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MPPT-Based Integrated Generator-Rectifier System for Wind Energy System

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ABSTRACT:

Offshore wind is rapidly becoming a key renewable energy source. It involves wind that flows from land towards the sea, and effectively harnessing this energy requires the use of large, multi-megawatt wind turbines along with highly efficient, high power density, and reliable power conversion systems to maintain a competitive Levelized Cost of Electricity (LCOE). An integrated system that incorporates both active and passive rectifiers with a multiport permanent magnet synchronous generator offers a promising solution for electro-mechanical power conversion. For offshore wind energy applications, these integrated systems must incorporate maximum power point tracking (MPPT), which is challenging due to the presence of multiple uncontrolled passive rectifiers. Additionally, AC-to-DC power conversion is critical in Wind Energy Conversion Systems to reduce system losses. This conversion process is essential for emerging high-power applications like electrified transportation and wind power generation. The project demonstrates the feasibility of MPPT by showing that controlling the active-rectifier d-axis current can regulate the total system output power. This MPPT capability presents new opportunities for integrated systems in offshore wind applications.

Keywords: AC-DC power conversion, dc power systems, maximum power point trackers (MPPT), wind energy generation.

I.INTRODUCTION:

With growing concerns about the environment, an increasing share of electricity is now produced from renewable sources. Renewable energy plays a crucial role in ensuring stable energy supplies and facilitating the transition away from fossil fuels. Currently, about 19% of the world's electricity comes from renewable sources. Among these, wind power is one of the most cost-effective options. In regions with strong wind resources, particularly in developed nations, onshore wind energy can compete with traditional fossil fuel-based power generation

[1].

Over the past decade, wind energy has seen remarkable growth and is widely recognized for its environmental benefits and economic viability. Wind turbines and wind farms are expanding rapidly, integrating substantial amounts of wind-generated electricity into power systems. However, the unpredictable nature of wind and the specific characteristics of wind generators present significant challenges when wind energy makes up a large portion of the power grid. In large wind farms connected to high-voltage transmission networks (110 kV – 220 kV), the primary technical concern is maintaining system stability, as disturbances can lead to transient instability. Another critical issue is voltage instability, which can result in voltage collapse. Both onshore and offshore wind power contribute significantly to achieving a carbon-neutral electricity system. While the fundamental technology behind wind turbines remains the same, their location, scale, and methods of transmitting electricity set them apart. A wind turbine converts wind's kinetic energy into electrical power, and large-scale wind farms, consisting of thousands of turbines, collectively produce over 650 gigawatts of electricity worldwide, with an additional 60 GW being added annually[2-3].

The use of onshore wind to harness energy dates back to the 1880s, when it was utilized for tasks such as grinding grain and pumping water. However, the commercial development of onshore wind energy in the UK began with the launch of the Delabole wind farm in 1991. Today, Great Britain is home to more than 1,500 active onshore wind farms, collectively generating over 12 gigawatt hours (GWh) of electricity for the national grid. In 2020, onshore wind accounted for 11% of the UK's electricity supply, producing 34.7 terawatt hours (TWh)—a volume sufficient to power approximately 18.5 million households for a full year.

Offshore wind farms, on the other hand, harness wind energy from open bodies of water, typically the sea. They are generally more efficient than onshore installations due to stronger and more consistent wind speeds, as well as the absence of obstacles such as buildings and terrain. Offshore wind power refers to the process of generating electricity through wind farms located in marine environments. Because wind speeds tend to be higher over water than on land, offshore wind farms produce greater amounts of electricity relative to their installed capacity. Additionally, these farms are often considered less disruptive to communities and landscapes, making them a more widely accepted renewable energy solution [4].

II. MPPT CONTROL FOR INTEGRATED GENERATOR-RECTIFIER SYSTEM

The demand for renewable energy resources has been rising significantly in recent years. Among the most widely used options are wind and solar energy, both of which offer the benefits of being clean and freely available. However, wind energy typically has lower installation costs compared to solar power. One of the main challenges associated with wind energy is its intermittent nature, requiring backup from other power sources to ensure a stable energy supply. Wind energy systems capture kinetic energy from the wind and convert it into electricity, but the amount of power generated depends on wind speed [5-6]. Due to the nonlinear behavior of wind turbines, maintaining optimal power output under varying wind conditions is a complex task. As a result, extensive research has been conducted on strategies for tracking the maximum power point of wind turbines, a process known as Maximum Power Point Tracking (MPPT) as shown in fig.1.

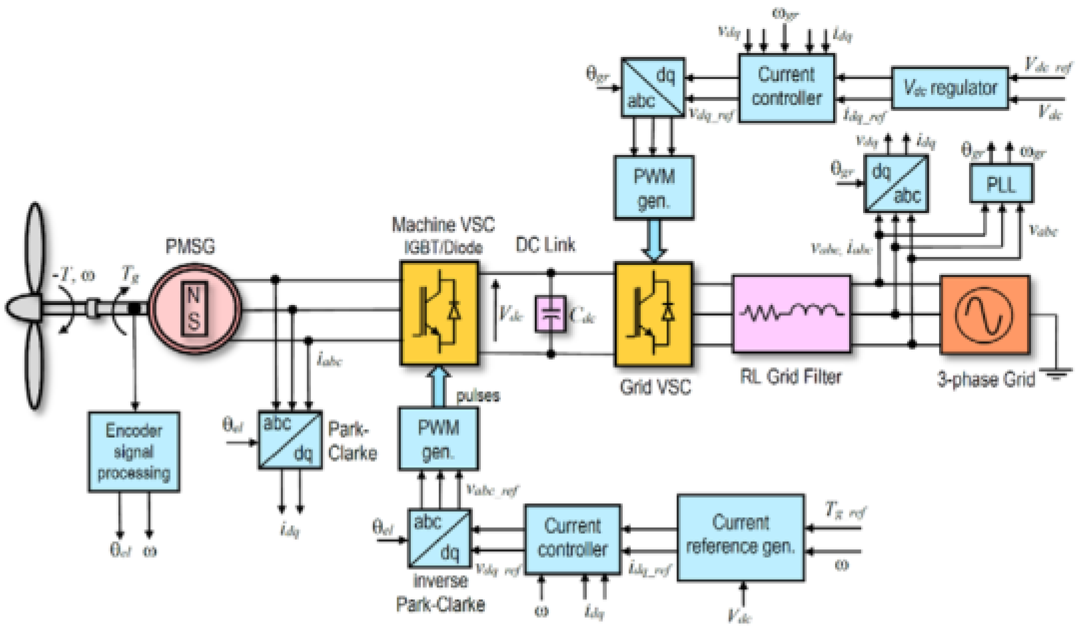

Figure.1. MPPT control for integrated generator-rectifier system

A control strategy has been proposed that utilizes the relationship between the active rectifier d-axis current and the total DC bus power to achieve MPPT. Additionally, this approach eliminates the need for filter capacitors at the passive rectifier outputs. By adjusting the phase alignment of different AC ports supplying the passive rectifiers, DC bus voltage ripple is minimized. Implementing MPPT control while removing bulky filter capacitors enhances the efficiency of the integrated generator-rectifier system, making offshore wind energy more cost-effective [7].

Several studies have explored MPPT control techniques for Wind Energy Conversion Systems (WECS) using different types of generators. The primary methods for optimizing power extraction can be classified into three main categories: Tip Speed Ratio (TSR) control, Power Signal Feedback (PSF) control, and Hill Climb Search (HCS) control. The TSR method adjusts the generator's rotational speed to maintain an optimal tip speed ratio, ensuring maximum power extraction. This approach requires monitoring or estimating wind speed and turbine speed, as well as having prior knowledge of the turbine's ideal TSR value. PSF control, on the other hand, relies on the wind turbine's maximum power curve to guide the control system. This curve must be determined through simulations or offline experiments for individual turbines. Using this method, the system follows the pre-recorded power curve or calculates reference power through the mechanical power equation of a wind turbine, with wind speed or rotor speed as input parameters [8].

III. MODELING OF MAXIMUM POWER POINT TRACKING FOR WIND TURBINE GENERATORS

An integrated generator-rectifier system based on a permanent magnet synchronous generator (PMSG) offers a highly efficient solution for energy conversion. In this system, mechanical energy from the turbine shaft is transformed into alternating current (AC) electricity through a multi-port PMSG. Each port is linked to either a passive or an active rectifier, enabling AC-to-DC conversion. The rectifiers' DC outputs are connected in series to create a high-voltage DC bus, with each rectifier handling only a fraction of the total DC-bus voltage. As a result, approximately 60% of the total power is processed by passive rectifiers, leading to a 47% reduction in conversion losses at optimal operating conditions. This configuration also enhances system reliability and power density by reducing the size of active rectifiers. Despite these benefits, managing power flow in the integrated generator-rectifier system presents a challenge due to the presence of multiple passive rectifiers. A key objective of this approach is to demonstrate that overall DC bus power flow remains controllable, even with a series connection of uncontrolled passive rectifiers. Effective power management is essential for achieving maximum power point tracking (MPPT), a crucial requirement in wind energy applications [9-10].

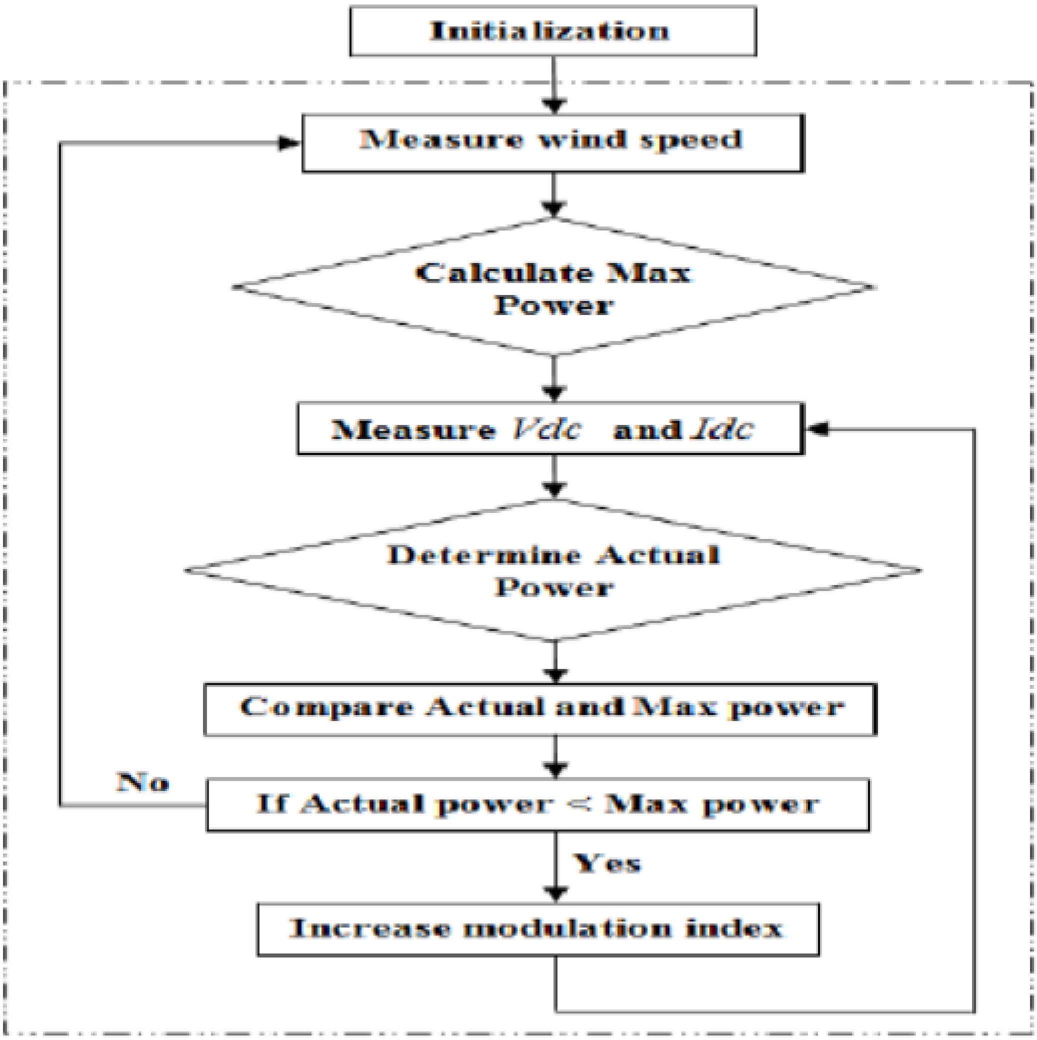

Figure.2. Proposed MPPT technique control flowchart

To implement MPPT, a control strategy is introduced that establishes a relationship between the active rectifier's d-axis current and total DC bus power. Additionally, the need for filter capacitors at passive rectifier outputs is eliminated. By adjusting the phase alignment of various AC ports supplying the passive rectifiers, DC bus voltage ripple is significantly reduced. The combination of MPPT control and the removal of bulky filter capacitors enhances the efficiency of the integrated generator-rectifier system, making it a cost-effective solution for offshore wind energy applications [11].

IV. SIMULATION RESULTS

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A three-port permanent magnet synchronous generator (PMSG) is represented using three voltage sources in series, each with associated resistance and inductance. The frequency and amplitude of these voltage sources are determined by an external reference-speed signal. Ports 1 and 2 are connected to three-phase diode rectifiers, with their phase-A voltages—along with phase-B and phase-C—shifted by π/6\pi/6 electrical radians relative to each other. This phase shift helps reduce voltage ripple at the DC output of the passive rectifiers. Meanwhile, Port 3 supplies power to an insulated-gate bipolar transistor (IGBT)-based active rectifier, which operates at a switching frequency of 2 kHz. The rectifier outputs are connected in series to form a high-voltage DC bus, which is stabilized at 5.7 kV to facilitate grid integration.

Additionally, a simulation is conducted for a variable-speed direct-drive PMSG system that incorporates a passive rectifier, a DC-to-DC boost converter with MPPT control, and an adaptive hysteresis band current-controlled voltage source converter (VSC) to maintain a stable DC link voltage. The MPPT control method used follows a step-and-search algorithm that regulates the DC voltage based solely on VDCV_{DC} measurements. This strategy ensures that the DC link voltage remains stable even under fluctuating wind speeds. The adaptive hysteresis band current controller dynamically adjusts the hysteresis bandwidth according to the measured line current of the grid-connected inverter. This technique effectively stabilizes the DC link voltage, even during transient variations in grid current.

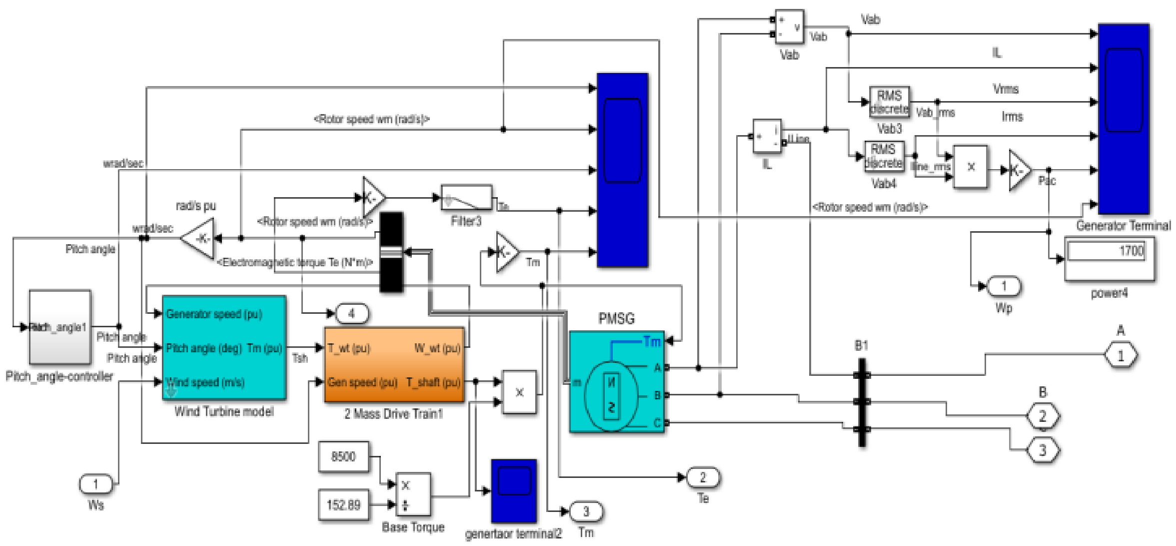

Figure 3. Simulink Design of Wind Turbine

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Figure.3 illustrates the design of a wind turbine generation system. It comprises key components such as controllers, a wind turbine model, a mass drive train, and a permanent magnet synchronous generator (PMSG). This simulation is utilized to analyze and optimize wind energy generation.

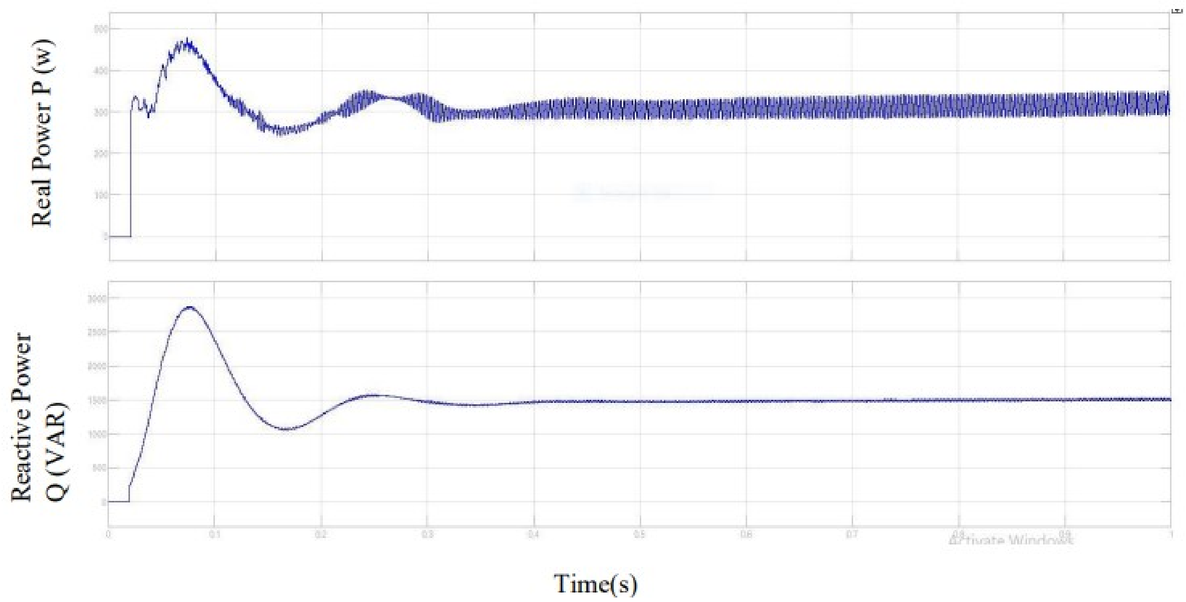

Figure.4. Waveform of Real power (P) and Reactive power (Q)

Fig.4 represents the overall power quality of the system, which helps assess its performance. By analyzing power quality, the stability of power flow within the system can be evaluated. In this figure, the X-axis represents time in seconds, while the Y-axis displays real power (P=472.5WP = 472.5 W) and reactive power (Q=2875VARQ = 2875 VAR).

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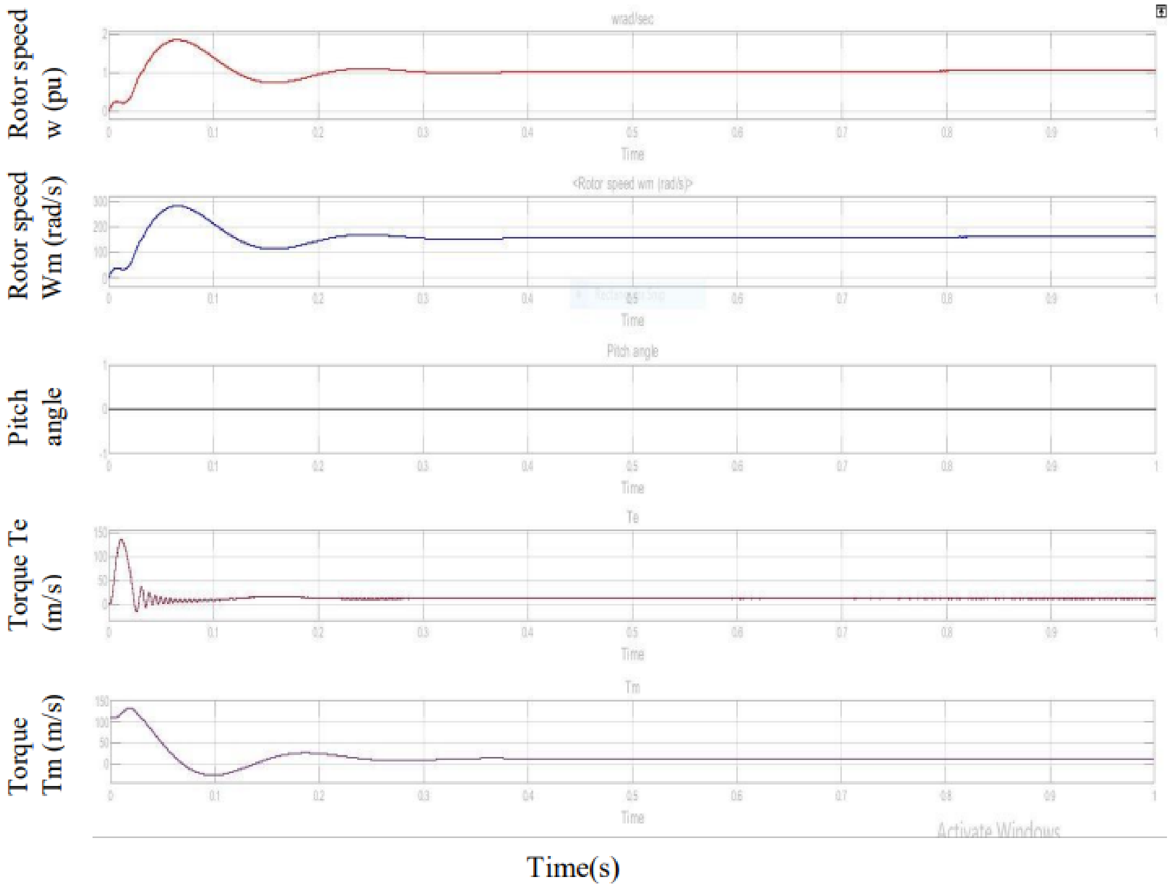

Figure.5. Rotor speed, Pitch Angle Torque for Wind power Generation

Fig.5 presents the output characteristics of different components within the wind generation system. The first graph illustrates the relationship between phase-A back EMF (Y-axis) and time (X-axis). The second graph depicts the variation of rotor speed (WmW_m) over time. The third graph shows the pitch angle as a function of time. The fourth graph represents the correlation between electrical torque and time, while the fifth graph displays the relationship between motor torque and time. The system parameters include a maximum rotor speed of Wm=1.9W_m = 1.9 p.u., a rotor speed of 263 rpm, a maximum electrical torque (TeT_e) of 137.5 N·m, and a motor torque (TmT_m) of 136 N·m.

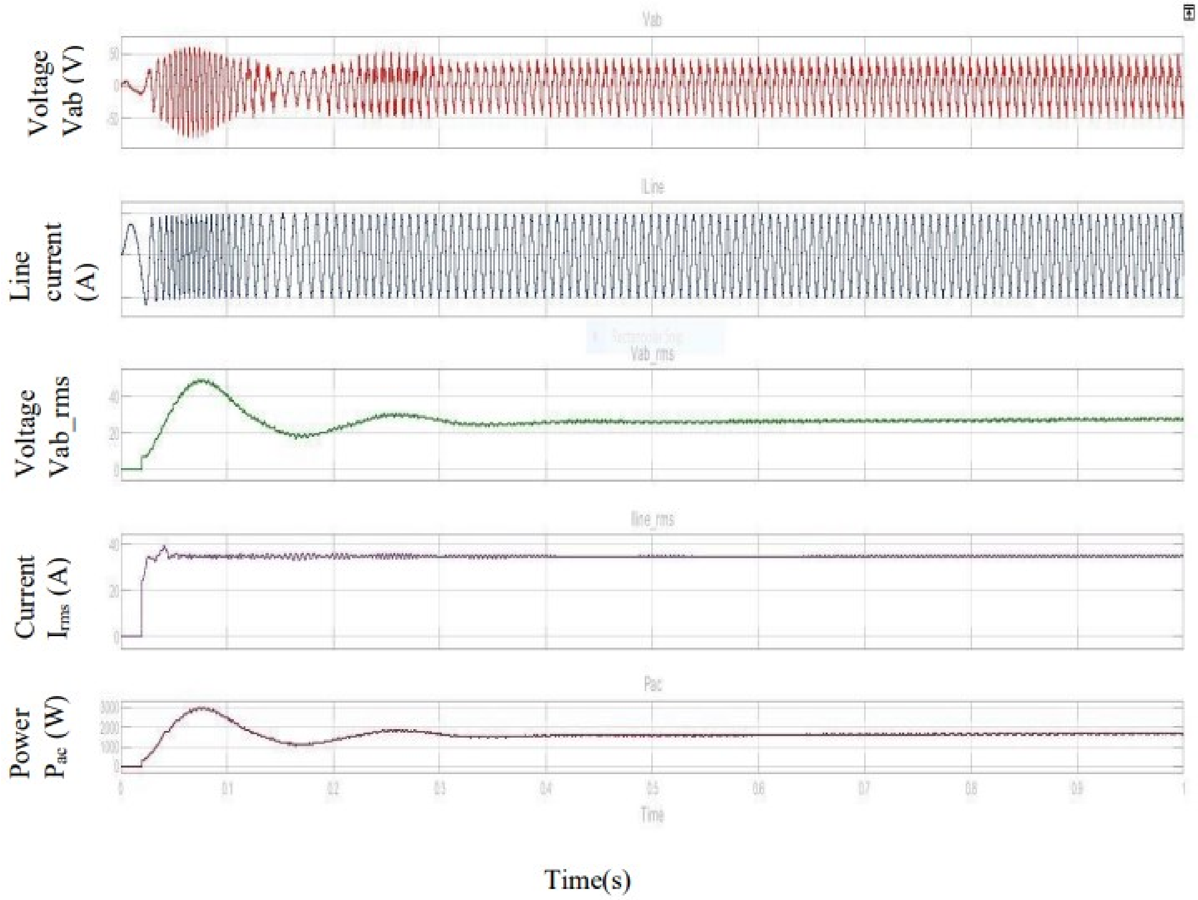

Figure.6. Voltages, Currents and Power at Generator terminal

Fig.6 presents the results of the generator terminal, displaying various system parameters over time. The first graph illustrates the relationship between rotor speed (Y-axis) and time (X-axis). The second graph shows the variation of voltage VabV_{ab} with respect to time. The third graph also represents the relationship between VabV_{ab} and time. The fourth and fifth graphs depict the variation of line voltage over time. Finally, the last graph demonstrates the relationship between power (Y-axis) and time (X-axis).

V.CONCLUSION:

This work introduces a Maximum Power Point Tracking (MPPT) approach for an integrated generator-rectifier system. An analytical relationship between the DC-bus power and the active-rectifier d-axis current is derived and verified through MATLAB simulations. A cascaded control structure is proposed for practical application, with the inner loop consisting of PI current controllers enhanced by feed-forward terms, and the outer loop featuring a PI power controller. The system demonstrates effective power tracking performance. By controlling the DC-bus power, the power flow management enables MPPT for the wind turbine. This functionality highlights the potential of integrated generator-rectifier systems in wind energy applications.

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