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Design And Development Of Hybrid Renewable Energy Source For Grid Integration

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Abstract
Growing depletion of fossil fuel reserves has created a critical demand for robust, scalable renewable energy solutions. The inherently intermittent nature of individual solar and wind resources posed significant operational challenges, impacting the reliability and consistency of power generation The paper focuses on the design, simulation, and experimental validation of a hybrid solar–wind renewable energy system for grid-connected applications. The system integrates photovoltaic (PV) and wind subsystems via a common DC link, interfaced to the grid through a two-level Voltage Source Inverter (VSI). To maximize power capture, Maximum Power Point Tracking (MPPT) algorithms are applied: Perturb & Observe (P&O) for PV and Tip-Speed Ratio (TSR) with Optimal Torque Control for wind. A DQ-frame current controller with a Phase-Locked Loop (PLL) ensures synchronized grid injection, regulates active and reactive power, and minimizes Total Harmonic Distortion (THD). The system is developed in MATLAB/Simulink and validated using a scaled hardware prototype comprising a MOSFET-based inverter, Arduino-driven PWM control, and optical driver circuits. Experimental results demonstrate balanced three-phase outputs of 60 V RMS (PV mode) and 54 V RMS (wind mode), with 120° phase-shifted sinusoidal waveforms, closely matching simulation results. The findings confirm the feasibility, reliability, and scalability of the proposed hybrid system for future smart grid integration and renewable energy expansion.
Keywords: *Hybrid renewable energy, Maximum power point tracking, Perturb & Observe (P&O), DQ-frame current control, Grid synchronization*

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I. Introduction

The global shift toward sustainable energy generation has accelerated the deployment of renewable energy systems (RES), with solar photovoltaic (PV) and wind energy emerging as the two most dominant sources [1]. While these resources offer significant potential to reduce carbon emissions and dependence on fossil fuels, their inherent intermittency poses a challenge to grid reliability, voltage regulation, and power quality [2]. Solar energy output fluctuates with irradiance, and wind generation varies with wind speed, resulting in unstable power delivery if used as stand-alone systems [3].

To mitigate these challenges, hybrid solar–wind energy systems have become increasingly popular. By leveraging the complementary nature of solar and wind resources, hybrid systems can deliver more consistent power output compared to single-source systems [4], [5]. However, integrating such systems into the grid requires sophisticated control strategies and power electronic interfaces to manage variability, ensure grid synchronization, and maintain power quality standards [6],[7]. The work focuses on the design, simulation, and hardware validation of a hybrid solar–wind system, utilizing a two-level Voltage Source Inverter (VSI) as the main grid interface. The system employs Maximum Power Point Tracking (MPPT)—Perturb & Observe (P&O) for the PV array and Tip-Speed Ratio (TSR) with Optimal Torque Control for the wind turbine to maximize power extraction under dynamic environmental conditions[8],[9]. Additionally, a DQ-frame current control strategy integrated with a Phase-Locked Loop (PLL) is used to regulate active and reactive power and minimize Total Harmonic Distortion (THD).

II. Proposed System

The proposed hybrid system integrates solar photovoltaic (PV) and wind energy units, each linked through a DC–DC boost converter to a shared DC bus. Regulated DC output from both paths supplies a two-level Voltage Source Inverter (VSI) for conversion into three-phase AC power. An LC filter reduces switching harmonics, ensuring the power quality limits. A controller executes MPPT algorithms for both sources, adjusts converter duty cycles, and applies DQ-frame current regulation with a Phase-Locked Loop (PLL) for grid-synchronized operation. Fig. 1 illustrates the configuration, showing energy flow from sources to grid.

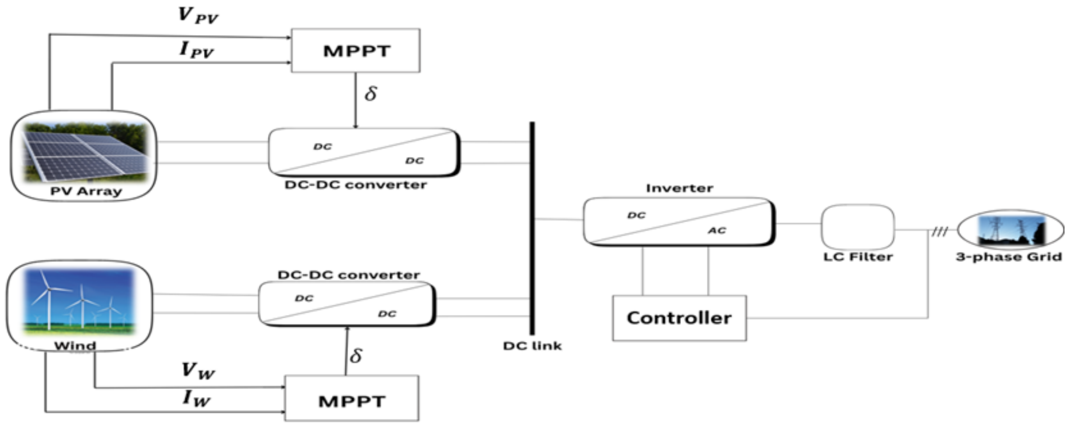

Fig.1 Block diagram of proposed system

III. Modelling And Simulation

The system employs MPPT control for both sources and a DQ-frame VSI current control strategy to achieve stable grid-connected operation. The overall control structure ensures maximum energy harvesting, voltage stability, and harmonic reduction.

MPPT Algorithm

For the PV subsystem, the Perturb and Observe (P&O) algorithm dynamically adjusts the duty cycle of the boost converter to maximize power. The duty cycle is updated using equation (1):

$$D(k+1) = D(k) + K_p \, . sgn\, (P(k) - 1)) \qquad (1)$$

where D(k) is the duty cycle at iteration k, K_p is the perturbation step, and P(k) is the measured PV power.

For the wind subsystem, a Tip-Speed Ratio (TSR) method ensures the turbine operates at its optimal speed-to-wind ratio. The reference generator speed is given by equation (2):

$$\omega_{ref} = \frac{\lambda_{opt} \cdot v_\omega}{R} \qquad (2)$$

where λopt is the optimal TSR, v_ω is wind speed, and R is rotor radius. The boost converter duty cycle is then adjusted to maintain the operating point corresponding to ω_{ref} [5], [6].

DQ-Frame Current Control

The Voltage Source Inverter (VSI) operates under a synchronous reference frame (DQ) current control strategy supported by a Phase-Locked Loop (PLL). The D-axis current governs the flow of active power, while the Q-axis current regulates reactive power to maintain grid stability. The control relationships are given by equation (3),(4):

$$v_{sd} = v_{gd} + R_s i_d + L_s \frac{di_d}{dt} - \omega L_s i_q + K_{pd}(i_d^* - i_d) \qquad (3)$$

$$v_{sq} = v_{gq} + R_s i_q + L_s \frac{di_q}{dt} - \omega L_s i_d + K_{pd}(i_q^* - i_q) \qquad (4)$$

where id* and iq∗ represent reference currents derived from specified active and reactive power targets, Rs and Ls denote filter parameters, ω is the grid angular frequency, and Kpd and Kpq are proportional-integral (PI) control gains.

The PLL ensures synchronization of the inverter’s output voltage angle with the grid, enabling the generation of sinusoidal, balanced, and phase-aligned currents across all phases.

Simulation Model

The MATLAB/Simulink model is developed to evaluate the performance of the hybrid solar–wind energy system under dynamic environmental conditions. The architecture integrates photovoltaic (PV) and wind subsystems, each connected to a common DC link through individual DC–DC boost converters for voltage stabilization and coordinated power delivery.

Maximum Power Point Tracking (MPPT) is implemented on both channels, employing the Perturb and Observe (P&O) method for the PV array and a Tip-Speed Ratio (TSR) approach with Optimal Torque Control for the wind turbine emulator. The regulated DC link supplies a two-level Voltage Source Inverter (VSI), controlled using a DQ- frame current regulator with a Phase-Locked Loop (PLL) to maintain phase and frequency synchronization with the grid while managing active and reactive power exchange.The simulation framework includes measurement blocks for tracking DC bus voltage, inverter phase voltages, line currents, and real-time power flow. System behaviour is analyzed under solar irradiance variations (200–1000 W/m²) and wind speed fluctuations (4–10 m/s) to verify voltage regulation, power tracking accuracy, and harmonic performance. The overall Simulink configuration is presented in Fig. 2

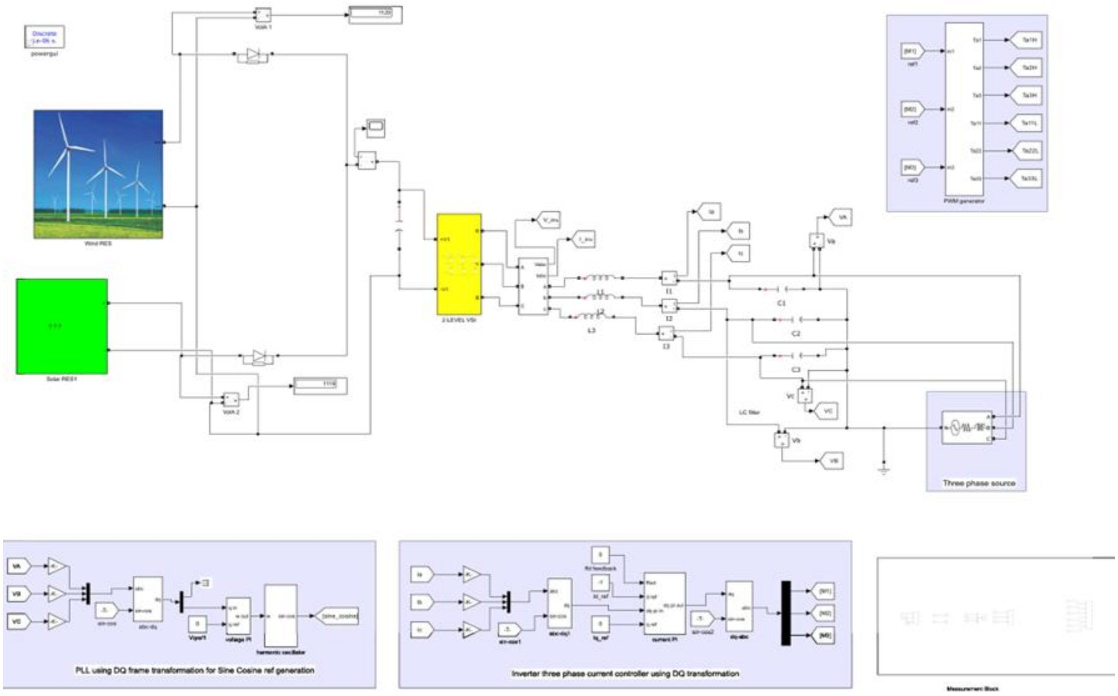

Fig.2. Proposed system model

IV. Hardware Implementation

The hybrid solar–wind energy system is implemented and to validate the operational performance of the proposed design. The configuration reflects the simulated model while operating under regulated voltage and power conditions to facilitate reliable results.

Hardware Configuration

Hybrid solar–wind energy system constructed as shown in Fig.3 integrates a 0–16 V, 10 W photovoltaic (PV) module paired with a battery interface to maintain a stable energy supply during irradiance fluctuations, along with a wind energy emulator derived from a 230 V AC source, stepped down, rectified, and filtered to provide a regulated DC input. Both sources feed two dedicated boost converters, each designed with toroidal inductors, high-capacitance output filters, and PWM-controlled duty cycles, elevating the source voltages shared to DC bus. The unified DC output powers a MOSFET-based three-phase Voltage Source Inverter (VSI), operated through an Arduino UNO (ATmega328P) control platform supported by CD4050 logic buffers and TLP250 optically isolated gate drivers to ensure reliable switching.

Stable operating voltages for the control and driver circuits are supplied by LM7805 and LM7812 linear regulators. The inverter output is given to the resistor load in star connected.

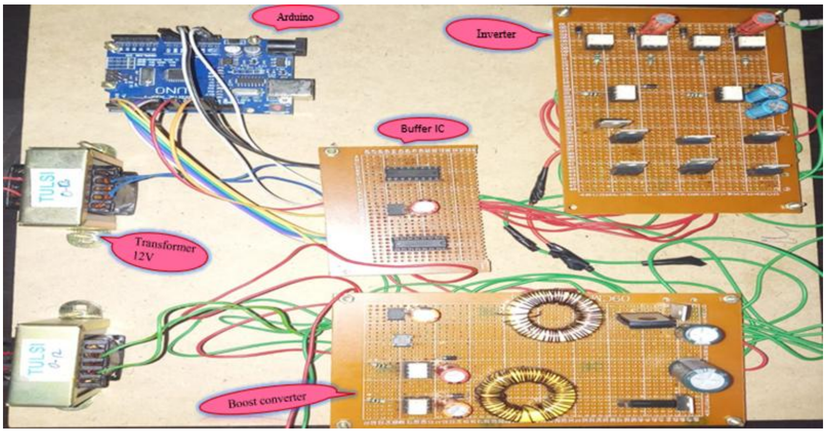

Fig.5 Hardware implementation

Design of Boost converter

The boost converter function as the DC–DC interface for both photovoltaic and wind energy sources, stepping up variable input voltages to a regulated level for the shared DC bus. During the switch-on interval, energy is stored in the magnetic field of the inductor, while the diode remains reverse-biased. When the switch turns off, the inductor releases stored energy, combining with the source to charge the output capacitor and supply the load, thereby achieving a voltage step-up effect.

The output voltage is determined by:

$$V_{dc} = \frac{V_s}{1 - D}$$

where Vs represents the source voltage, DDD denotes the duty cycle, and Vdc is the boosted DC output.
For continuous conduction mode (CCM) operation, the inductor value L is given by:

$$L = \frac{V_{in} \,.\, D}{f_s \,.\, \Delta I_L}$$

where ΔIL is the peak-to-peak inductor current ripple and fs is the switching frequency. The output capacitor CCC is selected as:

$$C = \frac{I_{out} \,.\, D}{f_s \,.\, \Delta V_{out}}$$

where Io is the load current and ΔVo is the allowed output voltage ripple.

V. Results And Analysis

Simulation Result

The output characteristics of the hybrid solar–wind system are shown in Fig. 4 presents simulated power responses of wind, solar, and combined outputs. Wind generation shows a rapid surge exceeding 10,000 W immediately after system startup, followed by moderate fluctuations and a gradual decrease over a 5-second interval, characterizing variability typical of wind sources. Solar output stabilizes near 2,000 W at peak and sustains a uniform level, confirming effective source coordination and reliable energy delivery from the hybrid system.

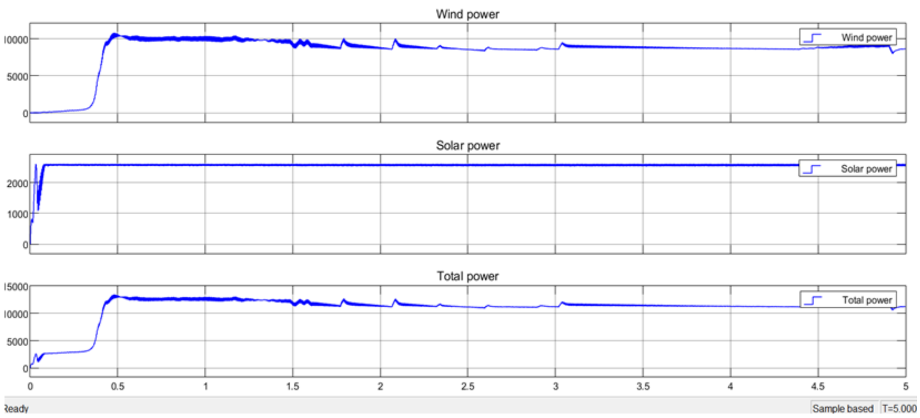

Fig.4 Waveforms of wind, solar and total power generated

The three-phase output current waveforms, labelled IA, IB, and IC as seen in Fig.5, each maintaining a sinusoidal shape with a consistent 120-degree phase displacement. Amplitude and frequency remain stable, indicating balanced current injection and minimized harmonic presence. The waveform symmetry reflects proper functioning of the grid-interfaced inverter, with each phase.

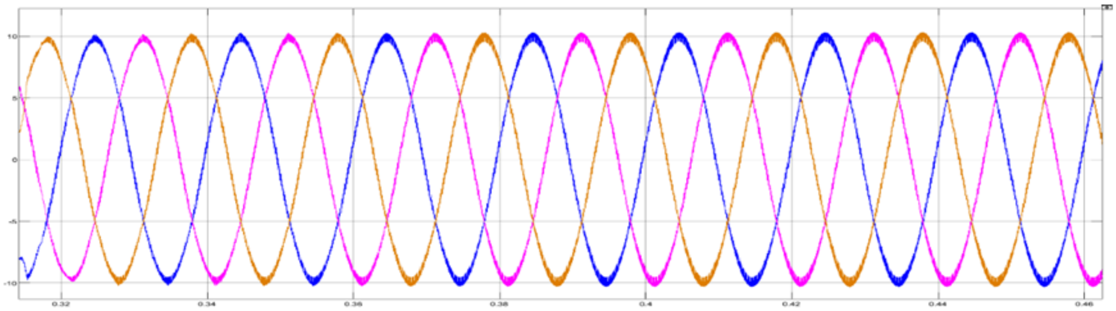

Fig.5 Grid current

The three-phase voltage waveforms of grid and inverter presented in Fig. 6 demonstrate symmetrical sinusoidal profiles across all phases, with each waveform separated by 120 degrees. Voltage magnitudes approach 400 units, indicating effective amplitude regulation. Phase alignment and waveform purity reflect proper operation of the inverter and modulation strategy. Absence of harmonic distortion or imbalance indicates high-quality output, fulfilling voltage waveform integrity required for grid integration. The inverter control and synchronization and three-phase voltage delivery under continuous operation.

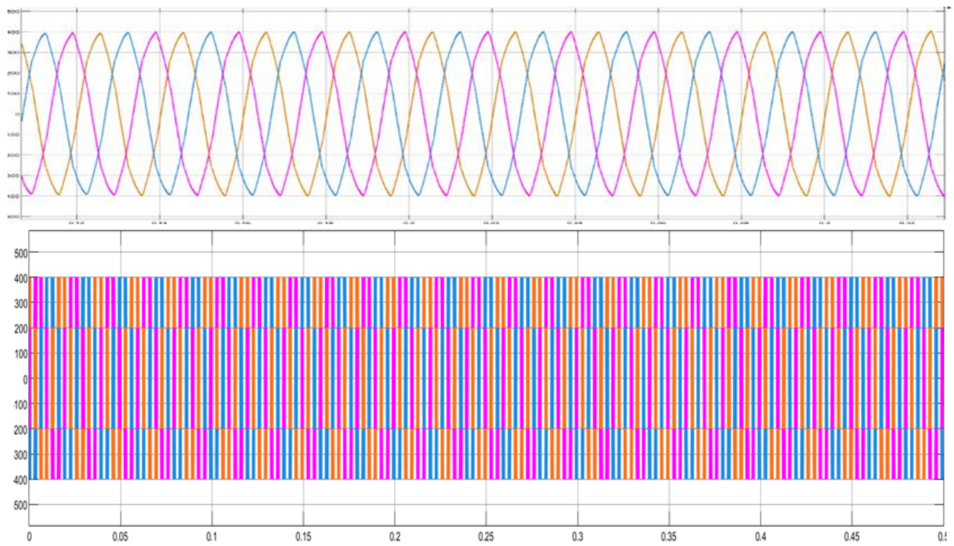

Fig.6 Grid Voltage and Inverter voltage

Hardware Results

The waveform depicted in Figure.7 illustrates the output of a DC–DC boost converter, with a measured Vrms of 7.2 V on Channel 1. The signal trace reveals a consistent and flat profile, indicating a stable DC level with minimal ripple.

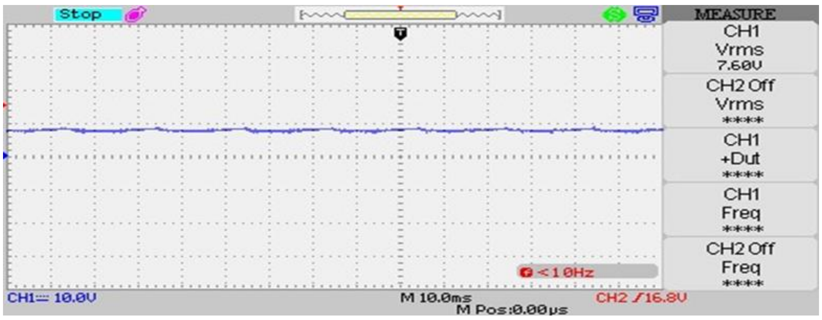

Figure.7 Output voltage of boost converter of wind RES

The output voltage waveform of the boost converter as shown in the figure 8, with Channel 1 measuring 7.60 Vrms. The trace exhibits a stable DC profile with minimal deviation, indicating consistent output regulation

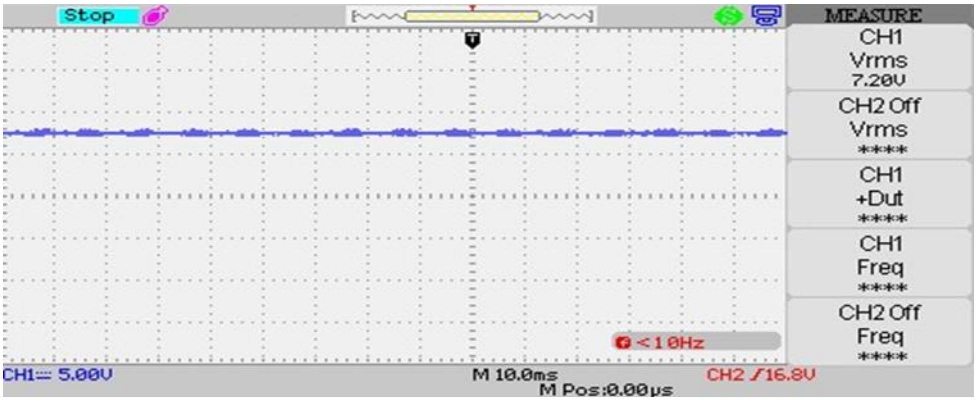

Figure.8 Output voltage of boost converter of solar RES

The oscilloscope waveforms captured in Figure.9 illustrates the voltage output characteristics of a two-level Voltage Source Inverter (VSI) supplying a three-phase load. the RMS voltage reaches a value of 5.80 V, accompanied by a duty cycle of 51.28% and a fundamental frequency of 42.96 Hz. Subsequent measurements yield an RMS voltage of 5.40 V with a corresponding duty cycle of 35.57%, while maintaining the same operating frequency. The third waveform presents an RMS voltage of 5.60 V, a duty cycle of 49.23%, and sustains the frequency at 42.96 Hz. A phase shift among the waveforms, by combining all three waveforms, a balanced three-phase output with 120 degree phase shift.

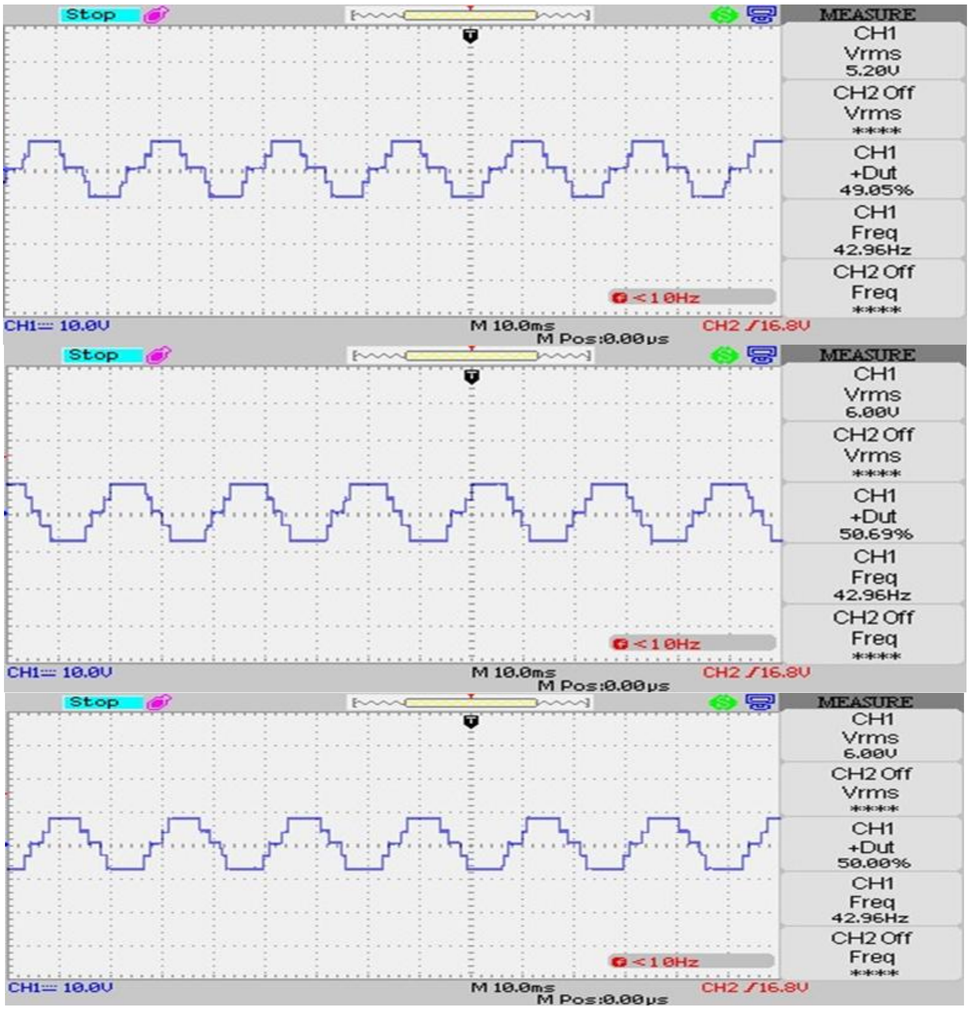

Figure.9 Three phase Inverter output voltage

VI. Conclusion

A hybrid renewable energy architecture combining solar photovoltaic and wind inputs was developed using coordinated DC–DC converters and control mechanisms. Independent MPPT algorithms ensured optimal energy harvesting under dynamic conditions. A unified DC link enabled stable integration of both sources, feeding a three-phase inverter for grid interfacing. The system delivered synchronized sinusoidal output with 120° phase displacement, confirming grid compatibility, voltage regulation and effective power transfer.

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