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# GENERATORS OF MODERN WIND TURBINES

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In this paper, various types of wind generator configurations, including power electronic grid interfaces, drive trains, are described. The performance in power systems is briefed. Then the optimization of generator system is presented. Some investigation results are presented and discussed.

**Keywords:** wind turbines, generator topologies, variable speed, direct-drive, power electronics, grid connection

## 1. INTRODUCTION

With rapid development of wind power technologies and significant growth of wind turbine installation capacity worldwide, various wind turbine concepts have been developed. The capacity of modern wind turbines/farms is increasing. Most of the large scale wind power generation systems are connected with power grids, in some cases, wind power plays a significant role in a power system. For example, wind turbines supplies about 20% of electricity consumption in Danish power systems at present, it is planned to supply 50% of the electricity consumption by 2025. The success of a wind turbine concept strongly depends on the ability of complying with both market expectations and the grid requirements. Research and development are being conducted actively to make wind energy conversion systems even more cost-effective, and to enable the wind turbines/farms become a competitive power source with good quality.

The paper presents an overview of various types of wind generators, also discusses the wind generator optimization.

## 2. WIND GENERATORS AND GRID CONNECTION

### Fix speed and direct grid connection wind turbines

Induction generators with cage rotor can be used in the fixed-speed wind turbines due to the damping characteristics. Fig 1 shows a squirrel-cage induction generator (SCIG), connected via a transformer to the grid and operating at an almost fixed speed. The power can be limited aerodynamically either by stall control, active stall, or pitch control. The reactive power energizing the magnetic circuits must be supplied from the network or parallel capacitor banks at the machine terminal. The advantages of wind turbines with induction generators are the simple and cheap construction, in addition that no synchronization device is required. Those solutions are attractive due to cost and reliability. Some drawbacks are: (i) the wind turbine has to operate at constant speed, (ii) it requires a stiff power grid to enable stable operation, and (iii) it may require a more expensive mechanical construction, in order to absorb high mechanical stress, since wind gusts may cause torque pulsations on the drive-train. The high starting currents of induction generators are usually limited by a thyristor soft-starter, which typically limits the RMS value of the inrush current to a level below two times of the generator rated current. The soft-starter effectively dampens the torque peaks associated with the peak currents and hence reduces the loads on the gearbox.

The soft-starter it is short circuited by a contactor, when the connection to the grid has been completed.

A wound rotor induction machine has a rotor with copper windings, which can be connected to an external resistor or to ac systems via power electronic systems. Fig. 2 shows wounded rotor induction generator with rotor resistance control (Dynamic slip control). In this scheme, the rotor windings is connected with variable resistors. The equivalent resistance in the circuit can be adjusted by an electronic control system in a limited range. This solution still needs a soft-starter.

Both cage induction generators and rotor resistance controlled wounded induction generators need to operate at a super-synchronous speed to generate electricity. Both of them draw reactive power which might be supplied from the grid or from installed compensation equipment, such as capacitor banks or additional power electronic equipment. Modern MW-class turbines have thyristor-switched capacitors allowing for a more dynamic compensation. A Static Var Compensator (SVC) or similar technology may be needed to improve the dynamic responses of the wind farm.

### Variable speed doubly fed induction generator

The stator of a doubly-fed induction generator is connected to the grid directly, while the rotor of the generator is connected to the grid by electronic converters through slip rings, as shown in Fig. 3, the DFIG normally uses a back-to-back converter, which consists of two bidirectional converters sharing a common dc-link, one connected to the rotor and the other one to the grid. The power electronic converters have the ability to control both the active and reactive power delivered to the grid. This gives potential for optimizing the grid integration with respect to the operation voltage, power quality and stability.

The generator can deliver energy to the grid at both super-synchronous and sub-synchronous speeds. The advantage is that only a part of the power production is fed through the power electronic converter. Hence, the nominal power of the power electronic converter system can be less than the nominal power of the wind turbine. In general, the nominal power of the converter may be about 30 % of the wind turbine power.

The reactive power to the grid from the generation unit can be controlled as zero or to a value required by the system operator within the converter rating limit. In general the harmonics generated by the converter are in the range of some kHz. Thus filters are used to reduce the harmonics. The doubly-fed induction generator solution needs neither a soft-starter nor a reactive power compensator.

### Full rated power electronic interface

Synchronous generators are excited by an externally applied direct current or by permanent magnets. Synchronous generators need to be integrated into power systems with full rated power electronic converters. Cage induction generators may also use such power electronic interface system. The full-scale power converter between the generator and grid gives the added technical performance. Usually, a back-to-back voltage source converter is used in order to achieve full control of the active and reactive power, though with synchronous generators, diode rectifiers may be used [1, 3]. The generator can operate at a wide variable frequency range for optimal operation while the generated active power will be sent to the grid through the grid side converter which can be used for controlling the active and reactive power independently.

Fig. 4 shows one of the possible solutions with full-scale power converters. There is considerable interest in the application of the multiple-pole synchronous generators (either with permanent magnet excitation or with an electromagnet) driven by a wind-turbine rotor without a gearbox or with a low ratio gear-box.

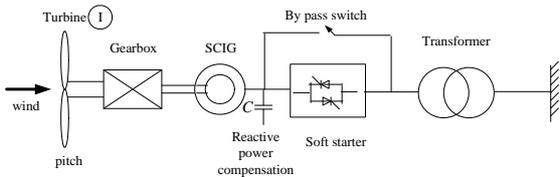


Fig. 1. A cage induction generator based fixed speed wind turbine.

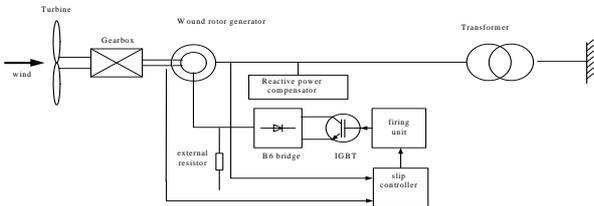


Fig. 2. A wound rotor induction generator with rotor-resistance converter.

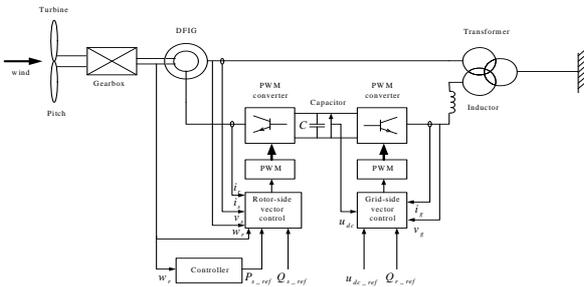


Fig. 3. Wind turbine topologies with Doubly-fed induction generator.

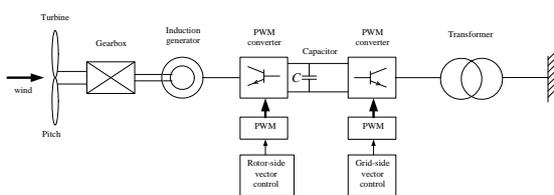


Fig. 4. Full rate power electronic interfaced wind turbine.

### 3. WIND TURBINE DRIVE TRAINS

The common way to convert the low-speed, high-torque mechanical power to electrical power is using a gearbox and a generator with standard speed. The gear-box adapts the low speed of the turbine rotor to the high speed of the generator, though the gear-box may not be necessary for multi-pole generator systems.

#### Three-stage geared drive trains

Cage rotor induction generators and DFIG normally use multi-stage gearbox in the drive train. A PM synchronous generator system may also use a multiple-gearbox to further reduce the generator's volume and improve the generator efficiency.

Compared to the multi-stage geared drive DFIG system, a multi-stage geared PM synchronous generator is brushless generator and has the better efficiency and grid-fault ride through capability due to the full rated power electronic converter, while the converter is larger, more expensive, (100% of rated power instead of 30%), also the losses in the converter are higher because all power is processed by the power electronic converter.

#### Direct drive

The direct-drive generator rotates at a low speed, because the generator rotor is directly connected on the hub of the turbine rotor. Delivering a certain power at a lower speed makes it necessary to produce a higher torque. Therefore, for direct drive generators, the low speed and high torque operation require multi-pole, which demand a larger diameter for implementation of large number of poles with a reasonable pitch. Moreover, for a larger direct-drive generator, considering the current loading and gap flux density limitations, a higher torque also requires a larger machine's volume, so that the torque density could not be further significantly increased. To increase the efficiency, to reduce the weight of the active parts, and to keep the end winding losses small, direct-drive generators are usually designed with a large diameter and small pole pitch. In addition, the advantages of direct-drive wind turbines are the simplified drive train, the high overall efficiency. Induction generators may not be made in such large number of multi-poles for direct-drive application.

#### Single-stage geared drive trains

Due to the low speed operation, direct drive generators have large diameter, heavy weight, and tends to be more expensive. With the increase of rated power levels and the decrease of wind turbine rotor speeds, these direct-drive systems are becoming even larger and more expensive, more difficulties for transport and assembly. Therefore, an interesting alternative may be a mixed solution with a single-stage planetary gearbox and a medium-speed generator. In this wind turbine concept, the generator, gearbox, main shaft, and shaft bearing are all integrated within a common housing. The common generator-gearbox housing is supported by a tubular bedplate structure. This concept has gained the attention.

## 4. GENERATOR OPTIMISATION

### Design optimization of wind generators

An improved genetic algorithm (IGA) is used for optimization of different wind generators. The objective function is given in (1) for the minimization of the generator system cost, including the costs of generator active materials, generator structures, gearbox, power electronic converters and other electrical subsystem.

$$C_w = C_{g\_act} + C_{g\_str} + C_{con} + C_{subsystem} + C_{gear} \quad (1)$$

where

$C_{g\_act} = c_{cu} G_{cu} + c_{Fe} G_{Fe} + c_m G_m$  is active material cost;

$c_{cu}, c_{Fe}, c_m$  are the unit costs of the copper, the active iron and the PMs, respectively;

$G_{cu}, G_{Fe}, G_m$  are the weight of the copper, the active iron and the PMs, respectively.

$C_{g\_str}$  generator structure cost.

$C_{con}$  cost of power electronic converter.

$C_{subsystem}$  other electrical subsystem cost, which includes transformer, cable, switchgear and so on.

$C_{gear}$  single-stage or three-stage gearbox cost (if present).

In order to optimize the objective function (1), six variables are considered, including the air gap radius ( $r_s$ ), the stator length ( $L$ ), the slot height ( $h_s$ ), the pole pitch ( $\tau_p$ ), the peak air gap flux density ( $\hat{B}_{g0}$ ) and the peak stator yoke flux density ( $\hat{B}_{ys}$ ).

Fig. 5 shows the flow chart of the optimization procedure. Firstly, at a given rated power and a gear box (if present), the initial population is randomly generated for the six variables within a specific range. Then, according to the IGA models and the analytical models of the generator, the optimization is performed for minimizing the generator system cost under constraint conditions. Once the best design is obtained, the program will update the power level and repeat the optimization until the optimal designs in a given range have been finished. In addition, when the gear ratio is taken as an optimized variable, the optimal gear ratios of the most cost-effective system are also obtained.

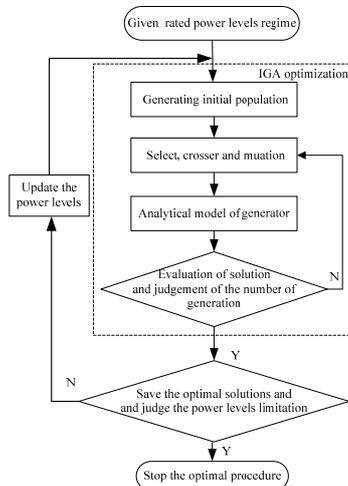


Fig. 5 The flow chart of the optimization procedure.

### Comparison of Optimized generator systems

The designed generators include:

- Squirrel cage induction generator (SCIG)
- Doubly fed induction generator (DFIG)
- Electrically excited synchronous generator (EESG)
- Permanent magnet synchronous generator (PMSG)

Different drive train concepts are considered, such as direct drive (DD), single stage gear (1G) and multi stage gear (3G).

Some results of the generator system's cost and the annual energy yield (AEP) per cost are summarized in Fig. 6 for the rated power of 0.75-MW, 3.0-MW and 10-MW. It can be seen that the single-stage geared wind generator system has the lowest cost in small and medium power ranges; however, the DFIG\_3G system may be the cheapest when the rated power increases towards 10MW, while the direct-drive generator systems are most expensive. On the other hand, it can be seen the single-stage geared wind generator systems (DFIG\_1G and PMSG\_1G) have the highest AEP per cost at small and medium rated power levels, however, when the rated power increased towards 10-MW, the DFIG\_3G and DFIG\_1G systems seem to be more attractive solutions. In addition, it can be also observed that the EESG\_DD system has the lowest AEP per cost for each rated power level. Although the optimization is a preliminary study, many factors are simplified, the developed procedure and methods could be a good guide.

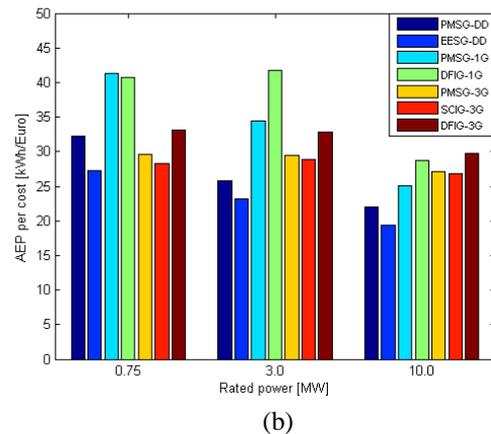
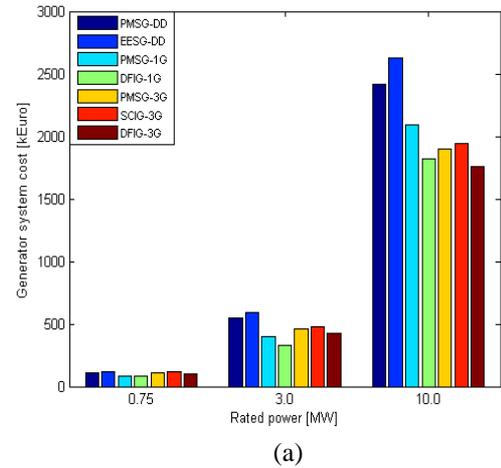


Fig. 6. The comparison of seven wind generator systems  
(a) System cost, (b) AEP per cost

## 5. POWER SYSTEM PERFORMANCE

An important issue of integrating large scale wind farms is the impact on the stability of the power systems. The fault ride-through capability is an important requirement to modern wind turbines.

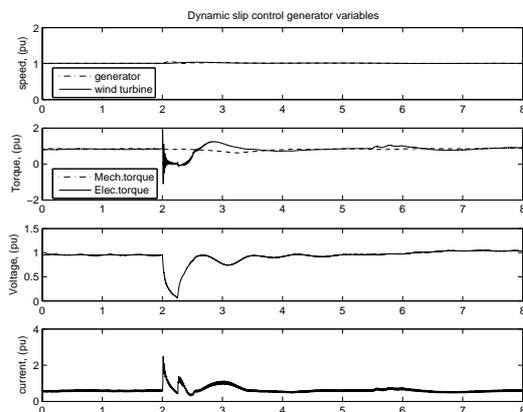
During a short-circuit fault in a power system where the wind turbines are connected, the short circuit current may result in a voltage drop at the wind generator terminal. Due to the voltage dip, the output electrical power and the electromagnetic torque of the wind turbine are significantly reduced, while the mechanical torque may be still applied on the wind turbine. Consequently, the turbine and generator will be accelerated due to the torque unbalance.

After the clearance of the fault, the voltage of the power system tends to recover. If the voltage is not able to be recovered back to around the normal value or the generator speed is too high, there may be no sufficient electromagnetic torque to balance the mechanical torque. Hence, the machine would continue to accelerate. If this happens, the wind turbine may have to be disconnected and failed to ride-through the fault. Such wind turbine disconnection should be avoided because losing a significant part of the power generation capacity could threaten the security of the power system.

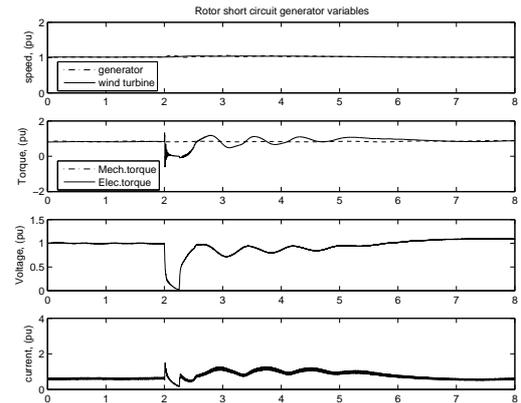
The results of an example system, where two generators (one cage rotor and one wound rotor with rotor resistance and pitch control) connected in parallel, are shown in Fig. 7 [12]. It can be seen that the operation of STATCOM can improve the voltage. The combined strategy of dynamic slip and pitch control will be even more effective in recovering the system operation.

## 6. CONCLUSIONS

This paper presents an overview of various types of wind generator configurations and drive trains. The optimization of generator system is reported. The performance improvement in power systems is briefed.



(a) Dynamic slip rotor resistance control generator variables



(b) Rotor short circuited induction generator variables

Fig. 7. Simulation results with STATCOM, rotor resistance and pitch control in operation

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