

Design and Functional Analysis of Battery Energy Storage Systems for Renewable Power Applications

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Abstract – The increasing penetration of renewable energy sources in modern power systems has introduced significant challenges related to power quality, stability, and reliability due to their inherent intermittency. To address these issues, this thesis presents the design, modeling, and performance analysis of a hybrid renewable energy system integrated with a battery energy storage system (BESS) for power quality optimization. The proposed system combines solar photovoltaic (PV) and wind energy sources with a battery storage unit through a common DC bus, enabling coordinated energy management and continuous power delivery under varying environmental and load conditions. An enhanced Perturb and Observe (P&O) maximum power point tracking (MPPT) algorithm is developed to improve energy extraction from the PV system. The proposed MPPT technique incorporates adaptive perturbation step sizing, anti-misdirection logic, and oscillation suppression near the maximum power point, resulting in faster convergence, reduced steady-state oscillations, and improved tracking accuracy compared to conventional P&O methods. This enhancement contributes to improved DC-link voltage stability and reduced voltage and current ripples. Power quality analysis reveals a Total Harmonic Distortion (THD) of 5.34%, which complies with IEEE 519 standards, confirming the effectiveness of the inverter modulation and control techniques in producing a near-sinusoidal output voltage. Overall, the proposed hybrid renewable energy system with intelligent control and enhanced MPPT provides an efficient, stable, and high-quality power supply, making it a viable solution for modern grid-connected and standalone renewable energy applications.

Keywords: Hybrid Renewable Energy System; Solar Photovoltaic (PV); Wind Energy Conversion System; Battery Energy Storage System (BESS); Power Quality Improvement;

I. Introduction

An electrical system incorporating energy storage devices and distributed generation can greatly benefit from the integration of Battery Storage Systems (BSS). Most conventional electricity generation relies on centralized power plants, which offer economies of scale but suffer from high transmission losses and environmental pollution. The deployment of distributed generation combined with BESS allows energy to be stored close to the point of use, reducing transmission losses, improving supply reliability, and decreasing the need for additional infrastructure such as power lines.

BSS technology enables the accumulation and controlled release of energy from multiple sources, including solar PV, wind, and other renewable or conventional generators. It can balance supply and demand in real time by absorbing excess energy when generation exceeds load and releasing energy during deficits. Additionally, BSS can smooth rapid fluctuations in power output, enhance system stability, and improve power quality by providing fast response to transient events.

Advanced energy storage configurations often combine BSS with supercapacitors to create multilevel energy storage systems. While BSS provides bulk energy storage for long-term balancing, supercapacitors handle short-term fluctuations and transient loads due to their high power density and fast response capabilities. This combination ensures optimal utilization of stored energy, prolongs battery life, and reduces operational stress on the storage system.

Modern BSS solutions include lithium-ion, lead-acid, and other battery chemistries, integrated with intelligent energy management systems that optimize charging, discharging, and overall system operation. These systems can operate autonomously or in coordination with distributed generators, making them suitable for residential, commercial, and industrial applications. By providing load leveling, peak shaving, backup power, and voltage/frequency support, BESS plays a crucial role in improving the reliability, efficiency, and sustainability of modern electrical systems.

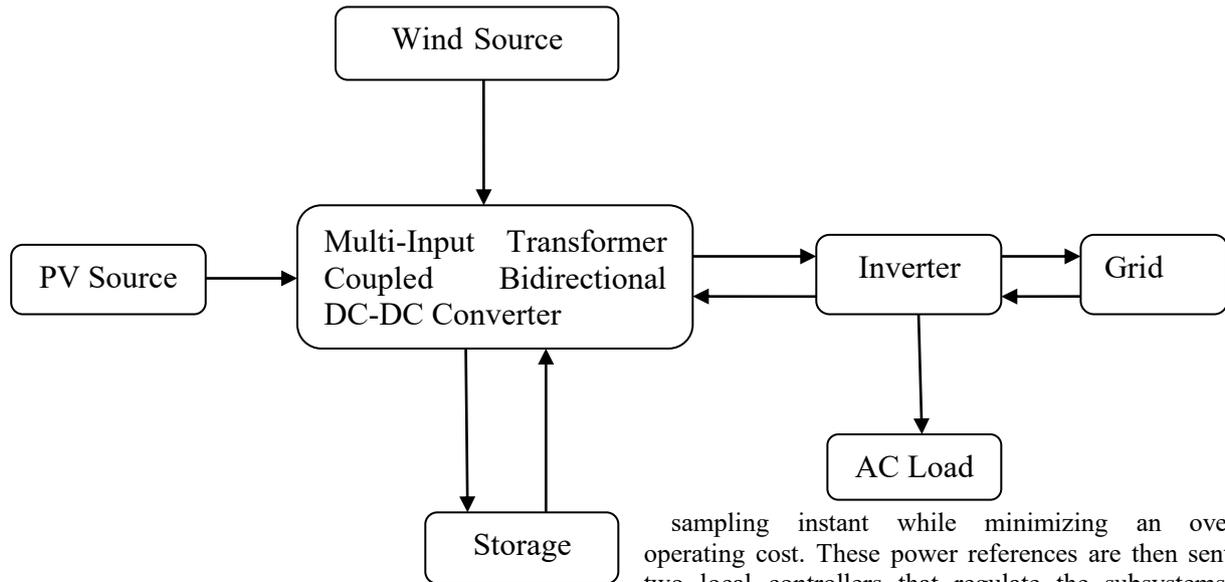


Fig.1 Grid-connected hybrid PV-wind-battery based system

II. Literature Review

Qingsong Wang et al [1], “Design and analysis on different functions of battery energy storage system for thermal power units frequency regulation”, In this study, a comprehensive simulation model of a BESS-assisted frequency regulation system is developed using MATLAB/Simulink. The model is employed not only to evaluate system performance during steady-state operation but also to examine and validate operational strategies when faults occur. Simulation results demonstrate that, under normal conditions, the incorporation of energy storage reduces grid frequency deviation by 38.1% and enhances power response speed by at least a factor of 25 compared to conventional regulation methods. Furthermore, the total harmonic distortion of the grid-connected voltage and current is limited to 2.54% and 1.72%, respectively, indicating excellent power quality. Under fault conditions, an adaptive protection strategy is implemented in which the BESS is selectively connected to or disconnected from the system based on predefined boundary criteria. This approach effectively safeguards the energy storage system, extends battery lifespan, and minimizes maintenance requirements for associated equipment.

W. Qi et al. [2], “Supervisory Predictive Control of Standalone Wind/Solar Energy Generation Systems,” This work focuses on developing a higher-level predictive control strategy for the efficient management and operation of standalone hybrid wind-solar energy systems. The supervisory system is designed using model predictive control, which calculates power reference values for the wind and solar subsystems at each

sampling instant while minimizing an overall operating cost. These power references are then sent to two local controllers that regulate the subsystems to deliver the required power. The study also explains how practical issues, such as extending equipment lifetime by reducing high input or surge currents, can be included in the predictive control formulation. Several simulation case studies are presented to show the effectiveness and practicality of the proposed supervisory predictive control approach.

S. Bae et al. [3], “Dynamic modeling and operation strategy for a microgrid with wind and photovoltaic resources,” This paper presents a dynamic modeling and operation strategy for a residential microgrid mainly powered by wind and solar energy. A current-source-interfaced bidirectional DC-DC converter is used to connect renewable energy sources to a common DC bus. The proposed system can be applied to locations such as communication sites or residential areas. A direct-driven permanent magnet synchronous generator is used for wind power generation, operating under a variable-speed control strategy to capture maximum wind energy below the rated wind speed. The study considers variations in wind speed, solar irradiance, and load demand. As a case study, a 30-kW hybrid wind-solar system is modeled and analyzed. The results show that the proposed microgrid configuration is suitable for residential microgrid applications.

C. W. Chen et al. [4], “Modeling and controller design of a semi-isolated multi-input converter for a hybrid PV/wind power charger system,” This paper proposes a semi-isolated multi-input converter (S-MIC) for a hybrid PV/wind battery charging system. The main aim is to simplify the power conversion system, reduce cost, and provide continuous and reliable power. The proposed S-MIC consists of a forward-type isolated voltage source cell for PV input and a SEPIC converter for the wind source, both capable of performing maximum power point tracking (MPPT). Due to its semi-isolated structure, the converter can handle large voltage differences between PV and wind sources. The paper explains the

operating principles of the S-MIC and develops a small-signal AC model. Simulation results and experimental tests on a prototype are presented to validate the performance of the proposed converter.

W. M. Lin et al. [5], “Neural network-based MPPT control of a stand-alone hybrid power generation system,” This paper presents the design of a complete standalone hybrid power generation system consisting of solar energy, wind power, an internal combustion engine, and an intelligent power controller. MATLAB/Simulink is used to develop and simulate the dynamic model of the system. To achieve fast and stable power management, the intelligent controller uses a radial basis function network (RBFN) and an improved Elman neural network (ENN) for maximum power point tracking (MPPT). The turbine pitch angle is controlled using the ENN, while the RBFN is used to control the DC–DC boost converters to achieve MPPT for the renewable sources.

III. Proposed Methodology

The proposed hybrid system comprises three main components: a solar PV array, a wind energy conversion system (WECS), and a BESS. The PV and wind systems are connected to a common DC bus via **power electronic converters**, enabling controlled integration of multiple renewable sources. The DC bus serves as an interface to the battery and load systems. The BESS can charge when renewable generation exceeds load demand or discharge when generation is insufficient, thus maintaining system balance and regulating frequency. The total power available at any time is expressed as:

$$P_{\text{total}}(t) = P_{\text{PV}}(t) + P_{\text{Wind}}(t) + P_{\text{BESS}}(t)$$

where $P_{\text{pv}}(t)$ and $P_{\text{wind}}(t)$ are the instantaneous powers generated by solar and wind sources, respectively, and $P_{\text{BESS}}(t)$ is the net battery power, positive for discharging and negative for charging.

The frequency deviation of the system is defined as:

$$\Delta f(t) = f_{\text{nominal}} - f_{\text{actual}}(t)$$

where f_{nominal} is the standard grid frequency (50 Hz or 60 Hz) and f_{actual} is the measured instantaneous frequency. The control strategy aims to minimize $\Delta f(t)$ by dynamically regulating the BESS output.

Modeling of Renewable Energy Sources

Solar PV Model

The PV system converts solar irradiance into DC electrical power. The PV array is modeled using the **single-diode model**, which accounts for the photocurrent, diode characteristics, series and shunt resistances, and temperature effects:

$$I_{\text{PV}} = I_{\text{ph}} - I_0 \left(e^{\frac{V_{\text{PV}} + I_{\text{PV}} R_s}{n n_i V_t}} - 1 \right) - \frac{V_{\text{PV}} + I_{\text{PV}} R_s}{R_{\text{sh}}}$$

where I_{PV} and V_{PV} are the output current and voltage, I_{ph} is the photocurrent, I_0 is the diode saturation current, R_s and R_{sh} are series and shunt resistances, $n n_i$ is the ideality factor, and V_t is the thermal voltage. A **Maximum Power Point Tracking (MPPT)** algorithm is employed to maximize power output under varying irradiance and temperature conditions.

Wind Energy Conversion System (WECS) Model

The mechanical power captured by the wind turbine is given by:

$$P_{\text{Wind}} = \frac{1}{2} \rho A C_p(\lambda, \beta) V_w^3$$

where ρ is air density, A is rotor swept area, V_w is wind speed, and $C_p(\lambda, \beta)$ is the turbine power coefficient, dependent on tip-speed ratio λ and pitch angle β . The aerodynamic model is coupled with a generator model to convert mechanical power into electrical output. Wind speed variations are modeled as time-dependent stochastic signals to simulate realistic operating conditions.

Battery Energy Storage System (BESS) Model

The BESS is a critical component for **frequency regulation and energy optimization**. It is modeled using a first-order equivalent circuit that includes internal resistance and open-circuit voltage:

$$V_{\text{BESS}}(t) = V_{\text{oc}} - R_{\text{int}} I_{\text{BESS}}(t)$$

The battery **state of charge (SOC)**, representing stored energy, is updated at each time step according to:

$$SOC(t) = SOC(t - 1) + \frac{\eta_{ch} I_{BESS}(t) \Delta t}{C_{BESS}}$$

where C_{BESS} is battery capacity, η_{ch} is charging efficiency, and $I_{BESS}(t)$ is battery current (positive for charging). Constraints are applied to ensure the SOC remains within safe limits ($SOC_{min} \leq SOC(t) \leq SOC_{max}$) to prevent overcharging or deep discharging, thereby prolonging battery life.

The BESS can operate in two modes: charging mode when excess renewable energy is available, and discharging mode when additional power is required to maintain frequency stability.

Frequency Regulation Control

The system frequency is regulated using a **proportional-integral (PI) control strategy**, where the BESS responds to frequency deviations:

$$P_{BESS-ref}(t) = K_f \cdot \Delta f(t) + K_c \cdot \int_0^t \Delta f(\tau) d\tau$$

Here, K_f and K_c are proportional and integral gains tuned to provide fast transient response and eliminate steady-state errors. When frequency drops below nominal, the BESS discharges to inject power; when frequency rises above nominal, it absorbs excess energy, smoothing the system response.

The proposed method targets power quality optimization in a hybrid renewable energy system (e.g., PV-wind) interfaced to loads/grid through a Voltage Source Inverter (VSI) and supported by a Battery Energy Storage System (BESS). The primary objective is to:

- minimize Total Harmonic Distortion (THD) in grid/load current,
- maintain stable PCC voltage (or DC-link voltage in DC microgrid),
- suppress voltage-current mismatch (difference between reference and measured values),
- ensure smooth power flow despite renewable intermittency.

A multi-loop control structure is adopted:

1. Outer voltage/DC-link regulation loop,
2. Inner current control loop,
3. Harmonic compensation loop (selective harmonic mitigation),

4. BESS power management loop to stabilize DC-link and support real/reactive power demand.

Power Quality Indices and Optimization Target

THD Definition

For current THD (most used in grid-connected renewable systems), THD is defined as:

$$THD_i(\%) = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I_1} \times 100$$

Where:

- I_1 = RMS value of fundamental current component
- I_h = RMS value of the h^{th} harmonic component

Similarly, voltage THD:

$$THD_v(\%) = \frac{\sqrt{\sum_{h=2}^{\infty} V_h^2}}{V_1} \times 100$$

Objective Function (Optimization Formulation)

The control/optimization target is formulated as a weighted multi-objective cost function:

$$J = w_1 \cdot THD_i + w_2 \cdot e_v^2 + w_3 \cdot e_i^2 + w_4 \cdot \Delta u^2$$

Where:

- $e_v = V_{ref} - V_{PCC}$ (voltage tracking error)
- $e_i = I_{ref} - I_{meas}$ (current tracking error)
- Δu = control effort variation (limits switching stress)
- w_1, w_2, w_3, w_4 = tuning weights

Minimization problem:

min J subject to system constraints

Constraints (typical):

$$SOC_{min} \leq SOC \leq SOC_{max}$$

$$I_{inv} \leq I_{rated}, V_{dc} \leq V_{dc,max}$$

Reference Generation and Error Computation

Grid Synchronization (PLL)

A phase-locked loop (PLL) extracts phase angle θ for reference transformation.

Reference Current (Active/Reactive Power Control)

For a grid-tied VSI, the reference current in the synchronous dq frame is derived from desired active and reactive power:

$$P = \frac{3}{2} (V_d I_d + V_q I_q)$$

$$Q = \frac{3}{2} (V_q I_d - V_d I_q)$$

If PLL aligns the d -axis with grid voltage, $V_q \approx 0$. Then:

$$P \approx \frac{3}{2} V_d I_d, Q \approx -\frac{3}{2} V_d I_q$$

So reference currents become:

$$I_d^{ref} = \frac{2 P^{ref}}{3 V_d}$$

$$I_q^{ref} = -\frac{2 Q^{ref}}{3 V_d}$$

Voltage and Current Error Signals

$$e_v(t) = V_{ref}(t) - V_{pcc}(t)$$

$$e_{id}(t) = I_d^{ref}(t) - I_d(t), e_{iq}(t) = I_q^{ref}(t) - I_q(t)$$

Proposed Control Strategy for THD Reduction

Outer Loop: DC-Link Voltage Regulation (BESS + VSI Support)

The DC-link voltage V_{dc} is stabilized using a PI or intelligent controller:

$$I_d^{ref} = K_{pv} e_{vdc}(t) + K_{iv} \int e_{vdc}(t) dt$$

$$e_{vdc}(t) = V_{dc}^{ref} - V_{dc}(t)$$

This ensures constant inverter input energy, preventing distortion caused by DC-link ripple.

Inner Loop: Current Control with Decoupling

The inverter filter (L or LCL) dynamics in dq are commonly:

$$L \frac{dI_d}{dt} = V_{inv,d} - V_{g,d} + \omega L I_q - R I_d$$

$$L \frac{dI_q}{dt} = V_{inv,q} - V_{g,q} - \omega L I_d - R I_q$$

Control law (with decoupling terms):

$$V_{inv,d} = V_{g,d} + R I_d + L \frac{dI_d^{ref}}{dt} - \omega L I_q + u_d$$

$$V_{inv,q} = V_{g,q} + R I_q + L \frac{dI_q^{ref}}{dt} + \omega L I_d + u_q$$

Where u_d, u_q are outputs of PI/fuzzy controllers based on e_{id}, e_{iq} .

Harmonic Compensation (Selective Harmonic Mitigation)

To explicitly reduce harmonics, a harmonic compensator is added in parallel:

$$I_{comp}(t) = \sum_{h \in H} k_h \cdot I_h(t)$$

Typical harmonic set: $H = \{5,7,11,13\}$ (dominant inverter/grid harmonics).

The compensated reference becomes:

$$I_{ref}^*(t) = I_{fund}^{ref}(t) - I_{comp}(t)$$

This forces the inverter to inject a current that cancels harmonic components.

BESS Power Management for Voltage and THD Stability

Power Balance Equation

At DC-link:

$$P_{RES} + P_{BESS} = P_{inv} + P_{loss}$$

Battery power command:

$$P_{BESS}^{ref} = K_b (V_{dc}^{ref} - V_{dc})$$

Battery current reference:

$$I_{batt}^{ref} = \frac{P_{BESS}^{ref}}{V_{batt}}$$

SOC update (discrete-time):

$$SOC(k+1) = SOC(k) - \frac{\eta I_{batt}(k) \Delta t}{C_{batt}}$$

Where:

- C_{batt} = battery capacity (Ah)
- η = efficiency
- Δt = sampling time

Switching Strategy (PWM) and THD Minimization

To minimize THD, **Sinusoidal PWM (SPWM)** or **Space Vector PWM (SVPWM)** can be used.

Modulation index:

$$m_a = \frac{V_{ref}}{V_{carrier}}$$

SVPWM is typically preferred because it reduces switching losses and lowers THD compared to SPWM.

PV Model and Governing Equations

The PV output power is:

$$P(k) = V(k) \cdot I(k)$$

Where:

- $V(k)$ = PV voltage at sampling instant k
- $I(k)$ = PV current at sampling instant k
- $P(k)$ = PV power at sampling instant k

Changes in power and voltage are computed as:

$$\begin{aligned} \Delta P &= P(k) - P(k-1) \\ \Delta V &= V(k) - V(k-1) \end{aligned}$$

The objective of MPPT is to drive the operating point toward the MPP, where:

$$\frac{dP}{dV} = 0$$

IV. Simulation Result

In the proposed research work, a hybrid system for renewable power generation has been developed. The hybrid system comprises Photovoltaic panels, a Wind Energy Conversion System, and a Battery Energy Storage System. The hybrid system will provide a continuous supply of power regardless of variations in environmental parameters such as solar intensity and wind speed.

- The hybrid system architecture facilitates:
- Power generation by PV modules during daytime.
- Power production through wind turbines when ideal winds are present.
- Energy storage and backup power using the battery.
- Real time power balance based on load demand.

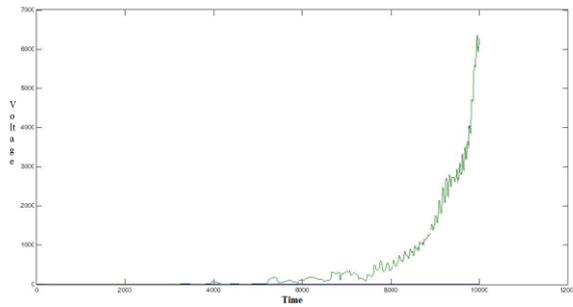


Fig.:2 Wind voltage with respect to Time

The rotor speed varies in response to changes in wind speed. As the wind speed fluctuates, the generator adjusts its rotational speed accordingly, producing power that corresponds to the current wind conditions.

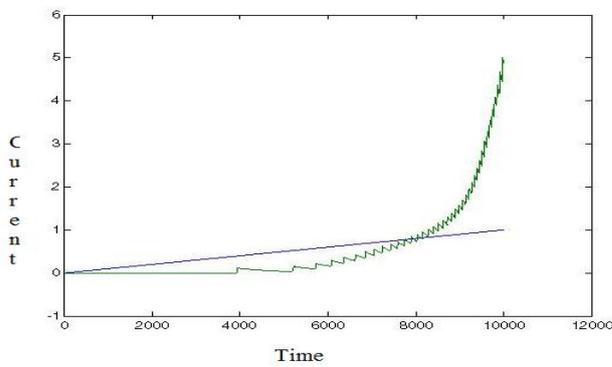


Fig.:3 Wind current with respect to Time

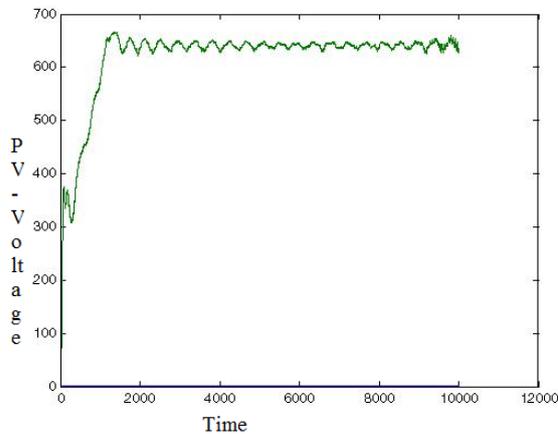


Fig.:4 PV voltage with respect to Time

Figure 4 below shows a graph of the PV output voltage with respect to time under varying irradiance levels using a photovoltaic cell. The graph shows how the output voltage of the PV cell changes over time in response to varying solar irradiance.

Figure 5 below shows how the PV output current produced by the photovoltaic cell varies with time when under different irradiance levels.

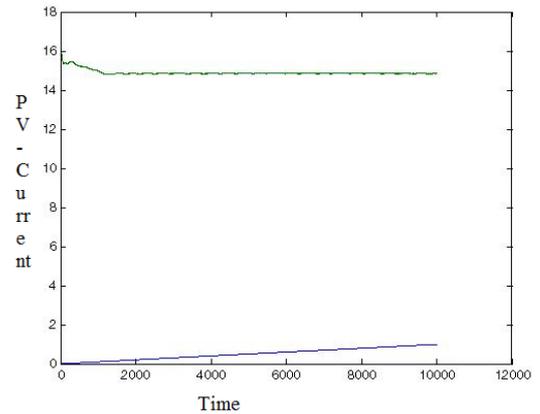


Fig.: 5 PV Current with respect to Time

Figure 6 shows the graph of power distribution among the load, PV array, battery, and wind generator. The graph consists of four different wave forms, each marked in a distinct color.

Cyan represents the power in the batteries, which can view charge/discharge cycles based on system requirements.

The pink curve represents the output from the wind power, which fluctuates with varying wind speed.

The yellow waveform corresponds to PV Power Output, which varies depending on Sun Light Exposure and is controlled by an MPPT Controller.

The red waveform in this graph shows the load power, illustrating the power being used by the load during the simulation time.

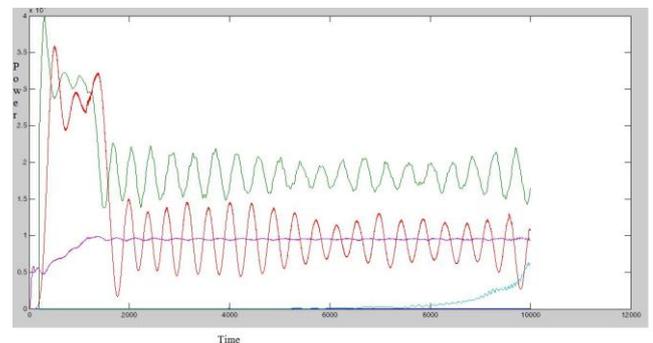


Fig. 6: Different power compares with respect to Time

Figure 7 shows the voltage supplied to the load during changing load conditions. As can be seen, the hybrid power system is dynamically responding to provide a steady voltage profile during changing load conditions with time. The results show that:

- The load voltage is always within the range of acceptance.

- The hybrid control strategy does not introduce any noticeable time delay or discontinuation in the voltage supply during load transitions.
 - Variations in generation and load demand are well compensated by the system, allowing consistent power quality.
- This confirms that the hybrid PV–wind–battery system provides reliable voltage regulation even under fluctuating operating conditions.

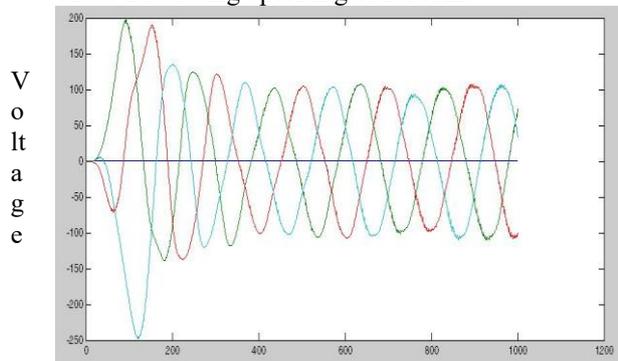


Fig 7: Output Voltage with respect to Time

Figure 4.12 illustrates the Total Harmonic Distortion (THD) of the output voltage of Time hybrid power system. The measured THD value is 5.34%, which is significantly low for a renewable energy–based system. This low THD value indicates that the output waveform is very close to a pure sinusoidal signal, with minimal harmonic content.

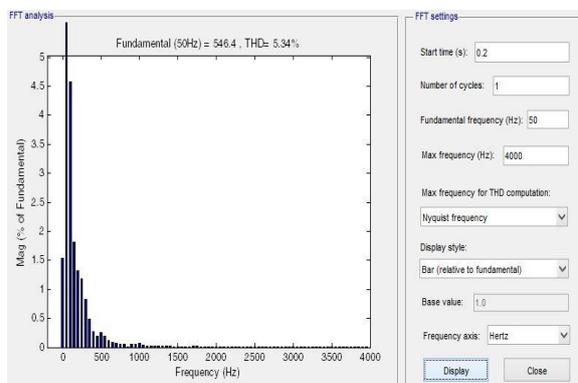


Fig. 4.12: THD Value

	(P&O, INC)	MPP, slower response	near MPP	oscillations
[11]	Grid-connected PV–Wind with DC bus control	DC-link voltage ripple \approx 8–10%	Ripple < 4%	Improved DC voltage stability
[3]	PV–Wind microgrid without storage	Power interruption under low RES	Continuous power using battery support	Uninterrupted supply
[22]	PV–Wind system with basic power management	Limited source coordination	Dynamic power sharing among PV, wind, battery	Improved power balance
[20]	Wind farm with battery support	Battery used only for smoothing	Battery used for charging, discharging & backup	Efficient energy utilization
[6]	Hybrid system with conventional inverter control	Load voltage fluctuation \pm 10%	Load voltage within acceptable limits	Enhanced voltage regulation
[7]	Converter-based DG system	THD \approx 7–8%	THD = 5.34%	Better harmonic performance
[25]	IEEE-519 harmonic limits	THD < 8% required	THD well within standard	Full IEEE-519 compliance
[32]	Hybrid RES with EMS	Delay during load transitions	No delay or discontinuity observed	Faster dynamic response

Table 1 Quantitative Comparison with Existing Methods

Ref. No.	Existing Method	Reported Performance	Proposed Hybrid PV–Wind–Battery System	Improvement Achieved
[18]	Conventional MPPT	Oscillations near	Stable operation	Reduced voltage

V. Conclusion

This paper presented the design, modeling, and performance evaluation of a hybrid renewable energy system integrated with a battery energy storage system (BESS) for power quality enhancement. The proposed architecture combines solar photovoltaic (PV) and wind

energy sources through a common DC bus with a battery storage unit, enabling effective energy coordination and reliable power delivery under variable environmental and load conditions. The inclusion of the BESS effectively mitigates the intermittency of renewable sources, ensuring continuous power supply and improved system stability.

An enhanced Perturb and Observe (P&O) maximum power point tracking (MPPT) algorithm was developed to improve energy harvesting from the PV system. By incorporating adaptive perturbation step sizing, anti-misdirection logic, and oscillation suppression near the maximum power point, the proposed MPPT technique achieves faster dynamic response, reduced steady-state oscillations, and higher tracking accuracy compared to conventional P&O methods. These improvements contribute to enhanced DC-link voltage regulation and reduced voltage and current ripples.

In addition, a coordinated voltage and current control strategy was implemented using power electronic converters in conjunction with the BESS. The proposed control approach effectively mitigates voltage sag and swell, minimizes harmonic distortion, and ensures precise tracking of reference voltage and current signals. Simulation results confirm that the system meets standard power quality requirements and demonstrates improved efficiency, robustness, and operational reliability.

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