# MODELLING, STABILITY ANALYSIS AND HARMONIC MITIGATION OF HYBRID PHOTOVOLTAIC–WIND ENERGY INTEGRATION IN THE NIGERIAN NATIONAL INTEGRATED POWER PROJECT NETWORK USING PSO-OPTIMIZED CONTROL ALGORITHMS

**Amos, C.[1], Visa, M.I.[1*], Musa, S.Y.[1], Aminu, M.[1], Ayuba, D.M.[2], Zirata, B.K.[1] and Abdullahi, A.[1]**

[1]Department of Electrical and Electronics Engineering Modibbo Adama University Yola, Adamawa State, Nigeria

[2]National Centre for Technology Management

*Corresponding email: visaibrahim@gmail.com

## ABSTRACT

*The increasing penetration of renewable energy sources, particularly photovoltaic (PV) and wind power systems, alongside the widespread use of power electronic devices and fluctuating load conditions, has significantly increased harmonic distortion and operational instability in modern power systems. These challenges degrade power quality, reduce system efficiency, accelerate equipment deterioration, and may ultimately lead to partial or complete system failure if not properly mitigated. This study therefore presents the modelling, simulation, and stability analysis of a renewable-integrated power system with emphasis on harmonic mitigation and variable loading conditions. A reduced 10-bus Nigerian National Integrated Power Project (NIPP) network, comprising six generating stations and twelve transmission lines, was developed. A hybrid photovoltaic–wind turbine (PV–WT) system was designed and integrated into the grid, and three harmonic mitigation control strategies were implemented, namely the Proportional-Integral Harmonic Mitigation Control Algorithm (PI-HMCA), the Multi Anti-Windup Proportional-Integral Harmonic Mitigation Control Algorithm (MAWPI-HMCA), and the Dual Anti-Windup Proportional-Integral Harmonic Mitigation Control Algorithm (DAWPI-HMCA). The controller parameters were optimally tuned using Particle Swarm Optimization (PSO). Simulation results showed that all proposed control schemes effectively reduced current and voltage harmonic distortions within IEEE standard limits under varying operating conditions. Comparative analysis further revealed that the DAWPI-HMCA outperformed the MAWPI-HMCA and PI-HMCA in harmonic suppression capability and overall system stability enhancement. These findings demonstrate the effectiveness of advanced anti-windup PI-based harmonic mitigation strategies for improving power quality in renewable-integrated power systems, with DAWPI-HMCA emerging as the most robust and efficient approach therefore it is recommended as the most effective control strategy for harmonic mitigation in renewable-integrated power systems. Future work may focus on real-time implementation and testing under actual grid conditions to further validate performance and scalability*.

**Key words**: Solar PV, Wind, PI, MAWPI, DAWPI, HMCA

## 1 INTRODUCTION

Power system stability is a critical requirement for the secure and reliable operation of modern electrical power networks. It refers to the ability of a power system to maintain synchronism and continue operating within acceptable limits following disturbances such as faults, sudden load changes, switching operations, or generator outages [1]. As electricity demand continues to grow and renewable energy resources are increasingly integrated into conventional power systems, ensuring system stability has become more challenging and essential. Consequently, stability remains a fundamental performance indicator and a key consideration in the planning, design, and operation of contemporary power networks. The worldwide transition toward renewable energy (RE) has gained significant momentum due to growing concerns over climate change, environmental degradation, and the depletion of conventional fossil fuel resources. Global energy demand is expected to increase by nearly 30% by 2040, creating an urgent need for sustainable and environmentally friendly energy alternatives [2]. Renewable energy technologies, particularly solar photovoltaic (PV) and wind power systems, have emerged as viable solutions for reducing greenhouse gas emissions and enhancing energy sustainability. However, the intermittent and stochastic nature of these resources presents considerable operational challenges when integrated into existing power systems [3]. High levels of renewable energy penetration can adversely affect voltage regulation, power quality, frequency control, and overall grid stability, thereby necessitating the adoption of advanced control strategies and enhanced grid management techniques. Nigeria is endowed with abundant renewable energy resources, especially solar and wind energy potentials [4, 5, 6]. The country receives high levels of solar irradiation throughout most of the year, while several regions possess favorable wind conditions suitable for electricity generation. Despite these advantages, renewable energy deployment remains relatively low, and the national electricity supply continues to depend predominantly on conventional fossil-fuel-based generation technologies [7]. Furthermore, the Nigerian power system faces numerous operational challenges, including inadequate generation capacity, transmission bottlenecks, high transmission and distribution losses, and recurring grid disturbances. These limitations significantly hinder the reliable supply of electricity and complicate the integration of large-scale renewable energy resources into the national grid. To address these challenges, renewable energy technologies have increasingly been considered as viable alternatives for improving power system reliability, energy security, and environmental sustainability. Solar PV and wind energy systems are particularly attractive because of Nigeria's favorable climatic conditions and resource availability. Nevertheless, the successful integration of these renewable energy sources into the existing grid requires comprehensive assessment of technical issues such as system stability, harmonic distortion, voltage regulation, power quality, and controller optimization. Several researchers have investigated the integration of renewable energy systems into the Nigerian electricity network. Joseph *et al.* [8] developed a MATLAB-based simulation framework to assess the impact of solar PV and wind energy integration on grid reliability in Nigeria. Their findings indicated that renewable energy technologies can significantly improve electricity supply reliability when supported by appropriate control mechanisms and effective grid management strategies. The study further emphasized the importance of advanced modelling and simulation tools for evaluating renewable energy penetration within the Nigerian power system. Similarly, Sunday and Mutah [9] examined the role of renewable energy technologies in enhancing operational efficiency within Nigeria's power sector. Their results revealed that the integration of solar and wind energy systems can improve overall system performance while reducing dependence on conventional fossil-fuel-based generation. However, the authors identified several barriers to widespread renewable energy adoption, including inadequate infrastructure, limited investment opportunities, and regulatory constraints. The influence of renewable energy integration on power system stability has also received considerable research attention. Ozioko *et al*. [10] evaluated the impact of wind turbine generators on the transient stability performance of the Nigerian power system using detailed simulation studies. Their findings demonstrated that although wind energy contributes significantly to sustainable electricity generation, high levels of wind penetration may adversely affect system stability because converter-based renewable generation systems provide lower inertia compared to conventional synchronous generators. Consequently, the study highlighted the necessity for advanced control schemes and stability enhancement techniques to maintain reliable grid operation. Apart from stability concerns, power quality issues have emerged as major challenges associated with renewable energy integration. These issues include harmonic distortion, voltage fluctuations, reactive power imbalance, and voltage flicker. Esobinenwu [11] investigated the application of smart inverter technology for improving voltage stability in Nigeria's power grid. The results showed that smart inverters equipped with advanced control functionalities significantly reduced voltage sag occurrences and enhanced system recovery following disturbances. Specifically, voltage sag depth was reduced by approximately 40%, while voltage recovery time improved by more than 50%, demonstrating the effectiveness of intelligent inverter control for grid-connected solar PV systems. Research efforts have also focused on the integration of large-scale renewable energy systems into Nigeria's transmission network. Onwuzuruike *et al.* [12] analyzed the impact of variable renewable energy resources on the Nigerian transmission system and emphasized the importance of accurate modelling frameworks for determining acceptable renewable penetration levels while preserving network stability. Their study concluded that successful renewable energy integration requires advanced control techniques, improved transmission infrastructure, and sophisticated simulation tools for effective system planning and operation. Furthermore, investigations involving specific renewable energy installations have highlighted the technical implications of large-scale grid-connected renewable projects. Biragbara [13] studied the integration of a 65 MW solar photovoltaic plant into the 132 kV transmission network in Port Harcourt. The results indicated that large-scale PV integration significantly affects voltage profiles, power flow patterns, and overall system stability, particularly in weak networks characterized by substantial transmission losses. The study further reported that transmission and distribution losses within Nigeria's power system remain relatively high, reaching approximately 28%, thereby posing additional challenges to renewable energy integration. Hybrid renewable energy systems have also been proposed as practical solutions for addressing Nigeria's persistent energy supply deficit. Jumare *et al*. [14] evaluated a grid-connected hybrid PV–wind–biogas energy system for northern Nigeria using the Hybrid Optimization of Multiple Energy Resources (HOMER) software. Their findings demonstrated that hybrid renewable energy systems can enhance energy supply reliability, reduce dependence on fossil-fuel-based generation, and promote sustainable energy development. Despite these notable contributions, most existing studies in Nigeria have focused primarily on energy planning, policy formulation, economic assessments, and renewable penetration analysis. Comparatively little attention has been devoted to the development of advanced control architectures and harmonic mitigation techniques for large-scale hybrid renewable energy integration. In particular, there is a scarcity of studies that incorporate scalable simulation frameworks, multilevel inverter configurations, advanced converter control strategies, and dedicated harmonic mitigation algorithms for hybrid PV–wind systems connected to the Nigerian power grid. HRES, which combine multiple renewable energy sources such as solar PV and wind energy, have emerged as promising alternatives for overcoming the intermittency limitations associated with individual renewable technologies. By exploiting the complementary generation characteristics of different renewable resources, hybrid systems can provide a more stable and reliable power supply. For example, solar PV systems typically generate maximum output during daytime periods, whereas wind energy resources may be more available during nighttime hours or under low solar irradiance conditions. This complementary behavior enhances generation continuity, improves system reliability, and supports more effective utilization of renewable resources [15,16]. Despite their advantages, the integration of hybrid renewable energy systems introduces several operational and technical challenges. Variability in renewable generation can cause power imbalances, voltage instability, and frequency deviations, all of which may adversely affect grid performance [17]. Moreover, renewable energy systems rely extensively on power electronic converters for energy conversion and grid interfacing. These converters can introduce power quality problems, including harmonic distortion, voltage flicker, and reactive power imbalance [18]. Therefore, effective synchronization mechanisms and advanced control techniques are essential to ensure stable and reliable operation of renewable-energy-based power systems [19]. Although numerous studies have investigated renewable energy integration and power system stability enhancement, relatively few have focused on scalable hybrid renewable energy models combined with advanced harmonic mitigation control strategies. Within the Nigerian context, existing research has largely concentrated on voltage stability improvement using Flexible AC Transmission System (FACTS) devices or the determination of renewable penetration limits, with limited emphasis on detailed modelling of hybrid renewable systems and associated converter control architectures. Therefore, this study develops a comprehensive MATLAB/Simulink-based simulation framework for the integration of hybrid solar photovoltaic and wind turbine systems into a utility grid. The proposed framework incorporates scalable models of solar PV and wind generation systems interfaced through multilevel converter topologies for efficient grid connection. A multilevel active power filter is employed to mitigate harmonic distortions and improve overall power quality. Furthermore, different harmonic mitigation control strategies are investigated, including a conventional Proportional–Integral (PI) controller and advanced controller variants, namely the Modified Adaptive Weighted Proportional–Integral (MAWPI) controller and the Dynamic Adaptive Weighted Proportional–Integral (DAWPI) controller. The proposed approach seeks to enhance harmonic suppression, improve grid synchronization performance, and facilitate the reliable integration of hybrid renewable energy systems into modern utility power networks.

## 2 LITERATURE REVIEW

The integration of renewable energy resources into modern power systems and their implications for system stability have attracted considerable research attention in recent years. Flynn et al. [20] investigated the effects of increasing wind energy penetration on power system stability, emphasizing the ongoing transition from conventional power systems dominated by synchronous generators to converter-interfaced renewable generation networks. Likewise, Kabouris and Kanellos [21] examined the influence of high wind power penetration on power system planning, design, and operational performance, while Vittal and Keane [22] explored optimal wind farm placement strategies with consideration for system reliability and operational efficiency. Several studies have also focused on addressing the operational challenges associated with the integration of variable renewable energy resources. Eftekharnejad *et al*. [23] analyzed modifications required in power dispatch strategies to accommodate large-scale photovoltaic generation within existing power networks. Similarly, Martín-Martínez *et al*. [24] investigated wind power curtailment techniques aimed at enhancing system reliability and improving operational flexibility. In addition, various approaches for mitigating active power fluctuations in photovoltaic power plants have been proposed and evaluated to improve system performance and stability [25]. Among renewable energy technologies, solar photovoltaic and wind energy systems represent the most widely adopted generation sources worldwide. Solar energy generation is directly dependent on solar irradiance and therefore predominantly occurs during daylight hours. In contrast, wind energy generation depends on prevailing wind conditions and can occur during both daytime and nighttime periods. Although both energy sources exhibit stochastic behavior, wind energy generally demonstrates greater variability due to the unpredictable nature of wind speed fluctuations [26]. Solar energy production, however, tends to follow more predictable daily irradiance patterns. Furthermore, the output of both solar and wind energy systems is influenced by seasonal changes and varying meteorological conditions [27, 28]. At relatively low penetration levels, renewable energy resources exert minimal influence on power system stability. However, as renewable penetration increases, their impact on system dynamic performance becomes increasingly significant. High levels of renewable generation may result in reduced system inertia, increased power fluctuations, and greater difficulty in maintaining frequency and voltage stability. These challenges have motivated extensive research into advanced control techniques, stability enhancement methods, and power quality improvement strategies for renewable-integrated power systems. Within the Nigerian power system context, several researchers have explored approaches for improving grid performance and facilitating renewable energy integration. Li *et al*. [29] proposed fault control mechanisms capable of supporting increased wind energy penetration within the Nigerian grid, although the long-term effects on system stability were not comprehensively addressed. Ozioko *et al*. [30] reported that the Nigerian power grid could accommodate only about 10% penetration of doubly-fed induction generator (DFIG)-based wind farms without substantial improvements in voltage profile performance. Similarly, Adetokun and Muriithi [31] demonstrated that large-scale solar photovoltaic integration has the potential to improve voltage stability within the Nigerian electricity network. Despite these valuable contributions, existing studies have largely concentrated on renewable energy penetration assessments, voltage stability enhancement, and the application of Flexible AC Transmission System (FACTS) devices. Comparatively little attention has been devoted to the development of scalable hybrid renewable energy simulation models incorporating advanced converter control architectures and harmonic mitigation techniques. Furthermore, the utilization of multilevel converter-based active power filters and advanced controller variants for harmonic suppression in hybrid photovoltaic–wind grid integration remains relatively underexplored, particularly within the

Nigerian power system environment. Consequently, there is a need for comprehensive simulation frameworks capable of evaluating the effectiveness of advanced harmonic mitigation control strategies under realistic Nigerian grid conditions.

## 3 METHODOLOGY

### 3.1 Modelling of Renewable Energy Resource Integration

This study examines the effects of renewable energy integration on the stability performance of the Nigerian power system. To achieve this objective, a hybrid renewable energy system comprising solar photovoltaic (PV) and wind turbine (WT) generation units is developed and integrated into an existing thermal-based multi-machine power system model. The proposed system is modelled and simulated using the MATLAB/Simulink platform, taking advantage of relevant power system, renewable energy, and control system toolboxes. A data-driven modelling approach is adopted to represent the dynamic behaviour of the renewable energy systems and associated control mechanisms. The controller design process involves offline parameter tuning through an iterative procedure consisting of system simulation, data acquisition, controller development, performance evaluation, and parameter optimization. The optimization process is formulated to minimize the Sum of Squared Error (SSE) between the desired reference response and the actual system response, thereby ensuring improved dynamic performance and control accuracy. Figure 1 illustrates the proposed renewable energy integration framework. In this configuration, solar photovoltaic and wind turbine microgrid systems are interfaced with the Nigerian power system model through dedicated grid-connection points. Three separate integration buses are incorporated into the model to facilitate the evaluation of different renewable energy penetration scenarios. These scenarios include standalone photovoltaic integration (PV-only), standalone wind turbine integration (WT-only), and combined photovoltaic–wind turbine integration (Hybrid PV–WT). This configuration enables a comprehensive assessment of the individual and combined effects of renewable energy resources on power system stability, dynamic performance, and power quality.

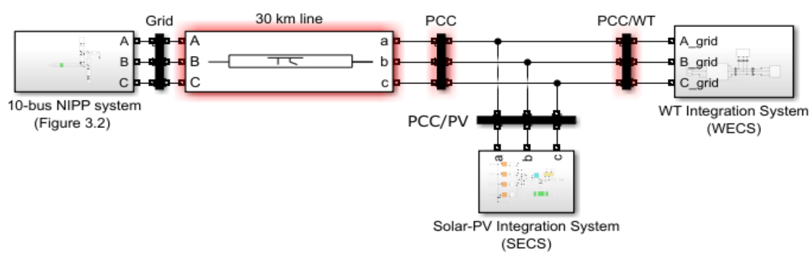


Figure 1. SIMULINK model of the proposed hybrid-PVWT resource integration system

### 3.2 Model of the Proposed Wind Energy Conversion System (WECS)

The proposed Wind Energy Conversion System (WECS) consists of several interconnected components required for the conversion of wind energy into electrical power, as illustrated in Figure 2. The generated power is integrated into the utility grid through a 0.575/33 kV step-up transformer, which facilitates voltage matching and efficient power transmission. The transformer is connected to the remaining parts of the system through a choke consisting of a series RL network, which provides impedance matching between the renewable energy source and the utility grid, thereby facilitating efficient power transfer. The wind farm generation unit, represented by the Wind Turbine (WT) Generator Model, supplies electrical power to the grid and is depicted by the rightmost SIMULINK block in Figure 2. Power generated by the wind turbine system is delivered to the utility network through an Active Power Filter (APF), which serves as the primary grid-interface unit. The utility grid is connected to the APF through a 30 km distribution feeder, as shown in Figure 2. In addition, both linear and nonlinear loads are connected at the point of common coupling (PCC), located between the APF and the wind generation system. The inclusion of these loads enables the assessment of harmonic distortion and power quality issues under realistic operating conditions. Since the primary focus of this study is harmonic mitigation, emphasis is placed on the modelling and control of the harmonic filtering system, specifically the grid-side converter control algorithm. The APF consists of an AC–DC–AC power conversion structure that performs multiple functions, including harmonic filtering, voltage regulation, power conditioning, and system stabilization. It controls and converts the electrical output of the wind energy conversion system into a form suitable for grid synchronization and seamless integration with the utility network. Furthermore, the APF operates as an automatic generation control mechanism for the WECS by regulating power exchange between the wind generation system and the grid while maintaining acceptable power quality standards. The operational principles and control methodology of the proposed WECS are presented in the subsequent sections.

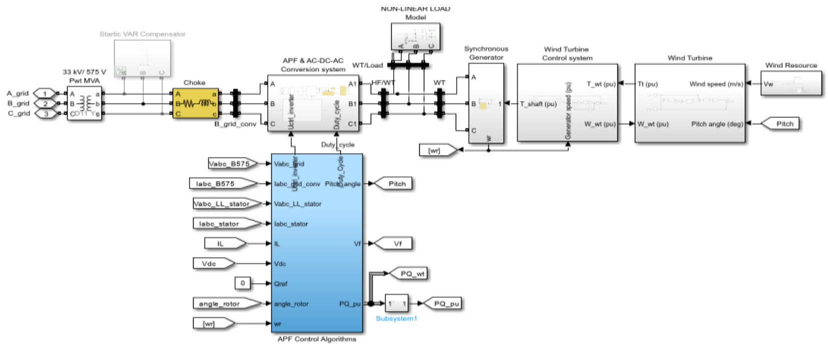

Figure 2. SIMULINK model of the proposed WT based WECS

The APF control algorithm is responsible for generating the switching and control signals required for both the DC–DC boost converter and the Voltage Source Converter (VSC)-based inverter. To enable grid integration, the alternating current (AC) output generated by the wind farm is first converted into direct current (DC) using a three-phase full-wave bridge rectifier. The resulting DC power is subsequently conditioned and regulated before being converted back into AC power through the inverter stage. The inverter output is synchronized with the utility grid in terms of voltage magnitude, frequency, and phase angle. This synchronization process is accomplished through the proposed Harmonic Mitigation Control Algorithm (HMCA), which ensures seamless grid integration while maintaining power quality and system stability.

### 3.3 Model of the Proposed AC–DC–AC Converter-Based APF Control System

The proposed AC–DC–AC converter-based Active Power Filter (APF) is designed to facilitate synchronization between the Wind Energy Conversion System (WECS) and the utility grid while ensuring maximum power transfer, enhanced reliability, and improved system stability. The converter structure consists of three major stages: a three-phase full-wave bridge rectifier, a DC–DC boost converter, and a Voltage Source Converter (VSC)-based inverter. To achieve effective synchronization, harmonic suppression, and stable grid operation, the proposed Harmonic Mitigation Control Algorithm (HMCA) employs a series of logically coordinated control stages. The control architecture is based on a Particle Swarm Optimization (PSO)-tuned Proportional–Integral (PI) controller strategy, which optimizes controller parameters to improve dynamic response and overall system performance [34]. As shown in Figure 2, the AC–DC–AC converter-based APF control system comprises the following key components: Bridge Rectifier: Converts the AC output of the wind energy conversion system into an equivalent DC voltage for subsequent processing, DC–DC Boost Converter: Regulates and boosts the rectified DC voltage to match the required DC-link voltage level, thereby ensuring adequate energy transfer and converter operation and Voltage Source Inverter (VSI): Converts the regulated DC-link voltage into synchronized AC power suitable for grid integration, while maintaining the required voltage, frequency, and phase characteristics of the utility network. Through the coordinated operation of these components the overall performance, stability, and power quality of the integrated wind energy conversion system.

### 3.4 Proposed Harmonic Mitigation Control Algorithm

The proposed Harmonic Mitigation Control Algorithm (HMCA) consists of five primary control stages designed to enhance power quality, improve grid synchronization, and ensure stable system operation. These stages include the DC-link voltage regulation stage, reactive power (VAR) regulation stage, AC voltage regulation stage, direct-axis (d-axis) current regulation stage, and quadrature-axis (q-axis) current regulation stage. In addition, a signal modulation unit and a dq-transformation block are incorporated at the output stage to regulate and modulate the dq-axis voltage components to the desired operating levels. The coordinated and cascaded arrangement of these control stages enables improved dynamic response, enhanced harmonic suppression, and superior overall system performance. The primary objective of this study is to reproduce the conventional Proportional–Integral (PI)-based HMCA and subsequently enhance its performance through optimal parameter tuning using the Particle Swarm Optimization (PSO) technique. To develop the individual control subsystems constituting the HMCA, a data-driven modelling approach is adopted. As previously discussed, this approach facilitates offline controller modelling, parameter estimation, tuning, and optimization based on system operating data. Particle Swarm Optimization (PSO) is employed as the optimization tool due to its robust search capability and effectiveness in determining optimal controller parameters. The optimization process is formulated using the Sum of Squared Error (SSE) between the desired reference signal and the predicted system response as the objective function. Minimizing the SSE ensures that the controller achieves accurate tracking performance and improved dynamic behavior under varying operating conditions. All offline data-driven models developed in this study are based on the conventional first-order Autoregressive with Exogenous Input (ARX-1) model, as illustrated in Figure 3. The parameters of the ARX-1 models are estimated using the Weighted Least Squares Error (WLSE) technique, which provides reliable parameter identification while accounting for variations in the measured data. The resulting models serve as the foundation for controller design, performance evaluation, and PSO-based parameter optimization throughout the study.

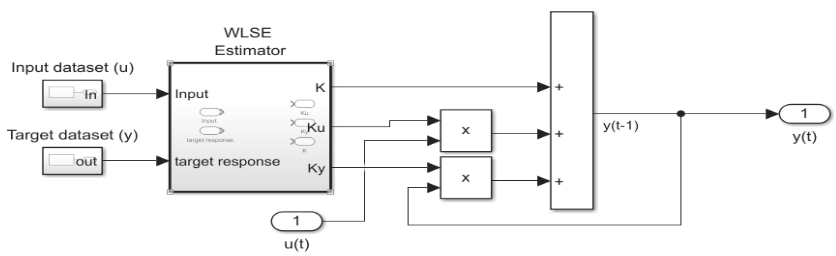

Figure 3. Block Diagram of the proposed ARX-1 model

In general, a simple nth order ARX-n model is expected to have 2n+1 unknown variable, representing linear coefficient of the n delayed inputs. Therefore, in this work, the ARX-1 is designed to have three unknown variables. Additionally, the model control observer-based data driven controller design technique is illustrated using Figure 4.

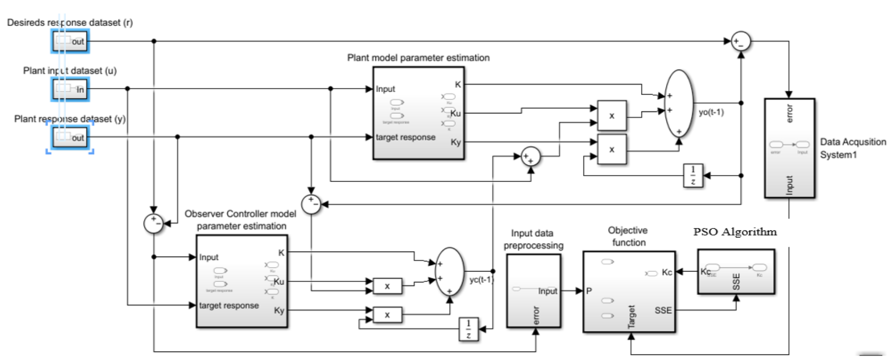

Figure 4. Block Diagram of the proposed data driven offline controller design technique

In the proposed offline controller design framework illustrated in Figure 4, both the plant and controller models are first identified using the Weighted Least Squares Error (WLSE) parameter estimation technique. The identified models are subsequently interconnected as shown in Figure 4 to determine the control input required to drive the actual system toward its desired steady-state operating condition. The resulting control input signal is then recorded and utilized as the reference response (target output) during the controller development process. To obtain optimal controller parameters, the Particle Swarm Optimization (PSO) algorithm is employed [34]. During the optimization process, PSO iteratively generates candidate controller parameter vectors, denoted as (K_c), and evaluates their performance using a predefined objective function. The objective function computes the corresponding Sum of Squared Error (SSE) between the desired reference response and the predicted system output based on the preprocessed input data and target dataset. The controller parameter vector is subsequently adjusted to minimize the SSE, thereby improving tracking accuracy and overall control performance. Furthermore, the proposed HMCA development methodology is primarily centered on the implementation and optimal tuning of a multi-PI-controller-based harmonic mitigation strategy. This approach utilizes multiple coordinated PI controllers to regulate the various control loops within the system, thereby enhancing harmonic suppression capability, dynamic response, and grid synchronization performance [26, 35].

### 3.5 Multi-PI-Controller-Based Harmonic Mitigation Technique

In this stage, all Proportional–Integral (PI) controllers are designed, tuned, and optimized using the data-driven offline controller design methodology described previously in Figure 4. The controller development process adopts the model-based control-oriented approach, where the identified system models and optimization framework are utilized to determine the optimal PI controller parameters for each control loop. Figure 5 illustrates the SIMULINK implementation of the overall PI-controller-based Harmonic Mitigation Control Algorithm (PI-HMCA) whereas Figure 6 illustrates the SIMULINK model of the proposed multi-AWPI-controller based HMCA [35]. The proposed control architecture consists of five coordinated control subsystems arranged in a logical cascade structure to ensure effective harmonic suppression, voltage regulation, current control, and grid synchronization. In addition to these primary control loops, the algorithm incorporates a signal modulation unit and a DQ–ABC voltage transformation block for generating the appropriate control signals required by the power electronic converter interface [25, 35]. The cascaded arrangement of the control stages enables coordinated regulation of key system variables, thereby improving dynamic performance, enhancing power quality, and ensuring stable grid integration of the renewable energy system.

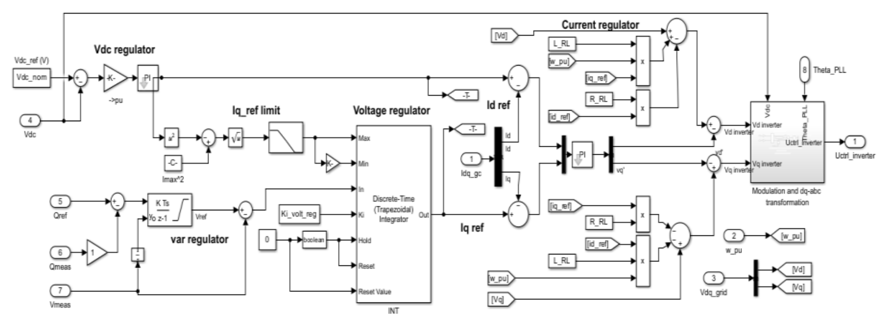

Figure 5. SIMULINK model of the proposed multi-PI-controller based HMCA

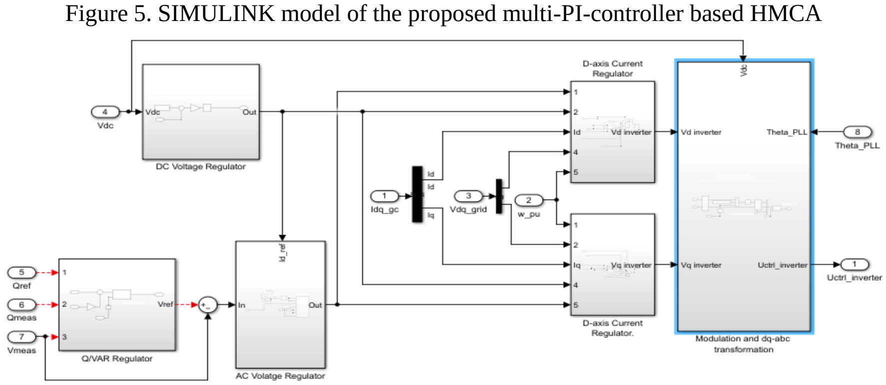

Figure 6. SIMULINK model of the proposed multi-AWPI-controller based HMCA

### 3.6 Dual-AWPI-Controller-Based Harmonic Mitigation Technique

The Dual Anti Windup Proportional–Integral (DAWPI) control strategy is developed to reduce controller complexity while simultaneously enhancing system performance and reliability. This is achieved by consolidating the first three control stages into a simplified control structure and directing their functional requirements to the remaining d-axis and q-axis current regulation stages. Consequently, the original DC-link voltage regulation, reactive power regulation, and AC voltage regulation stages are eliminated, while the d-axis and q-axis current control loops are retained and further strengthened to assume the responsibilities of the removed stages [35]. The DAWPI control approach is expected to deliver superior dynamic performance due to its adaptive control characteristics. Unlike the conventional PI controller, which utilizes fixed proportional and integral gains, the DAWPI controller employs a variable integral gain mechanism that continuously adapts to changing system operating conditions. This adaptive feature enhances controller responsiveness, improves disturbance rejection capability, and promotes more effective harmonic mitigation under varying grid and load conditions. Figure 7 presents the SIMULINK implementation of the overall Dual Anti Windup PI-based Harmonic Mitigation Control Algorithm (DAWPI-HMCA). In the proposed architecture, enhanced d-axis and q-axis current regulation controllers replace the five principal control stages utilized in the conventional PI-HMCA framework. To compensate for the elimination of the first three control loops, the DAWPI controllers are initially developed using simulation data obtained from the dq-axis current regulation stage of the AWPI-HMCA. Subsequently, the controller parameters are refined through an online optimization process involving iterative simulation and performance evaluation. By reducing the number of control stages, the DAWPI-HMCA significantly lowers computational requirements and implementation complexity while maintaining a high level of control effectiveness. Despite its simplified structure, the proposed DAWPI-HMCA demonstrates performance and reliability characteristics that are comparable to, and in some cases superior to, those of the AWPI-HMCA and conventional PI-HMCA approaches. As shown in Figure 7, the input data preprocessing stage involves the computation of the relative errors between the measured utility grid variables and the corresponding hybrid PV–WT microgrid variables. These error signals are subsequently normalized and processed to generate adaptive control actions that enhance current regulation, harmonic suppression, and grid synchronization performance.

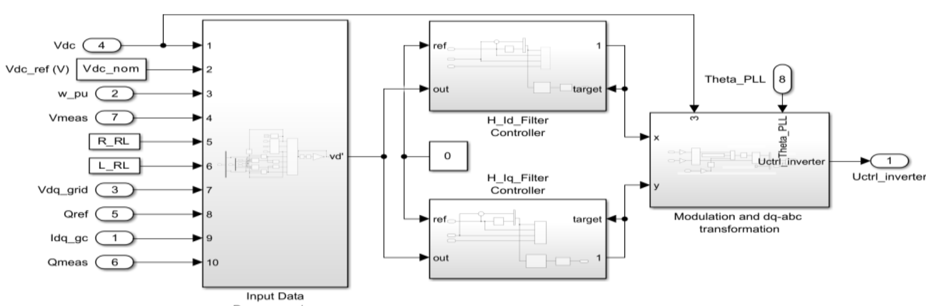


Figure 7. SIMULINK model of the proposed dual-AWPI-controller based HMCA

In the proposed DAWPI-HMCA framework, input data preprocessing begins with the measurement of all relevant system state variables and the computation of their corresponding control errors. These error signals are subsequently aggregated to form a composite system error response, which serves as one of the primary inputs to each Anti Windup Proportional–Integral (AWPI) controller. The reference error signal is set to zero, representing the desired steady-state operating condition. The calculated control errors include the DC-link voltage error, grid voltage magnitude error, reactive power injection error, d-axis grid current error, q-axis grid current error, d-axis grid voltage error, and q-axis grid voltage error [35]. The summation of these error components constitutes the first input to each AWPI controller. The second input is obtained from the unit-delayed (previously sampled) d-axis and q-axis voltage signals associated with the respective controllers. Meanwhile, the target response corresponds to the most recent d-axis and q-axis voltage values. By integrating all system error signals into a unified control input, the DAWPI-HMCA effectively incorporates the dynamic effects of the previously defined control stages and their associated state variables into the two adaptive controllers. This consolidated approach enables the d-axis and q-axis controllers to capture the overall system dynamics while maintaining a simplified control architecture. As illustrated in Figure 7, the measured signals are first processed within the *Input Data Pre-processing* block and subsequently applied directly to the *H_Id_Filter Controller* and *H_Iq_Filter Controller*, which function as the proposed AWPI-based d-axis and q-axis current regulators, respectively. A key distinction between the DAWPI-HMCA and the other proposed harmonic mitigation strategies lies in the nature of their outputs. The DAWPI-HMCA directly estimates the d-axis and q-axis inverter reference input voltages required for converter control. In contrast, both the PI-HMCA and AWPI-HMCA initially estimate the corresponding d-axis and q-axis current references, which must then undergo additional regulation stages to generate the inverter reference voltages. Consequently, the DAWPI-HMCA offers a more streamlined control structure with reduced computational complexity while maintaining effective harmonic mitigation and grid synchronization performance [35, 36].

### 3.7 Model of the Proposed Solar Energy Conversion System (SECS)

This study proposes a scalable Solar Energy Conversion System (SECS) based on solar photovoltaic (PV) technology for utility-grid integration, as illustrated in Figure 8. The proposed PV farm consists of four solar PV array units connected in parallel, with each array interfaced through an individual DC–DC boost converter. The electrical output from the individual PV units is aggregated at a common DC-link, which serves as the intermediate energy storage and power conditioning stage prior to grid integration. To maximize energy extraction under varying environmental conditions, each PV unit is equipped with a Maximum Power Point Tracking (MPPT) controller. The MPPT system continuously adjusts the operating point of the PV array to ensure maximum power generation under changing solar irradiance and temperature conditions [36]. The SIMULINK implementation of the proposed MPPT-enabled DC–DC boost converter, together with its corresponding circuit. In addition, the MATLAB-based pseudocode describing the implementation of the proposed MPPT algorithm is provided in Plate 1. A Voltage Source Converter (VSC)-based inverter is employed to convert the regulated DC-link voltage into its AC equivalent and synchronize the generated power with the utility grid in terms of voltage magnitude, frequency, and phase angle. To facilitate efficient power transfer and minimize interface losses, a suitably designed RL choke is incorporated to provide impedance matching between the PV-based microgrid and the utility network. Furthermore, a Static VAR Compensator (SVC) is integrated into the system to provide reactive power support, improve voltage regulation, and mitigate the propagation of local disturbances into the utility grid. This additional compensation enhances overall system stability and power quality during both normal and disturbed operating conditions. For grid interconnection, a 0.260/33 kV step-up transformer is installed at the Point of Common Coupling (PCC) between the photovoltaic system and the utility grid. The transformer provides the necessary voltage transformation for efficient power injection into the distribution network while ensuring compliance with grid connection requirements. The overall SECS architecture therefore combines maximum power extraction, voltage regulation, reactive power compensation, and grid synchronization capabilities to support reliable and efficient integration of solar photovoltaic generation into the power system.

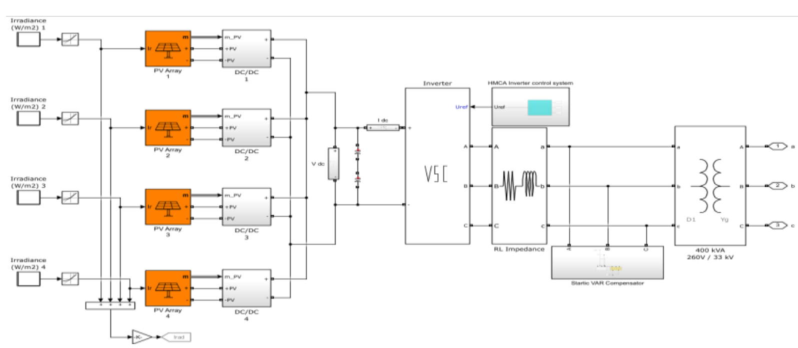


Figure 8. SIMULINK model of the proposed solar-PV based SECS

**Algorithm-1:** The Maximum Power Point Tracking (MPPT) algorithm

```
This algorithm predicts the optimum duty cycle (D0) required for MPPT
Input: Dinit; % Initial value for D
Input: Dmax; % Maximum value for D
Input: Dmin;   % Minimum value for D
Input: dD; % Incremental value for D
Input:  t; % Simulation Time
If t = 0
    V0 = 0;
    P0 = 0;
    D0 = Dinit;
Else
    Input: P0; % Output power of PV array
    Input: V0; % Terminal voltage of PV array
    Input: D0; % Initial value for D
End
P   = V*I;
dV = V – V0;
dP = P – P0;
If dP NOT 0
    If dP < 0
        If dV < 0
            D = D0 - dD;
        Else
            D = D0 + dD;
        End
    Else
        If dV < 0
            D = D0 + dD;
        Else
            D = D0 - dD;
        End
    End
Else D=D0;
End
If D >= Dmax
    D=D0;
End
If D <= Dmin
    D=D0;
End
Output: D0 = D;
Output: V0 = V;
Output: P0  = P;
```

Plate 1. MATLAB based pseudocode of the proposed MPPT algorithm

## 4 RESULTS AND DISCUSSION

This section presents and discusses the simulation results obtained from the three Harmonic Mitigation Control Algorithms (HMCAs) developed in this study. The performance of the Proportional–Integral Harmonic Mitigation Control Algorithm (PI-HMCA), the Multi Anti Windup Proportional–Integral Harmonic Mitigation Control Algorithm (MAWPI-HMCA), and the Dual Anti Windup Proportional–Integral Harmonic Mitigation Control Algorithm (DAWPI-HMCA) are evaluated and comparatively analyzed. The simulation was conducted using a MATLAB/Simulink-based power system model incorporating the proposed renewable energy integration framework and harmonic mitigation strategies. The input parameters, operating set-points, and optimal controller gain settings for the PI-HMCA, MAWPI-HMCA, and DAWPI-HMCA were specified prior to simulation execution. While only the key parameters are discussed herein, detailed system and controller parameters are available in [33] and may be provided upon request. These parameters constitute the initial conditions required for the successful implementation and execution of the simulation model.

### 4.1 Harmonic Mitigation Analysis Simulation Setup

As previously described, Particle Swarm Optimization (PSO) was employed as the optimization technique for controller design and parameter tuning throughout this study. The swarm population size was set to 10 particles, while the maximum number of iterations was fixed at 1000 [34]. The Sum of Squared Error (SSE) between the predicted system response and the desired reference response was adopted as the objective function to guide the optimization process. The remaining PSO parameters were initialized using MATLAB's uniform random number generation function. To evaluate the effectiveness of the proposed control strategies, a controller replacement approach was adopted. Under this approach, the MATLAB/Simulink test power system was executed independently using each of the three harmonic mitigation control algorithms, namely PI-HMCA, MAWPI-HMCA, and DAWPI-HMCA [35]. The simulation outputs obtained from each controller configuration were recorded and exported to the MATLAB workspace for subsequent analysis. The simulation results are presented using graphical plots and performance charts to facilitate visualization, interpretation, and comparative assessment of the controllers. The detailed results and corresponding discussions are presented in the following subsections.

### 4.2 Effect of the HMCAs on Wind Turbine Generator Speed

The proposed harmonic mitigation control algorithms utilize the measured angular speed of the Wind Turbine Generator (WTG) as a key feedback variable for regulating system operation. This regulation ensures effective harmonic suppression while maintaining proper synchronization between the Active Power Filter (APF) and the utility grid. At the commencement of the simulation, the wind turbine generator operates at a relatively high speed due to the absence of control action and load demand. However, as the harmonic mitigation controllers become active and the renewable generation system begins supplying power to the grid, the generator speed gradually decreases and stabilizes at its nominal reference value of 1.0 per unit (pu), as illustrated in Figure 9. This stabilization process is associated with the establishment of steady-state operating conditions following load connection and power injection into the network. Figure 9 demonstrates that all three control strategies successfully regulate the wind turbine generator speed and maintain stable system operation. Nevertheless, differences in dynamic performance can be observed among the controllers [35]. The DAWPI-HMCA exhibits superior performance, characterized by reduced overshoot, faster settling time, and smoother convergence to the reference speed. The MAWPI-HMCA also demonstrates satisfactory performance but with slightly slower stabilization characteristics compared to the DAWPI-HMCA. The conventional PI-HMCA achieves acceptable speed regulation; however, it exhibits comparatively higher overshoot and longer settling time. Based on the observed dynamic response characteristics, the overall performance ranking of the controllers with respect to wind turbine generator speed regulation can be expressed as: DAWPI-HMCA > MAWPI-HMCA > PI-HMCA.

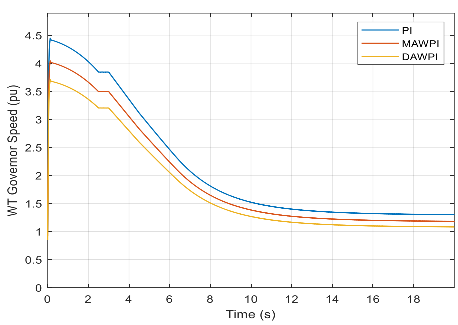


Figure 9. The WT generator (governor) speed regulation

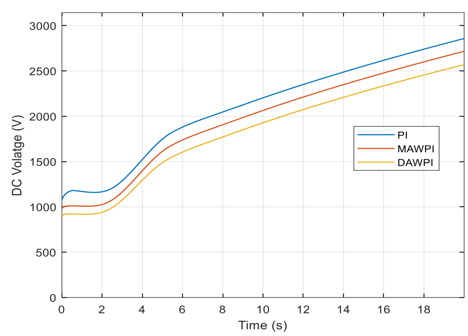


Figure 10. The DC-link voltage regulation

### 4.3 Effect of the HMCAs on DC-Link Voltage

The DC-link voltage constitutes one of the principal control variables within the proposed Harmonic Mitigation Control Algorithms (HMCAs). It is continuously monitored and utilized across multiple control stages to regulate system currents and voltages while facilitating effective harmonic mitigation. Furthermore, the DC-link voltage serves as a critical input to the modulation stage, where it is employed in generating the inverter reference voltage required for grid synchronization and power conditioning. Under ideal operating conditions, where harmonic distortions are absent or fully compensated, the DC-link voltage is expected to stabilize at its predefined reference value. However, in the presence of uncompensated harmonics or transient operating conditions, the DC-link voltage may continue to increase gradually over time until it reaches a saturation level determined by the electrical and operational limits of the converter components. Figure 10 presents a comparative analysis of the instantaneous DC-link voltage responses obtained using the PI-HMCA, MAWPI-HMCA, and Dual Anti Windup Proportional–Integral Harmonic Mitigation Control Algorithm (DAWPI-HMCA). Although the responses produced by the three controllers exhibit similar overall characteristics, subtle differences in performance can be observed. The DAWPI-HMCA demonstrates the most desirable response, characterized by a slightly lower DC-link voltage magnitude and a reduced rate of voltage rise compared to the other approaches. This behavior indicates improved voltage regulation capability and enhanced control effectiveness [26]. The MAWPI-HMCA also provides satisfactory performance, while the conventional PI-HMCA exhibits the highest DC-link voltage levels among the three control strategies. Based on the observed DC-link voltage regulation characteristics, the overall performance ranking of the controllers can be expressed as: DAWPI-HMCA > MAWPI-HMCA > PI-HMCA.

## 4.4 Performance Analysis of the Proposed HMCAs

To analyse the performance of the proposed PI, MAWPI, and DAWPI controller based HMCAs, the voltage and current THDs measured at the PCC, load, and WT buses, were evaluated and presented as bar charts in Figures 11, and 12. At the PCC, in Figure 11, the PI techniques outperform both the MAWPI and DAWPI on phase-A, with a slightly lower voltage THD. Whereas, the DAWPI took over on phase-B with a relatively stable performance across all the phase. On the other hand, MAWPI also performed slightly better in phase-C. In general, all the techniques are able to mitigate the voltage harmonics and achieved a lower voltage THD than the IEEE standard threshold of 3%. Additionally, considering the total harmonics injected by the combined Load and WT buses, both the PI and DAWPI have a closely relative performance, and supersedes the MAWPI strategy. On the other hand, At the PCC, in Figure 12, the DAWPI techniques outperform both the PI and MAWPI on phase-A, due to higher currents harmonics injection at the Load and WT buses [26]. This similar scenario occurred on phase-C. In general, all the techniques are able to mitigate the current harmonics and achieved a lower current THD than the IEEE standard threshold of 5%. Additionally, considering the total harmonics injected by the combined Load and WT buses, both the PI and DAWPI have a closely relative performance, and supersedes the MAWPI algorithm.

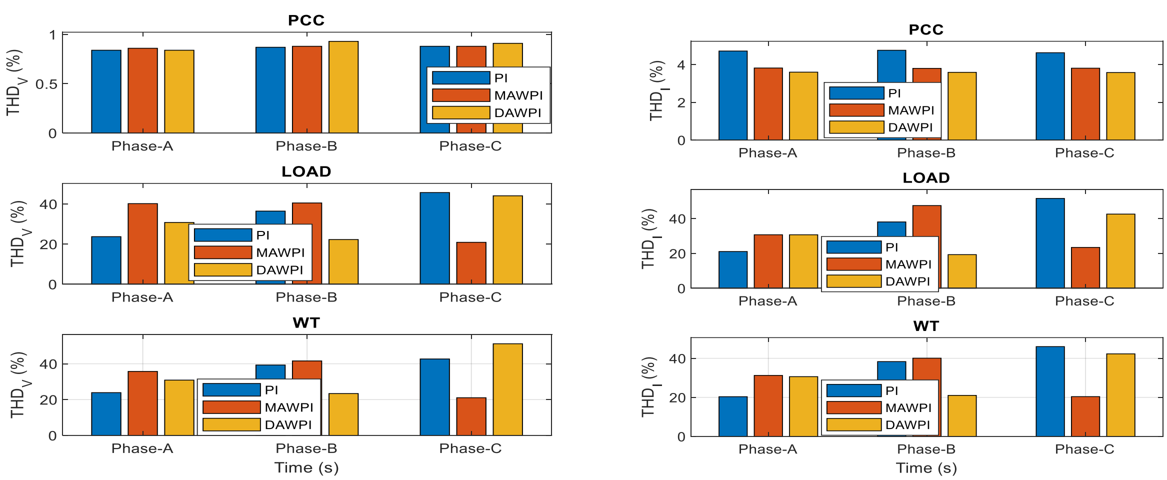


Figure 11 and 12: Comparing 3-phase voltage and current THDs at the PCC, load, and WT buses

## 4.5 Comparison of voltage individual harmonics distortions ($IHD_V$)

During the simulation, the resulting individual voltage harmonics for all the 3-pahses at the PCC, load, and WT bus were also saved and presented and compared using bar charts shown in Figures 13, 14, and 15, respectively for phases A, B, and C. In can be observed that the fundamental harmonic is absent in all the figures. Additionally, the 3rd harmonic is also absent at the PCC due to controller action. The odd harmonics are considered due to their adverse effects on power system components. In general, the individual voltage harmonics exponentially decays as the order increases. Whereas, the IHDs randomly varies across the phase due to load nonlinearity, and unbalancing [25].

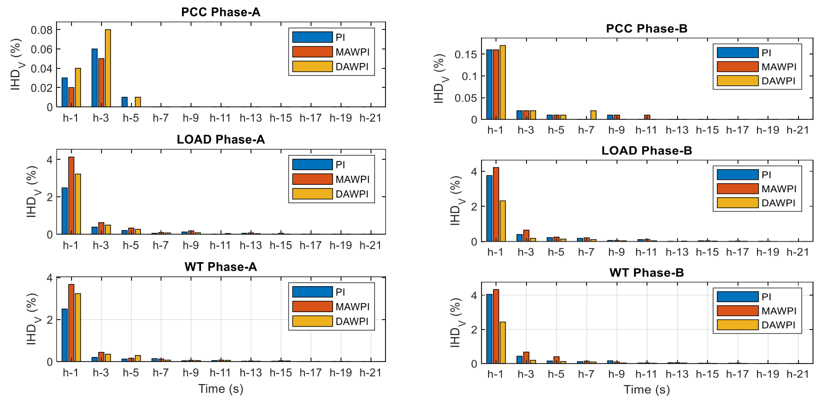


Figure 13 and 14: Comparing phase-A and B voltage IHDs at the PCC, load, and WT buses

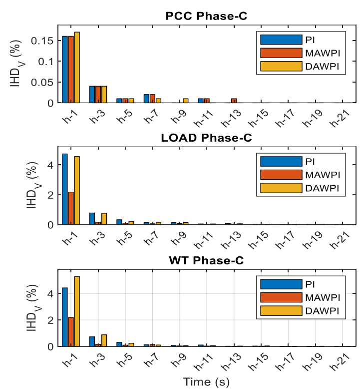


Figure 15: Comparing phase-C voltage IHDs at the PCC, load, and WT buses

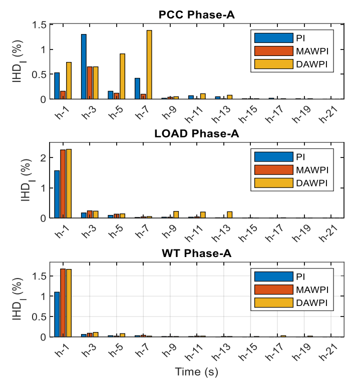


Figure 16: Comparing phase-A current IHDs at the PCC, load, and WT buses

## 4.6 Comparison of current individual harmonics distortions ($IHD_I$)

Furthermore, the current individual harmonics for all the 3-pahses at the PCC, load, and WT bus were also saved, presented and compared using bar charts shown in Figures 16, 17, and 18, respectively for phases A, B, and C. The fundamental harmonic can be observed to be absent in all the figures, whereas the 3rd harmonic is also absent at the PCC due to controller action. The odd current individual harmonics are considered due to their adverse effects on power system components. In general, the current individual harmonics also exponentially decays as the order increases. Whereas, the IHDs randomly varies across the phase due to load nonlinearity, and unbalancing [25].

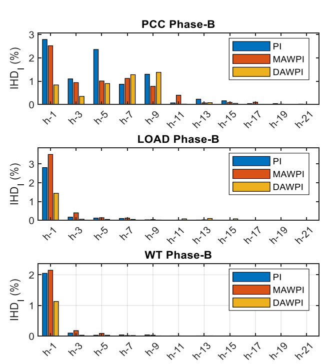


Figure 17. Comparing phase-B current IHDs at the PCC, load, and WT buses

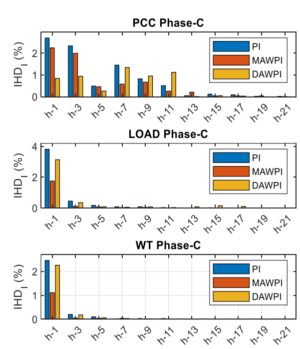


Figure 18. Comparing phase-C current IHDs at the PCC, load, and WT buses

## 5 CONCLUSIONS

A comparative performance evaluation of the proposed Proportional–Integral Harmonic Mitigation Control Algorithm (PI-HMCA), Modified Adaptive Weighted PI Harmonic Mitigation Control Algorithm (MAWPI-HMCA), and Dual Adaptive Weighted PI Harmonic Mitigation Control Algorithm (DAWPI-HMCA) was conducted based on their ability to reduce voltage and current Total Harmonic Distortion (THD) levels in a grid-connected wind turbine power system. The analysis of voltage THD reduction revealed that the PI-HMCA achieved the highest harmonic suppression performance in Phases A and B, while the DAWPI-HMCA exhibited superior performance in Phase C. Overall, the PI-HMCA demonstrated the best voltage harmonic mitigation capability, achieving a performance advantage of approximately 6.9% over its closest competitor, which recorded a maximum voltage THD reduction of 76.8%. In contrast, the current THD analysis showed that the DAWPI-HMCA achieved the highest harmonic reduction in Phases A and C, whereas the PI-HMCA performed slightly better in Phase B. When considering overall current harmonic mitigation, the DAWPI-HMCA outperformed the other control strategies, achieving an improvement margin of approximately 27.8% relative to its nearest counterpart, which attained a maximum current THD reduction of 98.5%. To provide a comprehensive assessment of controller performance, a Root Mean Square (RMS)-based performance index was developed to combine the harmonic reduction achieved in both voltage and current waveforms. Based on this overall harmonic mitigation index, the DAWPI-HMCA emerged as the most effective control strategy, achieving an overall RMS harmonic reduction of 89.1%. This was followed by the PI-HMCA, which achieved an overall reduction of 76.4%, while the MAWPI-HMCA demonstrated a commendable performance with an RMS harmonic reduction of 63.6%. The results obtained from this study indicate that all three proposed harmonic mitigation control algorithms are effective in reducing harmonic distortions and enhancing power quality in grid-connected wind energy conversion systems. However, the DAWPI-HMCA demonstrated the best overall performance due to its adaptive control capability, simplified architecture, and superior harmonic suppression characteristics. Consequently, the DAWPI-HMCA is recommended as a robust and efficient control strategy for harmonic mitigation and grid integration of renewable energy systems, particularly in wind-powered utility applications.

## REFERENCES


1. Kundur. P. (1994). Power System Stability and Control. *McGraw-Hill, New York*.

2. Dou, X., Wang, Y., Ciais, P., Chevallier, F., Davis, S.J., Crippa, M., Janssens-Maenhout, G., Guizzardi, D., Solazzo, E., Yan, F., Huo, D., Zheng, B., Zhu, B., Cui, D., Ke, P., Sun, T., Wang, H., Zhang, Q., Gentine, P., Deng, Z. and Liu, Z. (2022). Near-real-time global gridded daily $CO_2$ emissions. *The Innovation*, vol. 3, no. 1, Article 100182, pp. 1-11.

3. Iweh, C.D., Gyamfi, S., Tanyi, E. and Effah-Donyina, E. (2021). Distributed generation and renewable energy integration into the grid: Prerequisites, push factors, practical options, issues and merits. *Energies*, vol. 14, no. 17, Article 5375, pp 1-34, 2021. [Online]. Available: https://www.mdpi.com/1996-1073/14/17/5375.

4. Abdulkarim, H., Sansom, C., Patchigolla, K. and King, P. (2020). Statistical and economic analysis of solar radiation and climatic data for the development of solar PV system in Nigeria. *Energy Reports*, vol. 6, pp. 309-316, 2020. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2352484719306675.

5. Somoye, O.A. (2023). Energy crisis and renewable energy potentials in Nigeria: A review. *Renewable and Sustainable Energy Reviews*, vol. 188, Article 113794, pp. 1-17.

6. Obada, D.O., Muhammad, M., Tajiri, S.B., Kekung, M.O., Abolade, S.A., Akinpelu, S.B. and Akande, A. (2024). A review of renewable energy resources in Nigeria for climate change mitigation. *Case Studies in Chemical and Environmental Engineering*, vol. 9, Article 100669, pp. 1-17.

7. Oyedepo, S.O. (2012). Energy and sustainable development in Nigeria: The way forward. *Energy, Sustainability and Society*, vol. 2, Art. no. 15, pp. 1-16.

8. Joseph, U.J., Obuah, E.C., Clement, K.B., Ekwere, W.A., Akang, I.S. and Edet. E.U. (2025). Grid integration of renewable energy for reliable and efficient power supply in Nigeria. *Journal of Engineering Research and Reports*, vol. 27, no. 10, pp. 97-118.

9. Sunday, P. and Mutah. W.M. (2014). Integration of renewable energy sources into power systems in Nigeria for operational efficiency. *ALSYSTECH Journal of Education Technology*, vol. 3, no. 1, pp. 16-27.

10. Ozioko, I.O., Ugwuanyi, N.S. and Ekwue, A.O. (2025). Grid Stability Assessment of Emerging Power Systems with DFIG Wind Integration. *Energy Systems Research*, vol. 8, no. 4, pp. 78-88.

11. Esobinenwu, C.S. (2025). Assessment of smart inverter integration for voltage stability in Nigerian power grid. *Research Journal of Engineering and Allied Sciences*, vol. 13, no. 3, pp. 29-41.

12. Onwuzuruike, J.A., Hussein, S.U., Adetokun, B.B. and Oghorada, O. (2025). Integrating Large-Scale Variable Renewable Energy Resources on the Transmission Grid: A Case Study of the Nigerian Transmission System. *Nigerian Journal of Technological Development*, vol. 22, no. 5, pp. 273-280.

13. Biragbara, P.B. (2025). Grid Stability and Power Quality Analysis of 65 MW Solar Photovoltaic Integration into the 132 kV Transmission Network in Port Harcourt, Nigeria. *Indonesian Journal of Electrical Engineering and Renewable Energy*, vol. 5, no. 2, pp. 127-137.

14. Jumare, I.A., Bhandari, R. and Zerga, A. (2020). Assessment of a decentralized grid-connected photovoltaic (PV)/wind/biogas hybrid power system in northern Nigeria. *Energy, Sustainability and Society*, vol. 10, Art no. 30, pp. 1-27.

15. Yao, X., Yi, B., Yu, Y., Fan, Y. and Zhu, L. (2020). Economic analysis of grid integration of variable solar and wind power with conventional power system. Applied Energy, vol. 264, Article 114706, pp. 1-13.

16. Shaker, H., Zareipour, H. and Wood, D. (2016). Impacts of large-scale wind and solar power integration on California's net electrical load. *Renew. Sustain. Energy Rev*., vol. 58, pp. 761-774.

17. Chen, X., Wang, Y. and Zhang, J. (2020). Hybrid renewable energy systems for power grid stability. *IEEE Transactions on Smart Grid*, vol. 11, no. 3, pp. 1245-1260.

18. Zhao, L., Tang, W. and Chen, Z. (2019). Power quality challenges in hybrid renewable grids. *J. Renew. Power Syst.*, vol. 45, no. 3, pp. 589-602.

19. Singh, B. and Kumar, N. (2020). Impact of Renewable Energy Sources on Power System Protection. *Electr. Power Syst. Res*., vol. 180, Article 106212, pp. 1-12.

20. Flynn, D., Rather, Z., Ardal, A., D'Arco, S., Hansen, A.D., Cutululis, N.A. and Wang, Y. (2016). Technical impacts of high penetration levels of wind power on power system stability. *Wiley Interdisciplinary Reviews: Energy and Environment*, vol. 6, no. 2, Article e216, pp. 1-19.

21. Kabouris, J. and Kanellos, F.D. (2010). Impacts of large-scale wind penetration on designing and operation of electric power systems. *IEEE Trans. Sustain. Energy*, vol. 1, no. 2, pp. 107-114.

22. Vittal, E. and Keane, A. (2013). Identification of critical wind farm locations for improved stability and system planning. *IEEE Trans. Power Syst*., vol. 28, no. 3, pp. 2950-2958.

23. Eftekharnejad, S., Heydt, G.T. and Vittal, V. (2015). Optimal generation dispatch with high penetration of photovoltaic generation. *IEEE Transactions on Sustainable Energy*, vol. 6, no. 3, pp. 1013-1020.

24. Martín-Martínez, S., Gómez-Lazaro, E., Molina-Garcia, A. (2014). Impact of wind power curtailments on the Spanish power system operation. *IEEE PES General Meeting, National Harbor, Maryland, USA*, pp. 1-5.

25. Kazerani, W.A. and Salama, M.M.A. (2011). Investigation of methods for reduction of power fluctuations generated from large grid-connected photovoltaic systems. *IEEE Trans. Energy Convers*., vol. 26, no. 1, pp. 318-327.

26. Shakirov, V. (2019). An analysis of wind and solar power variability to assess its implications for power grid. *EPJ Web of Conferences*, vol. 217, Article 01019, pp. 1-7.

27. Khare, V., Nema, S. and Baredar, P. (2016). Solar–wind hybrid renewable energy system: a review. *Renew. Sustain. Energy Rev*., vol. 58, pp. 23-33.

28. Leung, D.Y.C. and Yang, Y. (2012). Wind energy development and its environmental impact: a review. *Renew. Sustain. Energy Rev*., vol. 16, no. 1, pp. 1031-1039.

29. Li, C., Chen, D., Liu, X., Shahidehpour, M., Yang, H., Liu, H., Huang, W., Wang, J., Deng, X. and Zhang, Q. (2024). Fault mitigation mechanism to pave the way to accommodate over 90% renewable energy in electric power systems. Applied Energy, vol. 359, Article 122623, pp. 1-13.

30. Ozioko, I.O., Ugwuanyi, N.S., Ekwue, A.O. and Odeh, C.I. (2022). Wind energy penetration impact on active power flow in developing grids. *Scientific African*, vol. 18, Article e01422, pp. 1-11.

31. Adetokun, B.B. and Muriithi, C.M. (2021). Impact of integrating large-scale DFIG-based wind energy conversion system on the voltage stability of weak national grids: A case study of the Nigerian power grid. *Energy Reports*, vol. 7, pp. 654-666.

32. Zhou, X., Usman, M., He, P., Mastoi, M.S. and Liu, S. (2021). Parameter design of governor power system stabilizer to suppress ultra-low-frequency oscilltions based on phase compensation. *Electrical Engineering*, vol. 103, no. 1, pp. 685-696.

33. Ibrahim, M.B., Jiya, J.D., Gana, M.A., Mustapha, I. and Jafaru, U. (2024). Optimal tuning of power system stabilizer using optimal foraging algorithm. *Nigerian Journal of Engineering Science and Technology Research*, vol. 10, no. 1, pp. 167-184.

34. Su, H. (2017). Siting and sizing of distributed generators based on improved simulated annealing particle swarm optimization. *Environmental Science and Pollution Research, Berlin, Germany: Springer*, vol. 24, no. 36, pp. 29773-29782.

35. Li, X.L., Park, J.G. and Shin, H.B. (2011). Comparison and eveluation of anti-windup PI controllers. *Journal of power Elecronics*, vol. 11 no.1, pp. 45-50.

36. Liu, K., Mao, Y., Chen, X., He, J. and Dong, M. (2023). Research on Dynamic Modeling and Parameter Identification of the Grid-Connected PV Power Generation System. *Energies*, vol. 16, no. 10, pp. 1-18.