Article 6: The Single Wind Turbine: From the Blades to the Grid

Article 6 starts where Article 5 ends. Article 5 explains the conversion of wind energy into the energy in rotating blades turning a shaft. It involves the visible story – the front office. Article 6 completes the story that results in grid-suitable electricity. Mostly, the components in Article 6 are inside the wind turbine's nacelle; they are the back office. The back office is evolving. Some turbines now dispense with the gearbox, produce power at a wider range of wind speeds, and feature longer lasting, lighter, and smaller components.

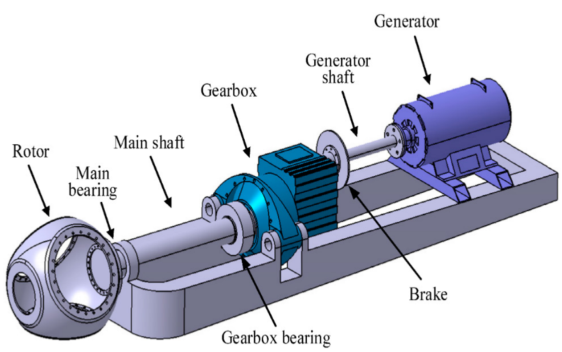

Figure 6.2: The wind turbine gearbox, which couples the main shaft and the generator shaft. Source: Qian, Ma, Zhang, https://www.mdpi.com/1996-1073/10/10/1583/xml.

6.1 The Wind Turbine Electro-Mechanical System

After the turbine blades have converted the energy in the wind into the rotational motion of the main shaft, there are two further steps before electricity can be placed on the grid. First, the rotational energy in the main shaft is transformed into electricity by a gearbox and a generator. Second, the characteristics of the electricity are manipulated to become compatible with the strict requirements of the electrical grid.

Figure 6.1 shows a block diagram of the mechanical and electrical components of a wind-turbine's energy-conversion system, from the blades to the grid. Figure 6.2 shows the physical layout of a portion of Figure 6.1: the rotor, the gearbox, and the generator. The "rotor" in both Figure 6.1 and Figure 6.2 refers to the blades and hub, which turn a rotating shaft. A different "rotor" is the portion of the generator that rotates; in this distillate, we will call it the "generator rotor."

The remaining three sections of this article address the three main components: the gearbox, the generator, and the transformer.

6.2 The Gearbox

The shaft of a wind turbine that rotates with the heavy blades and hub is spinning much too slowly for a conventional generator to produce power efficiently. A

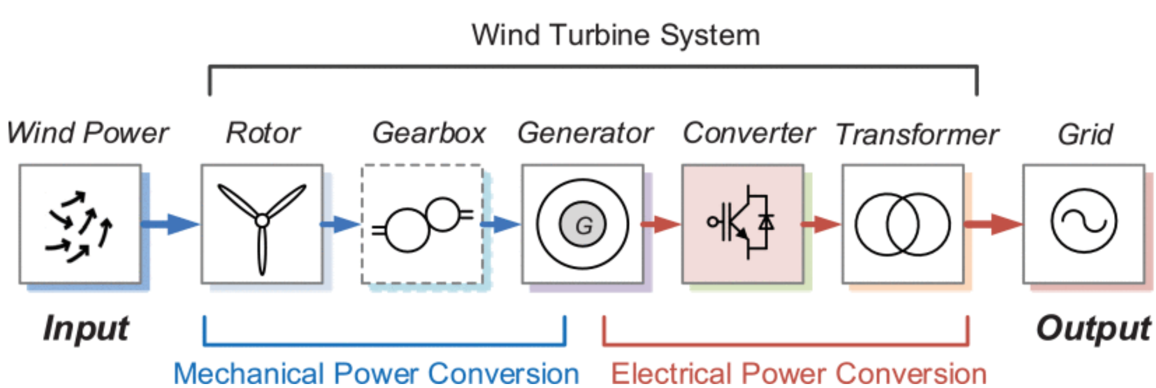

Figure 6.1: Block diagram of a wind turbine system. Source [1].

gearbox is used, conventionally, to connect that shaft to a second shaft and to spin the second shaft at a much higher rotational speed. The fast-spinning shaft rotates inside the generator and produces electricity.

For megawatt-level wind turbines, a typical rotation rate for the blades is 10 revolutions per minute (rpm) or, equivalently, six seconds for a complete rotation of the blades. The turbine completes 1/6 of a cycle per second. The electric grid operates on alternating current (AC) with oscillations at a constant frequency that is hundreds of times higher: depending on the country the frequency is either 50 cycles per second (3,000 rpm) or 60 cycles per second (3,600 rpm).

A gearbox typically uses gears in three stages to achieve this high multiplication of the rotational frequency from the slow-turning shaft to the fast-turning shaft. Figure 6.3 shows such a three-stage gearbox, with a low-speed stage, an intermediate stage, and a high-speed stage.

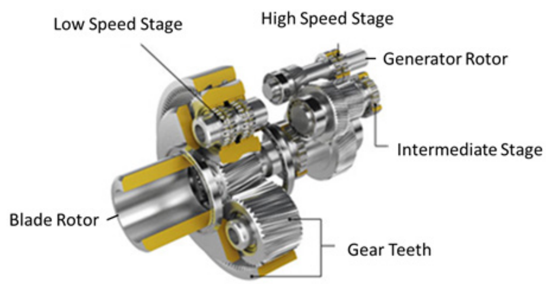

Figure 6.3: A representative three-stage gearbox. Source: Olympus, https://www.olympus-ims.com/it/applications/rvi-wind-turbine/.

The gearbox occupies 5 to 15 percent of the nacelle volume, weighs several tons, and contributes 20 to 30 percent of the turbine cost [2]. No gear system is 100 percent efficient: as a rule of thumb, roughly one percent of the power is lost at each gear stage. Thus, a 500 kilowatt three-stage gearbox running at full capacity dissipates energy at a rate of about 15 kilowatts. This heat is removed by a cooling system.

Much effort in the wind industry has been directed toward reducing the costs associated with the gearbox. The source of the high costs is the relatively short lifetime of the gearbox and its need for regular maintenance. Even with regular inspection and maintenance gearboxes often failed within an operating period of five years, while the typical target lifetime of a utility-scale wind turbine is twenty years. The lifetime of the gearbox is limited by mechanical stresses that originate in events like the random gusting of the wind that bends and twists the shaft and misaligns the gear teeth, producing uneven wear and degradation. Technical advances in many areas are extending the lifetime of the gearbox and reducing its maintenance costs: new materials, heat treatment, lubricants, and innovative mechanical structures, all of them coupled to improved power electronics and automatic control.

6.3 The Generator

The modern generator makes heavy use of advanced power electronics to produce constant-frequency electricity at the frequency required by the grid (60 cycles per second in the U.S., 50 cycles per second in much of the rest of the world). The generator has a stator and a rotor. The stator is a fixed structure mounted on a supporting base, and the generator rotor spins within or outside the stator. As the generator rotor spins, it creates a rotating magnetic field, which causes currents to flow within the stator, generating electricity that can be fed into the electric grid. Energy is transferred from the generator rotor to the stator through electromagnetic coupling. Today's large wind generators weigh from 10 to 50 tons.

Two broad classes of turbines dominate the wind industry, differing in the way they transform the slow rotation of the blades and hub into the fast rotation of the generator rotor. The first class achieves the required frequency multiplication with a gearbox, as just discussed, that couples the rotating blades and hub to a kind of "high-speed" generator widely used in other applications. The second class dispenses with the gearbox in favor of the "direct-drive" generator, where the same shaft that turns with the blades also turns the generator's rotor at the same low speed (again, think, 10 rpm); the direct-drive generator is also called a "low-speed" generator. The gearbox is shown as a box with dashed boundaries in Figure 6.1 to represent the possibility that the gearbox may not be present.

How does the direct-drive generator achieve the frequencies required by the grid without two shafts and a gearbox that connects them? It does so by placing a large number of pairs of magnets on the rotor or the stator of the generator, so that one turn of the rotor creates an electromagnetic excitation of every pair,

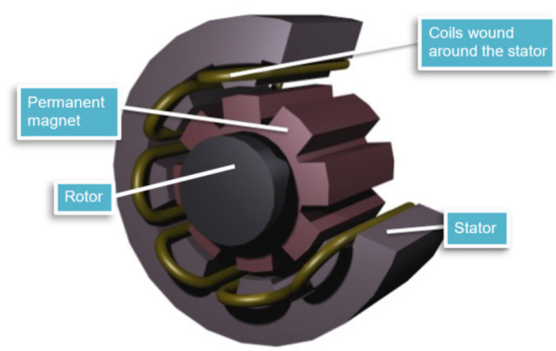

Figure 6.4: Key components of a direct-drive permanent magnet generator. Multiple pairs of permanent magnets perform frequency multiplication, instead of gears. Source: COMSOL, https://www.comsol.com/blogs/simulating-permanent-magnet-generators/.

boosting the frequency to a value close to what the grid requires. Then, the converter uses power electronics to get the exact required voltage [3].

The magnetic pairs are usually permanent magnets. See Figure 6.4 for a schematic of a direct-drive generator and Figure 6.5 for a photograph showing permanent magnets being placed inside the stator at a General Electric facility. The diameter of the "direct-drive" generator can exceed ten meters.

Figure 6.5: The manufacture of a permanent magnet generator. The permanent magnets are the silver brick-shaped objects, arrayed end-to-end along the inner perimeter of the stator; the left hand of the operator standing inside the stator is nearly touching one. Photo: General Electric, https://www.ge.com/reports/where-ge-makes-haliade-turbines/.

Both kinds of turbines are improving and dividing the market. The direct-drive generator avoids the costs associated with the gearbox (discussed above) and has fewer parts. But it is larger, and the technology is newer [4]. Its first costs are generally higher, but its maintenance costs are lower. As a result, the direct-drive generator is more competitive for offshore wind farms, where maintenance offshore is particularly costly. The generator rotor shown in Figure 6.5 is a part of a generator for an offshore wind farm. But, both onshore and offshore, developers of new farms are currently making both choices: either high-speed generators or direct-drive generators.

The dichotomy above, where there are just two turbine concepts, is an oversimplification. There are hybrid versions, "medium-speed" generators, which use a gearbox for some of the frequency multiplication and direct-drive for the rest. The high-speed stage of the gearbox is eliminated (which is the most difficult stage to make durable), and fewer permanent magnets are required for the direct-drive.

6.4 The Transformer

The electricity produced by the generator is not immediately suitable for the electricity grid, even though its frequency is now matched to the grid frequency. The voltage leaving the generator is much too low, usually around 600 to 1,000 volts, while the voltage of the distribution lines on the grid, which the wind turbine output must match, is typically 68,000 volts or higher. The grid voltage is high in order to reduce electrical losses and the size and weight of transmission cables.

The voltage "step-up" between the wind turbine and the grid is accomplished by transformers [5]. The transformer can be either inside the nacelle or at the base of the tower. The conventional transformer for wind turbines is made of magnetic materials and has copper windings. It is heavy and bulky: it can weigh tens of tons and contribute up to 30 percent of the overall system weight. However, the transformer does not need to be in the nacelle but can be at the base of the turbine or nearby, and therefore weight is not as important a consideration as it is for gearboxes and generators.

The successor of the conventional transformer, still in the research stage, may be the solid-state transformer, which uses power electronics to manipulate voltages and is much smaller and lighter. This emergent technology leverages the broad advances in semiconductors of recent decades. The major benefit of the solid-state transformer is that it allows greater flexibility in connecting the wind turbine to the grid. Reducing its cost and improving its reliability are the current challenges, here and throughout the wind turbine's innovation frontier.

References

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