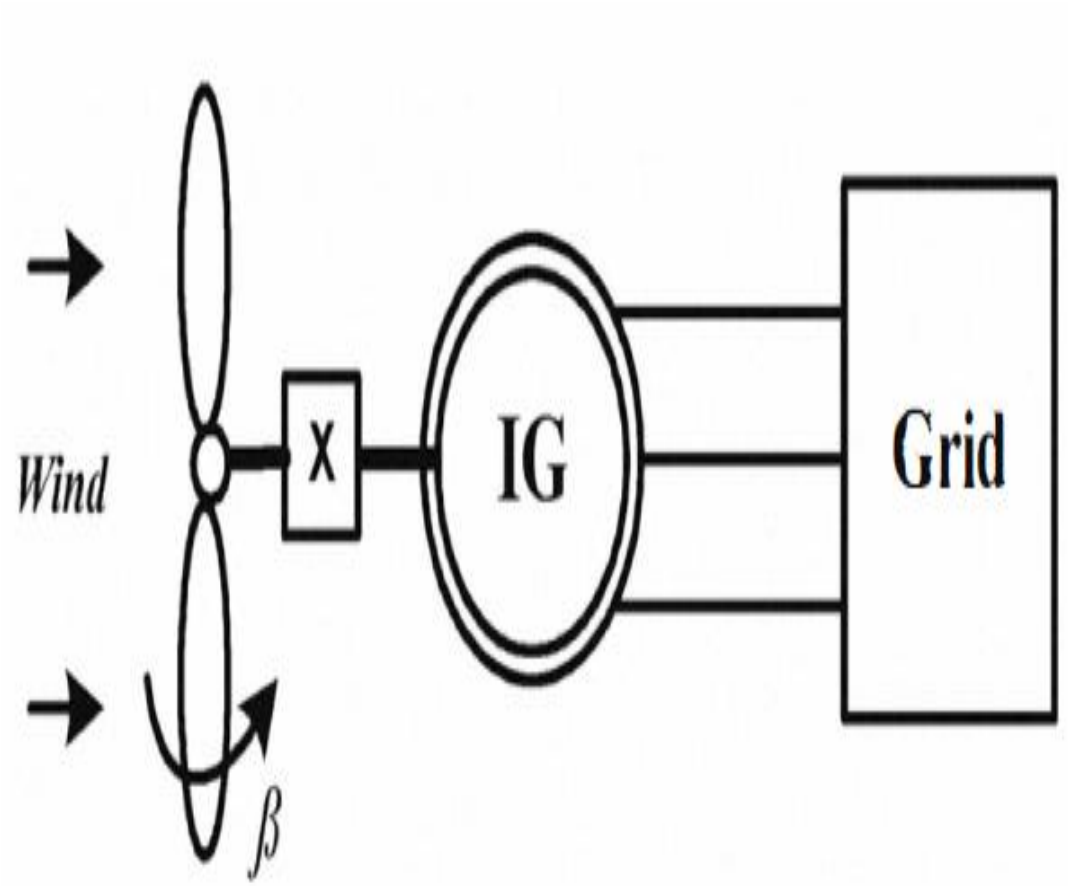
constant speed

- generator directly coupled to the grid, no control of reactive power and grid distortion.
- easy construction, but without any softness between rotor and grid



Features of fixed speed Turbines

- In the past we used fixed speed turbines for the production of electric energy.



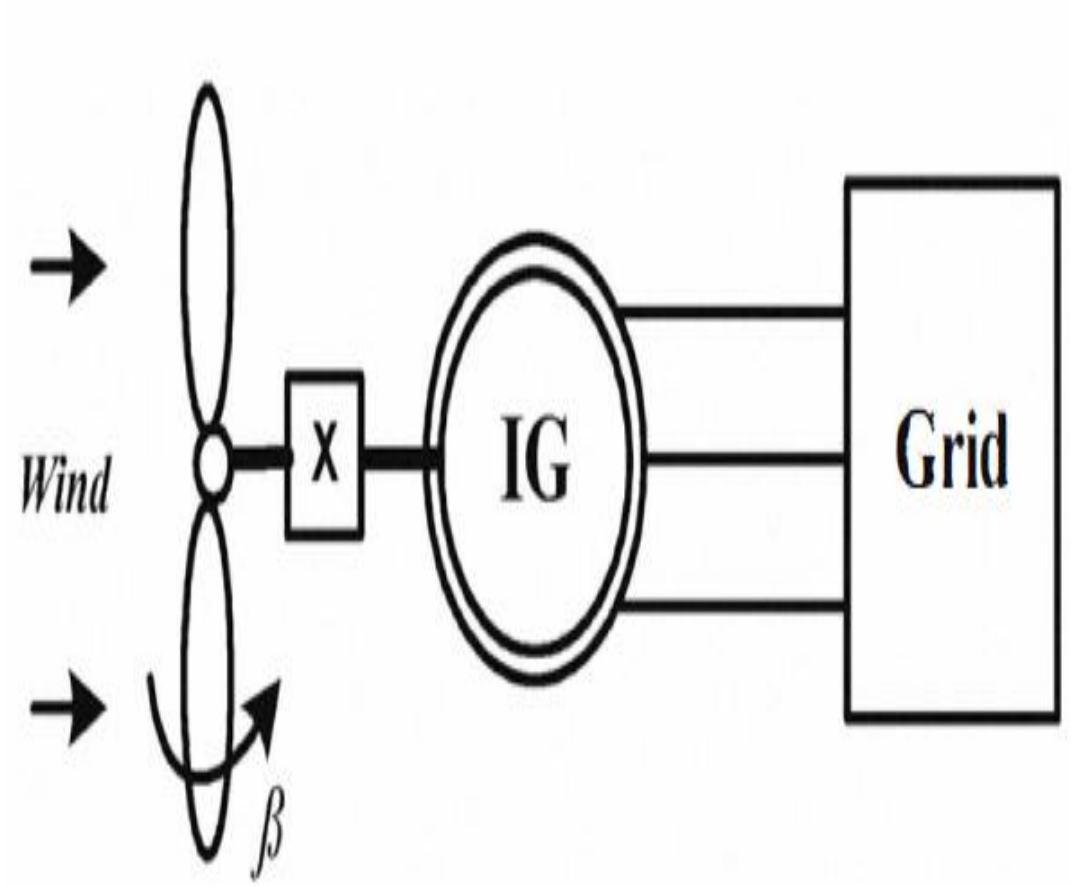
Features of fixed speed Turbines

1-They rotate at almost a constant speed, which is determined by:

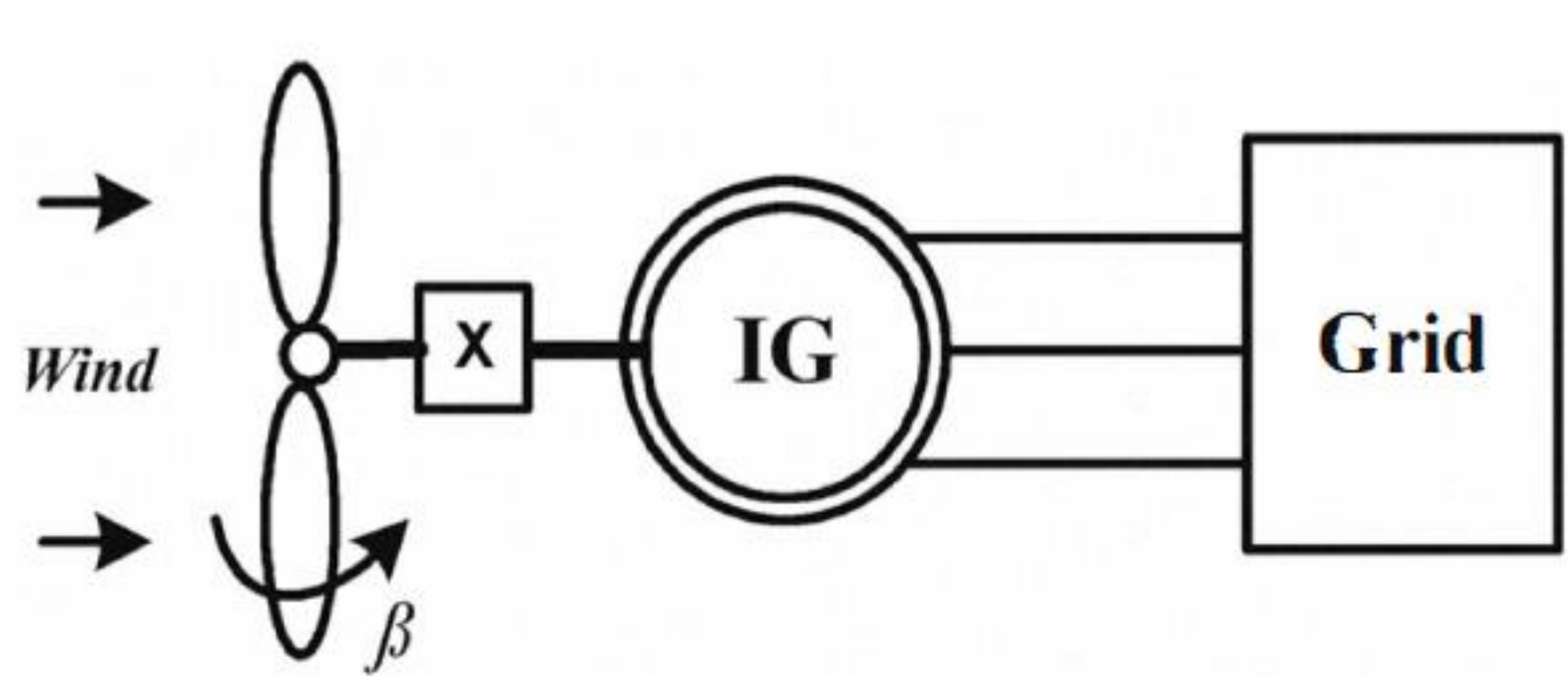
i. gear ratio

ii. grid frequency &

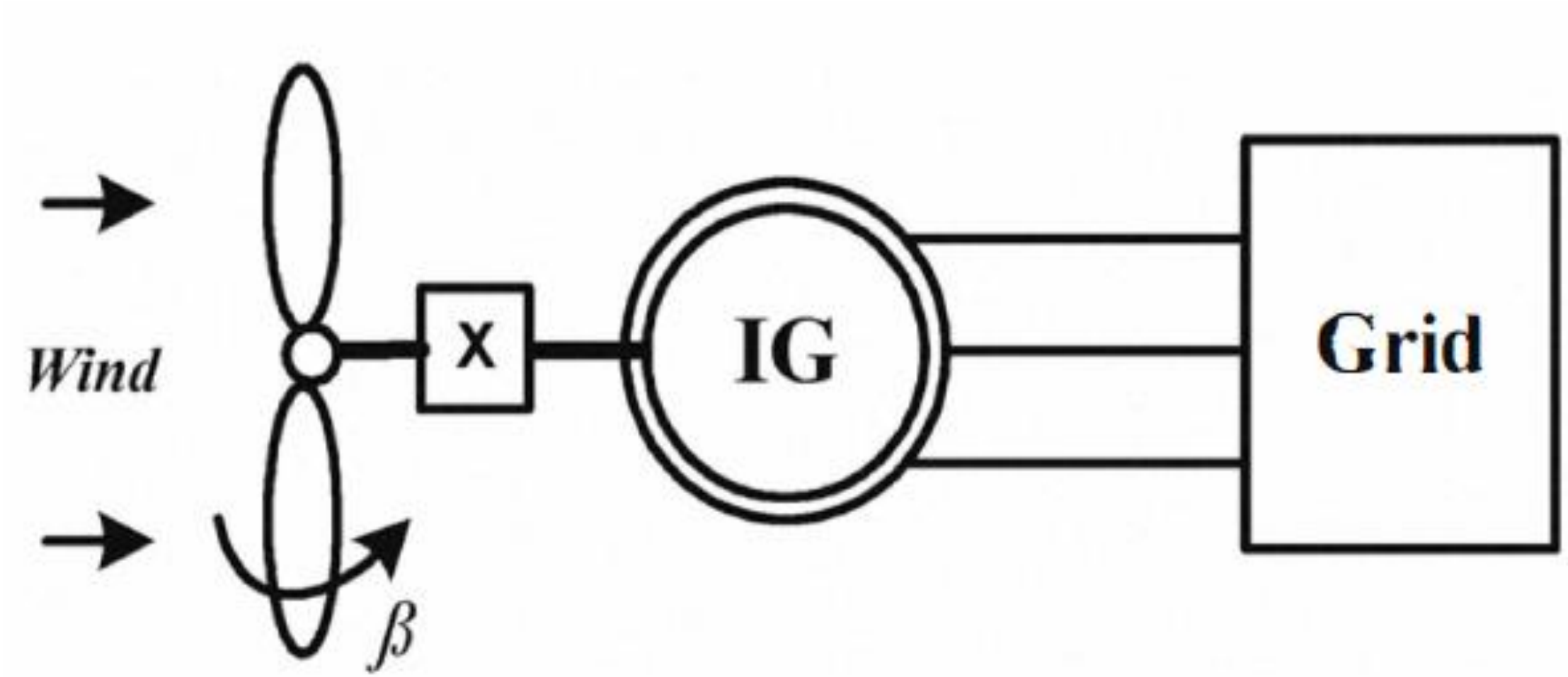
iii. number of poles of generator.



Derive an equation involving (i) constant speed (ii)frequency &(iii) No.of poles?

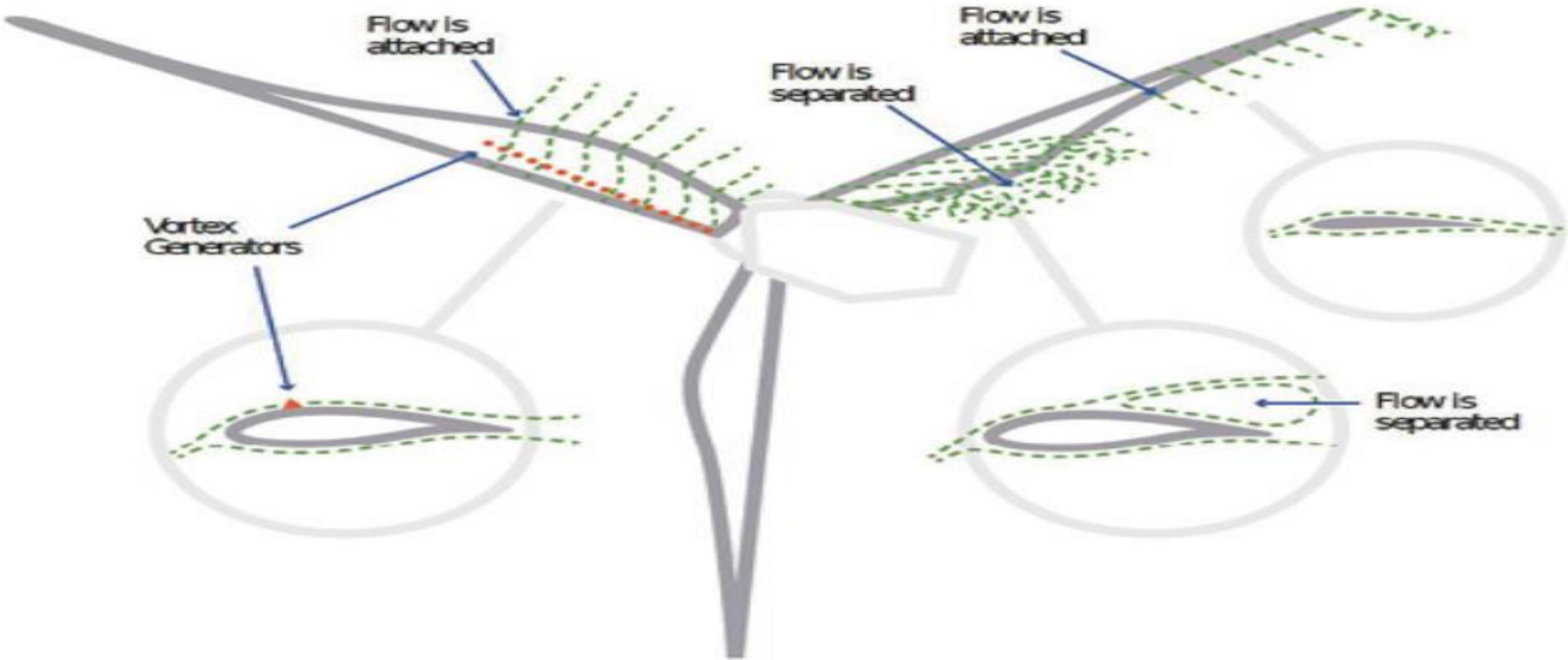


N=120f/p

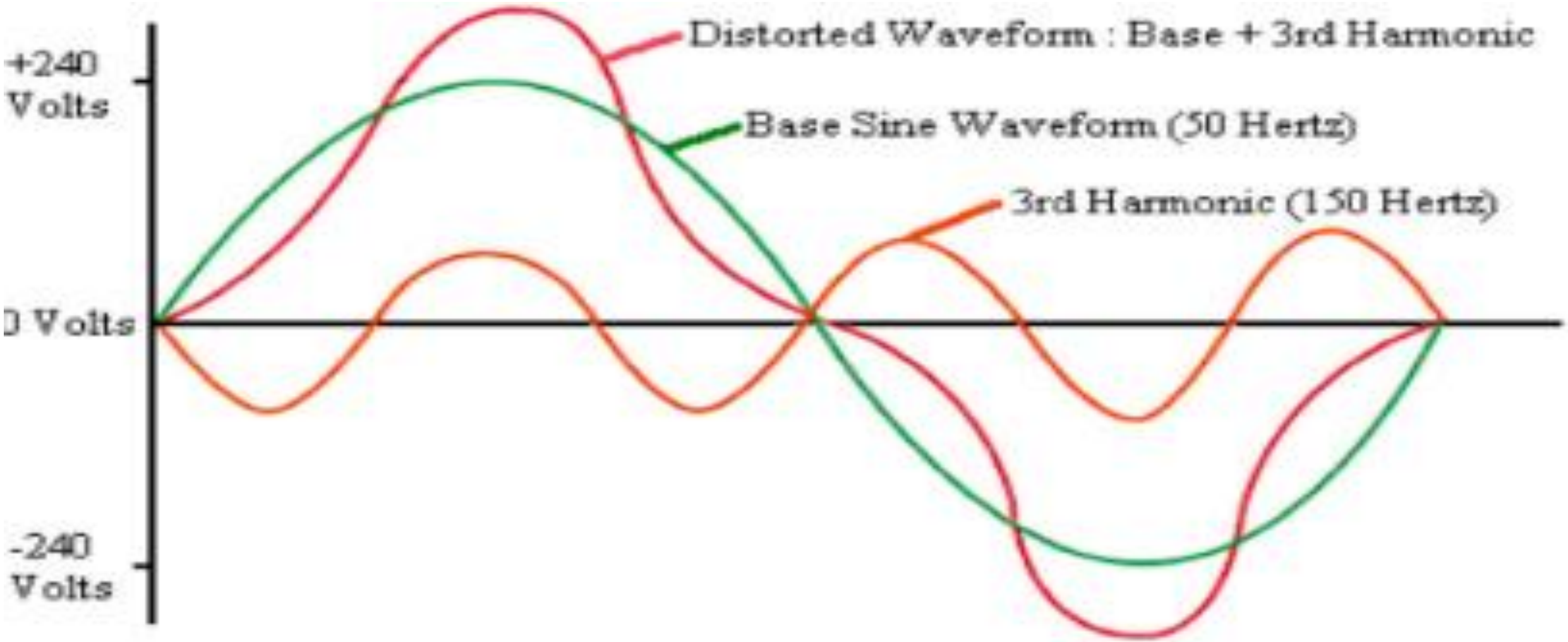


2-Maximum conversion efficiency can be achieved only at its designed wind speed.

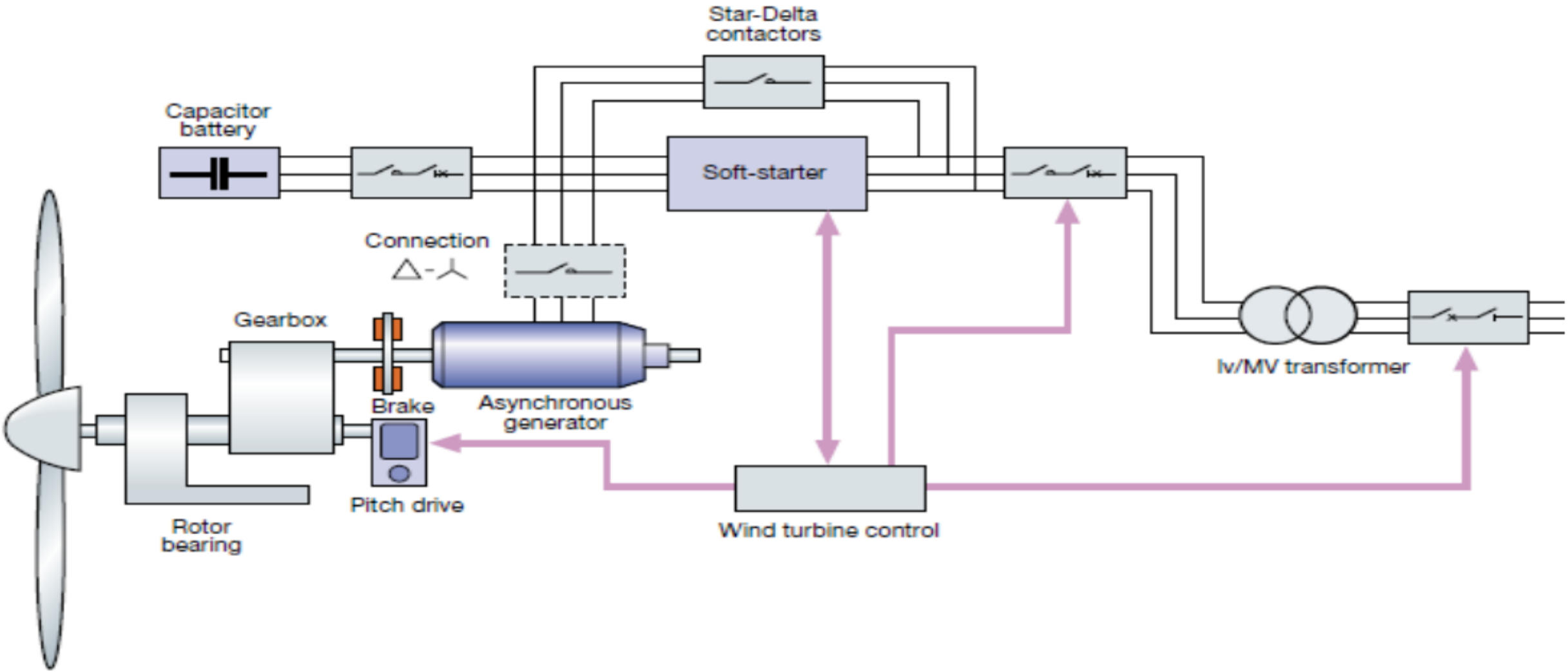
3-Turbine is protected by aerodynamic control of blades from possible damage caused by high wind gusts.



4-Fixed-speed turbine generates highly fluctuated output power to grid causing disturbances to power system.

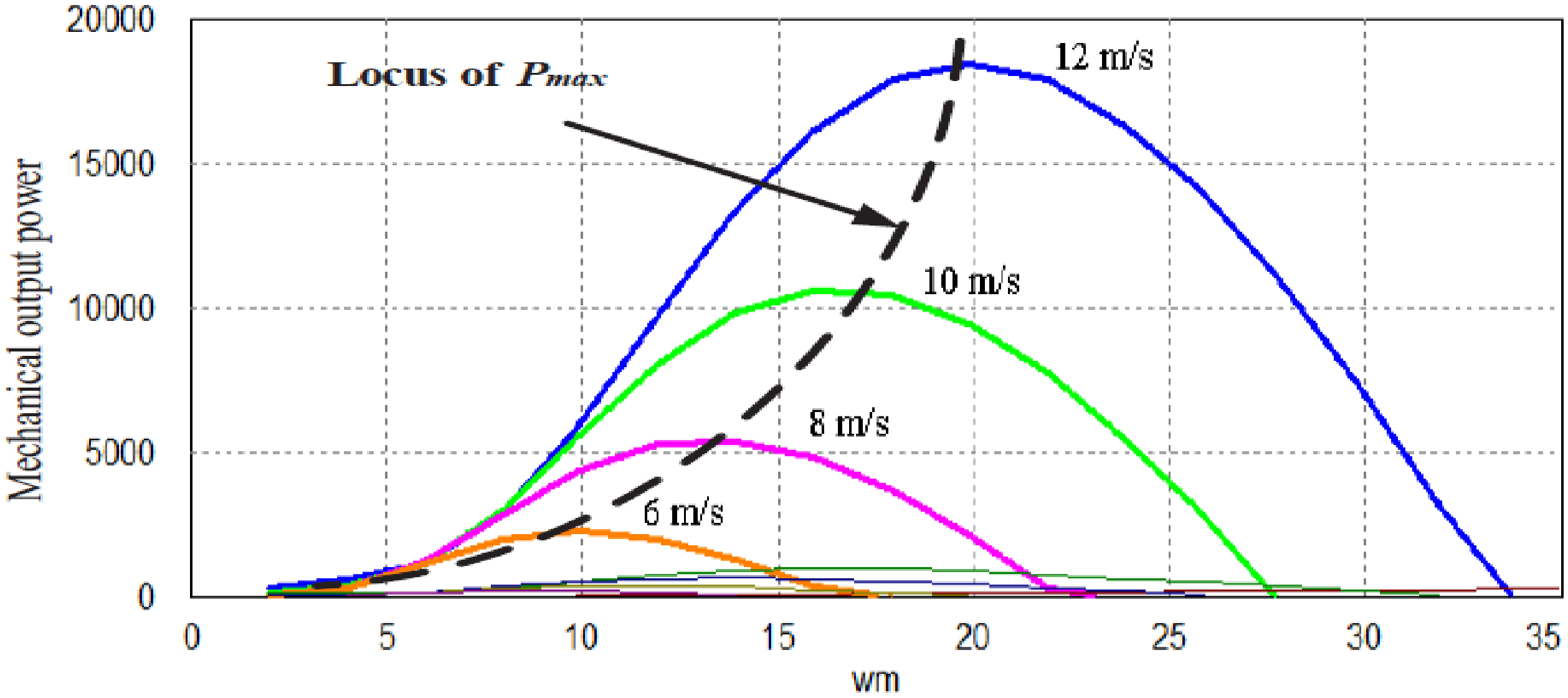


5-Requires a sturdy mechanical design in order to absorb high mechanical stresses.



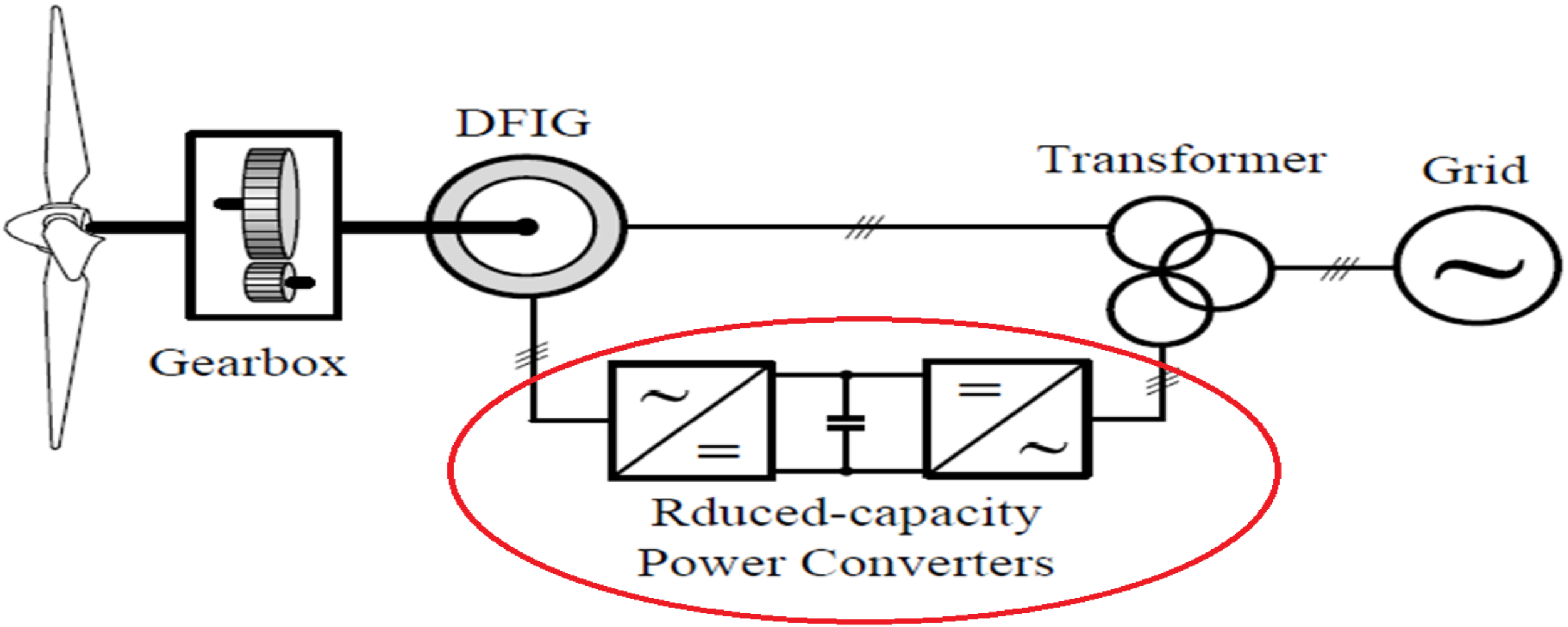
Features of Variable speed Turbines:

1-can achieve maximum energy conversion efficiency over a wide range of windspeeds.

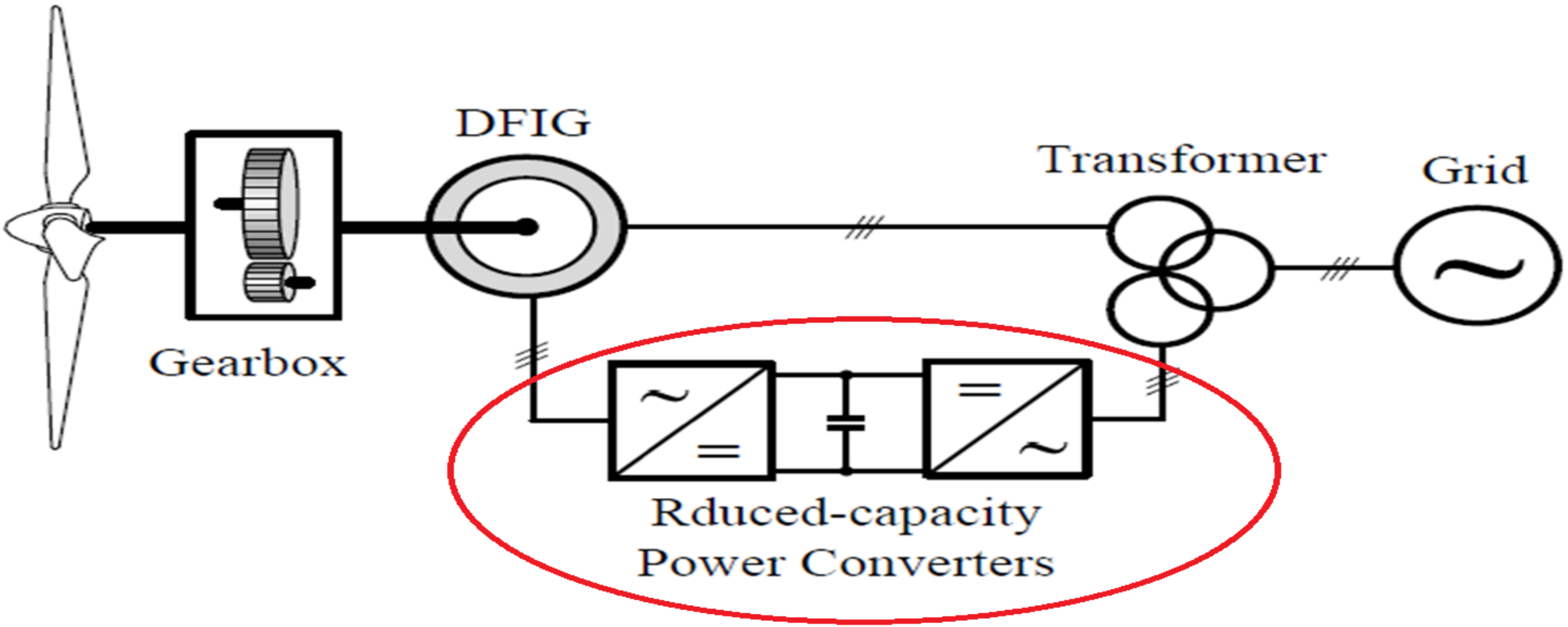


2-can continuously adjust its rotational speed according to the wind speed.

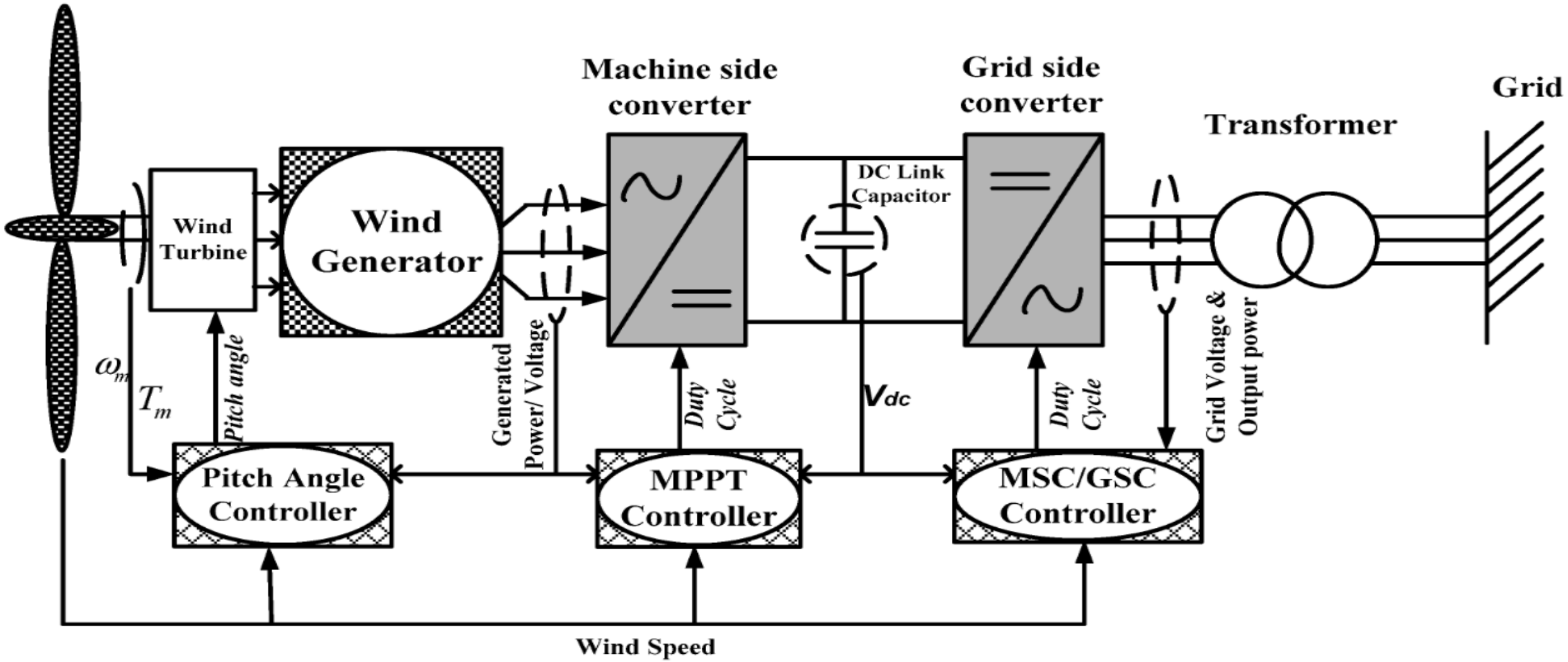
Q. For making turbine speed adjustable what should we do?



Answer. Wind turbine generator must be connected to grid through power converter



Converter controls the speed of the generator i.e mechanically coupled to the rotor (blades) of the wind turbine.



Write 3 main advantages of variable-speed turbine?

3 main advantages of variable-speed turbine

1. increased wind energy output,
2. improved power quality and
3. reduced mechanical stress

Write 2 main drawbacks of variable-speed turbine?

2 main drawbacks of variable-speed turbine?

1.Increased manufacturing cost

2. Power losses due to use of power converters.

Additional cost & power losses can be compensated by:

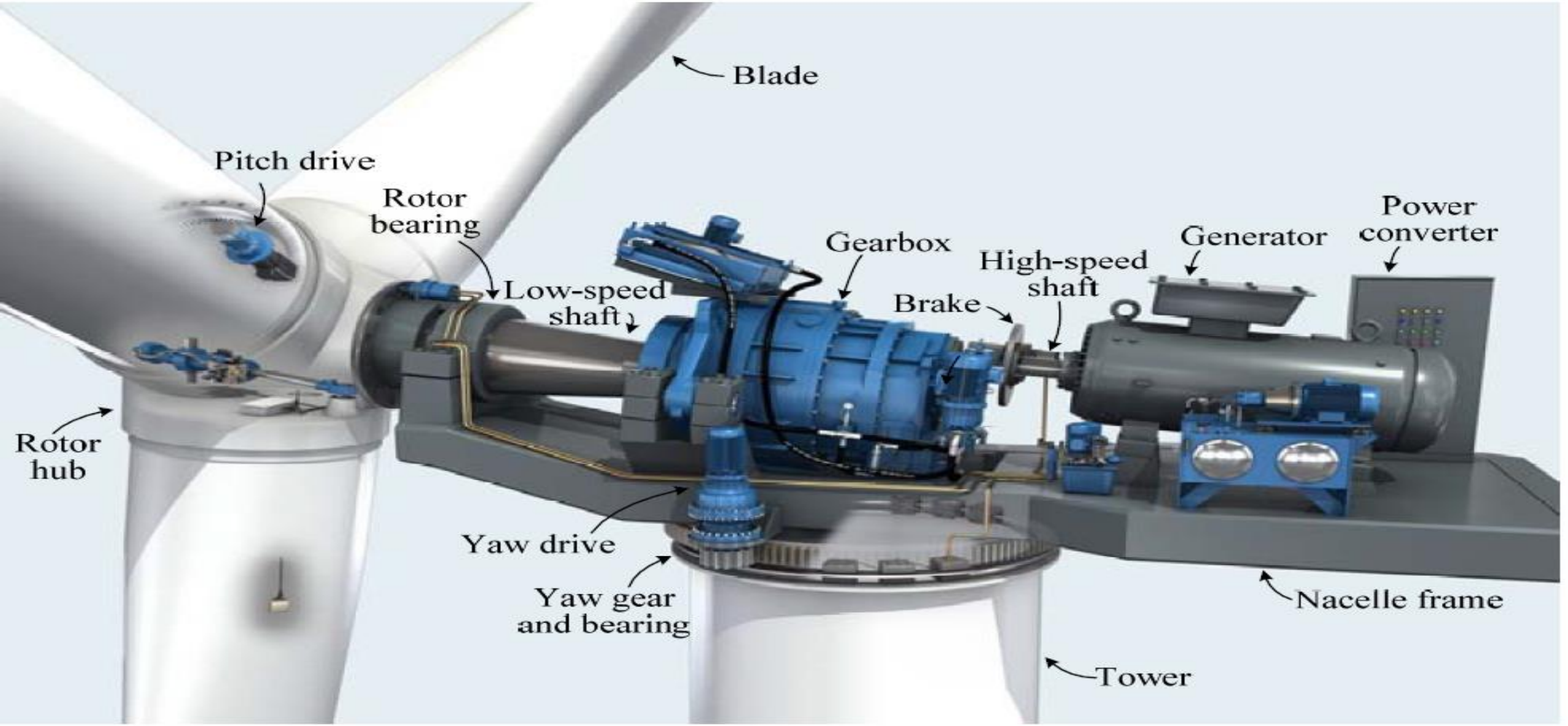
Additional cost & power losses can be compensated by:

- **higher energy production.**

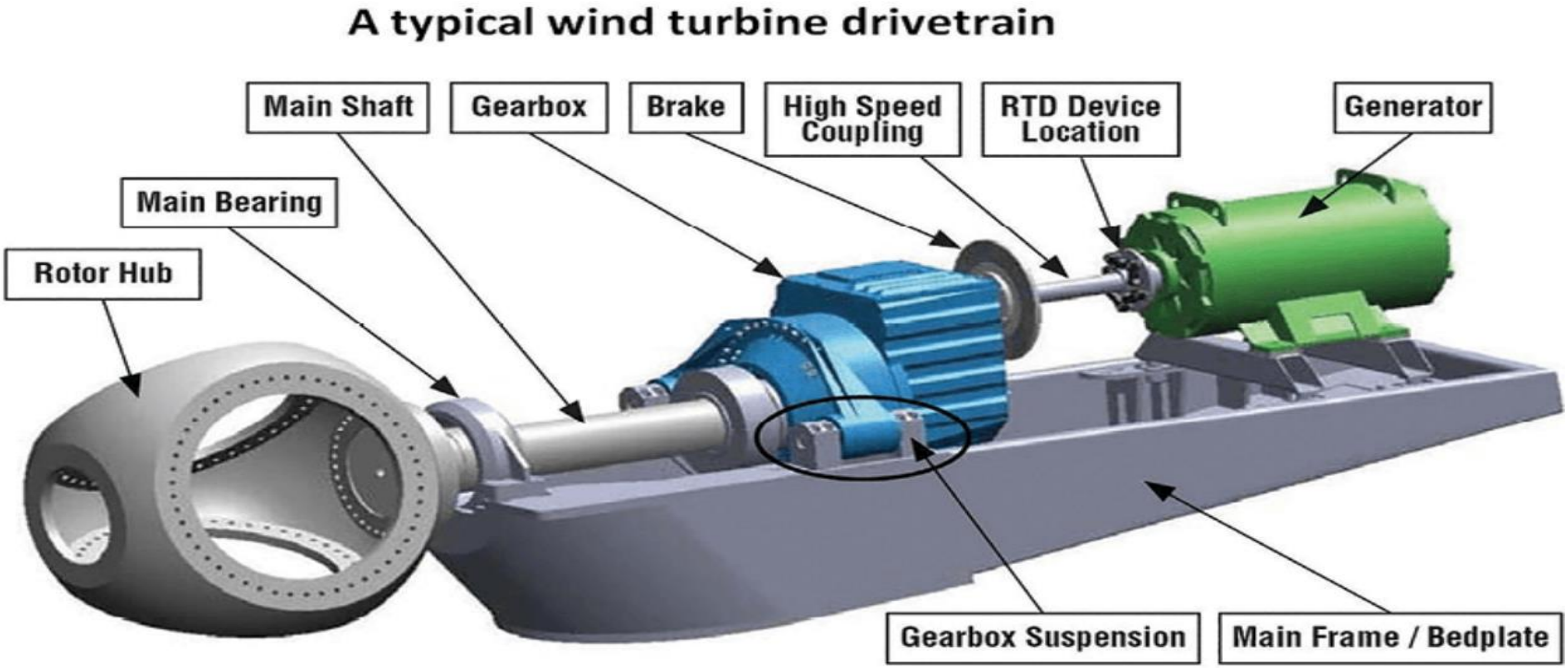
Variable-speed turbines dominate market because:

- Smoother operation provided by:
- controlled generator reduces mechanical stress on:

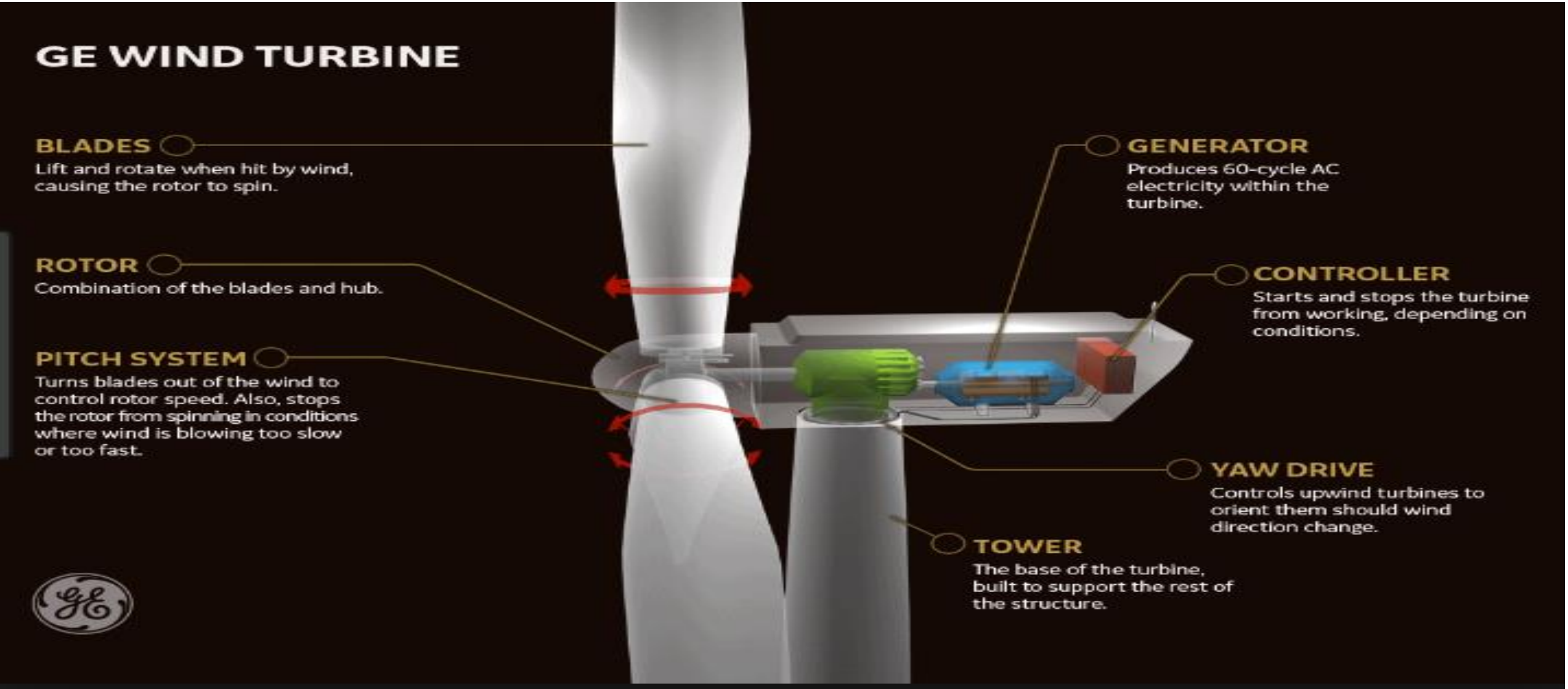
1. Turbine


Blade
Pitch drive
Rotor bearing
Low-speed shaft
Gearbox
Brake
High-speed shaft
Generator
Power converter
Rotor hub
Yaw drive
Yaw gear and bearing
Nacelle frame
Tower

2. Drive train



3.Supporting structure.

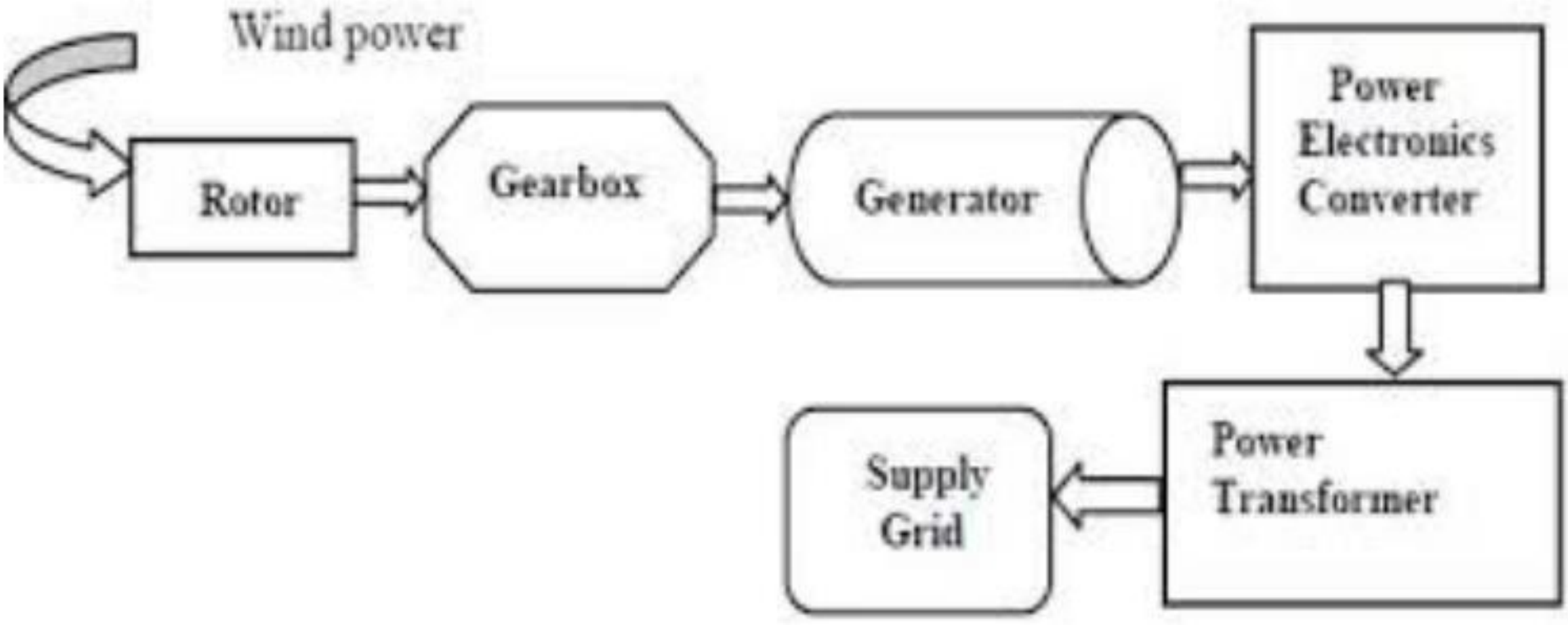


That`s why manufacturers develop larger wind turbines as they are more cost effective.

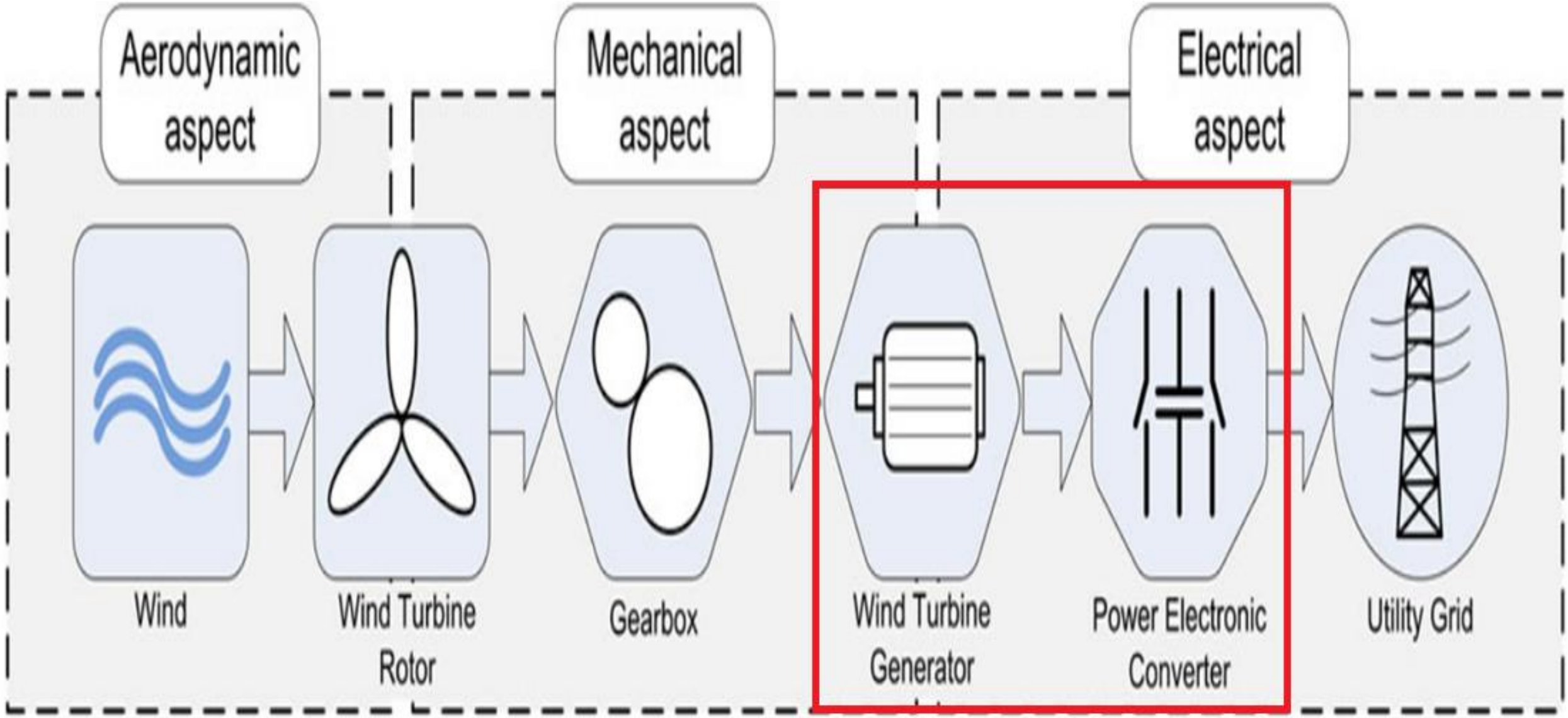
Main advantages & disadvantages of fixed & variable-speed turbine

Speed mode	Advantages	Disadvantages
Fixed Speed	• Simple, robust, reliable • Low cost and maintenance	• Relatively low energy conversion efficiency • High mechanical stress • High power fluctuations to the grid
Variable Speed	• High energy conversion efficiency • Improved power quality • Reduced mechanical stress	• Additional cost and losses due to use of converters • More complex control system

1.4 WECS Configurations

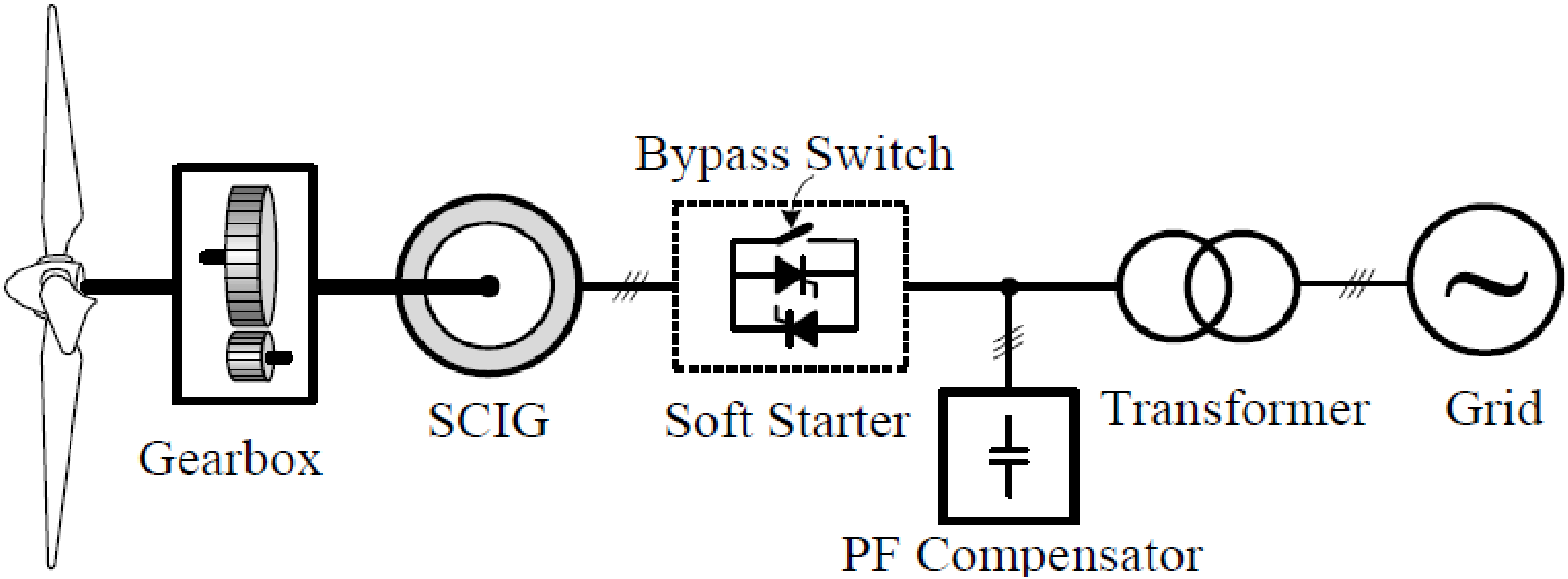


Generator & power converter in a WECS are 2 main electrical components.

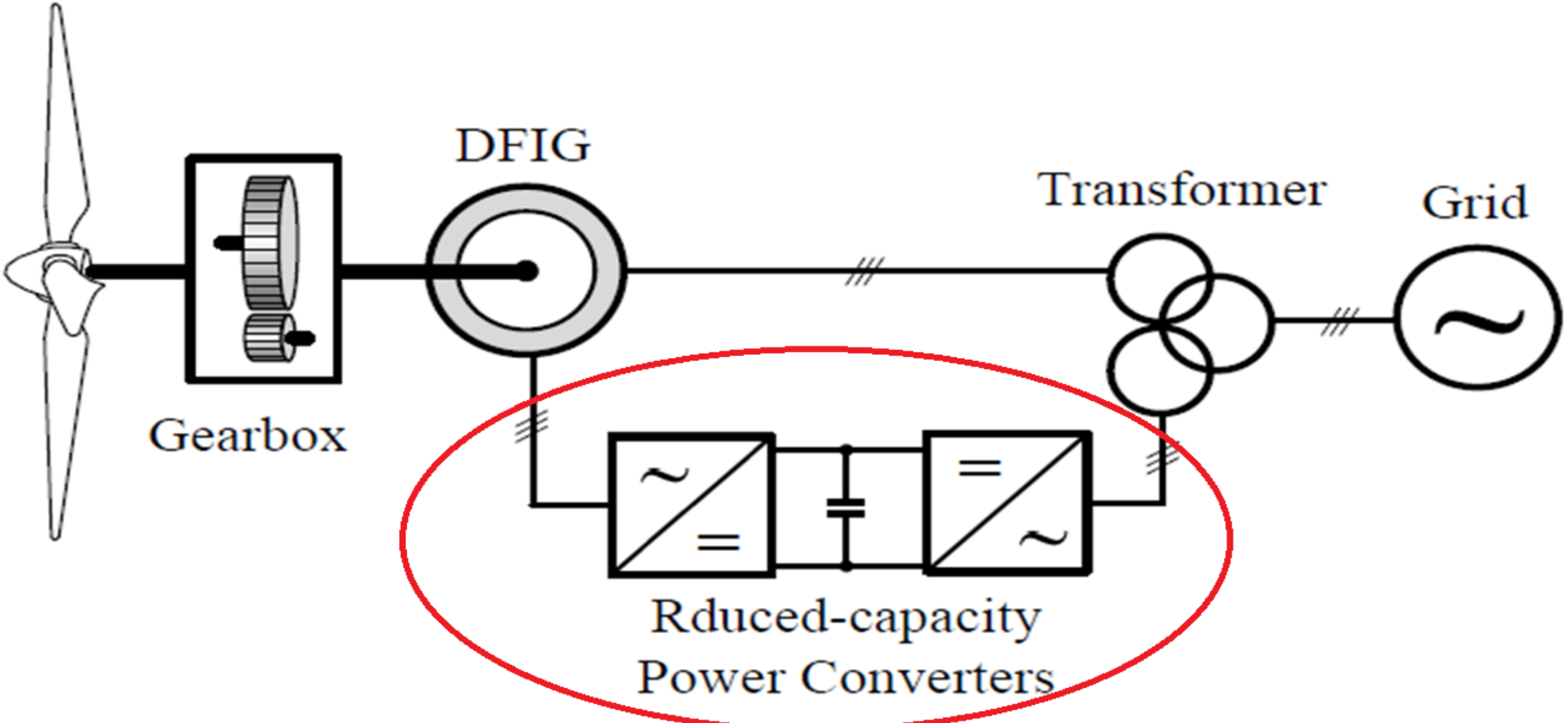


Different designs & combinations of generator with power converter lead to a wide variety of WECS configurations:

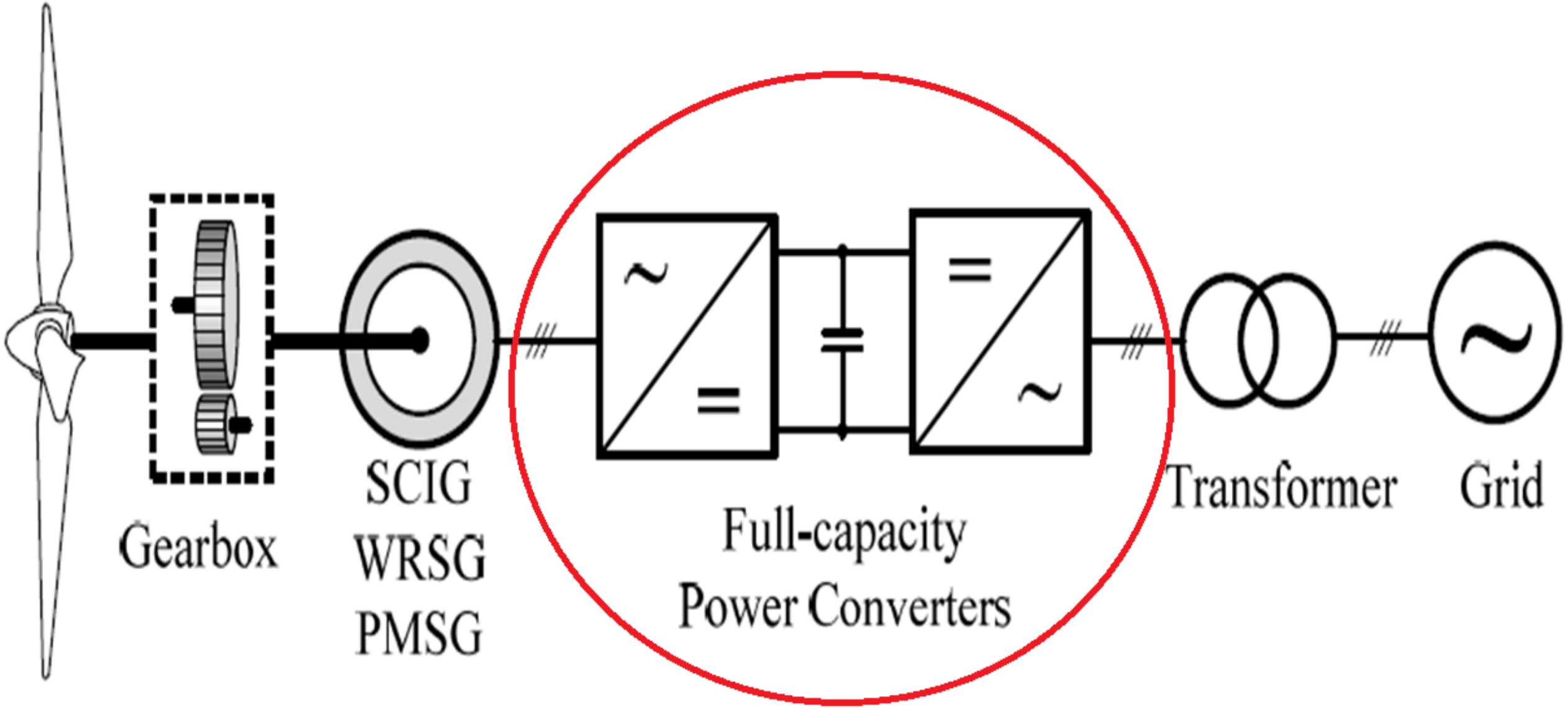
1) Fixed-speed WECS without power converter interface.



2) Variable-speed WECS using reduced-capacity converters



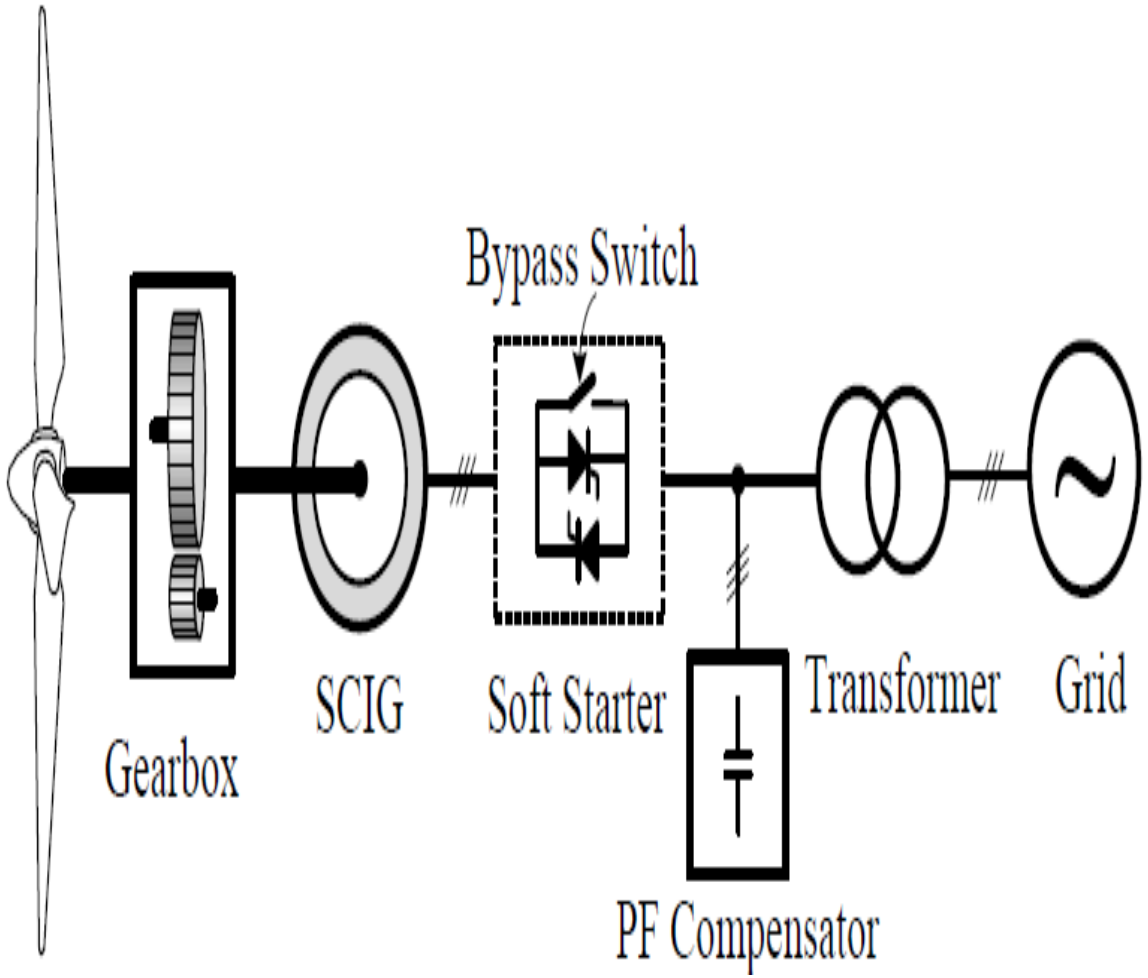
3) Variable-speed WECS using Full-capacity converter



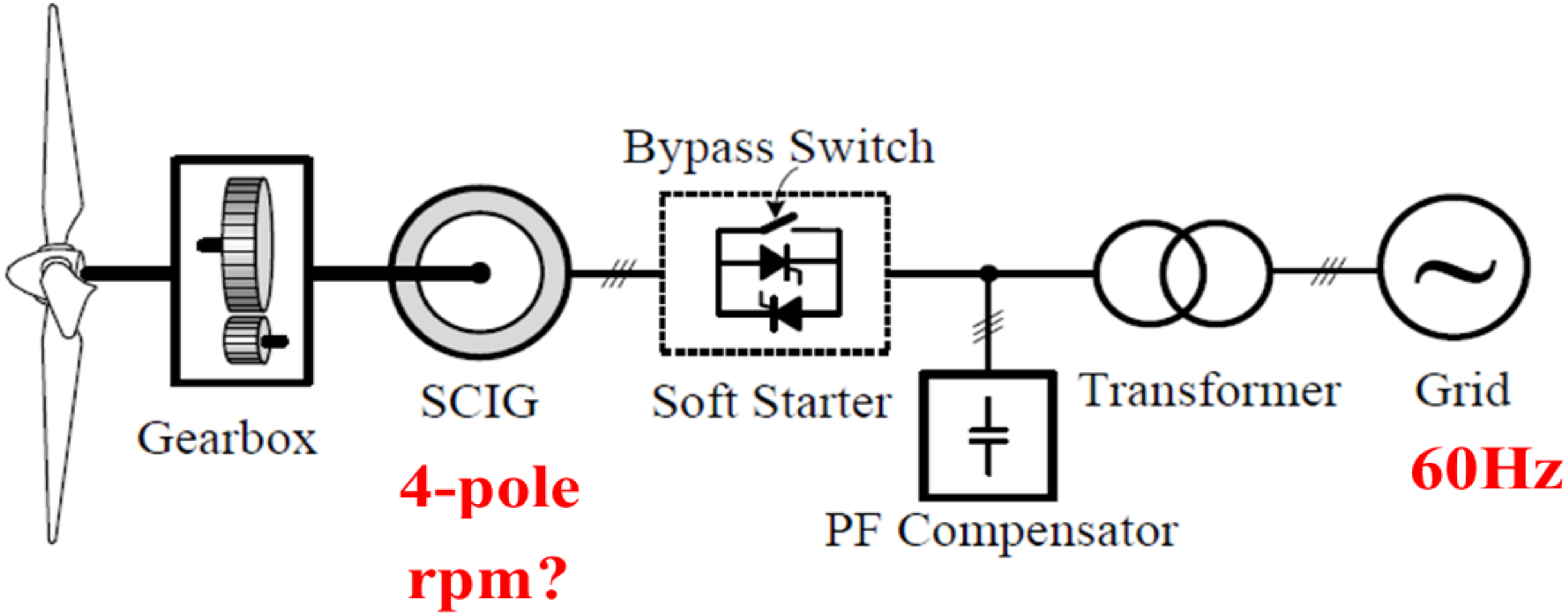
1.4.1 Fixed-speed WECS without Power Converter Interface

- Rotational speed of Squirrel Cage Induction Generator (SCIG) is determined by:

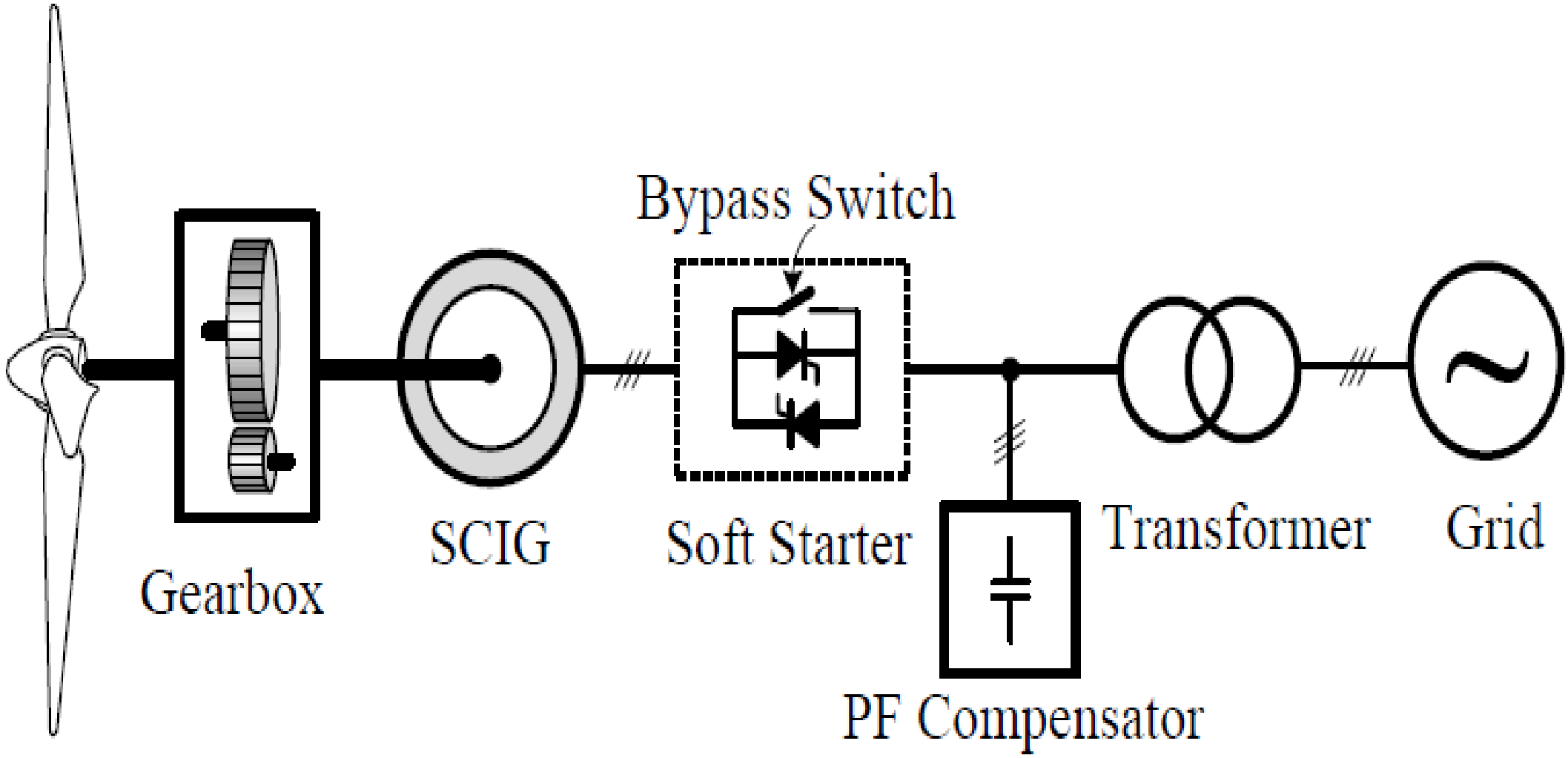
1. **grid frequency &**
2. **number of poles of stator winding**.



For 4-pole MW generator connected to grid of 60Hz, generator operates at a speed slightly higher than -------- rpm?

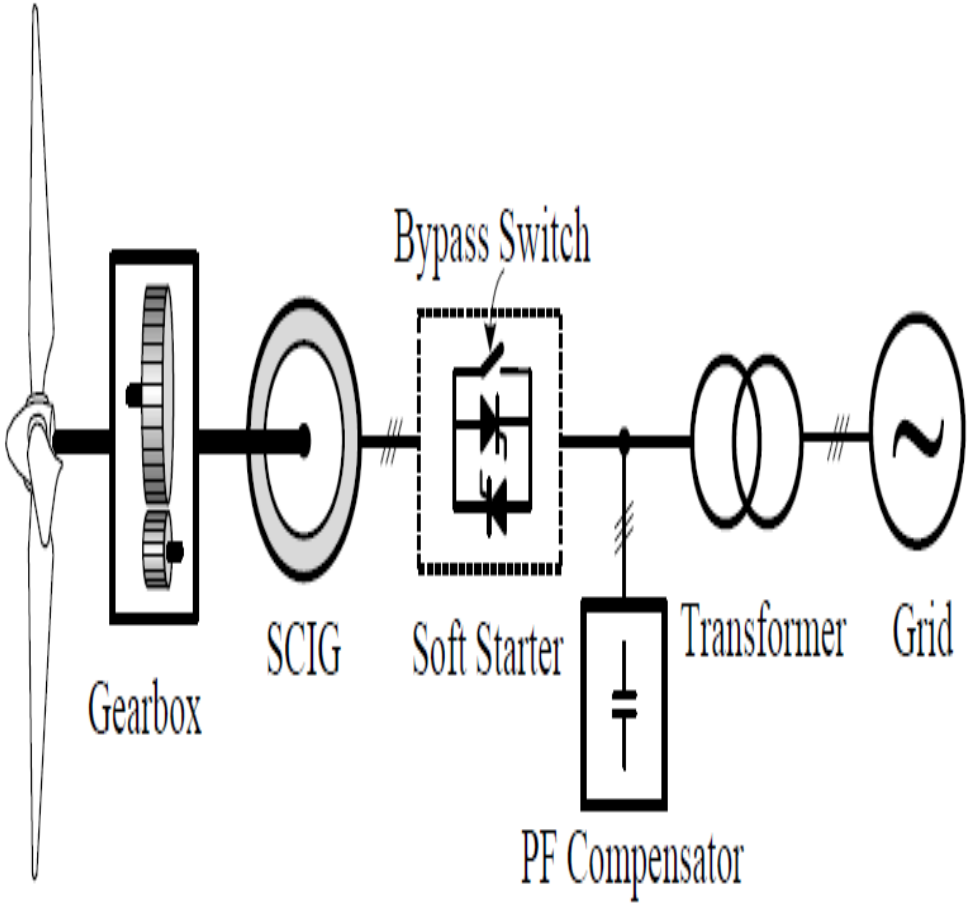


Why this system is called a fixed-speed WECS?

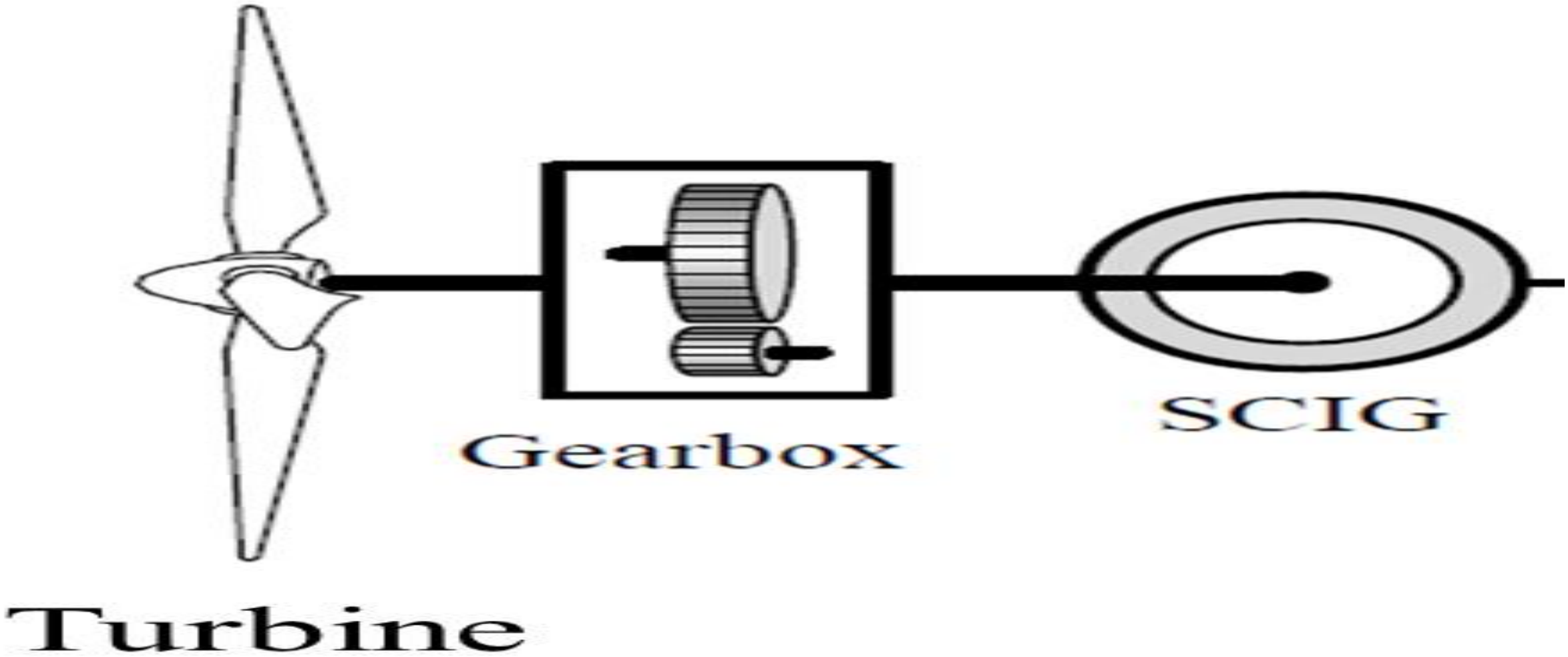


Why this system is called a fixed-speed WECS?

- At different wind speeds, generator speed varies within 1% of its rated speed
- so this variation is so small
- That's why this system is known as a fixed-speed WECS.

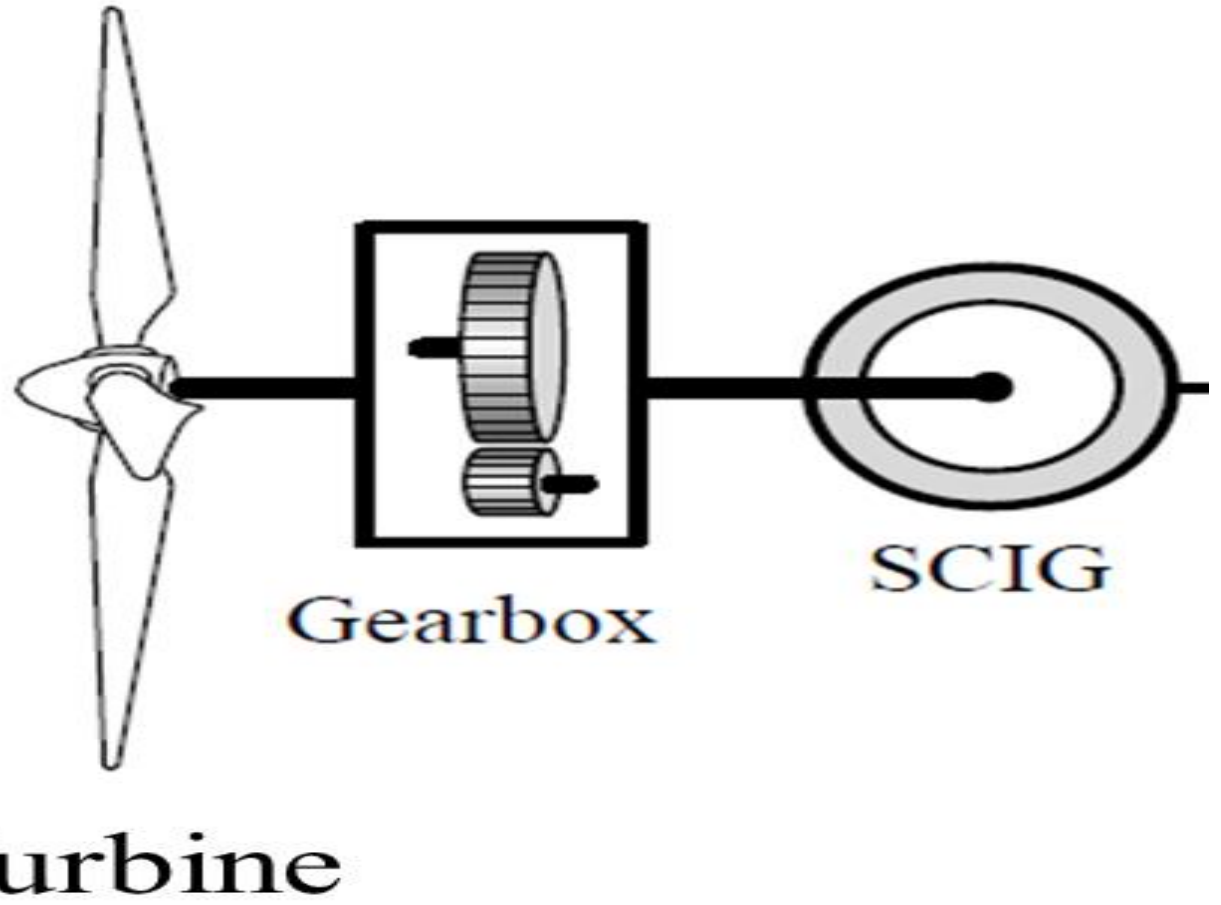


What is the essence of gearbox?



Essence of gearbox

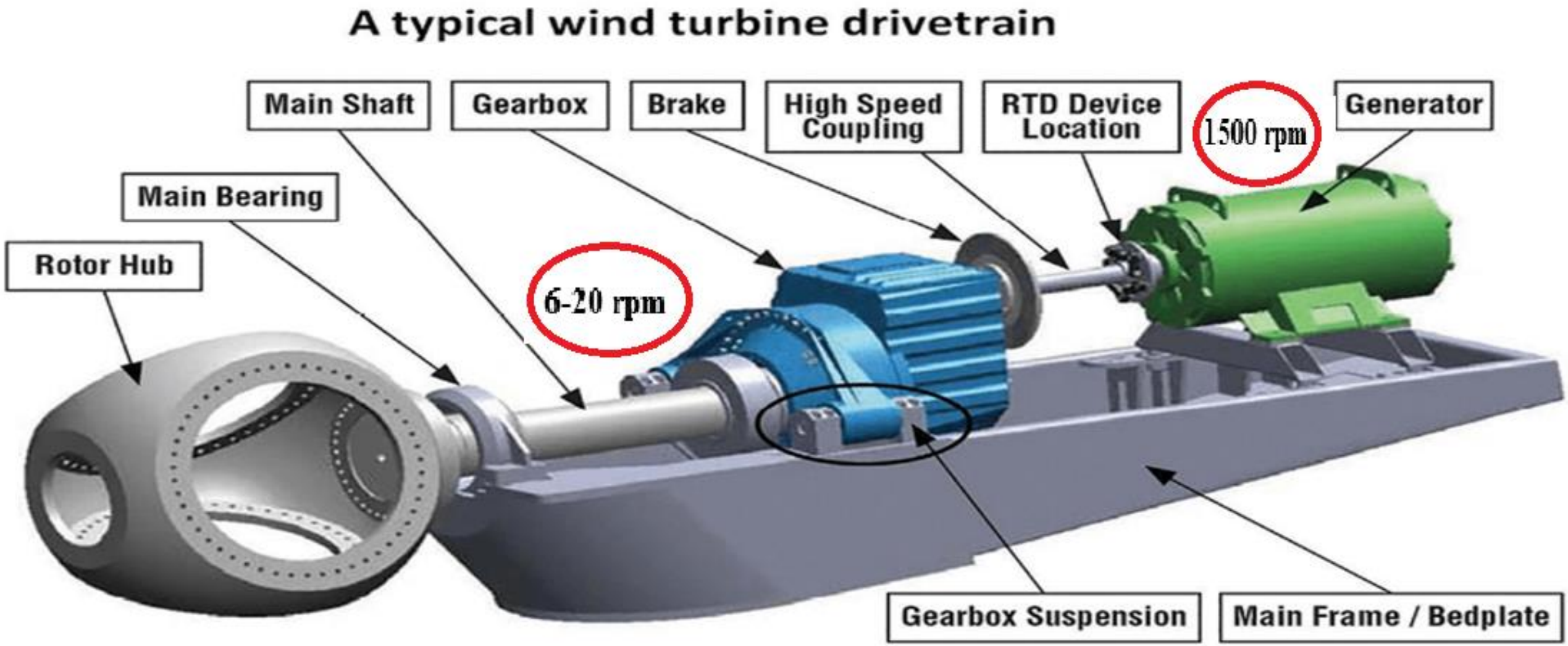
- A gearbox is normally required to:
- match speed difference between Turbine & generator such that:
- **generator can deliver its rated power at rated wind speed.**



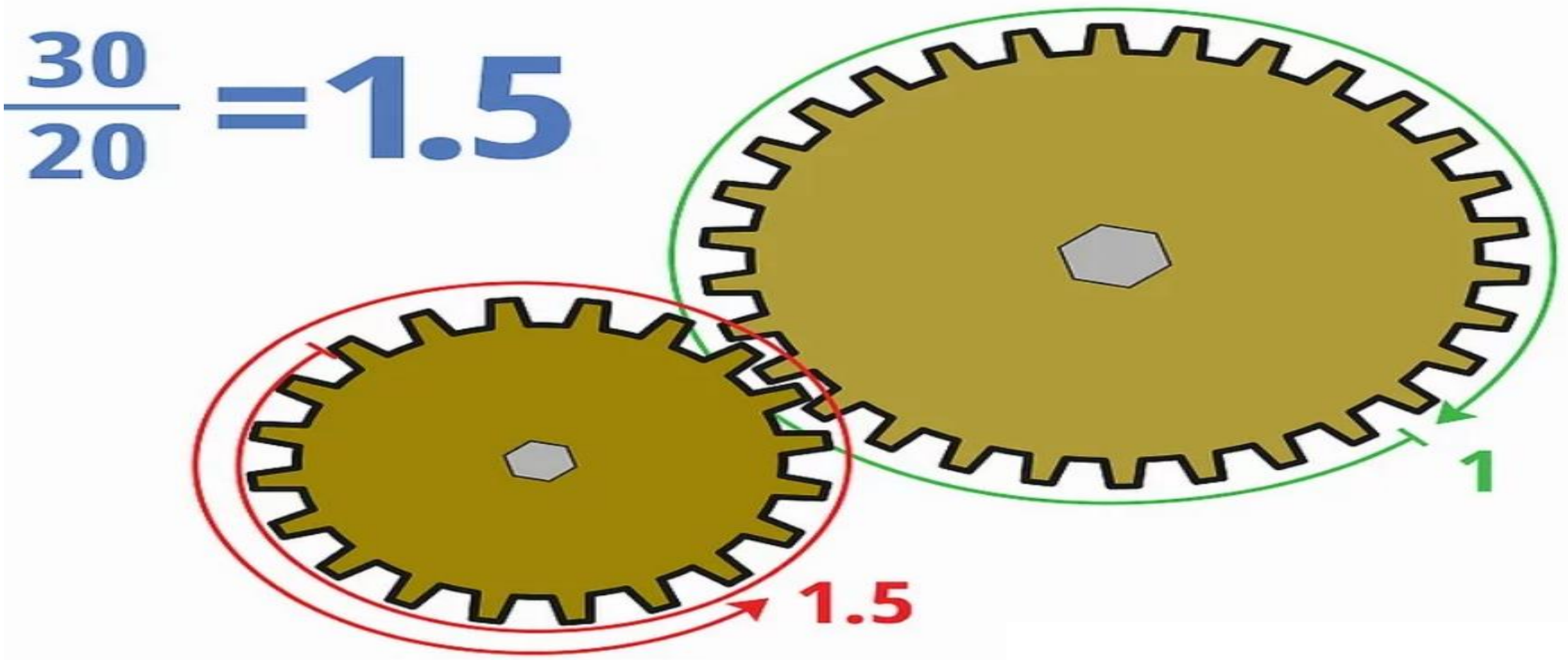
Rotor of a large 3-blade wind turbine operates in a speed range _____rpm?

Standard 4 pole wind generator with 50 Hz stator frequency have rated speed of **____rpm?**

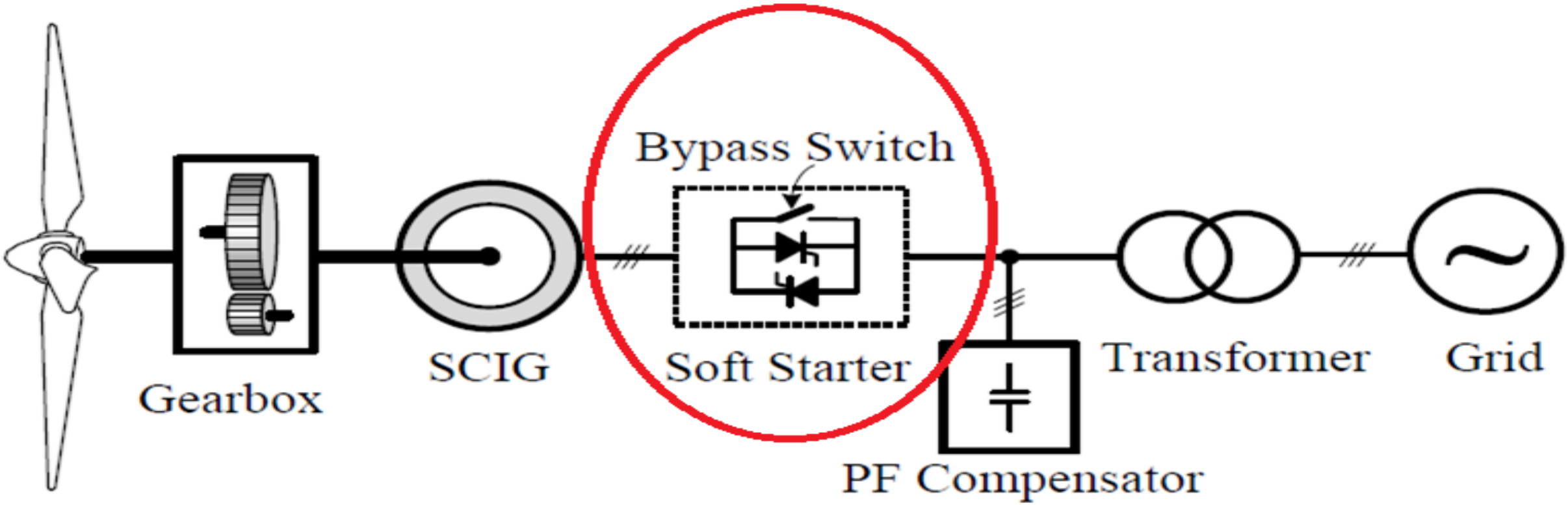
Therefore a gearbox is necessary to adapt low speed of turbine rotor to high speed of generator.



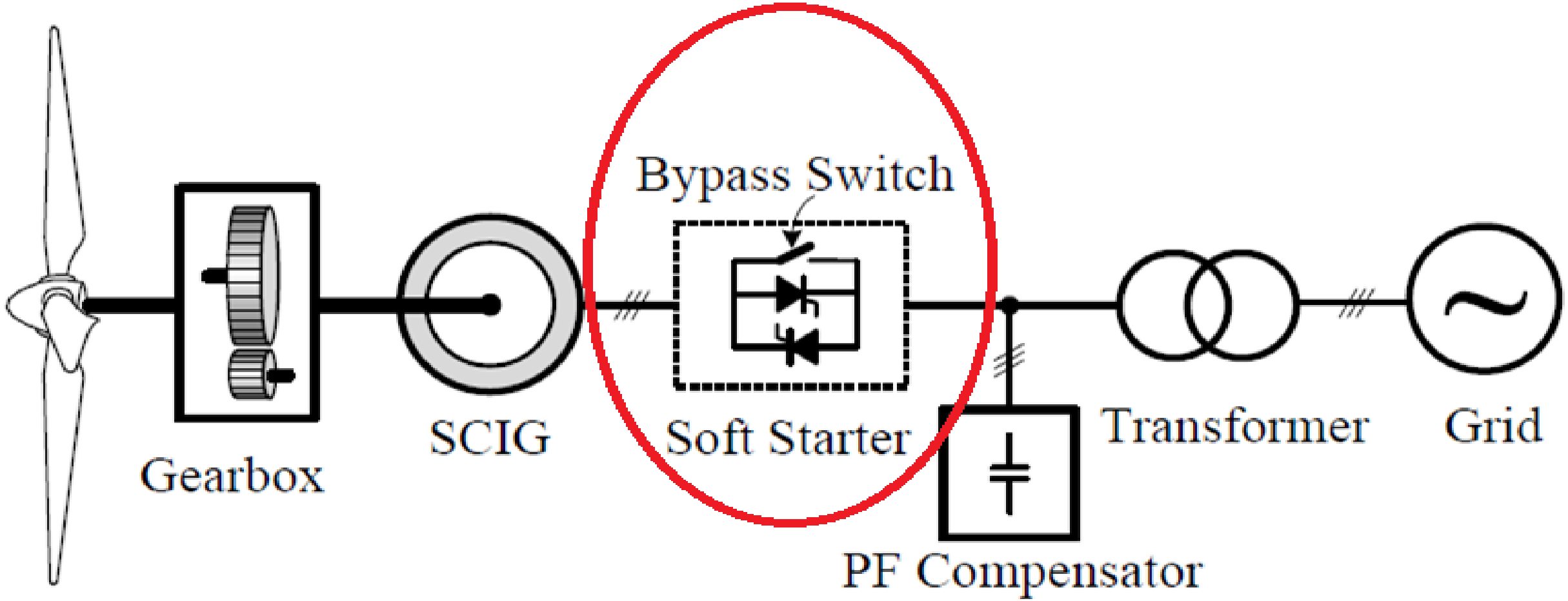
Gearbox conversion ratio r_{gb} or gear ratio, is designed to match high-speed generator with low-speed turbine blades.



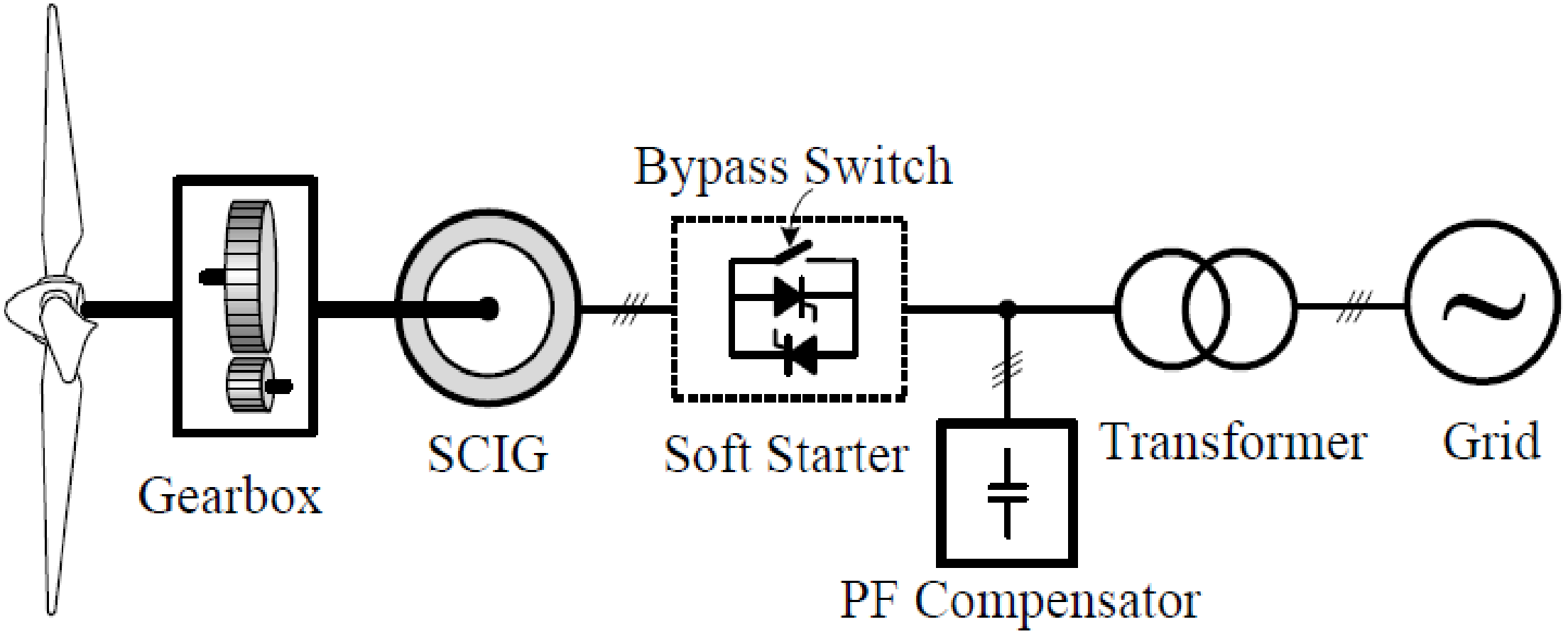
Why we use Soft-starter?



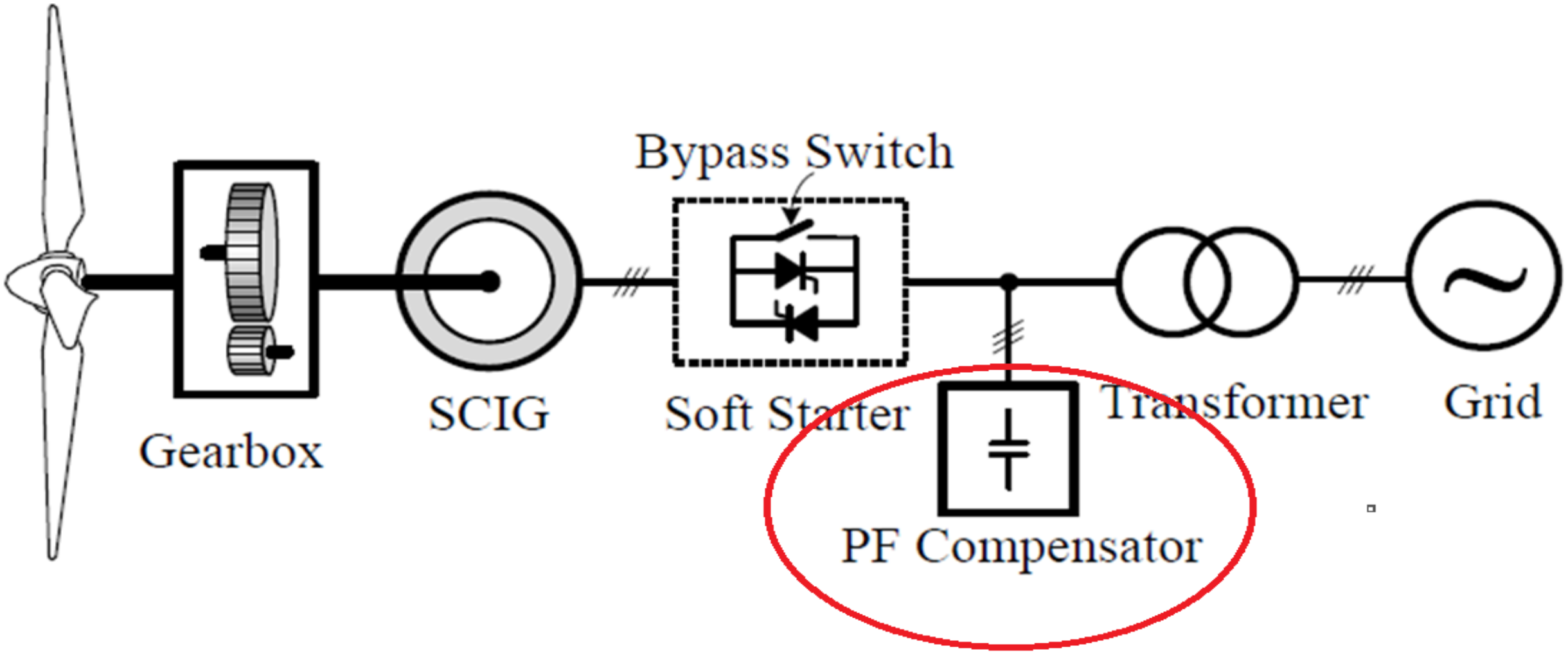
Soft starter limits high inrush currents during system start up



During normal operation, system does not need any power converter.



A 3-phase capacitor bank is required to compensate reactive power drawn by induction generator.



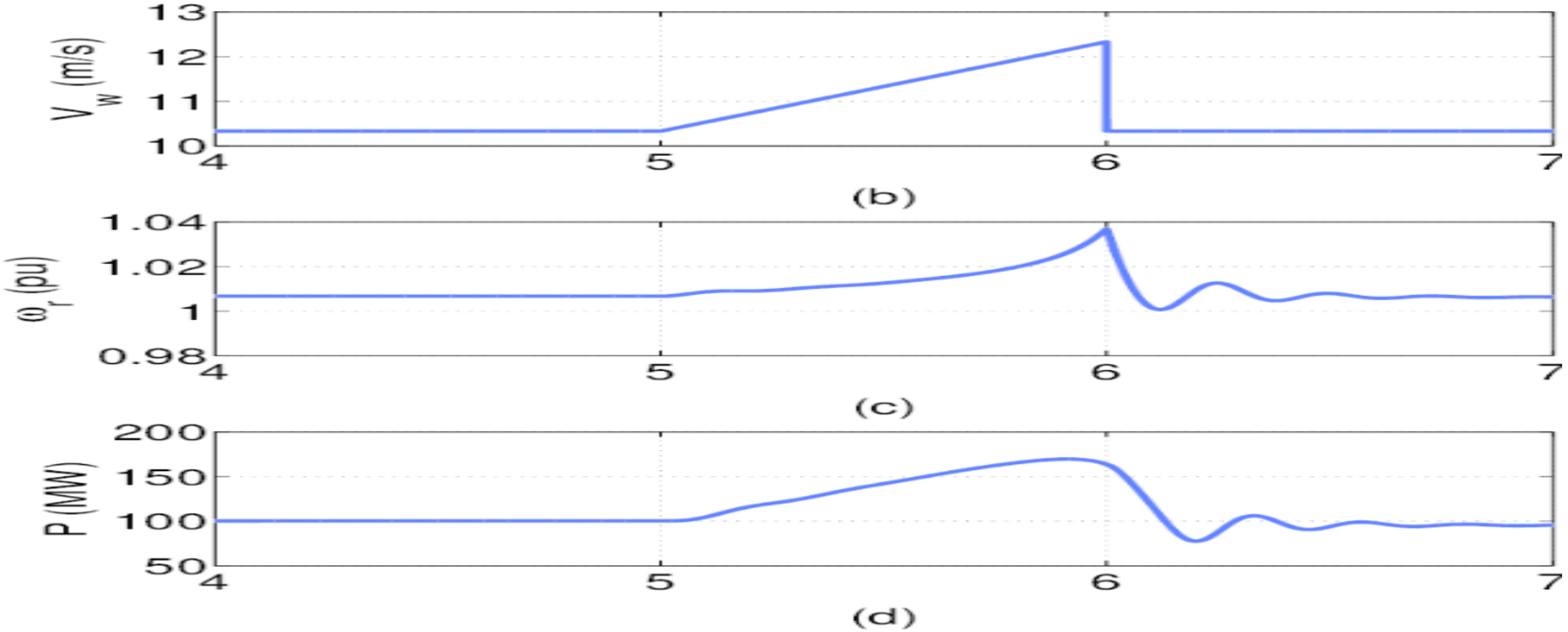
Advantages of fixed-speed WECS

1. Simplicity
2. Low manufacturing/maintenance costs
3. Reliable operation

Main drawbacks of fixed-speed WECS

1.System delivers rated power to grid **only at a given wind speed**

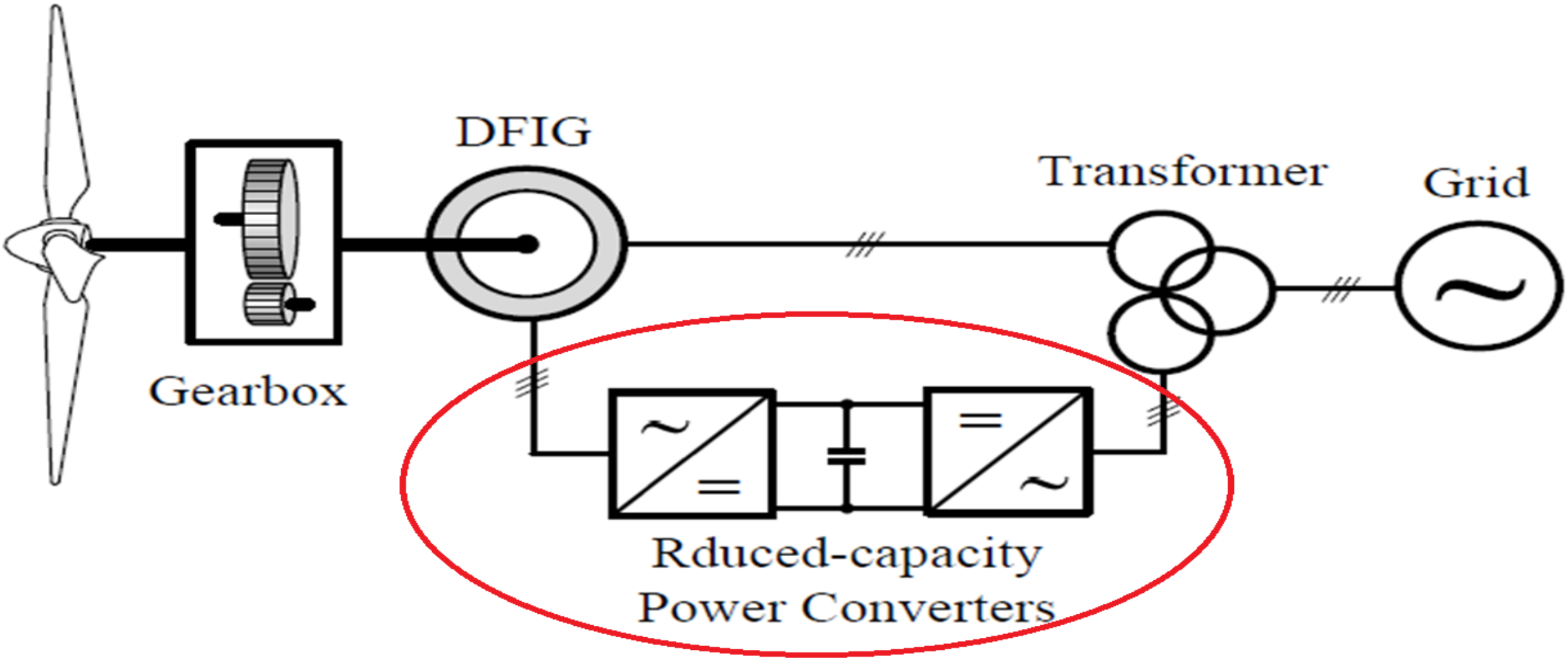
2.Power delivered to grid fluctuates with wind speed, causing disturbances to grid.



Despite disadvantages, fixed-speed WECS is still widely accepted in industry

Parameter	Vestas V82-1.65
Power rating	1.65MW
Turbine diameter	82m
Numbers of blades	3
Turbine speed	14.4rpm
Wind speed (cut-in/rated/cut-out)	3.5/13/20 m/s
Generator	SCIG
Gearbox	Planetary/helical stages
Pitch/stall mechanism	Active stall

1.4.2 Variable-speed Systems with Reduced-Capacity Converters



Variable-speed operation has a series of advantages over fixed-speed wind systems:

1. It ⬆ energy conversion efficiency

2. It ⬇ mechanical stress caused by wind gusts.

- This has +ve impact on design of structure & mechanical parts of turbine and enables construction of larger wind turbines.

Main drawback of variable-speed WECS:

- is need of a **power converter** to control generator speed, which adds cost & complexity to system.
- Power converter decouples generator from grid, which enables control of grid-side active and reactive power.

Classification of Variable-speed WECS

1. Variable-speed WECS with reduced-capacity power converter

2. Variable-speed WECS with full-capacity power converter.

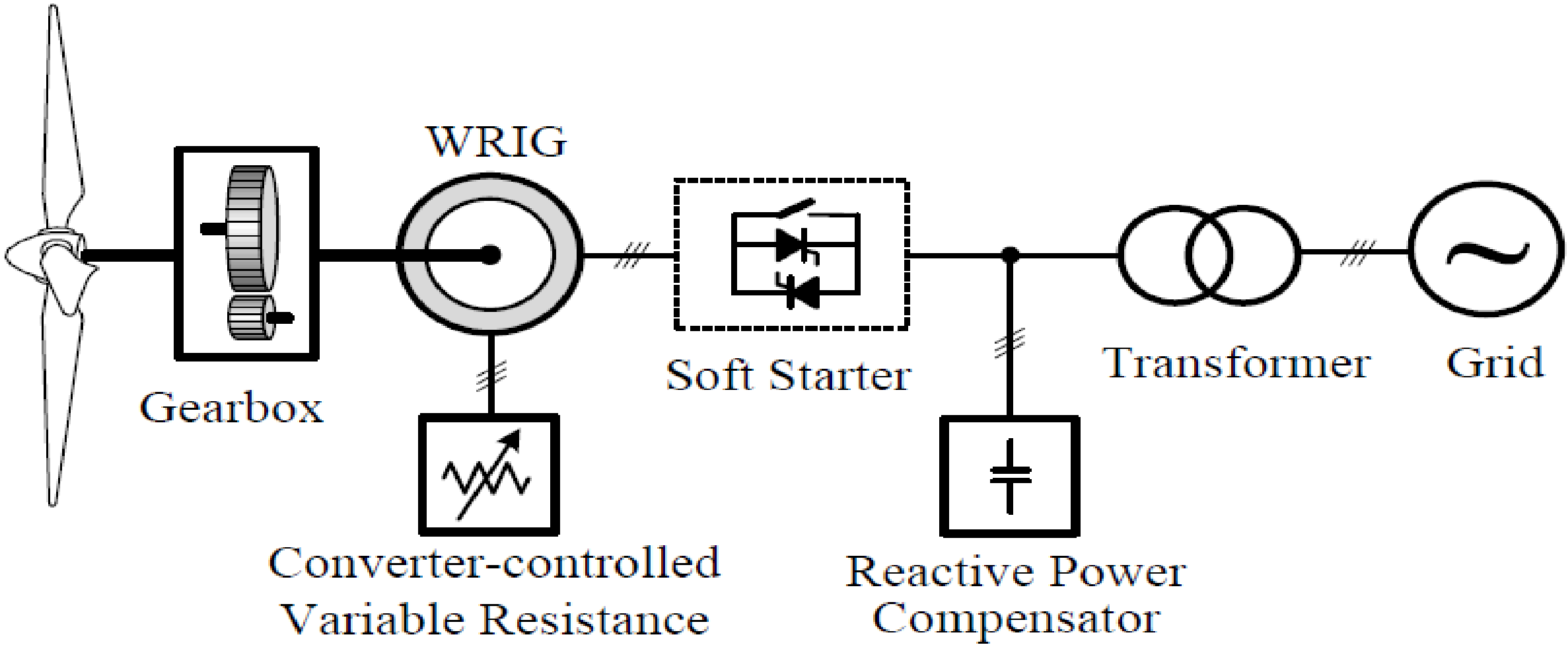
Variable-speed WECS with reduced-capacity converters are:

- Only feasible with Wound Rotor Induction Generators (WRIG)
- Since variable-speed operation can be achieved by **controlling rotor currents** without need to process total power of system.

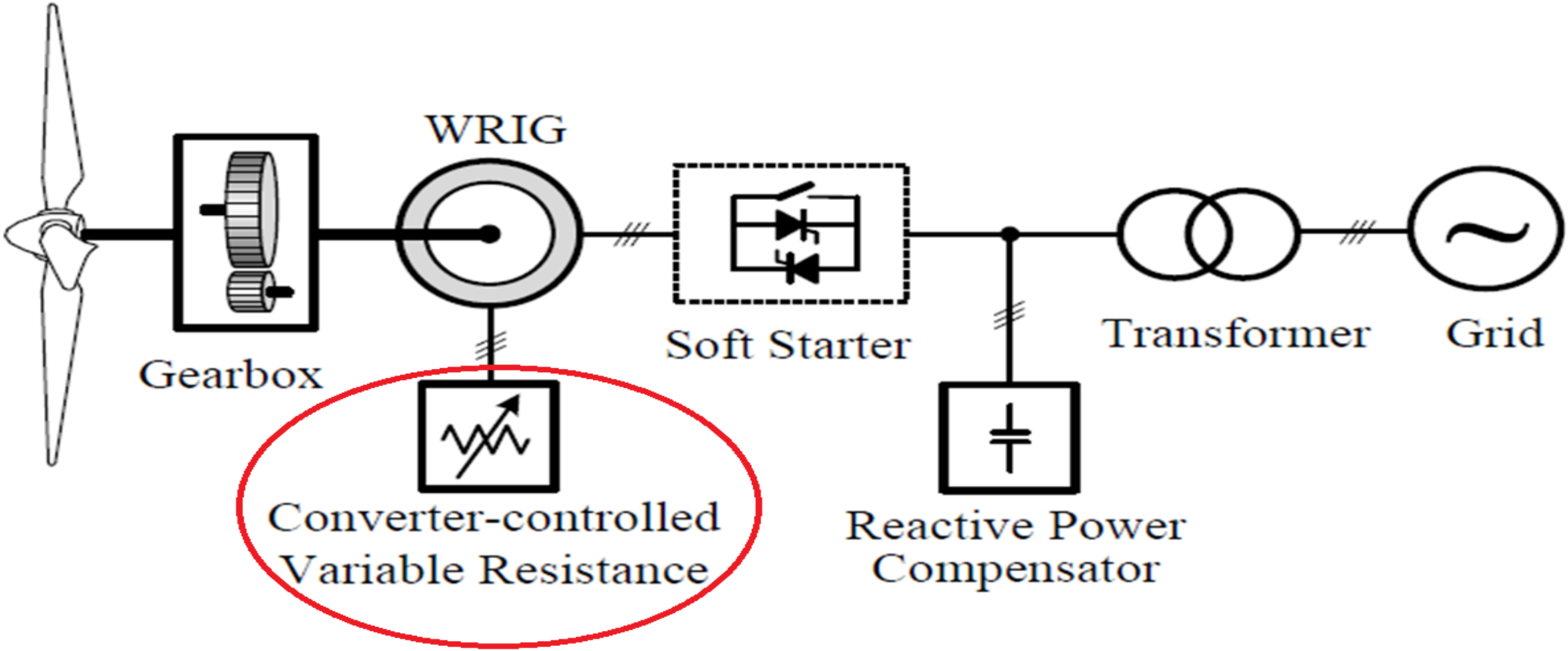
There are 2 designs for Wound Rotor Induction Generator

1. With a converter-controlled variable resistance,
2. With a 4-quadrant power converter system.

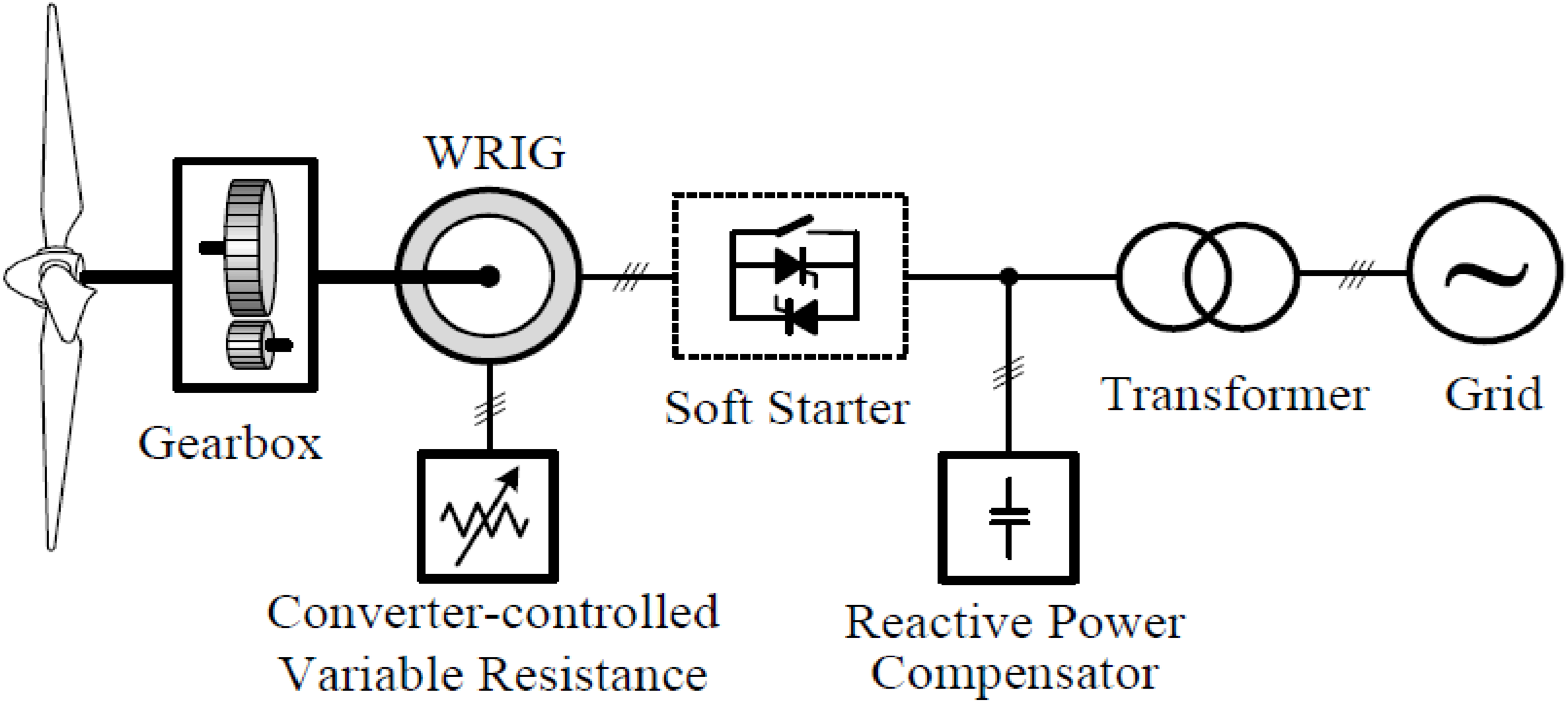
A. Wound Rotor Induction Generator with Variable Rotor Resistance



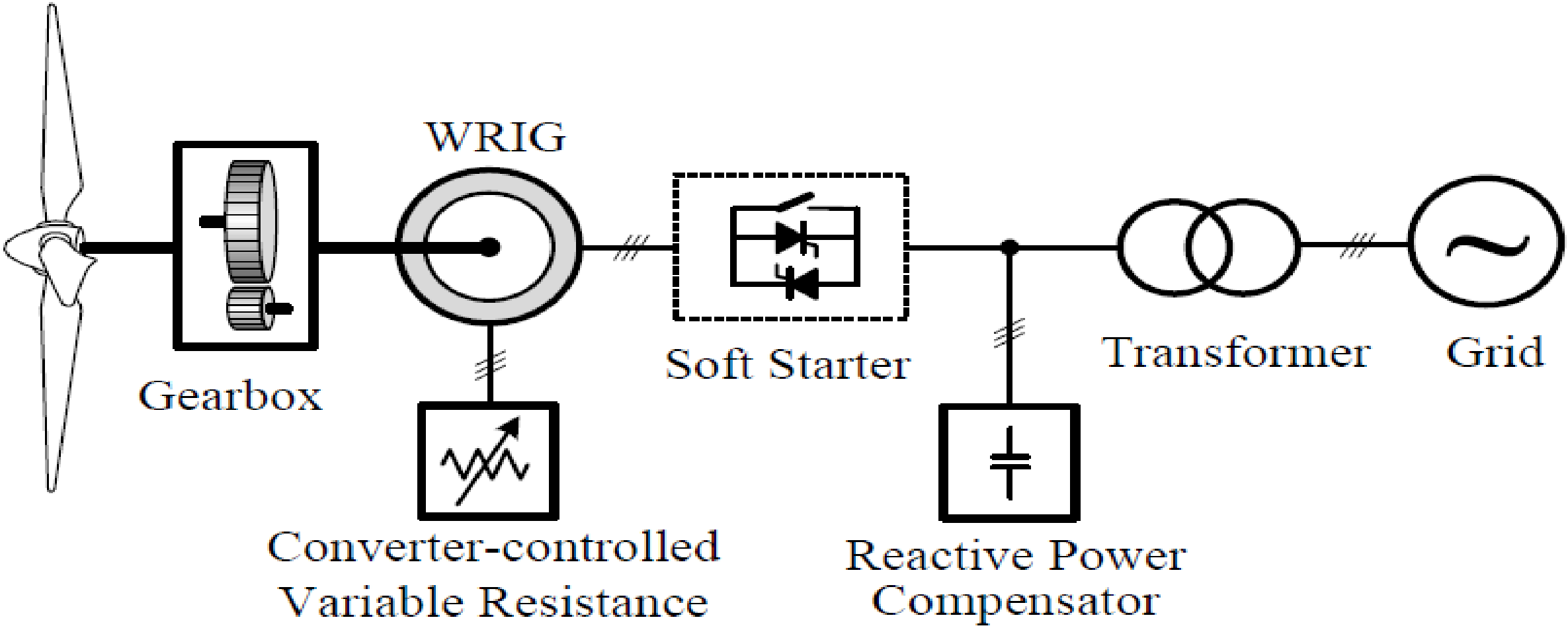
Change in rotor resistance affects torque/speed characteristic of generator, enabling variable-speed operation of turbine.



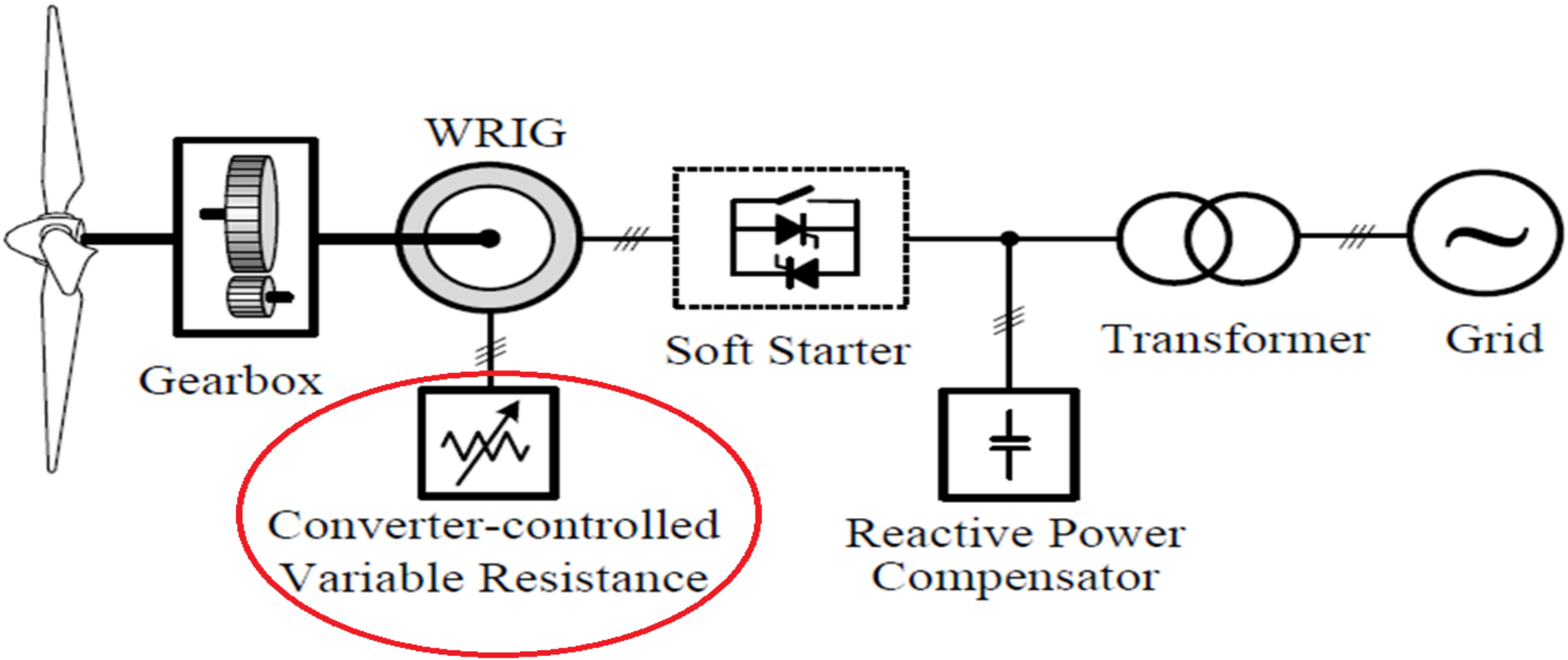
Speed adjustment range is limited to 10% above synchronous speed of generator



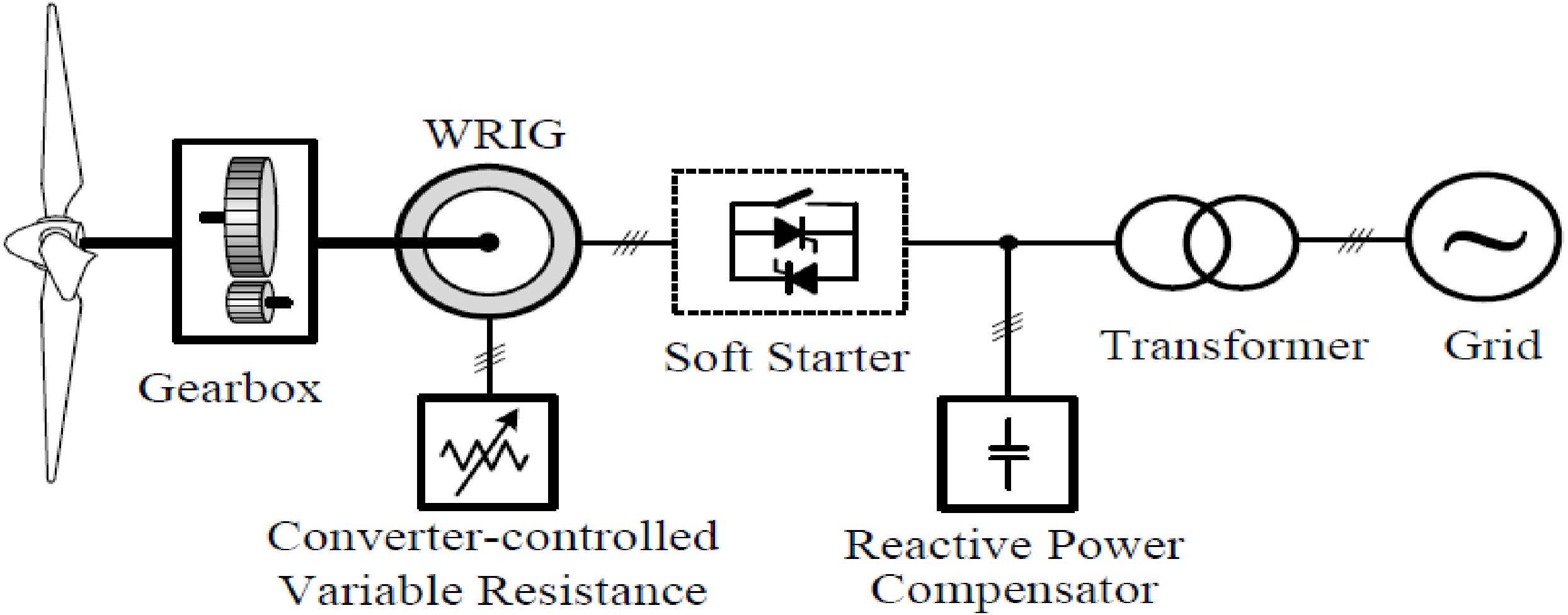
With variable-speed operation, system can capture more power from wind ,but has serious flaw?



There is energy losses in **rotor resistance**



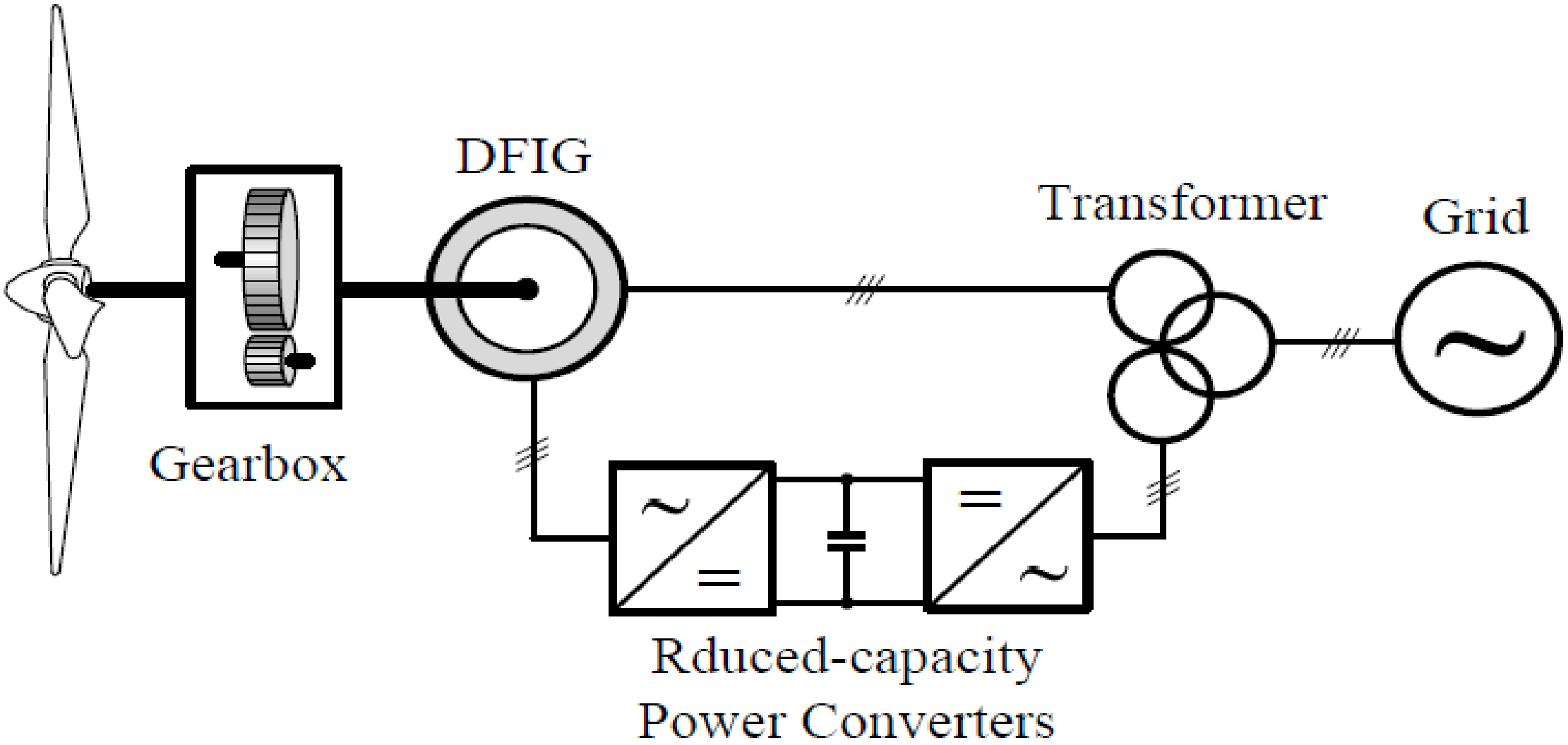
This configuration also requires a soft starter & reactive power compensation.



Example of commercial WECS with variable rotor resistance

Parameter	Vestas V80-1.8US
Power rating	1.8MW
Turbine diameter	80m
Turbine speed	15.5 or 16.8 rpm
speed (cut-in/rated/cut-out)	4/15/25 m/s
Generator	WRIG
Gearbox	Planetary/parallel axle
Pitch/stall mechanism	Pitch

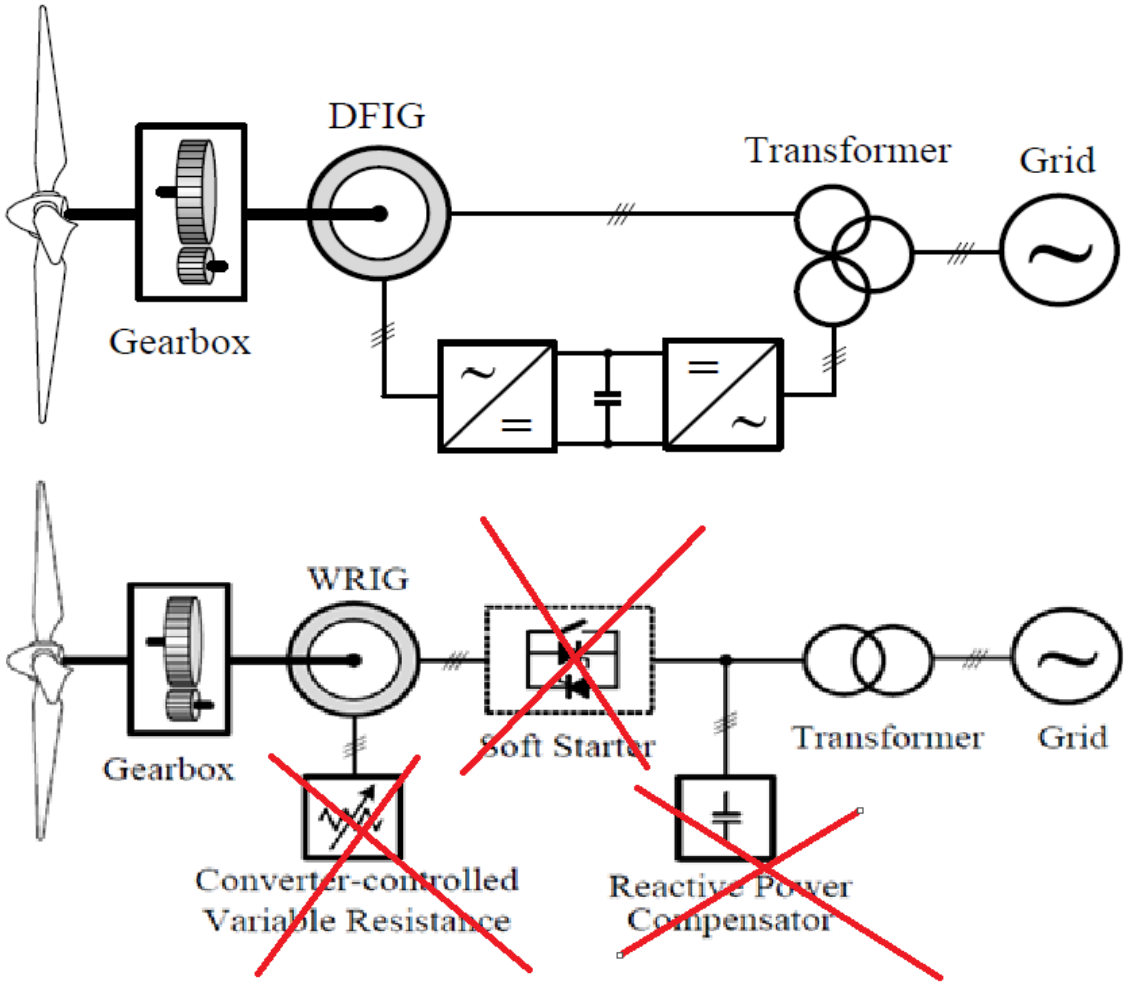
B. Doubly Fed Induction Generator with Rotor Converter



Configuration of this system is same as that of Wound Rotor Induction Generator(WRIG) system except that:

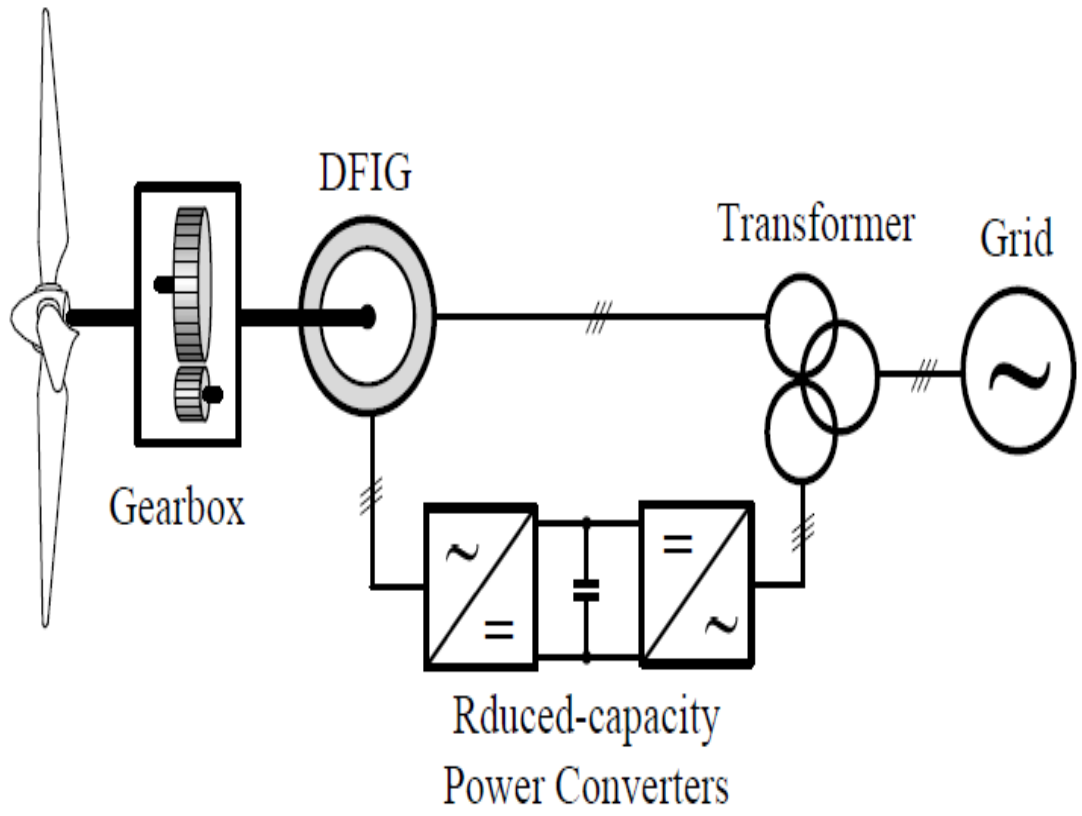
1) Variable resistance in rotor circuit is replaced by a grid-connected converter

2) No need for soft starter or reactive power compensation.

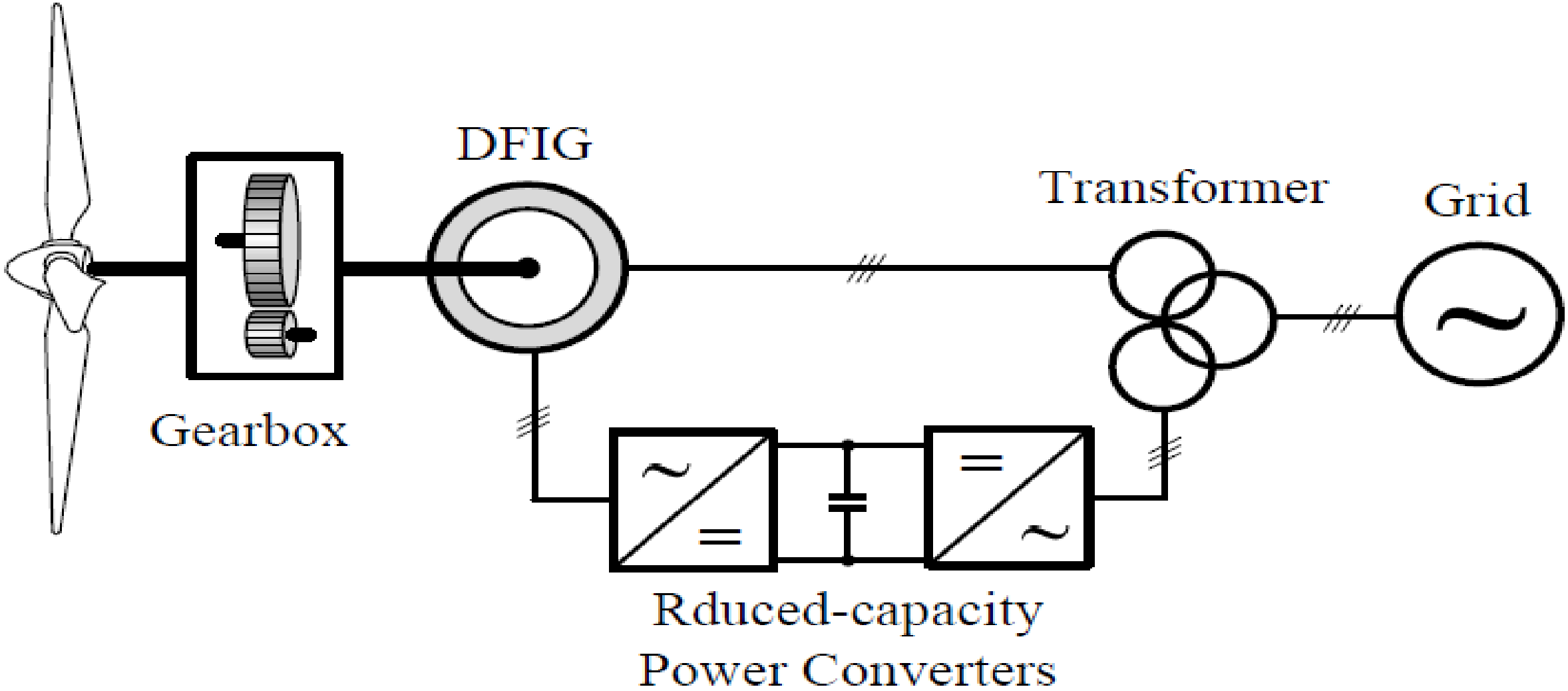


Power factor of system can be adjusted by power converters.

- Converters only have to process slip power in rotor circuits,
- Slip power=30% of rated power of generator,
- resulting in reduced converter cost in comparison to wind energy systems using full-capacity converters



Use of converters also allows bidirectional power flow in rotor circuit & increases speed range of generator.

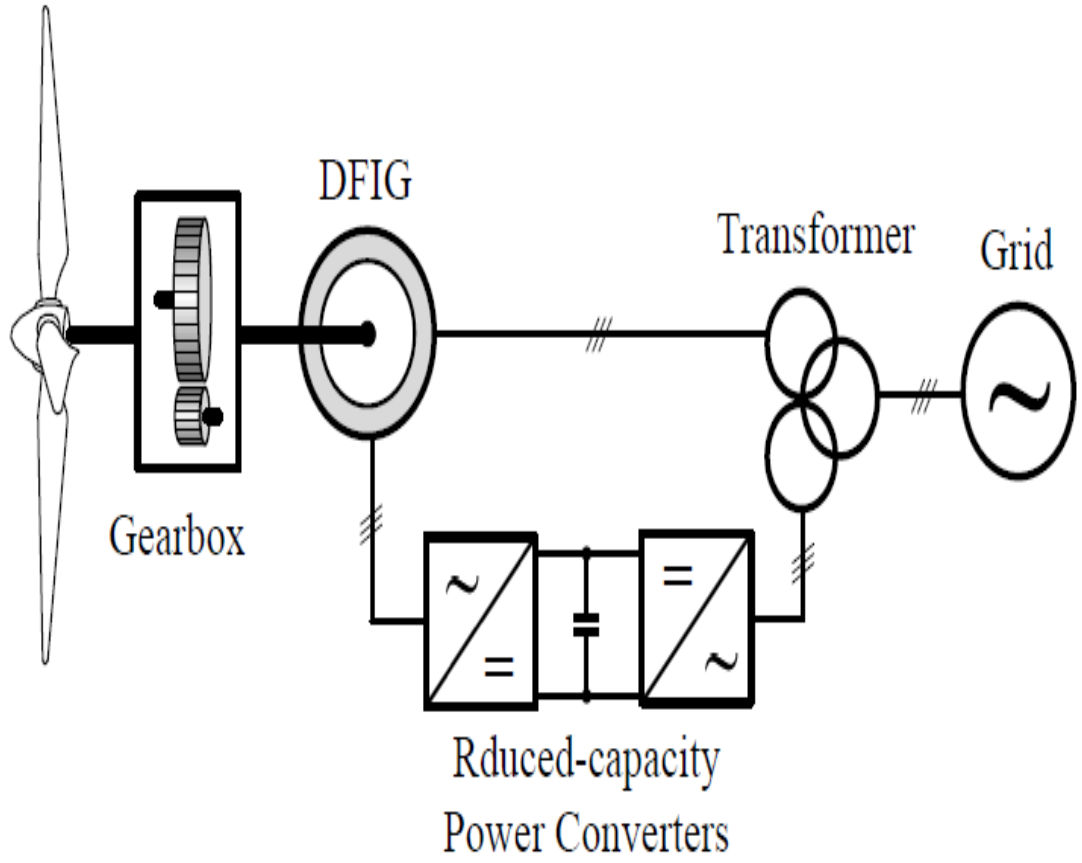


DFIG wind energy system widely accepted in today's market.

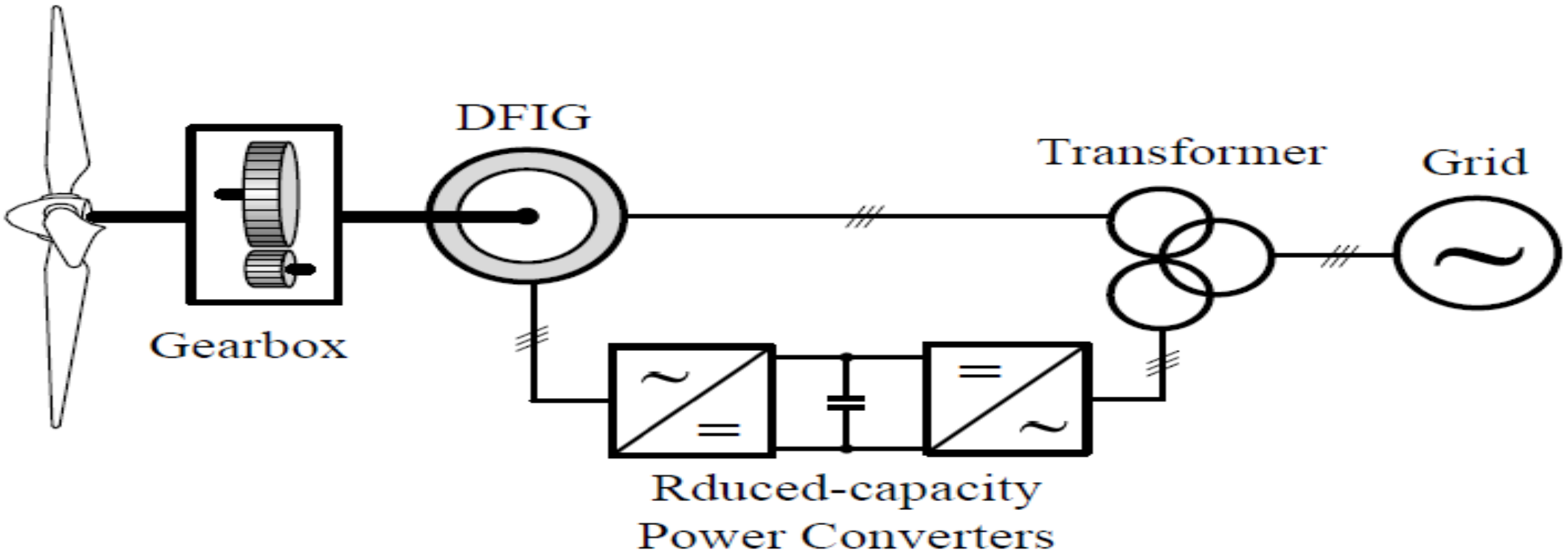
- Because the system features:

i. improved overall power conversion efficiency

ii. extended generator speed range (±30%) &



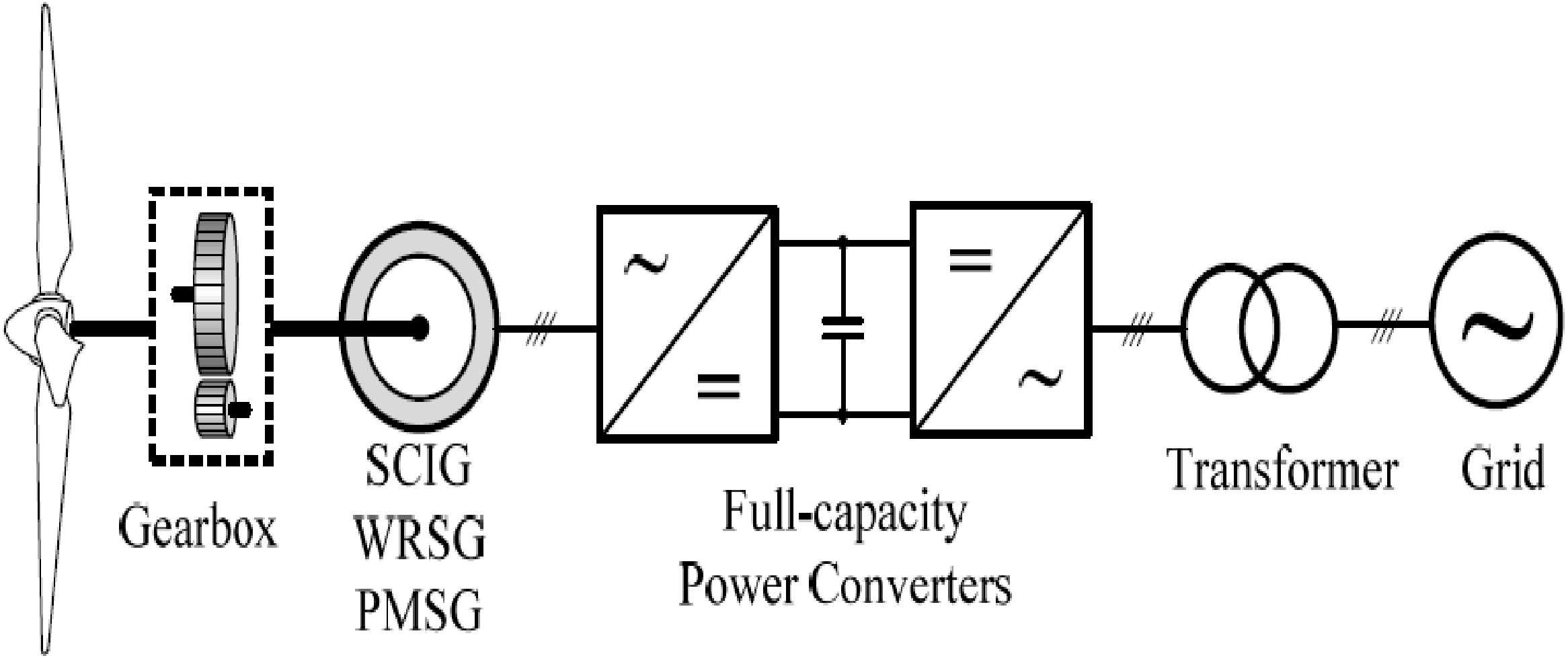
Enhanced dynamic performance as compared to fixed-speed WECS & variable resistance configuration.



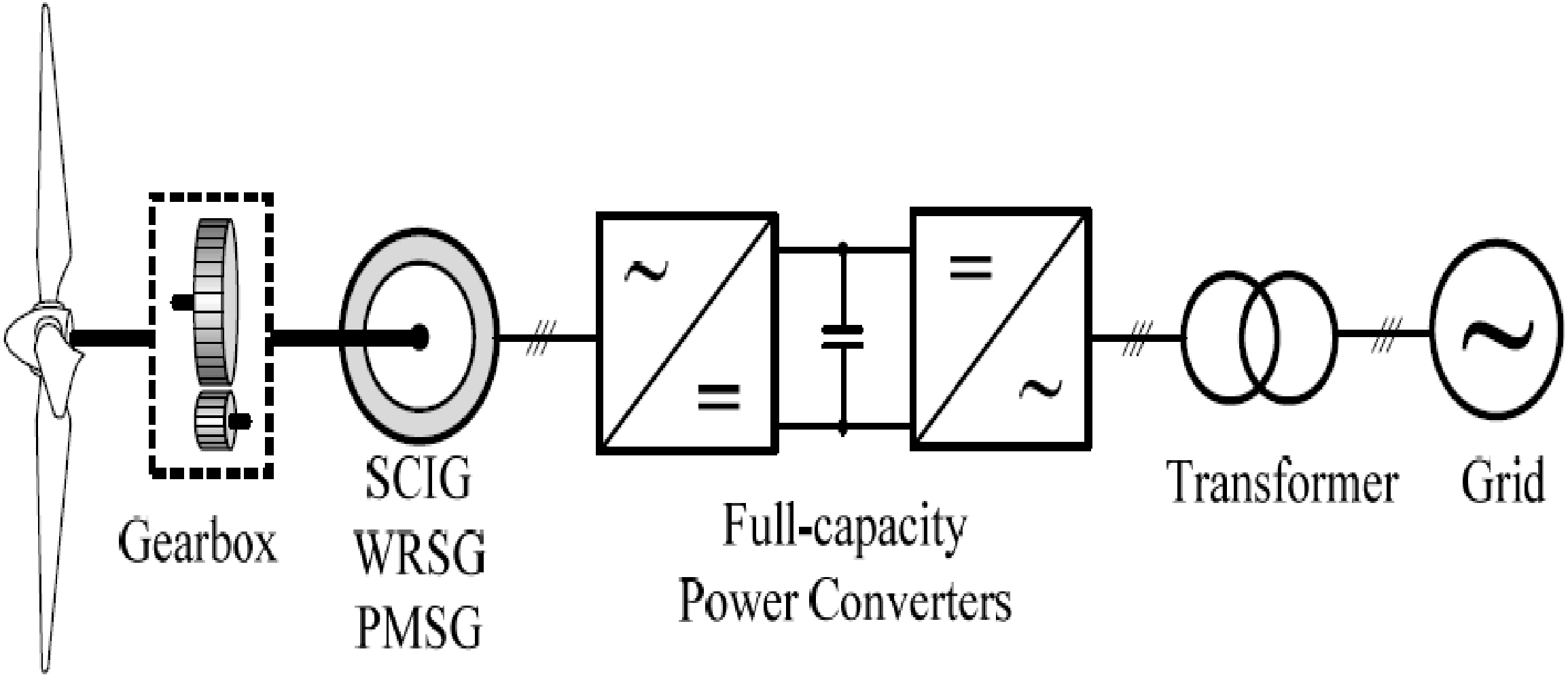
Examples of commercial DFIG WECS

Parameter	Model		
	Nordex N100	Vestas V90	Repower 5M
Power rating	2.5MW	3MW	5MW
Turbine diameter	100m	90m	126m
Turbine speed	9.6 ~ 14.9 rpm	8.6 ~ 18.4 rpm	7.7 ~ 12.1 rpm
Wind speed (cut-in/rated/cut-out)	3/13/20 m/s	3.5/15/25 m/s	3.5/14/25 m/s
Generator	6-pole WRIG	4-pole WRIG	6-pole WRIG
Gearbox	Planetary/spur stages	Planetary/helical stages	Planetary/spur stages
Pitch/stall mechanism	Pitch	Pitch	Pitch

1.4.3 Variable-speed Systems with Full-capacity Power Converters

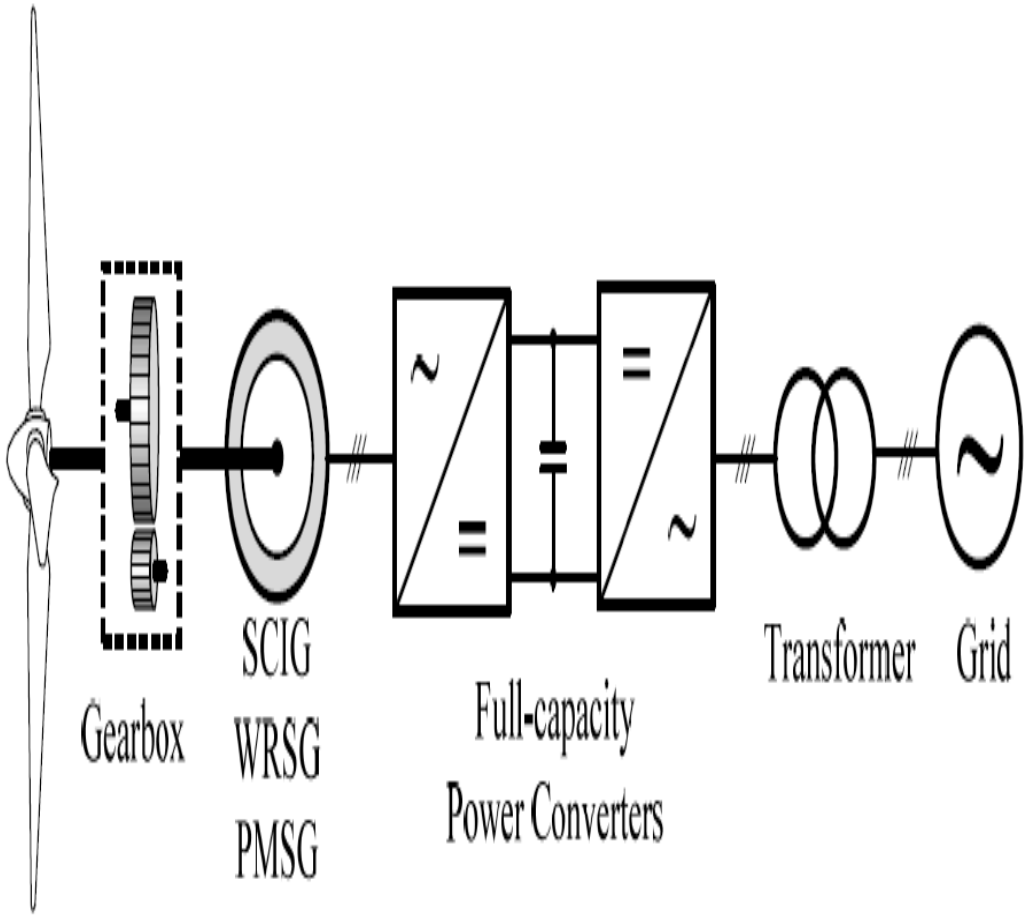


Performance of wind energy system can be greatly enhanced with use of full-capacity power converter.



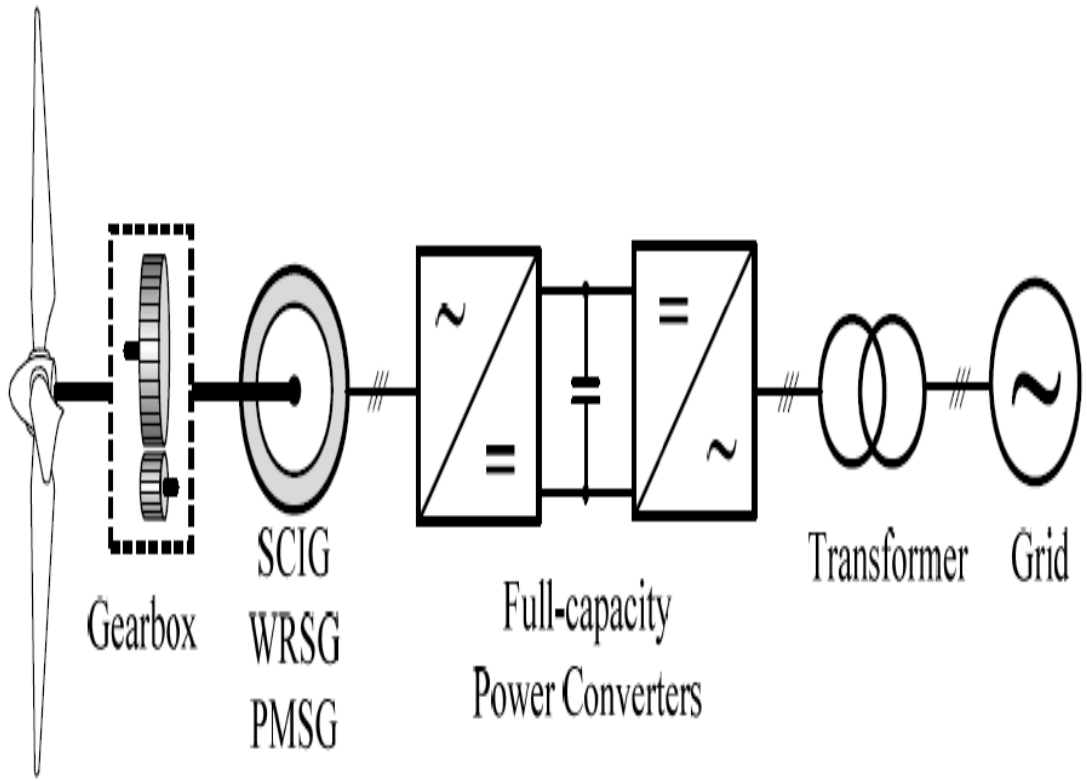
Applications in Variable-speed Systems with Full-capacity Power Converters

1. Squirrel cage induction generators(SCIG),
2. Wound rotor synchronous generators(WRSG), and
3. Permanent magnet synchronous generators (PMSG)



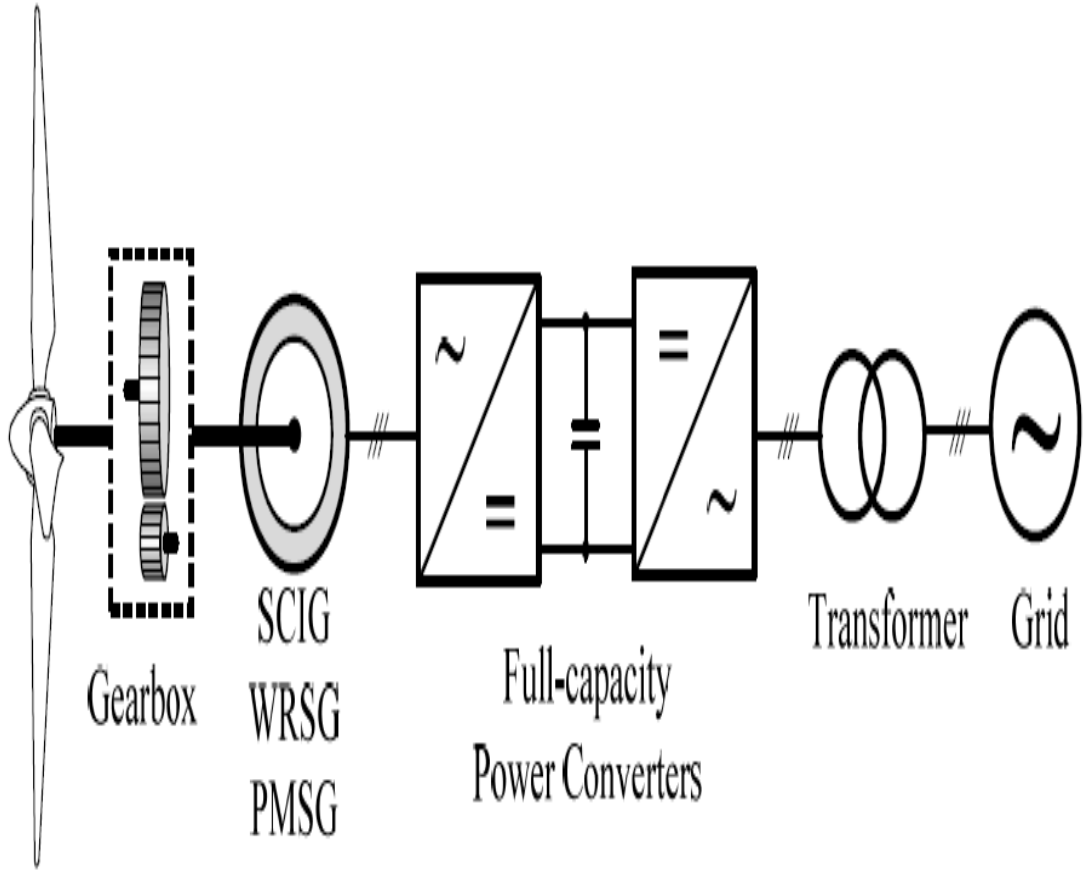
Power rating of converter is normally same as that of generator.

- With use of power converter, generator is fully decoupled from grid, and
- can operate in full speed range.

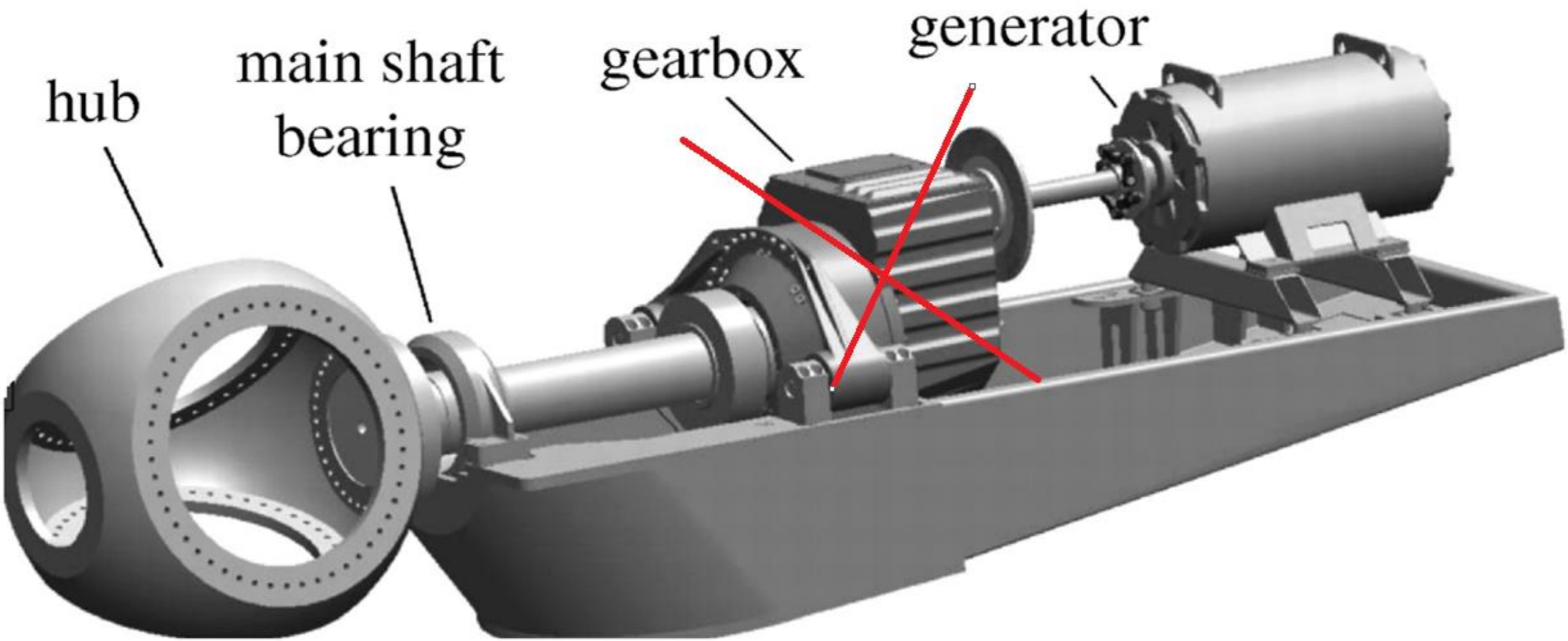


Main drawback

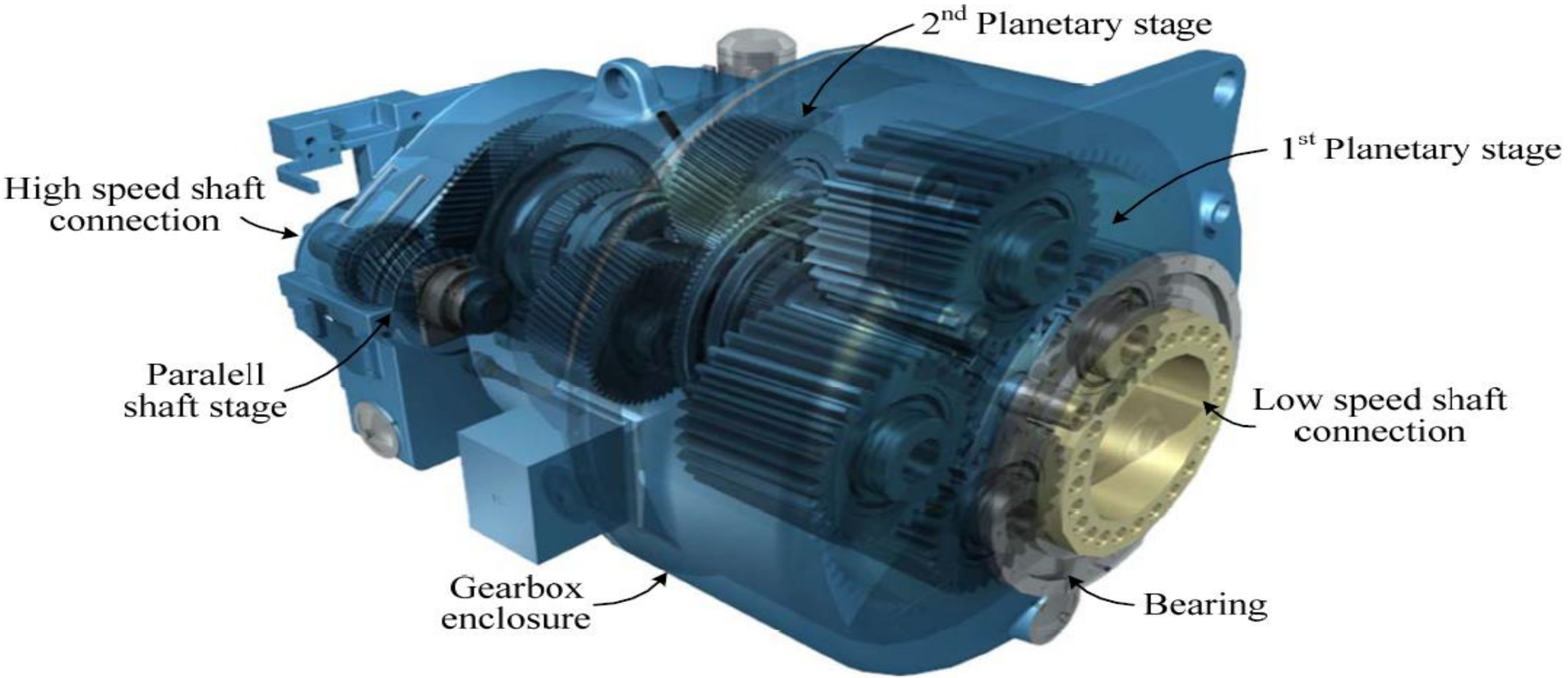
- More complex system with
- increased costs.



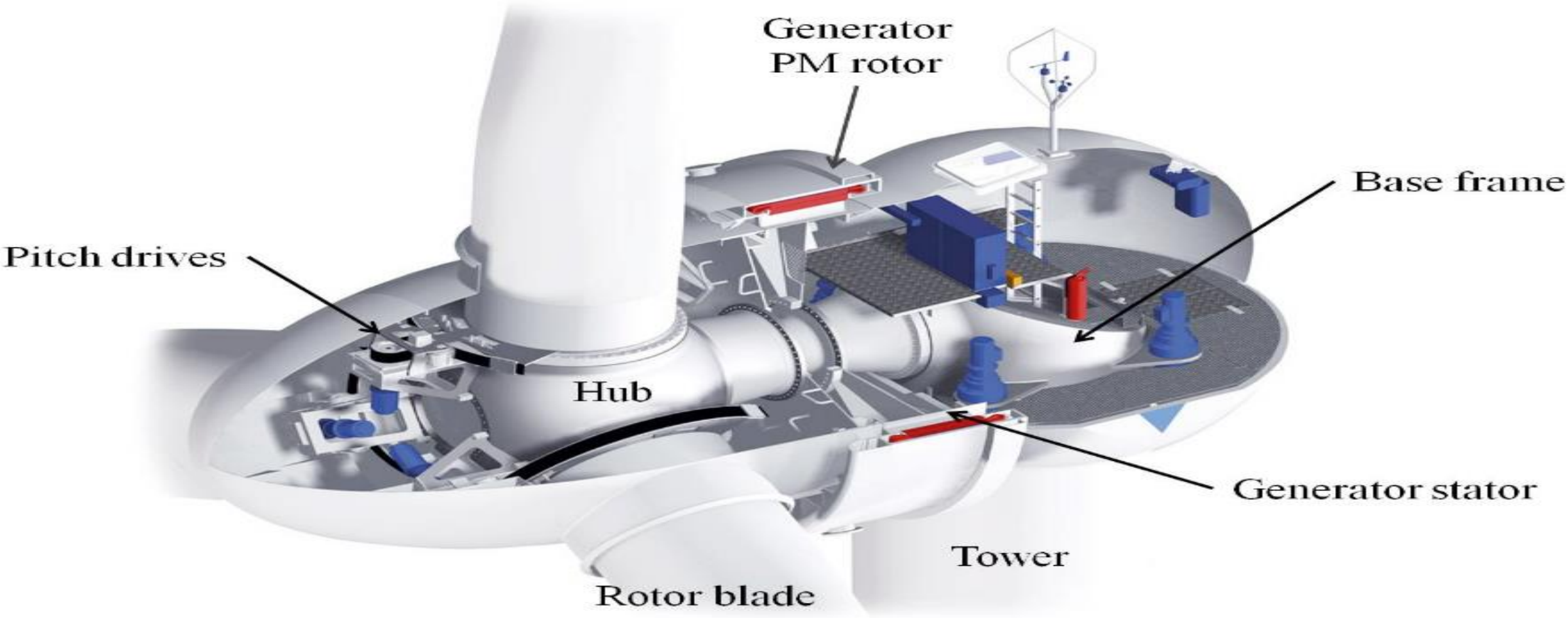
Elimination of gearbox



Gearbox of a large wind turbine



If a low-speed synchronous generator with a large number of poles is used then we can eliminate gear box



Why we eliminate gearbox?

Why we eliminate gearbox?

1. Improves efficiency of system
2. Reduces initial costs &
3. Maintenance.

Low-speed generator has larger diameter to accommodate large number of poles on perimeter,

Examples of variable-speed configurations with full-capacity converters

System power rating, turbine speed, generator type, & power converter topology

Parameter	Model		
	Enercon E-82E3	Vestas V-112	Avantis AV928
Power rating	3MW	3MW	2.5MW
Turbine diameter	82m	112m	93.2m
Turbine speed	6 ~ 18.5rpm	4 ~ 17.7rpm	6 ~ 18rpm
Wind speed (cut-in/rated/cut-out)	na/na/28-34m/s	3/12/25 m/s	3/11.3/25-30 m/s
Gearbox	Gearless (direct drive)	Planetary/spur stages	Gearless (direct drive)
Generator	Multipole WRSG	PMSG	120-pole PMSG
Converter system	Diode+boos+2L-VSC	na	4 quadrant 2L-VSC
Pitch/stall mechanism	Pitch	Pitch	Pitch

System power rating, turbine speed, generator type, & power converter topology(Cont.....)

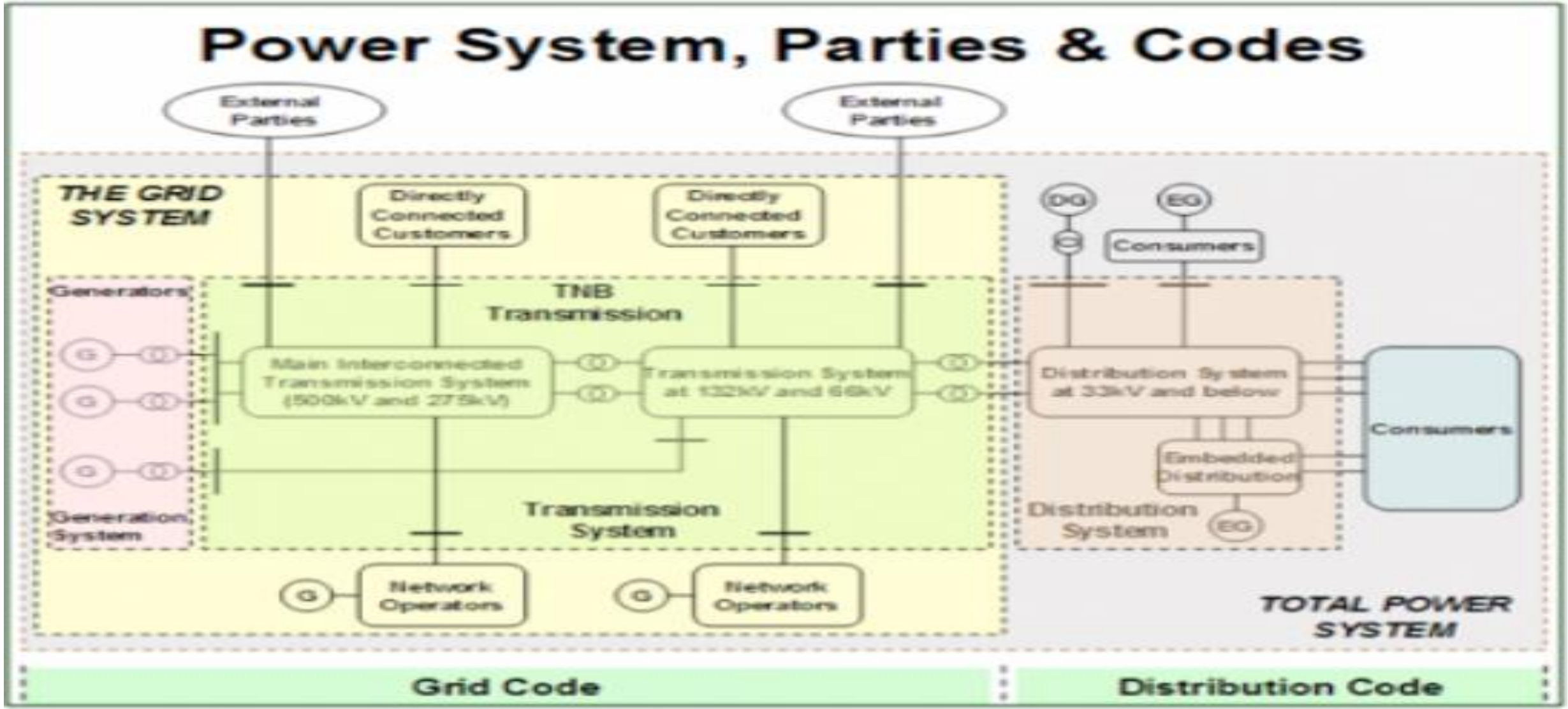
Parameter	Clipper Liberty 2.5	Siemens SWT 3.0-101	Goldwind 2.5 PMDD
Power rating	2.5MW	3MW	2.5MW
Turbine diameter	100m (C-100 model)	101m	99.8m
Turbine speed	9.6 ~ 15.5 rpm	6 ~ 16 rpm	6.5 ~ 14.5 rpm
Wind speed (cut-in/rated/cut-out)	4/na/25 m/s	3/13/25 m/s	3/13.5/25 m/s
Gearbox	Distributed gearbox	Gearless (direct drive)	Gearless (direct drive)
Generator	4 x PMSG	Multipole PMSG	Multipole PMSG
Converter system	4x diode+2L-VSC	4-quadrant	diode+boost+2L-VSC
Pitch/stall mechanism	Pitch	Pitch	Pitch

Some of the most common converter topologies used for this type of WECS include:

- 2-level Voltage Source Converter (2L-VSC) in back-to-back configuration, Diode+boost+2L-VSC
- Diode bridge rectifier plus DC-DC boost stage and 2L-VSC, and
- 3-level Neutral Point Clamped Converter (3L-NPC) in back-to-back configuration.

What are the Grid Code?

1.5 Grid Code


Power System, Parties & Codes
External Parties
External Parties
THE GRID SYSTEM
Directly Connected Customers
Directly Connected Customers
DG
EG
Consumers
Generators
TNB Transmission
Main Interconnected Transmission System (500kV and 275kV)
Transmission System at 132kV and 66kV
Distribution System at 33kV and below
Consumers
Embedded Distribution
Transmission System
Generation System
Distribution System
EG
Network Operators
Network Operators
TOTAL POWER SYSTEM
Grid Code
Distribution Code

Grid codes are usually based on experience acquired through operation of power systems

- Grid codes may vary from 1 utility to another.

- Differences in various grid codes also stem from regional and geographical conditions.

Key elements in different grid codes remain similar across globe since their ultimate goal is to ensure:

1. Safe
2. Reliable &
3. Economic operation of power system.

Updated grid codes for renewable energy power generation

- Due to rapid development of renewable energies & their integration into grid,
- Grid codes in many countries have been updated to address issues related to renewable energy power generation.

According to updated grid codes:

- ***Wind farms are considered as power generation plants,***
- which should perform in similar manner as conventional/uninterruptable power generation plants.

Main elements in grid codes include:

1. Fault ride through requirement,
2. Active/reactive power control,
3. Frequency/voltage regulation,

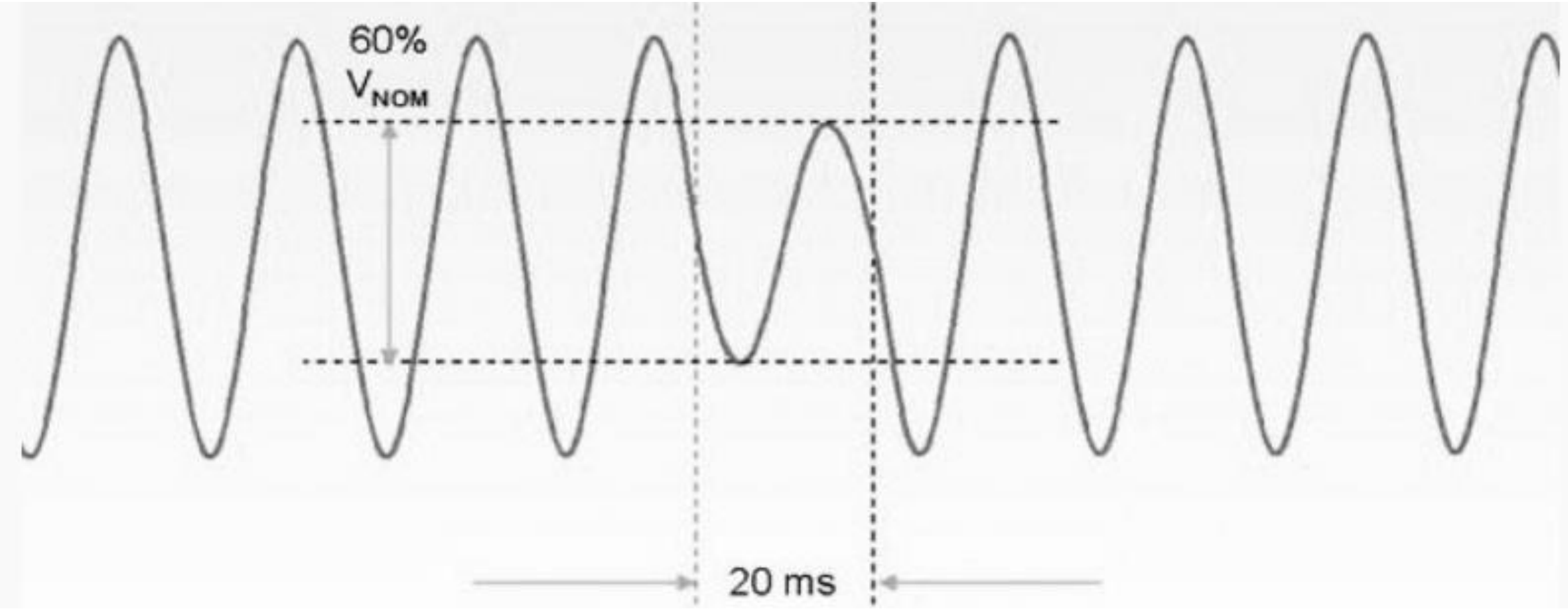
Main elements in grid codes include(cont…)

4. Power quality &

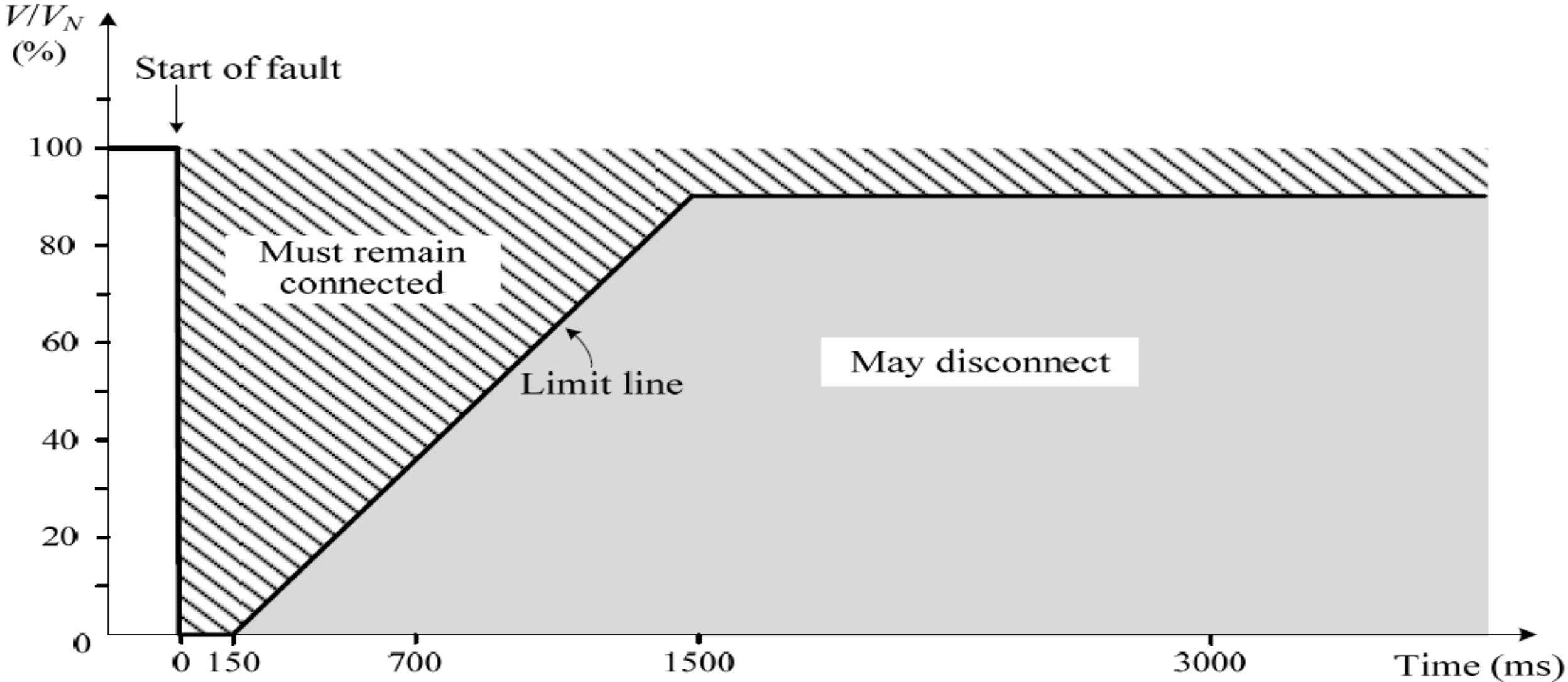
5. System protection.

1.5.1Fault Ride-through Requirements

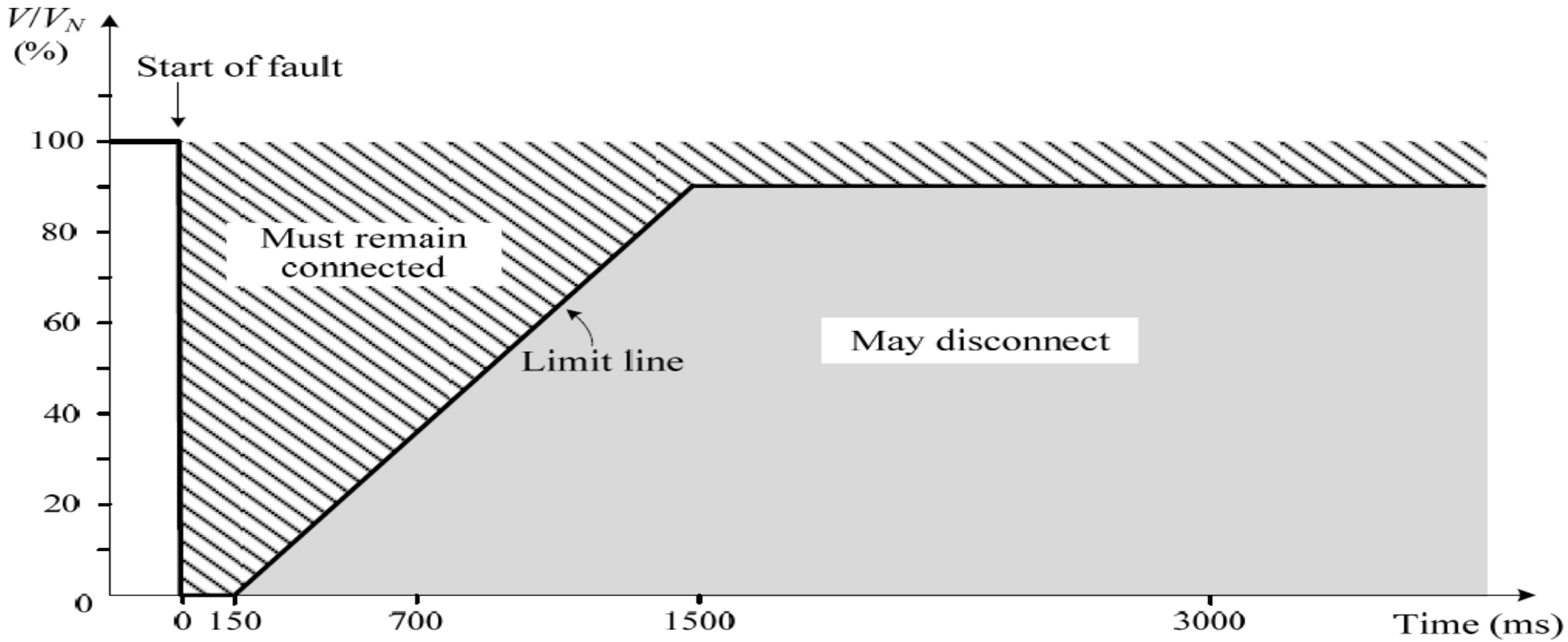
Grid disturbances such as severe **voltage dips** caused by short-circuit faults can lead to power generating units disconnected from grid.



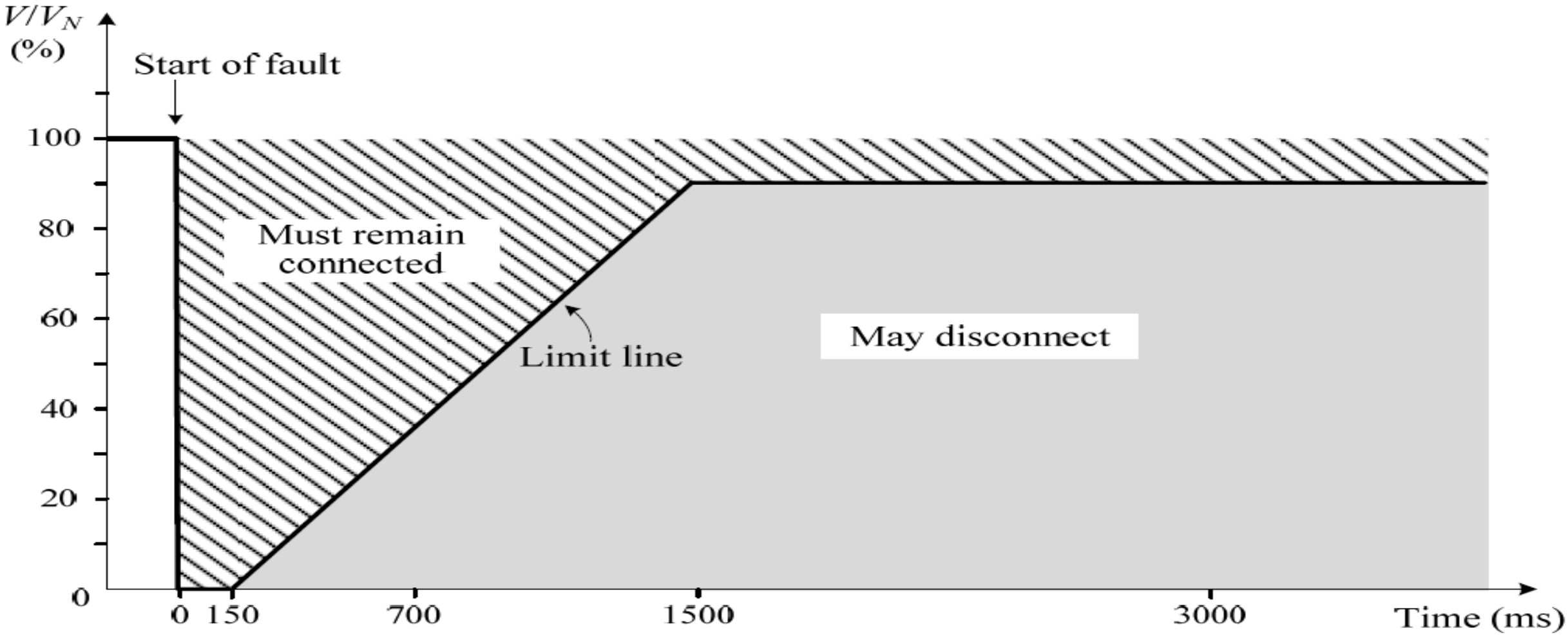
For stable operation grid code requires power generating units to remain connected



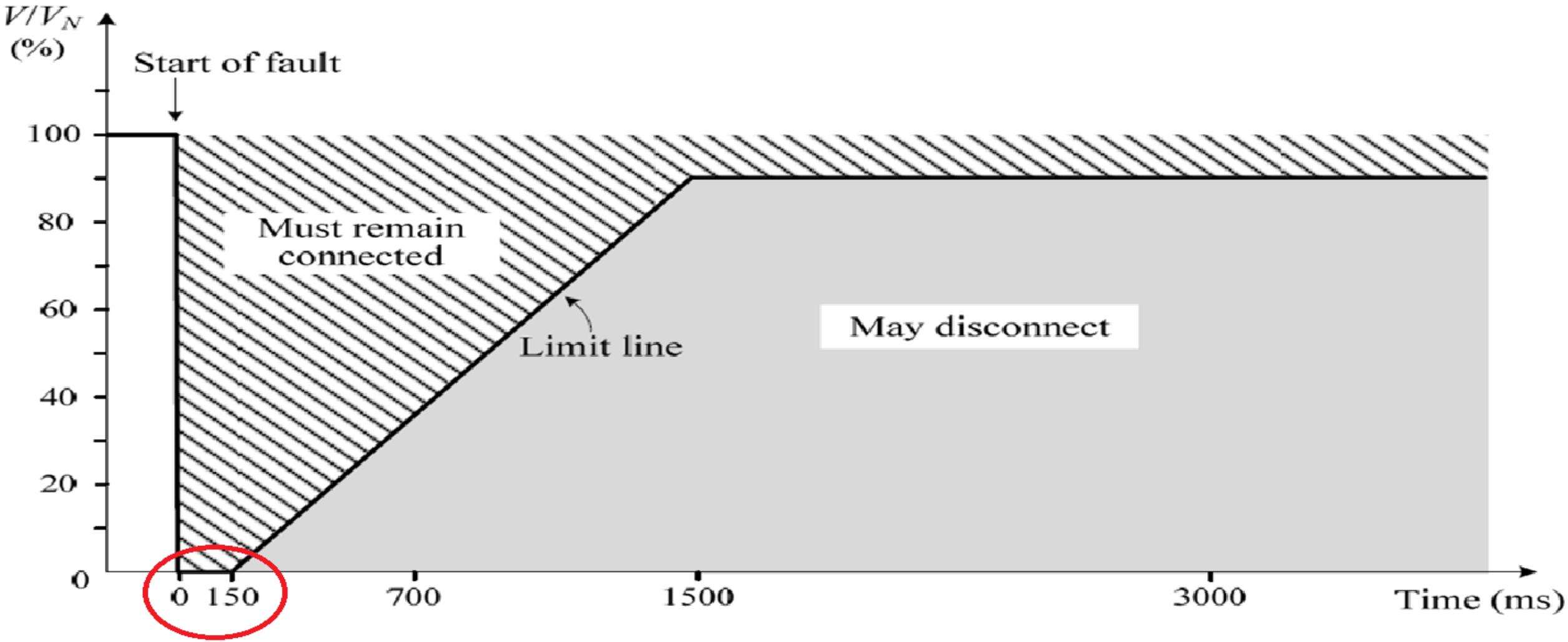
Depth & duration of voltage dips are usually defined in a voltage-time diagram.



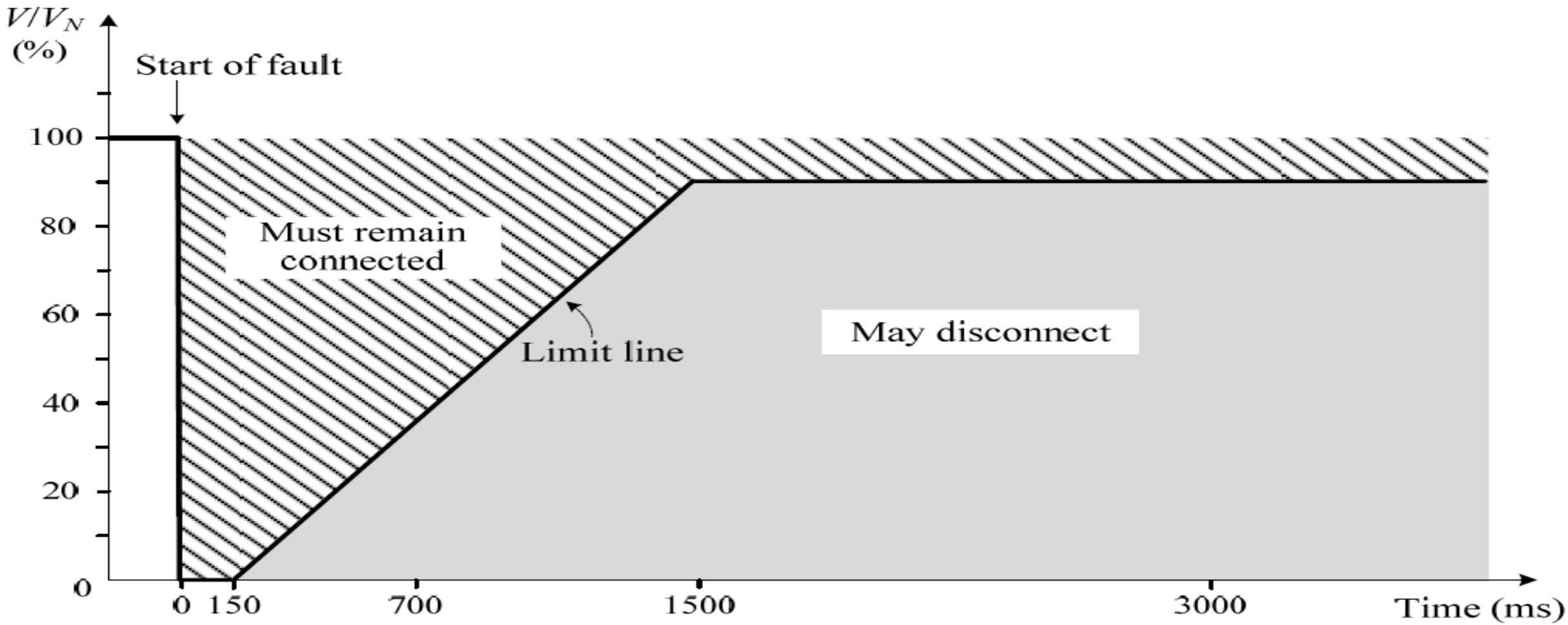
Example of low voltage ride through (LVRT) requirements during grid faults,



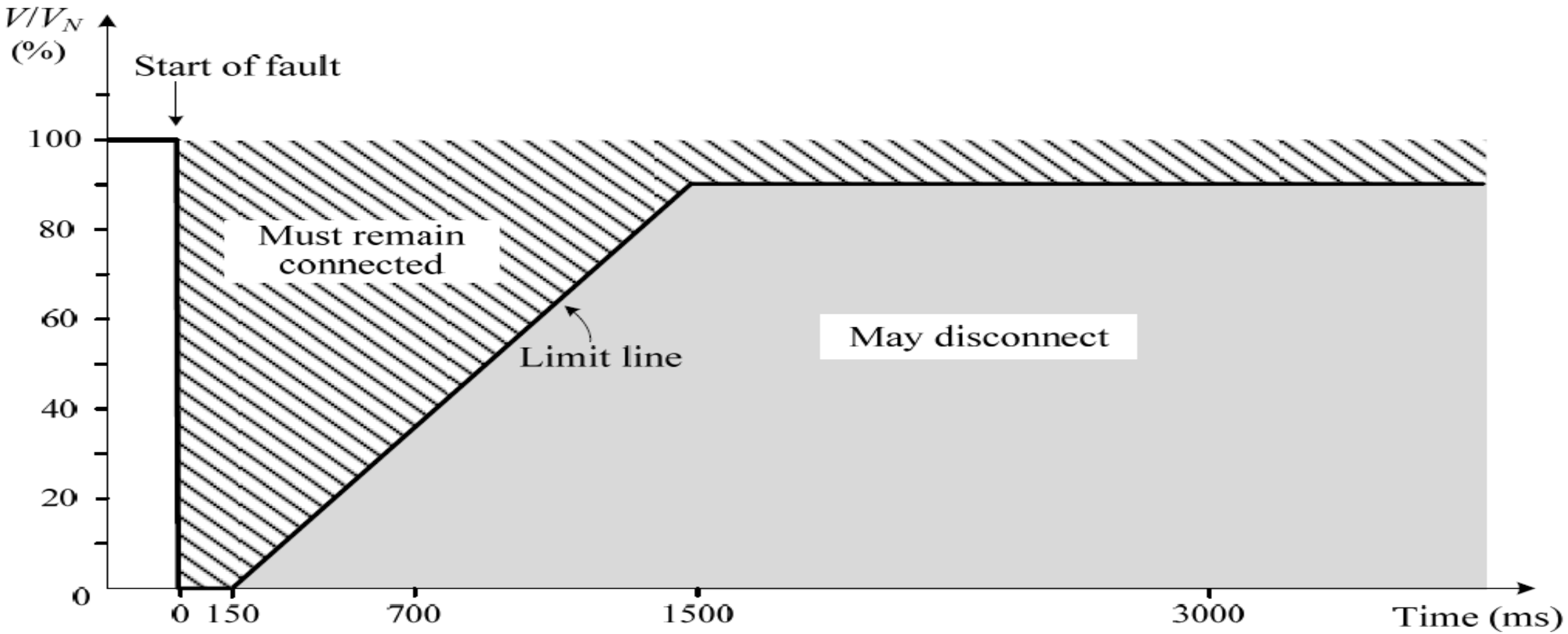
Above limit line, a power generating system must remain connected during fault even when grid voltage falls to 0 with duration of <150ms.



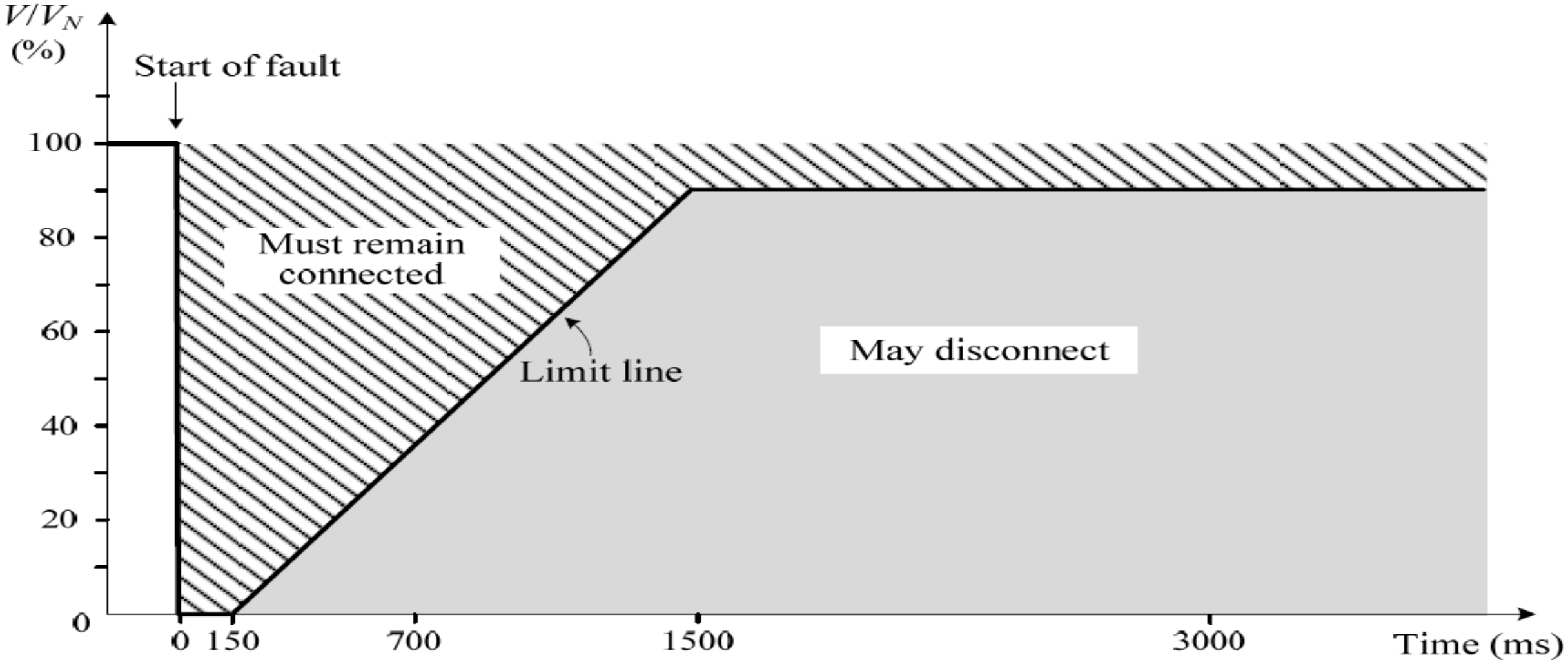
System is allowed to be disconnected from grid only when voltage dips are in area below limit line.



Grid codes also require system to supply certain amount of reactive current to: support grid voltage during fault .



Limits & ranges for LVRT requirements vary with grid operators in different countries. But they all share a common background and purpose.



Summary

- Horizontal- & Vertical-Axis Wind Turbines
- Fixed & Variable-speed Turbines
- Wind Energy Conversion System Configurations
- Grid Code
- Fault Ride-through Requirements
- Reactive Power Control