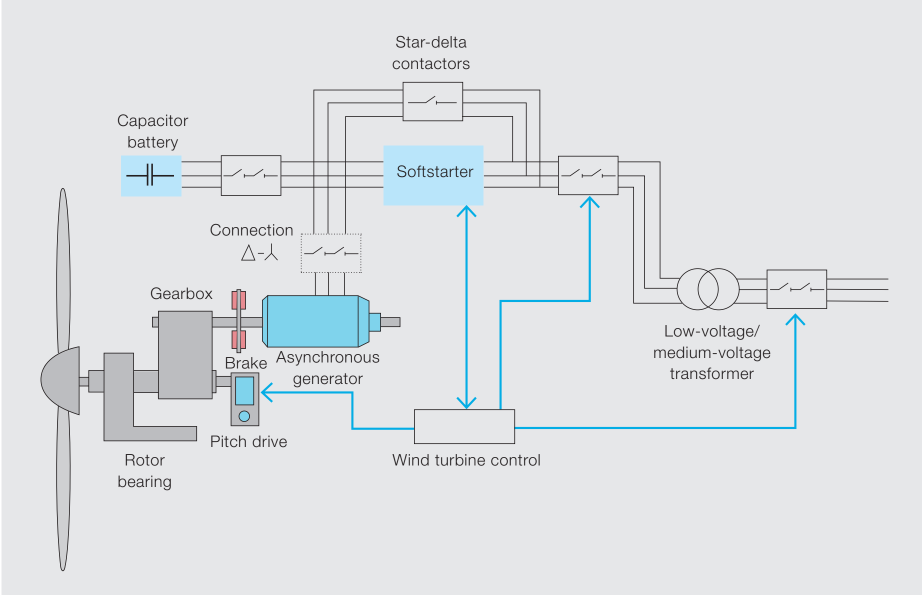
Wind protection

Low-voltage switching and protection strategies in wind turbines

ANTONIO FIDIGATTI, PAOLO BARONCELLI, MARCO CARMINATI, ENRICO RAGAINI – Wind turbines come in different designs, each with its own electrical behavior that needs a unique approach when it comes to switching and protection. A review of the three most common turbine designs reveals the important factors to be taken into consideration in the choice of switching and protection components.

1 Simplified diagram of wind turbine with a FSIG



More than 150,000 wind turbines are currently installed worldwide. Over 90 percent of these generate electrical power at low voltages (≤ 1,000 V).

Challenges for wind turbine protection and control

The electrical protection and control systems that are so critical to keeping wind turbines running safely present conflicting requirements related to conversion efficiency, production continuity, fault disconnect, climatic and mechanical constraints, compactness and the need to reduce the effects of faults in the tight space inside the nacelle.

Conversion efficiency

Wind speed and direction can change rapidly or the wind can drop altogether so the turbine's mechanical and electrical configuration must be capable of rapid adaption. This causes frequent operation of control actuators (eg, for pitch adjustment), which, in turn, produces repeated connection and disconnection of the power circuit, with the attendant risk of component overheating.

Title picture

A critical factor in any wind turbine is the choice of switching and protection devices. How does turbine design influence this choice?

Power production continuity

Power production continuity requires high reliability during the entire lifetime of the wind turbine. The difficulty of physical intervention makes high reliability even more desirable. A good strategy here is to use components for their main function only (eg, circuit breakers for protection, contactors for switching, etc.) rather than trying to squeeze secondary functions from them. Generous tolerances are also obligatory.

Fault-disconnect behavior

The need to guarantee linear behavior even during network disturbances has led to the definition of grid codes, compliance with which is mandatory. In many cases, the control of reactive power flow under standard service conditions as well as under disturbed conditions requires a high number of operations by the connection devices of capacitor banks and filters.

> Protection systems must work in a wide range of electrical conditions while at the same time correctly and quickly discriminating between normal and fault conditions.

Climatic and mechanical constraints

The environmental stresses suffered by a wind turbine can be severe: Vibrations can be of several millimeters' amplitude and thermal conditions can range from below – 25 °C when heating and de-icing functions are switched off during inactivity to + 50 °C when power-dissipating components are operating in overload conditions. The aging effects of this operational environment as well as the effects of frequent switching, salt air, humidity, pollution, etc., must be taken into account in lifetime calculations.

Compactness

Further mechanical constraints are linked to the requirements for compactness and low weight because of the limited space available in the nacelle and the need to minimize mechanical stresses on the structure. These factors necessitate trade-offs with the overdimensioning required for high efficiency and service continuity.

Faults in the nacelle

Faults in the nacelle are a particularly critical issue: The protection and control system, besides preventing and limiting the catastrophic effects of faults in the reduced space available, should ensure electrical transients do not damage the valuable mechanical system (which rep-

2 Requirements for switching/protection devices with FSIG

	Main power circuit	Main auxiliary circuit
Load current (A)	≤ 1,800	≤ 320
Voltage (V)	≤ 690	≤ 690
Frequency (Hz)	50-60	50-60
Prospective short-circuit current (kA)	≤ 35 @ 690 V	
Type of load classification according to [2]	Resistive	Induction motor or transformer
Presence of inrush current	No	Yes
Life time (years)	20	20
Number of mechanical operations with electrical isolation from the voltage sources (maintenance or out of service)	100-1,000	< 1,000
Number of generator-to-network or reconfiguration connect/disconnect mechanical operations (or electrical operations at low current)	10,000-100,000	Not applicable
Number of electrical operations	< 100 (trips or emergency stop)	< 100 (trips or emergency stop)
Protection against overload and short circuit	Yes	Yes
Optimum solution	Circuit breaker plus contactor	Circuit breaker

A good strategy is to use components for their main function only rather than trying to squeeze secondary functions from them.

resents about 80 percent of the turbine cost). This translates into several requirements that sometimes conflict with each other, such as:

- Avoid unwanted tripping but also dangerous overvoltages.
- Operate rapidly to reduce mechanical stress and strain on the drivetrain, as well as fire risk.
- Detect the small short-circuit current contribution from the generator.
- Correctly identify the faulty feeders on the auxiliary circuits after a noncritical electrical fault in order to increase power generation availability.
- Limit the fault energy (and trip fast at low current) in order to protect weak components like the brushing system.
- Isolate faulty sections safely.
- Isolate safely during maintenance, while providing the energy required by the auxiliary systems.

The key characteristics, then, for the control and protection components are, in order of importance:

- high switching reliability
- reduced maintenance
- compactness and reduced weight
- cost

These four requirements are often incompatible with each other and trade-off choices regarding protection and switching have to be made. Optimal strategies in this trade-off can be explored by examining the three main wind turbine technologies:

- An asynchronous generator directly connected to the grid: fixed-speed induction generator (FSIG)
- An asynchronous generator with its rotor excited at a variable frequency, directly connected to the grid: doubly-fed induction generator (DFIG)
- A permanent magnet synchronous (or asynchronous) generator connected to the grid through a full-scale frequency converter (FSFC)

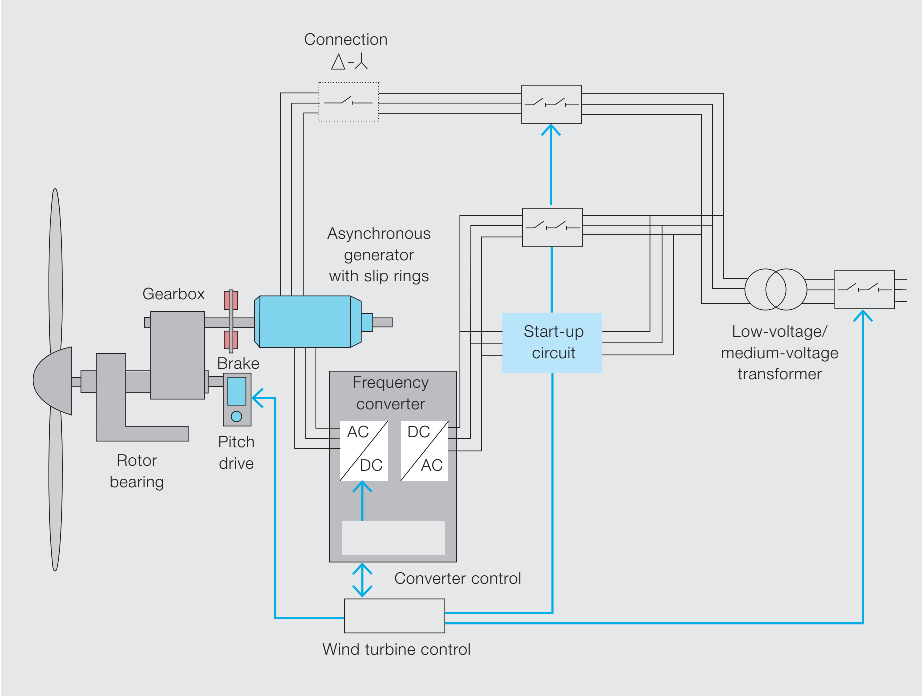
Fixed-speed induction generator

In the FSIG configuration, with a brushless asynchronous generator directly connected to the grid, only very limited deviations from the synchronism speed are possible. Reactive power is, therefore, delivered by capacitor banks, the switching of which is relatively frequent [1]. The start-up phases of the generator are managed by a softstarter equipped with parallel-connected contactors, which are closed once the steady state has been reached. Star-delta connection to the winding(s) of the generator is generally employed for the proper management of different wind regimes. Also, the generator can have multiple poles to extend the working range → 1–2. This electrical configuration is simple and highly efficient, but:

- The reduced production speed range is unsuitable for variable wind areas.
- A long-time overload condition has to be withstood, so the main circuit components have to be oversized.
- The contactor-based step control on the capacitors could produce overvoltage effects; in many such cases

The aging effects of the operational environment as well as the effects of frequent switching, salt air, humidity, pollution, etc., must be taken into account in lifetime calculations.

3 Simplified diagram of wind turbine with a DFIG



interaction with the softstarter could be problematic.
– The system is unable to follow fast grid perturbations without disconnection.

Therefore, this configuration is only suitable for small- to medium-sized wind turbine sizes that are installed on a network with a low wind energy production penetration (< 5 percent).

The protection and control system should ensure electrical transients do not damage the valuable mechanical system – which represents about 80 percent of the turbine cost.

Doubly-fed induction generator

This configuration employs a slip-ring induction generator, the rotor circuit of which is powered at a variable frequency → 3–4. Wider variations in the rotation speed of the system are possible compared with the FSIG approach since the excitation frequency of the rotor allows displacements from the synchronism speed to be compensated for [1]. Generally, the excitation circuit, where power can flow in both directions (European approach), is sized at 20 to 30 percent of the rating of the main circuit. The converter is used to control the generator speed and power factor, allowing a wider speed range for power production as well as the ability to feed reactive power to support the grid. In some cases, star-delta connection to the generator is used for the proper management of different wind regimes with rotor current values optimized in term of slip-ring and brushing system life. The advantages compared with constant speed turbines are:

– Variable-speed operation increases kilowatt-hour production.
– Utilization of a small converter, sized at up to one-third of the nominal power, allows reactive power to be supplied to the grid in normal and abnormal conditions with a good voltage and power factor control.
– Total system efficiency is high.

On the other hand, some disadvantages have to be considered:
– The direct connection between the grid and the generator transfers network perturbations to the mechan-

4 Requirements for switching and protection devices with DFIG

	Main power circuit	Main excitation circuit	Start-up circuit
Load current (A)	≤ 4,000	≤ 630	≤ 5
Voltage (V)	≤ 1,000	≤ 690	≤ 690
Frequency (Hz)	50-60	50-60	50-60
Prospective short-circuit current (kA)	≤ 30 @ 1,000 V	≤ 50 @ 690 V	≤ 50 @ 690 V
Type of load classification according to [2]	Resistive	Induction motor	Induction motor
Presence of inrush current	No	No	Yes
Life time (years)	20	20	20
Number of mechanical operations (or electrical operations at low current) with electrical isolation from the voltage sources (maintenance or out of service)	100-1,000	< 1,000	Not applicable
Number of generator-to-network or reconfiguration connect/ disconnect mechanical operations (or electrical operations at low current) with electrical isolation from the voltage sources	10,000-100,000	1,000-10,000	Not applicable
Number of electrical operations	< 100 (trips or emergency stop)	< 100 (trips or emergency stop)	< 10,000 (excitation circuit insertion)
Protection against overload and short circuit	Yes	Yes	Yes
Optimum solution	Circuit breaker if < 1 operation/ day or circuit breaker plus contactor if more*	Circuit breaker coordinated with contactor in parallel with the start-up circuit	Circuit breaker plus contactor

* The speed of wind turbine generators is more often in the lower range than in the rated range, resulting in frequent switching on and off at typically 2,000-5,000 cycles per year (depending on wind turbine generator type), which makes contactors the best technical solution

ical drive chain, reducing the ability of the system to stay connected.
- The slip-ring brush rotor is a high-maintenance weak point.

Full-scale frequency converter

With an FSFC design, rotation speed may vary over a wide range because frequency variations can be compensated for by a drive placed between generator and network [1]. In the full converter concept, the converter decouples the generator and the mechanical drivetrain from the grid → 5–6. All the generated power flows through the converter to the grid. The converter provides generator torque and speed control. There are three main full converter concepts: high-speed, medium-speed and low-speed. These use use different gearbox and generator solutions. The advantages of an FSFC design compared to constant-speed turbines are:
- There is no direct electrical connection between generator and grid. This reduces mechanical shocks on the turbine during grid faults and increases grid code compliance.
- A full speed range is enabled with increased annual power yield.
- Full control of active power is possible, with full reactive power production.

In the FSFC configuration, circuit breakers are often employed for multiple purposes:
- To safely disconnect and isolate for normal operation or maintenance.
- To protect: In a fault involving the inverter or the sections between the generator and the inverter (eg, cable connection section), the circuit breaker is the only device able to detect safely the short circuit and disconnect from the power source. This requires protection releases (trip units) specifically designed for variable-frequency operation that can work in the specified environmental conditions.
- The circuit breaker provides generator disconnection redundancy.

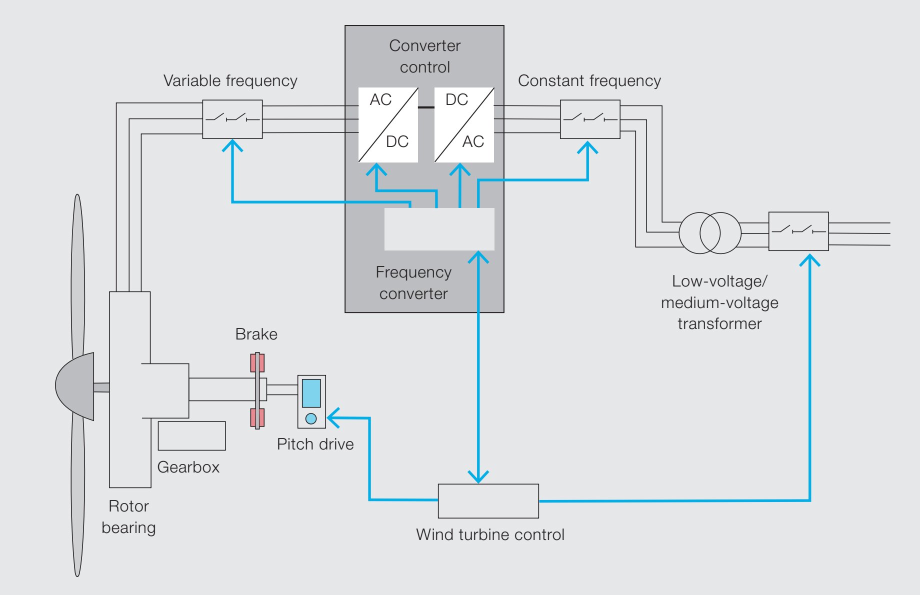
Breaking news

A choice of switching and protection components appropriate to a particular wind turbine design is essential for smooth operation and the minimization of the effects of faults.

The protection of wind turbines and other renewable generators is an area of intense research and development in which ABB is heavily involved. In recent years, ABB has released a series of solutions that protect plants with variable frequency in the wind, mini-hydroelectric, wave and traction power sectors – a prominent example of which is the Tmax

Equipment has to be compact and light because of space constraints and the need to minimize mechanical stresses on the structure.

5 Simplified diagram of wind turbine with FSFC



6 Requirements for switching/protection devices with FSFC

	Main power circuit on the variable-frequency side	Main power circuit on the grid side	Main auxiliary circuit
Load current (A)	≤ 5,000 or n x 700-1,600	≤ 5,000 or n x 700-1,600	≤ 250
Voltage (V)	≤ 1,000	≤ 690	≤ 690
Frequency (Hz)	1-16, 30-80, 40-140	50-60	50-60
Prospective short-circuit current (kA)	≤ 15 @ 1,000 V*	≤ 50 @ 690 V	
Type of load classification according to [2]	Resistive	Resistive	Induction motor
Presence of inrush current	No	No	Yes
Life time (years)	20	20	20
Number of mechanical operations (or electrical operations at low current) with electrical isolation from the voltage sources (maintenance or out of service)	100-1,000	< 1,000	< 1,000
Number of generator-to-network or reconfiguration connect/disconnect mechanical operations (or electrical operations at low current) with electrical isolation from the voltage sources	Not available (in general, the generator remains connected to the drive)	1,000 - 100,000 (according to the control strategies)	Not applicable
Number of electrical operations	< 100 (trips or emergency stop)	< 100 (trips or emergency stop)	< 100 (trips or emergency stop)
Protection against overload or short circuit	Yes	Yes	Yes
Optimum solution	Circuit breaker if protection is required for connection cables or inverter switch. Switch disconnector and external protection system is present.	Circuit breaker if < 1 operation/day or circuit breaker plus contactor if more	Circuit breaker

* Depending on the power and the configuration of the plant

VF and Emax VF circuit breakers that can operate in the range from 1 to 200 Hz.

The major benefits of this new range of circuit breakers for variable frequency applications are: Compatibility with all types of generators – even in overspeed conditions – thanks to the high rated voltage of the circuit breakers (up to 1,000 V); standardization of switchboard design, regardless of the end market; and optimization of stock management thanks to dual IEC/UL circuit breaker marking. This new family of trip units, together with optimized current sensors, ensures high-precision protection over an extended frequency range. Whilst improved arcing chamber and contacts guarantee high breaking capacity over the whole frequency range, the dimensions are the same as standard circuit breakers.

Developments in protection and switching devices are ongoing – for example, to harness the power of the Internet and the cloud to allow remote optimized power control at any time and from anywhere.

This article is based on the following IEEE paper: A. Fidigatti, P. Baroncelli, M. Carminati and E. Ragaini, "Selection of low voltage switching and protection devices in wind power generators," Industry Applications Society Annual Meeting (IAS), © 2011 IEEE, Orlando, FL, 2011, pp. 1–5.

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[1] *Wind Power Plants, ABB Technical Application Paper No. 13,* document number 1SDC007112G0201 in the ABB Library.

[2] *Low-voltage switchgear and control gear – Part 1: General rules,* IEC Standard 60947-1, 2014.