Optimized Power Extraction in PMSG Wind Turbines using MPPT and Sliding Mode Control

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Abstract: *Wind energy stands out as one of the most promising and advanced renewable energy sources in recent years. Connecting a Wind Energy Conversion System (WECS) to a load or utility grid requires a critical power electronic interface, which consists of generator and grid side converters. The Controlling technique of these converters presents notable challenges, with the primary goal of the generator side converter being the implementation of Maximum Power Point Tracking (MPPT). This project enhances the conventional Hill Climbing Search MPPT algorithm by incorporating logic theory, significantly improving its accuracy and speed. The refined algorithm ensures continuous extraction of maximum wind energy by generating an optimal rotor speed reference. For the generator-side converter, the Vienna rectifier is chosen due to its considerable advantages in WECS applications. To achieve effective speed control, a non linear Sliding Mode Control (SMC) scheme is employed, offering superior performance compared to traditional linear controllers. Simulation results validate the effectiveness of both the modified MPPT algorithm and the control scheme. The experimental analysis highlights the speed control performance of SMC and MPPT controllers. By introducing innovative control strategies and algorithmic improvements, this project contributes significantly to optimizing wind energy conversion systems, promoting efficient and reliable wind power utilization for sustainable energy generation.*

Keywords: **MPPT, Wind Energy Conversion System, Renewable Energy, MPPT, SMC**

1. Introduction

The Permanent Magnet Synchronous Generator is a type of electrical generator, it produce magnetic field by permanent magnets interacts with wind-driven rotor motion to generate electrical energy. It operates based on the principles of electromagnetic induction and it is commonly used in wind energy conversion systems [1]. PMSG have high energy conversion efficiency as they do not require external excitation or field windings and it eliminates additional power losses. The absence of excitation windings and associated components makes PMSGs more compact and lightweight, which is advantageous for wind turbine applications [2-3], especially in offshore wind farms where space and weight are critical considerations.PM offer a stable magnetic field over time, resulting in improved reliability and reduced maintenance compared to other types of generators like induction or wound rotor synchronous generators [4]. PMSGs work seamlessly with modern power electronic interfaces allowing for precise control of power quality, frequency, and voltage when connected to the grid or standalone loads [5-6]. This in turn has motivated a large quantity of research on renewable energy in the last decade [7].PMSGs are favored in WECS for their high efficiency, wide operational speed range, compact design, and compatibility with variable speed turbines[8-11]. These advantages make them an ideal choice for extracting maximum energy from wind while ensuring reliability and reducing operational costs. In [12-14], MPPT control algorithm was proposed. This work is organized as follows: introduction and followed by Section 2 describes the PMSG. Section 3 discusses the control Strategies of proposed system.

Section 4 presents the simulation results and discussion. Finally, Section 5 provides the conclusion.

2. Permanent Magnet Synchronous Generator

A PMSG is a type of synchronous machine that uses permanent magnets instead of field windings for excitation. The rotor contains permanent magnets, eliminating the need for an external excitation system. The stator has a three-phase winding where voltage is induced as the rotor moves. The frequency of the output voltage depends on the rotor speed. It operates in synchronism with the magnetic field without requiring slip rings or brushes. Torque is produced by the interaction between the magnetic field of the rotor, created by permanent magnets, and the stator's current. It is directly proportional to the current and depends on the phase difference between the stator and rotor fields.

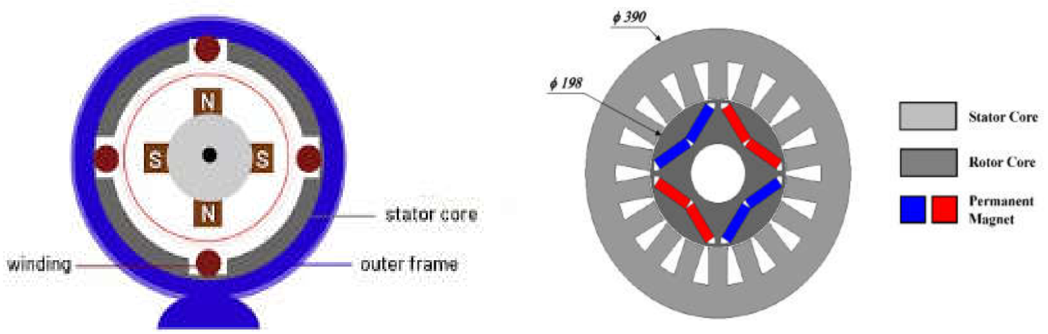


Figure.1 Structure of the Permanent Magnet Synchronous Generator

The use of permanent magnets makes the machine compact, smaller, and more efficient. However, PMSG requires a power converter to regulate voltage and frequency. Unlike wound-rotor machines, the magnetic field strength cannot be adjusted, limiting flux control capabilities. Fig.1 illustrates the structure of the Permanent Magnet Synchronous Generator, and Table 1 presents the specifications of the PMSG used in this work. It commonly used in wind power generation with high efficiency, reliability, and reduced maintenance cost.

Table 1. Specifications of PMSG drive

Parameters	Values
Number of Phases	1 phase
Number of Stator Poles	2 pole
Number of Rotor Poles	2 pole
Rated speed	300 RPM
Rated torque	2 Nm
Rated Current	0.5A
Rated Voltage	12V

2.1. Proposed System:

The proposed system is going to achieve stable power output corresponding to the present wind speed, with a primary focus on maintaining output power stability under various unstable wind conditions. By detecting the actual output power of the WTG, the error is determined, and MPPT is achieved by regulating the rotating speed of the WT based on power signal feedback. The generator output is first fed into a DC-DC converter to boost the voltage level. The boosted DC output is then supplied to an inverter, which converts it into AC power for the corresponding load. This method ensures stable operation and is well-suited for large wind turbines. However, it requires obtaining the optimal power curve in advance. The environmental factors can alter the actual trajectory of the curve and it reducing its accuracy and ultimately limiting efficient wind energy capture. The Fig 2 describes the block diagram of proposed system.

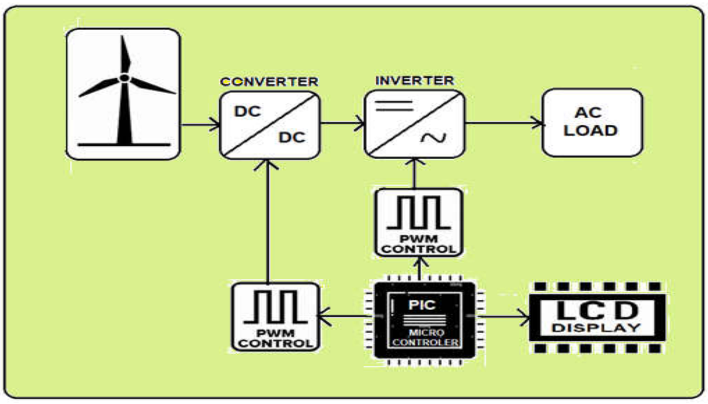


Figure 2. Block diagram of proposed system

The bandwidth of a wind power system refers to the range of wind speed frequencies to which the wind turbine generator (WTG) can effectively respond. To enhance this tracking bandwidth, an error feed forward signal based on the difference between the aerodynamic power and the WTG's output power is incorporated into the control system.. The result is that the tracking speed of the WT becomes obviously quicker. Since the constant bandwidth control method will increase the machine load, which affects the operating life of the machine, to solve this problem, the response surface analysis method is firstly applied to fit the statistical relationship between the optimal bandwidth and the turbulence wind speed characteristic index and then the optimal bandwidth is set on line according to the wind speed characteristics. This method realizes the complete optimization of the wind energy capture and the load. However, the load loss coefficient in practical application needs further confirmation power curve.

2.2. DC to DC Buck-Boost Converter:

A DC-DC Boost Converter is a power electronic circuit that converts a lower DC voltage into a higher DC voltage level.

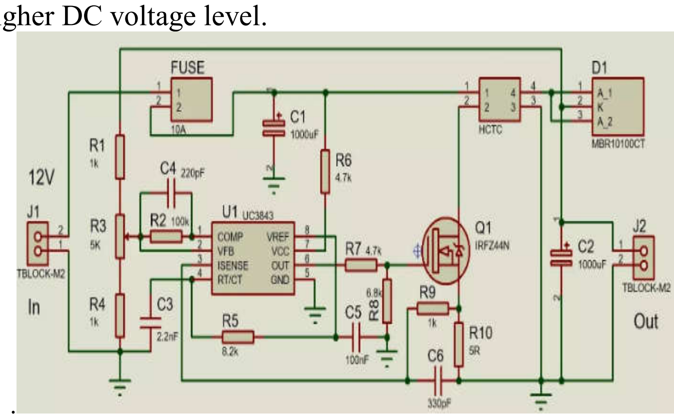


Figure 3. DC-DC buck boost converter circuit

It operates using key components such as an inductor, a switching device (MOSFET/IGBT), a diode, and a capacitor. When the switch is turned ON, the inductor stores energy from the input source. Once the switch is turned OFF, the inductor releases the stored energy, which combines with the input to raise the output voltage. The diode prevents reverse current flow, while the capacitors smooth the output voltage. The DC to DC buck-boost converter circuit is illustrated in Fig.3. The output voltage is determined by the duty cycle of the switching signal. Due to their high efficiency and compact design, boost converters are commonly utilized in renewable energy systems, electric vehicles, and portable electronics.

2.3. Simulink Diagram of PMSG:

The final output of the system is either connected to a local electrical load or interfaced with the utility grid. The simulation of such a system can be performed using tools like MATLAB/Simulink, which provide blocks for modeling electrical machines, power converters, and control strategies. Fig.4. shows the proposed simulation diagram of PMSG. Overall, the simulation diagram of a PMSG system provides a comprehensive platform to analyze and optimize the performance of renewable energy systems under various operating conditions.

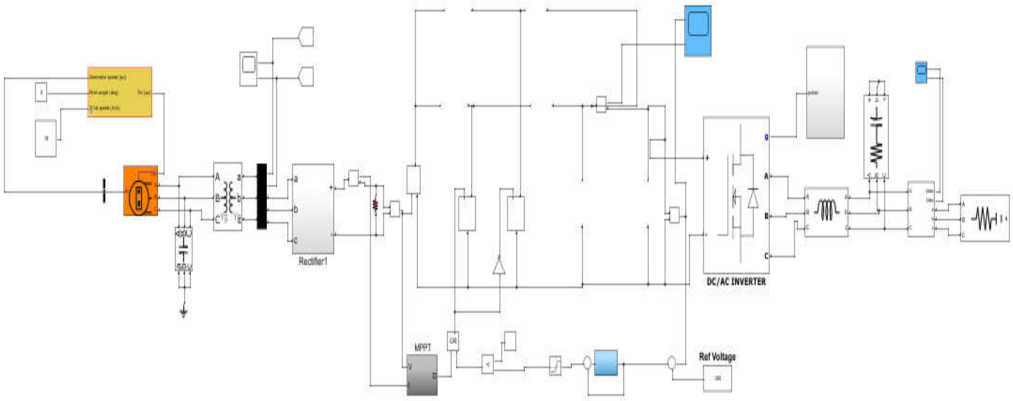


Figure 4. Simulation diagram of PMSG

The three-phase diode bridge rectifier is a circuit used to convert three-phase AC power into DC power. It consists of six diodes for bridge configuration. The three phase AC input supply lines named as a, b, and c, are connected to the rectifier, and the DC supply output is taken from the positive and negative terminals. At any given moment, two diodes conduct one from the positive group and one from the negative group allowing current to flow through the load in one direction.

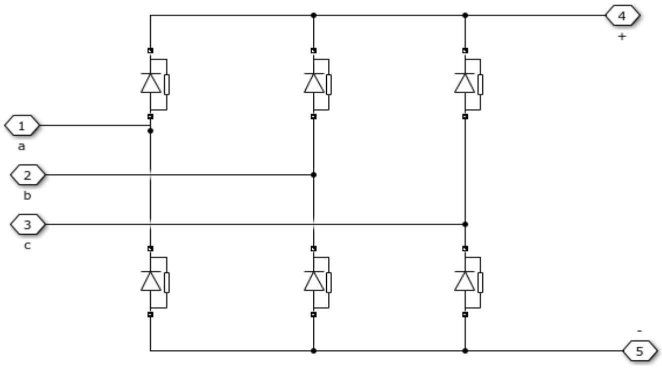


Figure 5. Modeling of rectifier circuit

Fig.5 shows the modeling of rectifier circuit, these results in a pulsating DC output with fewer ripples compared to a single-phase rectifier. The converter circuit is simple and low cost; it’s commonly used in wind energy systems with PMSG, battery charging systems, and industrial motor drives. Since it uses diodes only, it is an uncontrolled rectifier with no voltage regulation.

3. Control Strategies

3.1. Sliding Mode Technique:

Sliding Mode Technique (SMT) is a nonlinear control method designed to provide robust performance in dynamic systems despite uncertainties and disturbances. It operates by forcing the system to reach a predefined sliding surface in finite time and then maintaining it there, ensuring stability and desired behavior.Fig.6 shows the control circuit by using MATLAB simulation.

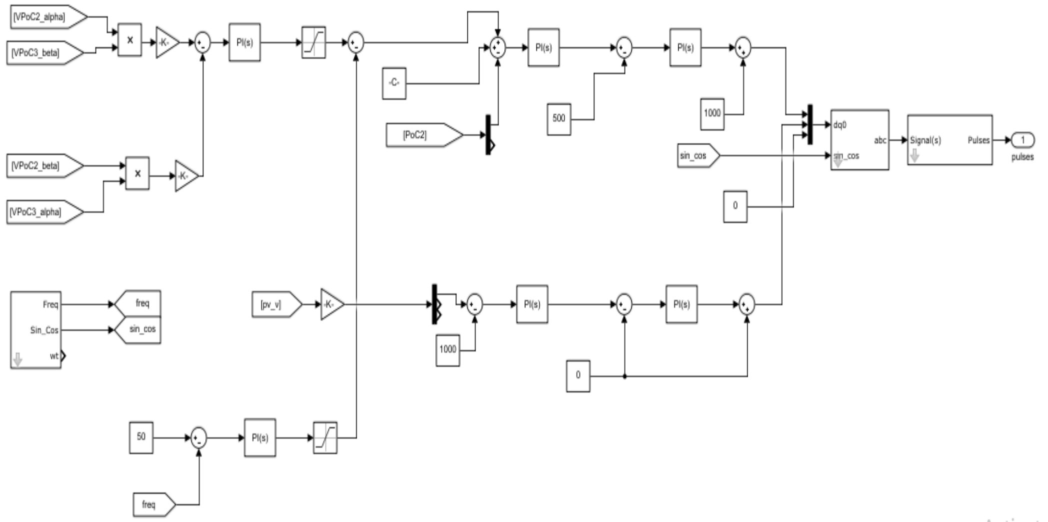


Figure 6.Simulation Diagram of the Control Circuit for a Three-Phase Rectifier System

A key characteristic of SMT is its use of a discontinuous control signal, which enables rapid switching between control actions. However, this switching can cause a phenomenon known as chattering, which may be mitigated using smoothing techniques. Due to its robustness and fast response, SMT is widely applied in renewable energy systems, electric vehicles, robotics, and aerospace applications, where precise and reliable control is essential.

3.2. Maximum Power Point Tracking:

MPPT is an advanced control technique used in renewable energy systems, particularly in wind energy systems, to maximize power extraction under varying environmental conditions.

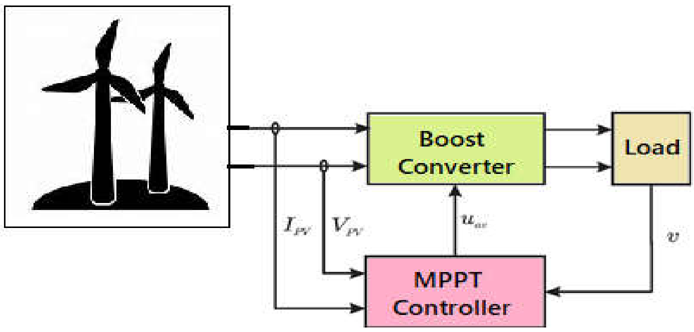


Figure 7. Block Diagram of MPPT Control for PV System Using Boost Converter

This fig.7 shows a PV module connected to a boost converter, which steps up the voltage to supply a load. The MPPT controller regulates the duty cycle of the converter to ensure the PV module operates at its Maximum Power Point (MPP). The power output of these systems depends on factors such as solar irradiation, temperature, and wind speed, which fluctuate throughout the day. MPPT ensures that the system operates at its optimal power point, thereby improving efficiency and performance.

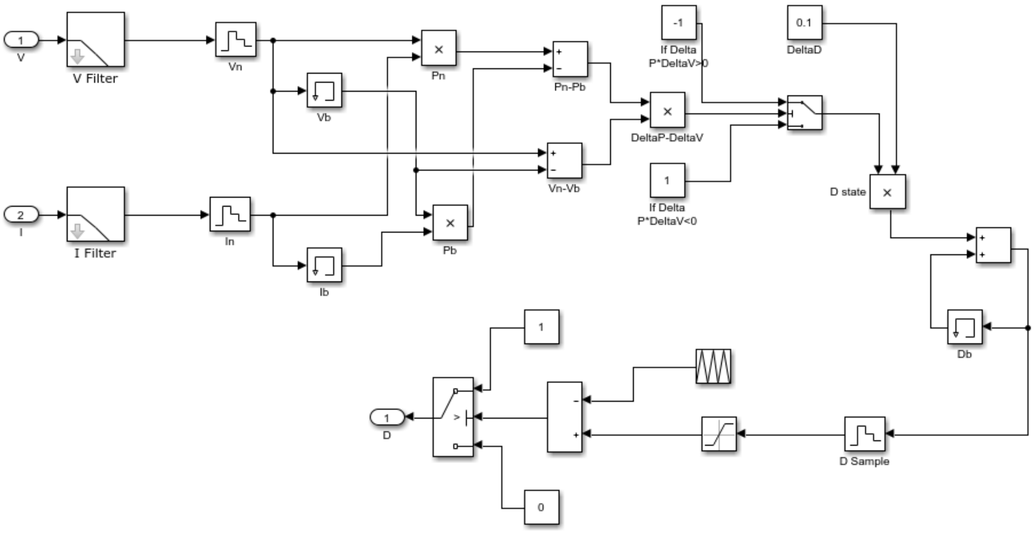


Figure 8.Simulink Model of Perturb and Observe MPPT Algorithm

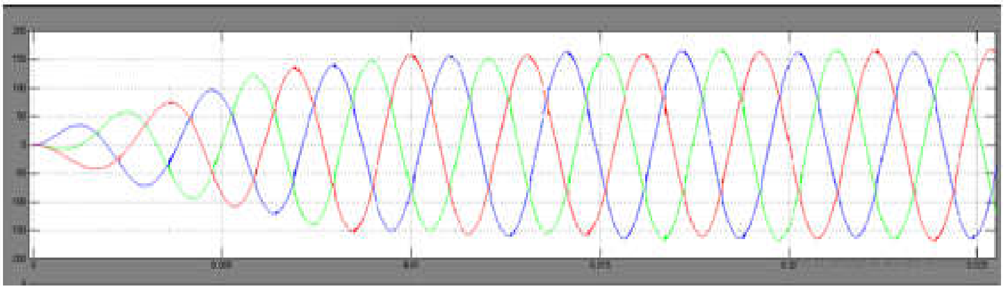
The fig.8 shows Simulink diagram represents the Perturb and Observe algorithm used in MPPT for photovoltaic systems. The MPPT controllers endlessly monitor the voltage and current to determine the maximum power point (MPP) and adjust the operating parameters for that reason. MPPT is widely used in solar inverters, wind turbine controllers, and battery charging systems to optimize energy harvesting. Its implementation significantly increases the efficiency of renewable energy systems, making them more reliable and cost-effective in both residential and industrial application.

4. Simulation Results and Discussion

The proposed MPPT-SMC approach is validated through MATLAB/Simulink environment to assess its performance under dynamic conditions. The results indicate enhanced power extraction, rapid convergence to the MPP, and minimized chattering effects compared to conventional PI controllers and standalone MPPT methods. The various simulation results are obtained with different wind speed conditions.

4.1. Wind Speed Analysis at 3000rpm and Corresponding Phase to Ground PMSG Output Voltage:

The phase-to-ground output voltage of the PMSG is a crucial factor in determining the quality and stability of the generated electrical power. At 3000 RPM, the voltage waveform should exhibit minimal distortions and maintain consistent amplitude, ensuring efficient power conversion. Fig.9-11shows the various parameters of PMSG with sliding mode control.



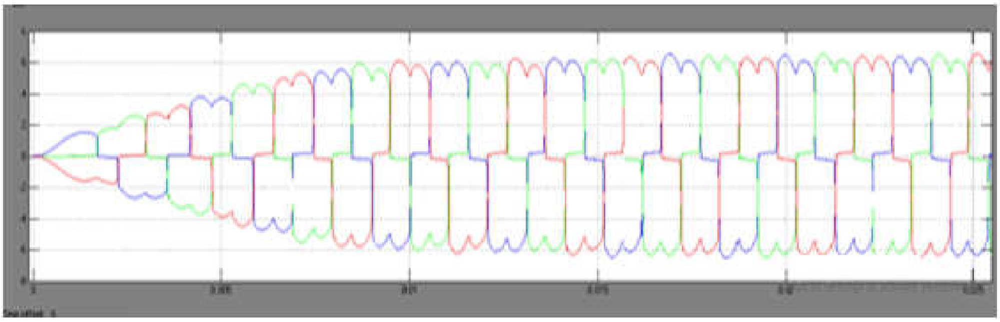


Figure.9 Phase to Ground PMSG output voltage

4.2. Wind Speed Analysis at 2000 RPM and Corresponding Phase to Phase PMSG Output Voltage:

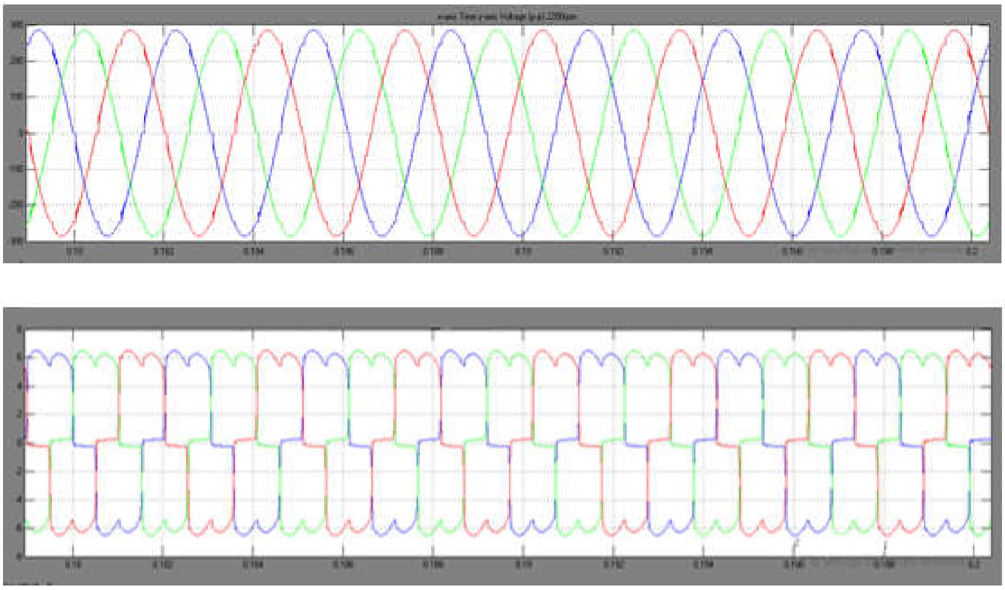


Figure.10 Phase to Phase PMSG output voltage

4.3.MPPT with Rectifier Output Voltage:

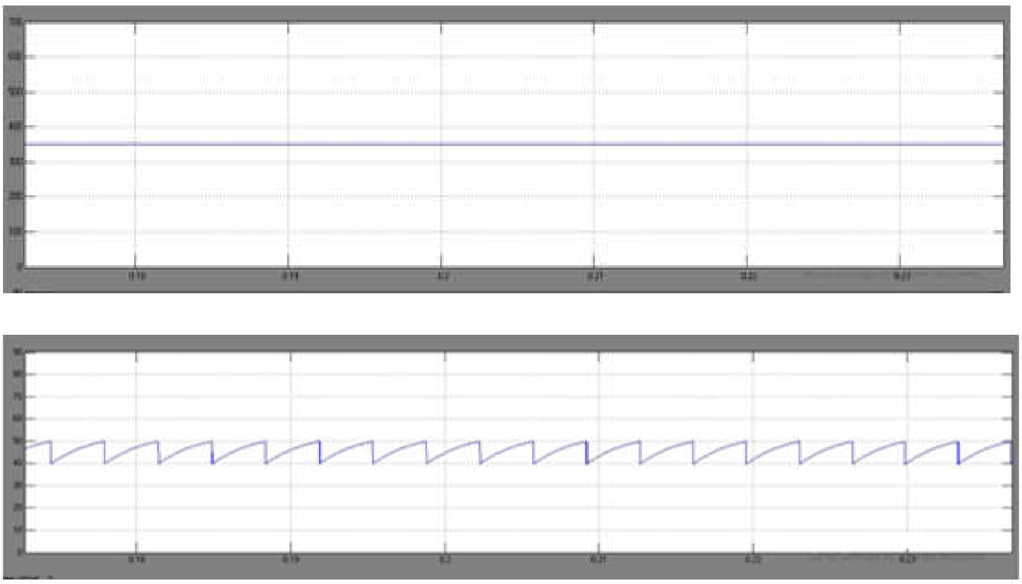


Figure.10 Rectifier output voltage

4.4.Output Voltage and Current at 2000rpm:

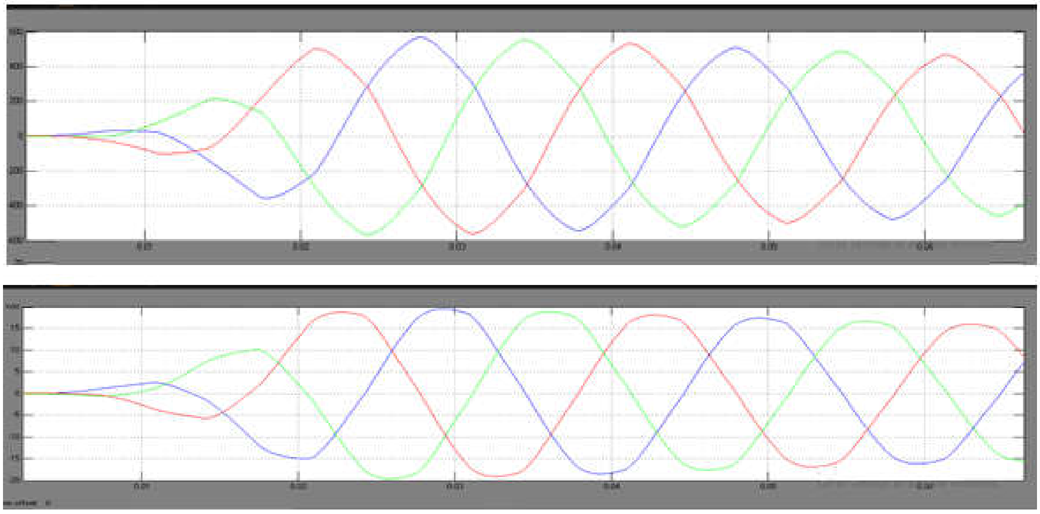


Figure.11 Output voltage and current

5. Conclusion

A robust sliding mode control method, incorporating a unique smooth continuous function, was developed to mitigate the chattering issue inherent in conventional sliding mode control (CSMC). This approach was applied to a variable wind speed system based on a permanent magnet synchronous generator (PMSG).Additionally, a novel high-gain single-switch DC-DC boost converter architecture is introduced, ensuring continuous input and output currents. The voltage enhancement process, along with the ON/OFF time intervals of the main power switch and all diodes, is comprehensively analyzed. This design improves the wind power transfer ratio without the need for isolated transformers or coupled inductors. Compared to conventional boost converters, the proposed topology significantly reduces voltage stress on the power switch, enhancing reliability in practical applications. Furthermore, all diodes experience the same voltage stress as the power switch, which remains relatively low. The presence of inductors at both the input and output further enhances its suitability for wind power applications. Moreover, integrating an optimized MPPT algorithm with Sliding Mode Control introduces significant advancements in wind energy systems. These enhancements address the limitations of existing methods, enabling more efficient wind energy utilization and supporting the transition to renewable power solutions. The effectiveness of the proposed PMSG-based system was validated through simulations performed in the MATLAB/Simulink environment under varying wind conditions. A comparative analysis of the simulation results confirmed the suitability of the recommended control strategy for a wind power conversion system utilizing a variable-speed PMSG. Future research will focus on refining these strategies and exploring their broader applications in energy systems.

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