

Analysis of Wind Turbine-Driven Electric Drive Systems for Distributed Generation

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DOI: <https://doi.org/10.5281/zenodo.19224276>

Published Date: 25-March-2026

Abstract: Electric drive systems driven by wind turbines are essential to distributed generation (DG) because they lower transmission losses, enhance grid stability, and promote sustainable energy goals. Local renewable energy production is made possible by these systems, supporting the objectives of sustainable energy. This article examines the performance of wind turbine systems that use electric drives, such as induction generators and power electronic converters, for distributed generation (DG) applications, as well as the obstacles that arise during integration and the technological breakthroughs that have been made. Our evaluation of the system's fault tolerance, frequency control capabilities, and efficiency is accomplished through the examination of simulation models and case studies based on the real world. The most important findings suggest that integrating energy storage and advanced control systems allows for the reduction of variability issues, which can result in distribution networks reaching constant output of up to 9 megawatts. DG penetration is optimized through the use of hybrid systems, and the paper closes with recommendations for future research in hybrid systems.

Keywords: Wind Energy Conversion System (WECS), Electric Drive, Wind turbine Distributed Generation (DG), Power Electronics, Grid Integration.

I. INTRODUCTION

The production of electricity from small-scale sources that are placed close to the point of consumption is referred to as distributed generation. This is in contrast to the production of electricity from centralized power plants. Wind turbines are a renewable source of distributed generation (DG) that convert the kinetic energy of the wind into electrical power through the use of electric drive systems. These systems typically consist of turbines, generators, and converters [1]. In order to reach global renewable targets, such as Indonesia's goal of procuring 25% of its power from renewable sources by the year 2025, these systems are absolutely necessary. Challenges like as changing wind speeds and grid faults are addressed by the electric drive component, which enables effective power conversion and grid integration [2].

Because renewable energy sources have a low system inertia, the integration of wind power into modern networks necessitates the implementation of effective frequency regulation. In the context of distributed generation (DG), this article investigates the construction, performance analysis, and valuation of electric motors that are driven by wind turbines [3].

II. BLOCK DIAGRAM OF WIND TURBINE-DRIVEN ELECTRIC DRIVE SYSTEM FOR DISTRIBUTED GENERATION

The figure depicts the process of transforming wind energy into electrical energy by utilizing a system that consists of wind turbines. The blades of the wind turbine are responsible for capturing the kinetic energy that is generated by the wind and converting it into mechanical rotation. This rotation is then delivered to the generator shaft by means of a gearbox or a direct drive. The electrical generator, which is commonly a PMSG or DFIG, is the component that is responsible for transforming this mechanical energy into current [5]. Considering that the power that is created is variable, a control unit that utilizes techniques such as MPPT, vector control, and PLL is able to maximize the speed of the turbine, the power output, and the grid synchronization as shown in figure 1.

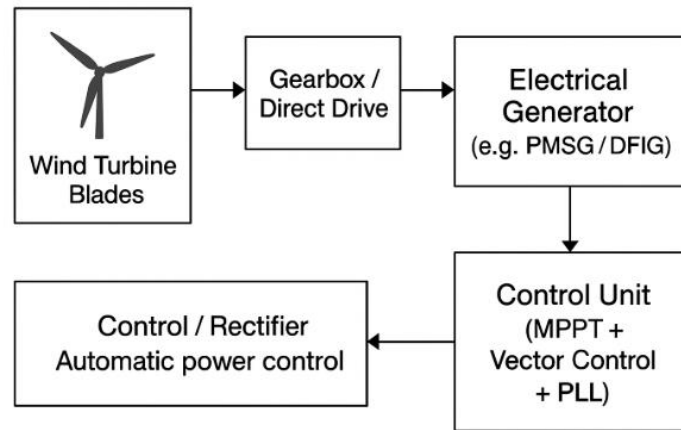


Figure 1: Wind Turbine-Driven Electric Drive System for Distributed Generation [7]

The maximum power point tracking (MPPT) system guarantees that the maximum amount of power is extracted, while the control or rectifier block regulates and conditions the power that is generated in order to ensure that it is delivered to the grid or load in a steady and efficient manner, hence assuring the overall dependability and performance of the system [4].

III. LITERATURE REVIEW

Recent research has shed light on the development of electric machines and drives tailored specifically for wind power generation. Modern systems choose variable-speed operations that make use of doubly-fed induction generators (DFIG) or permanent magnet synchronous generators (PMSG) in conjunction with power converters in order to achieve the highest possible level of power capture results. Despite the fact that issues such as cost and fault ride-through continue to exist, a detailed evaluation highlights the prospects that exist in brushless doubly-fed reluctance machines and stator PM machines. These machines offer great efficiency and decreased maintenance [6]. It has been demonstrated through performance evaluations that wind turbines are efficient DG units. Under normal conditions, for example, a 9 MW system that is equipped with squirrel-cage induction generators and is coupled to a 25 kV network demonstrates reliable power supply. The active power stabilizes at 3 MW per turbine pair, and the voltage is 0.984 p.u. Transient resilience can be revealed by fault simulations, which are made possible by protective devices such as STATCOM. Energy storage system (ESS) integration is one of the most crucial elements of frequency regulation. The coordinated functioning of wind turbines with energy storage systems (ESS), such as hydrogen storage, can reduce frequency fluctuations in high-penetration scenarios. Evaluation studies show that standardized frameworks have drawbacks, even though they also emphasize the advantages of dispersed wind energy in terms of flexibility, resource diversity, and supplementary services. Solar photovoltaics can be supplemented by distributed wind, which can improve the overall reliability of renewable energy sources. Wind turbines operating at high speeds have an effect on transient stability, which, when properly integrated, results in improved power system dampening. Investigations into voltage stability reveal improved profiles with wind DG, in particular when advanced controls such as modified second-order sliding mode for low-voltage ride-through are utilized [7].

IV. SYSTEM DESIGN AND COMPONENTS

The turbine blades, rotor, gearbox (or direct-drive), generator, power converter, and grid interface are the components that make up a typical electric drive system for distributed generation (DG) that is driven by wind turbines.

- Electricity is generated by wind turbines in what methods? The Detailed Instructions
- The following types of generators are frequently used: Squirrel-Cage Induction Generator (SCIG): Simple and cost-effective, fixed-speed operation.
- Doubly-Fed Induction Generator (DFIG): Variable-speed, partial converter (30% rating).
- Permanent Magnet Synchronous Generator (PMSG): High efficiency, full converter for direct-drive systems.

Power converters, such as back-to-back voltage source converters, enable MPPT and grid synchronization. For DG, systems are often behind-the-meter, offsetting local loads in homes, farms, or businesses [8].

Table 1: compares electric drive systems:

Drive System	Generator Type	Converter Requirement	Efficiency	Cost	Suitability for DG
Fixed-Speed	SCIG	None/Soft Starter	Medium	Low	Small-scale, simple grids
Variable-Speed (Partial)	DFIG	Partial (Rotor-side)	High	Medium	Medium-scale DG with variability
Variable-Speed (Full)	PMSG	Full	Very High	High	Distributed systems requiring high reliability

V. WIND TURBINE TECHNOLOGY TRENDS AND METHODOLOGY

From 2016 to 2050, this bar chart shows how different energy sources generated power. Over time, total energy output has increased, with renewable energy sources like solar PV and wind contributing [4]. The energy sector was dominated by coal, oil, and natural gas in 2016, but by 2050, their share is predicted to decrease. Reflecting the global trend toward sustainable energy, solar PV and wind power are expanding at the quickest rates. Hydropower and bioenergy are making a constantly growing contribution [7]. Additionally, the proportion of geothermal and nuclear energy is gradually rising.

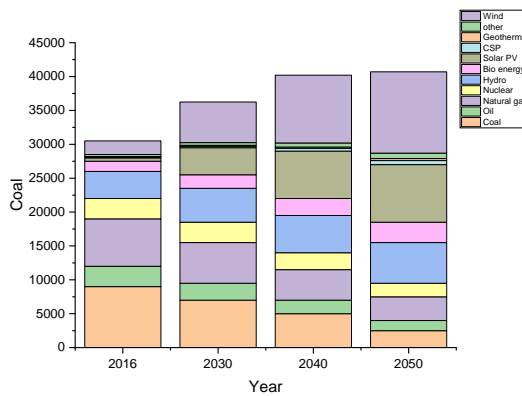


Figure 2: Wind Turbine Technology Trends [1]

The majority of energy will come from renewable sources by 2050. The energy transition and worldwide carbon reduction are highlighted by this trend. This information shows how legislation and technology encourage the use of renewable energy [4]. It symbolizes the future of a cleaner, more sustainable renewable energy infrastructure. The total installed electric capacity (GW) across energy sources for 2016 and 2050 is displayed in a bar chart in Figure 3. Global energy capacity was dominated in 2016 by fossil fuels including coal, oil, and natural gas, with renewable energy sources like wind and solar PV contributing less. There will be a considerable change by 2050 when renewable energy sources, especially wind and solar PV, gain substantial installed capacity. Wind and solar PV have the largest capacities.

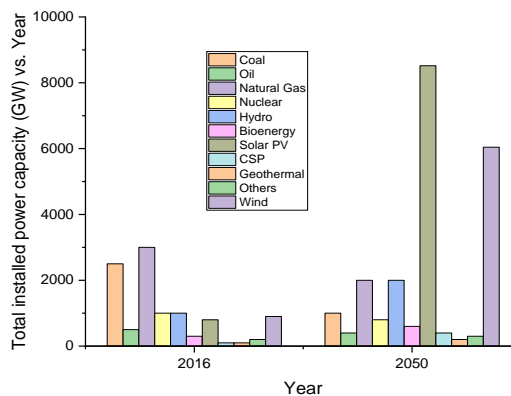


Figure 3: total installed power capacity (GW) comparison in 2016 to 2050 [1].

There has been a significant drop in the proportion of coal and oil, which suggests that fewer fossil fuels are being used. Although its percentage has slightly increased, nuclear power still plays a very small role. Growing energy demand and a move toward sustainability are reflected in the expanding capacity [7]. This movement is being driven by global policy-led decarbonization, environmental consciousness, and renewable technologies.

Methodology

In this study, MATLAB/Simulink modeling is utilized, and it is built on previously known frameworks [2]. Through the use of a 25 kV distribution line that is connected to a 120 kV grid, a 9 MW wind farm that is comprised of three 3 MW turbines is replicated. With pitch control (Kp=5) for optimization, wind speeds can range anywhere from 4 to 10 meters per second. Among the equations are:

$$\text{Wind power: } P = \frac{1}{2} \rho A v^3 C_p(\lambda, \beta)$$

and

$$\text{Tip speed ratio: } \lambda = \frac{\omega_r R}{v}$$

Fault scenarios involve a three-phase short circuit at t=15 s. Performance metrics: active/reactive power, voltage stability, and frequency response.

VI. RESULTS AND DISCUSSION

Under normal conditions, active power at bus B25 increases to 9 MW within 12 seconds, with reactive power at 2.3 MVAR. Pitch angle adjusts from 0° to 8° for optimal operation.

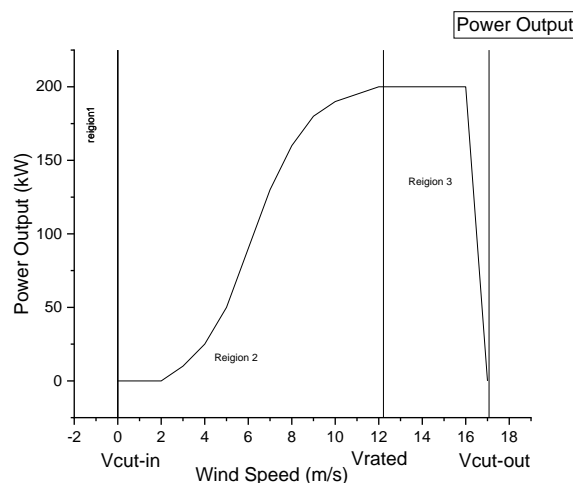


Figure 4: Typical power curve of a pitch regulated wind turbine.

During faults, one turbine trips, but the system recovers with remaining units supplying 6 MW, voltage dipping transiently to 0.98 p.u.

Table 2: Simulation Parameters

Parameter	Value
Nominal Power	2*1.5e6 / 0.9 VA
Voltage (Low)	575 Vrms
Frequency	50 Hz
Stator Resistance (Rs)	0.005003 p.u.
Rotor Resistance (Rr')	0.004380 p.u.

Discussion

The findings provide evidence that induction-based drives are reliable for distributed generation, with ESS integration providing a solution to frequency problems. A number of obstacles exist, such as the high initial costs of advanced drives and the requirement for uniform valuation in order to account for benefits such as robustness. AI might be incorporated into future systems for predictive control, which would result in increased DG efficiency.

CONCLUSION

Electric drive systems that are powered by wind turbines are essential for sustainable distributed generation because they provide dependable electricity when properly integrated. The development of converters and storage technologies will lead to increased adoption, which will promote energy transitions on a worldwide scale.

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