Development of Induction Machines in Wind Power Technology

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Abstract—This paper gives an overview of the development of the induction machine as a generator for wind turbines from the middle of the 20th century up to now. After a short history chapter the different energy conversion concepts are presented. At first a squirrel cage machine is direct coupled to the grid (Danish concept). To adjust the machine speed the second step is a wound rotor machine with collector rings to change rotor resistance. This concept allows the first adaption of the operating point of the wind turbine and the induction machine. Another concept is to connect the stator of a squirrel cage machine with a full inline voltage source converter to the grid to get the flexibility in rotational speed and to control the reactive power. The doubly fed induction machine is the latest development. This concept uses a bidirectional voltage source converter in the rotor circuit with a rated power of only 30% of the rated generator power. Now it is possible to change the rotational speed and the reactive power independently and in a wide range. A generalized control scheme of a modern doubly fed induction machine (DFIG) is shown in the last part to explain the variability and the range of application. Today over 70% of the wind turbines are build up with DFIG.

Keywords—Induction Machines, DFIG, Wind Power

I. HISTORY OF INDUCTION GENERATORS IN WINDMILLS

The energy of the wind is used for more than thousand years. The first history proven usage has been around the year 650 in Tibet for religious aims. These early models are vertical axis wind turbines based on the principle of scoop drag-type devices which are today used only in anemometers. At the beginning of the second millennium horizontal axis windmills became popular mainly in southern Europe and the Netherlands for pumping water.

The first production of electrical energy with wind power was done in 1887 by Charles Brush in Cleveland, Ohio. The rated Power of the used dc-generator was 12kW and was designed to charge batteries. The induction machine was used at the first time in 1951.

II. ENERGY CONVERSION CONCEPTS

There exists several basic principles of producing electrical power with wind energy and induction machines.

A. Fixed Speed Wind Generator

The easiest principle is to connect a squirrel cage induction machine with a gearbox directly to the grid. This is called the Danish concept (see figure 1). The gearbox is necessary to convert the low rotational speed of the wind rotor to a compatible frequency of the available grid, for example around 1500rpm in

Fig. 1. Danish concept - fixed coupled induction machine

case of a 4-pole generator in the European 50Hz grid. The rotational speed of the wind turbine depends on the diameter of the blades. A common squirrel cage machine with a rated power of 600kW and a blade diameter of 44m uses 26rpm for the turbine. The maximum speed at the tip of the blade is 60m/s.

The Danish concept has the major benefit of a very simple construction of the whole wind turbine with very low investment and maintenance costs. No power converter or complex controller is needed. The major disadvantage is the fixed rotational speed. This is important for several aspects:

- ⊖ The blades are not in the optimal operating point for a wide wind speed range.
- ⊖ The electrical power of the generator cannot be regulated quickly because the only possibility to influence is the pitch-angle of the blades.
- ⊖ Wind gusts and the back pressure of the tower result directly in power fluctuations.

To reduce this disadvantages, it is possible to build a generator with a higher slip ratio, because slip means elasticity of the system. In figure 2 a slip versus rated power diagram of standard industrial machines is shown. The over-all tendency is the increasing slip with higher number of poles. A six or eight pole generator has a higher elasticity than a generator with two poles. This elasticity is required to reduce the power fluctuations, which stresses the drive train and causes power peaks in the grid. In figure 3 two diagrams show the power fluctuation of a squirrel cage machine with 2% rated slip on the left side and with 8% rated slip on the right side. A generator with 2% rated slip causes power fluctuations in the range of 20% of rated power,

Fig. 2. Slip as a function of rated power (parameter pole numbers)

Fig. 3. Power fluctuation of a squirrel cage machine (parameter rated slip)

one with 8% operates with only 5%. The variability in the time domain of seconds is a result of wind speed which clearly can be recognized in figure 3. In the Danish concept the generator is directly coupled to the grid, so the only way to reduce the dynamic loads of drive train and grid is to design a generator with a high number of poles. This has the disadvantage of increasing volume and masses of the generator and lowers the efficiency of the whole system.

In figure 4 an array of characteristic curves of direct grid-coupled

Fig. 4. Characteristic curves of wind turbines with fixed speed generators

wind turbines is described and parameterized by wind speed. The rated wind speed is 6m/s and in this operating point the characteristic curve of the induction generator fits perfect. With in-

creasing wind speed the speed of the generator lowers and with decreasing wind speed the speed of the generator is higher. This behavior is possible by changing the slip over a range of several percent. If the wind speed is below 4m/s, no delivery of power to the grid is possible.

To avoid this problem the first step was to build wind turbines with two generators, one for weak wind condition with lower rated power and lower rotational speed and the other for the strong wind conditions. For example a 600kW rated power wind turbine operates with a generator of 200kW in weak wind conditions and with the 600kW generator in strong wind conditions. The other possibility is only one generator with a switchable number of poles to adapt different wind speeds. An operating diagram is shown in figure 5. The diagram describes the characte-

Fig. 5. Characteristic curves of wind turbines with two fixed speed generators

ristic array of curves of output power as a function of rotational speed. The rated operating point of the strong wind generator is at 11m/s wind speed and the weak wind generator works optimal at 7.5m/s. There has to be a hysteresis between the switching points of the weak and the strong wind generator to avoid unnecessary dynamic loads to the mechanical and electrical components by switching frequently.

B. Adjustable Speed Wind Generator

Adjustable speed generators which are very common in modern wind turbines have several advantages:

- ⊕ Mechanical stress of all parts of the turbine can be reduced because wind gusts can be absorbed by the inertia of the turbine.
- ⊕ Power fluctuations in the grid are reduced because the impacts of the wind are buffered in mechanical energy and are not passed onto the grid. Even the back pressure of the tower can be compensated (see figure 7).
- ⊕ The system efficiency is improved by the adaption of the rotational speed as a function of the wind speed. The maximum output power can be achieved over a wide wind speed range (see figure 14).
- ⊕ The pitch control can be simpler because the time constant can be longer with variable speed [2].
- ⊕ The noise emission is reduced in weak wind conditions because the turbine is rotating with lower speed.

The first way to get an adjustable speed generator for a reasonable price is to change over from squirrel cage induction machine to a wound rotor machine with collector-rings. By changing the rotor resistor it is possible to adapt the operating point of the induction machine in order to get a better adaption in start-up, weak wind condition and strong wind condition. With this tech-

Fig. 6. Induction generator with variable rotor resistor

nique it is also possible to change the rotor resistance in a very dynamic way. In figure 7 the torque, the output power and the slip is plotted. The torque curve lowers dramatically when one rotor blade rides through the back pressure zone of the tower. If a very dynamic slip control allows the adjustment of the rotor resistance as shown in the diagram it is possible to compensate this effect in the power dissipation to the grid.

Fig. 7. Induction generator with variable rotor resistor

There are several principles more to build up adjustable speed wind turbines. One possibility is to change the Danish concept in the electrical connection with a direct in line frequency converter (VSC) which connects the stator of the generator with the grid (see figure 8). In this concept the generator has not to be changed but several disadvantages are apparent:

- ⊖ The frequency converter has to be dimensioned for the maximum power of the turbine and therefore it is expensive.
- ⊖ The converter efficiency effects the entire power and has to be very high over the full power range to guarantee high performance.

Fig. 8. Variable speed induction generator with full powered converter

The reasons for choosing this topology are:

- ⊕ The power factor can be controlled in a wide range.
- ⊕ Wind gusts can not only be buffered in the mechanical inertia but in the energy storage of the intermediate circuit [1].
- ⊕ The squirrel-cage induction machine is very rugged and causes few maintenance costs.

In figure 9 an array of characteristic curves are described. The variation of the stator frequency allows to adjust the characteristic curve of the squirrel cage induction machine. The power electronic adapts the operating point of the generator to the different operating points of the wind turbine.

Fig. 9. Characteristic curves of wind turbines with full powered converter

C. Doubly Fed Induction Generator

The doubly fed induction machine became more and more common in wind power generation. Today more than 70% of the build wind turbines are equipped with this type of induction machine. Usually the voltage source converter is connected with the machine side to the wound rotor via collector rings. The grid side converter and the stator of the induction machine are directly connected to the grid (see figure 10). A few years ago a transformer has to be placed between converter and the grid to adapt the voltages. Today it is not necessary any more, because it is possible to dimension the rotor windings and the power electronics, that the rotor voltage even in the area of low rotor frequencies (synchronous operating point) is high enough to feed into the grid only by using an inductance.

This system has the following assets and drawbacks:

- ⊕ The costs of the converter are reduced, compared to the full inline converter, because it is rated for only 30% of the total

Fig. 10. Doubly fed induction generator

power of the generator.

- ⊕ The emc-filters are cheaper because of the lower power, too.
- ⊖ The wound rotor induction machine is not as rugged as the squirrel case machine. Collector rings are necessary and have to be maintained regularly.
- ⊖ A complex control is necessary.

D. Non Induction Machines

A synchronous generator with separate excitation is used mainly by one company in Europe to build a gearless wind turbine. Although it is not mainly discussed in this paper the main attributes should be described shortly:

- ⊕ Because of the abolition of the gearbox the turbine is more reliable and needs less maintenance.
- ⊕ A direct inline converter is necessary like in figure 11 with its above described advantages but high costs.
- ⊖ The synchronous machine has to have a high number of poles (100 to 300) which results in machines with large diameter.

Fig. 11. Synchronous generator without gear

Other types of machines like dc-generators, permanent magnet machines or variable-reluctance generators are not important in the state of the art market in wind power generation [2]. The prices for special magnets (NdFeB) decreased extremely in the last years. So it could be interesting to build up wind power generators with permanent magnet machines. In spite of the difficulties in handling, corrosion, long time stability and control of the system first pilot plants are build.

III. COMPONENTS OF A STATE OF THE ART WIND POWER NACELLE

In figure 12 the outline of a nacelle of a state of the art wind turbine from Nordex is shown.

Fig. 12. Nacelle of a state of the art wind turbine

1. rotor blade	10. generator and gearbox cooler
2. rotor hub	11. wind sensors
3. nacelle frame	12. nacelle control
4. main bearing	13. hydraulic system
5. rotor shaft	14. yaw drive
6. gearbox	15. yaw bearing
7. safety brake	16. nacelle cover
8. generator coupling	17. tower
9. induction generator	

Modern wind turbines are build with a rotor hub (2) and three rotor blades (1), each of them is independently and redundant adjustable in pitch angle. The main bearing (4), which has to absorb all the static and dynamic loads, supports the rotor shaft (5). In the gearbox (6) the low speed of the blades is transformed to the nominal speed of the induction generator (9). In the drive train in between the gearbox and the generator a safety brake (7) and a coupling is located. All this heavy components are mounted on the nacelle frame (3). A special cooler (10) for the generator and the gearbox is needed to control the temperatures in high wind or high temperature operating points. A control unit (12) and an hydraulic system is placed in the nacelle, too. The complete nacelle with its cover (16) is mounted on the tower (17) with a yaw bearing (15). Dependent of the wind direction, which is measured by wind sensors (11) the yaw drive (14) aligns the nacelle.

In figure 14 a characteristic output power curve of the Nordex N90 wind turbine with a rated power of 2300kW is plotted. The plant starts generation at a wind speed of 3.5m/s with an optimal pitch angle and very low speed of 10rpm. The control mode of speed variation is possible up to a wind speed of 12.5m/s. At this operating point the rated power is produced and the maximum speed of 17rpm is achieved.

The actual torque of the machine is calculated from the d and q current and is compared to the output of the speed controller [12], [13]. The reference turbine-speed is set by the active power control which generates the optimal speed of the turbine with a lookup table and the measured wind speed. This is necessary to control the revolution speed of the turbine (see figure 9). The wind speed is measured independently for example with an anemometer.

Fig. 14. Power curve of the Nordex N90 2,3MW Turbine.

The actual value of the active and reactive power is calculated by the grid voltages and currents which is shown in a simplified manner. The phase angle ϕ_g is calculated, too, which is necessary to transform the voltages and currents into the d-q coordinates.

In case of a sudden disconnection of the generator from the grid due to for example circuit breaker or short breaks, high voltage pulses in the rotor circuit can occur. To protect the rotor side converter a so called crowbar is usually implemented which short circuits the rotor of the generator. After a short while the control disconnects the stator from grid with ordinary circuit breakers [3]. The problem of this protection is the grid code which demanded often a fault ride through. This is not possible in case of a crowbar activation because the whole turbine has to be restarted.

V. CONCLUSION

The development of the induction machine in wind power technology from a squirrel cage machine to a doubly fed induction machine shows the tremendous potential of this kind of electrical generator. The first wind turbines with squirrel cage machine were build in the late 1980s with a rated power of less than 100kW. The state of the art wind turbines with doubly fed induction machine have a rated power up to 5.0MW. These turbines are constructed for a very high efficiency, performance and very low maintenance in order to go offshore with the next generation of wind turbines.

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