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Carrier PWM for Solar Power and SVPWM for Wind: A Synergized Control Strategy for Hybrid Systems

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Abstract
In this study, we propose a coordinated control scheme for solar-wind hybrid power systems that use space vector pulse width modulation (SVPWM) for wind power and carrier pulse width modulation (PWM) for solar power. The proposed approach is designed to enhance energy efficiency, stability, and power quality in hybrid systems, addressing the challenges of variability in renewable energy sources. Carrier PWM is implemented for the solar power system to regulate the operation of photovoltaic inverters, ensuring optimal energy conversion under varying solar irradiance conditions. Simultaneously, SVPWM is applied to the wind energy system to control the operation of the wind turbine-driven, delivering high-quality voltage output with reduced harmonic distortion. The integration of these control techniques is facilitated through a centralized hybrid energy management system, enabling seamless energy distribution, synchronization, and grid connectivity. Simulation results demonstrate the effectiveness of the proposed strategy in maintaining power balance, reducing total harmonic distortion (THD), and ensuring reliable operation under dynamic load and environmental conditions. This work underscores the potential of advanced PWM techniques in advancing hybrid renewable energy systems toward greater efficiency and sustainability.

Keywords: Carrier PWM, Solar power system, SVPWM, Wind power systems.

1. INTRODUCTION

The importance of energy in our day-to-day activities cannot be overstated. The degree to which a nation's population makes use of energy is a good indicator of the level of progress and civilization that exists within that nation. The rise in population, urbanization, and industrialization are all contributing factors that are driving up the need for energy on a daily basis. This means that the supply of fossil fuels around the world, which includes coal, petroleum, and natural gas, will be exhausted within a few hundred years. As a result of the rising rate of energy use, the supply is decreasing, which is leading to inflation and a shortage of energy. This is referred to as the energy crisis. Consequently, meeting future energy demands will include the exploration and development of renewable or alternative energy sources.

Based on the opinions of numerous specialists in the field of renewable energy, a modest "hybrid" electric system that combines house solar electric (photovoltaic or PV) technologies with home wind electric technologies offers a number of benefits that are not available with each single system [1].

Wind speeds are often low throughout a significant portion of the United States during the summer months, when the sun is at its brightest and longest. During the winter, when there is less sunshine available, the wind is very fierce. There is a greater likelihood that hybrid systems will generate power at the precise moment that you require it. This is because different solar and wind systems have different peak working hours throughout the day and year. There are a lot of hybrid systems that are independent and run "off-grid," meaning they aren't linked to the regular power grid. While the wind and solar panels aren't producing electricity, most hybrid systems will use batteries and/or an engine generator powered by conventional fuels like diesel to keep the lights on [2].

In the event that the batteries become depleted, the engine generator has the capability to supply electricity and recharge the batteries. However, current electronic controllers are able to manage these systems automatically, despite the fact that the addition of an engine generator makes the system more complicated. Additionally, the size of the other components that are required for the system can be reduced by using an engine generator. Remember that when charging is not in use, the storage capacity must still be enough to fulfil electrical power demands. It is common for a battery bank's capacity to be enough to power an electric load for a day or two.

Over the past several years, there has been a significant growth in the demand for electricity on a substantial scale. As a result, the electrical networks have become more sophisticated, to the point where even a minor disruption in the network or utility grid can result in a power outage that lasts for a longer period of time in remote areas [3]. Solar, wind, tidal, and wave power are just a few examples of renewable energy sources that can help with the issues mentioned above.

It is possible to create a hybrid energy system by combining two or more renewable sources, depending on the amount of electricity that is required and the availability of those sources. The majority of hybrid systems combine photovoltaic and wind power with other forms of renewable energy. Within the past ten years, WECS has had the most rapid expansion. The requisite control system, along with a power electronic converter, an electric generator, and a wind turbine, comprise the WECS infrastructure. One way to classify these is by the speed of the generator; this will indicate if the WECS is constant speed or variable speed. During the early phases of developing WECS, devices that generate power at a steady pace were widely used.

The fast depletion of traditional energy sources is increasing the demand for the use of alternative energy sources. The abundance and promise of renewable energy sources like wind and solar power drew the majority of the world's attention. In order to put the available resources to good use, a great deal of thought and technology has been produced over many years [4]. Depending on the specific weather conditions, the amount of power generated by wind and solar systems can change. In order to get the most out of each source, specific methods are provided for them. One common method used in photovoltaic (PV) systems is multiple power point tracking (MPPT). The Incremental Conductance (INC), Perturb and Observe (P&O), Open Circuit Voltage (OCV), and Short Circuit Current (SC) methods are some of the most used MPPT methodologies. There are restrictions associated with each of these methods. The P&O can still generate oscillations at the Maximum Power Point (MPP) even in the presence of steady light.

The INC method outperforms the P&O method in terms of accuracy and effectiveness regardless of the weather, but it has a more involved controlling circuit. For units that generate a lot of energy, the simple OC voltage and SC current strategy doesn't work. A photovoltaic (PV) system's performance can be enhanced by applying the two-model maximum power point tracking (MPPT) method. Typical methods allow for the combination of any two approaches according to local climate; for example, using Incremental Conductance in conjunction with Open Circuit Voltage yields accurate and efficient results in any climate [5]. A wide range of generator designs are included in the Wind Energy Conversion System (WECS), which includes both fixed and variable speed wind turbine generators. Here it is equipped with a wind turbine that is controlled by pitch angle and uses MPPT technology that works with the wind speed, as well as a Permanent Magnet Synchronous Generator (PMSG).

A variable-speed wind turbine generator known as a permanent magnet synchronous generator (PMSG) outperforms its doubly fed induction counterpart in terms of efficiency. Energy from renewable sources, such as wind and solar, is integrated into the microgrid. Power is converted from direct current (dc) to alternating current (ac) by means of an inverter after it has been amplified. The inverter end power is controlled using the Space Vector Pulse Width Modulation (PWM) method. We supply this technology that improves efficiency and decreases distortions in the output voltage. What makes this study unique is that it employs better approaches to boost the PV system's and the WECS's power generation capacities.(1) Among the contributions of the paper are an analysis of several maximum power point tracking (MPPT) strategies for a photovoltaic (PV) system and the creation of a two-model MPPT technique. We are also considering developing a WECS with PMSG [6] in addition to deploying the pitch angle regulating technique and an Optimal Power regulating MPPT technique. Optimizing the output power performance is possible through the integration of photovoltaic (PV) and wind energy conversion systems (WECS), as well as the use of SVPWM technology on the inverter side.

It has been discovered that a variable speed multi pole PMSG is more favorable with gearless construction. This type of PMSG has a number of benefits, including high controllability, low maintenance, decreased losses, and lower costs [7]. MATLAB/Simulink is used to construct a PMSG-based WECS, which is presented in this study. Whereas renewable energy sources like fuel cell systems and photovoltaic (PV) systems produce direct current (DC) power, the WECS produces electricity in the form of an alternating current supply.

Synchronizing the phase, amplitude, and frequency of the voltages and currents that are created is one of the numerous challenges that are encountered throughout the integration process in AC. The integration of photovoltaic and wind power into a direct current (DC) supply form is a method that can be utilized to circumvent this complication. This approach requires only the synchronization of the voltages supplied by the systems together. Due to the fact that the incorporation of renewable sources offers numerous benefits in direct current (DC) form in comparison to alternating current (AC), it is necessary to convert the power that is generated by wind power generation into direct current (DC).

2. LITERATURE REVIEW

It is common practice to use a capacitor filter in conjunction with a diode bridge rectifier to convert AC to DC for low-power applications. More control over the bridge rectifier's switches has been made possible by new power electronic devices, such as SCRs and IGBTs. These innovations also make using Pulse Width Modulation (PWM) techniques to switch converter switches more advantageous. Power-pulse-width (PWM) signals are a type of pulse train that can have a set magnitude, frequency, or both. Pulse width varies with each pulse in response to modulating signal. The ON/OFF state of the switch can be changed by applying this pulse width modulation signal to its gate. Controlling the output voltage and reducing harmonic content is achieved by varying the pulse width. One kind of pulse width modulation is sinusoidal pulse width modulation (SPWM), while another is space vector pulse width modulation (SVPWM) and still another is multiple pulse width modulation (MPWM). When it comes to enhancing current quality and decreasing harmonics, SVPWM is head and shoulders above the competition [8]. A novel approach to managing solar-wind hybrid power systems is introduced in this study. The approach employs a synergized management strategy that merges Carrier PWM and SVPWM.

In order to compensate for the unpredictability of renewable power sources, this method improves the system's efficiency, stability, and power quality. When it comes to photovoltaic inverters, carrier PWM is the way to go for effective energy conversion in the face of fluctuating solar irradiance, while for systems driven by wind turbines, SVPWM means less harmonic distortion and more high-quality voltage output. A centralised hybrid energy management system oversees the integration of these control techniques, allowing for smooth energy distribution, synchronisation, and grid connection. Power balancing, reduced Total Harmonic Distortion (THD), and reliable operation under dynamic load and climatic circumstances are all demonstrated by the simulation results, proving the effectiveness of the technique. Improved efficiency and longevity in hybrid renewable energy systems may be within reach with the use of modern pulse width modulation (PWM) methods, as demonstrated in this study.

The agricultural sector, which contributes 17.2% of India's GDP, is one of the most important since it is highly reliant on the monsoons. It has been discovered that its contribution to GDP is continuously decreasing as a result of the unpredictability of rainfall. It is estimated that over twenty million water pumps are installed across the nation in order to meet the demand for water. These pumps utilize approximately 92 billion units of energy annually, which accounts for twenty-two percent of the nation's total electricity usage. The vast majority of the energy needed to meet this water demand comes from fossil fuels, accounting for 67 billion units out of 92 billion units. Conventional WPSs contribute to climate change since they generate energy from fossil fuels, which increases emissions of greenhouse gases. Further drawbacks include engine burnouts, maintenance caused by voltage variations in the grid, power cuts and outages occurring frequently, losses in transmission and distribution, and poor grid power quality. Exploring the potential for efficient utilization of renewable sources to meet energy demands is one way to address this issue [9]. The continual decline in the price of photovoltaic (PV) modules and the developments in computer and power electronics have encouraged many researchers to design and implement effective REWPSs.

The standard pumping system's Life Cycle Cost (LCC) includes the purchase price of the motor pump, the cost of repairs and maintenance, and the cost of energy consumed during pumping. Over eighty-two percent of the pumping limitation capacity is attributable to the energy consumed during pumping [10]. So, the energy's improper use could lead to more greenhouse gas emissions and a larger long-term carbon footprint for the pump. Renewable energy sources, including wind and solar photovoltaics, also exhibit non-linearity. Consequently, for the optimum LCC of REWPS, it is crucial to install a suitable power conditioning circuit and control technique to maximize power extraction from the chosen renewable source.

There have been a great number of review articles on REWPSs published in the literature up until this point. There are five different types of renewable energy sources that have been identified as having the potential to be used for water pumping. Solar thermal, wind, biomass, photovoltaic (PV), and hybrid wind-PV are some of these options. We go further into the subject of SPWPSs, focusing on system sizing. Solar photovoltaic (PV) systems, wind power, and hybrid wind-PV systems are all potential future energy sources for efficient and ecologically friendly water pumping, according to the authors. Previous work on the classicalation of SPWPSs driven by DC motors and AC induction motors (IMs) is cited in [12]. Some of the things covered in this research include the phases of power converters, methods for maximum power point tracking (MPPT), and the microcontrollers utilized for their implementation. Having said that, DC motors and AC IM are the only topics being explored in this paper. Economic feasibility, pumping technique, sizing, degradation study, performance analysis of installed SPWPS, and efficiency improvement of SPWPS are some of the several issues that have been studied in relation to [13].

The number of research articles that were examined for the efficient improvement portion was relatively low. Detailed design procedures for both grid-connected and freestanding SPWPS have been presented. In addition, the writers have shared their thoughts on several ways for modeling a solar photovoltaic system and methods for optimizing the system's size. The authors of [14] have framed SPWPS as an interdisciplinary topic that addresses issues in disciplines as diverse as control, computer, electrical, mechanical, and civil engineering. The writers tackle a wide range of obstacles, thus they compress the issues pertaining to the many kinds of motors and control algorithms. The research provided in [15] investigated design procedures, SPWPS modeling, field performance, reliability, system sizing, and control methodologies.

In addition, the authors have examined a few research articles that are based on control systems that are solely applicable to water pumps that are powered by DC motors. Additionally, in [16], a case study was reported regarding a 0.5 HP mono-block directly connected dc motor pump in the western Himalayan region of India. This case study was the first of its kind and was conducted in the context of directly coupled SPWPS. It has been noted that directly connected SPWPS are vulnerable to underutilization of solar photovoltaic (PV) power and require an algorithm for maximum power point tracking (MPPT) in order to make efficient use of solar PV power.

3. METHODOLOGY

3.1 System Design and Control Strategy Development:
The model represents a renewable energy system that combines solar and wind power, with different control approaches applied to each subsystem to ensure optimal performance. In the solar subsystem, photovoltaic (PV) inverters are operated optimally through the use of carrier pulse width modulation (PWM), guaranteeing maximum efficiency in energy conversion regardless of changes in solar irradiation. At the same time, systems driven by wind turbines are controlled using Space Vector Pulse Width Modulation (SVPWM), which allows for the production of high-quality voltage output with drastically decreased harmonic distortion. The hybrid system's overall efficiency and power quality are both improved by this integrated approach.

3.2 Centralized Hybrid Energy Management System:

A centralized hybrid energy management system is developed to integrate the Carrier PWM and SVPWM control techniques, ensuring seamless coordination between the solar and wind energy subsystems. This system is responsible for managing energy distribution, synchronization, and grid connectivity, allowing for the efficient integration of both solar and wind energy sources. By centralizing the control, the system ensures optimal operation, balancing the energy flow and maintaining stable connectivity to the grid, thus enhancing the overall reliability and performance of the hybrid renewable energy system.

3.3 Simulation and Validation:
The hybrid system is simulated under dynamic environmental and load conditions to evaluate its performance, with key metrics such as power balance, Total Harmonic Distortion (THD), and system stability being measured and analyzed. These measurements show how well the system can keep running smoothly and with good power quality no matter what. A comparison with traditional methods further confirms the efficacy of the suggested control strategy, showing that it outperforms the latter in terms of optimizing energy efficiency and decreasing harmonic distortion.

3.4 Performance Metrics and Optimization:
The system's ability to handle the variability in solar and wind resources is thoroughly assessed, ensuring it can adapt to fluctuating environmental conditions. Optimization approaches are used to fine-tune the settings of Carrier PWM and SVPWM, with the purpose of improving efficiency and power quality, further enhancing the system's performance.

These adjustments ensure that the system operates optimally, even under changing resource availability, maximizing energy conversion and minimizing losses.

This methodology ensures that the hybrid system achieves enhanced energy efficiency, reduced harmonic distortion, and reliable operation, addressing the challenges posed by the variability of renewable energy sources.

3.5 Controllers

3.5.1 Carrier Pulse Width Modulation (PWM) for Solar Power System:
The photovoltaic (PV) inverters in a solar power system are controlled by the Carrier PWM controller. In order to keep the inverter operating at peak efficiency, this controller adjusts the pulse width. To maximize the inverter's efficiency and the amount of energy converted from the photovoltaic panels into usable electrical power, the Carrier PWM adjusts the duty cycle of the PWM signal depending on changes in solar irradiation. Because the system must adjust to

variations in solar input in order to maximize energy harvesting, this becomes even more important when sunshine conditions change.

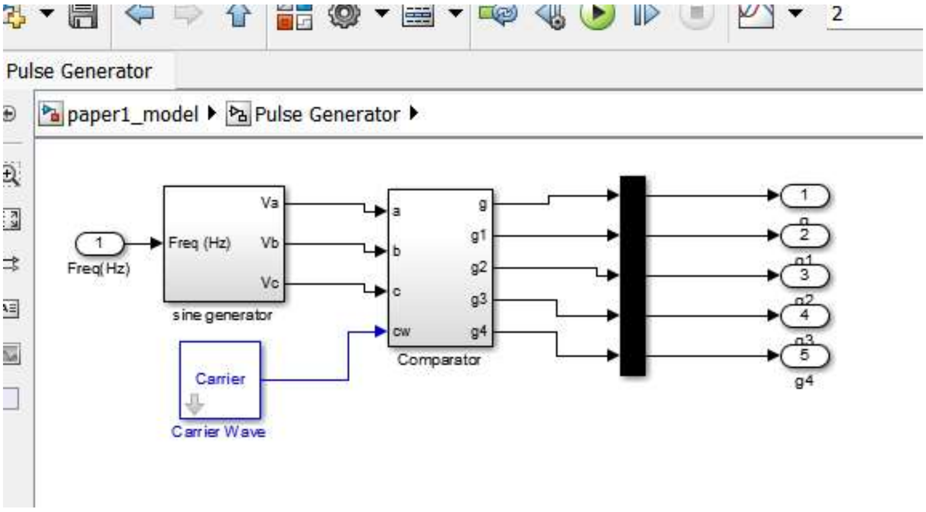

Fig 1: Simulation diagram for Carrier Pulse Width Modulation (PWM).

Fig 1 depicts the simulation diagram for Carrier Pulse Width Modulation (PWM), which is used to optimize the operation of photovoltaic inverters in the solar power subsystem. This diagram demonstrates how PWM controls the inverter to maximize energy conversion efficiency under varying solar irradiance conditions.

3.5.2 Space Vector Pulse Width Modulation (SVPWM) for Wind Power System:

The SVPWM controller is used in the wind energy system to control the operation of the wind turbine-driven generator. SVPWM is a sophisticated modulation technique used to generate high-quality voltage waveforms with reduced harmonic distortion. This is crucial for maintaining stable and reliable power output from the wind turbine system. By using SVPWM, the wind power system can produce a more sinusoidal voltage waveform, which minimizes harmonic content and improves the overall power quality. This ensures that the energy generated by the wind turbine is effectively delivered to the grid or energy storage systems, enhancing the system's efficiency and reducing losses due to harmonics.

Together, these controllers enable the hybrid renewable energy system to manage both solar and wind power efficiently, ensuring optimal performance and power quality while minimizing losses and maintaining stable operation.

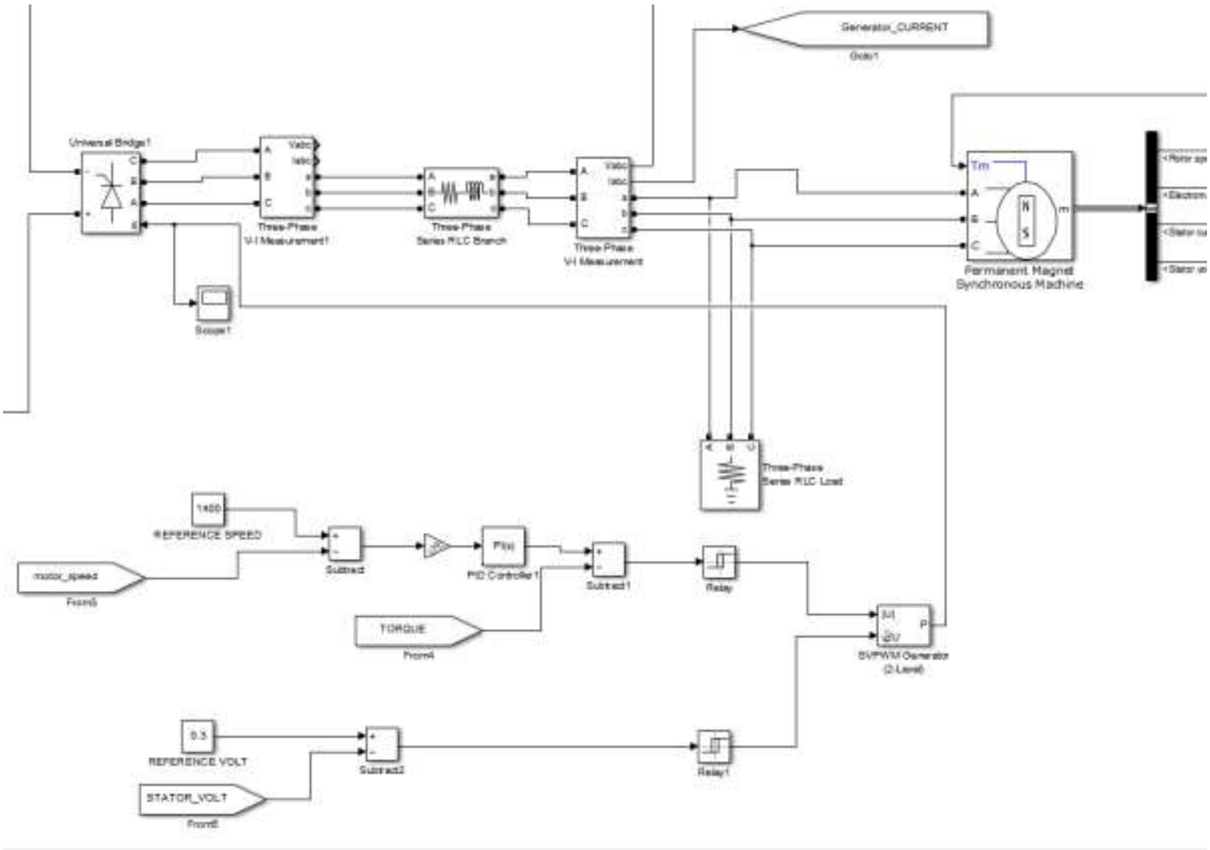

Fig 2: Simulation diagram for Space Vector Pulse Width Modulation (SVPWM)

Space Vector Pulse Width Modulation (SVPWM) is a control approach that produces high-quality voltage waveforms for systems driven by wind turbines; its simulation diagram is shown in Fig. 2. It highlights the modulation technique's role in reducing harmonic distortion and ensuring efficient power conversion in the wind energy subsystem.

4. RESULTS AND STUDY

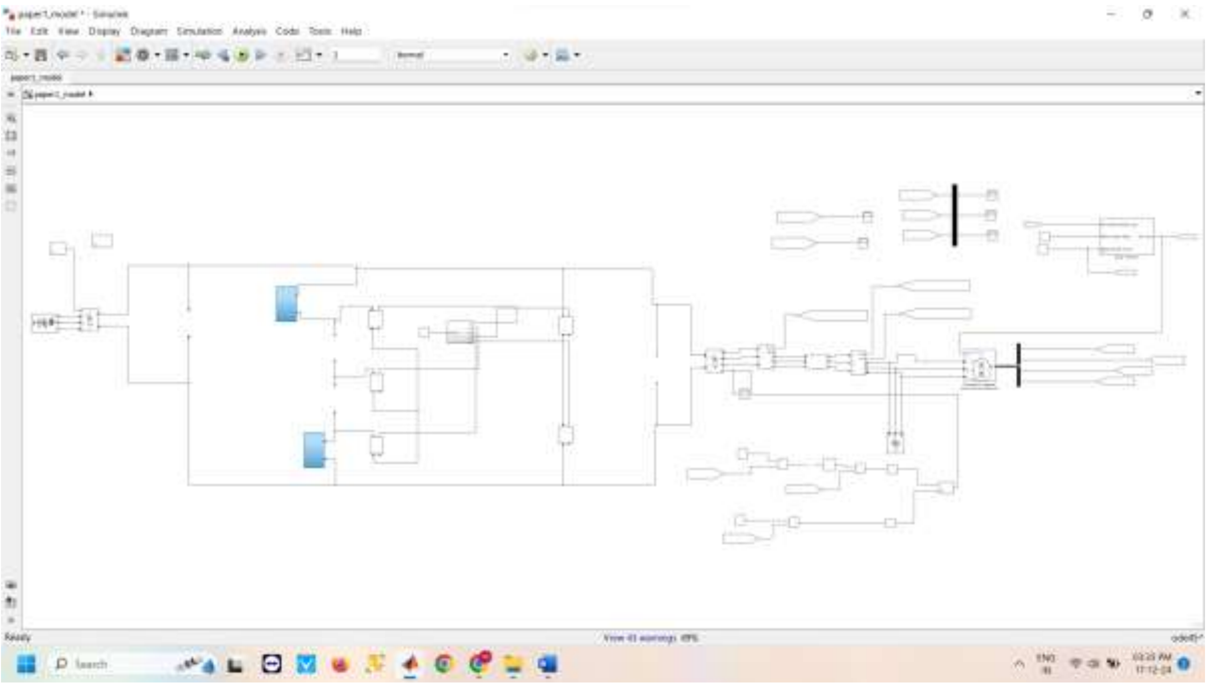

Fig 3: Simulation block diagram.

Fig 3 presents the simulation block diagram, illustrating the integration of the solar and wind energy systems within the hybrid setup. It outlines the key components, including the controllers and energy management system, that coordinate the flow of energy and ensure stable operation under dynamic conditions.

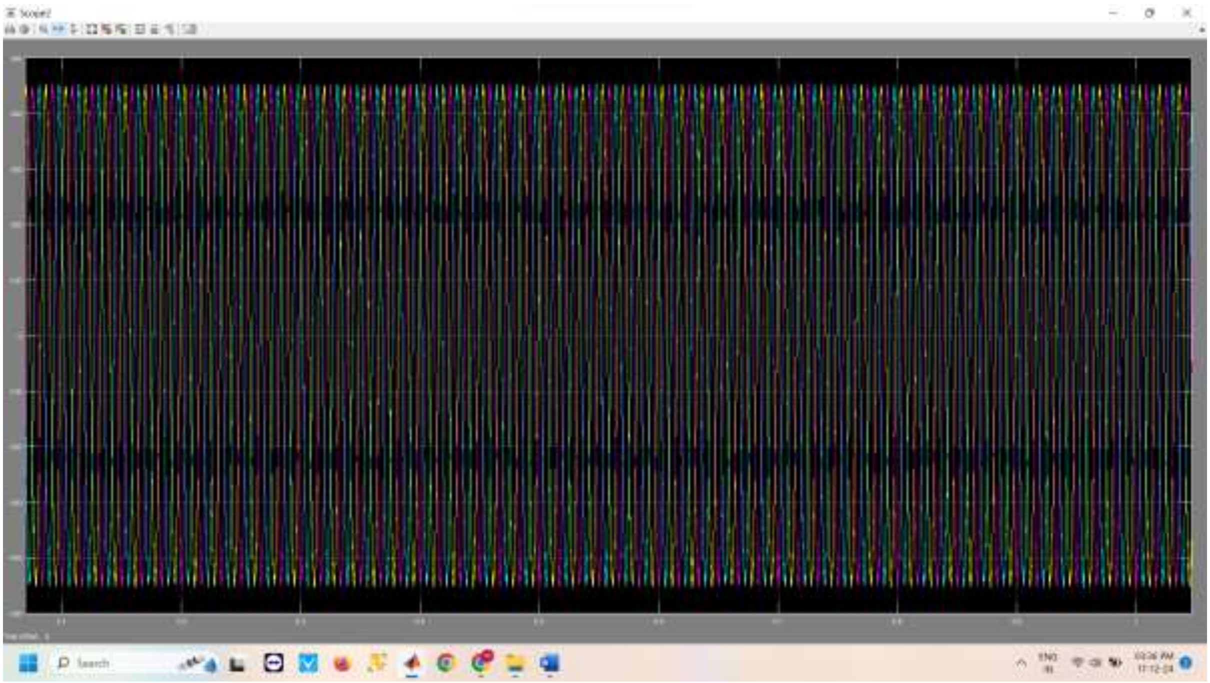

Fig 4: Three-phase Generated Voltage.

Fig 4 shows the three-phase generated voltage, representing the output waveform from the wind turbine-driven system.

Fig 5: Three-phase Generated Current.

Fig 5 displays the three-phase generated current, which corresponds to the current output from the wind turbine system.

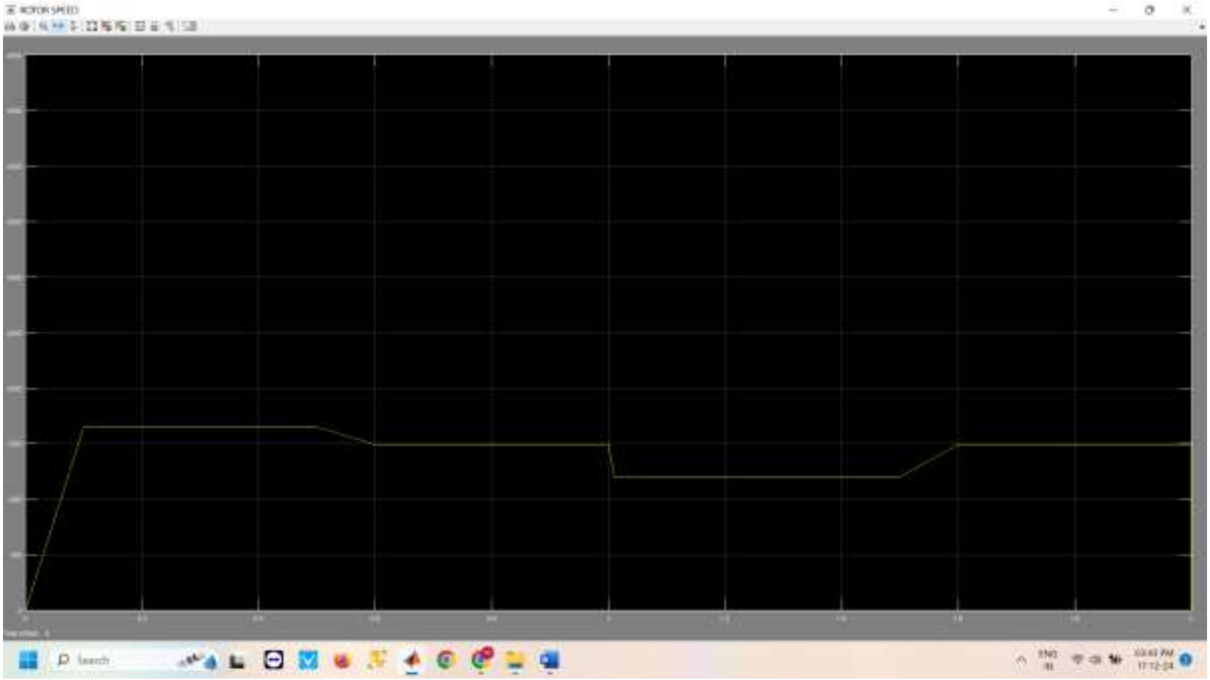

Fig 6: Rotor speed.

Fig 6 illustrates the rotor speed of the wind turbine system, showing how the speed fluctuates in response to changes in wind conditions.

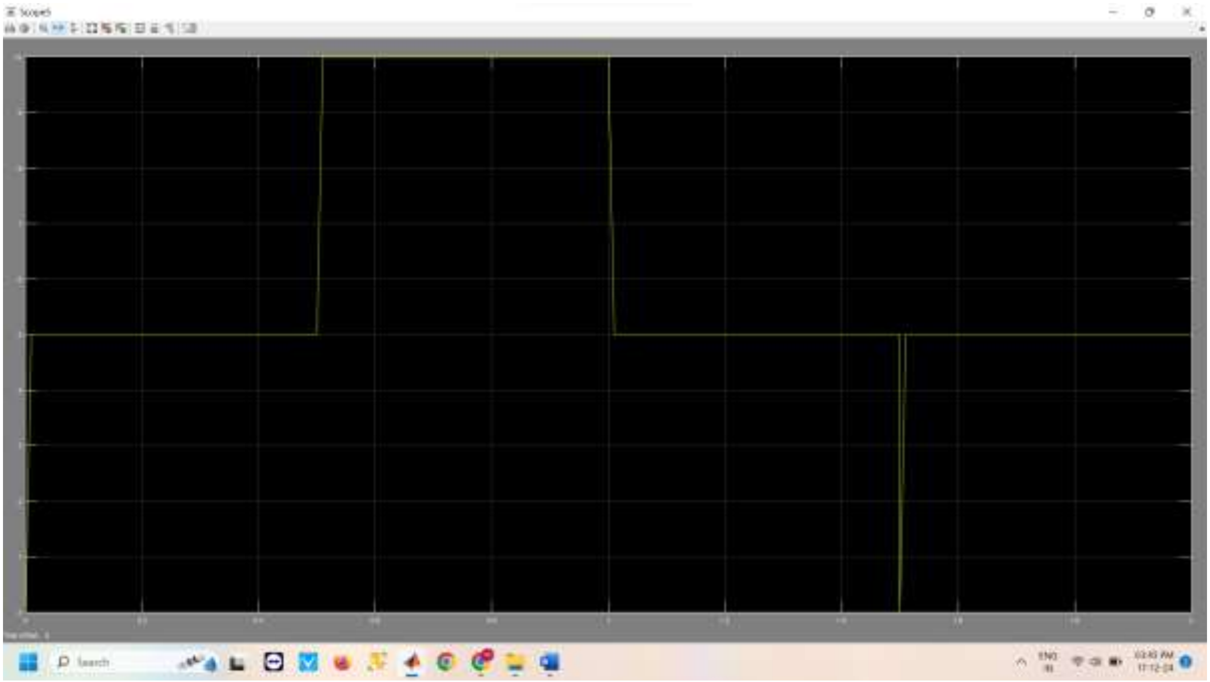

Fig 7: Torque.

Fig 7 shows the torque generated by the wind turbine, depicting its variation in response to changing wind speeds.

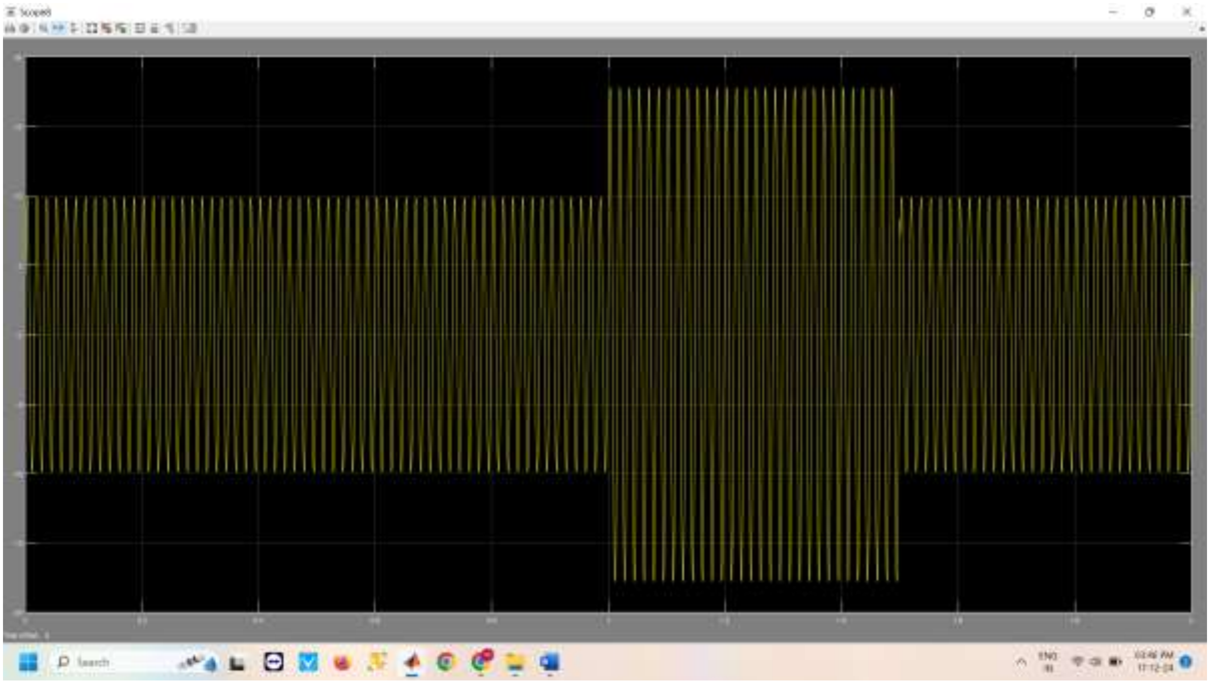

Fig 8: Stator current.

Fig 8 displays the stator current of the wind turbine system, illustrating its behavior under varying load and wind conditions.

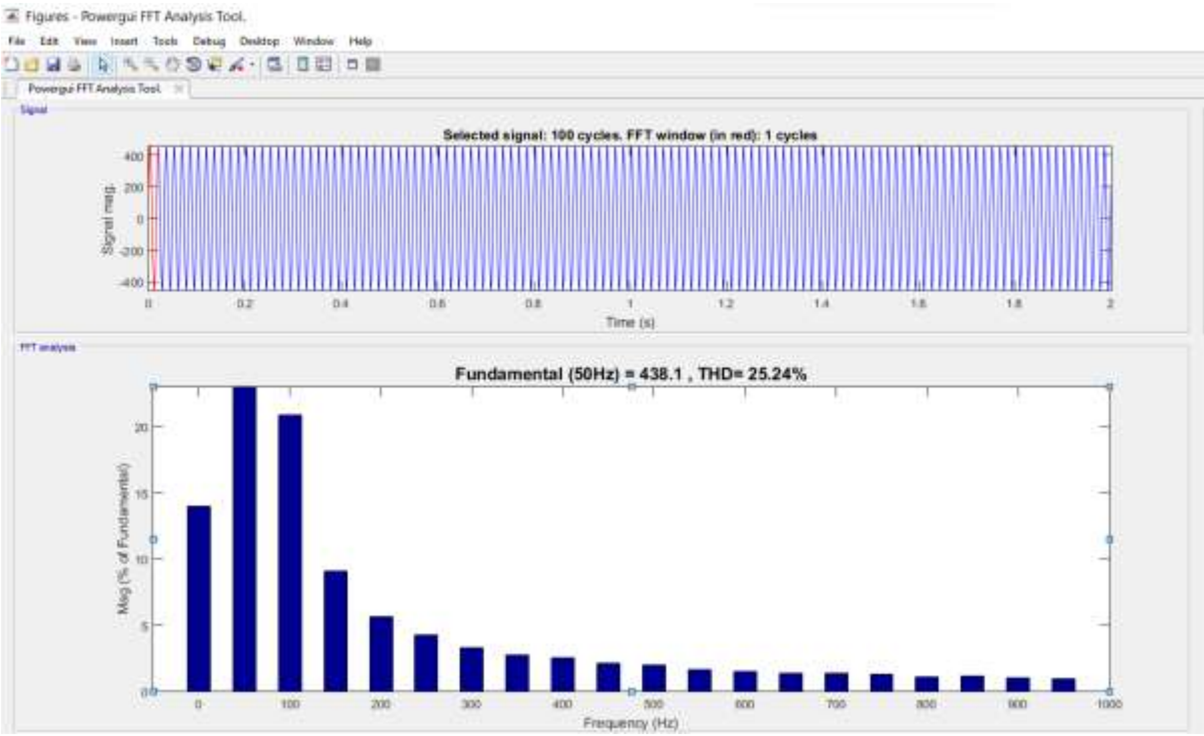

Fig 9: THD for Three-phase Generated Voltage.

Fig 9 presents the Total Harmonic Distortion (THD) for the three-phase generated voltage, showing the level of harmonic content in the voltage waveform.

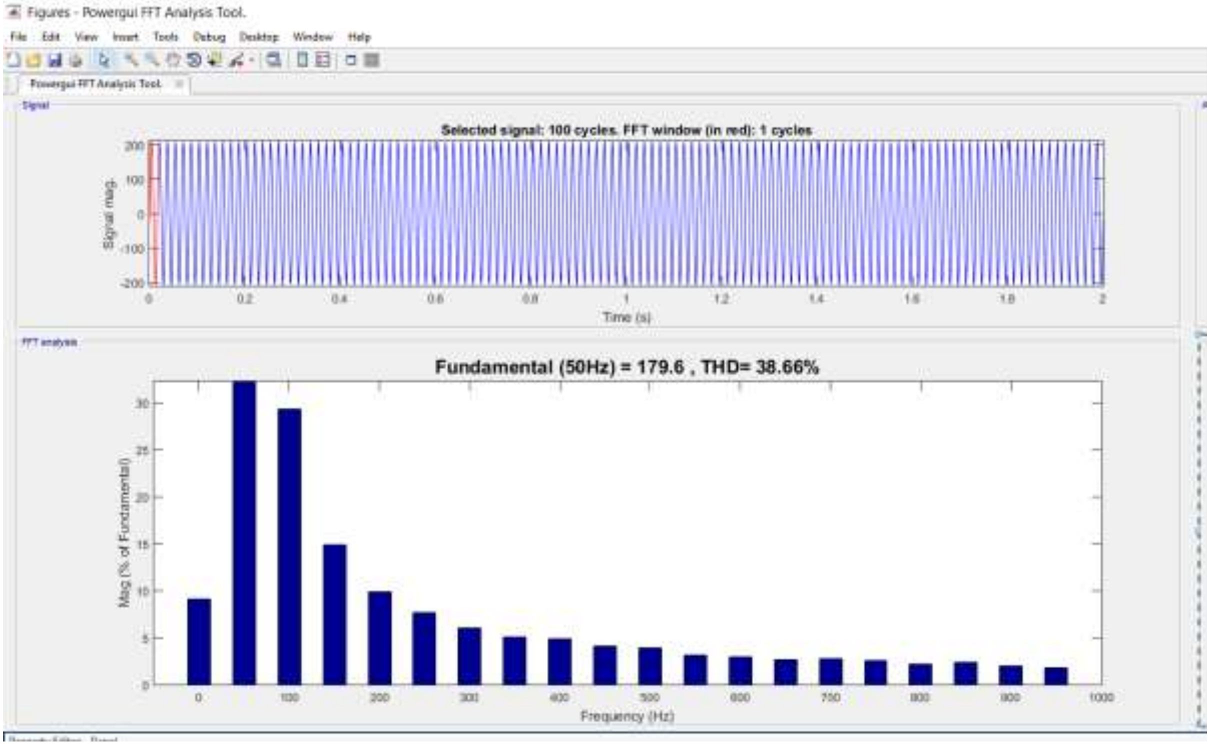

Fig 10: THD for Three-phase Generated Current

Fig 10 shows the Total Harmonic Distortion (THD) for the three-phase generated current, illustrating the level of harmonic content in the current waveform.

CONCLUSION

The proposed synergized control strategy effectively integrates Carrier PWM for solar power systems and SVPWM for wind energy systems to enhance the performance of hybrid renewable energy systems. By leveraging Carrier PWM for optimal photovoltaic inverter operation under varying solar irradiance and SVPWM for high-quality voltage output with reduced harmonic distortion in wind turbine-driven systems, the approach significantly improves energy efficiency, stability, and power quality. The centralized hybrid energy management system ensures seamless energy distribution, synchronization, and grid connectivity, addressing the challenges posed by the variability of renewable energy sources. Simulation results confirm the strategy's capability to maintain power balance, reduce Total Harmonic Distortion (THD), and ensure reliable operation under dynamic load and environmental conditions. This work highlights the potential of advanced PWM techniques in advancing hybrid renewable energy systems toward greater efficiency, sustainability, and reliability.

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