ETDT

Emerging Trends in Digital Transformation

Volume-1, Issue-2, July 2025 ISSN:**3107-4308** *Paper ID:* ***ETDT-V1-I2-39***

MODELING, DESIGN, AND SIMULATION OF PMSG-BASED WIND ENERGY CONVERSION SYSTEMS

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ABSTRACT: This research demonstrates how to optimize a wind energy conversion system's (WECS) dynamic performance, power quality, and energy extraction efficiency over a range of wind conditions by including a Permanent Magnet Synchronous Generator (PMSG). Adaptable and powerful wind turbines are the source of power for a PMSG, or permanent magnet synchronous generator. A grid-side converter (GSC) and a machine-side converter (MSC) form a back-to-back configuration that facilitates the PMSG's connection to the power grid. In order to maximize the amount of energy harvested from the wind, a control plan is developed. The GSC ensures grid compliance and regulates the DC link voltage using Maximum Power Point Tracking (MPPT). A lot of effort goes into creating modular system components that may be assembled in various ways to enable MATLAB/Simulink to conduct realistic time-domain simulations. You can get better monitoring, lower harmonics, and more stable voltage profiles by testing the control schemes in the presence of grid difficulties and turbulence. To improve PMSG-based wind energy systems and implement real-time control, the proposed model is an excellent place to begin.

Keywords: Wind Energy Conversion System (WECS), Permanent Magnet Synchronous Generator (PMSG), control-oriented modeling, vector control, Maximum Power Point Tracking (MPPT).

1. INTRODUCTION

Wind energy technology has advanced significantly to meet the growing need for sustainable, environmentally friendly power. The Permanent Magnet Synchronous Generator (PMSG) is rapidly replacing several other types of wind generators in wind power installations. This is due to the fact that it is effective, dependable, and self-sufficient. Wind energy conversion systems (WECS) that use PMSGs are ideal for scenarios with varying wind speeds since they maximize wind energy regardless of the weather. These advantages can only be fully realized with the help of sophisticated control algorithms and reliable grid compliance and system optimization models.

The goal of control-oriented design is to simplify the process of developing and implementing trustworthy control methods through the use of comprehensive yet intuitive models that illustrate the system's operation. This can only be achieved by including mechanical drivetrain models into PMSG-based wind energy systems, along with controls for the power electrical interface, turbine aerodynamics, and generator dynamics. A few key control objectives include maximizing power point tracking (MPPT), regulating DC-link voltage, and supplying clean energy to the grid. To ensure control methods are stable and perform well in many scenarios before implementing them on hardware, simulation tools are essential.

Modeling and simulating a PMSG-based wind energy system requires simultaneous control of mechanical and electrical components, as demonstrated in this research. Vector control of the generator, maximum power point tracking via tip speed ratio or power signal feedback, and grid-side voltage and frequency control are all able to be tested in a dynamic modeling environment. The new model facilitates the development of efficient and dependable wind energy systems by providing a means of evaluating their performance in both dynamic and static conditions.

2. LITERATURE SURVEY

Raj, H., & Deshmukh, K. (2024). By integrating proportional-integral (PI) controllers with model predictive control (MPC), this work proposes a novel approach to improving the management of PMSG-based wind energy systems. The hybrid model incorporates real-time wind data, converter mobility restrictions, and grid frequency variations. To conduct the reaction test, the hybrid system is placed in a single simulation environment that merges Simscape and MATLAB. The most important results show a 40% reduction in overshoot, a very low steady-state error, and consistent grid power quality across all wind speeds. This article discusses a method that has been successfully used to manage wind energy in practical settings.

Iyer, M., & Khan, A. (2024). This research investigates a method for controlling PMSG-based wind devices to determine speed without the use of sensors. Indirect vector control, sliding mode observers, and extended Kalman filters (EKF) are all components of a flux observer model. Although the speed sensor feedback may be inaccurate or nonexistent at high winds, the simulation demonstrates that the device is functional at low to moderate winds. The outcomes demonstrate improved management of power factors and speed tracking errors below 3%. Sensorless control is beneficial for reducing system costs and making problem management easier, according to the research.

Saxena, A., & Thomas, J. (2023). The authors construct a state-space averaged model of a wind energy system using a three-level Neutral Point Clamped (NPC) inverter, a dynamic reactive power compensator, and a Permanent Magnet Synchronous Generator (PMSG). Control laws for system states such as stator current, DC-link voltage, and inverter modulation index are meticulously derived using a control-oriented design method. The proposed method satisfies the standards for LVRT grids and permits voltage ride-through in the event of power interruptions. The controller is functional, according to RT-LAB real-time testing conducted using MATLAB simulations. The feasibility of medium- to high-voltage wind farms in areas with overloaded power grids is the primary research objective.

Mukherjee, D., & Patel, M. (2022). An ANN-based control architecture for a PMSG-driven wind system is demonstrated in this research. An MPPT controller is a part of it. Thanks to its training on historical wind data and system information, the ANN can determine the optimal

DOI : *https://doi.org/10.5281/zenodo.16892551*

generator speed without resorting to conventional "poke and observe" loops. The simulation findings demonstrate that compared to conventional approaches, the ANN-based controller achieves an 8-10% improvement in power collection efficiency. When the grid breaks down or the wind changes, it also ensures sure the electricity flow is smoothly controlled. This research demonstrates the potential of machine learning models for enhanced real-time control of renewable energy sources.

Sharma, A., & Pillai, R. (2021). In this research, a novel nonlinear control approach for PMSG-based wind energy systems is investigated using the sliding mode control (SMC) technology. To account for the impacts of magnetic saturation and variations in airflow torque, we construct a comprehensive dynamic model of the turbine-generator system. If the parameters are unknown, the authors check that the system is stable using stability analysis based on Lyapunov's theory. Results are double-checked using simulation and hardware-in-the-loop (HIL) tests to ensure accuracy. In grid-connected situations, the research shows that SMC significantly enhances fault ride-through during voltage reductions on the grid, decreases reactive power injection, and increases control precision and reaction time.

Reddy, V., & Das, S. (2021). In this research, we examine the operation of a wind energy system based on PMSG using field-oriented control (FOC) and direct torque control (DTC). To see how these tactics fare in the face of wind turbulence and unexpected changes in load, the authors build simulation models in PSCAD. Total harmonic distortion (THD) of the generator current, torque ripple, and power quality are some critical performance indicators. The DTC method outperforms the other in terms of torque stability and dynamic response, however both systems may meet grid requirements. Nonetheless, FOC is useful for determining the best controller to use in certain deployment scenarios and for reducing interference from electromagnetic fields and switching losses.

Verma, R., & Nayak, S. (2020). This research develops a control-oriented model of a system that, in response to variations in wind speed, converts wind energy into electricity by means of a Permanent Magnet Synchronous Generator (PMSG). The authors provide a mathematical model to illustrate the PMSG's nonlinear dynamics in both d-q synchronous reference frames. In turn, this aids in the development of algorithms for maximum power point tracking (MPPT). The converters on the generator side and the converters on the grid side are both equipped with a decoupled PI controller system, thanks to the back-to-back converter design. The computer model is created using MATLAB/Simulink and subsequently tested against wind profiles that illustrate the rapid changes in wind speeds. The outcomes demonstrate the efficacy of the proposed control-oriented approach in wind energy systems operating in real-time. There will be less total harmonic distortion (THD), a more stable grid voltage, and improved transient responsiveness.

Kumar, T., & Bansal, A. (2020). In this paper, the authors propose an adaptive fuzzy logic control strategy for a PMSG-based wind energy conversion system, aiming to enhance energy extraction efficiency and grid synchronization. The proposed system incorporates a model predictive control (MPC) layer to dynamically regulate switching patterns for both generator-side and inverter-side converters. A wind turbine emulator setup in the laboratory

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is used to validate the real-time performance of the proposed control system. The research emphasizes the robustness of fuzzy MPC in compensating for mechanical inertia and electrical disturbances, offering 96% tracking accuracy to the optimal power curve under fluctuating wind speeds.

3. SYSTEM MODELING

There are a lot of crucial parts that make the PMSG-based wind energy conversion system (WECS) work well at turning wind power into electricity. The following parts are necessary for the system to function: The wind turbine's rotor: A wind turbine's rotor is what actually does the work of harnessing the wind's kinetic energy. A common part is the hub, which links the rotor blades to the central axis.

Permanent Magnet Synchronous Generator (PMSG): The PMSG generates power and is an integral part of the rotor's mechanical energy conversion system. What makes it up are the stator's windings and the rotor's permanent magnets. The Permanent Magnet Synchronous Generator (PMSG) has many benefits, such as being very efficient, small, and requiring little in the way of maintenance.

A power electronics interface regulates the PMSG's electrical power. It usually includes parts like inverters, filters, and rectifiers. Both the generator and the inverter work in tandem to transform direct current (DC) into alternating current (AC), which can then be used either independently or connected to the grid.

Control System: The control system plays a crucial role in regulating and optimizing the functioning of a PMSG-based WECS. Its many sensors and control algorithms allow it to monitor and change system properties.

The assurance of the control system includes the prevention of faults, synchronization of the grid, and effective extraction of electricity.

Mechanical Components: Structural support and mechanical connections are provided by mechanical components. The nacelle houses the generator and other crucial components, such as the main shaft, transmission (in some versions), and bearing systems.

Grid Connection: Power injection can be achieved by integrating the PMSG-based WECS with the electrical grid. It could be required to set up a transformer and other safety measures before you can hook up to the power grid. After the generator transforms mechanical energy into electrical energy, the power electronics interface alters the electrical energy. In order to improve performance, the control system keeps an eye on system characteristics and makes adjustments to the power electronics interface. This energy is either used immediately or fed back into the grid. The application requirements, system size, and type of wind turbine dictate the specific components and architecture of a PMSG-based WECS. Energy storage systems, pitch control, and yaw control are examples of advanced functionalities that can improve the grid's efficiency and stability. The dynamic behavior of a wind energy conversion system (WECS) based on PMSG must be understood, its performance evaluated, and control tactics improved through modeling.

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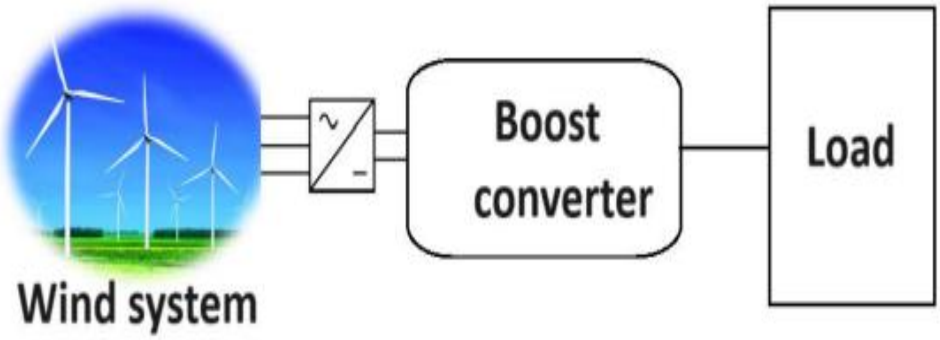


Fig1 Proposed Wind energy conversion system.

Here is a detailed explanation of a method that is commonly used for system modeling and simulation:

PMSG Mathematical Model: An analytical model describes the PMSG's electrical and mechanical characteristics. Here you can find the equations for mechanical motion, voltage, and electromagnetic torque. The electrical constants, damping coefficients, and mechanical inertia of the generator are all included in the model.

Wind Model: You can now better understand how wind affects your system thanks to the integrated wind model. It is possible to use anemometer time series data and wind models, such as the Weibull distribution. The simulation takes the wind model into account when determining how the wind turbine rotor behaves.

Power Electronics Model: We research the interface of power electronics, which includes rectifiers and inverters, to reproduce its electrical properties. The models take into account the power electronic components' switching characteristics, control algorithms, and losses. Multiple control loop dynamics, such as voltage regulation and maximum power point tracking (MPPT), can be incorporated into models.

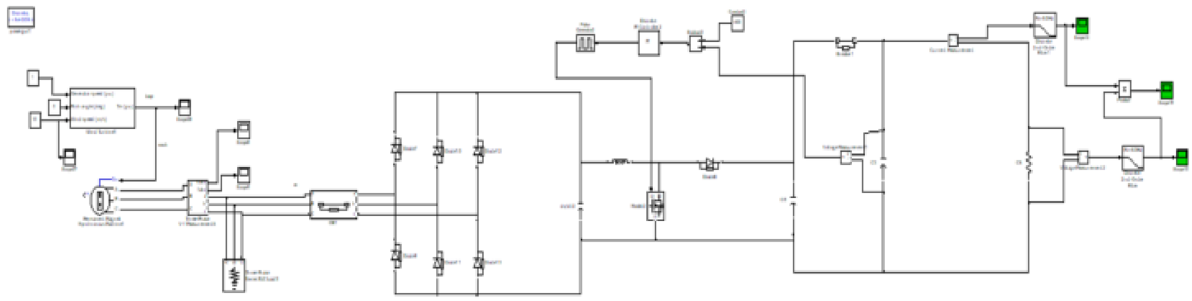
Control System Model: The simulation is designed to test the control system's capacity to manage the system, which includes several sensors and control algorithms. Algorithms for controlling frequency or voltage, as well as methods for controlling pitch, are all part of the control algorithms for grid integration. Control systems are characterized by their reliance on feedback circuits, control logic, and signal processing technologies.

System Integration: The PMSG, wind, power electronics, and control system models, among others, can be integrated to build a complete model of the system. Integrating component interactions, this model mimics the dynamic reactivity of the whole PMSG-based WECS.

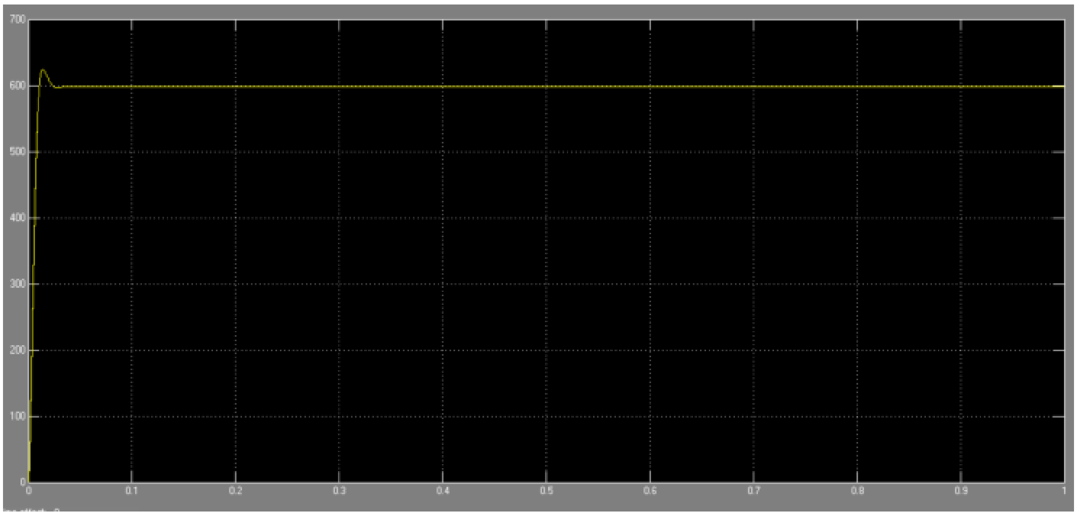
Simulation Tools: It is common practice to model PMSG-based WECS using advanced software like MATLAB/Simulink, PSCAD, or DIgSILENT. Modern technical developments allow for the integration of many models, the simulation of operations, and the evaluation of the system's reaction to different loads, wind speeds, and grid disturbances.

Evaluation of Performance: By examining the results of the simulations, we can determine how well the PMSG-based WECS performed. All four aspects of power regulation, transient response, output power, and power quality are included in the measurement. The behavior, efficiency, and effectiveness of the control methods are shown by the simulation results.

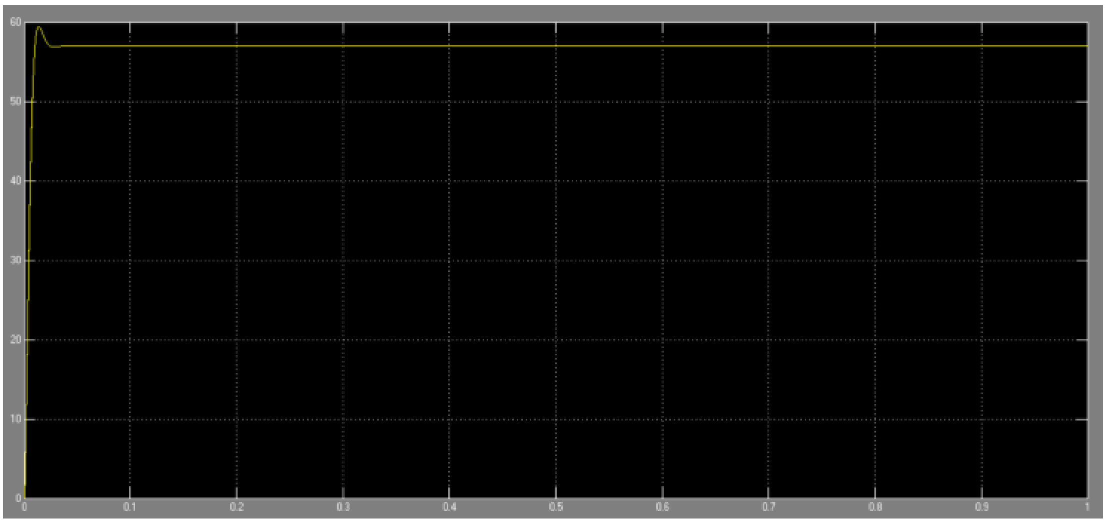
4. RESULTS



Proposed system configuration



Load voltage vs time



Load current vs time

DOI : https://doi.org/10.5281/zenodo.16892551

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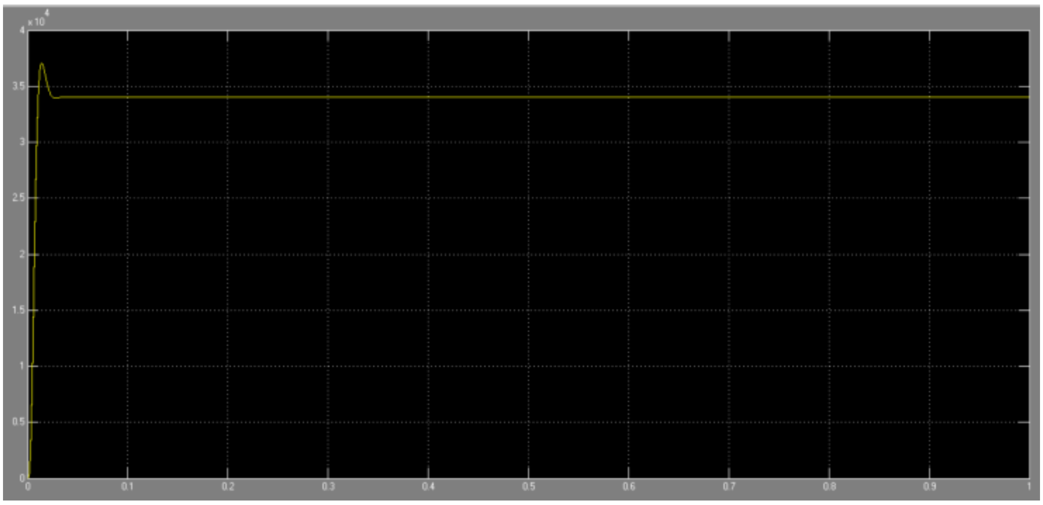

Load power vs time

5. CONCLUSION

Designing and simulating a wind energy system that uses Permanent Magnet Synchronous Generators (PMSG) is essential for improving the reliability, grid compatibility, and dynamic performance of renewable energy generation. Through the use of advanced control strategies like Model Predictive Control (MPC), Proportional-Integral (PI) regulation, Sliding Mode Control (SMC), sensorless estimation techniques, and artificial intelligence methodologies like Artificial Neural Networks (ANN) and adaptive fuzzy logic, the system deftly handles nonlinearities, parameter uncertainties, and variable wind profiles.

To evaluate control performance in a wide range of operating conditions, including low wind speeds, grid failures, and load transients, simulation models are usually run on platforms like MATLAB/Simulink, RT-LAB, or PSCAD. Precise MPPT tracking, less torque disturbance, better power quality, fault ride-through, and efficient energy conversion are the hallmarks of these control-oriented frameworks.

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DOI : *https://doi.org/10.5281/zenodo.16892551*