Power quality enhancement for a grid connected wind turbine energy system with PMSG

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ABSTRACT

This project investigates the burgeoning potential of gearless wind turbine systems as a pivotal clean energy resource. Unlike conventional gearbox-based turbines, which grapple with issues like frequent breakdowns, intricate repairs, and prolonged downtimes, gearless systems present a suite of advantages. Chief among these is heightened reliability, diminished maintenance costs, and augmented efficiency. By circumventing the need for a gearbox, gearless turbines shed weight, bolster reliability, and demand less upkeep. The incorporation of permanent magnet generators further elevates their efficiency and renders them well-suited for offshore deployment. The emergence of gearless wind turbines heralds a promising frontier for effectively and efficiently harnessing wind power. Their streamlined design and robust performance potential position them as a transformative force in the renewable energy landscape, poised to catalyze substantial advancements towards sustainable energy goals. As research delves deeper into their capabilities and optimization, gearless turbines are poised to emerge as a cornerstone technology in the global pursuit of clean energy solutions.

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1. INTRODUCTION

In recent years, the global capacity of installed wind turbines has expanded rapidly, reaching around 300 GW by 2013 [1]. This significant increase underscores the wind turbine industry's progress, establishing wind energy as a competitive and mainstream renewable resource with a favorable cost per kWh compared to traditional fossil fuels. These advancements are largely attributed to innovations in electrical generators and power electronics.

One major challenge with energy of renewables in its intermittent availability power generation is not always constant. To address this, various integration techniques have been developed, including the use of power electronic inverters. These inverters help manage both active as well as sustained grid voltage during faults and voltage sags, control frequency, and manage reactive power [2]-[4]. Several control schemes for wind turbines, whether they are linked to the grid or run autonomously, have been studied [5], [6].

In order to optimize wind power extraction, machine-side controllers often utilize field-oriented or vector control approaches, such as fuzzy logic, adaptive controllers, and hill-climbing control [7]. On the other hand, grid-side controllers are made to guarantee that the grid receives both active and reactive electricity in an efficient manner [8], [9]. By converting the three-phase system into a two-phase reference frame, theoretical frameworks like Akagi's instantaneous power (PQ) theory make the extraction of active and reactive power easier [10]. As an alternative, reference-frame conversions are avoided when analyzing current and voltage in their three-phase form using the conservative power theory (CPT) [11], [12].

The control framework for three-phase, four-wire systems is presented in this paper with the goal of improving the grid-side converter's performance in a wind turbine configuration [13]. The proposed method employs CPT to generate current references for targeted disturbance compensation, effectively handling both single-phase and three-phase loads, including balanced and unbalanced configurations. It also covers the use of four-leg converters or traditional three-leg converters with "split-capacitor" configurations to build three-phase, four-wire inverters [14]-[16]. Four-leg converters use an extra switch leg for improved controllability, whereas three-leg converters link the AC neutral wire straight to the DC bus's middle [17]-[19]. The CPT framework aids in identifying and quantifying resistive, reactive, unbalanced, and nonlinear load characteristics under varying supply voltage conditions in a four-wire system. This paper builds on previous work presented at the 2015 IAS annual meeting [20].

2. METHOD

2.1. Gearless wind turbine with PMSG

In this project, a dynamo motor serves as the key component of the wind turbine system, converting wind energy into electrical power. The process begins with the wind turbine strategically placed to capture maximum wind flow [21], [22]. As the wind turns the rotor of the dynamo motor, it generates alternating current (AC) electricity. This AC power is then routed through a voltage divider circuit, converting it into direct current (DC) suitable for battery storage. The stored DC power in the battery acts as a reliable energy reservoir, ensuring uninterrupted power availability even during periods of low wind. When electricity is required, the DC power is transformed back into AC using an inverter module, facilitating compatibility with standard appliances and devices [23]. The system's functionality is further enhanced by integrating Arduino technology, allowing real-time monitoring of wind speed and battery voltage. This data provides valuable insights into energy generation and storage, enabling optimization of system performance for maximum efficiency and longevity [24]. Through the seamless integration of dynamo motor-based wind turbines, DC-to-AC conversion, battery storage, and Arduino monitoring, this project presents a comprehensive approach to harnessing wind energy for sustainable power generation [25]. Figure 1 depicts a full-scale power converter and a variable-speed wind turbine. Figure 2 illustrates the gearless wind turbine's active and reactive power control methods using a permanent magnet synchronous generator (PMSG).

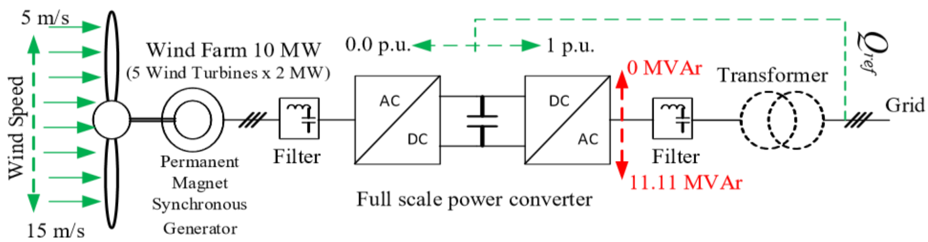

Figure 1. Variable speed wind turbine with full-scale power conversion

2.2. Power control in wind turbine systems: active and reactive

Doubly-fed induction generator (DFIG) wind turbine system operates at a variable speed, it makes use of its ability to regulate both active and reactive power, which lowers the cost of power electronics converters and minimizes power losses as compared to fixed-speed wind turbine generators. These cutting-edge devices produce greater power quality and are more effective at capturing wind energy. Variable-speed wind turbines can adjust the turbine's output power, thereby reducing mechanical stress on components such as blades and towers. This results in improved power efficiency, extended system lifespan, and better power quality, making them a cost-effective option despite their higher initial investment [26], [27]. The integration of power electronics converters into wind energy systems enhances their control and grid connectivity. Emphasis is placed on power schemes that enable complete control using either partial-scale or full-scale power converters, active and reactive power under all operating situations [28]. Figures 3 and 4 illustrate the reactive and active power of the module, respectively. For example, a control method for full-scale converter-based wind turbines is depicted in Figure 5. Because of the DC-link, this technique has the advantage of control decoupling between the wind turbine and the grid. Moreover, the DC-link facilitates the integration of energy storage devices, allowing for more intelligent management of active power flow into the grid. Additionally, this characteristic strengthens the wind turbine system's capacity to sustain the electrical grid. Reactive power is handled by the grid-side converter in this configuration, whereas active power is managed by the generator-side converter [29]. A DC chopper is frequently employed to dissipate surplus turbine power in reaction to abrupt voltage dips in the grid, preventing DC-link overvoltage during grid breakdowns [30]-[32]. Five wind turbines in all, each rated at 2 MW (5 turbines × 2 MW = 10 MW), were used in this study, as Figure 6 illustrates. These turbines have a nominal operating power of 10/0.9 = 11.11 MVA. A Q-reference input parameter that is proportionate to the nominal power is used to control reactive power. Three wind speeds such as five, ten, and fifteen meters per second were examined, and the Q-reference values varied from 0.0 to 1.0 p.u. The type-4 wind turbine was chosen due to its adaptable design and mode of operation. Table 1 displays data on voltage versus time.

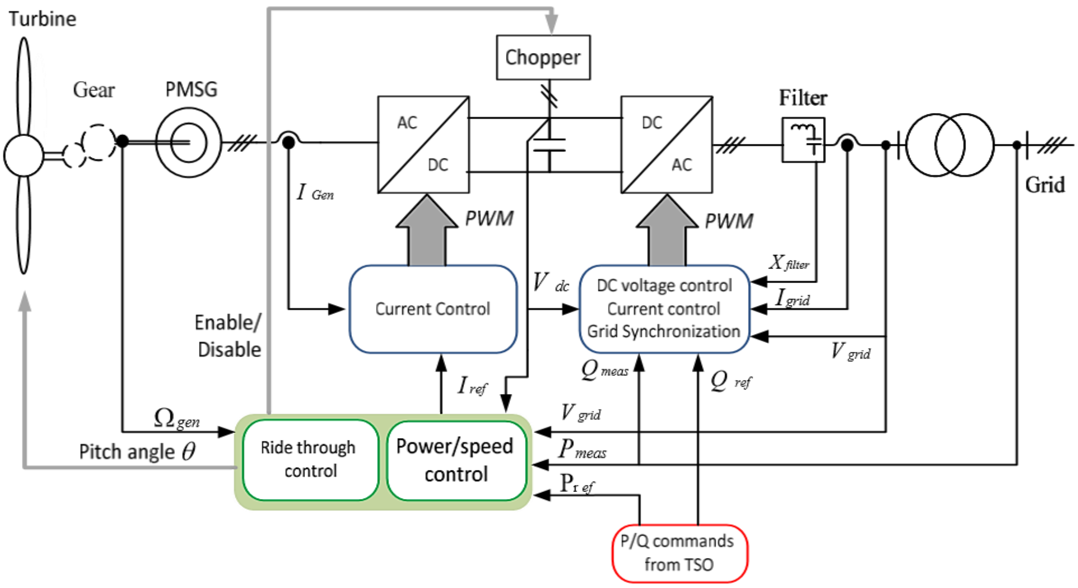

Figure 2. Controlling both active besides reactive power in a gearless wind turbine using PMSG

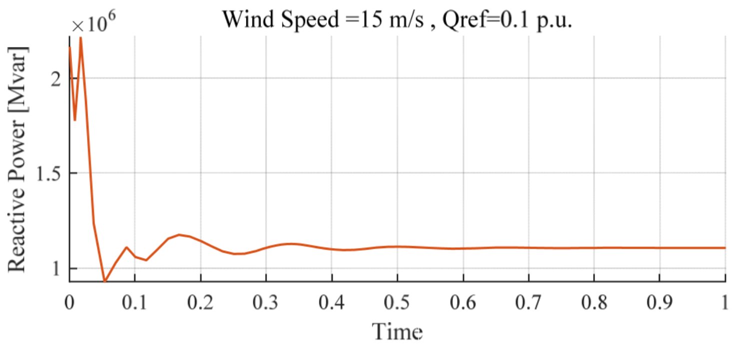

Figure 3. Reactive power of the module

Table 1. Voltage vs time

S.No	Time (in sec)	Voltage
1	0	2900
2	0.05	2500
3	0.01	1650

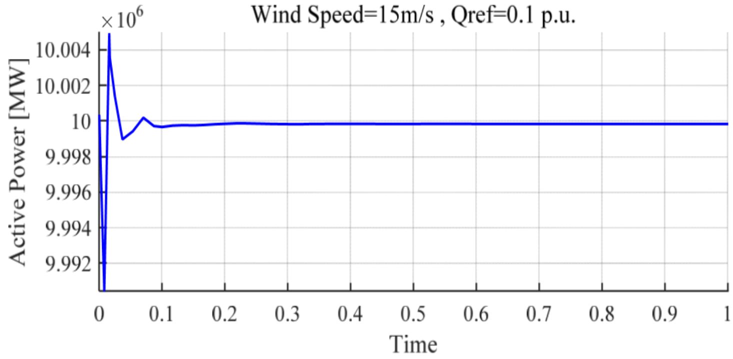

Figure 4. Active power of the module

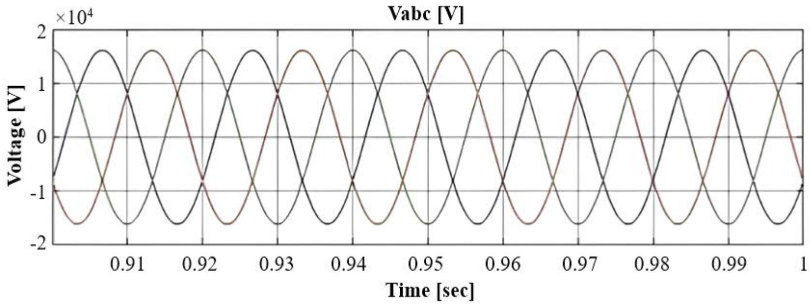

Figure 5. Obtained voltage from the module

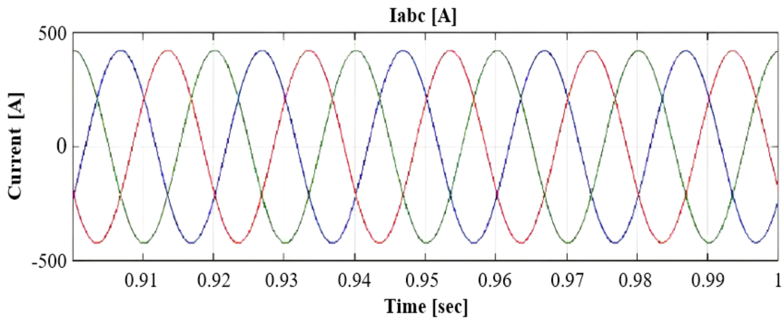

Figure 6. Obtained current from the module

The main issue with renewable energy is its intermittent availability. Power electronic inverters regulate active/reactive power, frequency, and grid voltage during utility integration. Various control algorithms have been developed for wind turbine systems, both freestanding and coupled to grid. Grid-side controllers transfer active and reactive power to the grid. Electrical power systems use many power theories to analyze current and voltage components, including the instantaneous power (PQ) theory for three-phase systems. Table 2 shows active and reactive power readings. The proper procedural steps and precautions for controlling both active besides reactive power in a gearless wind turbine using PMSG are as follows:

- Connect the output of the dynamo motor to a voltage divider circuit.
- Use the voltage divider circuit to convert the generated AC power into DC power.
- Direct the DC power to a battery for storage.
- Ensure the battery is connected and properly charged to store the generated DC power.
- Connect an inverter module to the battery to convert the stored DC power back into AC.
- Ensure the inverter module is capable of providing the required AC voltage and frequency.
- Connect the output of the inverter module to various loads, such as bulbs or appliances, for power consumption.
- Utilize appropriate sensors to measure wind speed and voltage levels.

- Interface Arduino with the wind turbine system to monitor wind speed and battery voltage.
- Implement Arduino programming to display real-time data and provide feedback on energy generation and storage.
- Continuously monitor wind turbine performance, battery charge status, and power consumption using Arduino.
- Analyze data to optimize system efficiency and ensure reliable power supply.
- Adjust system parameters as necessary to maximize energy generation and storage capacity.

The DC voltage has a peak value of 2900 volts in 0 seconds, a constant value of 1650 volts in 0.01 seconds, and is 2500 volts in 0.05 seconds. A wind turbine system's DC voltage varies according on wind speed. Wind velocity ranging from 4.0 to 5.0 m/s is required to rotate the blade or turbine. Wind turbine blades transform kinetic energy into mechanical energy. The mechanical energy produced depends on the pitch curve of the blade. The mechanical energy rotates the shaft. The shaft has two ends: one connected to the turbine and the other to the generator shaft. The generator shaft is simply an armature shaft. Rotating the shaft causes the linked generator shaft to revolve, producing electricity power.

2.3. Mathematical analysis

Reactive power is managed through control strategies that adjust the output to maintain voltage stability and support the grid through the Q-reference input parameter, which scales with the nominal power. Three different wind speeds such as 5 m/s, 10 m/s, and 15 m/s were used to test the system. The values of Q-reference varied between 0.0 and 1.0 p.u. Table 2 shows a distinct trend: reactive power increases from 0.0 to 11.11 Mvar as the Q-reference climbs from 0.0 to 1.0 p.u. Furthermore, as wind speed increases, so does the active power. The observed active power at a 5 m/s wind speed was 0.64 MW. It increased to 5.56 MW at 10 m/s and 10 MW at 15 m/s for the active power.

A total of wind turbines used	= 5	Acceptable power of the wind turbines generator	= total rating/0.9
Each rating	= 2 MW		= 10/9 => 11.11
Total rating	= 10 MW		= 11.11 MVA

Table 2. Readings of active as well as reactive power

q-ref	Active power (MW)			Reactive power (Mvar)		
	5 m/s MW	10 m/s MW	15 m/s MW	5 m/s MW	10 m/s MW	15 m/s MW
0.0	0.64	5.56	10	0.0	0.0	0.0
0.1	0.64	5.56	10	1.11	1.11	1.11
0.2	0.64	5.56	10	2.22	2.22	2.22
0.3	0.64	5.56	10	3.33	3.33	3.33
0.4	0.64	5.56	10	4.44	4.44	4.44
0.5	0.64	5.56	10	5.55	5.55	5.55
0.6	0.64	5.56	10	6.66	6.66	6.66
0.7	0.64	5.56	10	7.77	7.77	7.77
0.8	0.64	5.56	10	8.88	8.88	8.88
0.9	0.64	5.56	10	9.99	9.99	9.99
1	0.64	5.56	10	11.11	11.11	11.11

3. RESULTS AND DISCUSSION

Wind turbine designs offer a diverse array of technological options. Among these, some manufacturers prefer gearless or direct-drive wind turbines that eliminate the gearbox. This approach reduces the number of moving parts, addresses issues related to gear teeth and oil cooling systems, and minimizes potential fire hazards and environmental spill risks. This project represents a significant advancement in wind energy utilization by integrating dynamo motor-based wind turbines with DC-to-AC conversion, battery storage, and Arduino-based monitoring. By optimizing turbine placement for maximum wind capture and employing effective conversion and storage techniques, we offer a comprehensive solution for sustainable power generation. The integration of these technologies, coupled with real-time monitoring and optimization, enhances both the efficiency and longevity of the system. This project not only highlights the viability of wind energy as a renewable resource but also emphasizes the importance of innovation and collaboration in advancing clean energy solutions. Special thanks are due to my guide and faculty for their invaluable support throughout this project. Ongoing research and development in this field will continue to drive progress towards a greener and more sustainable future. Figures 3 and 4 illustrate the reactive and active power of the module, respectively, while Figures 5 and 6 display the module's output voltage and current.

4. CONCLUSION

There are many different technology solutions available for wind turbine designs. Some manufacturers recommend gearless or direct-drive systems. In addition to having fewer moving parts and resolving frequent concerns like gear wear, oil cooling issues, potential fire dangers, and environmental spills, these direct-drive wind turbines also do away with the gearbox. Research points to the great efficiency of gearless wind turbine technology. MATLAB/Simulink has been used to validate a comprehensive simulation model of a gearless, variable-speed wind turbine system using a permanent magnet synchronous generator (PMSG). This model demonstrates how independent control of both active and reactive power is possible over a wide range of wind speeds with a gearless wind turbine system. As a result, the gearless wind turbine method seems to be feasible, offering consistent power production in a range of wind speeds.

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AUTHOR CONTRIBUTIONS STATEMENT

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Movva Naga Venkata Kiranbabu		✓				✓		✓	✓	✓	✓	✓		
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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. Authors state no conflict of interest.

DATA AVAILABILITY

The authors confirm that the data supporting the findings of this study are available within the article.

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