

ELG4126

Wind Turbine Generators for Wind Power Plants

The application of WTGs in modern wind power plants (WPPs) requires an understanding of a number of different aspects related to the design and capabilities of the machines involved.

Basing on IEEE PES Wind Plant Collector System Design Working Group

Introduction

- The principle of wind turbine operation is based on two well-known processes:
 - Conversion of kinetic energy of moving air into mechanical energy using aerodynamic rotor blades and a variety of methodologies for mechanical power control.
 - Electromechanical energy conversion through a generator that is transmitted to the grid.
- Usually wind turbines are classified by their mechanical power control, and further by their speed control.
- All turbine blades convert the motion of air across the air foils to torque and then regulate that torque in an attempt to capture as much energy as possible.
- Further wind turbines may be classified as either stall regulated or pitch regulated.

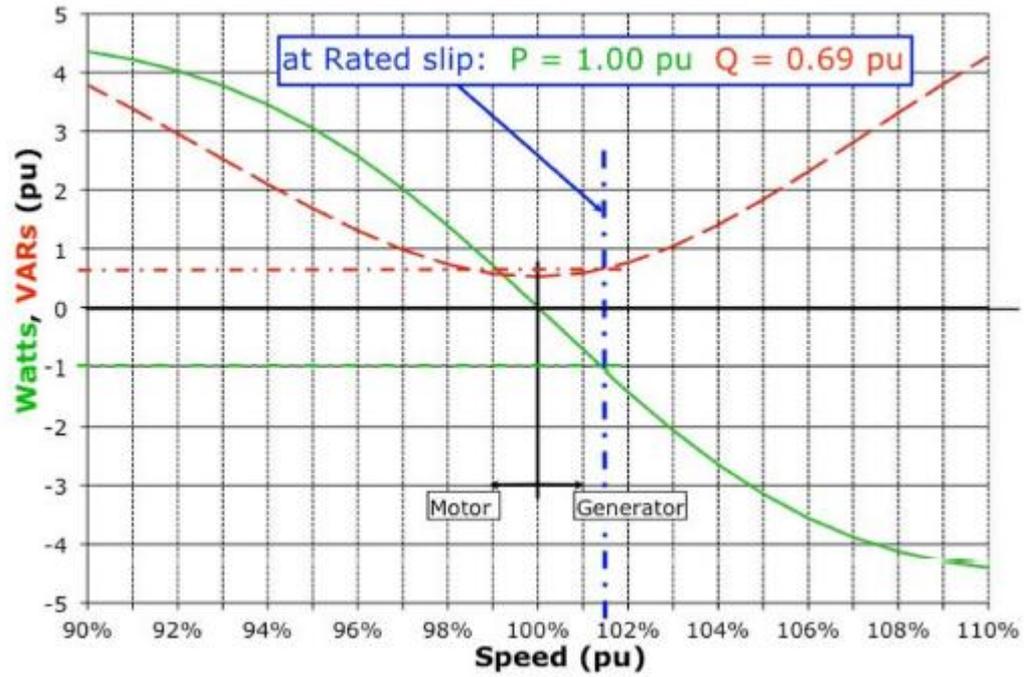
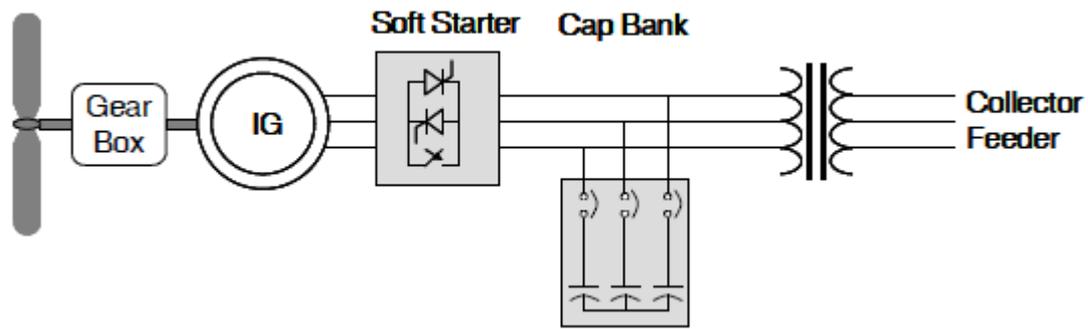
Regulation

- **Stall regulation** is achieved by shaping the wind turbine blades such that the airfoil generates less aerodynamic force at high wind speed, eventually stalling, thus reducing the turbine's torque; this technique is simple, inexpensive, and robust.
- **Pitch regulation**, on the other hand, is achieved through the use of pitching devices in the turbine hub, which twist the blades around their own axes. As the speed of wind increases, the blades quickly pitches to the optimum angle to control torque in order to capture the maximum energy or self protect, as needed.

Types of Wind Turbines

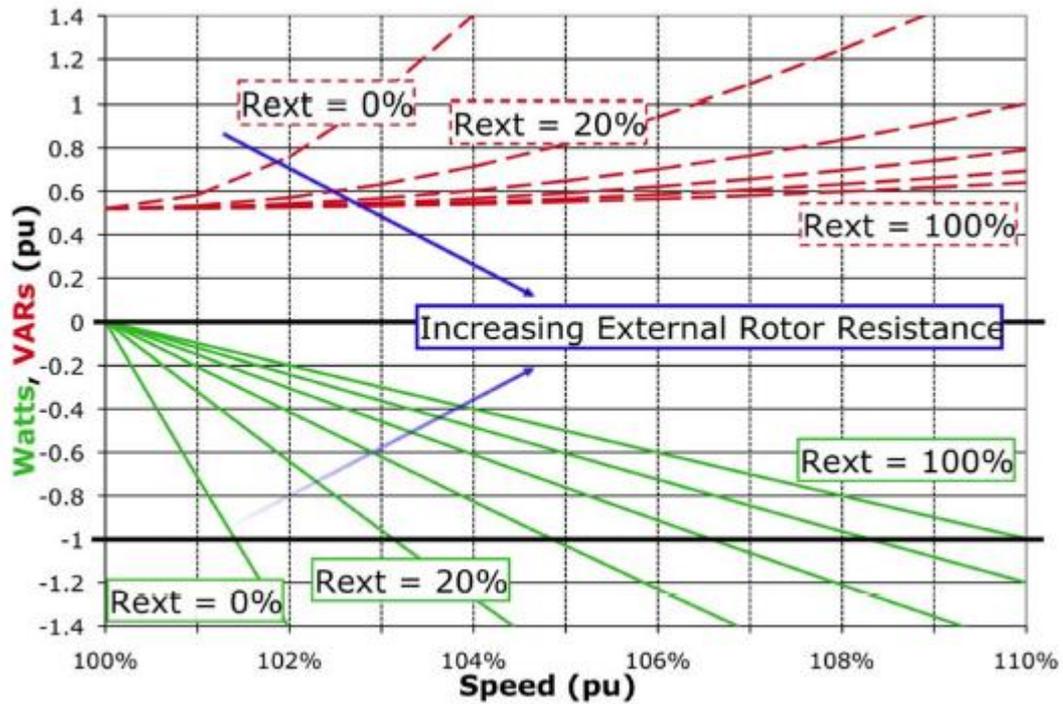
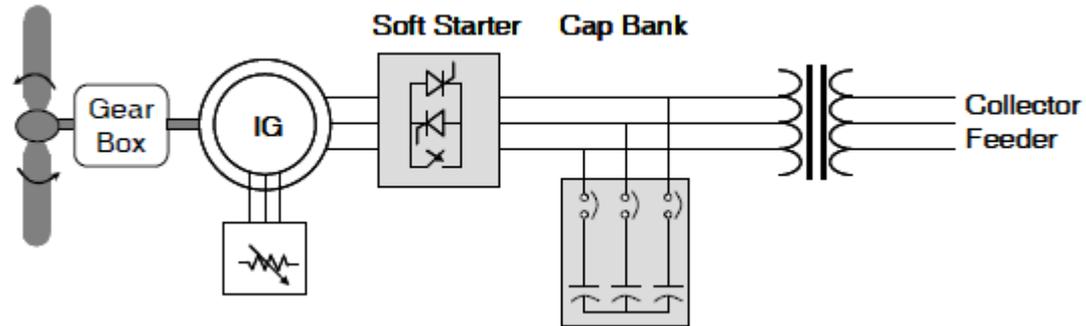
Type 1 (WT1G1): Limited Variable Speed

- Squirrel-cage Induction Generator (SCIG) connected directly to the step up transformer.
- The turbine speed is fixed (or nearly fixed) to the electrical grid frequency.
- It generates real power (P) when the turbine shaft rotates faster than the electrical grid frequency creating a negative slip (positive slip and power is motoring convention).
- For a given wind speed, the operating speed of the turbine under steady conditions is a nearly linear function of torque. For sudden changes in wind speed, the mechanical inertia of the drive train will limit the rate of change in electrical output.



Limited Variable Speed (Type 2)

- Wound rotor induction generators are connected directly to the WTG step-up transformer in a fashion similar to Type 1 with regards to the machines stator circuit, but also include a variable resistor in the rotor circuit.
- This can be accomplished with a set of resistors and power electronics external to the rotor with currents flowing between the resistors and rotor via slip rings.
- Alternately, the resistors and electronics can be mounted on the rotor, eliminating the slip rings—this is the Weier design.
- The variable resistors are connected into the rotor circuit softly and can control the rotor currents quite rapidly so as to keep constant power even during gusting conditions, and can influence the machine's dynamic response during grid disturbances.

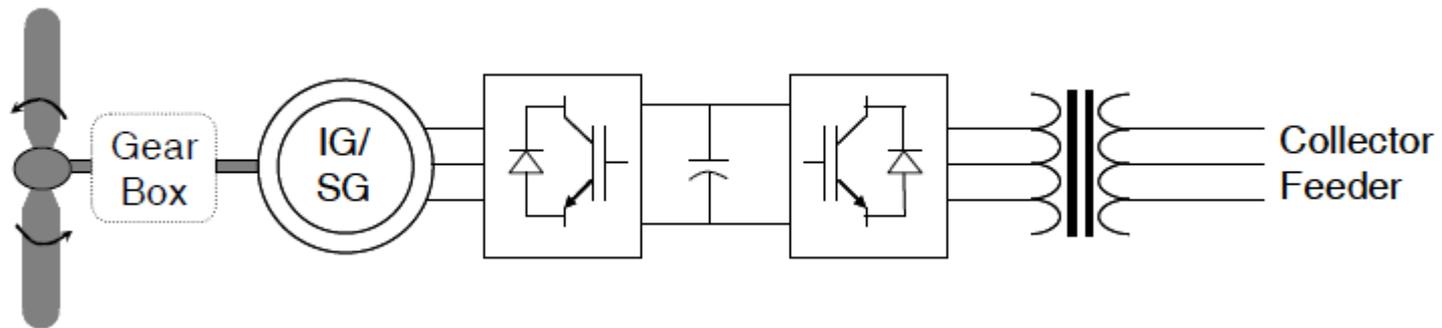


Variable Speed with Partial Power Electronics Conversion (Type3)

- The Type 3 turbine, known commonly as the Doubly Fed Induction Generator (DFIG) or Doubly Fed Asynchronous Generator (DFAG), takes the Type 2 design to the next level, by adding variable frequency ac excitation (instead of simply resistance) to the rotor circuit.
- The additional rotor excitation is supplied via slip rings by a current regulated, voltage-source converter, which can adjust the rotor currents' magnitude and phase nearly instantaneously.
- This rotor-side converter is connected back-to-back with a grid side converter, which exchanges power directly with the grid.

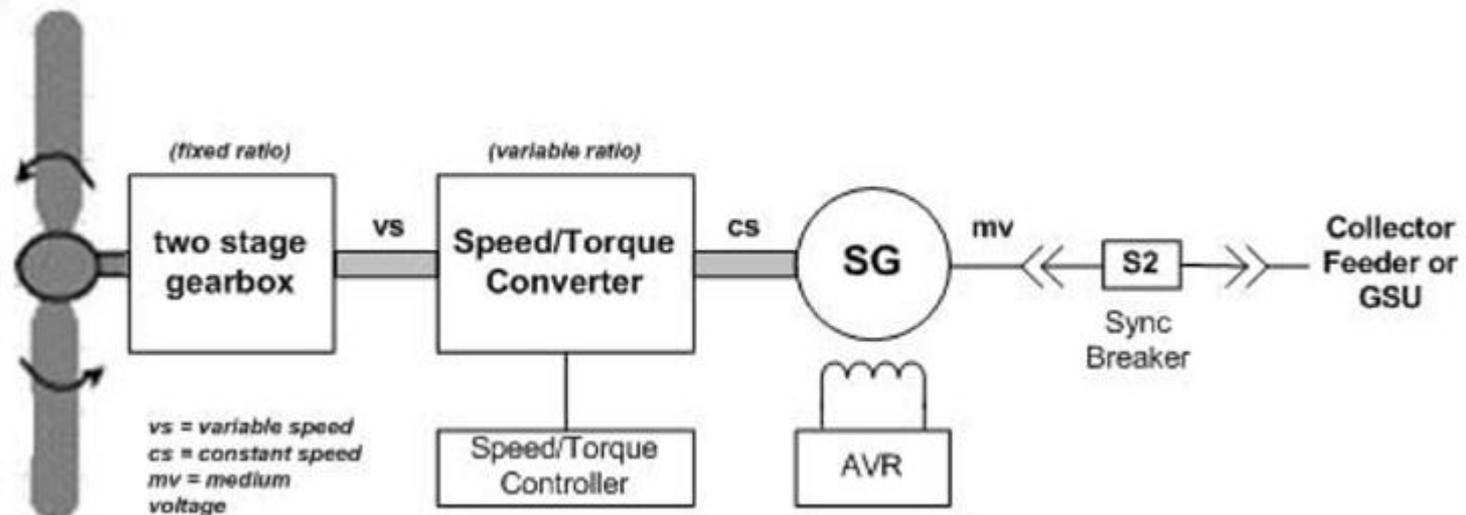
Variable Speed with Full Power Electronics Conversion (Type4)

- The Type 4 turbine offers a great deal of flexibility in design and operation as the output of the rotating machine is sent to the grid through a full-scale back-to-back frequency converter.
- The turbine is allowed to rotate at its optimal aerodynamic speed, resulting in a “wild” AC output from the machine.
- In addition, the gearbox may be eliminated, such that the machine spins at the slow turbine speed and generates an electrical frequency well below that of the grid.
- The rotating machines of this type have been constructed as wound rotor synchronous machines, similar to conventional generators found in hydroelectric plants with control of the field current and high pole numbers, as permanent magnet synchronous machines, or as squirrel cage induction machines.

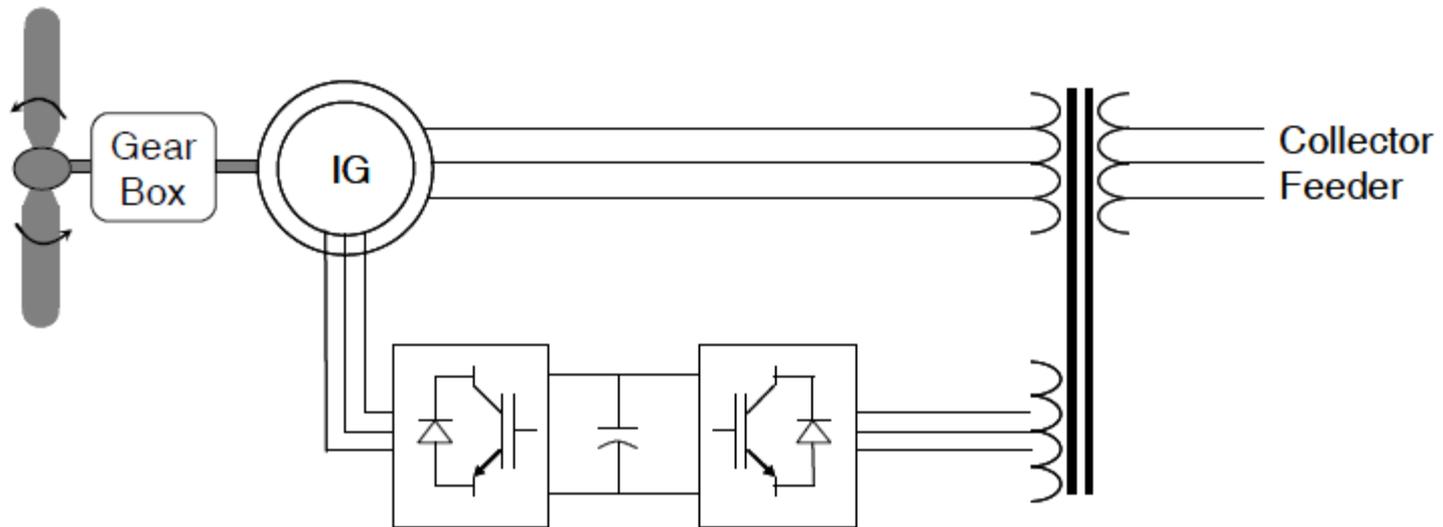


Type 5

- Type 5 turbines consist of a typical WTG variable-speed drive train connected to a torque/speed converter coupled with a synchronous generator. The torque/speed converter changes the variable speed of the rotor shaft to a constant output shaft speed.
- The closely coupled synchronous generator, operating at a fixed speed (corresponding to grid frequency), can then be directly connected to the grid through a synchronizing circuit breaker.
- The synchronous generator can be designed appropriately for any desired speed (typically 6 pole or 4 pole) and voltage (typically medium voltage for higher capacities).
- This approach requires speed and torque control of the torque/speed converter along with the typical voltage regulator (AVR), synchronizing system, and generator protection system inherent with a grid-connected synchronous generator.



- A small amount power injected into the rotor circuit can effect a large control of power in the stator circuit. This is a major advantage of the DFIG — a great deal of control of the output is available with the presence of a set of converters that typically are only 30% of the rating of the machine.
- In addition to the real power that is delivered to the grid from the generator's stator circuit, power is delivered to the grid through the grid-connected inverter when the generator is moving faster than synchronous speed.
- When the generator is moving slower than synchronous speed, real power flows from the grid, through both converters, and from rotor to stator. These two modes, made possible by the four-quadrant nature of the two converters, allows a much wider speed range, both above and *below* synchronous speed by up to 50%, although narrower ranges are more common.



Voltage Control Capabilities

- The voltage control capabilities of a WTG depend on the wind turbine type.
- Type 1 and Type 2 WTGs can typically not control voltage. Instead, these WTGs typically use power factor correction capacitors (PFCCs) to maintain the power factor or reactive power output on the low-voltage terminals of the machine to a setpoint.
- Types 3 through 5 WTGs can control voltage. These WTGs are capable of varying the reactive power at a given active power and terminal voltage, which enables voltage control.
- The voltage control capabilities of individual WTGs are typically used to control the voltage at the collector bus or on the high side of the main power transformer.
- Usually a **centralized wind farm controller** will manage the control of the voltage through communication with the individual WTGs.

Reactive Power Capabilities

- The reactive power capabilities of modern WTGs are significant as most grid codes require the WPP to have reactive power capability at the point of interconnect over a specified power factor range, for example 0.95 leading (inductive) to 0.95 lagging (capacitive).
- Type 1 and Type 2 WTGs typically use PFCCs to maintain the power factor or reactive power of the machine to a specified setpoint.
- The PFCCs may be sized to maintain a slightly leading (inductive) power factor of around 0.98 at rated power output. This is often referred to as no-load compensation.
- With full-load compensation, the PFCCs are sized to maintain unity power factor or, in some cases, a slightly lagging (capacitive) power factor at the machine's rated power output.
- The PFCCs typically consists of multiple stages of capacitors switched with a low-voltage AC contactor.

- Type 3 (DFIG) WTGs typically have a reactive power capability corresponding to a power factor of 0.95 lagging (capacitive) to 0.90 leading (inductive) at the terminals of the machines.
- Type 4 WTGs can vary the grid side converter current, allowing control of the effective power factor of the machines over a wide range. Reactive power limit curves for different terminal voltage levels are typically provided.
- The synchronous generator in a Type 5 WTG has inherent dynamic reactive power capabilities similar to that of Type 3 and 4 machines.

Behavior During Grid Short Circuit

- The response of WTGs to short circuits on the grid depends largely on the type of WTG. While the response of Type 1 and Type 2 WTGs are essentially similar to that of large induction machines used in industrial applications, the response of Type 3, 4, and 5 WTGs is dictated by the WTG controls.
- In short circuit calculations, a Type 1 WTG can be represented as a voltage source in series with the direct axis sub-transient inductance.
- Type 2 WTGs employing limited speed control via controlled
- external rotor resistance are fundamentally induction generators. If, during the fault, the external resistance control were to result in short-circuiting of the generator rotor, the short-circuit behavior would be similar to Type 1.

- For Type 3 WTGs (DFIG), if during the fault, the rotor power controller remains active, the machine stator currents would be limited between 1.1 to 2.5 p.u. of the machine rated current.
- In turbines employing full-rated power converters as the interface to the grid (Type 4), currents during network faults will be limited to slightly above rated current. This limitation is affected by the power converter control, and is generally necessary to protect the power semiconductor switches.
- Type 5 WTGs exhibit typical synchronous generator behavior during grid short circuits. Generator contribution to grid faults can be calculated from the machine constants obtainable from the generator manufacturer. Fault current contribution for line to ground faults will depend on the type of generator grounding used. Typical generator fault current contribution can range from 4 to more times rated current for close-in bolted three-phase faults.