Grid Stability Analysis of Hybrid System Using VSI-PLL Circuitry and PCC Technique with Various Controllers using MATLAB/ Simulink

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Abstract

Hybrid systems integrate various sources of renewable energy such as Solar, Wind and Hydro as well as others to generate electricity. The objective of this research paper is to create a Hybrid System connected to the Grid, which combines Photovoltaic (PV) and Wind Systems and to analyze the performance using MATLAB/ Simulink. The paper discusses essential control strategies for managing voltage, current, and power within the hybrid system. In this system, power conditioning phenomena are controlled by a DC to-DC boost converter, a voltage source inverter (VSI), and a PI controller. The paper also employs a voltage-oriented vector control approach for designing the three-phase inverter (VSI). Additionally, A Phased Locked Loop (PLL) is designed to align the VSI with the utility grid for synchronization purposes, with a PI controller serving the purpose of grid current control. The main contribution of this paper is its focus on generating a sustainable grid voltage while taking into account varying solar irradiation and fluctuating wind speeds. A key finding of this paper is that all grid signals maintain THD below 2% and overshoot within acceptable limits, which is gained through the tuning process of the controllers. The entire system, along with its performance, has been meticulously evaluated using MATLAB/ Simulink for simulation and in-depth analysis, demonstrating a rigorous and comprehensive assessment process.

Key words: Phase locked Loop (PLL); VSI; PMSG; Boost Converter; Point of Common Coupling (PCC)

1. Introduction

To effectively meet electricity demands, reliance must be placed on sustainable energy sources. Renewable energy reserves, such as wind and solar power systems, are being recognized as essential contributors to environmental protection while ensuring sustainable energy supply [1]. Renewable energy sources can operate in a decentralized manner, functioning independently to provide electricity without requiring elaborate transmission infrastructure. This feature is especially advantageous in remote regions where connecting to the grid is difficult. Hybrid power systems, which integrate multiple renewable energy sources such as Wind power, solar power, Bio-energy, Geothermal and hydroelectric power, offer a promising solution to meet electricity demand.

This paper aims to model and simulate a grid-connected hybrid system using Simulink, comprising wind turbines and solar panels. It also investigates the system's stability under varying solar radiation and fluctuating wind speeds. According to A. F. Tazay and A. M. A. Ibrahim et al.

According to A. F. Tazay and A. M. A. Ibrahim et al. [2], the authors focused on employing a Back-To-Back Converter, which consists of two converters: the Rotor Side Converter (RSC) and the Grid Side Converter (GSC), linked by a DC-Bus Capacitor. The GSC manages the constant DC-Bus Voltage and controls the reactive power exchange between the Back-To-Back Converter and the grid.

Additionally, to optimize power output from the wind farm under varying speeds, a modified MPPT is applied in the RSC. This setup also incorporates Voltage Source Inverters (VSI) within a photovoltaic (PV) system.

Unlike the above discussed reference paper, the proposed system involves the use of a Permanent Magnet Synchronous Generator (PMSG) with a boost converter for the wind system. The PV and wind components are combined through a DC link to create a hybrid system where the PCC (Point of Common Coupling) technique is used. A Voltage Source Inverter (VSI) is utilized to change the hybrid system's DC voltage into AC voltage, and afterward, this hybrid system is connected to the grid.

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In [3], the authors employ an Adaptive Network-Based Fuzzy Inference System (ANFIS) to oversee the management of the equilibrium between overall power generation and energy requirements. In case there is any disparity between power generation and demand, the utility grid is programmed to autonomously establish or sever its connection to the shared bus.

In this paper, the proposed wind system incorporates a designed switching condition. This condition operates in a way that, when the speed of wind falls below a certain threshold (known as the cut-in speed) or exceeds another threshold (known as the cutout speed), the torque generation is deactivated. This results in the wind system being disconnected from the grid side, a measure taken to prevent potential damage to the turbine blades.

In [4], the authors mainly focused on controlling the power fed into the grid through a common DC link with a grid interface inverter. PLL with a PI controller for current control on the wind side had been designed.

In contrast, the main emphasis of the present paper is not only on controlling grid-side power but also on maintaining a stable voltage supplied to the grid, even under varying wind speeds and solar irradiation levels.
In [18], one of the key power quality issues in the electric power industry is the distortion of sinusoidal voltage and current waveforms due to harmonics. To achieve improved power quality, it is crucial to monitor harmonic levels, as they can significantly degrade the performance of electrical devices.

The proposed model in this research, achieves better results regarding inverter voltage curves and reduces Total Harmonic Distortion (THD) levels in all the grid signals. This paper introduces a novel approach by implementing wind speed versus torque control using switching conditions.

II. SYSTEM MODELING AND DESIGN

The proposed system comprises a Photovoltaic Array, a Maximum Power Point Tracking Technique (MPPT), a Wind Turbine, a Permanent Magnet Synchronous Generator (PMSG), a Pitch Angle Controller, PI and PID Controllers and a DC-DC Boost Converter. The wind turbine's mechanical energy powers the generator, producing AC electricity, which is later converted into DC power to establish a standard DC link. The photovoltaic array produces DC power, usually at a voltage lower than required for the DC link. To address this, a DC/DC boost converter increases the array voltage to match the standard DC level [4]. An inverter on the grid side converts DC electricity from both the wind turbine and the PV array into grid-compatible AC power in terms of voltage and frequency. In this section, the system's component models are explained and a suggested voltage control plan for this hybrid system is outlined and modeled. A PI controller is designed within the inverter for the purpose of grid current control. To achieve grid synchronization, a PI controller is incorporated inside the Phase-Locked Loop (PLL). In the wind system, a PID controller is designed specifically for pitch angle control. Within the Photovoltaic system, a PI controller is implemented to establish the maximum operating point of the Maximum Power Point Tracking (MPPT). The choice of a PI controller, as opposed to a PID controller, is made for grid current control in the inverter. This decision is influenced by the fact that the % overshoot in grid current increases, although the overshoot in inverter current decreases when a PID controller is used. The implementation of a PI controller aims to reduce the steady state error of the output signal, ensuring that the offset value of the signal remains zero. A schematic diagram of the proposed Hybrid system is depicted in Fig.1

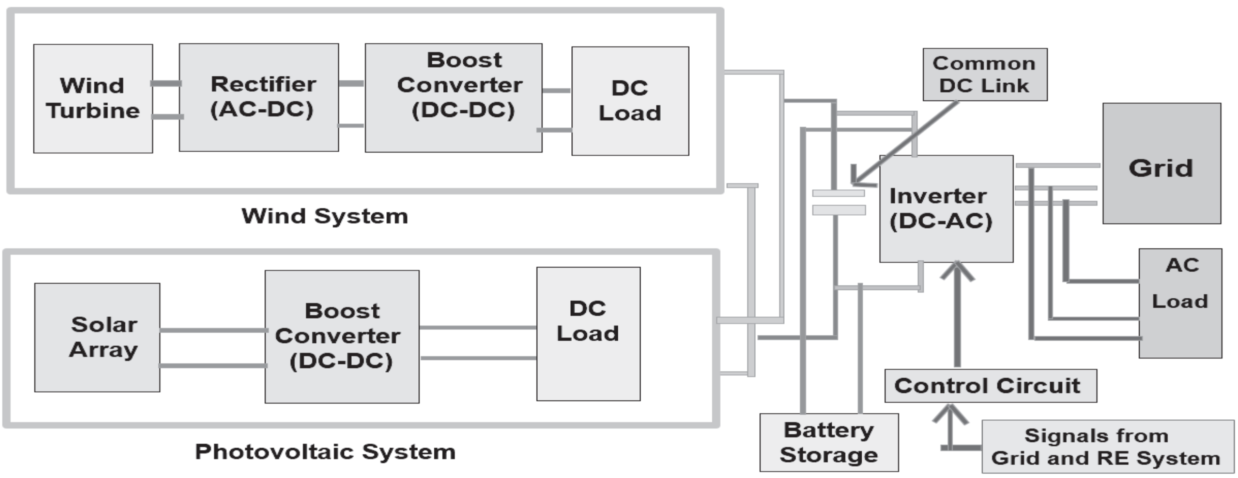

Fig. 1. Schematic diagram of the proposed Hybrid system

2.1 Point of Common Coupling (PCC)

The Point of Common Coupling (PCC) is a strategy that combines wind and photovoltaic (PV) systems, creating a hybrid system. In this method, a coupling capacitor is connected in parallel with a resistor at the common terminal shared by both systems. This configuration enables effective integration and coordination between the two renewable energy sources, optimizing their combined output and enhancing the overall efficiency of the hybrid system.

2.2 Battery Storage System (BSS)

The literature indicates the utilization of various battery types in renewable energy systems, including Lead–acid, Lithium-ion, Nickel–cadmium, Sodium–Sulphur, Vanadium redox, and Zinc–bromine. Lead-acid batteries are commonly chosen for renewable energy applications due to their prevalent use, cost-effectiveness, and ready availability, despite their low initial costs and power density [15].

In this proposed circuit, the battery is designed for energy storage purposes with a rated capacity of 5.4 Ah. The battery is charged from the hybrid DC portion and serves as a DC source to supply energy to DC loads. When the battery charge falls below 25%, it is charged from the hybrid system. A switch, connected to the battery, can disconnect it from the rest of the system once it is fully charged.

2.3 Designing and Modeling of Wind Turbine

Wind energy is an environmentally friendly and sustainable resource. The Wind Turbine, Pitch Angle Controller, Permanent Magnet Synchronous Generator (PMSG), Rectifier, and Boost Converters are crucial components of a wind system for converting wind energy. The PMSG generator is composed of the generator rotor, turbine shaft, gearbox and blades [5].

2.3.1 Wind Turbine

The wind turbine converts the wind's kinetic energy into mechanical energy by applying torque to the generator shaft, which is subsequently utilized to produce electrical power.

The power generated by a wind turbine can be expressed using the following equation in [6]·

$$\mathbf{p_{turbine}} = \frac{1}{2}\mathbf{C_p(\alpha_1, \beta_1). A. \rho_1. V_w^3} \quad (1)$$

Where,
$P_{turbine}$= Wind turbine's mechanical power output.
α_1= The ratio of the rotor blade's tip speed.
β_1= Angle of blade pitch in degrees.
C_p= Coefficient represents the performance of the turbine.
V_w= Speed of the wind measured in meters per second (m/s).
ρ_1= Density of Air (kg/m3).
The performance coefficient model $C_p(\alpha_1, \beta_1)$ can be written as in [6],

$$\mathbf{C_p(\alpha_1, \beta_1) = C_1(\frac{C_2}{\alpha_a} - C_3.\beta_1 - C_4).e^{(\frac{-C_5}{\alpha_a})} + C_6} \quad (2)$$

Where,
The values of these constant parameters, denoted as C_1 to C_6, depend on the specific design of both the wind turbine rotor and the blades. Additionally, α_a is a parameter calculated using the following provided equation in [6].

$$\frac{1}{\alpha_a} = \frac{1}{\alpha_1 + 0.08\,\beta_1} - \frac{0.035}{\beta_1^3 + 1} \quad (3)$$

2.3.2 Torque and Power Generation with Variable Wind Speeds

A Permanent Magnet Synchronous Generator (PMSG) is employed in conjunction with wind turbines. The PMSG is designed to maximize power output when wind speeds fluctuate.

It possesses attributes like strong initial torque, minimal rotational inertia, and exceptional efficiency even in challenging conditions such as Frequent Start-Stop Cycles and Low-Speed Operation. Furthermore, PMSGs demonstrate high efficiency and dependable performance in small-scale wind turbine applications [8]. The paper utilizes varying wind speeds while ensuring a consistent DC output voltage from the wind turbine through wind speed adjustments. The main feature of wind speed is its variability [7]. The following Fig. 2, displays a wind turbine model that has been altered through the implementation of switching conditions.

This model uses wind speed and generator speed as inputs to determine the torque exerted on the generator shaft. The torque is influenced by both the generator's speed and power. It incorporates switching conditions, with a Cut-In Speed of 5 m/s and a Cut-Out Speed of 14 m/s, as shown in Fig. 3.

If the wind speed is 5 m/s or higher, it allows a signal to pass, enabling power generation to commence; otherwise, it sends a zero signal. When the wind speed exceeds 14 m/s, known as the Cut-out speed, the wind turbine doesn't provide any

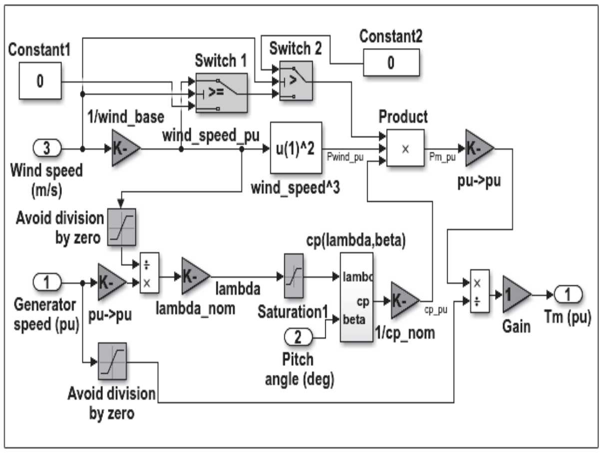

Fig. 2: The Wind Turbine Model (Subsystem)

torque to the generator, resulting in minimal or no power generation. When the speed falls below 5 m/s, the wind turbine also provides zero torque, leading to limited or no power production. In the 5 m/s to 14 m/s speed range, the turbine supplies adequate torque for the generator to develop the necessary power. These switching conditions serve to protect the wind turbine from blade corrosion during uncontrolled wind speeds.

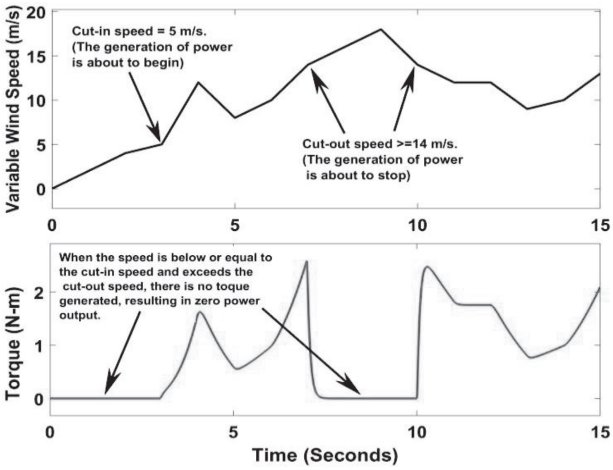

Fig. 3. Variable wind speeds and their impact on torque

2.3.3 Pitch Angle Controller

To prevent wind turbine blade corrosion in high wind speeds, a pitch angle controller is employed. Pitch control aims to regulate the blade angle to attain a specific rotor speed. This involves adjusting the blade pitch angle when dealing with high wind speeds. Pitch angle controller for wind turbine is depicted in Fig. 4.

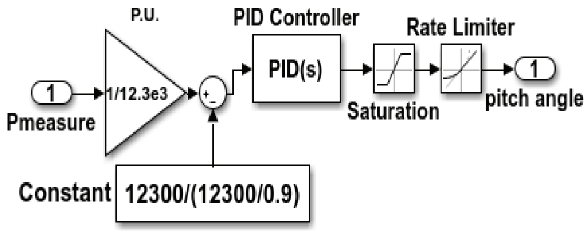

Fig. 4. Pitch angle controller for wind turbine

2.3.4) PID Controller

Various classic control technologies exist, and one of them is the PID Controller. PID Controllers find applications in various sectors, including Industrial Engineering.

The PID Controller equation is as follows [9].

$$G(S) = K_p + \frac{K_i}{S} + K_d S \quad (4$$

To enhance efficiency, it is essential to implement pitch control. A PID Controller is specifically designed for this task. When the wind speed surpasses the rated speed of 12 m/s, the pitch angle should deviate from zero, assuming a certain value. However, when the wind speed falls below the rated speed, the pitch angle should remain at zero. This approach is crucial for safeguarding the blades against damage.

2.4 Designing and Modeling a Photovoltaic Module for Converting Solar Energy

Solar energy is the radiant energy emitted by the sun, which can be captured and transformed into electricity or heat. As a renewable and sustainable power source, it can be harnessed in multiple ways to fulfill our energy requirements.

2.4.1 Photovoltaic (PV) System

Solar panels in photovoltaic systems, made from semiconductor materials, convert sunlight directly into electricity. The solar cells generate an electric current when exposed to sunlight, which can then be utilized to power homes, businesses, and various other uses. Over the last thirty years, researchers have explored the comprehensive mathematical model of solar cells. This model involves components such as a series resistor, parallel resistor (representing leakage current), photo-current and diode. It adheres to both PV Cell Principles and Kirchhoff's Circuit Laws.

The solar cell current can be represented in the following manner in [6],

$$I_{pv} = I_{gc} - I_o[\exp^{(\frac{ev_d}{KFT_c})} - 1] - \frac{V_d}{R_p} \quad (5)$$

The light-generated current (I_{gc}) primarily relies on Solar Irradiation and Cell Temperature, as described in[6],

$$I_{gc} = [\mu_{sc}(T_c - T_r) + I_{sc}]\,G \quad (6)$$

Moreover, the saturation current (I_o) of the cell varies with the temperature of the cell, as explained by,

$$I_o = I_o\alpha(\frac{T_c}{T_r})^3.\exp^{[\frac{ev_g}{KF}(\frac{1}{T_r} - \frac{1}{T})]} \quad (7)$$

$$I_o\alpha = \frac{I_{sc}}{\exp^{(\frac{ev_{oc}}{KFT_c})}} \quad (8)$$

Where,

$I_o\alpha$ = the reverse saturation current of the cell under specific PV radiation and standard temperature values.

V_g = The energy difference of the semiconductor utilized in the cell.

V_{oc} = Voltage measured across the cell's terminals in open circuit conditions [6].

This research constructs a comprehensive photovoltaic (PV) model utilizing MATLAB/ Simulink, ensuring a consistent output voltage despite fluctuations in solar irradiation. The model utilizes cell temperature and solar irradiation as input data, resulting in the production of photovoltaic voltage and current as its outputs. Usually, the parameters for the PV model are obtained from the data sheet provided by the manufacturer.

2.4.2 PV Panel

The main inputs for the proposed photovoltaic module include solar radiation, the temperature of the PV panel, and data from the PV manufacturing datasheet. The research

specifically focuses on the 1Soltech 1STH 215P PV panel, with its key specifications outlined in Table I

Table 1. Photovoltaic Panel

Module	1Soltech 1STH 215P
Parallel strings no	17
Series-connected Module per string	4
Switching frequency, f	10000 Hz
Maximum Power (P_{max})	213.15 Watt
Voltage at peak power output (V_{mp})	29 V
Current at peak Power output (I_{mp})	7.35 A
Open Circuit Voltage (V_{oc})	36.3 V
Short Circuit Current (I_{sc})	7.84

The performance of a solar panel is impacted by two crucial environmental factors: the temperature and the solar radiation intensity of the photovoltaic panel [10]

2.4.3 Maximum Power Point Tracking Method (MPPT)

Solar photovoltaic arrays exhibit non-linear output characteristics due to variations in cell temperature and solar irradiance caused by changing weather circumstances. The maximum power point of a photovoltaic module constantly fluctuates due to uncertain sunlight irradiation. To optimize the performance of the solar module at its peak power point, a Highest Power Point Tracker approach must be employed [12]. Therefore, the Perturb and Observe (PO) algorithm has been incorporated into this model. The PO algorithm adjusts the photovoltaic array's operating current periodically, analyzing changes in photovoltaic output power [6]. To achieve maximum power extraction, the MPPT sets an appropriate duty cycle value for the Insulated Gate Bipolar Transistor (IGBT) switch used in the boost converter. MPPT Incremental Conductance technique with an internal regulator has been designed, involving PI controllers to minimize errors in (dI)/(dV) and I/V values. These adjustments are made to the duty cycle, affecting the output of the DC to DC Boost Converter [6]. The MPPT system is simulated using MATLAB/ Simulink. The maximum power point tracking (MPPT) method is used to obtain the highest power, voltage, and current at the point of maximum power, which are 213.15 watts, 29 volts and 7.35 amps, respectively. The power generated by solar panels is directly proportional to the solar irradiation they receive [11]. Additionally, MPPT plays a role in controlling the inverter's output amplitude, significantly influencing system behaviour [13].

2.4.4 PI Controller

The tuning process is used to determine the values of KP and KI for the PI Controller. The primary function of this controller is to reduce the error between the set point (input power from the PV) and the plant point (output power from the PV). It is incorporated within the Perturb and Observe (P and O) algorithm of Maximum Power Point Tracking (MPPT) to enhance power transfer efficiency through the DC to DC converter [14].
The equations for the PI Controller is as follows in [14],

$$\mathbf{K_P}=\frac{3C}{20\,T_s} \quad \textbf{(9) [14]}$$

$$\mathbf{K_I}=\frac{K_P}{20T_s} \quad \textbf{(10) [14]}$$

3. Modelling and Controlling of Grid-Interactive Inverter

A variety of methods have been employed for developing models and controlling grid interactive inverters, including methods such as Grid Voltage Filtering, Zero-Crossing and PLL (Phase Locked Loop). PLL helps to determine the phase angle from grid voltages, ensuring the inverter produces the necessary phase angle and frequency [8].

Energy generated by a hybrid system combining wind and photovoltaic systems is in AC/DC form with different voltage and frequency levels. Power electronics interfaces are essential components for connecting these systems. These interfaces help to manage the conversion, control, and distribution of electrical power between the system and the grid. Power electronics interfaces help to synchronize the system with the grid. Grid synchronization ensures a seamless connection or disconnection of the system from the grid, preventing any disruptions. This process involves matching the phase and frequency of the system's output with the grid. Power electronic interfaces enhance the quality of the power delivered to the grid. Both photovoltaic and wind systems produce unregulated voltage. To regulate these signals and increase the voltage levels, DC-to-DC boost converters are used in both solar and wind systems. The DC voltages generated by these sources are combined to create a unified DC link voltage. This stable voltage is then fed into a Voltage Source Inverter (VSI), which converts the DC signals into AC. The AC output from the inverter is subsequently synchronized with the grid voltage through a Phase-Locked Loop (PLL).

The synchronization process guarantees that the inverter's output matches the grid's voltage and frequency, enabling the smooth integration of the hybrid system's energy into the grid. Once the hybrid system's output is aligned with the grid, it can be securely connected to the electrical grid, delivering renewable energy to consumers.

3.1 Design and Simulation of a Voltage Source Inverter.

A Voltage Source Inverter (VSI) is utilized to produce grid voltage in the AC form when connected to the grid. The VSI is designed in three components.

3.1.1 Three-Phase DC/AC Inverter

DC (Direct Current) signal is transformed into an AC (Alternating Current) signal using an inverter. A Voltage Source Inverter (VSI) with three phases is designed to change DC voltage into adjustable AC voltage with varying magnitude and frequency. This inverter comprises six switches (S1 to S6) and connects each phase output at the middle of every inverter leg [15]. To regulate the inverter's output AC voltage, three reference signals are compared with a high-frequency carrier waveform. The comparison results are employed to turn the switches ON or OFF in each leg, ensuring the avoidance of a dead short circuit in the DC supply through the interchangeable operation of switches. The proposed system, Voltage Source Inverter (VSI), is depicted in Figure 6. The Voltage Source Inverter (VSI), integrated with a Phase-Locked Loop (PLL) and control circuitry, enables bidirectional control between the hybrid system and the grid. Sinusoidal Pulse Width Modulation (SPWM) controls the output voltage of a Voltage Source Inverter (VSI) by comparing a sine wave reference signal with a high-frequency triangular carrier signal. According to the model proposed in [17] the equations are given below,

$$\mathbf{V_{ref}(t) = V_m Sin(\omega t)} \quad \mathbf{(11)}$$

$$\mathbf{m = \frac{V_m}{V_{carrier}}} \quad \mathbf{(12)}$$

Where:

V_m is the peak value of the sine reference signal,

ω is the angular frequency,

$V_{carrier}$ is the peak value of the triangular carrier signal,

m is the modulation index which controls the output voltage amplitude.

SPWM provides simple implementation and good harmonic performance in linear modulation range [17].

3.1.2 Phase Locked Loop

PLL is a closed-loop frequency control method used to synchronize the output voltage of the converter with the grid's voltage and current. It determines the angle of the grid voltage for the dq coordinates, functioning as a subsystem within the three-phase inverter (VSI) [16].

Additionally, a vector control method is used to regulate the three phase voltage source inverter (VSI) and align it with the utility grid. This includes incorporating a phase-locked loop (PLL) for synchronization purposes. Furthermore, a PI controller is included in the PLL setup to eliminate the Point of Common Coupling (PCC) voltage component and determine the synchronization angle. The vector control method enables the independent regulation of active and reactive power. The proposed system PLL circuitry is depicted in figure 7.

3.1.3 Current Controller

This system is a component of the inverter and manages the current flowing from the hybrid source to the grid. The current magnitude fluctuates due to changing irradiation levels in PV systems and varying wind speeds in wind systems over time. To ensure the grid receives the necessary current, this current controller is essential. A PI Controller-based approach is employed for this current control scheme. The proposed system grid current controller circuitry is depicted in figure 8.

3.1.4 Control of Power on the Grid Side

The grid-connected inverter uses power-controlled methods to ascertain the required control configurations. Maintaining a steady DC voltage enables the transmission of real power from the hybrid system, which is connected to both PV and wind sources, to the grid. To calculate the required generation of reactive power, different control techniques such as KVAR, current, voltage, and power factor can be employed [4].

Table 2. Specification of Apparatus of the Proposed System

Apparatus	Specification
Turbine	Nominal Mechanical Rated Output Power = 12.3 KW
	Power Factor = 0.9
	Grid Integration Voltage Level = 400V
	Frequency = 50 Hz
	Torque Generation : 2.588 N.m (Max)
Transformer	Three-Phase Two-Winding Transformer
	Star Connection in both Winding,
	Nominal Power = 100 KVA
	Turn Ratio = 2: 5
Loads	3-Phase Series RL Load (Inductive Reactive Power, Q_L = 800 VAR and Active Power, P = 1000 W)
	3-Phase Series RLC Load (Inductive Reactive Power, Q_L = 900 VAR, Capacitive Reactive Power, Qc = 400 VAR and Active Power, P = 1000 W)
Battery	Nominal Voltage = 7.2 V
	Rated Capacity = 5.4 Ah
Generator	Permanent Magnet Synchronous Generator.
	Rotor Type : Salient Pole
	Rated Generator Speed = 74.76 rpm

Table 3. Parameter Rating of the Proposed System

Grid Voltage	Grid Current	Grid Power
400 V	(3.94 – 5.388) A	(1328 - 1588) W

In the proposed circuit, the grid voltage consistently remains at 400V, irrespective of the type of load. Only the grid current and power exhibit slight variations. Additionally, all parameters of the inverter-such as current, voltage, and power-as well as those of the solar and wind systems, including the DC voltage of the circuit, remain constant across different load configurations.

Table 4. Controller Functions and Specification of the Proposed System

Controller	Function	Specification
PI Controller	Design inside the PLL(Phase Locked Loop) for grid synchronization	Proportional gain, Kp = 10 Integral gain, Ki = 10
PI Controller	Design for grid current control	Proportional gain, Kp = 10 Integral gain, Ki= 100
PI Controller	Design inside the MPPT circuit of PV system for defining maximum operating point	Proportional gain, Kp = 10 Integral gain, Ki = 0.79
PID Controller	Design for pitch angle control of wind turbine system	Proportional gain, Kp = 0.1 Integral gain, Ki = 0.02 Differential gain, Kd = 0.01

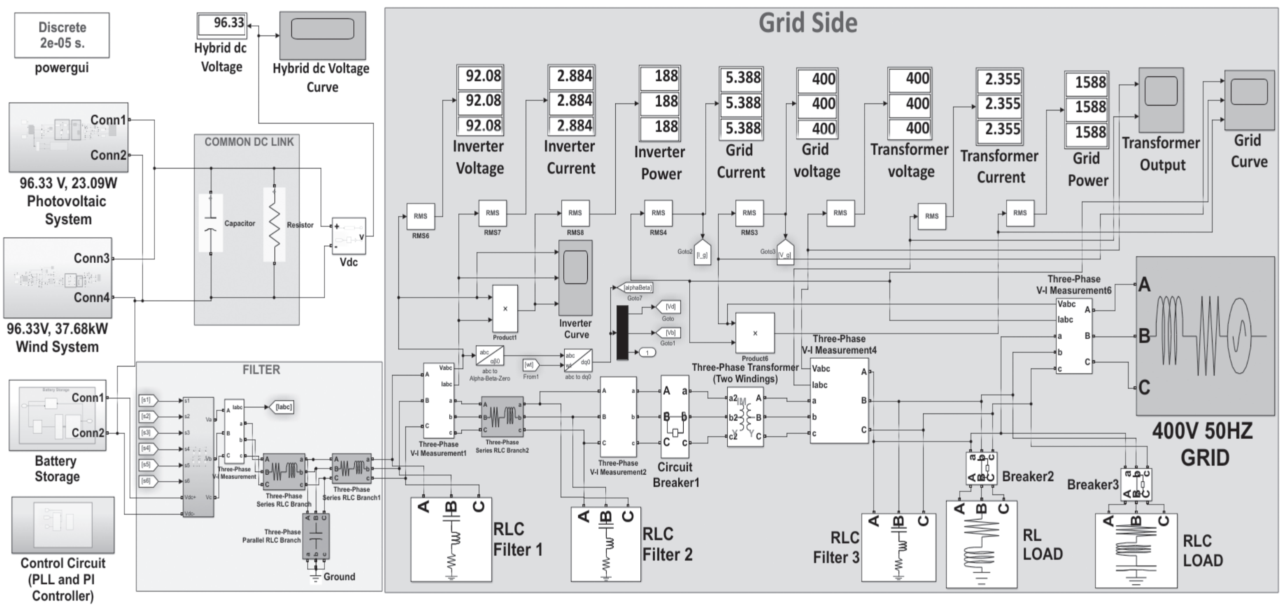

Fig. 5. Grid Connected Hybrid (Wind and Photovoltaic) system MATLAB/ Simulink Model

The proportional and integral gains are determined using the Transfer Function-based Tuner method, which adjusts the controller parameters to meet the specific performance requirements of the system.

A PI controller is designed with in the inverter for the purpose of grid current control. To achieve grid synchronization, PI controller is incorporated inside the Phase-Locked Loop (PLL). In the wind system, a PID controller is designed specifically for pitch angle control. Within the Photovoltaic system, a PI controller is implemented to establish the maximum operating point of the Maximum Power Point Tracking (MPPT). The percentage overshoot values for the R, Y, and B phases when utilizing a PID controller are 0.503%, 0.500%, and 0.502%, respectively. However, when applying a PI controller, the percentage overshoot for the R, Y, and B phases is 0.327%, 0.367%, and 0.357%, respectively. The choice of a PI controller, as opposed to a PID controller, is made for grid current control in the inverter. This decision is influenced by the fact that the % overshoot in grid current increases, although the overshoot in inverter current decreases when a PID controller is used. The implementation of a PI controller aims to reduce the steady-state error of the output signal, ensuring that the offset value of the signal remains zero

3.2 Schematic Diagram

3.2.1 Circuit Diagram of the Grid-Connected Hybrid System

The proposed grid-connected hybrid system has been effectively implemented using MATLAB/Simulink software, as illustrated in Fig. 5.

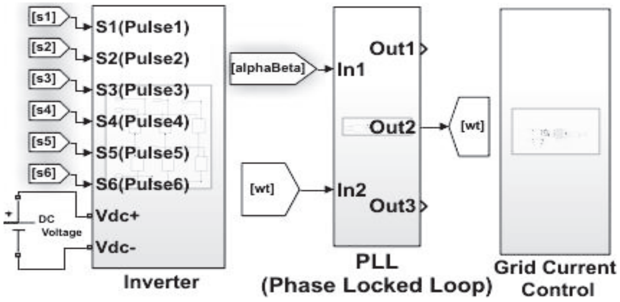

Fig. 6. Three-phase Voltage Source Inverter (VSI) connected with PLL and Control Circuitry

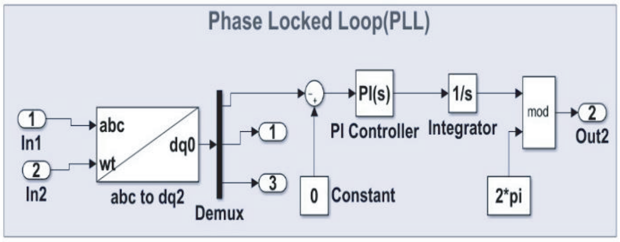

Fig. 7. Modeling and Simulation of a PLL Circuit in MATLAB/Simulink.

4. Simulation Result

4.1) Simulation Result of the Hybrid System

The proposed design is intended to efficiently handle variations in wind speed and solar irradiation, maintaining a consistent hybrid system output voltage of 96.33 volts DC, as illustrated in Figure 9.

4.2 Simulation Result of the Inverter

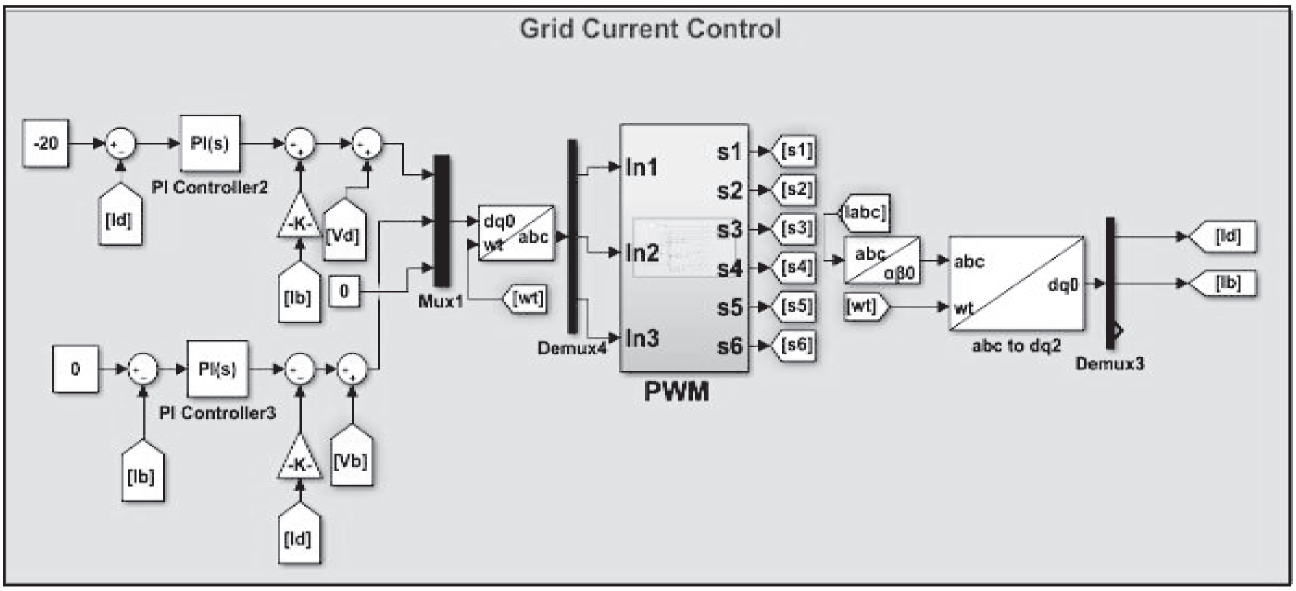

Fig. 8. Control Circuitry using MATLAB/Simulink

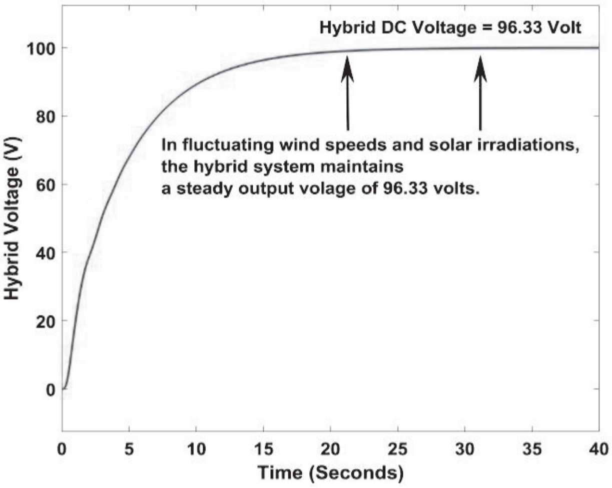

Fig. 9. DC Voltage Curve of Hybrid System

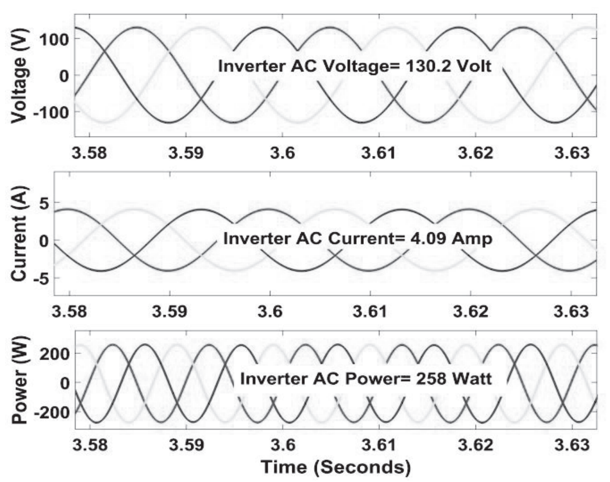

Fig. 10. AC Output Voltage, Current, and Power from the Three-Phase Inverter

4.3 Simulation Result from the Grid Analysis

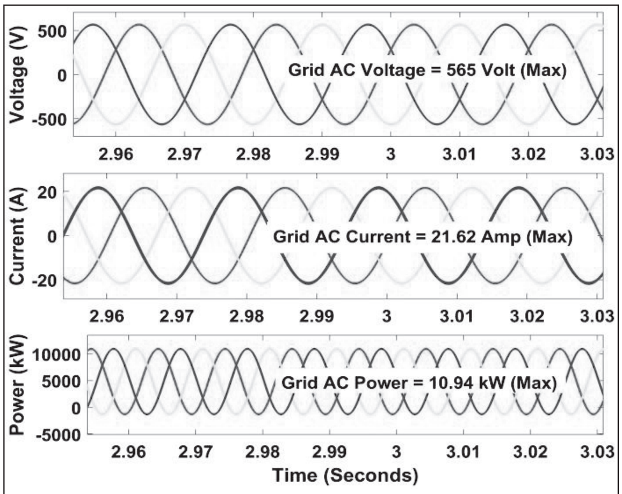

Fig. 11. Grid AC Output Voltage, Current and Power

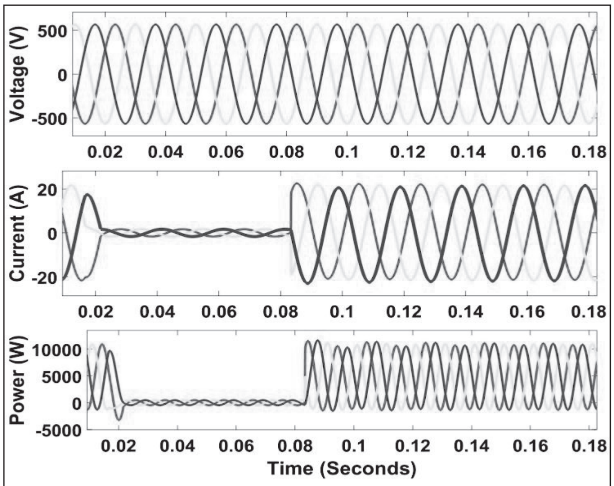

Fig. 12. Grid Synchronization

4.4 Outcomes of Overshoot and Total Harmonic Distortion (THD)

The Overshoot and Total Harmonic Distortion are shown in Fig.13 and 14, respectively.

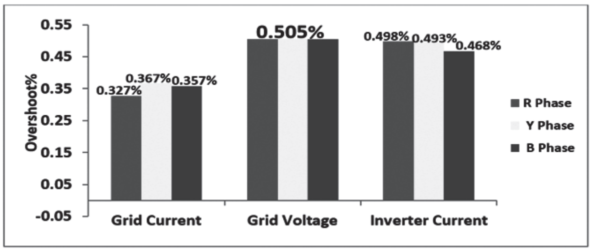

Fig. 13. Overshoot Graph

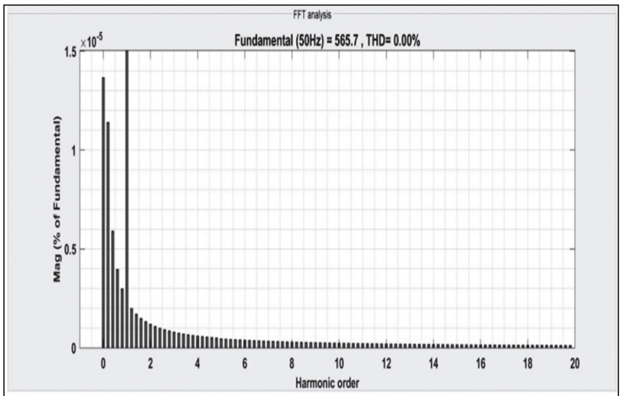

Fig. 14. THD Graph for the R phase of the Grid Voltage

4.5 Simulation Results Analysis

In Fig. 10, the maximum AC output voltage, current, and power from the three-phase inverter are 130.2 V, 4.09 A, and 258 W, respectively. In Fig. 11, grid signals are depicted and in Fig. 12, the synchronization of grid signals are illustrated. In Fig. 13, all signals exhibited desirable overshoot values, affirming the system's robust performance. Specifically, within the brief time interval from 0.1 seconds to 0.12 seconds, the grid voltage overshoot remained consistently low at 0.505% for all three phases. Concurrently, the R phase displayed a minor 0.327% current overshoot, while the Y phase demonstrated a mere 0.367% overshoot, and the B phase exhibited a slight 0.357% overshoot during the same 15-second time period. The overshoot values for Inverter current were observed at 0.498% for the R phase, a modest 0.493% for the Y phase, and 0.468% for the B phase. In Fig. 14, the paper demonstrates excellent Total Harmonic Distortion (THD) levels, indicating the generation of a high-quality sinusoidal AC signal even when dealing with fluctuating wind speed and solar irradiation. It consistently delivers a stable voltage to the grid. In grid voltage, there is a 0% THD for all three phases. A similar THD analysis reveals that the grid current for the R, Y, B phases is 0.11%, 0.13%, and 0.24% sequentially.

The main contributions of this paper include the generation of a consistent voltage output under varying wind speeds and solar irradiance conditions; the attainment of favorable Total Harmonic Distortion (THD) values (below 2%) for all signals (voltage and current); and achieving a 0% THD for the grid voltage, indicating that the three-phase grid voltage signals are purely sinusoidal. Additionally, a wind circuit has been implemented to protect turbine blades and to enable a shutdown of power generation when wind speeds fall below the cut-in threshold or reach/exceed the cut-out speed. The system also demonstrates improved responsiveness to fluctuating inputs, resulting in a shorter rise time and acceptable overshoot percentages in the grid signals. In the end, the objective of this Hybrid System is to provide consumers with reliable, consistent and highly efficient power, and the simulation outcomes surpass the results presented in the paper.

5. Conclusion

This research paper explores the design and implementation of a grid-connected hybrid system that integrates wind energy and photovoltaic (PV) sources using MATLAB/Simulink. The proposed design aims to effectively manage fluctuating wind speeds and solar irradiation, ensuring a steady hybrid system output voltage of 96.33 volts DC despite variations in both parameters in wind and PV system which is depicted in figure 9. The system maintains its stability at 96.33 volts DC even when range of wind speeds from 5 m/s to 14 m/s and solar irradiation varies between 500 W/m² to 1200 W/m².

To achieve this stability within the specified parameters, the system utilizes a Pitch Controller, PID Controller, and PI Controller, which adjust the electrical characteristics of the wind turbine.

Additionally, Boost converters are ingeniously utilized in both photovoltaic (PV) and wind systems to elevate the wind voltage from 88.33 to 96.33 volts DC and the PV voltage from 15.33 to 96.33 volts DC. This seamless adjustment impeccably aligns with the system's consistent output voltage of 96.33 volts DC and exemplifies the system's exceptional engineering ingenuity and precision. Additionally, a rectifier is utilized in the wind turbine system to convert the turbine-generated AC voltage into DC, while an inverter is incorporated into the overall hybrid system (integrating solar and wind) to convert the DC voltage to AC. This AC voltage is then supplied to the 400-volt 50-Hz grid. The 400-volt grid voltage remains stable even during variations in wind speed and PV irradiation. Grid synchronization was flawlessly achieved within an impressive 83-millisecond timeframe, showcasing exceptional efficiency. This remarkable accuracy highlights the system's superior performance and strict adherence to requirements. In the suggested circuit configuration, the battery is intended for the storage of energy. It undergoes charging through the hybrid DC section and subsequently operates as a source of DC power to fulfill the energy requirements of DC loads. In the context of this Hybrid System, both the grid voltage and current exhibit a rise time of 5.8 milliseconds, indicating that the system responds rapidly. Rise time functions as a measure of a system's ability to react swiftly to alterations in input. A shorter rise time corresponds to a quicker response, whereas a longer rise time implies a slower response. In this study, multiple categories of loads have been integrated and analyzed.

The THD values of all signals in the proposed system are below 2%, compared to approximately 5% reported in a referenced study. This significant improvement highlights a major contribution of the proposed system, made possible by its integrated controllers and filters. Furthermore, all signals demonstrate acceptable overshoot and rise time.

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