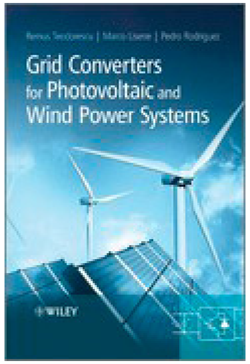


Grid Converters for Photovoltaic and Wind Power Systems

by R. Teodorescu, M. Liserre and P. Rodriguez

ISBN: 978-0-470-05751-3

Chapter 6

Grid Converter Structures for Wind Turbine Systems

Introduction

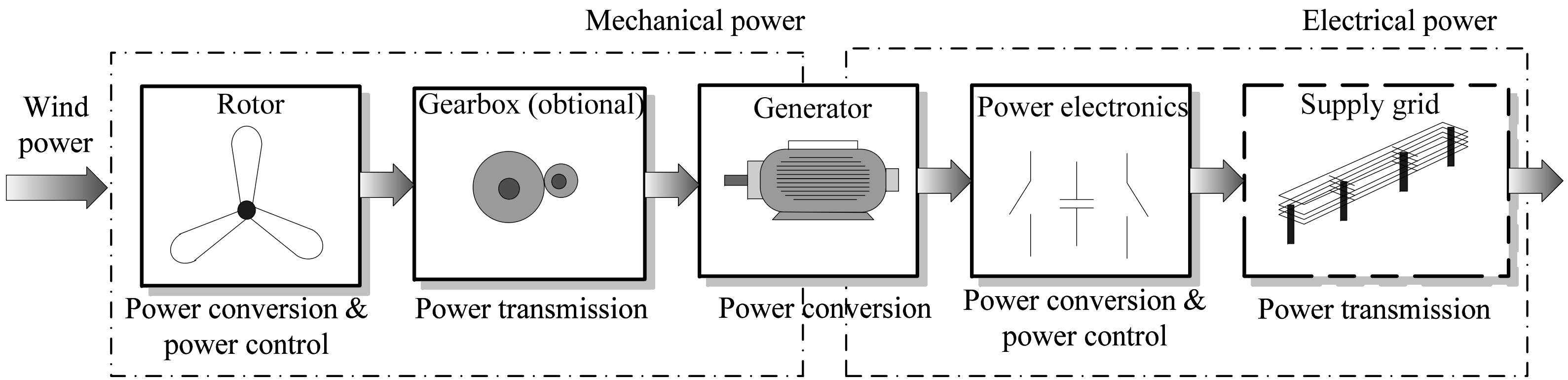
- Wind power could create problem to the transmission line designed for constant power and to the power system stability
- If the wind power plant (single large power wind turbine or wind-park) would behave as a classical power source allowing to decide how much power to inject and when, the main limitation to its use would cease to exist
- Use of power electronics, especially on the grid side, in connection with the control of the pitch angle of the blades can partially relive the problem allowing the WT power plant to behave similarly to a conventional power plant

Outline

- Wind Turbine Power Configurations
- Grid Power Converter Topologies
  - Single Cell
    - Medium Power
    - High Power
  - Multi-Cell
- Wind Turbine Control
  - Active and Reactive Power Control
  - Frequency Support
    - Primary Frequency Control
    - Inertia Emulation
    - Power Oscillation Damping
  - Voltage Support
  - Fault Ride Through

Wind Turbine Power Configurations

Basic Power Conversion Wind Turbine System

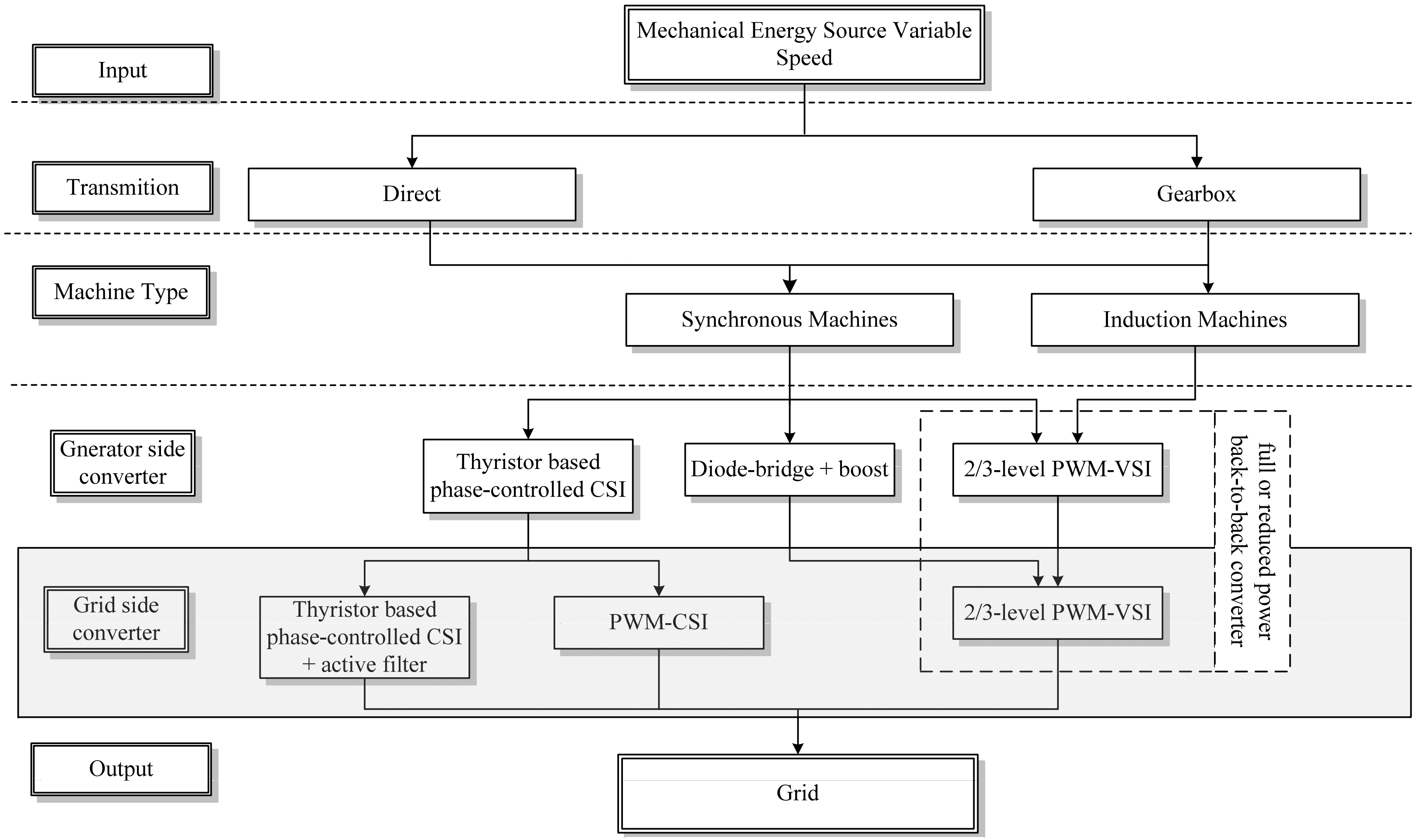


Extracts the energy from the wind and makes the kinetic energy of the wind available to a rotating shaft

The transformation of the electrical energy making it suitable for the electric grid (mainly in frequency and phase)

Wind Turbine Power Configurations

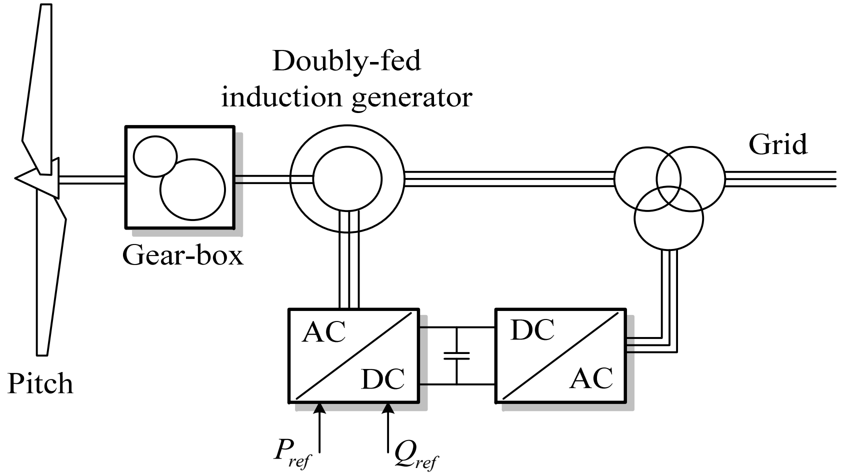
Power conversion structures for variable speed wind turbine systems:



Wind Turbine Power Configurations

Reduce power back-to-back converter options

Doubly-fed induction generator with back-to-back connected to the rotor:

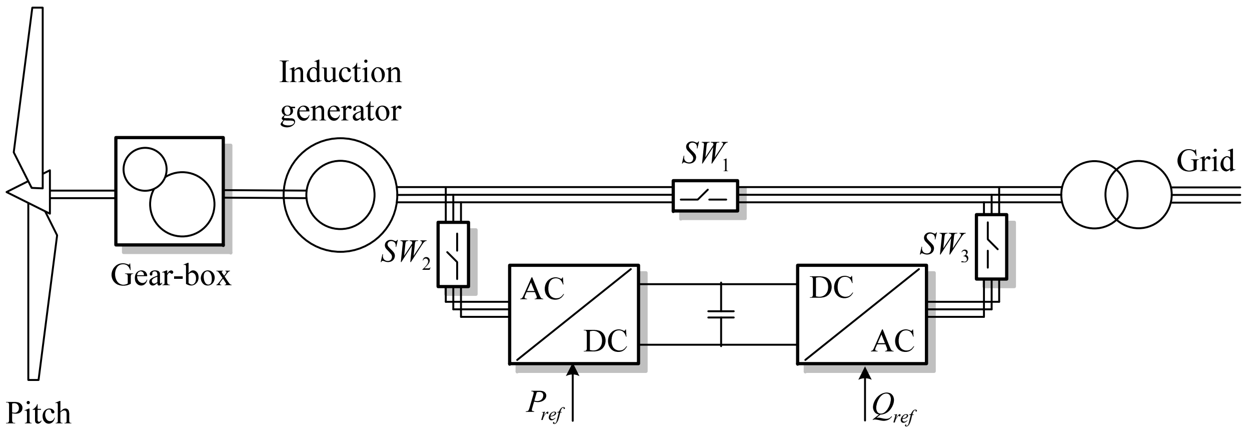


- 30% (x2) power rated converter in the rotor allowing variable-speed (+/- 30%)
- Acting on back-to-back converter is possible to vary the injected P and Q
- The system still contribute to the short-circuit power because the stator is directly coupled to the grid
- Slip rings are need in order to connect the converter on the rotor
- The gear is still needed and the speed regulation via the rotor is used only to optimize the power extraction from the wind
- This technology is used by companies like Vestas, GE, Gamesa, etc.

Wind Turbine Power Configurations

Reduce power back-to-back converter options

Double-fed Induction generator with back-to-back connected to stator:

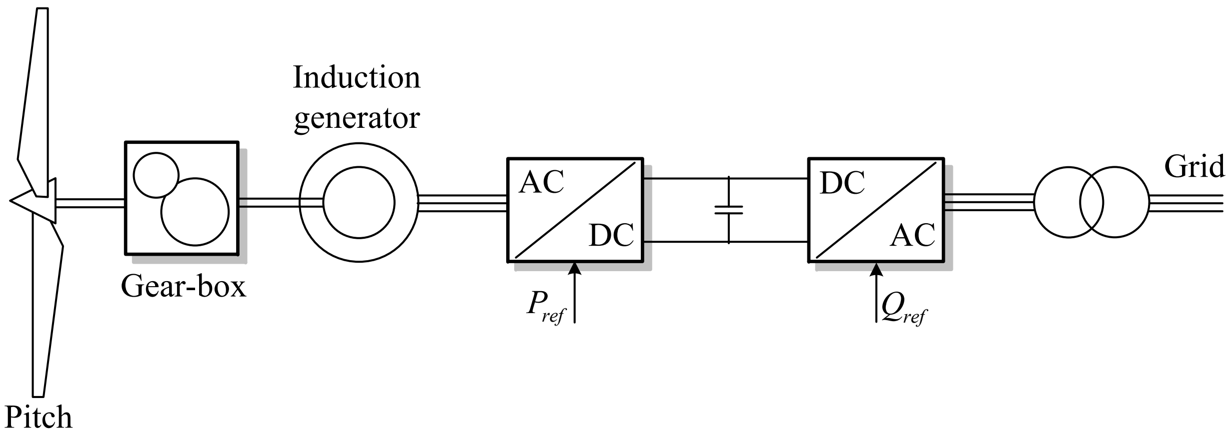


The back-to-back converter is only connected in two cases:

- At medium and low power to optimize the power extraction and transfer to the grid (SW_1 open SW_2 and SW_3 closed)
- At full power only the grid-side converter is connected to perform harmonic and reactive power compensations (SW_2 open , SW_1 and SW_3 closed)

Wind Turbine Power Configurations

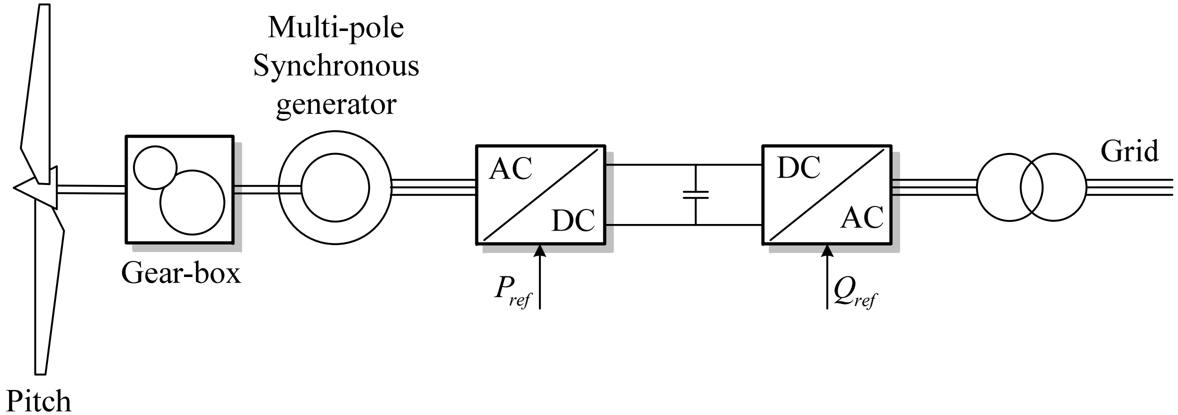
Full power back-to-back converter with induction generator:



- An induction generator completely decoupled from the grid and as a consequence this system has a complete rolling capacity and does not contribute to the short-circuit power. In this system the bandwidth of the control is quite high (0.5 ms) and it can completely stand-by and operate in islanding mode. However the gear is still needed and the power converter is full-scale 1 p.u. (x2)
- The advantages are that the range of variable speed are much larger than in the case of DFIG and also the controllability of injecting P and Q is higher
- The IG has two constructive shortcomings: require small airgap and exhibit low PF making the penetration in large powers problematic
- This technology is used by companies like Siemens

Wind Turbine Power Configurations

Full power back-to-back converter with synchronous generator



- Synchronous as the generated frequency is synchronous with the rotor rotation
- But the generated frequency is not synchronised with the grid frequency
- Same advantages as full power converter with induction generator in terms of variable speed range and P, Q controllability
- Synchronous machines exhibit typically higher PF and larger airgap then IG making them more practical for large power. They can be built with large nr of poles in order to eliminate the gear (direct drive)
- In the construction with permanent magnets excitation the synchronous generators exhibit higher efficiency as IG and is the preferred solution for WTG larger than 4 MW
- This technology is used by companies like Enercon and GE (SG) and Siemens(PMSG)

Grid Power Converter Topologies

Topologies for Wind Turbine Converters:

WT power structures are classified as:

- Reduced power converter (DFIG)
- Full-power converter (IG, SG and PMSG)

For efficient and reliable management of higher power, two possibilities:

- Single-cell $\rightarrow$ to use high power multilevel converters topologies (e.g. MV Neutral Point Clamped)
- Multi-cell $\rightarrow$ to use several medium power converters (e.g. LV 2-level FB) connected as parallel cells

Main demands for power converter topologies in wind turbine systems:

- High Reliability (20 years life-time)
- Minimum maintenance (specially offshore!)
- Limited physical size/weight
- High efficiency

Grid Power Converter Topologies

The AC/AC conversion in wind turbine from the generator to grid can be direct or indirect. In the indirect case there is a DC-link that connects two converters AC/DC and DC/AC converters. In the direct case the DC-link is not present (such as the matrix converter topology).

- The advantages of the indirect conversion: Decoupling between grid and generator (compensation for non-symmetry and other power quality issues). Helpful in case of low voltage ride through and for providing some inertia in the power transfer from generator to grid
- The disadvantages of the indirect conversion: Need for major energy-storage in DC-link (reduced life-time and increased expenses)
- The advantages of the direct conversion: The absence of dc-link storage (generally the less reliable part of the converters and the most subject to maintenance) makes this solution attractive especially for off-shore wind turbine systems characterized by difficult maintenance
- The disadvantages of the direct conversion: The fact that this is not a proven technology requiring higher number of components (hence more conduction losses) and a more complex control part. The grid filter-design is more complex and there is subunitary voltage transfer ratio

Grid Power Converter Topologies

Single-cell Converters

The grid converter topologies can be classified in:

- Voltage-stiff (voltage-fed or voltage-source): VSC
- Current-stiff (current-fed or current-source): CSC

Depending on the main power flow direction they are named:

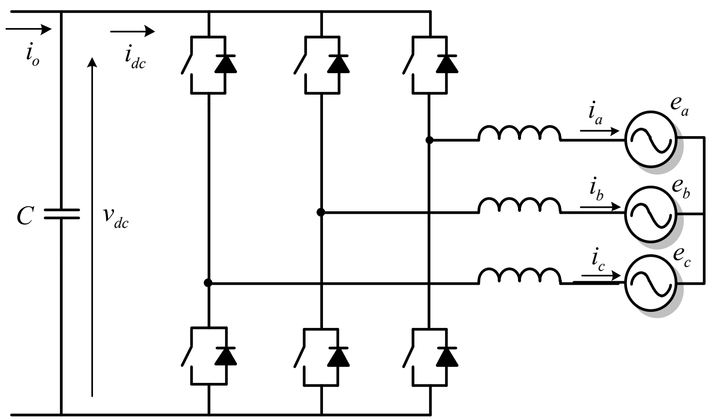
- Rectifiers or inverters or in case they can work with both power flows they are bidirectional

Then they can be classified as:

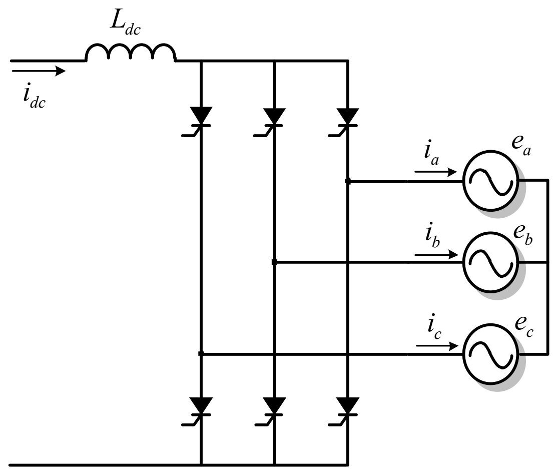
- Phase-controlled (typically using thyristors and natural commutation synchronized with the grid voltage) usually for CSC
- PWM using forced commutated device (typically IGBT and IGCT) usually for VSC

Grid Power Converter Topologies

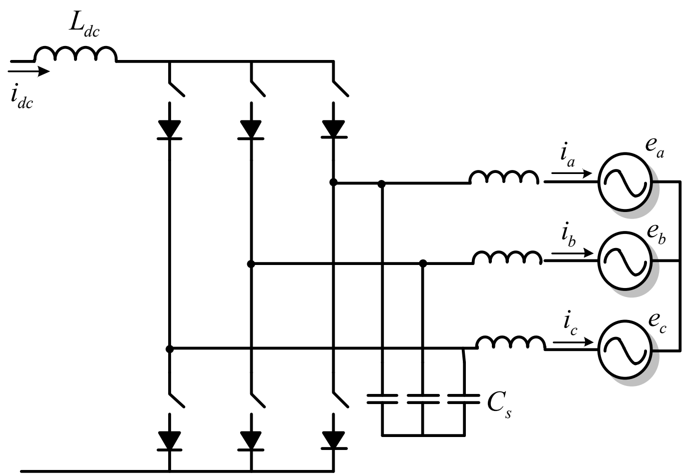
Single-cell grid converter in case of indirect type conversion:



Forced-commutated VSC (IGBT, IGCT)



Phase-controlled line-commutated converter (Thyristors)



Forced-commutated CSC (GTO)

Grid Power Converter Topologies

VSC vs. CSC:

The VSC is widely used. It has the following features:

- The ac output voltage is limited below and cannot exceed the dc voltage or the dc rail voltage has to be greater than the ac input voltage
- The upper and lower devices of each phase leg cannot be gated on simultaneously either by purpose or by EMI noise. Otherwise, a shoot through would occur and destroy the devices. Dead-time to block both upper and lower devices has to be provided in the VSC, which causes waveform distortion
- An output high order filter is needed for reducing the ripple in the current and comply the harmonic requirements. This causes additional power loss and control complexity

The CSC has the following features:

- The ac output voltage has to be greater than the original dc voltage that feeds the dc inductor or the dc voltage produced is always smaller than the ac input voltage. For grid converter applications this is a clear advantage
- At least one of the upper devices and one of the lower devices have to be gated on and maintained on at any time. Otherwise, an open circuit of the dc inductor would occur and destroy the devices. Overlap time for safe current commutation is needed in the I-source converter, which also causes waveform distortion, etc.
- The main switches of the I-source converter have to block reverse voltage that requires a series diode to be used in combination with high-speed and high performance transistors such as IGBTs. This prevents the direct use of low-cost and high-performance IGBT modules and IPMs

The traditional CSC had more limited application

Grid Power Converter Topologies

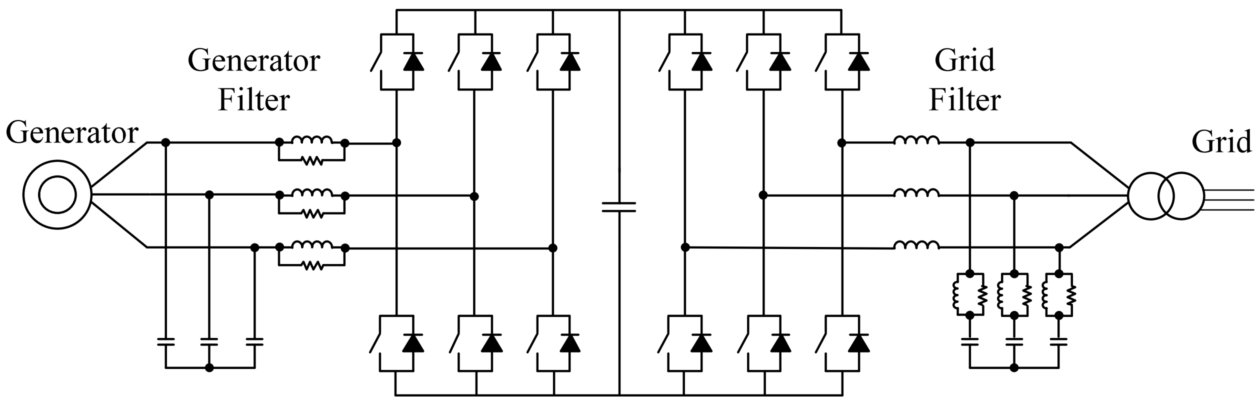
Single-Cell

Medium power converter

Medium power wind turbine systems of 2 MW are still the best seller on the market and their power level can still allow to find a good design trade-off using single-cell topologies with just six switches forming a bridge.

VSC

In all the cases forced commutated converters allow a better control on the injected power and harmonics. Between the forced commutated converters the preferred solution is the VSI. Particularly in case the VSI is adopted, as usual, on the generator side, the resulting configuration is called back-to-back.



Two-level back-to-back PWM-VSI

Grid Power Converter Topologies

Single-Cell

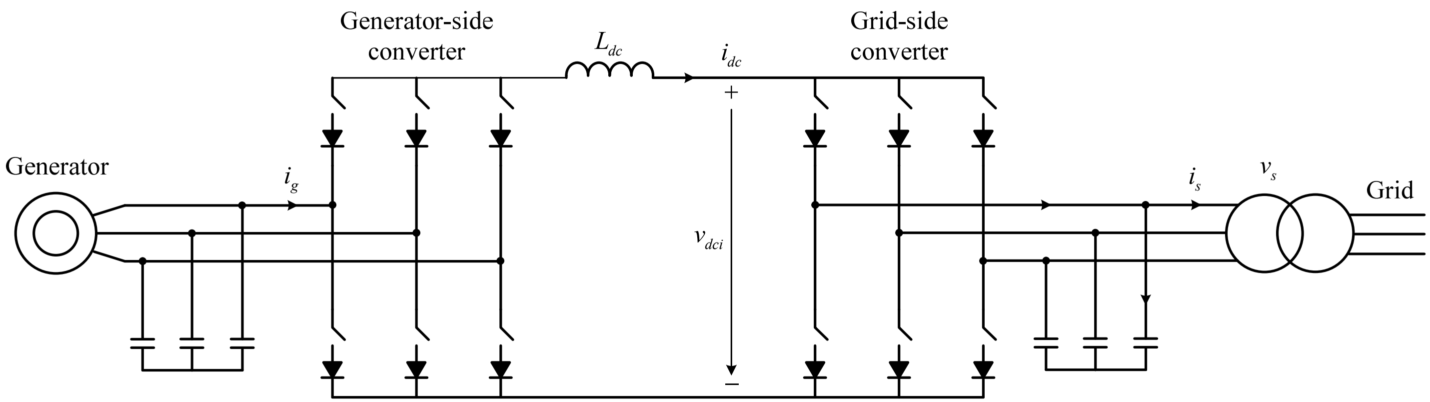
Medium power converter

The Two-level back-to-back VSI is a proven technology that employs standard power devices (integrated) however power losses (switching and conduction losses) may limit the use in higher power systems.

CSC

The alternative can be the use of CSCs that have three main advantages:

- A portion of the needed dc-link inductance is realized by exploiting the cable length (between two converters)
- The dc link reactor provides natural protection against short-circuit fault, and therefore, the fault ride through strategy required by the grid code can be integrated easily into the system
- A small filter is required on the ac side to cope with the standards in terms of harmonic requirements



Two-level back-to-back PWM-CSI

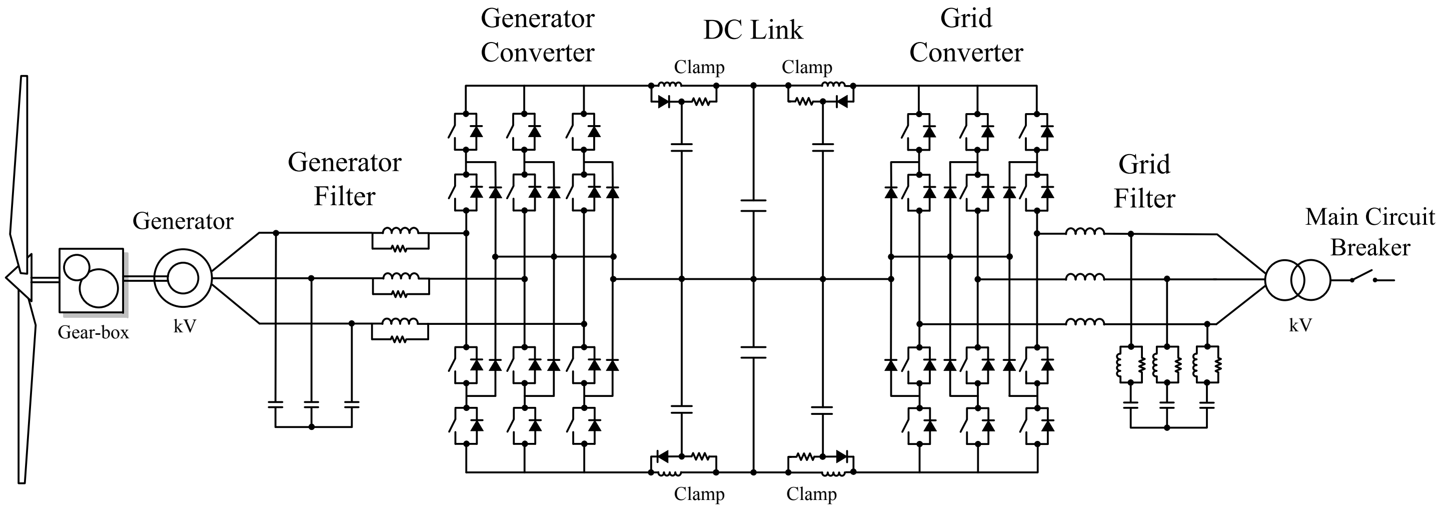
Grid Power Converter Topologies

Single-Cell

High power converter (NPC)

In case the power level increases over 2 MW a multilevel solution such as the three-level voltage source converter is a known technology that allows lower rating for the semiconductor devices and lower harmonic distortion to the grid (or lower switching losses / smaller grid-filter).

However the conduction losses are still high due to the number of devices in series through which the grid current flows and the more complex control that is needed to balance the dc-link capacitors.



Three-level back-to-back VSI

This MV (3.3 kV with IGBT) technology is used by Areva, Alstom and Multibrid and ABB(IGCT)

Grid Power Converter Topologies

Multi-Cell (interleaved or cascaded)

Another option to increase the overall power of the system is to use more power converter cells in parallel or in cascade.

In both the cases the power handling capability increases while the reliability:

- Decreases, if computed in terms of number of failures
- Increases, if computed in terms of system outages

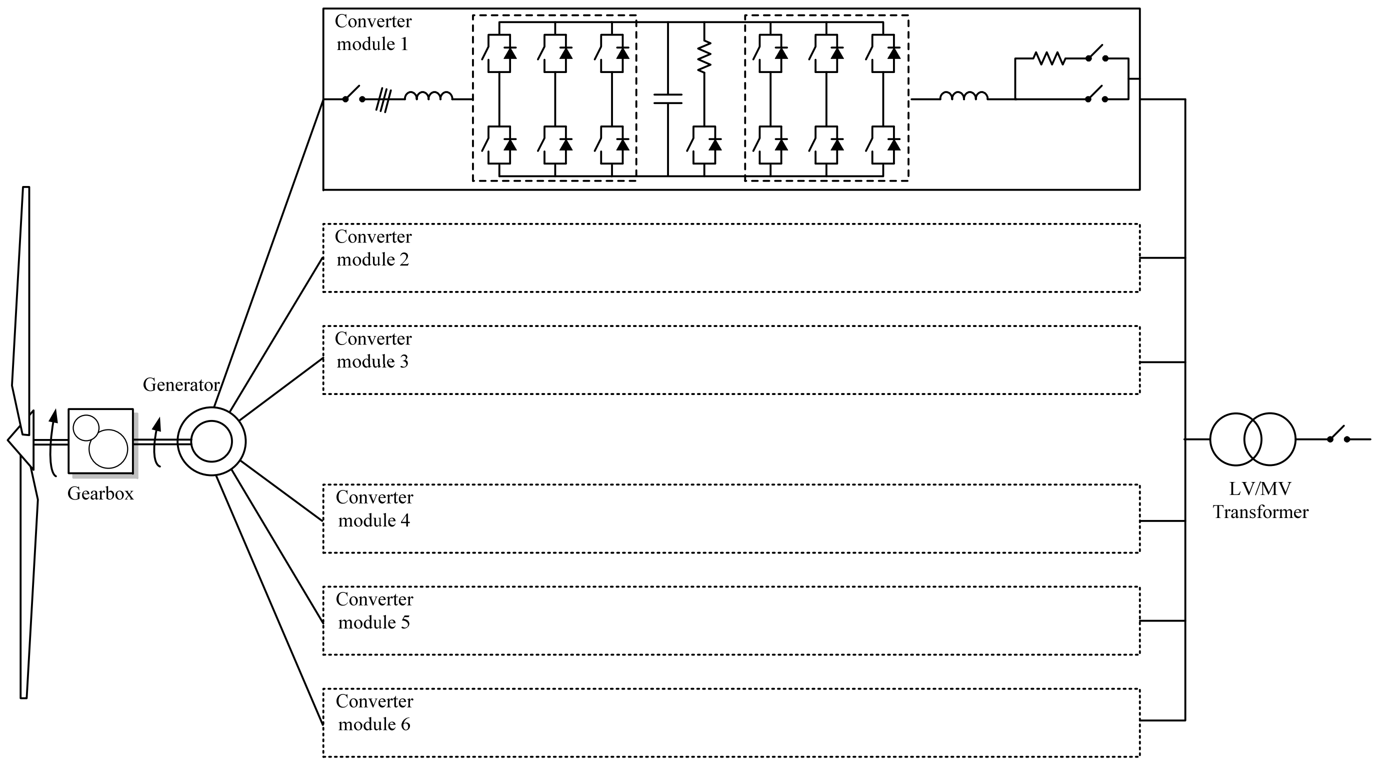
In fact the modularity implies redundancy that allows the system to continue to operate if one of the cells fails. Moreover the multi-cell option allows to use a reduced number of cells, with consequent reduced losses, in low wind condition when the produced power is low.

Typically the power cells are connected in parallel on the grid side to allow interleaving operation.
The PWM patterns are shifted in order to cancel PWM side-band harmonics. In this way the size of the grid filter can be considerably reduced.

Grid Power Converter Topologies

Multi-Cell:

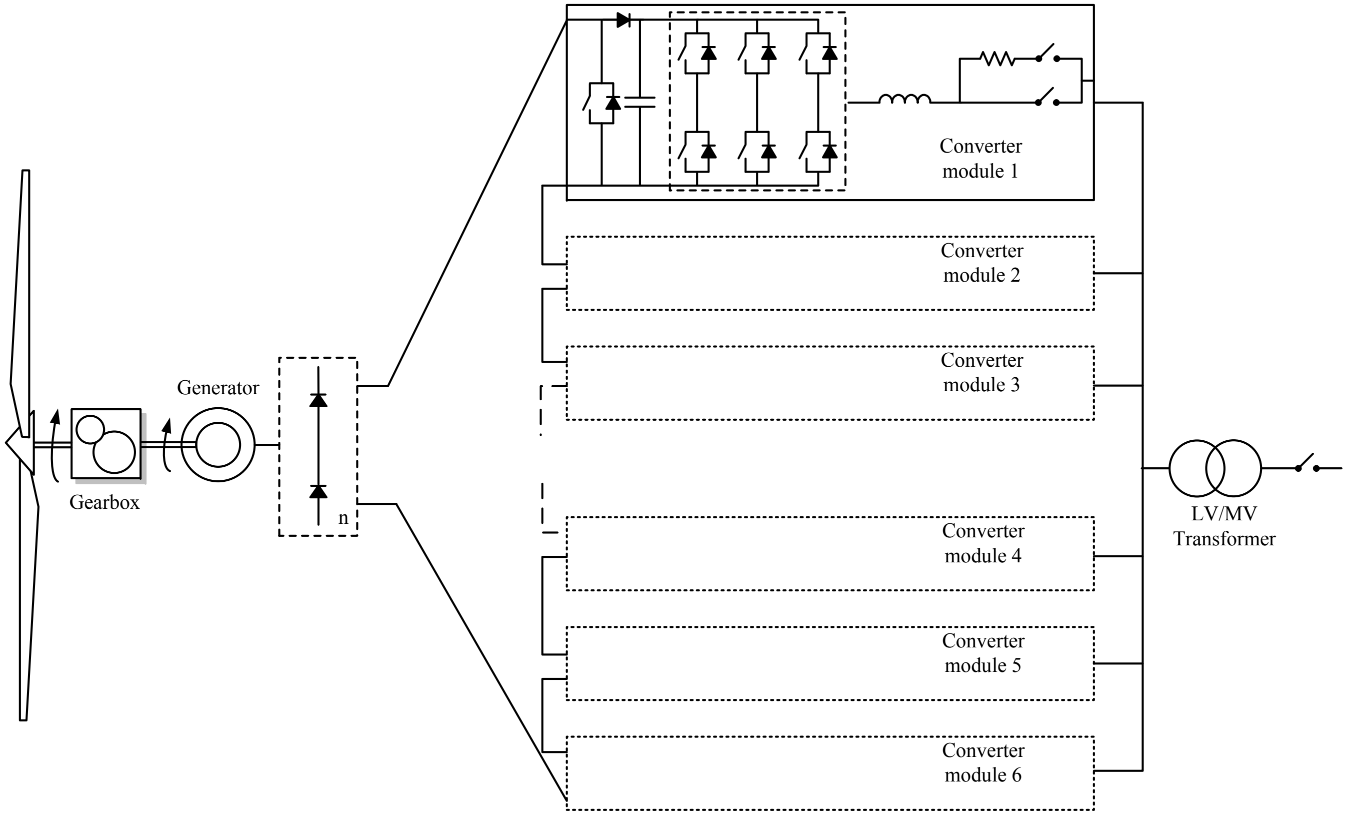
- A back-to-back converter fed by a six-phase generator and connected in parallel and interleaved on the grid side



Grid Power Converter Topologies

Multi-Cell

- A n-leg diode bridge fed by a synchronous generator producing a high dc voltage shared among several grid/converters connected in parallel and interleaved on the grid side

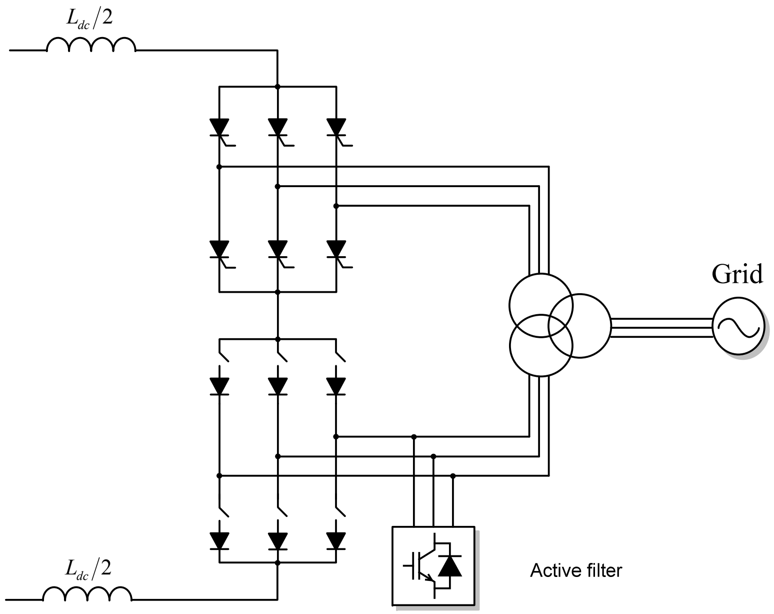


Grid Power Converter Topologies

Multi-Cell:

- Also can be achieved with CSC topologies forming the well-known 12 pulses converter in case the CSC is phase-controlled. The DC to AC conversion can be performed by the 2 series-connected current-source inverters (and) independently supplied by the two equal secondaries of a Y-Y-transformer

The CSC are connected in series on the DC side and in parallel on the AC side to reduce the ripple in the DC current, operate with higher DC voltage and double the power carrying capability.

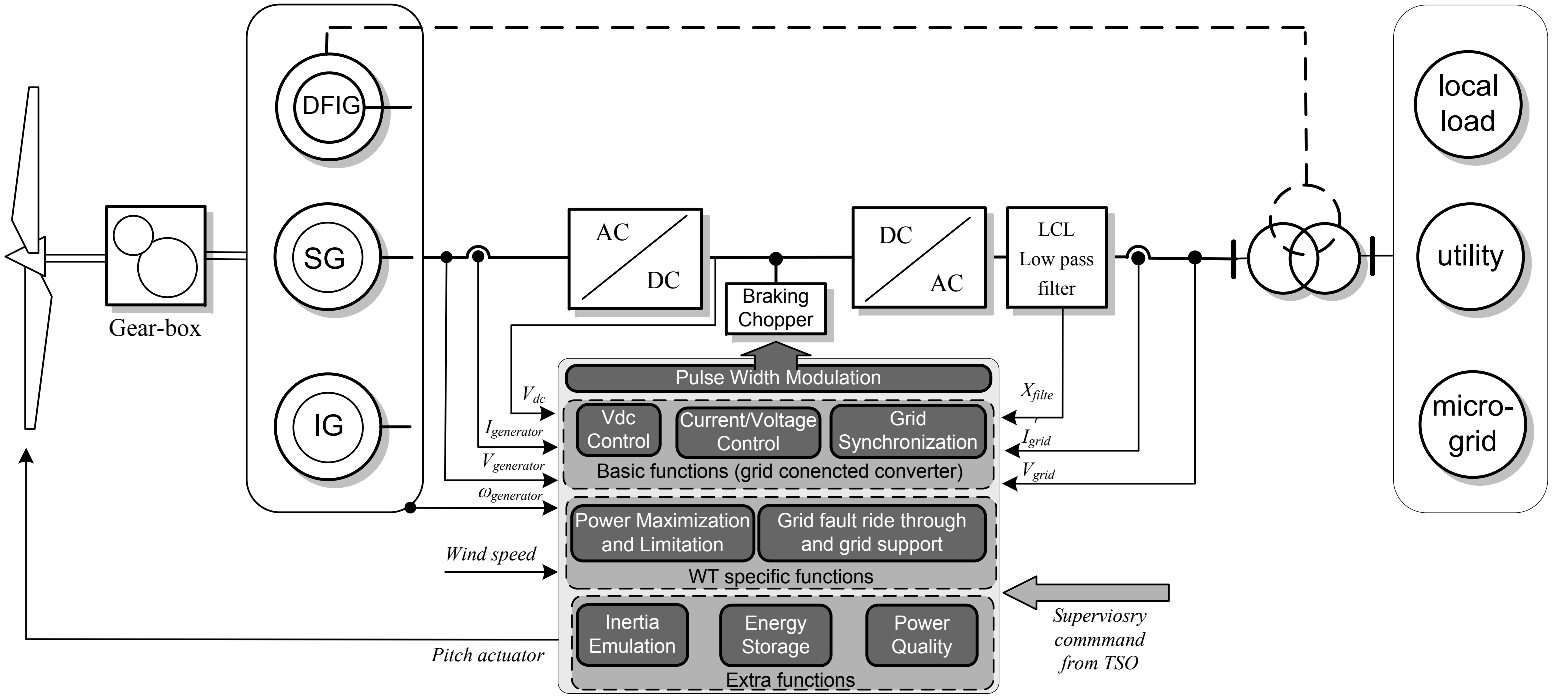


Thyristor based phase-controlled CSI + active filter

Source: P. Tenca, A.A. Rockhill, T. A. Lipo, P. Tricoli, "Current Source Topology for Wind Turbines With Decreased Mains Current Harmonics, Further Reducible via Functional Minimization," IEEE Transactions on Power Electronics, vol.23, no.3, pp.1143-1155, May 2008

Wind Turbine Control

Wind turbine control structure:



Power has to be controlled by means of the aerodynamic system and has to react based on a set-point given by a dispatched center or locally with the goal to maximize the power production based on the available wind power

Source: M. Liserre, R. Cardenas, M. Molinas, J. Rodriguez "Overview of Multi-MW wind turbines and wind parks" IEEE Transactions on Industrial Electronics, April 2011

Wind Turbine Control

Wind turbine control structure:

Both fast and slow control dynamics:

The electrical control is in charge of the interconnection with the grid and active/reactive power control but also of the overload protection

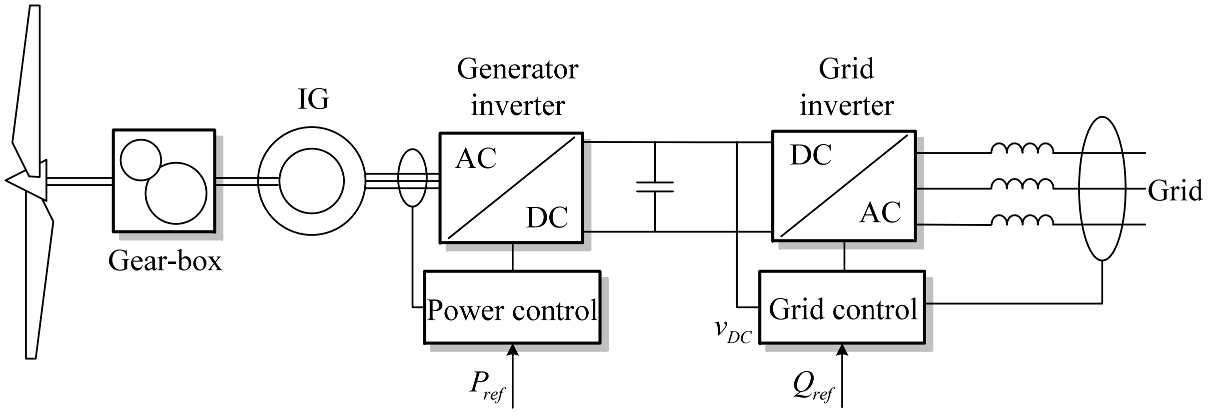
The mechanical subsystem is responsible of the power limitation (with pitch adjustment), maximum energy capture, speed limitation and reduction of the acoustical noise

Below maximum power production → speed proportional with wind speed + pitch angle fixed.
Pitch angle controller limits the power when reaches nominal power.

Generator-side converter control → maximum power from the wind.
Grid-side converter control → dc-link voltage fixed.
Internal current and voltage loops in both converters are used

Wind Turbine Control

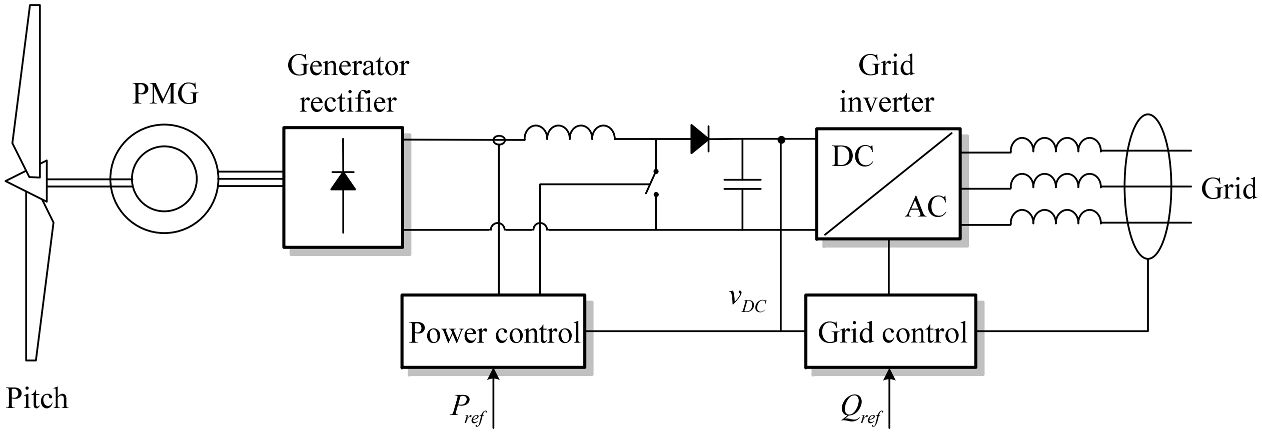
Squirrel cage induction generator control:



- The squirrel cage induction generator with a full power forced commutated back-to-back converter
- Often chosen by wind turbine manufacturers for low power stand-alone systems but recently has been used for high power wind turbines, as well
- The machine flux and rotor speed or electric torque is controlled via a Field Orientated Control (FOC) or Direct Torque Control (DTC), even if this last option is seldom adopted in WTS

Wind Turbine Control

Synchronous generator control



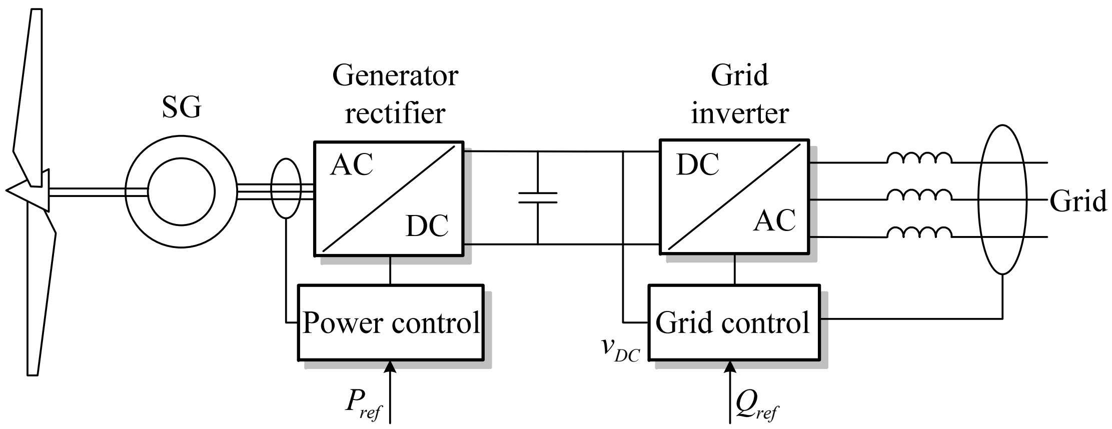
A passive rectifier and a boost converter to boost the voltage at low speed:

- Generator is controlled via the current control of the boost converter

Not possible to control selectively the harmonics in the current and the phase of the fundamental current respect to the generator electromotive force to achieve full torque-producing current.

Wind Turbine Control

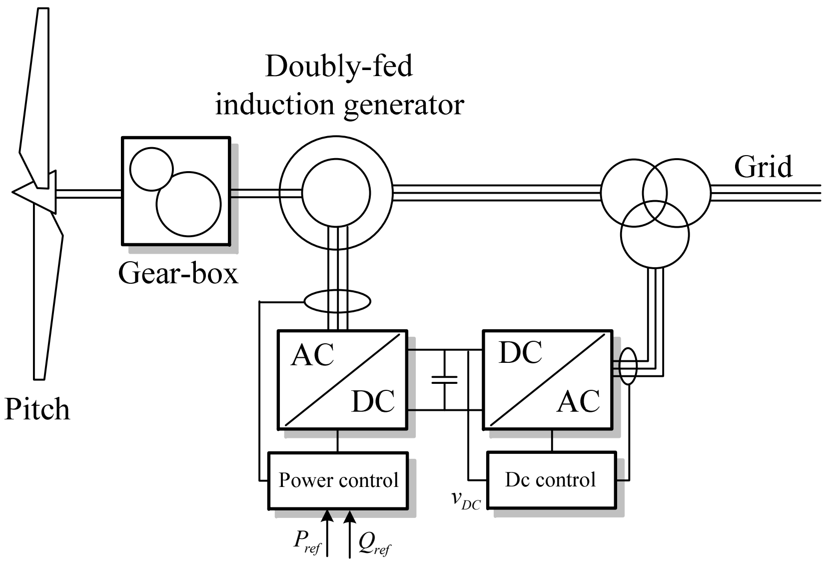
Synchronous generator control



Generator control is usually a standard FOC
the current component that controls the flux can be adapted to minimize the core losses and the reference speed is adapted to optimize the power injection into the grid

Wind Turbine Control

Doubly-fed induction generator control:



Electrical power control:
by controlling the doubly-fed generator through the rotor-side converter.

The control of the grid-side converter is simply just keeping the dc-link voltage fixed.

- Below maximum power production the wind turbine will typically vary the speed proportional with the wind speed and keep the pitch angle fixed
- At very low wind the speed of the turbine will be fixed at the maximum allowable slip in order not to have overvoltage
- A pitch angle controller will limit the power when the turbine reaches nominal power
- The power converter rating is limited to a 30% of the rated power of the system but also the rotor speed has a limited range of variability (- 30% + 20%)
- A ‘crowbar’ system can be adopted to ride-through grid faults

Wind Turbine Control

Doubly-fed induction generator control: (Cont'd)

The power produced by the turbine P_{mecc} follows two paths: stator and rotor

$$P_{mecc} = P_S - s \cdot P_S$$

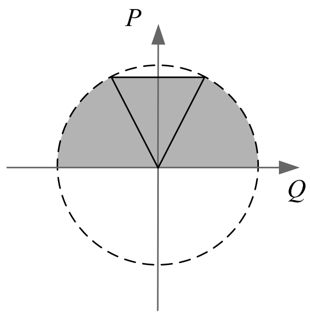
Where, P_S is stator power, s is slip.
It is obvious that the doubly-fed inject power into the grid both during over-synchronous $(s > 0)$ and subsynchronous operation $(s < 0)$

The machine stator is connected directly and continuously to the grid and exchanges active and reactive power with it.
If the machine equations are re-written in a *dq*-frame, oriented with the stator flux, it results

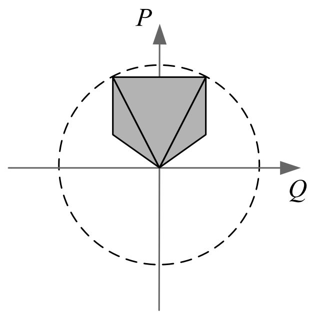
$$P_S = -a \cdot (V_S \cdot I_{rq})$$

$$Q_S = V_S \cdot (\frac{V_s^2}{b} - V_S \cdot I_{rd})$$

Hence:
I_{rq} can be used to control active power
I_{rd} can be used to control active power



FSC



DFIG

Conclusions

- DFIG is the most common WTG configuration but due to new demanding grid codes FDC solutions are wining increasing market shares
- PMSG and Multipole SG (direct-drive) in FSC configurations are used for large WTG > 4 MW (Vestas, GE, Siemens, Gamesa etc.)
- VSI is the typical converter topology used in WTG
- LV 2-levels FB VSI is used for WTGs for up to 5-6 MW by parallel converters build with 1700 V IGBTS
- New multilelevel VSI like NPC with HV IGBTs or IGCTs are emerging for large WTG with converter+filter mounted at the base of the towers (Areva, Multibrid, etc.)