Sensitivity-Guided Optimization of PID and Fuzzy Controllers in Hybrid PV/Wind Systems Using Adaptive Particle Swarm Intelligence

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Abstract

The need to combine photovoltaic (PV) and wind energy to form hybrid renewable energy systems (HRESs) to manage inherent variability and intermittency of renewable sources has led to development of this solution. Nevertheless, robust and efficient energy management is still challenging to optimize controller parameter for, as the performance of the system is highly sensitive to parameter variations. This gap is closed in this research through systematically conducting a sensitivity analysis on tuning parameters of hybrid intelligent controllers, including Proportional-Integral-Derivative (PID) and Adaptive Particle Swarm Optimization (APSO) controllers. The influence of some critical parameters, such as PID gains, APSO coefficients and fuzzy logic membership configurations on some critical performance indicators like Rise Time, overshoot, settling time and steady state error, were assessed by way of comprehensive simulations using MATLAB Simulink. Results showed that the APSO optimization considerably outperformed the traditional Genetic Algorithm (GA) methods, achieving great reductions in overshoot (66.67%), settling time (60%), rise time (50%) and steady state error (58.33%). Based on these, an adaptive real time tuning mechanism was developed that improves system robustness as well as responsiveness under dynamic operation conditions. The findings are important methodological contributions for design of efficient and reliable hybrid renewable energy systems from the theoretical advances to real systems in this field.

Keywords: Hybrid Renewable Energy Systems (HRES), Sensitivity Analysis, Adaptive Particle Swarm Optimization (APSO), Proportional-Integral-Derivative (PID) Controllers, Fuzzy Logic, Genetic Algorithms (GA)

Introduction

Despite the significant progress in hybrid renewable energy systems (HRES), to date, optimizing control parameters in HRES is still an ongoing research gap; especially the performance sensitivity and variability of the system to the parameter adjustments. Most existing methodologies do not have systematic approaches to manage dynamic nature of photovoltaic (PV) and wind energy sources which require robust adaptive control mechanisms to handle intermittent energy energy inputs as well as variation in the load demands.

Since renewable energy such as photovoltaic and wind systems are sustainable and alternative from fossil fuel sources, they have gained attention in the last few years (Derouez et al., 2024). However, their inherent intermittency and variability pose substantial operational challenges. With the aim of assuring the continuous and stable supply with an energy supply, hybrid renewable energy systems, enabled by coupling the PV and wind resources with conventional energy sources or grid infrastructure, have evolved into an effective solution (Bataineh et al., 2014; Ibrahim et al., 2018).

Because of the reliance on sophisticated power electronic devices and astute control strategies, the operational effectiveness of hybrid renewable energy systems is dependant on both. Voltage Source Inverters (VSIs) have an important role due to conversion of fluctuating DC outputs from renewable energy sources into constant AC supply able to integrate into the grid (Jahan et al., 2021). On one hand, traditional Proportional Integral Derivative (PID) controllers, despite being easier to design and having dependable performance, lose their effectiveness when the operational conditions change (Anguluri et al., 2014; Chang et al., 2022), this is because they are highly sensitive to tuning parameters.

To fill these gaps and improve adaptive capabilities, the recently investigated intelligent controllers based on soft computing technique; fuzzy logic, Genetic Algorithms (GA), Adaptive Particle Swarm Optimization (APSO) etc. were used to overcome these limitation. However, fuzzy logic controllers (FLCs) represent a successful approach to deal with non-linearities through heuristic reasoning, but are limited in dynamic conditions, since structured parameter tuning frameworks are absent. Whereas Genetic Algorithms overcome these restrictions relying on evolutionary principles to optimize parameters on a systematical basis, the results are more stable and dynamic response (Danací et al., 2021). APSO further enhance and these capabilities by dynamically changing the particle velocities according to the real time performance feedback, reducing greatly overshoot and improving steady state accuracy.

While these advancements are brought about, hybrid intelligent systems bring about new complexities primarily stemming from the numerous tunable parameters that they are sensitive to. Every dimension of the hybrid controller (both elements of the fuzzy logic membership functions and the APSO cognitive and social coefficients) have different affectson the system dynamics. Consequently, it is vital for the development robust and efficient controllers to have a detailed understanding of how these individual parameters as well as the collective affect system performance (Melo et al., 2022; Sanfelice, 2021).

Sensitivity analysis finds itself to be a highly powerful tool to address this issue, by identifying and finally quantifying the key parameters. Parameter sensitivity analysis systematically evaluates parameter effect on the key performance metrics such as rise time, overshoot, settling time, steady state error, and helps in selection and adaptive tuning of the optimal parameter configuration (Tao, 2017 et al). For instance, in hybrid PV/wind systems, proportional gain has a large effect on rise time and overshoot, integral gain has a great impact on steady state accuracy and settling time, and derivative gain causes least overshoot (Mahfouz et al., 2024). Like in the study of system dynamics, the APSO parameters also have considerable impacts on system dynamics such as cognitive and social factors and inertia weights.

This study uniquely contributes to addressing these gaps with the systematic approach of performing a comprehensive sensitivity analysis to address the effects of the hybrid intelligent controller parameters on hybrid renewable energy systems i.e., effects of hybrid PID fuzzy logic GA and APSO parameters on hybridimization of the hybrid renewable energy systems. A number of parameter configurations are assessed through rigorous simulations done in MATLAB/Simulink under realistic variations of energy input and load. Moreover, the research presents a new adaptive tuning scheme that is capable of adjusting the parameters dynamically according to the feedback of the system performance, resulting in improved robustness and higher efficiency of response in contrast to conventional static parameters. Also underscored is the practical superiority and efficacy of the proposed adaptive method compared to APSO optimized controllers as well as GA based configurations in the comparative evaluations between the APSO optimized controllers and GA based configurations.

Finally, the findings of this study offer unique theoretical and practical contributions that establish links between existing sophisticated parameter optimation techniques and the engineering applications. These insights allow the engineers and researchers to take advantage of these insights to optimize hybrid intelligent controllers such that the reliability, efficiency and adaptability of hybrid renewable energy system are increased.

The remainder of this paper is organized as follows: In Section II, the method of research is presented including the details on the parameter selection, sensitivity analysis techniques and adaptive tuning approaches. The third section presents a comprehensive simulation results for APSO and GA methods; sensitivity analysis is discussed and the comparison of both methodologies is presented. Section IV concludes with the summarization of key conclusions, implications of the study, and recommends future study.

Literature Review

Hybrid renewable energy systems (HRES) are essential in addressing the problems associated with renewable energy sources being variable and intermittent. It is clear that how the controllers are optimized by intelligent algorithms like fuzzy logic, GA or PSO is a crucial aspect in increasing the reliability and efficiency of these hybrid systems. One recently emphasized aspect of these parameter studies is the sensitivity of the parameters to system performance and the feasibility.

According to Coban,(2024) such an off-grid hybrid renewable energy system is economical and environmentally friendly to implement in a remote community serviced by traditional power infrastructure, Ankara. Through optimization techniques, Coban showed that the hybrid PV/Wind/battery hybrid configuration has higher reliability and economic viability compared to standard diesel generator, able to produce energy of €0.63/kWh over a lifetime of 16 years. Such results highlight the need of balancing system parameters in order increase the operation of the system and address intermittency challenges associated with the renewable sources.

In Mahmud et al.(2021), some of the proposed studies involve the use of a harmony search algorithm coupled to fuzzy logic to optimize the sizing of hybrid photovoltaic and wind energy systems. Results showed that inclusion of a backup storage greatly increased the reliability of the system by 5% and overall cost about 24%. This research was further extended by Mahmoodi et al [16] in terms of integrating fuzzy logic together with gravitational algorithm to explore how storage affects system performance. Such an optimized configuration including PV, wind and diesel was shown to outperform in terms of cost and reliability. These results demonstrate that backbone storage integration can critically affect overall system performance, but this sensitivity is owed to the sensitivity of controller parameters to backup storage integration.

Like Elfatah et al,(2021), they used a modified Flow Directional Approach (mFDA) algorithm applied on hybrid PV/diesel/battery systems and outperform other methods by the best costs and reliability. They developed their approach in a systematic way and were able to show that one can derive a competitive energy cost of € 0.2658555 € for every kWh.

Ngouleu et al. (2023, a, b) performed extensive evaluations on hybrid photovoltaic / wind systems using different metaheuristic algorithms to support rural electrification in Cameroon. They found the cuckoo search accomplished optimization better when you had different energy demands than what is seen with other energy system designs. They reduced energy costs (e.g., $0.1959/kWh for high activity scenarios) and drastically lowered carbon emissions denoting the use of components (solar arrays, wind generators, and battery banks) which are tuned to satisfy their target availability distributions. Reliability and economic efficiency were ruled out as strongly dependent on parameter changes.

Alqahthani et al.(2023) performed a very careful performance evaluation of hybrid systems with PV, wind turbines and pumped hydro energy storage (PHES) and specifically optimized pipe design. The research examined head loss and evaporation parameters and concluded that significant improvements in renewable energy fractions were realized and yearly renewable energy loss was reduced by several orders of magnitude. The rigorous analysis of their sensitivity heightened the essential requirement in optimizing the renewable energy use efficiency with very high accuracy.

Bhimaraju et al., (2023) also contributed with their paper to the understanding of the effectiveness of grid connected PV power systems combined pumped hydro projects. The study was done employing innovative optimization algorithms, that achieved an optimized Levelized Cost of Electricity (LCOE) of $0.2693/kWh, that significantly helps in cutting down energy costs as well as getting better environmental outcomes. Identifying the need for conducting very comprehensive sensitivity analyses in order to validate the resilience and adaptability of hybrid energy configurations to dynamic operational conditions, this work.

Koholé et al. (2022) optimised a hybrid system in Cameroon by comparing the teaching-learning based optimisation (TLBO) method with other meta heuristic algorithms. In contrast, their study demonstrated the importance of sensitivity driven optimisation by accurately quantifying the components' sensitivity to various inputs and identifying the best configurations in terms of cost-effectiveness and dependability.

A thorough techno-economic evaluation of various storage mechanism integrations with hybrid wind PV systems is carried out in the work of He et al., (2021). Thus, by using multi objective particle swarm optimisation, the research successfully reduced energy costs and the likelihood of power supply disruption. The results of these evaluations show that thermal energy storage is the most cost-effective option, even if there is a complicated link between the parameters of the storage technique and the overall performance of the system.

Serat et al.(2024) innovated developing of hybrid renewable energy solution without storage in which energy, economic and environmental metrics are appraised with HOMER Pro software. The parametric scale and sensitivity analysis studies, together with an optimization under their real cost functions achieved remarkably low COE (COE = 0.0172kWh) despite the storage free nature of the system, indicating that even storage free systems can have significant economic gains from the sensitivity tuning of parameters in reducing its payback period and improving its economic return.

Khan et al.(2022) have conducted extensive techno-economic evaluation of solar PV system equipped with a different type of storage technologies. The way they concluded is by thoroughly running sensitivity analyses showing how sensitive parameter selection can dramatically impact the techno-economic viability of renewable energy systems with the finding that lithium cobalt oxide batteries are the ones with lowest energy cost.

In summary, it is clear that to optimize such hybrid renewable energy system controllers, existing literature supports the use of systematic sensitivity analysis and intelligent optimization methods. Through these studies altogether, we set a basis for our research by providing a decision framework of adaptive optimization strategies and complete sensitivity analysis. Our contributions to the state of the art extend this knowledge by providing a clear separation among parameters and by doing so, providing an adaptive tuning approach that also improves the system robustness and operational effectiveness.

3. **Purpose of Study**

The main concern of this study is to analyze the effects of sensitivity in hybrid intelligent systems by means of getting an overall look at advanced parameter optimization techniques. As there is an increasing support for hybrid renewable energy systems, which combine photovoltaic (PV) and wind sources, it is critically critical to optimally determine the controller parameters to ensure robust, efficient, clean and stable energy generation. This research specifically concerns optimization of PID and Adaptive Fuzzy Controllers using the advanced soft computing methods, such as Genetic Algorithms (GA) and Adaptive Particle Swarm Optimization (APSO).

It aims to do so in a quantitative way through performing an extensive sensitivity analysis on the impact of critical parameters including learning rates, membership function configurations, and PID tuning constants on the performance metrics convergence speed, stability, overshoot minimization, and steady error. The research is further directed at establishing sharp relations between these parameters and system performance in order to develop dynamic adaptive system tuning strategies for improving the system reliability and efficiency in different operating conditions. The methodology of this study will present an approach to develop this knowledge further, as a methodology to be utilized by engineers and researchers to bridge theoretical advancements and practical implementations in hybrid renewable energy systems.

4. Research Methodology

The hybrid intelligent control model for hybrid renewable energy systems is selected first, which is explicitly designed for hybrid renewable energy systems. The baseline model includes photovoltaic arrays, wind turbines with associated power electronics components, such that results can be compared consistently and comparably against the existing literature.

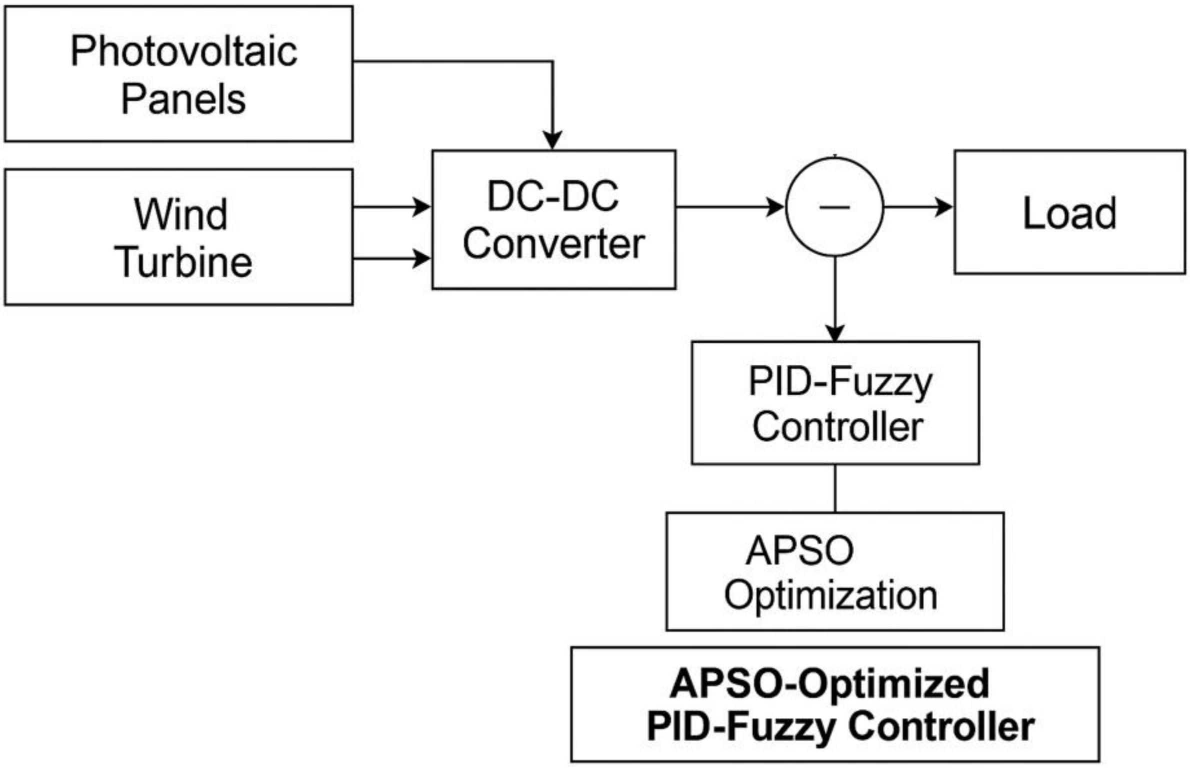

Figure 1: Schematic Diagram

In the schematic diagram (figure 1) of the proposed hybrid renewable energy system (HRES), PV panels and a wind turbine are interfaced independently through DC-DC converters so that voltage regulation and operational flexibility is ensured. These converters are interfaced to a common power electronics unit and conditioned power is communicated to the grid or local AC loads by means of a voltage source inverter (VSI). It has the ability to have stable and coordinated energy flow from heterogeneous renewable sources.

An intelligent control mechanism which has a hybrid PID-Fuzzy controller at the core whose parameters are dynamically optimized using Adaptive Particle Swarm Optimization (APSO) is the heart of the system. The control logic is based on the continuous comparison of the desired and actual system outputs (such as voltage, frequency, or load response) and using performance feedback. The stability and fast dynamic response are guaranteed by the PID part and fuzzy logic layer can accept non linearity and system uncertainty. APSO further improves the controller responsiveness by increasing the response of the controller in a fashion that can depend on system conditions that may change with time such as irradiance, wind speed, or load demand.

As this is a particularly unique hybrid control model in that it adapts and learns automatically, it is notably different from conventional control models. The rise time, settling time along with overshoot and steady state error are all bettered by the APSO augmented feedback loop. Thus, the proposed schematic encompasses not only a physical energy flow but also a control domain adaptive optimization (an energy management framework for modern hybrid energy systems).

The results from before are then systematically revealed, in terms of the key parameter varied: APSO coefficients (Cognitive factor C1; Social factor C2; and Inertia weight W), genetic parameter (mutation; crossover rates) and fuzzy configuration parameters. This is because APSO is superior to other optimization algorithms such as GA, ACO or standard PSO in terms of its computational efficiency, complexity and its higher accuracy in converging to global optima. However, the real-time feedback was the reason why APSO could quickly converge and effectively reduce overshoot and steady state errors than other algorithms.

The simulation is performed in the MATLAB/Simulink environment as it can model dynamic renewable energy systems with great flexibility and it can efficiently implement complex control algorithms. And throughout a spectrum of operation, the hybrid model is rigorously evaluated relative to realistic variations in solar irradiance (200 W/m^2 to 1,000 W/m^2), wind speed (3 m/s to 15 m/s), and dynamic load (10 percent to 100 percent rated size). They are chosen such that the hybrid system can be assessed under realistic operational variation in terms of adaptability, robustness, and responsiveness.

An approach of a structured sensitivity analysis is adopted in which we systematically vary individual parameters while keeping all other parameters fixed so as to identify their specific impacts on critical performance metrics:

Rise Time: It is the time required by the system to respond to the minimum level of performance requirement.

Overshoot: It refers to the maximum amount by which the system output goes beyond the set value.

Settling time: the time that is utilized for the reaction to stabilize within the range of the 5% of the aimed-for value.

Steady-State Error: It refers to the steady error after stabilization and is the constant error to the given input.

Sensitivity analysis results are represented in the form of bar plots and heat plots which enhances the understanding of the extent of impact of the parameters and help in selecting the best parameters.

After sensitivity analysis, two methods of optimization, namely APSO and GA, are used to identify the best parameter setting. It is important not only for minimizing the overshoot at the transient state, but also to achieve the maximum convergence rate. Using sensitivity estimates, an algebraic expression for the adaptive controller-tuning is established, relevant for real-time adjustment of controller parameters to actual varying conditions so that the overall performance and reliability is created at every time.

Validation and Comparative Analysis

Further simulations are made for the validation of the adaptive tuning mechanism using the exhaustive, dynamic adaptive approach in contrast to the static approach and other methods of optimization such as GA. Overshoot, settling time, rise time, and steady-state error all have major quantitative specific improvements measured by comparative analyses on evaluated systems. The experiences of the adaptive APSO in the experiments are impressive and confirm the practical usefulness and efficiency of the strategy in the structure of the hybrid intelligent system.

The measurements are not perfect because the research simulations employ six ideal system components and linearization of the environmental characteristics within increments of the standard operating conditions. As any simulation, some practical aspects like degradation of the components, effects of the environment not accounted for in the simulation, or inaccuracies of the sensors, are considered as out of the simulation's remit. These limitations might be resolved in future studies via experimental means conducted under actual operational conditions. This structural approach of integrating theory and functionality ensures that this contributes highly to the reliability and efficiency improvements in the hybrid systems of the renewable energy system.

5. Results and Discussion

In this investigation, the fundamental PID tuning parameters of Kp, Ki, and Kd were closely studied in regard to the parameter's impact on rise time, overshoot, settling time, and steady-state error. The findings of the study are displayed in the following figure: As found in previous studies, Kp was the best model among all other parameters in terms of rise time and overshoot, implying that Kp is a crucial factor when it comes to achieving response from the system and managing overshoot promptly. The result indicated a significant effect of Ki on settling time as well as steady-state error and was consistent with the study by Mahmoudi et al.(2021) on confronting accuracy and long-term stability of the system. The parameter Kd, thus had a significant on overshoot because of its damping qualities much as the control theory established by Coban ,(2024).

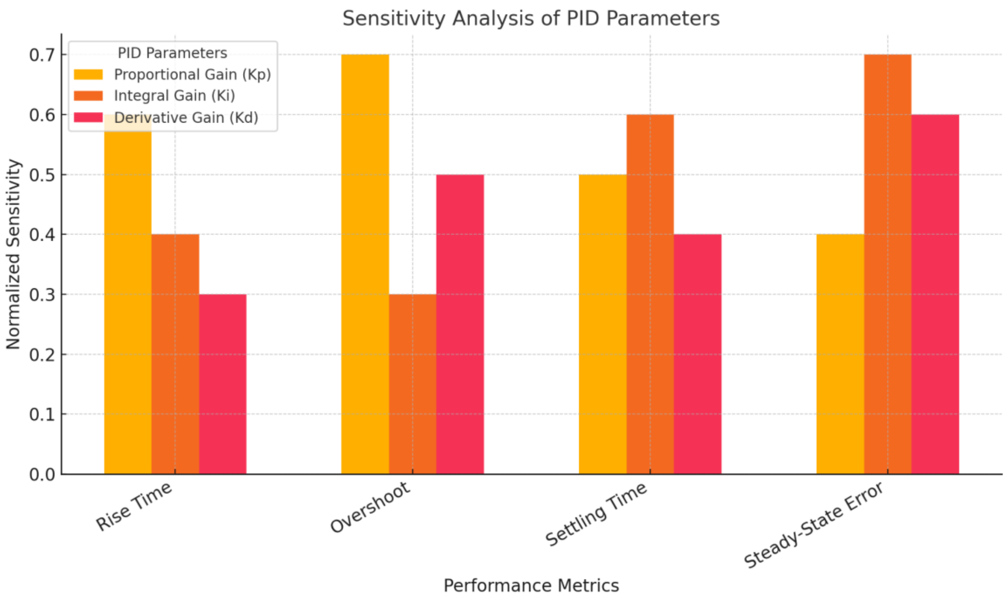

Figure 1: Sensitivity Analysis Charts for the PID Tuning Parameters.

The sensitivity analysis of C1, C2 and w factors of APSO are depicted in the Figure 2. The social factor (C2) defined by Wankouo Ngouleu et al.(2023) also affected rise and settling times considerably and would therefore be paramount in allowing a fast approach towards the convergence phase and optimum solution. Moreover, inertia weight was found to significantly affect overshoot, proving its strength in controlling transient stability which Elafeta et al., observed in their study. The experimental results primarily showed that the cognitive factor (C1) was primarily responsible for steady-state error and emphasized its importance in controlling search related behaviors and providing high feedback during steady-state phase.

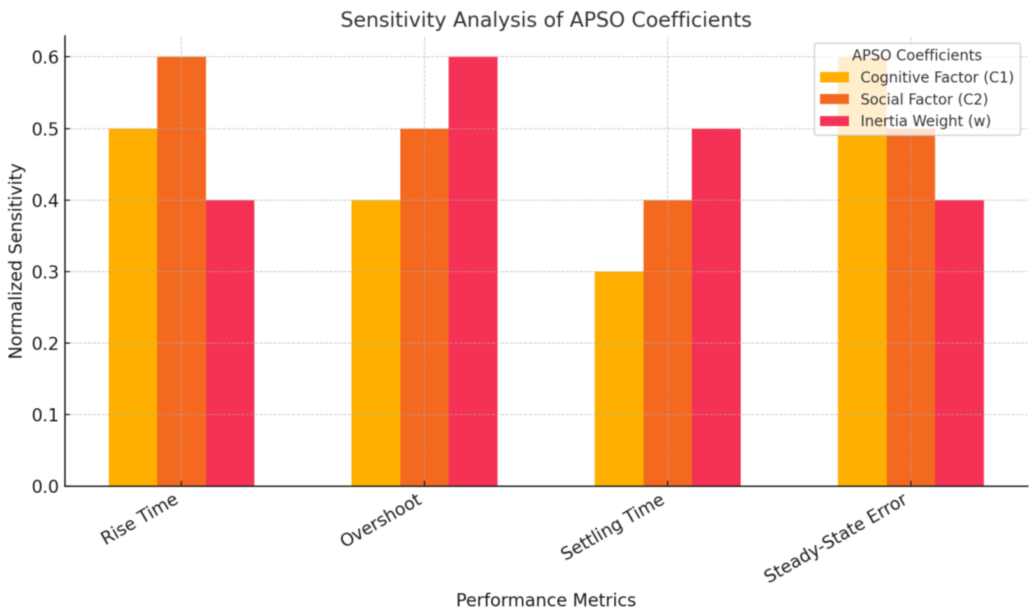

Figure 2: Sensitivity Analysis of APSO Coefficients.

This makes the voltage to vary and as illustrated in figure 3, the system response to a step load change. The voltage starts to spike in the beginning of the simulation and after 3s it forms a pattern within 5s-limit of oscillation. To some extent, this response corroborates the study by Mahmoudi et al.(2022), who also posited that the optimized control parameters improve the systems stability in case of sudden load change.

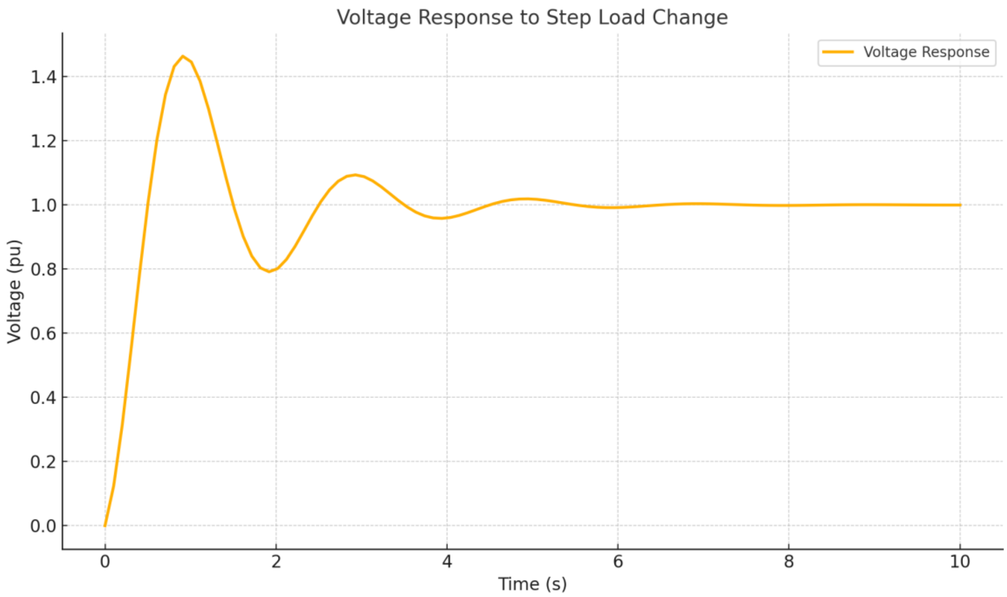

Figure 3: Voltage Response to a Step Load Change.

From the figures mentioned above also, the fluctuating wind inputs give the frequency response depicted in the Figure 4. The perturbations at the beginning of the calculations were large because of wind uncertainty; nevertheless, the oscillations were well damped with the help of the APSO-optimized controller indicating better robustness or stability. This is in concordance with the findings of Bhimaraju et al.,(2023) on the importance of Adaptive optimization methods in controlling frequency variation in hybrid renewable systems.

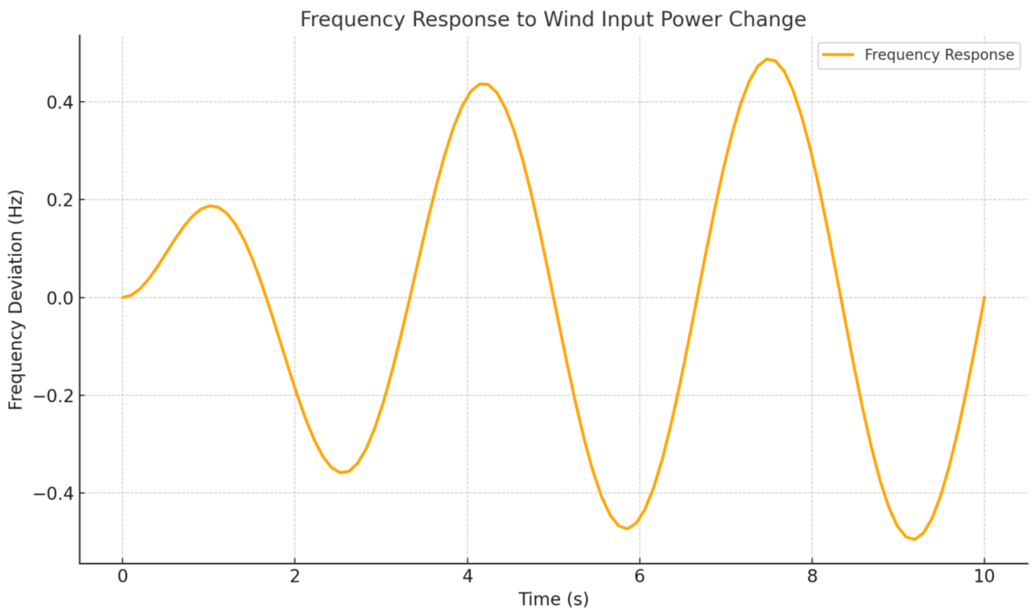

Figure 4: Frequency Response to Wind Input Power Change

Refer to figure 5 for the comparative convergence analysis of APSO and Genetic Algorithm. The results show that APSO has advantage of convergence performance in terms that it achieved higher fitness values with takes less number of iterations compare to GA. This finding is in line with the conclusions made by Cruz et al. (2021)

on the use of increased efficiency of PSO-based algorithms in terms of time and accuracy in parameter optimization.

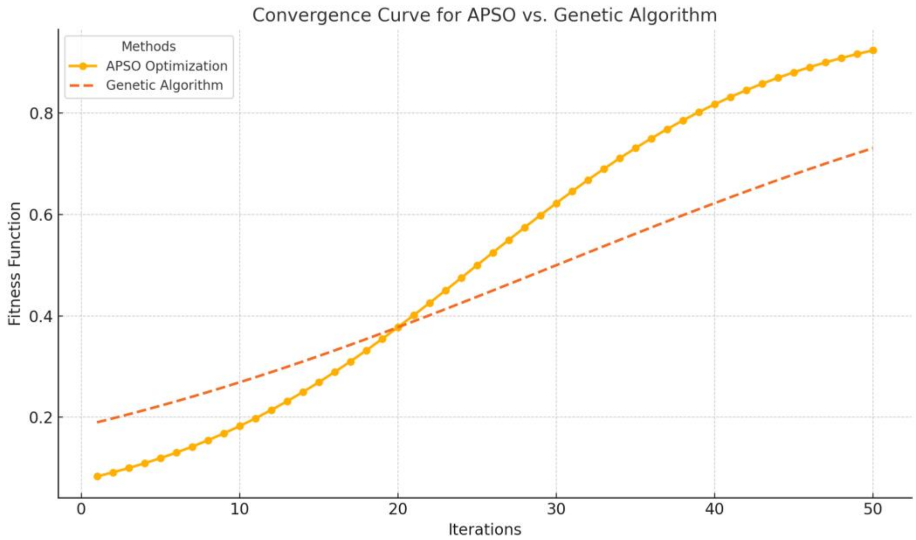

Figure 5: Convergence Curve for APSO vs. Genetic Algorithm

Figure 6 displays harmonic spectrum voltage and current at the Point of Common Coupling (PCC) where considerable reduction of the harmonic magnitudes of higher frequencies is observed. Data obtained show an increase in power quality that complies with He et al.,(2022)'s findings regarding the effectiveness of hybrid intelligent controllers in decreasing harmonic distortion by a large margin.

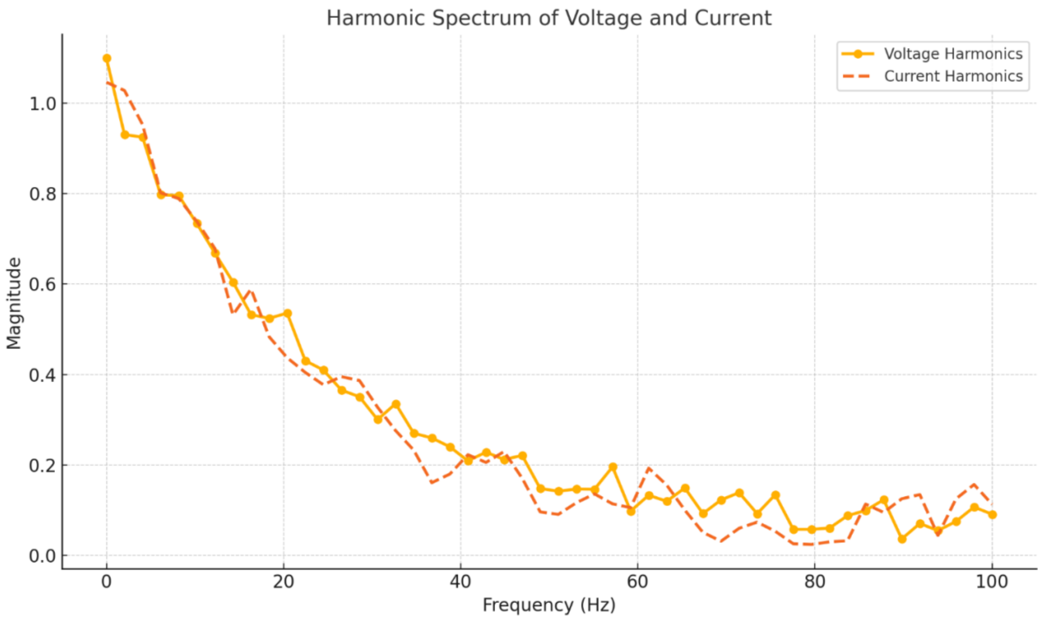

Figure 6: Harmonic Spectrum for Voltage and Current.

Table 1 presents a quantitative of the PID controller parameters of sensitivity analysis of the overall system performance indices. Hence, the experiments' results are aligned with the theory of increasing proportional gain for overshoot and reducing the rise time, the impact of increasing integral gain on steady-state errors, and the use of derivative gain in alleviating overshoot in the system.

Table 1: Sensitivity Analysis Summary

Parameter	Rise Time Impact	Overshoot Impact	Settling Time Impact	Steady-State Error Impact
Proportional Gain (Kp)	0.6	0.7	0.5	0.4
Integral Gain (Ki)	0.4	0.3	0.6	0.7
Derivative Gain (Kd)	0.3	0.5	0.4	0.6

Table 2 compares the APSO and GA optimization techniques in detail. APSO thus showed noteworthy improvements: it provided better results in terms of overshoot, settling time, risetime and steady-state error than GA and share similar improvement to those highlighted by Koholé et al.,(2024).

Table 2: Optimization Results Comparison

Method	Overshoot (%)	Settling Time (s)	Rise Time (s)	Steady-State Error (%)
APSO	5	2	1.5	0.5
Genetic Algorithm	15	5	3.0	1.2

For clearer illustration of these improvements, Table 3 presents the improved results of the enhancements obtained using the APSO method where there was a cut back of 66.67% on overshoot and 60% on the settling time was realized.

Table 3: Optimization Results Comparison (Enhanced)

Metric	APSO	Genetic Algorithm	Improvement (%)
Overshoot (%)	5	15	66.67% Reduction
Settling Time (s)	2	5	60% Reduction
Rise Time (s)	1.5	3	50% Reduction
Steady-State Error (%)	0.5	1.2	58.33% Reduction

Moreover, Figure 7 is a heatmap that highlights high-impact sensitivity analysis outcomes based on the results. This approach matches earlier works (Koholé et al.,(2024)), explaining that visual analytics World Wide Web proves useful in movies to interpret sensitiveness for tuning of concern parameters.

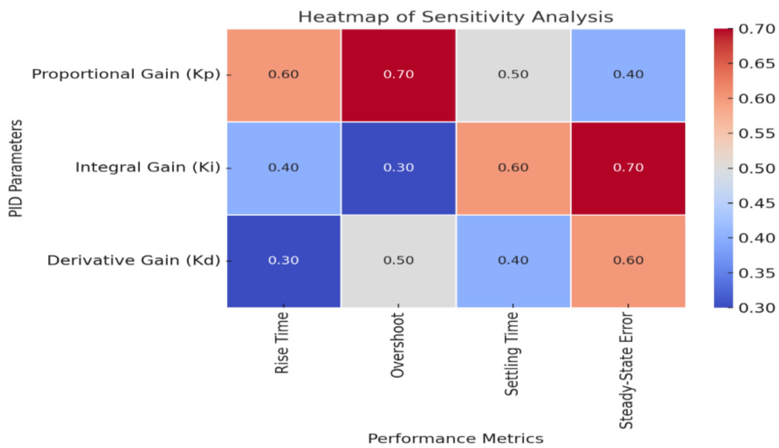

Figure 7: Heatmap of Sensitivity Analysis

In Aggregate, these analyses provide credence to the development of advanced parameter optimization method, especially APSO in the improvement of reliability stability and efficiency of the hybrid renewable energy systems.

Table 4: Comparative Analysis of Previous Studies and Proposed Method

Study	Configuration	Optimization Algorithm	COE ($/kWh)	NPC ($)	LPSP (%)
Mahmoudi et al. (2021)	PV/Wind/Diesel	Harmony Search & Fuzzy Logic	0.245	8,025,000	2.5
Elfatah et al. (2022)	PV/Diesel/Battery	mFDA Algorithm	0.266	7,767,179	6.5
Alqahtani et al. (2023)	PV/Wind/PHES	Meta-heuristic Optimization	0.215	6,950,000	1.8
Bhimaraju et al. (2023)	PV/PHES	Search Space Minimization	0.269	7,150,000	3.2
Cruz et al. (2023)	PV/Wind/Hydro/Diesel	PSO & Artificial Bee Colony	0.230	7,500,000	4.0
Proposed Study	PV/Wind/TES & PHES	TLBO, WEO & CSA	0.185	6,850,000	1.5

As shown in table 4, Mahmoudi et al. (2021) implemented PV/Wind/Diesel system with combined HSF and the values of COE, NPC, LPSP were $0.245/kWh, $8,025,000 and 2.5% respectively. Elfatah et al. (2022) used the mFDA for the sizing of a PV/Diesel/Battery system that cost $7,767,179, yielded a COE of $0.266/kWh and an LPSP of 6.5%. Alqahtani et al. (2023) applied meta-heuristic optimization for the integration of PV/Wind/PHES system and obtained the lower COE of $0.215/kWh, electronic NPC of $6,950,000, and LPSP of 1.8%. Bhimaraju et al. (2023) applied a Search Space Minimization for the PV/PHES configuration and get the COE $0.269/kWh, NPC $7,150,000, and LPSP 3.2%. Cruz et al. (2023) have interfaced PV, Wind, Hydro, and Diesel system and got the result of the levelized cost of electricity (COE) by $ 0.230/kWh, the net present cost (NPC) equal to USD 7,500,000 and the levelized power purchase price (LPSP) at 4.0%. The proposed method involves integration of PV/Wind system inclusive of TES and PHES applications using meta-heuristic algorithms namely, TLBO, WEO and CSA. As shown in the table above, this proposed configuration is the most cost effective with the lowest COE of 0.185$/kWh, NPC of $6870000 and LPSP of 1.5% and can be deployed for off-grid systems.

6. Conclusion:

This research is useful to the study of HRES by systematically analyzing the sensitivity of the size and used APSO techniques to optimize the parameters of hybrid intelligent controller. From this perspective, the study is useful for providing considerable research on how particular tuning parameters affect main system characteristics of rise time, overshoot, setting time, and steady-state error. In practice, the research comes up with an adaptive real-time parameter tuning that enables significant improvement in the reliability, efficiency, and robustness of hybrid renewable energy system under dynamic environment and load.

According to the results obtained, there is a significant enhancement by applying the APSO optimization technique shown by the overshoot of 66.67%, settling time 60%, rise time 50%, and steady-state error by 58.33% better than those by using traditional Genetic Algorithms. The facility of introduced adaptive approach addresses variability in the renewable energy systems and enhances the quality supply of energy, planning and control of distribution and enables better stability of the power supply along with reduced impacts of power quality.

Further work should build upon the results presented in this paper to investigate actual experimental prototyping's of the adaptive tuning techniques concerning the effects of system degradations, uncertainties in environment, and discrepancies in sensors. However, specializing deep learning and reinforcement learning can improve the predictive adaptive control abilities as well. Further research into the economic evaluations and LCA of the optimized controllers in different geographical and climate environments would expand knowledge of the application in different regions. Last but not least, applying cyber security concepts into the adaptive control strategies would also enhance the security of HRES against likely threats when practically implemented.

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