

Optimal Tuning of Five-Parameter Fractional Order PID Controller Using Hybrid Jaya–Grey Wolf Optimization for Robust Renewable Energy Conversion Systems

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Abstract

The growing deployment of renewable energy sources in current power systems poses many obstacles in terms of power fluctuation, voltage instability, and harmonic distortion which demand efficient control methods to address such issues. In this study, an HJGWO based FOPID controller for enhancing the dynamic performance of renewable energy-based power conversion system is introduced. The main emphasis of the proposed methodology is on the tuning of the five most important FOPID controller parameters, i.e., proportional gain (K_p), integral gain (K_i), derivative gain (K_d), fractional integral order (λ), and fractional derivative order (μ), through the exploration ability of the Jaya algorithm and exploitation ability of Grey Wolf Optimization. The optimal process has been framed using multi-objective function which incorporates the voltage tracking error and harmonic suppression. The proposed controller is tested for dynamic performance using voltage disturbances, renewable power fluctuations, and load variation scenarios. The simulation outcomes show that the presented HJGWO-FOPID controller shows higher convergence speed and better voltage regulation with lower transient error and harmonic suppression than conventional controllers. The optimized controller effectively enhances disturbance rejection performance while keeping the system stable without the need for any manual adjustment of the tuning parameters. It is concluded from the results that fractional order control together with the proposed hybrid optimization is an efficient approach for precise and reliable control of renewable energy power conversion systems.

Keywords: Hybrid Jaya–Grey Wolf Optimization (HJGWO), Fractional Order PID Controller (FOPID), Controller Parameter Optimization, Renewable Energy System, Voltage Regulation, Harmonic Reduction, Power Quality, Dynamic Control.

I. Introduction

The growing presence of renewable energy sources-based loads has resulted in a need for techniques that enhance the power quality in such systems. Intelligent control methods based on optimization are considered to be a good choice because they help to increase stability, compensate harmonics and dynamic behavior under different conditions. The use of hybrid optimization methods leads to increased exploration and exploitation and can be used successfully for the power system control problem [1]. In the field of photovoltaic energy conversion systems, the MPPT algorithm plays an important part because it helps to harvest energy at its maximum value. Due to the fact that maximum power point varies in dependence on irradiance and temperature changes, conventional controllers cannot provide

stable operation in dynamic regimes. That is why modern MPPT algorithms and intelligent control are needed in order to achieve higher efficiency [2].

The performance of solar energy systems is significantly influenced by the choice of proper control techniques that ensure stable operation in uncertain environmental conditions. Traditional methods of MPPT can be characterized by low tracking speed, oscillations near the optimal operating point, and low efficiency when the conditions of operation change dynamically. Intelligent optimization techniques that have been developed as control methods are efficient tools for increasing the PV system adaptability and performance [3]. DC microgrids and renewable energy converters demand efficient controllers with high stability under nonlinear behaviour, nonstationary operation, and changes in loading. PID control systems are widely employed due to their simplicity; however, they depend greatly on correct parameter tuning. FOPID control systems have overcome some restrictions of PID control systems due to the introduction of fractional integral and derivative orders [4].

The optimization process of FOPID controller parameters is a difficult process since it is difficult to optimize K_p , (proportional gain), K_i , (integral gain), K_d , (derivative gain), λ (fractional integral order), and μ (fractional derivative order) simultaneously. It is not always possible to get an optimal response through manual tuning due to nonlinear and time varying operating environment. So, metaheuristic optimization techniques have become popular for obtaining the optimal values of control parameters for minimizing error [5]. Renewable energy-based systems perform very badly under uncertainty in the environment. There must be some kind of control for such systems which will ensure stability without frequent tuning of the parameters. The optimization technique can be used in order to select the optimal values of control parameters automatically according to the operating conditions [6].

The Grey Wolf Optimizer (GWO) technique has proved to be efficient as a meta-heuristic optimization method for tuning of controller parameters because of a well-balanced combination of its abilities of exploration and exploitation. It allows the efficient search for an optimal solution and has been used efficiently in PV MPPT optimization, control parameter tuning, and stabilization of power systems. Optimization control methods based on GWO have proven better convergence features than traditional methods [7]. Despite the availability of many MPPT algorithms that have been proposed for PV systems, their fast, accurate, and robust tracking in fast-changing conditions still poses some challenges. The choice of proper optimization and control algorithms is critical for ensuring good performance of PV systems under the varying conditions of operation [8]. The MPPT and optimization methods based on artificial intelligence are more adaptable than the traditional ones and hence are suitable for modern renewable energy systems [9].

Fractional order controllers have been attracting much interest in contemporary power systems owing to their ability to offer increased flexibility and superior disturbance rejection than integer order controllers. With the additional fractional orders, there is a better tuning of the dynamics of the controllers, hence improved stability and robustness even in uncertain environments [10]. Also, hybrid optimization methods that integrate different metaheuristic

techniques offer improved convergence and accuracy through an effective balance of global and local search methods [11].

Fractional-order control and its integration with optimization algorithms has been applied to power electronics and renewable energy systems as well. New optimization algorithms have been studied to optimize control and performance of converters as well as voltage regulation and power quality performance. Most of the existing methods have only concentrated on specific optimization algorithms and little attention has been given to the development of hybrid optimization algorithms for simultaneous optimization of all five parameters of FOPID [12]. Selection of proper optimization algorithm plays an important role in the design and tuning of both PID and FOPID controllers as the performance of controllers directly depends on parameter optimization. Metaheuristic algorithms are an effective way of solving the problem of non-linear controller optimization but still faster convergence and improved accuracy are needed [13].

The recent innovations in PV control systems have emphasized the need for the application of high-end MPPT algorithms and converter control to enhance the energy conversion efficiency of renewable sources. The use of intelligent control systems along with DC-DC converter system is more effective for voltage regulation and energy transfer capability [14],[15].

The main objective of this study is to perform optimization on five controller parameters of the FOPID controller by means of Hybrid Jaya Grey Wolf Optimization (HJGWO) method. This optimization is performed to attain improved performance in terms of better convergence, better accuracy, and robustness.

Table 1. Comparative analysis of recent optimization-based control strategies for renewable energy systems and their relevance to the proposed HJGWO-FOPID controller.

Ref.	Objective	Technique / Method	Application	Major Findings	Limitation / Research Gap	Relevance to Present Work
[1] Srilakshmi et al. (2024)	To improve power quality and reduce harmonic distortion in renewable energy-fed EV charging	Hybrid Jaya–Grey Wolf Optimization (HJGWO) based control strategy with three-	Renewable energy integrated EV charging station.	HJGWO improved optimization capability by combining exploration and exploitation characteristics	Focused mainly on active filtering and harmonic compensation; optimization of FOPID controller	Supports the motivation for using hybrid Jaya-GWO optimization. The present work

	systems.	level hybrid active filter.		tics, resulting in enhanced harmonic compensation and improved power quality.	parameters and voltage regulation performance were not investigated.	extends HJGWO for five-parameter FOPID tuning and voltage control.
[2] Mazumdar et al. (2024)	To optimize MPPT performance of grid-connected PV systems under uncertain atmospheric conditions.	Grey Wolf Optimization (GWO)-based Fractional Order PID (FOPID) MPPT controller.	Grid-connected photovoltaic system.	GWO-based FOPID improved PV tracking capability under irradiance and temperature variations with better dynamic response.	Uses only GWO optimization; hybrid optimization approaches for improving convergence and robustness are not explored.	Directly supports the proposed FOPID parameter optimization approach. The present work introduces HJGWO for improved tuning accuracy.
[3] Mohanty & Mohanty (2024)	To improve energy management and control performance in DC microgrids.	State machine-based fractional-order PID (FOPID) control strategy.	Fuel cell-based DC microgrid energy management.	FOPID control improved system response and optimized energy utilization in DC microgrid operation.	Does not consider metaheuristic optimization of all FOPID parameters and does not focus on harmonic reduction.	Supports the advantage of fractional-order controllers for nonlinear renewable energy systems.

[4] Santra & De (2023)	To enhance transient stability of microgrids using optimized fractional-order control.	Grey Wolf Optimization (GWO)-based fractional-order PID inertia injection controller.	Renewable energy integrated microgrid stability control.	GWO-FOPID improved transient stability and disturbance rejection capability.	Optimization is limited to GWO; hybrid optimization and multi-objective tuning are not considered.	Supports the use of GWO for FOPID parameter optimization and motivates HJGWO improvement.
[5] Ayyappan et al. (2023)	To achieve optimal load frequency regulation in interconnected power systems.	Multi-objective Grey Wolf Optimization (GWO)-based FOPID controller tuning.	Three-area interconnected power system.	Optimized FOPID controller reduced frequency deviations and improved system stability.	Focuses on load frequency control; voltage regulation, THD reduction, and renewable converter applications are not addressed.	Supports ITAE-based multi-objective optimization of FOPID parameters used in present work.
[6] Liu (2025)	To improve PV MPPT performance considering environmental variations.	PID-type sliding mode control with improved Grey Wolf Optimization.	Photovoltaic MPPT system under changing environmental conditions.	Improved GWO enhanced PV tracking accuracy and system response under irradiance variations.	Does not investigate fractional-order controllers or hybrid optimization-based parameter tuning.	Supports the need for robust optimization under renewable fluctuations.
[7] Aguila-	To optimize	Grey Wolf	Solar photovoltaic	GWO achieved	Limited to MPPT	Provides justification

Leon et al. (2023)	PV MPPT controller performance using bio-inspired optimization.	Optimizer-based MPPT compared with traditional optimization algorithms.	c systems.	improved MPPT efficiency and faster convergence compared with conventional techniques.	optimization and does not consider FOPID controller tuning or voltage regulation.	n for selecting GWO as an optimization component in HJGWO.
[8] Yang et al. (2024)	To review current developments and challenges in PV maximum power point tracking.	Review of conventional and advanced MPPT technologies.	Solar photovoltaic energy systems.	Identified the importance of intelligent MPPT approaches for handling changing PV operating conditions.	Review-based study; does not propose an optimized controller framework.	Supports the requirement for intelligent control strategies in PV systems.
[9] Mazumdar et al. (2024)	To analyze conventional and artificial intelligence-based MPPT techniques.	Review of AI-based optimization and MPPT approaches.	Solar PV systems.	Highlighted the advantages of AI optimization methods in improving PV efficiency and tracking performance.	Does not develop a hybrid optimization controller for voltage regulation applications.	Supports the research motivation for advanced optimization-based control.
[10] Zaid et	To improve	Intelligent fractional-	Interconnected	FOPID-based	Does not include	Supports the

al. (2023)	frequency regulation in modern power systems with renewable integration .	order load frequency control with virtual inertia control.	renewable power systems.	control improved frequency stability and disturbance handling capability.	optimization of five FOPID parameters using hybrid algorithms .	application of fractional-order control for robust renewable energy systems.
[11] Mishra et al. (2024)	To improve frequency control performance of interconnected power systems.	Hybrid Grey Wolf Optimization and Firefly Algorithm .	Modern interconnected power systems.	Hybrid optimization improved convergence and control performance.	Does not focus on FOPID tuning or renewable converter voltage control.	Supports the use of hybrid metaheuristic algorithms for controller optimization.
[12] Labbaf-Khaniki et al. (2024)	To improve converter control performance using intelligent fractional-order control.	Whale Optimization Algorithm-based Fractional Order Fuzzy Type-II PI controller.	Modular multilevel converters.	Optimization-based fractional control improved converter operation and dynamic response.	Uses different optimization and controller structures; HJGWO-based FOPID is not investigated.	Supports combining fractional control with optimization for power converter applications.
[13] Mojumder & Roy (2024)	To review metaheuristic optimization methods for PID parameter tuning.	Review of evolutionary and swarm optimization algorithms.	Automatic voltage regulator systems.	Demonstrated the importance of optimization algorithms for accurate	Does not focus on renewable energy systems or fractional-order PID controllers .	Provides background for selecting optimization-based controller tuning methods.

				PID tuning.		
[14] Endiz et al. (2025)	To review traditional and advanced MPPT approaches under different solar conditions.	Review of conventional and AI-based MPPT methods.	PV systems under uniform and partial shading conditions.	Identified AI-based optimization as an effective approach for improving PV performance.	Does not address hybrid optimization-based FOPID voltage control.	Supports the need for intelligent optimization in PV control systems.
[15] Batarseh et al. (2025)	To evaluate DC–DC converter performance and MPPT techniques for PV systems.	Performance assessment of non-isolated DC–DC converters and MPPT strategies.	Standalone photovoltaic systems.	Highlighted the importance of converter design and MPPT control for stable PV operation.	Does not consider hybrid optimization-based FOPID controller design.	Supports the converter control requirement of the proposed HJGWO-FOPID framework.

Table 1 presents the recent research works done in relation to optimization-based controller, FOPID control technique, MPPT technique, and the control applications in the field of renewable energy. The comparison emphasizes the methods used, contributions made, shortcomings of the techniques used, and the research gap filled by the proposed HJGWO-FOPID technique.

Existing studies have focused on using GWO-based FOPID controllers, MPPT optimization, and hybrid optimizations independently; however, little research effort has been devoted to using the hybridized Jaya-Grey Wolf Optimization (HJGWO) algorithm for the optimal design of a five-parameter FOPID controller for enhancing convergence, voltage regulation, harmonics reduction, and robustness of the system. In the present work, an attempt has been made to bridge this research gap through the design of the FOPID controller using HJGWO. The main novelty of this research is that it presents the design of an HJGWO-based FOPID controller for tuning five tuning parameters (K_p , K_i , K_d , λ , and μ) This approach provides enhanced convergence, voltage regulation, harmonic mitigation, and robustness in dynamic operation conditions.

II. Research Methodology

2.1 HJGWO-Based FOPID Controller Design

In this approach, the FOPID controller parameter optimization will be conducted through the use of Hybrid Jaya-Grey Wolf Optimization (HJGWO) for better voltage regulation, dynamic behavior, harmonic reduction, and robustness. FOPID controller has been used due to the presence of additional parameters which are in fractional form and give more flexibility when compared to the traditional PID controller. The five parameters considered in this case are K_p , K_i , K_d , λ , and μ . These parameters affect the transient behavior, stability, disturbance rejection, and steady state of the system.

The equation of the FOPID controller is mathematically represented by:

$$G(s) = K_p + \frac{K_i}{s^\lambda} + K_d s^\mu \quad (1)$$

In which K_p are proportional, K_i are integral, and K_d are derivative gains, while λ and μ are fractional order of integration and differentiation respectively. The use of fractional parameters makes the controller flexible for better performance in case of nonlinear and time-varying operating conditions.

2.2 Hybrid Jaya–Grey Wolf Optimization (HJGWO) Strategy

Optimization of the five FOPID controller parameters is done using the HJGWO technique. The optimization process is conducted due to the fact that manual tuning of the K_p , K_i , K_d , λ , and μ is hard, taking into consideration interactions between parameters, nonlinearity of the system, and operating constraints.

The HJGWO algorithm uses the exploring power of Jaya optimization algorithm and exploiting power of the GWO technique. The Jaya algorithm helps enhance global search capability by bringing solutions closer to the optimal one while avoiding bad solutions, but GWO helps conduct a local search through alpha, beta, and delta wolves' searching techniques.

Steps in the optimization process include:

- Generating random FOPID parameters to initialize the candidates.
- Evaluating each candidate through the objective function.
- Global search through the Jaya optimization algorithm.
- Local search through Grey Wolf Optimization algorithm.
- Selection of optimized K_p , K_i , K_d , λ , and μ .
- Optimized FOPID controller implementation for system evaluation.

The optimization process is carried out through the minimization of an objective function with multiple objectives that includes the minimization of voltage tracking error and current harmonic distortion. This objective function takes into account the minimization of voltage error using ITAE and THD.

2.3 Overall Optimization Workflow

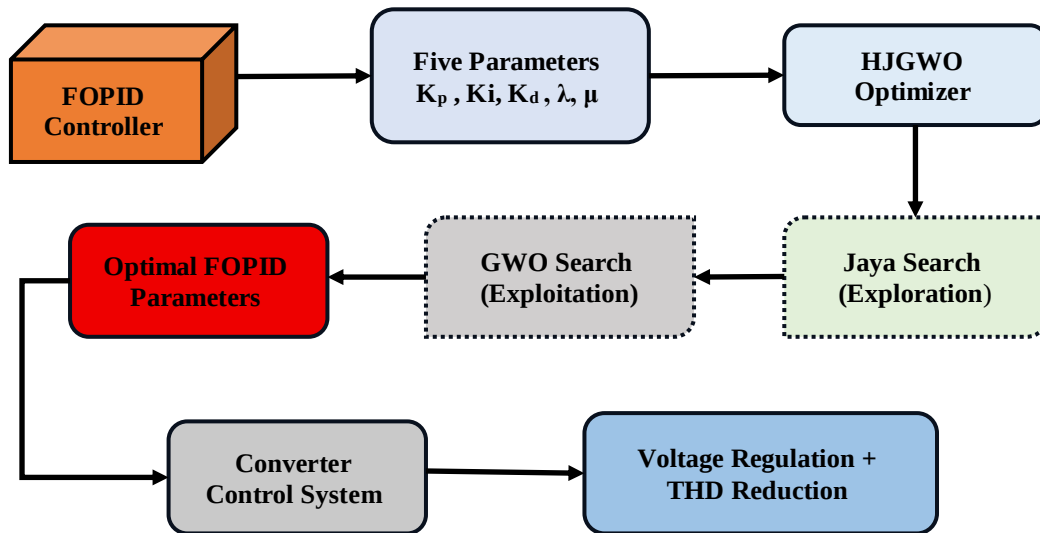


Figure 1 Framework of the proposed HJGWO-based FOPID controller parameter optimization process

Figure 1 shows the proposed approach that determines the five FOPID controller parameters ($K_p, K_i, K_d, \lambda, \mu$) through the use of HJGWO method. First, the FOPID parameters are fed into the HJGWO optimizer, and the Jaya method executes exploration in order to identify good solutions, while the GWO executes exploitation in order to refine the optimum solution. The optimized FOPID parameters are then used to implement the converter control system, improving its dynamic behavior. Finally, the goal is to obtain better voltage regulation and lower THD values.

III. Results & Discussion

3.1 Convergence Performance of HJGWO Optimization

The performance of HJGWO in optimization was assessed by studying the behavior of the algorithm while tuning the five FOPID control parameters (K_p, K_i, K_d, λ , and μ). In order to accomplish the task of minimizing the objective function, the ITAE and THD were considered together in the fitness criteria.

Figure 2 shows the evolution of the five FOPID controller parameters during the optimization process using HJGWO. In the figure, the x-axis denotes the number of optimization iterations while the y-axis shows the variation of the optimized controller parameters.

Initially, there are huge changes in the values of the FOPID parameters until the algorithm reaches some possible solutions to the optimization problem as it searches for the best solutions. With the increase in the number of iterations, the parameters tend to converge, which indicates that the optimization problem is moving closer to its optimal solution.

The proportional gain K_p parameter quickly increases during the early stages of optimization and then tends to converge towards a stable value of about 8.5, which means that the

optimizer was successful in adjusting the proportional action of the controller. The fractional integral order λ initially varies and then converges towards 0.8 whereas the fractional derivative order μ tends to converge near 0.35.

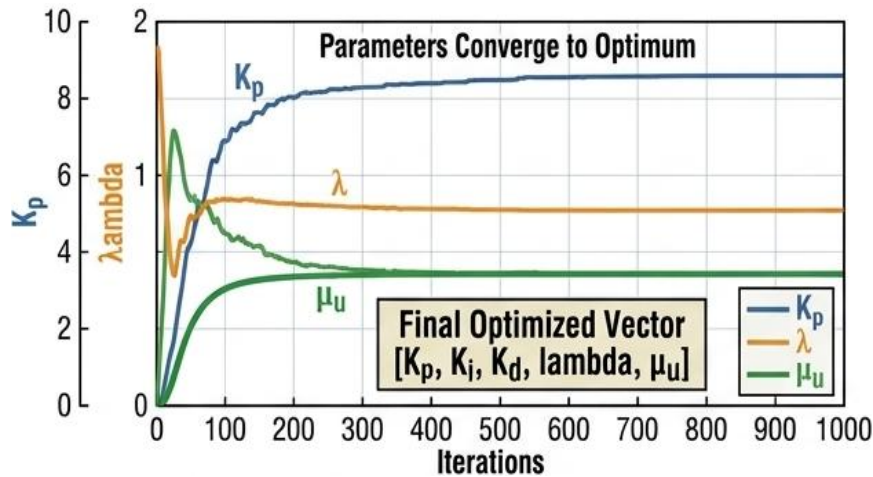


Figure 2. Convergence characteristics of HJGWO algorithm for multi-parameter tuning of FOPID controller.

Stabilization of these parameters after a number of iterations clearly indicates that the HJGWO algorithm is able to locate the optimal combination of FOPID parameters.

3.2 Voltage Regulation Performance

The figure 3 below illustrates the performance comparison of different control methods for mitigating grid voltage disturbances (sag and swell conditions). It shows how the proposed controller improves voltage regulation compared with conventional methods.

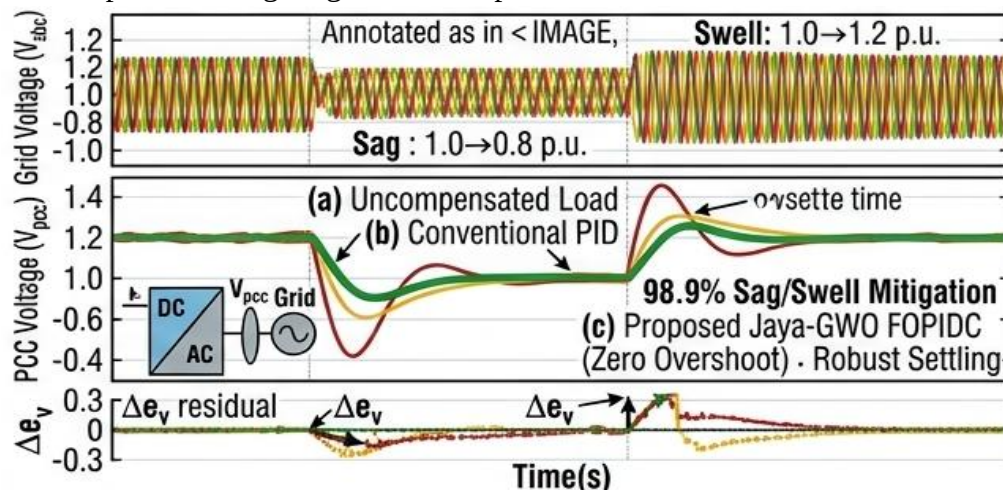


Figure 3. Dynamic voltage response of HJGWO-FOPID controller under voltage sag and swell conditions.

In the top waveform, the grid voltage experiences disturbances in the form of voltage swell (increase from 1.0 to 1.2 p.u.) and voltage sag (decrease from 1.0 to 0.8 p.u.). These variations represent abnormal grid conditions that can affect power quality.

The middle waveform compares the response of three cases:

- Uncompensated load: The voltage experiences large deviations during sag/swell events, indicating poor disturbance handling.
- Conventional PID controller: The voltage deviation is reduced, but noticeable overshoot and settling time are observed due to slower dynamic response.
- Proposed Jaya-GWO FOPIDC controller: The voltage quickly returns to the reference value with almost zero overshoot, demonstrating improved disturbance rejection and faster stabilization.

The voltage error residual is presented in the last waveform, where the proposed controller generates the minimum error when compared to other controllers. On the whole, the findings suggest that the proposed control technique can mitigate voltage sags/swells to 98.9%, provide quick settling response, and enhance voltage stability.

3.3 Harmonic Reduction Performance

The figure 4 below demonstrates the effect of various filters in terms of harmonic distortion reduction for non-linear loads. This is shown for the magnitudes of the harmonics without any filter compensation, using a normal shunt filter, and using the proposed GWO-FOPIDC filter.

In the below chart, the x-axis denotes the order of harmonics (3rd, 5th, 7th, 9th, and 11th harmonics) whereas y-axis denotes the magnitude of the harmonics (p.u.). Red-colored bars denote the magnitude of harmonics before the application of any filter, in which the non-linear load generates considerable amount of harmonic distortion. In other words, it shows that the overall harmonic distortion is 18.5%. The yellow-colored bars indicate the effect of the conventional shunt filter in which the harmonics are reduced, resulting in a harmonic distortion of 6.2%. The green-colored bars indicate the effect of the proposed GWO-FOPIDC filter, in which the harmonic distortion is reduced greatly, resulting in a very low harmonic distortion of 2.1%.

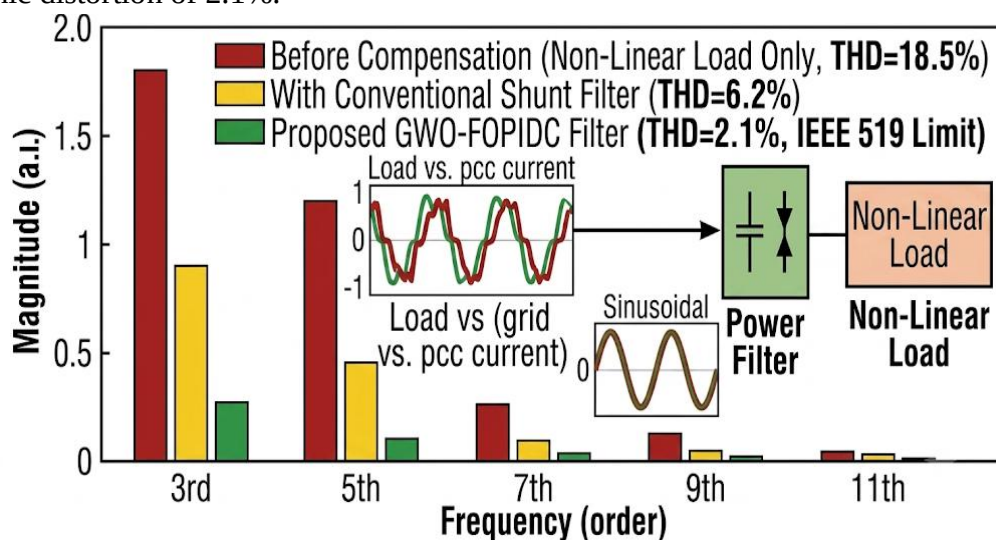


Figure 4. FFT-based harmonic spectrum comparison of different controllers.

3.4 Robustness Analysis

To determine the robustness of the developed HJGWO-FOPID controller, various dynamic operating conditions were considered, ranging from fluctuations in renewable power sources and varying loads. Due to high dependency on environmental conditions, any sudden change in the output power of renewables leads to disturbances in the voltage level of the control system. Consequently, the ability of the proposed controller to ensure stable operation amid the changes becomes one of the key indicators of its performance.

Under dynamic operating conditions associated with fluctuations in renewable power sources, the HJGWO-FOPID controller successfully modifies the control action based on changes in operating conditions through modification of the switching regime of the converter. The controller is able to ensure the required voltage value by continuous compensation of input power variations. Unlike traditional controllers that would require additional tuning of parameters amid dynamic operation, the proposed one provides automatic regulation.

The increased robustness of the proposed controller is primarily due to the optimal tuning of the five FOPID parameters (K_p , K_i , K_d , λ , and μ). using the HJGWO approach. The two fractional-order parameters (λ , and μ) allow extra flexibility in tuning the controller since they introduce more degrees of freedom in dealing with nonlinearities and time variations in the plant behavior. In addition, the HJGWO algorithm provides an optimal tuning of the controller by making sure that the exploration and exploitation stages of the optimization process are balanced.

As a result of the optimal tuning of the FOPID controller, fast transient recovery after a sudden disturbance can be realized, steady-state errors can be minimized, and system stability is achieved. Moreover, the controller shows disturbance rejection characteristics by reducing voltage fluctuations and providing stable power flow during dynamic operation. Therefore, the effectiveness of the proposed HJGWO-FOPID controller proves its high robustness.

3.5 Discussion

The overall results findings support the efficiency of the proposed HJGWO-based FOPID controller in terms of convergence, precision, and robustness of the system during dynamic operation. In terms of convergence, it is clear that the Hybrid Jaya-Grey Wolf Optimization algorithm effectively tunes the five FOPID parameters K_p , K_i , K_d , λ , and μ is through stable parameter tuning after the optimization process. The ability to use Jaya for exploration and GWO for exploitation is highly effective in solving the problem efficiently without using incorrect parameters. Regarding the voltage regulation, the developed FOPID controller offers an efficient disturbance rejection capability in comparison with the existing methods of control. During the occurrence of voltage sag and voltage swell, the developed FOPID controller is highly efficient in restoring the voltage levels with lower overshoot and zero error. In addition, the harmonic analysis proves the effectiveness of the developed FOPID controller in improving the power quality of the system through minimizing harmonic

distortions. The drop in the THD from higher levels of distortion in the uncompensated case to significantly lower levels with the use of the proposed controller implies the effectiveness of the controller in terms of compensation and improved waveforms of currents. Robustness analysis in the presence of renewable power variations and load changes demonstrates another strength of the proposed controller. In addition to the advantages associated with the flexibility of the fractional order controller, the HJGWO method guarantees that the parameters can be selected optimally without needing retuning. Thus, the proposed HJGWO-FOPID controller provides fast transient response, less steady state error, improved voltage regulation, and system stability. The results show that the combination of fractional-order controllers and hybrid optimization is a powerful tool in designing robust control schemes for power converters based on renewable energy sources.

IV. Conclusion

The paper introduced an HJGWO-based FOPID controller to improve the performance of renewable energy-based power conversion systems via tuning of controller parameters. The hybrid optimization method is a combination of the explorative nature of the Jaya optimization algorithm and the exploitative nature of the Grey Wolf Optimization algorithm in optimizing five FOPID controller parameters to provide accurate tuning and stable convergence behavior. It provided better voltage regulation in the presence of voltage sag and swell events by minimizing voltage deviation, fast response time and dynamic stability improvement. Furthermore, a harmonics analysis proved the power quality improvement in terms of lower distortion compared to traditional compensation techniques. The robustness analysis in the presence of renewable power and changing load conditions validated the flexibility and reliability of the optimized controller without any additional tuning of controller parameters. Future works include exploring more intelligent optimization methods based on artificial intelligence and machine learning algorithms and implementing the controller in hardware and including energy storage.

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