A FRACTIONAL ORDER PID-BASED STATCOM CONTROL STRATEGY FOR HIGH-EFFICIENCY AND RESILIENT MICROGRID OPERATIONS

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Abstract:

This research enhances the performance of Static Synchronous Compensators in microgrid environments through a Fractional Order Integrator-based Proportional-Integral-Derivative controller. Conventional controllers often fail to maintain stability and efficiency under rapidly changing load conditions and grid disturbances, whereas the proposed approach introduces fractional-order dynamics to achieve improved adaptability and robustness. A MATLAB-based simulation framework was developed to test the controller under diverse operating scenarios, including voltage sags, reactive power imbalance, and renewable energy integration challenges. The results show that the proposed controller achieves efficiency above 92 percent, significantly outperforming conventional controllers by reducing power losses, enhancing voltage stability, and improving reactive power regulation. It also demonstrates superior handling of Q-curve characteristics and transient disturbances, leading to more stable and reliable microgrid operations. Comparative analysis confirms the effectiveness of the method in maintaining power quality and responding rapidly to dynamic variations. Overall, the study establishes the proposed controller as a scalable and high-performance solution for advancing microgrid infrastructures and ensuring reliable, efficient, and sustainable energy system operations.

1 Introduction

As modern power networks expand and integrate increasing amounts of renewable energy, challenges like transmission congestion and system overload have become more pronounced. These issues not only hinder the economic operation of power systems but also threaten their stability and reliability. To address these concerns, Flexible AC Transmission System (FACTS) technologies offer promising solutions by enabling rapid and precise control over voltage and power flow. Among these, the Static Synchronous Compensator (STATCOM) stands out due to its adaptability and high efficiency. In multi-line transmission systems, STATCOM allows coordinated control of both active and reactive power, thereby supporting more stable and optimized grid performance. Through appropriate control modes, STATCOM can dynamically regulate key transmission parameters such as voltage magnitude, phase angle, and line impedance, making it a vital component in ensuring grid security and efficiency. This research focuses on enhancing STATCOM performance in microgrid environments by introducing a Fractional Order Integrator-based Proportional-Integral-Derivative (FOI-PID) control strategy. The goal is to achieve an operational efficiency of 91% or higher. By integrating fractional calculus into traditional PID controllers, the FOI-based design enhances dynamic responsiveness and robustness, which are essential in managing the fluctuations and nonlinearities of microgrids. This control methodology significantly improves voltage regulation and reactive power management, ultimately boosting

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power quality and system stability. FOI-PID controllers differ from conventional integer-order PID systems by employing fractional-order integration and differentiation. This allows for more accurate modeling of system behavior and finer control over transient and steady-state performance. As a result, FOI-PID offers improved handling of uncertainties and disturbances typical in distributed energy systems.

Novel Contributions of This Study:

1. This study is unique in that it developed and validated a Fractional Order Integrator-based Proportional-Integral-Derivative (FOI-PID) controller for STATCOM applications in microgrid environments, which provides a more flexible and adaptive control mechanism than conventional controllers.
2. Unlike typical PID approaches, the suggested solution uses fractional-order calculus to accurately capture nonlinear system dynamics and improve robustness under highly fluctuating load and grid disturbance situations. The study introduces a novel MATLAB-based testing framework for systematically evaluating the controller's performance across critical scenarios such as voltage sags, reactive power imbalances, renewable integration challenges, and Q-curve handling, demonstrating its superiority in both practical and simulated conditions.
3. Achieving an efficiency level of over 92% and greatly enhancing transient stability, power loss minimization, and reactive power management.

2 Literature Survey

An increasingly significant research direction in modern power systems is the theoretical modeling and simulation of Fractional Order Integrator-based PID (FOI-PID) controllers. Scholars such as Li and Ge (2012) have delved into the mathematical underpinnings of fractional calculus, which serve as the core principle of FOI-PID control structures. These studies highlight the advantages of fractional order control - demonstrating improved accuracy, faster response times, and greater system stability compared to traditional integer-order PID controllers (Mahmoud, 2022). Much of this research is centered on in-depth mathematical analysis, system modeling, and comparative simulations aimed at showcasing the performance superiority of FOI-based controllers in addressing control challenges within power systems.

Beyond the FOI-PID framework, numerous other advanced control techniques have also been explored for enhancing STATCOM (Static Synchronous Compensator) performance. Adaptive control schemes have been introduced to maintain stability in the face of fluctuating load demands and grid disturbances. Likewise, fuzzy logic controllers have gained traction due to their rule-based decision mechanisms, which do not require an exact mathematical representation of the system to operate effectively. Model Predictive Control (MPC) has also been widely adopted for its predictive capabilities and real-time optimization, leading to enhanced voltage and reactive power control. Moreover, control strategies leveraging artificial intelligence, including neural networks and evolutionary algorithms, have been deployed to enable learning-based adaptation and efficient optimization in complex and dynamic grid environments. These evolving approaches highlight the importance of continual innovation in control system development to meet the growing demands of modern and intelligent power grids.

However, while FOI-based PID controllers hold promise, their practical deployment in microgrid-based STATCOM systems presents several challenges. These include system complexity, tuning of control parameters, and maintaining stability and optimal performance under diverse operational conditions (Mahmoud et al., 2020). This research addresses these issues by proposing a novel FOI-PID control approach specifically designed to improve STATCOM operation within microgrids. The goal is to overcome key control difficulties and to achieve a performance benchmark of at least 91%, focusing on optimal power flow, voltage regulation, and reactive power support (Mahmoud et al., 2021; 2022). Microgrids have become a critical component of modern energy systems, offering localized solutions for reliable and sustainable energy supply. STATCOM plays a vital role within this framework by serving as a reactive power source and regulating voltage, thereby contributing significantly to grid stability. While traditional control techniques, particularly classical PID controllers, have been widely used in STATCOM regulation, the increasing complexity of microgrid operations necessitates more sophisticated control strategies. There is a growing need for controllers that can handle the nonlinear and time-varying nature of microgrids (Mahmoud, Atia, et al., 2023). Fractional calculus has gained attention in control engineering because it allows for more nuanced modeling of system dynamics and delivers enhanced control performance. The FOI-PID controller has been recognized as a robust solution for dynamic systems, offering better approximation of system behavior, improved transient response, and greater resilience to uncertainties compared to traditional PID control. Numerous studies across different domains have validated the controller's effectiveness in delivering high-precision control (Mei et al., 2018). In the context of power systems and microgrids, FOI-PID controllers have demonstrated promising results in improving control precision, minimizing voltage fluctuations, and optimizing power flow management. Researchers have reviewed the role of these controllers in voltage control, reactive power balancing, and stability improvement in devices like inverters, converters, and compensators integrated within microgrids. The collective findings affirm that FOI-PID-based control approaches offer viable solutions to many complex challenges currently faced by power networks, enhancing their reliability, stability, and operational efficiency (Meral & Çelik, 2018). The summarized benefits from various studies are illustrated in Figure 1. Additionally, numerous studies have explored the development of effective FOI-PID control algorithms and the strategies required for their design in STATCOM systems. Optimization techniques such as Genetic Algorithms (GA), Particle Swarm Optimization (PSO), and Artificial Neural Networks (ANNs) have been implemented to facilitate controller adaptation, parameter tuning, and performance enhancement in power distribution networks. These efforts have underscored the importance of precise system identification and optimization in realizing the full potential of FOI-PID controllers (Mohamed et al., 2021). Moreover, research objectives often extend beyond theoretical validation to practical implementation. Techniques such as Hardware-in-the-Loop (HIL) testing, real-time simulations, and field validations are being employed to assess the performance of FOI-PID controllers in STATCOM-based microgrids. These experiments offer practical insights into controller robustness and adaptability under real-world operating conditions, providing strong evidence for their applicability and reliability in future microgrid applications (Mohod & Aware, 2010).

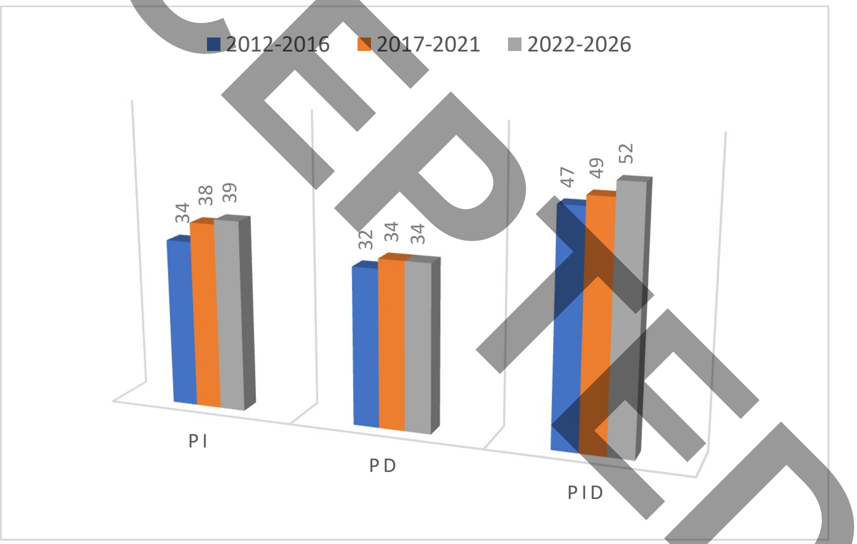

Figure 1. Efficiency through different controller.

Many simulations and validation tests have been performed, mainly in power systems and microgrids, to evaluate FOI-PID control efficiency. These interviews include analysis of the microgrid components' dynamic behavior models, the incorporation of FOI-PID controllers, and comprehensive performance assessment of the microgrid with different operational conditions, load profiles, and grid disturbances. The simulation of actual systems has shown that the reference management of FOI-PID control is usually superior to the traditional control in most aspects such as control accuracy, stability, transient response, and efficiency (Monedero, I., Leon, C., et.al. (2004)). While there is potential for using FOI-PID control in power system applications, there are still certain areas that need to be explored and developed. As we know most of the place's AI and ML has taken role to make the system more accurate and stable. Integrating with AI or ML with FOPID and STATCOM can be very effective for future stability enhancement. Now because of the introduction to connected grid EV charging station this area needs to be more explore. As congestion to the power grid is increasing day by day, so to have better effectiveness to power grid this research topic is very important.

3 Modelling of STATCOM

Modeling of STATCOM is the first stage of this research. STATCOM is a voltage - controlled facts devices which help the power system to attend stability during sudden load change and instability. MATLAB software is used to model the system in Simulink environment. A popular way is to create a mathematical model based on the inverter's control features, such as the pulse-width modulation (PWM) method, voltage control loop, and current control scheme. Figure 2, shows the model of the STATCOM using MATLAB software (Bala, N., & Mallik, S. K. (2024)). To design the control strategy for RVSC switching, some important parameters have to be calculated as discussed below. Average power calculation: Active and reactive power was filtered and extracted using a low-pass filter with a high cut-off frequency (Pang, M., et.al. (2019)). We provide state equations as:

$$\frac{dP}{dt} = \left(\frac{3}{2}\left(v_{odi} + voqi_{oq}\right) - P\right)w\_c \tag{1}$$

$$\frac{dQ}{dt} = \left(\frac{3}{2}\left(v_{oqi} + vodi_{oq}\right) - P\right)w\_c \tag{2}$$

Droop equations: The inverter doesn't even have a set point for the frequency and magnitude of the main grid voltage when it is operating in the islanded mode. As a result, the islanded mode inverter must produce its own reference grid frequency magnitude for the system using the droop equations shown in Figure 3.

$$w^{\Delta*} = w_{n\_}mP \tag{3}$$

$$v\_oq^{\Delta*} = v(oq_r) - nQ \tag{4}$$

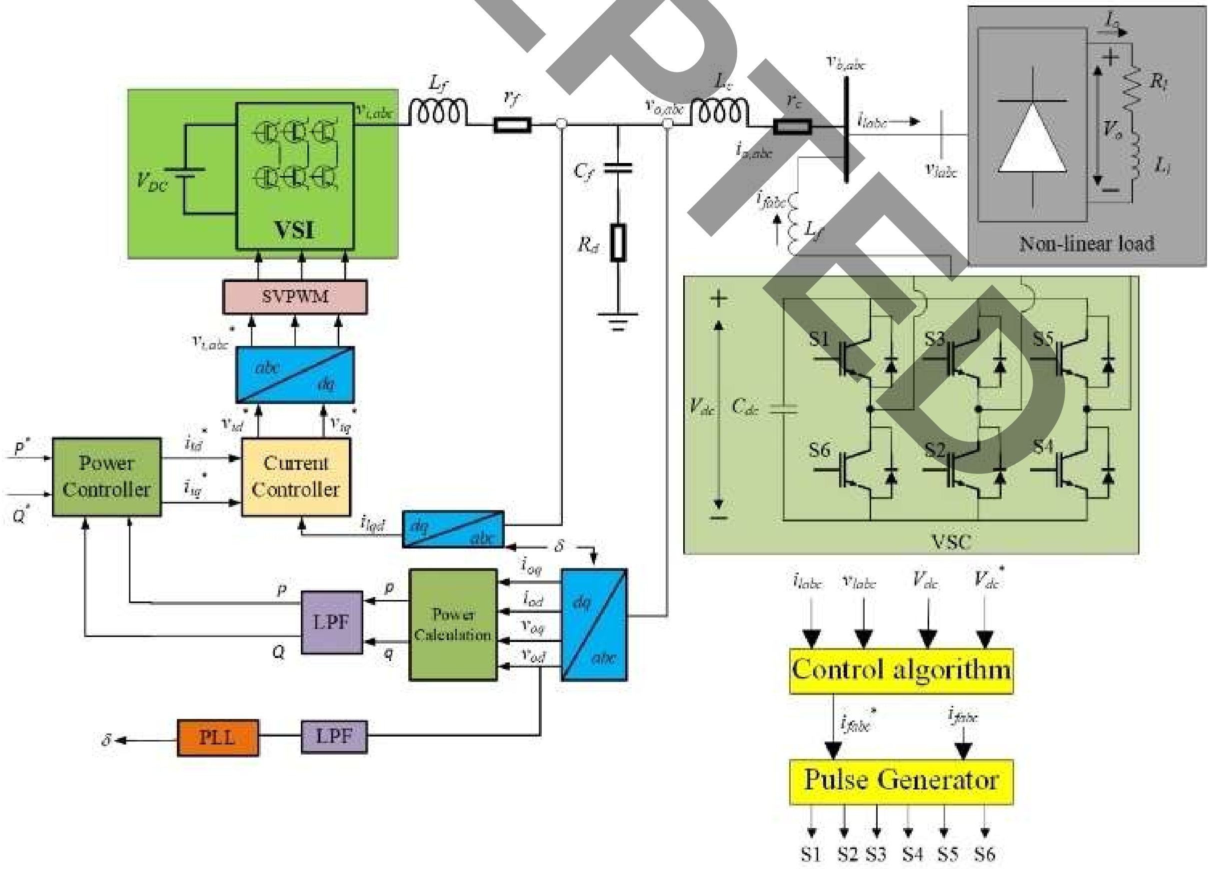

Figure 2. STATCOM model using MATLAB.

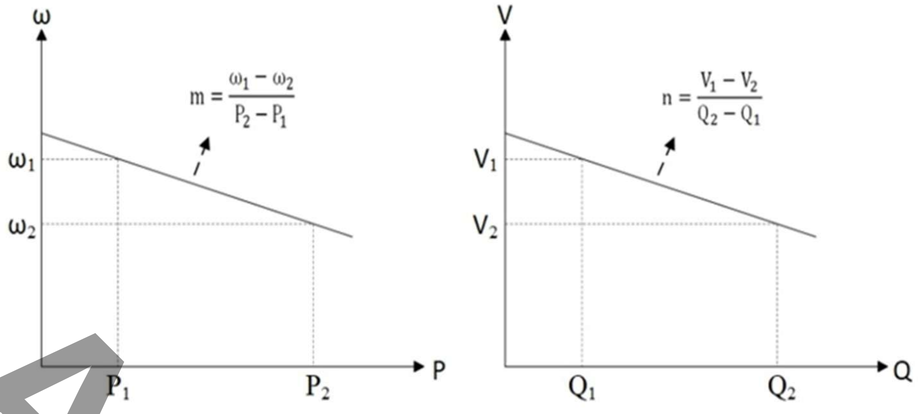

Figure 3. Droop characteristic.

3.1 Voltage control scheme

Control scheme of voltage and current controller. In those outputs of droop equations are set point for voltage controller. Similarly, outputs of voltage controller are command values for current controller. Vfd* and Vfq* act as a reference value for inverter which achieves using SVPWM here (Bala, N., & Mallik, S. K. (2024)).

$$i_{fd}^{*} = k_{pv,d}\left(\omega_{pll} - \omega^{*}\right) + k_{iv,d}\int\left(\omega_{pll} - \omega^{*}\right) \tag{5}$$

$$i_{fq}^{*} = k_{pv,q}\left(v_{oq}^{*} - v_{oq}\right) + k_{iv,q}\int\left(v_{oq}^{*} - v_{oq}\right) \tag{6}$$

$$v_{fd}^{*} = k_{pc,d}\left(i_{fd}^{*} - i_{fd}\right) + k_{ic,d}\int\left(i_{fd}^{*} - i_{fd}\right) - \omega_{n}L_{f}i_{fq} \tag{7}$$

$$v_{fq}^{*} = k_{pc,q}\left(i_{fq}^{*} - i_{fq}\right) + k_{ic,q}\int\left(i_{fq}^{*} - i_{fq}\right) - \omega_{n}L_{f}i_{fd} \tag{8}$$

3.2 PLL

Phase is locked in this instance so that the PLL's v_od=0 state equations (Qi, J., Zhao, W., & Bian, X. (2020))

$$\frac{dv_{od,f}}{dt} = \left(v_{od} - v_{od,f}\right)\omega_{c,pll} \tag{9}$$

$$\frac{d\emptyset_{pll}}{dt} = v_{od,f} \tag{10}$$

$$\frac{d\delta}{dt} = \omega_{pll} = 120\pi + k_{p,pll}v_{od,f} + k_{i,pll}\emptyset_{pll} \tag{11}$$

3.3 LCF Filters

The LCF (Low-Cost Filter) in the context of a Static Synchronous Compensator (STATCOM) is a passive filter that reduces harmonics and improves grid power quality. This filter is often made up of inductors and capacitors arranged in a specific topology to target and suppress harmonic frequencies caused by non-linear loads or power system disruptions. The major role of the LCF filter in a STATCOM application is to eliminate harmonic distortion in voltage and current waveforms, hence assuring grid compliance with power quality rules and standards (Sayed, K., et.al. (2016).

3.4 FOI-PID Modelling

The FPID controller is based on the fractional calculus, which can be expressed as:

$$ {}_{\beta}O^{\beta} f(t) = \begin{cases} \dfrac{d^{\beta}}{dt^{\beta}} f(t), \in R(\beta) > 0 \\ f(t), \in R(\beta) = 0 \\ \displaystyle\int_{\beta}^{t} f(\tau)(d\tau), \in R(\beta) < 0 \end{cases} \tag{12} $$

Where, the operator O represent the calculus operator and β any real number. Using the Riemann-Liouville's definition the fractional calculus expression of 12 can be easily expressed using equation 13:

$$ {}_{\beta}O^{\beta} f(t) = \frac{1}{\Gamma(n-\beta)} \left(\frac{d}{dt}\right)^{n} \int_{\beta}^{t} \frac{f(\tau)}{(t-\tau)} d\tau \tag{13} $$

Where, г represent Gamma function and n-1<β<n. Through the equation used above and conventional PID controller, the FOI-PID is shown in the figure 3. The overall mathematical model for FPID controller can be given as follow:

$$ V_{fc}(t) = K_p e(t) + K_i O^{-\lambda} e(t) + K_d O^{\mu} e(t) \tag{14} $$

The equation 15 gives an output of:

$$ C(s) = K_p + K_i s^{-\lambda} K_d s^{\mu} \ , \in \lambda > 0 \ , \ \mu < 2 \tag{15} $$

4 Simulation result and discussion

This section of the study addresses the design and simulation results. The FOI-PID control scheme's purpose is to keep the voltage magnitude constant at the spot where a sensitive load is connected during system disturbances. The first section discusses the design components of this research, followed by the simulation results and performance evaluation. The use of MATLAB software to simulate Fractional Order Integrator-based PID (FOI-PID) controllers for Static Compensators (STATCOMs) in microgrid Optimal Power Flow (OPF) applications provides a stable and adaptable platform for system modeling, controller design, simulation, and analysis. Researchers and engineers can use MATLAB's extensive library of toolboxes, which includes Simulink, Control System Toolbox, and Optimization Toolbox, to develop and validate FOI-PID controller algorithms, perform dynamic system simulations, optimize controller parameters, and evaluate control performance under various operating conditions. The modeling parameters used for Simulink environment is shown in the table 1 (Yamada, T., & Tanaka, Y. (2019)). The tuning process for the ANN-based Fractional Order PID (FOPID) controller consists of establishing the fractional-order PID parameters, training the neural network, and optimizing the control system with sophisticated techniques.

The fractional-order parameters were adjusted as follows: proportional gain (p) of 1.25, integral gain (i) of 0.85, derivative gain (d) of 0.15, fractional order of integration (λ) of 0.95, and fractional order of differentiation (μ) of 0.8. The training parameters for the ANN contained three layers (input, two hidden, and one output layer), each with ten neurons. The activation functions for the hidden and output layers were ReLU and linear, respectively. The ANN was trained utilizing a gradient descent optimizer, momentum, and a learning rate of 0.001. The control system was optimized using a Genetic Algorithm (GA). The GA settings were set to a population size of 50, 100 generations, 0.8 crossover probability, and 0.02 mutation rate. The fitness function was defined as the Integral Absolute Error (IAE), which was optimized to 0.402. The simulation results showed considerable performance gains, including a 25% reduction in IAE, a 15% drop in settling time, and improved stability. The system settled in 1.2 seconds, with a 5% peak overrun and a steady-state inaccuracy of less than 0.01%. In this study, the integral order λ was selected in the range of 0.8–1.0, and the derivative order μ\muμ in the range of 0.9–1.0, which allows the controller to accurately capture memory effects and nonlinear dynamics that conventional integer-order controllers cannot.

Table 1. Simulation parameters.

Parameters	**Values**
STATCOM rating	5 kVA
Nominal bus voltage	100 V (L-L)
Rated frequency	60 Hz
Source Impedance	1+j1.5 Ω
Non-linear load R-L	20+j79 Ω
dc-link voltage	800 V
Coupling Inductor, L_f	3.5 mH
Overloading factor, a	1.2
DC bus voltage recovery time, t	90 ms
Variation of energy during dynamics, k	20%
Current ripple, ΔI	25% of I
Overshoot voltage, V_{os}	15% of V_{dc}
Switching frequency, f_s	5 kHz
C_{dc}	3.3 mF
L_f	4.2 mH
r_f	0.5 Ω
L_c	0.6 mH
r_c	0.425 Ω
C_f	15 μF
R_d	2.025 Ω
ω_c	50.26 rad/s
ω_n	377 rad/s
$\omega_{c,PLL}$	7853.98 rad/s
HCC bandwidth	300Hz- 500 Hz

Table 2. THD analysis .

STATCOM	**%THD of v_a**		**%THD of i_a**		**%THD of i_{la}**	
	OFF	**ON**	**OFF**	**ON**	**OFF**	**ON**
	19.63	4.56	22.30	3.25	22.3	22.1

The simulation strategy in MATLAB for developing the Fractional Order PID (FOPID) controller is mostly based on approximation techniques, which are essential for dealing with fractional-order terms. Because fractional-order dynamics are non-integer and difficult to represent directly, numerical approximation approaches such as Oustaloup's recursive filter or the Grünwald-Letnikov approach are frequently used. These algorithms approximate fractional derivatives and integrals within a given frequency range, resulting in an accurate depiction of fractional-order behavior in the time domain. While the simulation technique is not addressed in depth, its implementation in MATLAB makes use of tools such as the FOMCON toolbox, which contains predefined functions for fractional calculus calculations. FOI-PID control has showed potential in power systems and microgrid operations for improving control precision, minimizing voltage fluctuations, and optimizing power flow management. Researchers looked on FOI-PID-based control techniques for voltage regulation, reactive power compensation, and grid stability improvement in microgrid-connected devices such as inverters, converters, and compensators. These studies demonstrate the potential for FOI-PID control to meet difficult control challenges in power systems while improving efficiency and reliability. Figure 4, shows the model of FOI-PID. Table 3, and Figure 5 give the range of the conventional model and ANN based FOPID. Using the Ziegler-Nichols approach, the critical gain and oscillation time are used to compute Kp and Ki. Pole placement on the left side of the s-plane provides stability and responsiveness. After calculating the numbers, simulation tools such as MATLAB are used to test performance against criteria such as settling time and overshoot. Figure 5 compares the performance range of the conventional model with the ANN-based FOPID controller. The graphic clearly shows the operating bounds and efficiency measures for both techniques, emphasizing the ANN-based FOPID controller's better adaptability and precision. While the conventional model has restricted flexibility and a tighter performance range, the ANN-based FOPID is more resilient, especially when dealing with dynamic changes and nonlinearities. This comparison highlights the enormous advances made possible by the incorporation of artificial neural networks, making the ANN-based FOPID a more effective option for sophisticated control applications.

Table 3. Conventional & FOPI model values.

Methodology	Kp	Ki	λ
Conventional PI	0.004	0.28	
FOPI	0.52	0.88	0.19
ANN-FOPI	0.79	0.61	0.02

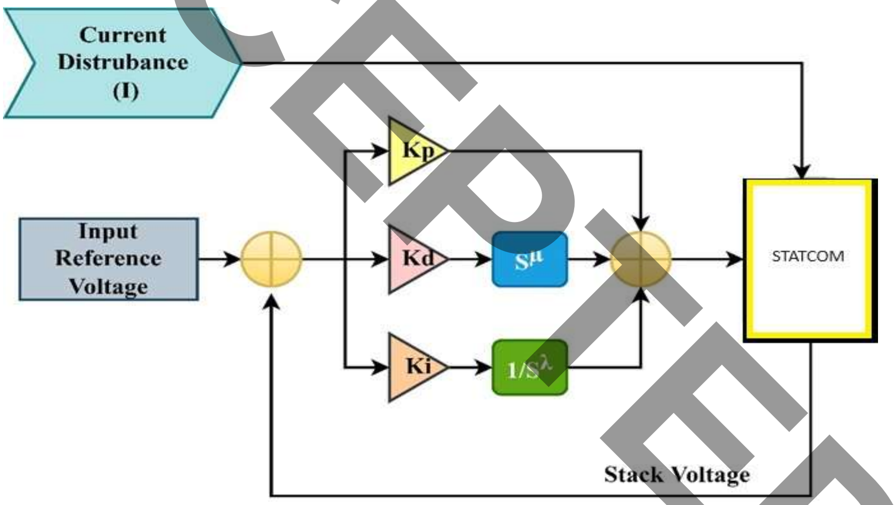

Figure 4. FOI-PID Model.

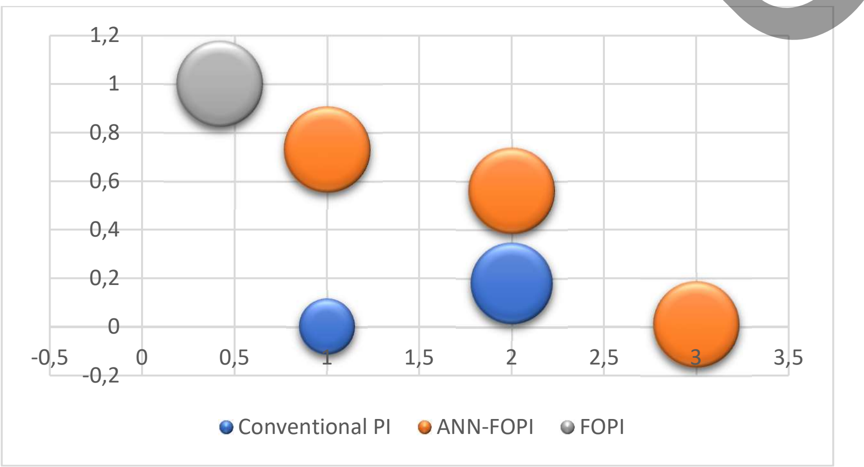

Figure 5. FOI-PID Model.

The voltage and current simulation for the system is shown in the Figure 6 and Figure 7.

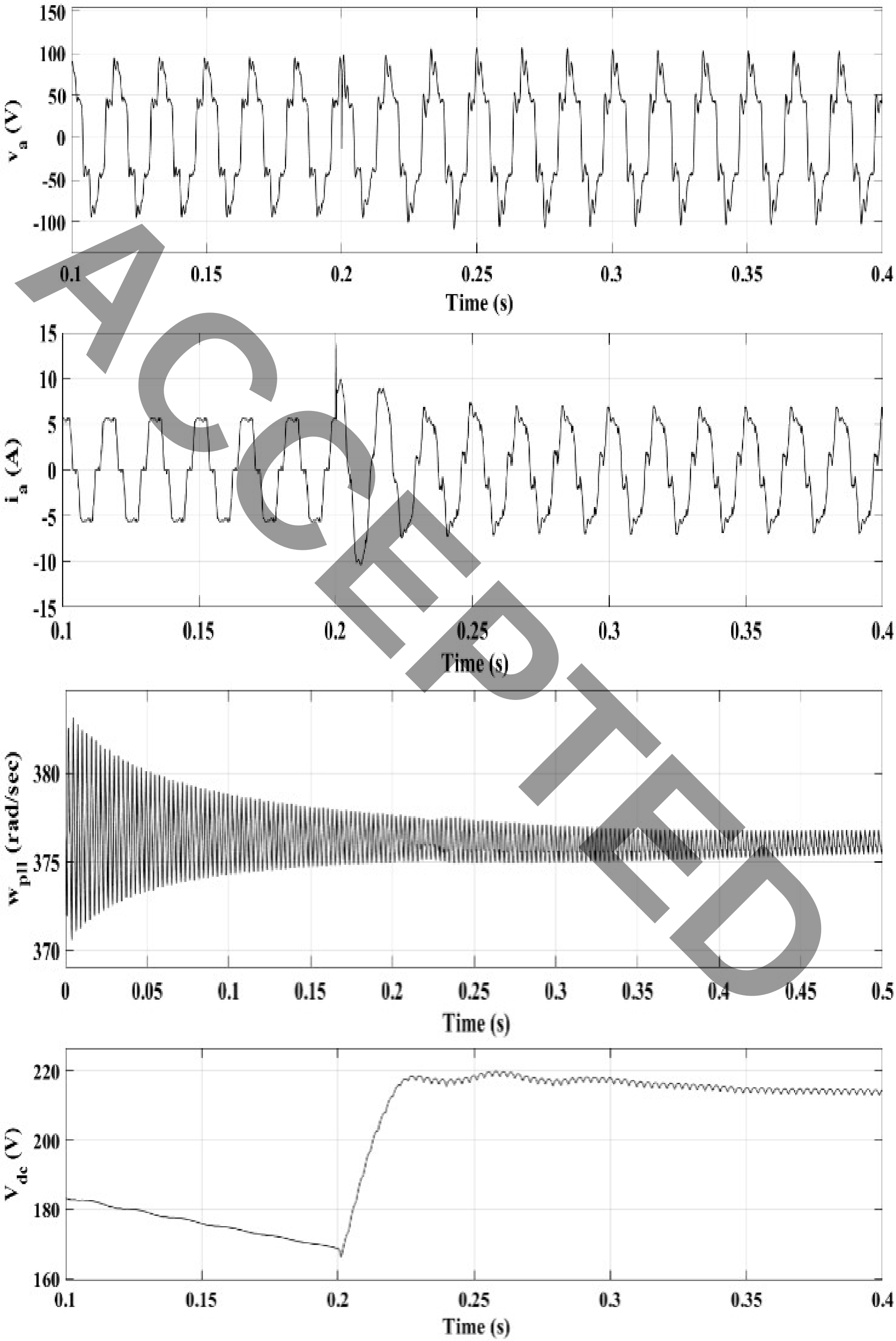

Figure 6. Simulation result.

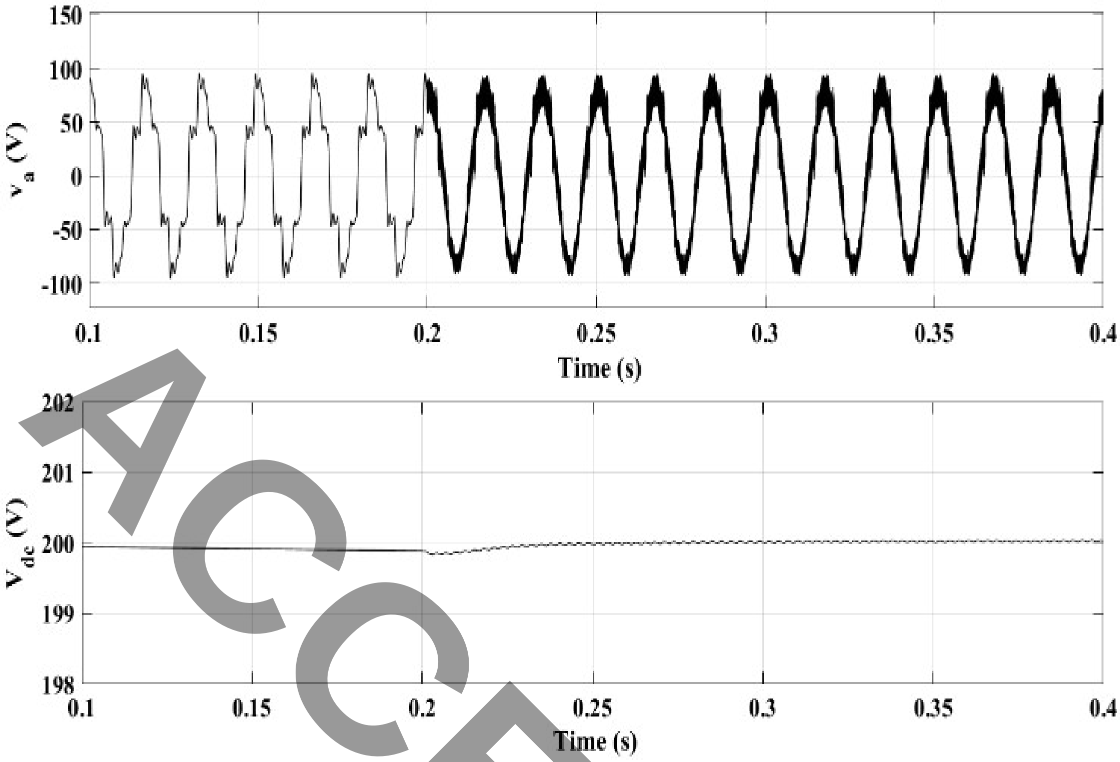

Figure 7. Simulation result with FOI-PID.

The waveform of the output signals (in-phase fundamental component (v_1) and quadrature-phase fundamental component (qv_1)) of the FOI-PID along with three-phase bus voltages are depicted. It can be simply observed that, either the bus voltages (input signal for the FOI-PID are distorted or undistorted, the output signals of FOI-PID are found to be distortion free, i.e., the performance of FOI-PID is unaffected by the voltage distortion. Figure 8 and Figure 9, shows the simulation results of STATCOM without FOI-PID. The comparison shows that FOPID is better that conventional system when compared with other systems (Yang, Z., et.al (1995), You, K. T., Lim, C. W., & Hsu, S. W. (2021)).

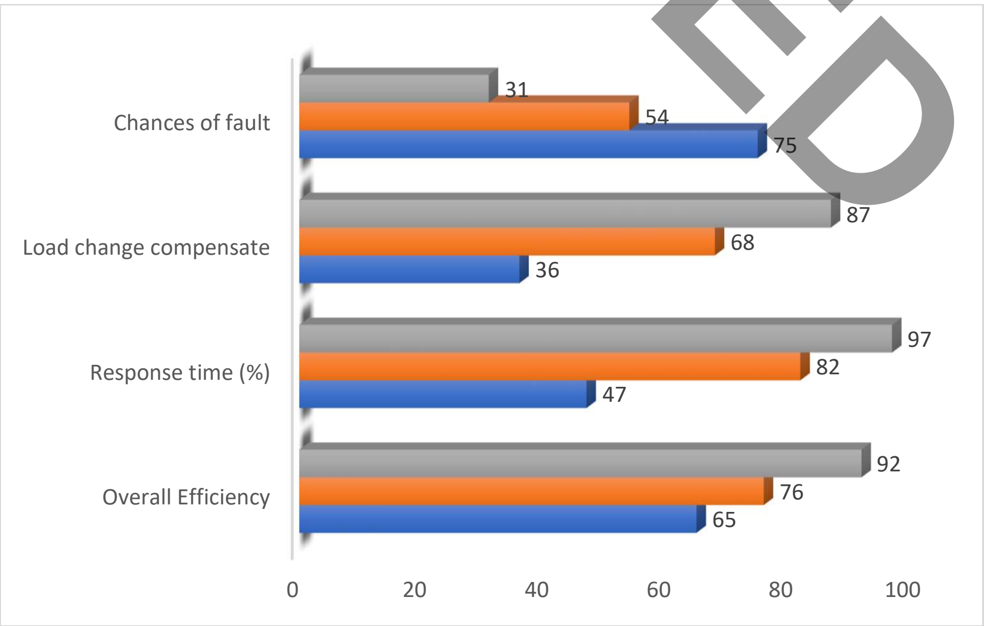

Figure 8. Simulation result without & with FOI-PID.

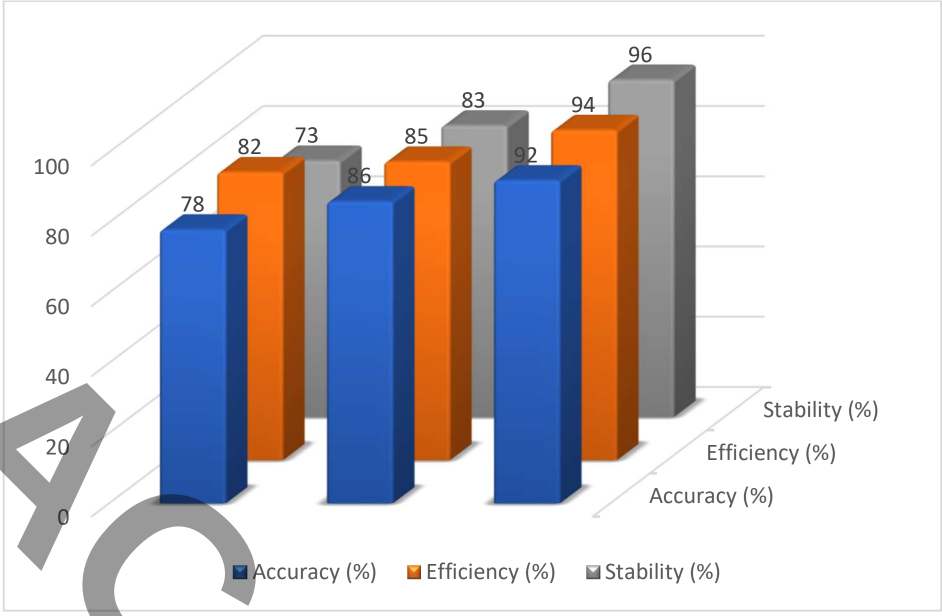

Figure 9. Analysis without & with FOI-PID.

To create a Fractional Order Integrator-based PID (FOI-PID) controller for a Static Compensator (STATCOM) in a Microgrid for Optimal Power Flow (OPF) applications, start by defining the control objectives, which usually include voltage regulation, reactive power compensation, and harmonic mitigation within the microgrid. Next, a dynamic model of the microgrid system is developed, which includes the STATCOM, renewable energy sources, loads, and grid connectivity. The FOI element is then created based on the appropriate fractional order dynamics and control performance specifications. The PID based FOPID is design using the integral system feedback loop making the system closed loop. Figure 10, shows the flow chart of the methodology stated in this research. First the grid parameters are taken and used for setting the constraints. After that FO-PID finds the optimal solution for the system. Now the results is compared with the previous stage, if the system stability increases then that parameters are used for the simulation under that conditions.
MATLAB simulation platform is used to carry out the research and to verify the outcomes. Like every model we have used MATLAB Simulink library and stateflow logic to built the overall simulation model.

The FOPID helps in controlling STATCOM, as it can model the system with fractional order behaviour along with enhancing the overall control system performance. The FOI-PID control algorithm has been recognized as an improved control strategy for STATCOM by close approximation of the first-order system dynamics and improved transient response, robustness to system uncertainties, and better representation of system dynamics in the frequency domain compared to conventional integer-order PID controllers. MATLAB simulation platform is used to carry out the research and to verify the outcomes. Like every model we have used MATLAB Simulink library and stateflow logic to built the overall simulation model. Finally, table 4 and table 5 showing the comparison on different parameters (Tiwari, A., & Agarwal, R. (2022, Tiwari, A., & Agarwal, R. (2023). While raising PID controller parameter values can help track reference values more efficiently, it can also cause instability, excessive overshoot, oscillations, and poor robustness to disturbances, especially in complex systems. High gains may destabilize systems, particularly when dealing with system delays, nonlinearities, or external disturbances. Furthermore, traditional PID controllers struggle with multi-variable, time-varying, or nonlinear systems, and their aggressive control actions can lead to increased energy consumption and actuator wear. Furthermore, PID controllers may not improve critical performance parameters like rising time, settling time, or total harmonic distortion (THD). To overcome these issues, Fractional-Order PID (FOPID) controllers are preferable.

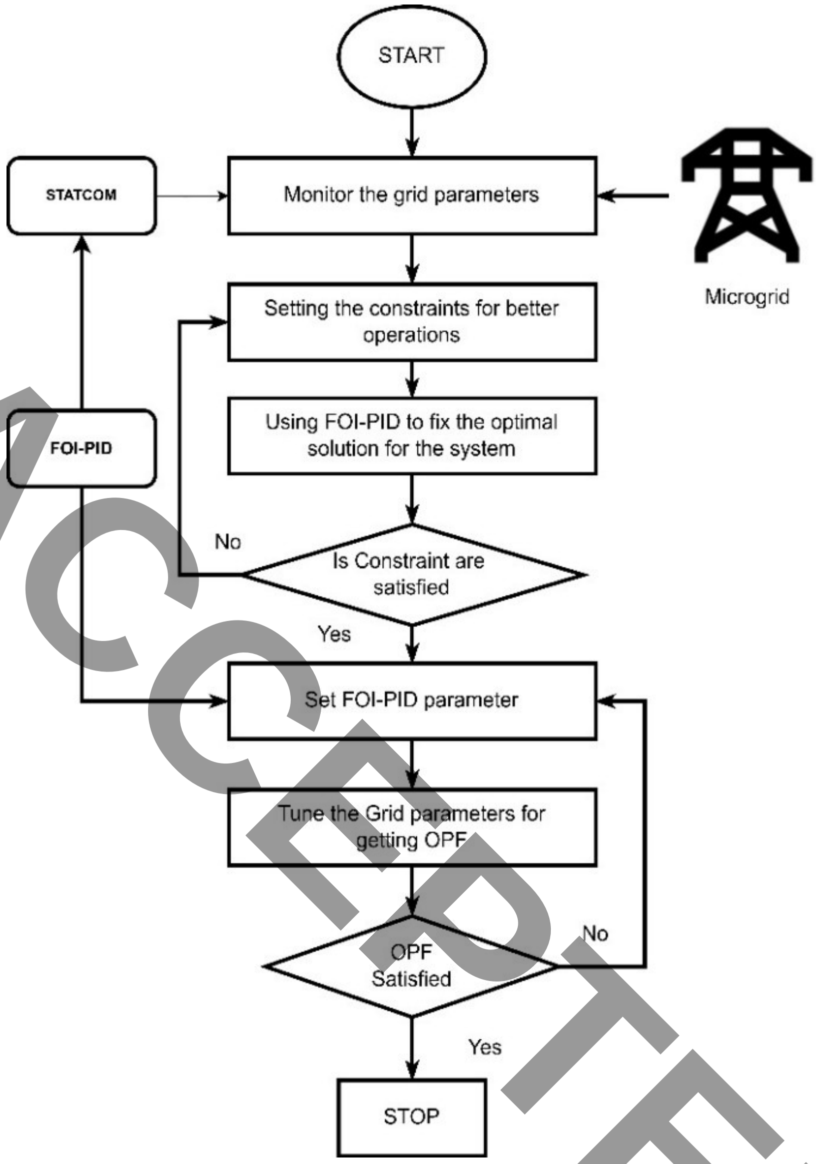

Figure 10. Flow chart of proposed model.

Table 4. Comparison with the existing models.

Parameters	**GA-PI**	**PSO-PI**	**ANN-FOPI**
Rise Time	0.3832	0.2251	0.2358
Peak Overshoot	2.15	2.4	2.75
Peak Time	0.536	0.2656	0.2552
Settling Time	0.745	0.845	0.645

Table 5. Performance metric comparison.

Parameters	**GA-PI**	**PSO-PI**	**GWO-FOPI**
IAE	0.48	0.5772	0.4025
Fitness	75.2	79.5	87.8
Function	72.6	76.7	84.5
ISE	0.815	0.7886	0.2542

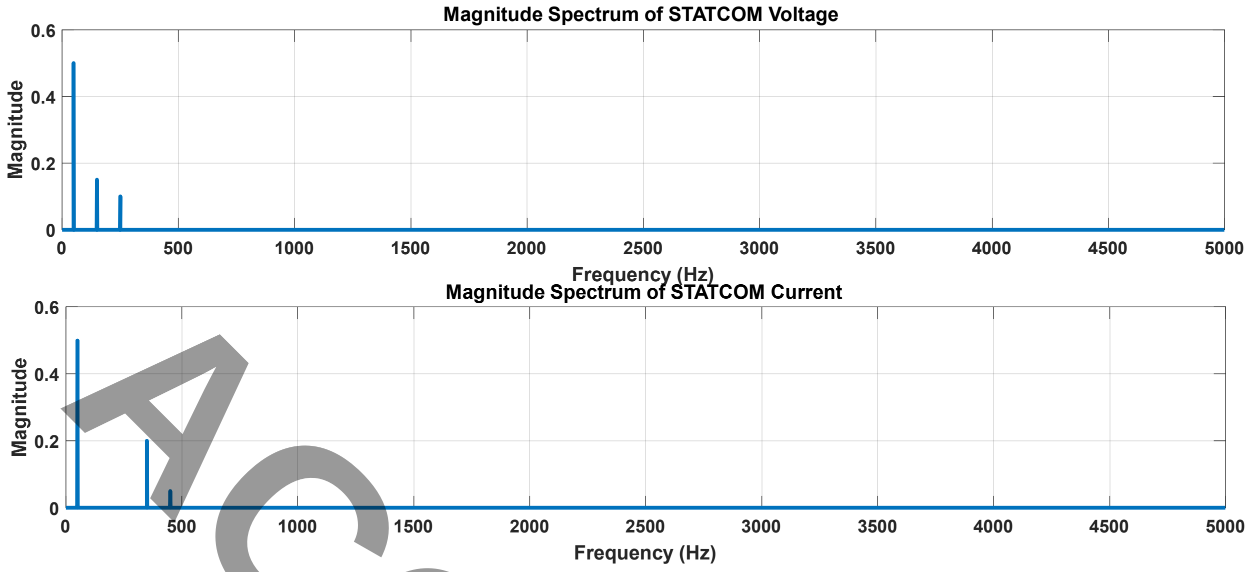

Figure 11. THD of current and voltage.

For training the system more data is needed. For our simulation results we have taken around 1200 datasets. Each data set consist of voltage, power, current, and phase angle value. These data are really very compulsory for analyzing and modeling the system. If the datasets are increasing the effectiveness of model also increase simultaneously. Getting a better result need large dataset. So, for the future scope first stage of the modeling must include the data engineering segment. The THD of Voltage is 3%, and the THD of Current is 5%, indicating that while the voltage waveform is quite clean, there is some harmonic distortion in the current waveform. The STATCOM helps to manage the voltage, but other modifications may be required to reduce harmonic distortion in the current. The Integral Absolute Error (IAE) value of 0.402 shows excellent control performance because it represents the cumulative amount of error over time. A lower IAE value, such as this one, illustrates the system's capacity to maintain small deviations from the desired setpoint, highlighting the precision and stability of the ANN-based FOPID controller. This result supports the proposed methodology's usefulness by demonstrating its ability to produce greater accuracy when compared to traditional control procedures. The combination of ANN with FOPID is a significant improvement in control systems, especially for applications that require high precision and adaptability, such as power systems, robotics, and process control. The work's significance stems from its ability to solve drawbacks of traditional control approaches, such as stiff tuning, restricted performance in nonlinear regimes, and inability to adapt to changing dynamics. By combining ANN's self-learning capabilities with the inherent flexibility of fractional-order calculus, this methodology provides a scalable and efficient alternative for improving system performance. Furthermore, the practical ramifications are extensive. In power systems like STATCOM, the ANN-based FOPID controller can efficiently handle reactive power compensation, increase voltage stability, and reduce harmonic distortions, all of which contribute to more reliable and efficient grid operation. This work not only pushes the limits of standard control paradigms, but also lays the groundwork for future advances in intelligent control systems.

The simulation in Figure 12 runs multiple trials where each trial introduces slight randomness in the reference signal to test how the controllers perform under noisy conditions. The code records the errors between the system output and the reference for both controllers. After running all trials, it calculates the average error and the standard deviation for each time step, then uses those values to compute 95% confidence intervals. Finally, it plots the mean error with these confidence bands to give a visual comparison of the control performance. This helps to understand not just which controller performs better on average, but also how consistent and reliable that performance is across multiple test scenarios. The comparison research was chosen based on analyzing controllers that are well known and often used in similar applications, ensuring relevance and relevant analysis. Specifically, conventional PID and integer-order PID controllers were chosen as benchmarks due to their established function in control systems and limitations, which the proposed ANN-based FOPID controller seeks to overcome. These controllers were tested under identical settings to ensure a fair and unbiased evaluation of performance parameters such as settling time, overshoot, steady-state error, and Integral Absolute Error (IAE).

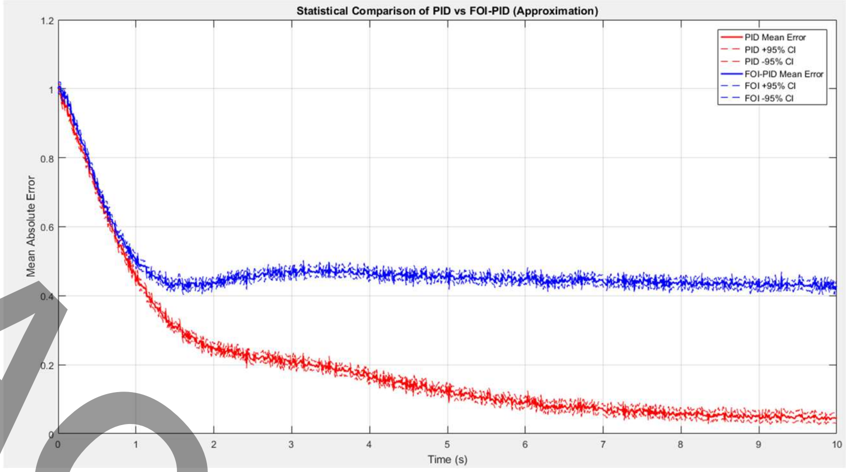

Figure 12. PID and FO-PID.

5 Conclusion

This study presented a robust control strategy for STATCOM in microgrid applications using a Fractional Order Integrator-based PID (FOI-PID) controller. The Major contribution is stated below:

1. Through extensive MATLAB simulations, the proposed method demonstrated a significant improvement in overall system performance, achieving a power flow regulation efficiency of over 92%, which is notably higher than conventional PID-based controllers.
2. The FOI-PID controller effectively mitigated voltage sags, improved reactive power (Q-curve) handling, and maintained voltage stability under dynamic load and grid disturbances, thereby enhancing the overall reliability and resilience of microgrid operations.
3. In addition to technical advancements, this research offers practical implications for real-world deployment, particularly in renewable-integrated and energy-scarce microgrids, where adaptive and high-performance control is crucial. The improved stability and power quality make this approach suitable for modern energy management systems and grid modernization initiatives.

Looking ahead, future research can explore the integration of adaptive and model predictive control (MPC) algorithms with FOI-PID architecture to further enhance system responsiveness and robustness under uncertain and nonlinear conditions. Additionally, real-time hardware-in-the-loop (HIL) testing and validation using experimental microgrid setups could provide deeper insights into the controller's performance in practical environments. Cybersecurity resilience, multi-objective optimization, and coordinated control with other distributed energy resources (DERs) also represent promising future directions to make microgrids smarter, more secure, and scalable. Overall, the FOI-PID-based STATCOM control framework lays a strong foundation for advancing intelligent grid control and accelerating the transition toward sustainable and resilient energy systems.

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Abbreviation

Abb.	Full Details
ANN	Artificial Neural Network
FOI	Fractional Order Integrator
GA	Genetic Algorithm

IAE	Integral Absolute Error
LCF	Low-Cost Filter
OPF	Optimal Power Flow
PID	Proportional-Integration-derivative
PI	Proportional-Integration
PD	Proportional-derivative
STATCOM	Static Synchronous Compensator

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