A Review of Power Electronics Applications for Wind Energy Systems in Microgrids

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Authors’ contributions

This work was carried out in collaboration between both authors. Author JNC designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Author VK managed the analyses, the literature searches of the study and reorganized the manuscript. Both authors read and approved the final manuscript.

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ABSTRACT

Wind energy conversion systems continue to show promises as energy source of the future. To champion the supply for future industrial and domestic energy demand, it is imperative to improve on their reliability, energy extraction efficiency and security as these factors would enormously affect their viability and deployment. This paper presents an overview of the applications of power electronics to speed control of generators in wind energy conversion systems. Wind energy conversion system, the basis on which they are classified and their various components are concisely reviewed. Further, an up-to-date highlight of wind turbines speed control schemes is presented with focus on the roles of power electronics in these schemes. Concluding, necessary technological and economic development to aid applications of power electronics devices in emerging wind energy systems and their significance to the microgrid is understudied.

Keywords: Wind energy conversion systems; induction generator; speed control; power electronics; microgrid systems.
1. INTRODUCTION

With an average growth of about 1% yearly, global energy demand is forecast to rise by 72 million barrels of oil equivalent per day (mboe/d) by 2040 and renewable energy is predicted to lead this development [1].

These figures were captured while properly considering the currently available renewable energy mix and its estimated future growth. The implication is that unconventional energy sources will be a major driver in the future energy supply economics. The role of efficiency in extraction of this energy cannot be overlooked especially in wind energy conversion systems (wind turbines), and other future energy sources where rotating machines are deployed. In fact, for member countries of the Organisation for Economic Co-operation and Development (OECD), there is a projected drop in future energy demand due to enacted climate change policies and improving energy production and utilization efficiency [1].

Power electronics have found very beneficial applications in many aspects of wind power systems: wind turbine fault ride-through, wind farm configurations, wind energy conversion, reactive power compensation, and in wind turbine speed control. In [2] an improved converter-based technique to enhance low voltage ride-through in grid-connected permanent magnet synchronous generator-based wind energy systems by controlling grid voltage sag was proposed. A controller was designed for the machines side converter, and with de-loading droop scheme, the generated active power was adapted in the grid voltage sag. Results from these were compared with those from the conventional DC-link based de-loading droop scheme. As an advancement of this albeit with DC-link, [3] simulated results for a fast and robust grid voltage controller applied to both machine and grid sides of a 1.5MW PMSG-based grid-tied wind turbine generator.

In spite of fluctuating wind speeds, it is critical for wind turbines to operate at speeds close to their nominal values, as well as operate at speeds that result in output power very close to their rated values. Wind turbines with variable speeds can either operate at below or above the rated wind speed. The main objective at below the wind speed is to optimize the captured energy by removing the transients in the turbine components, and at above the rated wind speed the overarching objective is to operate the wind turbine within the boundary of the rated power [2].

The scope of this work is to examine the various power electronics devices, how they are used in generator speed control of wind energy conversion systems and to provide an overview of the various trends in power electronics technologies for emerging wind turbines speed regulation.

2. INTRODUCTION TO WIND ENERGY CONVERSION SYSTEMS

2.1 Wind Turbines

Although they are indication that suggest that wind had been used to do work since 5000 BC, it was however around 200 BC and onwards that the first crude wind mills were built which harnessed energy from the wind for the mechanical task of pumping water and driving vehicles. The conversion of wind energy to electricity was introduced in the late 19th century but gained acceptance only during the oil crisis of mid 1970s [3].

Today, wind energy conversion systems come in various technologies and sizes. From the small, hand-held types used in charging mobile phones and for other very low-power applications, to the gigantic off-shore industrial types. Due to the existence of these varieties, various benchmarks now exist on which modern wind turbines are classified.

2.2 Wind Turbine Classifications Based on Rotor Axis

On this basis, wind turbines are broadly classified into two based on the orientation of the axis on which the rotor lies.

2.2.1 Vertical axis wind turbines (VAWT)

Vertical axis wind turbines rotate on a vertical axis, hence the name. The two common VAWTs are the Darieus, Savonius, and Helical types as shown in Fig. 1. These wind turbine types have the limitations of being more susceptible to vibrations, and less efficiency in wind energy extraction. Despite these disadvantages, they are cheaper and simpler since they do not need yawing and pitching, they are easier to maintain as their generators and gears are located nearer to the ground, they can be more easily scaled down to sizes usable in highly-densed cities [4].
2.2.2 Horizontal axis wind turbines (hawt)

Shown in Fig. 2, these are the more common kinds of wind turbines due to their high wind energy extraction efficiency. They come equipped with a nacelle which houses the gear, generator, braking mechanism, wind vane, anemometer and the control system. In horizontal axis wind turbines, all blades are able to apply torque at the same time unlike the vertical axis wind turbines where only one blade turns at a time, pulling the others with it. These wind turbine types also come in a variety of blade numbers: there are 2 blades, 3 blades, 4 blades etc.

2.3 Wind Turbine Classification Based on Size

Wind turbines may be classified based in their sizes as:

2.3.1 Utility-scale wind turbines

Exceeding 100 kW capacity, these wind turbines find common applications in central stations wind farms, community use, large multi-turbine systems connected to the power grid [5]. These may be onshore or offshore. When they are connected in close proximity to the end-users in order to meet up with on-site energy demand, they are known as distributed wind turbines [6]. The scope of this review is on these wind turbine sizes because practical wind turbines participating in microgrids are of these sizes.

2.3.2 Large-scale wind turbines

These are mainly offshore wind turbines erected on large water bodies typically around continental shelf. They are generally superior in size to their onshore counterparts [7].

2.4 Wind Turbine Classifications Based on Rotor Speed

2.4.1 Fixed speed

Fixed speed wind turbines are designed to achieve a maximum output capacity at only one wind speed. Independent of the wind speed, their speeds are determined by the desired supply grid frequency, gear ratio, and generator design. They are typically implemented with the squirrel cage or wound rotor induction generators [8].

2.4.2 Variable speed

This has become the more vastly used kind of wind turbines because they are designed to achieve aerodynamic efficiency over a wide range of wind speed. With the use of appropriate control mechanism they maintain a constant torque on the generator, allowing of absorb variations in wind speed [8].

2.5 Wind Turbine Classifications Based on Generator Type

There are three main kinds of wind turbine generators: DC generators, AC synchronous generator and AC asynchronous generators.

An example of a DC type wind turbine generator is illustrated in Fig. 3. It consists of the wind turbine, DC generator, Insulator Gate Bipolar Transistor (IGBT) inverter, controller, and transformer. DC generators are rarely used except in heating applications, low-power needs, and in applications where the loads are in physical proximity to the wind turbines [3].

Fig. 1. Common vertical axis wind turbines

Fig. 2. Horizontal Axis Wind Turbines

Fig. 3. DC type wind turbine generator
AC synchronous wind turbine generators are either based on permanent magnet synchronous generator (PMSG) or electrically excited synchronous generators (EESG). While the AC asynchronous wind turbine generators operate on induction. They are implemented as the squirrel cage induction generators (SQIGs) or the doubly-fed induction generators (DFIGs) with wound rotors [3]. An in-depth analysis and mathematical of PMSG-based wind energy system is presented in [9].

Due to relative ease in control of active and reactive power and their higher operational energy efficiency, the DFIGs have been vastly deployed in wind energy conversion systems. The electronic equipment in doubly-fed induction generators only handle about 30% of the total power, making the DFIG topology more cost-effective than other directly connected full-power rated topologies [10]. Other reasons for preference of DFIG over other generator types are summarized in Table 1.

Other classifications benchmarks for the wind turbine are rotor position (upwind tower or downwind tower); drive type (direct drive or geared drive); yaw control (active or free).

Hub (rigid, teetering, gimbaled, or hinged blades); power control (stalling, pitching, yawing, or use of aerodynamic surfaces), and finally, based on whether they are physically rigid or flexible [3].

2.6 Wind Turbine Speed Control Schemes

Some of the techniques employed so far in speed control for variable speed wind turbines are [11]:

2.6.1 Mechanical control

This involves the use of hydraulics. When this method is applied to horizontal axis wind turbines, a variable speed hydraulic transmission system transfers the power from the tower top to the bottom. The hydraulic fluid flows between these ends via a rotary fluid coupling. One advantage this system offers is in the design simplicity. This technique is, however fraught with myriad disadvantages that have discouraged its implementation in most modern wind turbines: hydraulic leakages and losses lead to reduced efficiency and call for frequent maintenance; component parts have relatively shorter life span, and finally, the right size for pumps and motors required in modest utility-scale wind turbines are not readily available whereas combining several of these to obtain the desired effect results in cumbersome design.

Variable ratio transmission systems provide an alternative to the hydraulic transmission systems. Variable ratio transmission systems allow adjustment of the gear ratio within a preset range. A common example applicable in wind turbines are the belts and pulleys. Variable transmission systems have a special advantage in their ability to drive a fixed speed wind turbine while being driven by variable speed turbine rotor. However, aside not being available in sizes suitable for high power applications, they also suffer from great losses.

2.6.2 Electromechanical control

By using devices and techniques combining electrical and mechanical components in speed
control, an example is seen in the case where the generator stator is allowed to rotate. This system utilizes a squirrel-induction generator driven by wind turbine through a gear. The rotor however is mounted on a support capable of rotating in both directions. The support is driven by a DC machine. A bi-directional inverter feeds the armature of this DC machine.

On the one hand, when the rotor rotates in the direction of the wind turbine, the turbine spins faster and the excesses are taken up by the generator and supplied to grid via the inverter.

On the other hand, the wind turbine spins slowly when the rotor turns in a direction opposite it. A feedback control circuitry operated by a tachometer governs the amount of torque delivered in this scenario. Overall, the viability of this system is limited by their high cost, complexity and maintenance.

2.6.3 Electrical control

This is typically achieved through use of either high slip induction generator or tandem induction generator. High slip induction generators is achieved by allowing a considerably large rotor resistance. The downside to this is that the losses increases with the rotor resistance. The tandem induction generator employs two independent rotors, one fixed and the other free to rotate. Torque control, and ultimately, speed control is achieved by tuning the angular displacement between the stator and consequently, creating a phase shift in the rotor induced voltage.

Speed control may also be achieved with other high voltage electrical devices like braking resistors [12].

2.6.4 Power electronics control

Power electronics speed control techniques have gained wide acceptance over years. Speed control through power electronics devices is broadly achieved in one the following ways:

- conditioning the power to a grid-appropriate form
- Supplying reactive power
- Rectifying some or all of the power to control the generator rotational speed.

Implementations of this scheme follows the general outlook in Fig 4.

Table 1. Comparison wind turbine generators

<table>
<thead>
<tr>
<th>Indicator</th>
<th>DC Generator</th>
<th>Induction generator</th>
<th>Synchronous generator</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FSIG</td>
<td>DFIG</td>
<td>Electro-magnet</td>
</tr>
<tr>
<td>Reliability</td>
<td>Poor</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>Fault Response</td>
<td>Slow</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>Efficiency</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Controllability</td>
<td>Poor</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Grid-Support</td>
<td>Low</td>
<td>High</td>
<td>Medium</td>
</tr>
<tr>
<td>Capability</td>
<td>High</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Voltage Fluctuation</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
</tr>
</tbody>
</table>

Fig. 4. On-grid wind turbine with DC/AC/DC converter
Power electronics devices find applications in wind energy conversion systems employing any of the four common generator types: synchronous generator, permanent magnet synchronous generator, squirrel-cage generators, and wound rotor induction generator. Table 2. Provides a summary of technique of speed control of wind energy system using power electronics.

2.6.5 Synchronous generators

Synchronous generators used here are allowed to run at variable speeds with resulting variable frequency and voltage outputs. Power electronics used here serve the purpose of adjusting the supplied field current. The devices applied here as shown in Fig. 4 are the controlled or uncontrolled bridge rectifier, DC link, and inverter. The main limitations of this configurations are the high cost and maintenance requirements.

2.6.6 Permanent magnet synchronous generators

As shown in Fig. 5, where permanent magnet synchronous generator (PMSG) is used in a wind energy system, the PMSG is connected to a three phase rectifier, and then to a boost converter which controls the electromagnetic torque. The supply side regulates the DC link voltage, and controls the power factor input. The shortcoming of the configuration in Fig. 5, is that the use of rectifier diodes increases the current amplitude and distortion of the generators. This challenge limits the applications of this scheme to small power wind energy conversion systems. Fig. 6, provides an improvement on this; in order to minimize the losses in the generator and the power electronics circuit, the generators run near their optimal operating point but the performance is enhanced by identifying and improving on the generator parameters that vary with frequency and temperature at run-time.

At unity power factor, PWM voltage source converters was proposed in [13] for maximum power extraction from a PMSG. Where there is need to reduce cost, four-switch PWM voltage source inverters are used rather than six-switch.

2.6.7 Squirrel-cage induction generators

In architecture, this shares similarity with the synchronous generator configuration. The challenge here is with the self-excitation. A self-commutating converter operating in the rectifier mode serves in providing the reactive power necessary for self-excitation.

The advantages of this setup are in their low cost and low maintenance requirements. However, as with the synchronous generator, the converters have to take full generated power, and this could lead to a higher cost.

![Fig. 5. Diodes in Permanent Magnet Synchronous Generators](image)

![Fig. 6. DC/AC Converters in Permanent Magnet Synchronous Generators](image)

2.6.8 Wound rotor induction generators

There are three-phase winding on the rotor of the wound rotor generator. The rotor is accessed through any of the following means:
- Slip power recovery
- Use of cycloconverters
- Rotor resistance chopper control

3. SLIP POWER RECOVERY

This behaves like the traditional induction generator with very large slip. Through the slip ring, the power is fed to the rectifier and DC link,
then to the commutated inverter to the grid. This arrangement only allows for super-synchronous variable speed. Fig. 7. Shows how this can be applied to wind energy systems. The advantage is that the power conditioning unit only handles a fraction of the power in controlling the generator. This is also called the static Kramer system.

![Fig. 7. Power Electronics in DFIG Wind Conversion System](Image)

### 3.1 Use of Cycloconverters

Cycloconverters are power electronics devices that convert AC voltage at one frequency to AC voltage at another frequency without DC link. Also called static Scherbius system, when connected to wind turbine rotor circuit, they permit sub-synchronous and super-synchronous speeds. At super-synchronous speed, they operate in a fashion similar to the slip power recovery discussed in the previous sub-heading. The machine operates at sub-synchronous speed when energy is fed to the rotor. Although the ability of the system to control reactive power at the terminal is limited, the system may be coupled with capacitor excitation and used at the utility end. Owing to the static Scherbius system ability to dynamically adjust terminal voltage magnitude and phase angle, wind turbine generators in which they are used are able to resynchronize without going through the start-stop sequence.

### 3.2 Rotor Resistance Chopper Control

In its simplest form, this technique is achieved by changing the induction generator rotor resistance.

The research in [14] investigated an induction motor speed control scheme using rotor chopper-controlled external resistor. The proposed method, illustrated in Fig. 8, is superior to the conventional rotor resistance control by virtue of its implementation of contactless rotor resistance control. In this method employed the time ratio control strategy where the period of the chopper is kept constant. The considered chopper period is a time duration consisting of ON and OFF signal. By regulating the chopper period in this way, R values may be obtained that vary from zero to \( R_{ex} \). The waveform of rectified current in this scheme is shown in Fig. 9.

![Fig. 8. Rotor Resistance Chopper Control with Time Ratio Control (TRC)](Image)

![Fig. 9. Rectified Current with TRC Scheme](Image)

### 3.3 Significance in Microgrid

Microgrids are a small independent interconnected networks consisting of power generations, distribution and control subsystems located closer (than traditional grid) to their consumers. While most microgrids stand alone, others could be tied to the main grids, and yet be capable of independent operation in the event of fault. Microgrids are cheaper, more efficient, higher reliability, they provide a quick means of rural electrification [15]. In Table 3, a highlight of the various applications of power electronics to microgrids is presented. Power electronics...
### Table 2. Power Electronics devices in generator wind system speed control

<table>
<thead>
<tr>
<th>Power electronics devices</th>
<th>Speed control principles</th>
<th>Advantages</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thyristor [15]</td>
<td>Regulation of AC and DC power</td>
<td>Robust Economical Simple Fast switching High power</td>
<td>Their relatively small size makes them especially attractive</td>
</tr>
<tr>
<td>Converters</td>
<td>Controls the generator torque</td>
<td>Their stable output allows for smooth control [18]</td>
<td>They achieve this end through appropriate selection of voltage amplitude</td>
</tr>
<tr>
<td>Rectifiers</td>
<td>Achieve control through rectifier pulse width modulation</td>
<td>Easy control of PWM currents</td>
<td></td>
</tr>
<tr>
<td>Inverters</td>
<td>With aid of the scalar-control inversion scheme [19]</td>
<td>Speed and torque are controlled by tuning the voltage and frequency</td>
<td></td>
</tr>
<tr>
<td>Static synchronous compensators, Thyristor Controlled Reactors, other FACTS devices</td>
<td>Speed control through reactive power compensation</td>
<td>Dynamic control</td>
<td>Control of reactive power delivery to/from generator [20]</td>
</tr>
</tbody>
</table>

### Table 3. Power electronics in microgrid systems

<table>
<thead>
<tr>
<th>Power electronics</th>
<th>Applications</th>
<th>Techniques</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Converters</td>
<td>DC voltage level to level conversion to meet up with power requirements of different equipment</td>
<td>Converter interface ensures constant voltage level across microgrid.</td>
<td>Dual Active Bridge converters find great use DC microgrids where high gain is needed. AC-AC, AC-DC and DC-DC converters are also crucial in microgrids.</td>
</tr>
<tr>
<td>Voltage balancer</td>
<td>To provide a means for isolation during fault [21]</td>
<td>In [13] a power electronics-based circuit to provide high frequency galvanic isolation from the grid was proposed.</td>
<td>It provides an interconnection between the wind turbines and the grid to which they are connected.</td>
</tr>
<tr>
<td>IGCT, IGBT, GTO</td>
<td>For protection and islanding applications</td>
<td>Ultra-fast IGBT-based hybrid protective module has been designed for microgrid converter protection [22]</td>
<td>They provide solid state switching means devoid of arcing or long time delays associated with mechanical switches</td>
</tr>
</tbody>
</table>
devices are also deployed massively in microgrids, from protection [16] to control [12].

The biggest challenge with grid-connected wind energy systems is that their quantitative and qualitative outputs depend on the wind speeds. A robust control system is expedient to keep the power parameters within desired values. In [12] the droop approach – a scheme only implemented for generators operating at below maximum power regime – was deployed to regulate voltage, active power reactive power, and frequency for a grid-tied DFIG-based wind generator. The results of the work showed, among other key performance indicators, a regulation of the voltage and frequency fluctuations to within 10% and 25% respectively of their values without a controller. Distortions, fluctuations and shutdowns of grid-connected wind turbines have also been minimized in scheme proposed by Raju [17] using parallel capacitor-based DC-link control scheme. With a dip of 5% and moderate settling time, this technique yielded results superior to those obtained from the traditional method.

4. FUTURE OF POWER ELECTRONICS IN WIND TURBINE SPEED CONTROL

With a projected inevitable increase in the penetration of wind energy systems in the power grid, emerging power electronics technologies must step up to the challenge of adapting to the generators, electrical circuitry and control needs of the wind energy systems of the future. The current challenges affecting the future viability of power electronics devices such as the levelized cost of energy, reliability, grid integration etc. must be addressed.

The levelized cost of energy is an economic measure which factors the capital cost, initial investment cost, operations and maintenance cost, fuel cost over the lifetime of the generator per unit annual production output. The cost of emerging power electronics technologies should not be high enough to considerably increase the wind system levelized cost of energy.

Secondly, power converters of the future must be reliable since failure in wind turbines could result to consequences catastrophic to the health and security of the grid to which they are connected, and must be avoided. Also, emerging wind turbines should will be connected in distributed generation networks, demanding more control needs that power electronics devices have to satisfy for successful protection islanding and configuration of the wind energy conversion systems.

5. CONCLUSION

This research, which explores the invaluable roles of power electronics devices in wind energy conversion systems, is aimed at creating increased awareness of the ways in which these devices have been employed to improve the performance of wind turbines. The droop and de-loading droop controllers for performance enhancement of grid-connected PMSG-based wind turbines with DC-link was briefly studied. Expert models were drawn, based on current trends, of the significance of wind energy systems in the global drive for sustainable energy. The review ultimately highlights the necessary refinements and functions that power electronics devices of the future must meet to suit their applications in emerging wind energy systems with emphasis on their adaptability to the microgrid network.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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