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Grey Wolf Optimization based FOPID Controller for Integration of Solar PV & Wind Power with Grid

Abstract: - To enhance the control performance of hybrid Solar PV & wind power integration with grid in full range of its operating conditions for achieving the stability under dynamic grid conditions. This paper proposed a Grey Wolf Optimization (GWO) based tuning algorithm for Fractional Order PID controller parameters. The performance assessment is focuses on control metrics such as: rise time, settling time, overshoot, settling minimum/maximum values, and peak time. The obtained results of proposed technique are compared with other PID and FOPID controllers that includes conventional, Path Finder (PF) based tuning algorithms. Three different cases of Solar Irradiance & Wind Speed have been considered as a test case for all tuned controllers for the proper synchronization. For validation purpose, output results are tested at two different locations first one is DC bus and second is inverter output. It has been obtained that the proposed GWO-FOPID demonstrates better control characteristics with rise time of 0.24 seconds, settling time of 0.32 seconds, and an overshoot of 5.65%.

Keywords: FOPID, Grid Integration, Grey Wolf Optimization, Solar PV Power, Tuning Algorithm

I. Introduction

Integration of renewable energy sources based power plants specifically wind and solar to the electrical grid presents a significant challenge for power and control engineers for maintaining the stability and reliability of electricity supply [1]. The traditional control algorithms are efficient enough for handling the intermittent and unpredictable nature of solar and wind. The Fractional-Order Proportional-Integral-Derivative (FOPID) controllers are the most promising solutions for integration which offers good flexibility and adaptability [2, 3]. In present era, for effectively handling the random and highly variability in solar and wind power generation, the ability of FOPID controllers to has been the subject of growing interest. Further, optimal tuning of FOPID controller parameters is critical for ensuring the desired performance during grid integration [4].

The PID and FOPID controllers are the milestones for achieving precise and reliable control performance [5] and specifically the PID controllers are widely adopted for industrial settings. This is due to their ability to deliver accurate and efficient control along with cost-effectiveness. Further, the recent trends in research have highlighted the continued relevance and evolution of these control strategies in the context of Industry 4. 0 [6, 7]. By the time-domain analysis proposed controller achieves the shortest settling time (0.0280 seconds), fast rise time (0.0210 seconds) and low overshoot (0.0166%) compared to other controllers. In AC-DC micro-grid with D-STATCOM, fuzzy-based controllers have been proposed to effectively enhance the performance of system compared to a traditional controller. Fuzzy-PID reduced fluctuations by 7.86% at 3-phase fault, 12.9% improvement in the system under dynamic performance during fault conditions and generates smoother voltage and current signals, contributing to better overall power quality of micro-grid [8]. Fuzzy Gain Scheduling-PID controller with adaptive scaling factors used to improve the efficiency and performance of a hybrid battery/photovoltaic system operating in grid-connected mode. The proposed technique highlighted the superior tracking efficiency, faster response time, and reduced oscillations [9]. A novel type-2 fuzzy fractional order PID based power system stabilizer has been proposed to enhance the dynamic stability of power systems with high penetration of renewable energy sources. In this, Type-2 Fuzzy Logic is used to compensate for modeling inaccuracies and reduce the computational burden of optimizing controller parameters. While a dynamic genetic algorithm and bacteria foraging algorithm based hybrid tuning algorithm. In a scenario of 50 MW MG penetrations, the proposed controller achieved an ITAE of 0.2101 and ITSE of 0.1968 [10].

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The FOPID controller surpasses the performance of conventional PID controllers across various performance metrics in which FOPID controller achieves a settling time of 0.014 seconds, while the settling time for conventional PID controllers ranges from 0.0127 to 0.0132 seconds. Further, the FOPID controller exhibits a significantly lower overshoot of 9.8e-3% which is lower than the other PID controllers, which ranges from 0.1205% to 7.9e-7% [11]. In, restructured load frequency control scheme with renewable and EV Penetration using quasi-oppositional equilibrium algorithm Optimized Parallel Fuzzy I-PID Controller for two-area power system. The performance has been evaluated under both step and random load disturbances and results demonstrate its effectiveness in restoring system dynamics and maintaining nominal system frequency [12]. The main problem associated with conventional PID controller in a hydraulic turbine regulating system is the problem of optimally tuning of PID parameters to achieve satisfactory performance. Therefore, adaptive grid PSO is used to solve the problem of tuning the PID controller. Unlike traditional single-objective optimization methods, proposed technique considers both settling time and overshoots level simultaneously [13]. The Complex FOPID controller is designed to overcome the limitations of the Real FOPID controller by introducing two extra parameters, which are the imaginary parts of the differentiator and integrator orders. The focus is achieving robustness against variation as the primary design by gain crossover frequency, phase margin [14].

In 2018, ref. [15] demonstrates the performance of Grouped Grey Wolf Optimization (GWO) for tuning of passive FOPID controller, applied to a grid-connected PV inverter for Enhanced MPPT efficiency. The proposed technique is tested under four main case studies such as: Solar Irradiation Variation, Temperature Variation, Power Grid Voltage Drop and PV Inverter Parameter Uncertainties. Improved GWO proposed for tuning a fuzzy-PID controller, primarily applied to frequency regulation in two area control of power systems. The primary focus is maintaining stable power system frequency despite load variations and it implies improved settling time and good stability with Faster Response as compare to others [16]. Ref. [17] describes a method for designing a FOPID controller using the Ant Lion Optimizer (ALO) and the technique could be applied to various control systems in different engineering fields. The results proved that the ALO tuned FOPID controller results in significant improvements in settling time (1.79 seconds) and overshoot (7.7475). For an Automatic Voltage Regulator system optimal FOPID controller has been designed using gradient-based optimization algorithm to minimize the Integral Time Absolute Error (ITAE), which serves as the fitness function [18]. The work presented in [19] is to design and evaluate the performance of a novel Cuckoo Search (CS) algorithm base FOPID controller for regulating power in Molten Salt Reactors. An improved hybrid PSO & cuckoo search (CS) algorithm based FOPID controller achieved settling time of 2.3 seconds under extreme operating conditions for micro gas turbine [20]. The existing literature sujjested that limited work has been proposed in the area of solar wind integration with grid using GWO based FOPID. Therefore, this paper makes several key contributions to the field of control systems for accurate synchronization of hybrid Solar PV and wind power with grid:

- To propose a GWO based algorithm for tuning the PID and FOPID controllers with an aim to improve the stability of grid under dynamic conditions due to variable input power source.
- For the validation of performance for proposed controller, there is in depth comparison of proposed with others like conventional and Path Finder algorithm based PID and FOPID.
- The results are evaluated at two different location first is at DC bus to check the synchronization and second is at Inverter to check the AC output voltage after synchronization. The effectiveness us tested under critical control metrics such as: 'rise time, settling time, overshoot, settling minimum/maximum values, and peak time'.
- Every approach performance is evaluated across three distinct scenarios of solar irradiance and wind speed to assess its effectiveness under dynamic fluctuations in order to ensure the substantial stability.

II. PROPOSED TECHNIQUE

In this section, the basic structures used (PID and FOPID) for presented work is discussed. The details of the discussion are as follows as:

A. FOPID Controller

The FOPID controller is a generalize form of classical PID controller, which has gained significant attention in recent years due to its ability to provide enhanced control performance in a variety of applications. The traditional PID controller, which uses integer-order derivatives and integrals, on the other hand, FOPID controller employs fractional-order operators, allowing for more flexibility in tuning which provides better performance to the dynamics of the controlled system [21]. In time domain, general equation for a FOPID controller is:

$$u(t) = K_p e(t) + K_i D_t^{-\lambda} e(t) + K_d D_t^{\mu} e(t) \quad (1)$$

In above equation, u(t) represents control signal, e(t) is the representation of the error signal, Kp is for proportional gain, Ki is the integral gain, Kd is the derivative gain, $-\lambda$ is the fractional integral operator of order and fractional derivative is of order μ. The optimal tuning ensures the controlled system achieves desired performance of FOPID in terms of Settling Time, Overshoot, Steady-State Error & Disturbance Rejection. The figure 1 shows the block diagram representation of typical structure of FOPID controller using WOA for its tuning [22, 23].

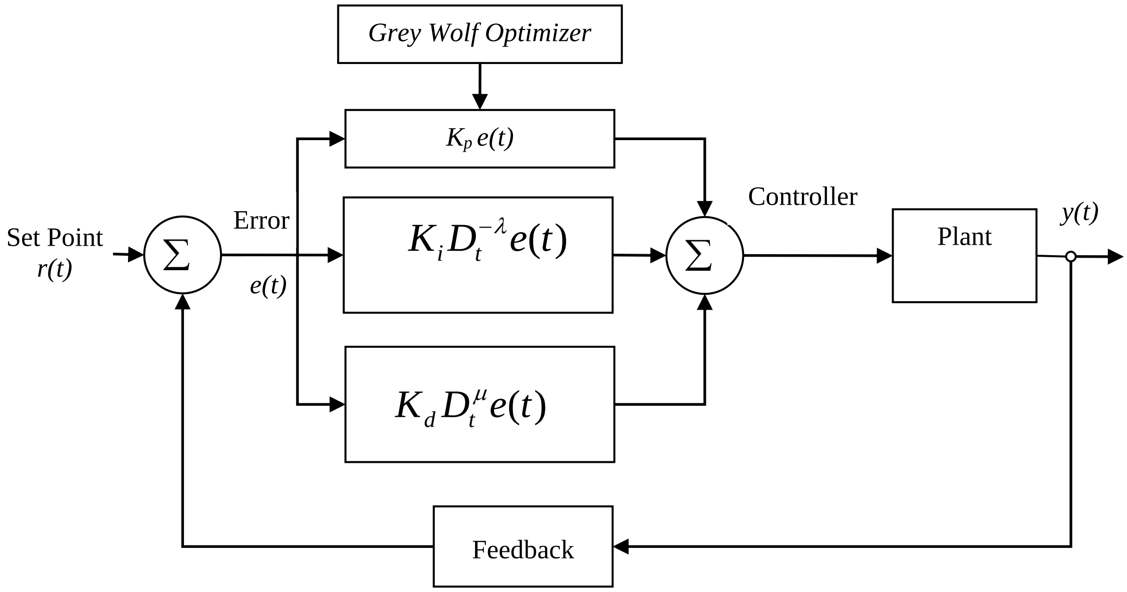

Figure 1: Basic Structure of FOPID Controller

The architecture of proposed solar wind grid integration based FOPID is shown in figure 2 in which GWO is used as a proposed tuning algorithm. Other tuning algorithms used are conventional technique and Path Finder (PF) algorithm based optimization technique.

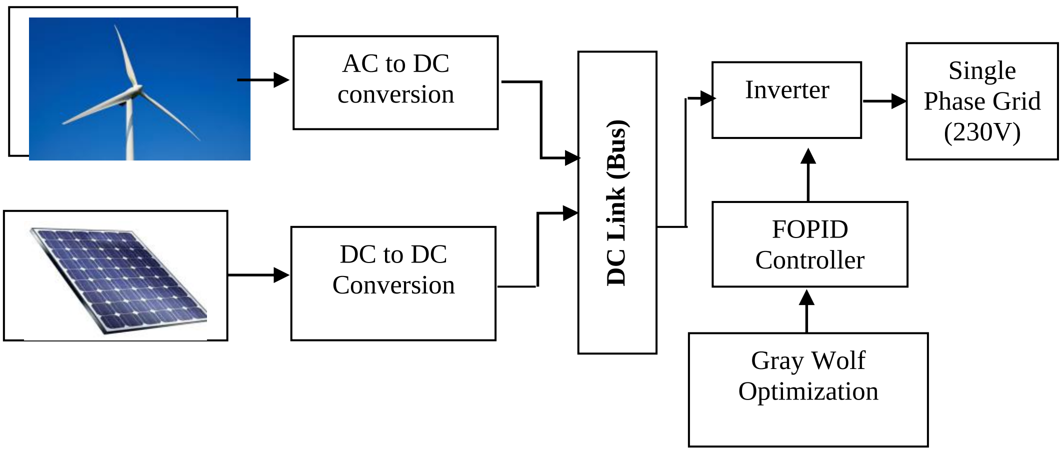

Figure 2: Proposed System Block Diagram

B. GWO based Tuning

It is a nature-inspired optimization algorithm introduced by Seyedali Mirjalili in 2014 which is inspired by the social hierarchy and hunting behavior of grey wolves [24]. GWO follows the leadership hierarchy and hunting mechanism of grey wolves which has having four types of individuals used in hierarchy: alpha, beta, delta, and omega [24, 26]. Following steps involved in GWO algorithm for FOPID tuning:

Step 1: First of all initialize the population of grey wolves with random positions in their search space.
Step 2: Then, calculate the fitness of each grey wolf by identifying alpha, beta, and delta wolves.
Step 3: Now, update the positions of all wolves.
Step 4: In this step, first of all evaluate the new positions and update alpha, beta, and delta if results are not as per requirements.
Step 5: Finally, repeat steps 3-4 until the optimum results not meet (i.e. number of iterations).

III. RESULTS AND DISCUSSION

In this analysis, there is evaluation and comparison of conventionally tuned, Path Finder (PF) tuned and proposed Grey Wolf optimization (GWO) tuned PID and FOPID controllers based on their performance metrics: “rise time, settling time, overshoot, settling min, settling max, and peak time”. The values of optimally tuned constants for PID and FOPID using tuning algorithms are given in table 2. For the evaluation of performance, all experiments are conducted in MATLAB under three cases of solar irradiance and wind speed. The proposed system involves a single-phase grid integrated with solar PV and wind power systems. The proposed solar & wind integrated single phase grid specifications are given in table 1. There is a performance comparison of the DC Bus voltage and output voltage for a time spam of 0 to 1second.

Table 1: Input Specifications of Proposed System

S. No.	Wind Turbine	PV Module of Solar	Converter (AC/DC)
1	Wind speed (m/s) at initial: 10	Isc (Amp.): 2.02	Snubber resistance: 105
2	Resistance of Stator (pu): 0.06	Vsc (V): 86.8	Diode resistance in Ω: 0.001
3		Im (Amp.): 1.93	Diode inductance in H: 0
4		Vm (V): 70.4	

A. DC Bus Voltage Analysis

In this analysis, there evaluation and comparison of various PID and FOPID controllers for three different cases based on their performance metrics: “rise time, settling time, overshoot, settling min, settling max, and peak time”. In Case I, there is examination of the response of the DC bus voltage under solar irradiance of 1000 W/m^2 and wind speed of 15 m/s, in Case II, the DC bus voltage response are at solar irradiance of 900 W/m2 and wind speed of 10 m/s. Finally, in Case III investigates the DC bus voltage response under solar irradiance of 850 W/m^2 and wind speed of 15 m/s. The DC bus voltage responses for Case I, Case II and Case III are given in table 3, table 4 and table 5 respectively.

Case I: In this, the conventional PID shows moderate performance across all metrics as given in table 3 and graphical waveforms are shown in figure 3. It has relatively high rise time (0.245 seconds), settling time (0.355 seconds), overshoot (0.0701) compared other techniques and settling range fluctuates between 86.6688 & 86.7389, with a peak time of 0.338 seconds. The PF tuned PID shows improvements in their performance in terms of rise time and peak time as compared to conventional PID, but the settling range lie between 86.6676 & 86.7356 and overshoot 0.068 remain relatively high. GWO-PID exhibits further improvements in rise time (0.21 seconds), settling time (0.245), and overshoot reduction compared to both conventional and PF-PID.

The conventional FOPID shows performance similar to conventional PID, with slightly lower rise time of 0.238 seconds but comparable settling time of 0.346 seconds and overshoot of 0.0679. The settling min. is 86.6675 and settling maximum is 86.7354. PF-FOPID demonstrates significant improvements in overshoot reduction with a value 0.0551 as compared to all other techniques, with a settling range lies between 85.6584 & 85.7135. However, it has relatively higher peak time of 0.483. The proposed GWO-FOPID exhibits the best overall performance among all techniques. It achieves the lowest overshoot of 0.0532, fastest settling time of 0.28 seconds, and a relatively low peak time of 0.32 seconds. The settling range varies between 86.668 & 86.7212. Hence, among the controllers analyzed, the proposed GWO-FOPID emerges as the most effective controller which exhibits superior performance metrics with quickest rise and settling times, the least overshoot, and reliable settling values.

Case II: The time taken for the system to raise the voltage to its final value by conventional PID is 0.231 seconds and time for the system to settle is 0.32 seconds given in table 4. The graphical waveforms are shown in figure 4. The minimum value the system settles is 85.6585 and maximum value the system reaches during settling is 85.7132 and time taken by the system to reach its maximum value is 0.33 seconds, indicating the time to reach the first peak. The rise time is reduced to 0.198 seconds using PF-PID, indicating a faster initial response as compared to conventional PID. The settling time remains at 0.32 seconds which shows no improvement in how quickly the system stabilizes compared to the conventional PID. The PF-PID has the value of Settling Min: 85.657 which is lower than the conventional PID at 85.657 and the Settling Max is 85.71 which is Slightly higher than Conventional PID at 85.71, showing a slightly higher peak. The time taken to reach this peak is slightly faster at 0.329 seconds, showing a minor improvement in reaching the peak value. The rise time of voltage is further reduced to 0.190 seconds and the wave setline in 0.25 seconds using GWO-PID which makes it the quickest with faster stabilization among all PID controllers. The value of Settling Min and Settling Max is 85.657 and 85.717 respectively which is same as that of PF-PID but the time taken by this to reach its Peak is 0.328 seconds indicating the quickest peak time among the PID controllers. The value of overshoot by Conventional PID is 0.0547 which lies in between Settling Min of 85.6585 and Settling Max of 85.7132. The time by the system to reaches its maximum value is 0.33 seconds. The PF-PID Overshoot is 0.06 with values of Settling Min is 85.657 and Settling Max of 85.717 which is lightly higher than conventional PID at 85.717. The time taken to reach Peak is slightly faster at 0.329 seconds, showing a minor improvement in reaching the peak value. The value of overshoot achieved by GWO-PID is 0.06 this is due to the deep settling min of 85.657 and peaky settling max of 85.717. The time taken to reach at the peak is 0.328 seconds which is clear indication for its quickest performance among all PID controllers. The value of Overshoot achieved by Conventional FOPID is 0.049 which is slightly lower than that of the conventional PID which indicates its better damping characteristics. The value of Settling Min and Settling Max is 85.6778 and 85.7268 respectively with peak time of 0.353 seconds. The PF-FOPID Overshoot is 0.0529 slightly higher than that of the conventional FOPID. The values of settling min and settling max is 86.6681 and 86.7210 respectively with longer peak time at 0.48 seconds, indicating a significantly slower time to reach the peak. The value of GWO-FOPID Overshoot is 0.0555 which is higher than the conventional FOPID. However, the value of Settling Min is 85.6583, indicating a comparable dip and Settling Max of 85.7138, showing a comparable peak. Hence, GWO-FOPID offers a good response speed and maintaining target values amongst all.

Case III: The rise time taken by the Conventional PID is 0.257 seconds, time taken for the system to settle within a certain range is 0.35 seconds given in table 5. The graphical waveforms are shown in figure 5. The value of overshoot is 0.1043 indicates a relatively high level of overshoot. The minimum value the system settles to during the settling time is 85.1717 and maximum value the system reaches during the settling time is 85.276. The time taken by the system to reach its maximum value is 0.63 seconds. The PF-PID rise time of 0.243 seconds, Settling Time of 0.335 seconds, overshoot of 0.058, Settling Min of 85.140, Settling Max of 85.1986 and Peak Time of 0.60 seconds, indicating its superior performance as compared to the conventional PID. The values of rise time, Settling Time, Overshoot, Settling Min, Settling Max and Peak Time achieved by GWO-PID are 0.24 seconds, 0.34 seconds, 0.0576, 85.141, 85.1986 and 0.60 seconds respectively. This technique exhibits the best performance among PID controllers.

The conventional FOPID rise time is 0.23 seconds, indicating a slightly faster initial response compared to conventional PID. The settling time is 0.35 seconds, similar to the conventional PID. The lower values of overshoot (0.0576), indicating its better damping characteristics. The values of Settling Min (85.141), Settling Max (85.1986) and Peak Time (0.60 seconds) are almost similar to GWO-PID and PF-PID. The PF-FOPID rise time (0.235 seconds), indicating a slightly faster initial response and settling time (0.37 seconds), showing a slight increase in its performance as compared to conventional FOPID. The Overshoot (0.0563) is the lowest among all controllers. The minimum settling value is 85.1416 is an indication for slightly higher dip during stabilization compared to GWO-PID and PF-PID and Settling Max of 85.1979, indicating a slightly lower peak during its stabilization. The time taken by PF-FOPID to reach peak is 0.483 seconds, indicating a faster time to reach the maximum value compared to conventional FOPID. The Rise Time and settling time taken by proposed GWO-FOPID is 0.24 seconds and 0.32 seconds respectively, showing an improvement in stabilization time compared with rise as compared to other FOPID controllers. The overshoot value is 0.0565 which is very low and lies between Settling Min of 85.1415 and minimum settling of 85.1415. The time to reach at peak is 0.362 seconds, indicating the fastest time among all controllers. Further the superiority of proposed tuning algorithm for FOPID can be seen in figure 3 to figure 5.

Table 2: Values of PID and FOPID Parameters for Tuning

Parameters	PID Conventional	PID PF	PID GWO	FOPID Conventional	FOPID PF	FOPID GWO)
Kp	0	-2.1984	1.2837	8.795	2.045	3.3333
Ki	-1	4.978	91.4387	18.3658	4.5458	1.7868
Kd	0	0.45308	0.0638	0.2378	-4.225	1.2861
Lamda				0.5641	0.4587	0.78346
Mu				0.9246	0.2556	1.0654

Table 3: Response of DC Bus Voltage at Solar Irradiance (1000 W/m^2) & Wind Speed (15 m/s)

	Conventional PID	PF-PID	GWO-PID	Conventional FOPID	PF-FOPID	GWO-FOPID
Rise Time	0.245	0.215	0.21	0.238	0.23	0.214
Settling time	0.355	0.35	0.245	0.346	0.32	0.28
Overshoot	0.0701	0.068	0.0677	0.0679	0.0551	0.0532
Settling Min	86.6688	86.6676	86.6675	86.6675	85.6584	86.668
Settling Max	86.7389	86.7356	86.7352	86.7354	85.7135	86.7212
Peak time	0.338	0.3085	0.30872	0.327	0.483	0.32

Table 4: Response of DC Bus Voltage at Solar Irradiance (900 W/m^2) & Wind Speed (10 m/s)

	Conventional PID	PF-PID	GWO-PID	Conventional FOPID	PF-FOPID	GWO-FOPID
Rise Time	0.231	0.198	0.190	0.23	0.218	0.21
Settling time	0.32	0.32	0.25	0.32	0.31	0.275
Overshoot	0.0547	0.06	0.06	0.049	0.0529	0.0555
Settling Min	85.6585	85.657	85.657	85.6778	86.6681	85.6583
Settling Max	85.7132	85.717	85.717	85.7268	86.7210	85.7138
Peak time	0.33	0.329	0.328	0.353	0.48	0.34

Table 5: Response of DC Bus Voltage at Solar Irradiance (850 W/m^2) & Wind Speed (15 m/s)

	Conventional PID	PF-PID	GWO-PID	Conventional FOPID	PF-FOPID	GWO-FOPID
Rise Time	0.257	0.243	0.24	0.23	0.235	0.24
Settling time	0.35	0.335	0.34	0.35	0.37	0.32
Overshoot	0.1043	0.0586	0.0576	0.0576	0.0563	0.0565
Settling Min	85.1717	85.140	85.141	85.141	85.1416	85.1415
Settling Max	85.276	85.1986	85.1986	85.1986	85.1979	85.1980
Peak time	0.63	0.60	0.60	0.60	0.483	0.362

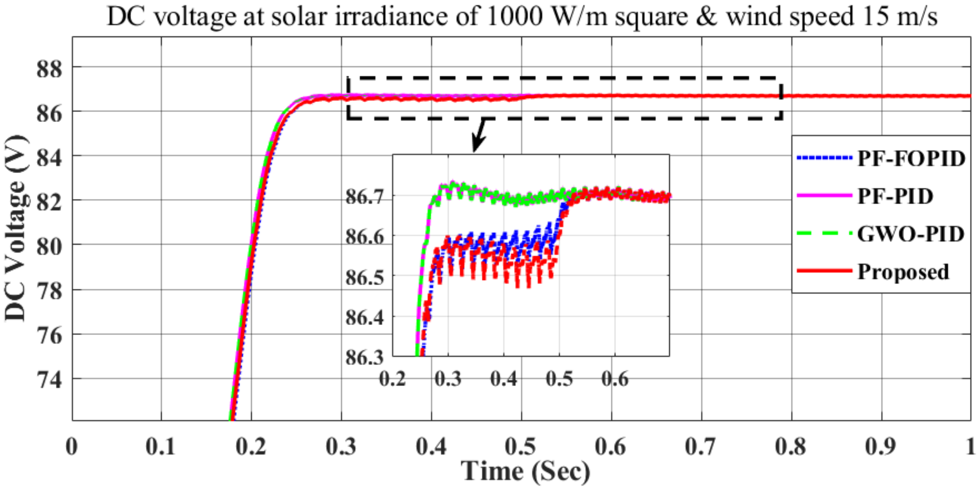

Figure 3: Voltage at DC bus for Solar Irradiance of 1000 W/m^2 & Wind Speed of 15 m/s

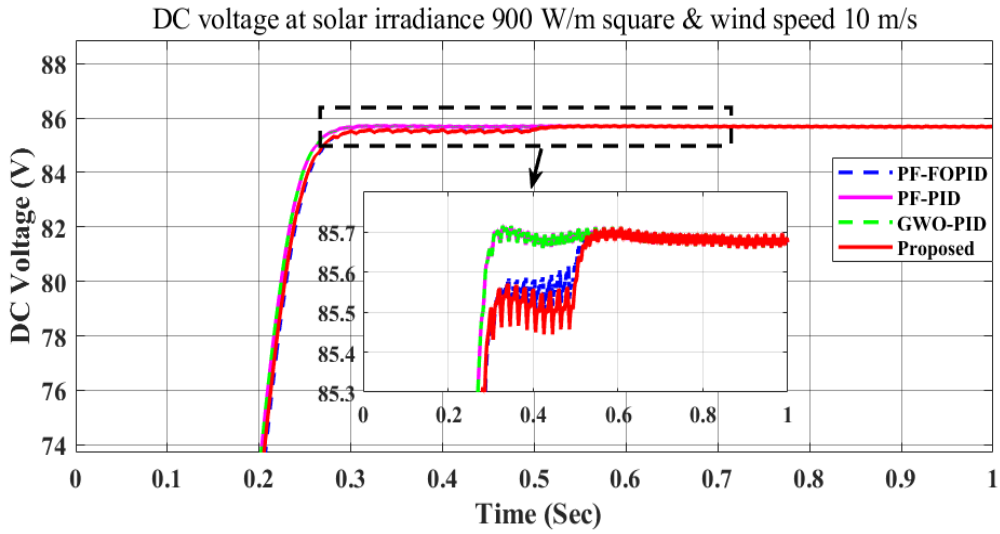

Figure 4: Voltage at DC bus for Solar Irradiance of 900 W/m^2 & Wind Speed of 10 m/s

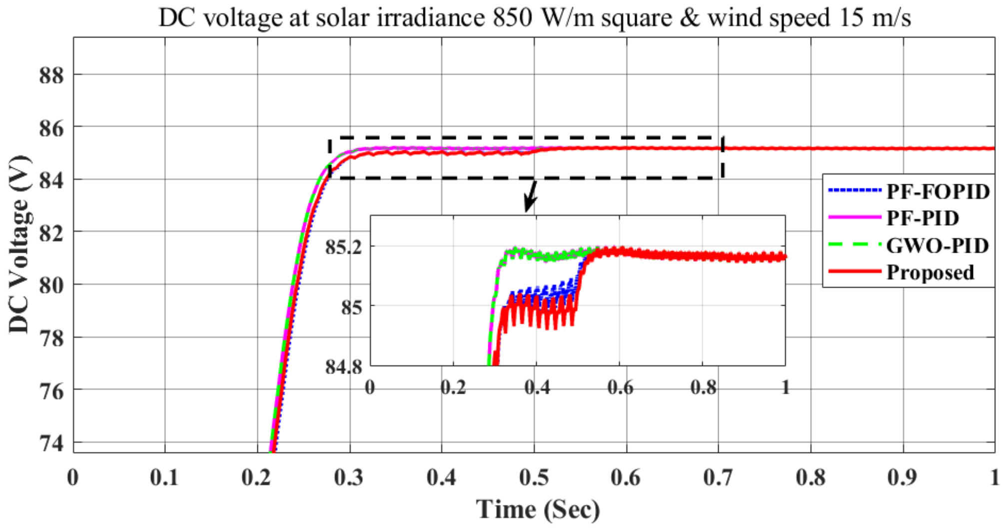

Figure 5: Voltage at DC bus for Solar Irradiance of 850 W/m^2 & Wind Speed of 15 m/s

B. Analysis of Output Voltage

The figures from figure 6 to figure 11 represents inverter's output waveform for the Case III at Solar Irradiance of 850 W/m^2 and Wind Speed of 15 m/s. The waveform is the represents of inverter output voltage for both PID and FOPID controller. The tuning algorithms used are conventional, PF and GWO algorithm and the peak to peak value of voltage is considered to be 230 V.

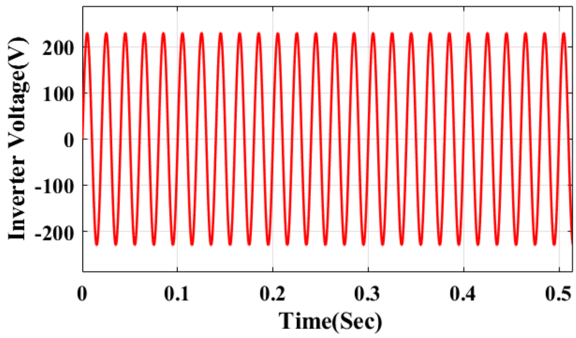

Figure 6: Inverter Output for conventional PID

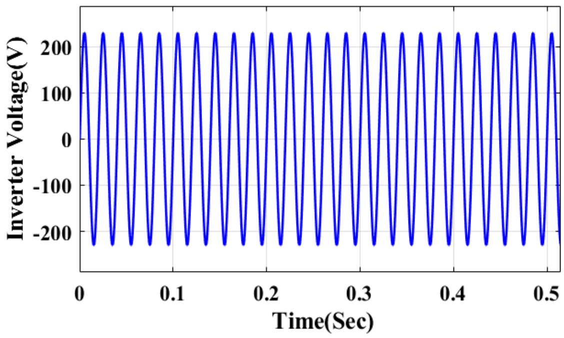

Figure 7: Inverter output for PF-PID

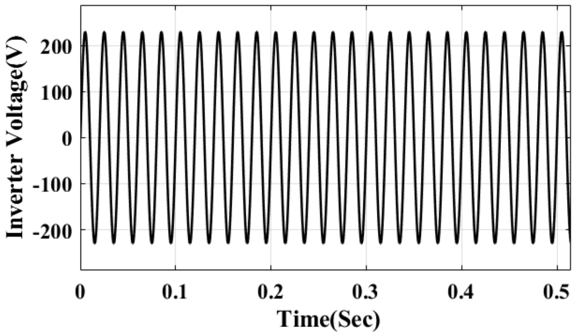

Figure 8: Inverter Output for GWO-PID

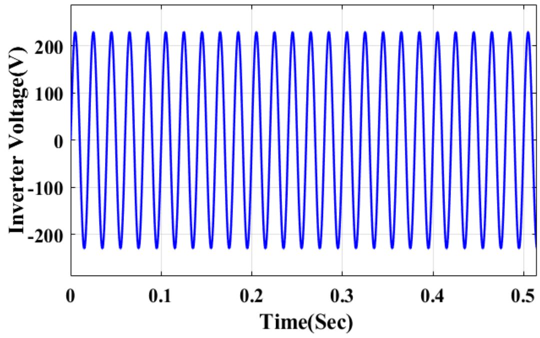

Figure 9: Inverter Output for PF-FOPID

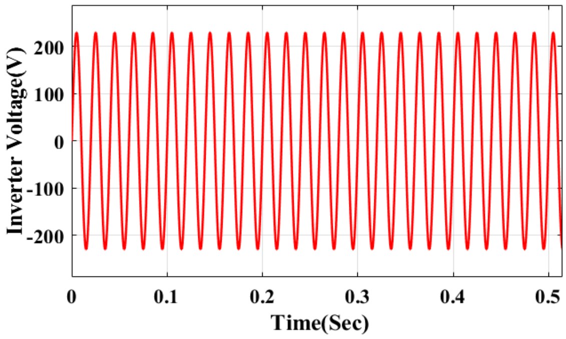

Figure 10: Inverter Output for conventional FOPID

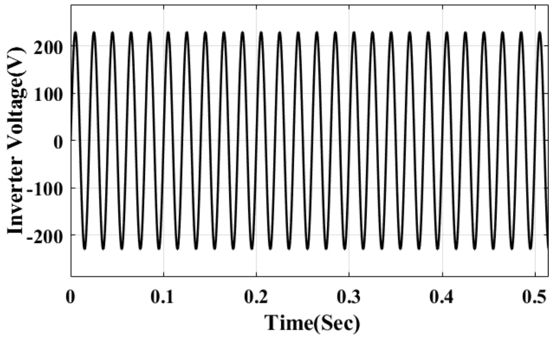

Figure 11: Inverter Output for GWO-FOPID

IV. CONCLUSION

This paper evaluates the performance of various PID and FOPID controllers, including conventional, PF, and GWO variants for parameters optimization, based on key metrics such as: rise time, settling time, overshoot, settling minimum/maximum values, and peak time. The proposed GWO based FOPID is utilized for a hybrid solar wind grid connected system. The performance of all in terms of DC link voltage with their responses is highlighted significantly. The results demonstrate that GWO-PID and GWO-FOPID controllers consistently outperform in which GWO-PID achieved the fastest rise time of 0.24 seconds, an improved settling time of 0.34 seconds, and the lowest overshoot at 5.76%. These results are the clear indication of its superior control and response characteristics. Similar to this, GWO-FOPID excelled with a rise time of 0.24 seconds, the quickest settling time of 0.32 seconds, and minimal overshoot at 5.65%. These attributes makes the proposed GWO-based controllers ideal for control applications. It has been concluded that for applications prioritizing quick response and precise control, GWO-PID and GWO-FOPID are the optimal choices due to their superior performance across all evaluated metrics. In future, more research should explore hybrid optimization techniques with their impact on controller performance to further enhance these findings.

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