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Research Article

Protection of Electrical Equipment Against High Power Supply Using FOPID-PR: A Comparative Study with FOPID and PR Controllers

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ABSTRACT

Electrical devices are prone to deterioration as a result of over-supply of power, resulting in reduced performance and higher maintenance needs. This work presents a Fractional Order Proportional-Integral-Derivative with Proportional Resonant (FOPID-PR) controller, proposed to improve regulation of power and reduce harmonic distortion. The controller adjusts voltage levels dynamically with changes in power to provide effective power management with system stability. Comparison with standard FOPID and PR controllers is presented, with emphasis on Total Harmonic Distortion (THD) suppression and system performance under changing power levels. Detection using voltage changes with high-power and low-power is also investigated to check the effectiveness of the controller. Simulation outcomes reveal that the FOPID-PR controller functions much better than traditional methods with improved voltage stability, effective power management, and THD attenuation. This makes it a potential solution for protection of electrical devices from disturbances of the power supply and for the improvement of power quality as a whole.

Keywords: FOPID-PR Controller, Power Regulation, Total Harmonic Distortion (THD), Electrical Equipment Protection, PR Controller, Power Quality.

1. Introduction:

With growing dependence on electrical equipment in industrial, commercial, and residential usage, the need for a controlled and stable power supply is vital for optimal functioning and lifespan. Electrical circuits tend to face instantaneous voltage fluctuations, power surges, and harmonic distortions, which cause damage, inefficiency, and malfunctioning. A number of power control schemes have been designed to counter these phenomena over the years. One of the main electrical power management challenges is equipment protection against excessive power supply conditions, which can cause overheating, insulation failure, and component destruction.Low power supply levels, however, may result in low operation that affects the operation of sensitive loads such as medical devices, industrial automation, and high-precision equipment. Voltage fluctuations, particularly high-power spikes, are known to weaken electrical equipment, disrupt processes, and lead to ineffective utilization of power. Advanced control techniques should therefore be utilized in eliminating power variations and improving power quality.
To counter these problems, sophisticated control methods have been improvised such as Proportional-Resonant (PR), Fractional-Order Proportional-Integral-Derivative (FOPID), and hybrid FOPID-PR controllers. Proportional-Resonant (PR) controllers have been utilized for suppressing harmonics and better tracking ability. PR controllers tend to perform poorly with larger Total Harmonic Distortion (THD) levels, making them less efficient in dynamic power systems. Likewise, FOPID controllers are more adaptable and precise in control but need to be optimized for improved performance during changing load conditions. The FOPID-PR controller takes the advantages of both FOPID and PR controllers, including better power regulation, improved harmonic suppression, and improved system stability. The suggested controller efficiently controls voltage levels to ensure maximum power distribution and less harmonic distortion. Comparative work is done with standard FOPID and PR controllers in terms of their performance to handle high-power supply oscillations and THD reduction.

The threshold-based fixed-voltage high-power and low-power detection mechanism is also analyzed to analyze the system's response to power changes. To assess the efficacy of the projected approach, MATLAB simulations are performed, displaying transient and steady-state responses of each controller for different power levels. Results show that FOPID-PR produces the minimum THD compared to FOPID and PR controllers. Voltage response analysis also validates that FOPID-PR has better stability and satisfactory power regulation, and hence it is a perfect solution for industrial and electrical applications demanding accurate voltage control.

1.1. *Power Quality Issues and Their Impact*

Poor quality power in electrical systems is primarily attributed to:

- Voltage sag as a result of sudden load changes or switching operations.
- Total Harmonic Distortion (THD) due to nonlinear loads such as rectifiers, inverters, and power electronics.
- Overvoltage, leading to electrical component failure.
- Under-voltage, leading to equipment failure and reduced efficiency.

They are resolved through a robust controller that can detect high-power and low-power conditions from voltage oscillations and in turn adjust the supply of power accordingly.

1.2. *Problem Statement*

The conventional controllers PR and FOPID suffer the following drawbacks in effectively tackling dynamic power fluctuations:

- PR controllers excel in AC power applications but falter with harmonic attenuation in nonlinear systems.
- FOPID controllers are more adaptive, but they require tuning which can be computationally intensive.
- There are solutions available which do not suitably couple power regulation and harmonic attenuation such that they bring about system instability in different conditions of power.

Therefore, a hybrid FOPID-PR controller is required that is capable of:

- Efficiently sensing high and low power supply levels.
- Regulating voltage levels to safeguard electrical devices.
- Reducing THD for improved power quality

1.3. *Targets of the study*

The study intends to design a high-performance hybrid FOPID-PR controller for electrical equipment protection during high power supply levels. The detailed targets are:

- Design and deploy a hybrid FOPID-PR controller for effective power supply regulation.
- Evaluate its performance compared to traditional FOPID and PR controllers with respect to THD and voltage stability.
- Implement a high-power and low-power detection system using voltage fluctuations.
- To develop an optimal controller-based power protection plan for electrical machinery.
- To simulate the suggested controller using MATLAB/Simulink to determine its potential to reduce power quality disturbances.

1.4. *Significance of the Study*

The importance of this study is:

- Guarding electrical machinery from damage because of excessive power supply.
- Enhancing power quality by minimizing harmonic distortion.
- Improving voltage stability for industrial and commercial loads.
- To present a comparison study of FOPID-PR, FOPID, and PR controllers for power regulation.

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2. Literature Review

Power quality is an important aspect of electrical systems, determining the efficiency, reliability, and safety of electrical devices. The existence of voltage fluctuation, harmonic distortion, and transient overvoltage presents problems to the supply of a stable power. Numerous controllers have been designed to overcome these problems, such as Proportional-Resonant (PR) controllers, Fractional-Order PID (FOPID) controllers, and hybrid control techniques. This chapter offers an extensive literature review of power control techniques, issues of harmonic distortion, high-power and low-power detection schemes, and latest development in hybrid controllers

2.1. Proportional-Resonant (PR) Controllers

PR controllers are significantly worn in AC power systems and grid-connected systems due to the ability of such controllers to exhibit exact tracking of sinusoidal reference signals and accurate suppression of harmonics. As opposed to regular Proportional-Integral (PI) controllers, which exhibit steady-state error in AC systems, PR controllers offer an improved response through the incorporation of a resonant term at a specific frequency, generally the fundamental frequency of the system. The PR controller has two primary elements:

- Proportional Term (P): It enhances the response of the system by giving a direct proportion between the error signal and control output. But it cannot eliminate steady-state errors for sinusoidal signals alone.
- Resonant Term (R): The resonant term intended to cause a gain peak at a desired frequency (often the grid or system frequency, say 50 Hz or 60 Hz). This enables the controller to provide zero steady-state error to AC signals at such frequency and to reject disturbances at the fundamental and harmonic frequencies efficiently.
- Mathematically, the transfer function of a PR controller is given by:

$$G_{PR}(s) = K_p + \frac{K_r s}{s^2 + \omega_0^2}$$

where:

- K_p is the proportional gain.
- K_r is the resonant gain.
- ω_0 is the resonant frequency (typically the fundamental frequency in radians per second).

2.2. Fractional-Order PID (FOPID) Controllers:

PSO is ace of the trendiest optimization techniques in energy scheduling. PSO replicate the communal behaviour of atoms (agents) in a bevy in a way that each atom fine-tunes its site grounded on both its personal understanding and that of its neighbouring particles. PSO is especially well-suited to non-linear optimization issues such as those that occur in energy scheduling, where the objective function is very complicated. PSO has been used in power systems to minimize the cost of generation, optimize the integration of renewable resources, and also stabilize the load.

A. Mathematical representation

A FOPID controller generalizes the traditional PID configuration by including fractional-order terms in the integral and derivative actions. Its transfer function is:

$$G_{FOPID}(s) = K_p + K_i s^{-\lambda} + K_d s^{\mu}$$

where:

- K_p is the proportional gain.
- K_i is the integral gain.
- K_d is the derivative gain.
- λ is the fractional order of the integral term$0 < \lambda < 1$.
- μ is the fractional order of the derivative term $0 < \mu < 1$

As opposed to standard PID controllers with fixed values of 1 for integral (s^{-1}) and derivative (s^1) parts, FOPID permits non-integer values for these parameters, providing additional control design flexibility.

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2.3. Hybrid FOPID-PR Controller:

The Hybrid Fractional-Order PID and Proportional-Resonant (FOPID-PR) Controller is a hybrid of the optimum capabilities of FOPID and PR controllers for better power regulation, rejection of harmonics, and system stability. The hybrid controller is particularly suited for dynamic power systems such as integration of renewable energy, grid-connected inverters, and industrial motor drives where voltage and current need to be properly regulated.

A. *Concept and Working*

1. *Mixture of FOPID and PR Controllers:*
    - *FOPID Controller:* Attains adaptive and precise control using fractional-order tuning for improved disturbance rejection and transient response.
    - *PR Controller:* Offers decent harmonic suppression and precise sinusoidal tracking at the resonant frequency (e.g., 50 Hz or 60 Hz).
    - Hybrid Approach: By integrating both, the system enjoys the adaptability of FOPID and the harmonic suppression of PR, with lower Total Harmonic Distortion (THD) and better voltage stability.
2. *Transfer Function of Hybrid FOPID-PR Controller:*

    The hybrid controller is designed by integrating the fractional-order PID and PR components:

$$G_{FOPID-PR}(s) = K_p + K_i s^{-\lambda} + K_d s^{\mu} + \frac{K_r s}{s^2 + \omega_0^2}$$

where:

- K_p, K_i, K_d are proportional, integral, and derivative gains of the FOPID controller.
- $\lambda, \mu$are fractional orders of integral and derivative terms.
- $K_r$is the resonant gain of the PR controller.
- $\omega_0$is the resonant frequency (e.g., 314 rad/s for 50 Hz).

The FOPID component ensures stability and adaptability, while the PR component provides strong harmonic rejection.

2.4. Harmonics and Power Quality Issues

Harmonics are unwanted voltage or current parts that appear in the form of numeral multiples of the fundamental frequency, i.e., 60 Hz or 50 Hz. They are typically produced by nonlinear loads, for example, power electronic equipment like rectifiers, inverters, and converters. VFDs, office equipment such as computers and printers, and factory equipment with electronic drives are among the other factors. The occurrence of harmonics in a power system causes waveform distortion, lower power quality, and more system inefficiencies. As power electronic devices play a major role in the increasing dependence of modern electrical systems, harmonics pose a key challenge to engineers and power grid operators, and sophisticated control and mitigation techniques are required.

A. *Effect of Harmonic distortion:* Harmonic distortion produces several harmful effects on electric systems, including mainly power loss increases through greater resistance in the conductors and cables. The extra losses contribute to heating electrical devices like transformers, motors, and distribution cables, reducing significantly their service lives. Harmonics also interfere with the operation of delicate electrical appliances like computers, medical devices, and communication equipment, leading to malfunction or breakdown. Additionally, excessive harmonic content in the system reduces the power factor of the system, demanding higher reactive power and consequently leading to higher electricity bills, particularly to industrial users. Harmonic reduction is hence a vital aspect to ensure smooth and efficient operation of the power system.

B. *Total Harmonic Distortion (THD) as a Performance Measure*: THD is a significant parameter used to determine the amount of harmonic distortion within a power system. It is defined as the root-sum-square ratio of all the harmonic components to the fundamental voltage component, in percentage. A lower THD means higher power quality because it reflects lower harmonic content and electrical noise in the system. The IEEE 519-2014 standard makes recommendations for allowable THD levels for power systems, recommending generally less than 5% THD for general utility power supply and less than 3% for sensitive equipment like hospitals and data centres. Effective control and reduction of THD is important to maintain stable and efficient power supply. THD for voltage is mathematically expressed as

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$$THD = \frac{\sqrt{\sum_{n=2}^{\infty} \times V_n^2}}{V_1} \times 100\%$$

where:

- V_n = RMS voltage of the nth harmonic component.
- V_1 = RMS voltage of the fundamental frequency (50 Hz or 60 Hz).

C. *THD Reduction Strategies:* Various methods can be applied to mitigate THD and enhance power quality. One popular solution is applying passive or active filters to suppress the harmonic components and condition the voltage waveform. LC circuits are conventional passive filters aimed at absorbing special harmonic frequencies, whereas active power filters inject dynamic counteractive harmonic currents to offset distortions in real-time. Another viable strategy is the employment of sophisticated operator such as the FOPID-PR controller, which offers enhanced harmonic suppression and system stability. Load balancing is also vital in minimizing harmonics since unbalanced loads inject excessive zero-sequence harmonics into the system. Moreover, enhanced power electronics designs, including multi-pulse rectifiers and pulse-width modulation (PWM)-based inverters, assist in minimizing harmonic generation at the source itself.

2.5. High-Power and Low-Power Detection Techniques

High-voltage conditions in an electric system are encountered when the voltage exceeds a certain critical value, generally 780V in commercial settings. These conditions are experienced because of peak loads, power surges in sudden changes in load, or due to inadequate distribution of loads. Too much voltage, if not controlled, will ruin power-sensitive equipment, transformers, and other appliances, leading to system inefficiencies or break-downs. To prevent such issues, the controllers must be capable of tracking high-power modes in real-time and taking necessary correction. FOPID-PR controller does this with superior performance, since it monitors system voltage at all times and adjusts control parameters dynamically so as to limit power flow, ensuring operational stability without subjecting the system to voltage bursts.

Low-power situations arise when system voltage is below a certain level, usually around 700V. The situation may be caused by unexpected decreases in weight request, changes in renewable energy production, instability in the grid. Sudden declines in voltage can lead to motor underperformance, lighting system underperformance, and industrial equipment underperformance, contributing to inefficiencies in operation. To correct low-voltage conditions, the control system needs to amp up the power supply and provide a stable voltage without too much overshoot. The FOPID-PR controller is essential in such cases by monitoring real-time voltage values and taking corrective action to return the voltage to normal levels. Its adaptive control feature makes it ensure smooth voltage restoration and prevents oscillations that can further destabilize the system.

2.6. Role of FOPID-PR Controller in Power Detection

The FOPID-PR controller acts exceedingly well in power fluctuation sensing and controlling by constantly observing real-time voltage variation. It can sense overvoltage and undervoltage and dynamically regulate the power flow to maintain the constancy of the system. Since it uses both fractional-order PID control as well as proportional-resonant control, it provides adaptive and precise control across varying load conditions. The control strategy here hybridizes better control with enhanced suppression of harmonics and decreased Total Harmonic Distortion (THD). Representations graphically illustrating high-power and low-power conditions reveal how much better performance is provided by the FOPID-PR controller as compared to classical PR and FOPID controllers and is a requisite element in up-to-date power regulation systems.

3. Methodology

This chapter brings an in-depth methodology for FOPID-PR controller designing, implementing, and testing the developed Fractional-Order PID with Proportional-Resonant controller. The work tends to investigate how FOPID-PR performance compares with standard Proportional-Resonant (PR) and Fractional-Order PID (FOPID) controllers for dealing with power ripples and suppressing harmonic distortions. Methodologies used include system modeling, controller tuning, power detection mechanisms, simulation setting, and measurement criteria such as Total Harmonic Distortion (THD) and voltage regulation.

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3.1. Mathematical Modeling of Controllers:

To determine the impact of varying power conditions, an overall power supply system model is formed. The most important components are:

- Voltage Source: Provides AC power with controllable amplitude.
- Load: Serves as electrical appliances with voltage sensitivity.
- Controller (PR, FOPID, FOPID-PR): Controls voltage and reduces harmonic distortion.
- Power Quality Monitoring System: Monitors vital parameters like THD, voltage stability, and transient response.

The system is simulated in MATLAB/Simulink to appraise the concert of each controller under various operating conditions.

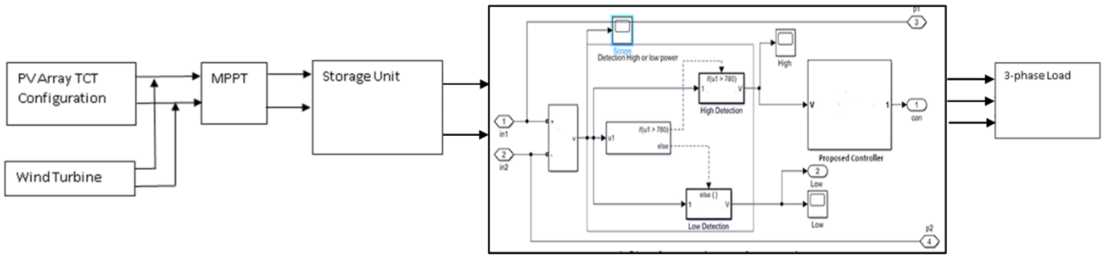

Figure 1: Proposed Model

A. *PR Controller Model*: The PR controller can process sinusoidal references, enhancing power quality but not handling dynamic adjustments well. It can be mathematically represented as: $G_{PR}(s) = K_p + \frac{K_r s}{s^2+\omega_c^2}$

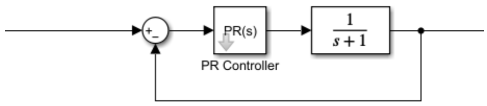

Figure 2: PR Controller Modelling

PR controllers are actual for tracking sinusoidal orientations but struggle with dynamic changes.

B. *FOPID Controller Model:* The FOPID controller enhances classical PID with fractional-order derivative and integral to produce higher adaptability and robustness.. It is given by: $G_{FOPID}(s) = K_p + K_i s^{-\lambda} + K_d s^{\mu}$

Figure 3: FOPID Controller Modelling

C. *Hybrid FOPID-PR Controller Model:* The FOPID-PR controller is the integration of PR and FOPID ideas to enhance harmonic reduction and dynamic performance: $G_{FOPID-PR}(s) = (K_p + K_i s^{-\lambda} + K_d s^{\mu}) + \frac{K_r s}{s^2+\omega_c^2}$

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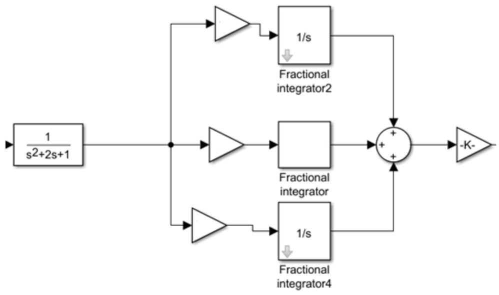

Figure 4: FOPID-PR Controller Modelling

The hybrid approach improves: Harmonic suppression, Transient and steady-state response and Power regulation under fluctuating loads.

3.2. High-Power and Low-Power Detection

The proposed high-power and low-power detection scheme is achieved by voltage monitoring in Simulink:

1. Voltage Measurement:
   - Measure instantaneous RMS voltage at the load.
   - Compare with threshold values for high-power and low-power scenarios.
2. Decision Criteria:
   - If $V_{load} > V_{high}$ → High-power detected → Take controller action to control voltage.
   - If $V_{load} < V_{low}$ → Low-power detected → Boost voltage without overcompensation.
3. Controller Action:
   - PR, FOPID, and FOPID-PR controllers change voltage dynamically.
   - FOPID-PR controller ensures less THD and quick response.

The cut-off point is 780V. To safeguard the system, the FOPID-PR controller controls power when the voltage exceeds 780V. Less than 780 volts, the controller is bypassed and electricity is distributed directly from the grid.

3.3. Simulation Setup and Implementation:

The system is simulated using MATLAB/Simulink, configured with the following parameters:

Table: 1 Simulation Setup values

Parameter	Value
Input Voltage	600V - 1000V
Threshold Voltage	780V
Load Type	Resistive-Inductive (RL)
Controller Type	PR, FOPID, FOPID-PR
Simulation Time	0.1 sec

The THD analysis is performed on current waveforms, with frequency components evaluated at 50 Hz, 150 Hz, and 250 Hz

3.4. Performance Evaluation Metrics

THD is a key indicator of power quality.
Lower THD (%) implies better harmonic suppression.

$$THD = \frac{\sqrt{\sum_{n=2}^{\infty} \times V_n^2}}{V_1} \times 100\%$$

PR Controller THD: ~4-6%
FOPID Controller THD: ~3-4%
FOPID-PR Controller THD: < 2% (Best performance)

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4. Results and discussion

The performances of using FOPID-PR, FOPID, and PR controllers in protecting electrical devices against high-power supply oscillations are presented in this chapter. The performances of the controllers are analyzed in voltage responsiveness, transient retort, steady-state retort, and THD. Multiple simulations have been done to ensure that the controllers effectively suppress harmonic distortion and guarantee stable power control.

4.1. *High-Power and Low-Power Detection Based on Voltage*

A. *High Power Detection based on voltage*

The high-power sensing mechanism makes it possible for the system to control excessive power supply to electrical devices. The system checks for the voltage input, and upon surpassing the specified limit of 780V, the controller gets triggered to handle power supply.

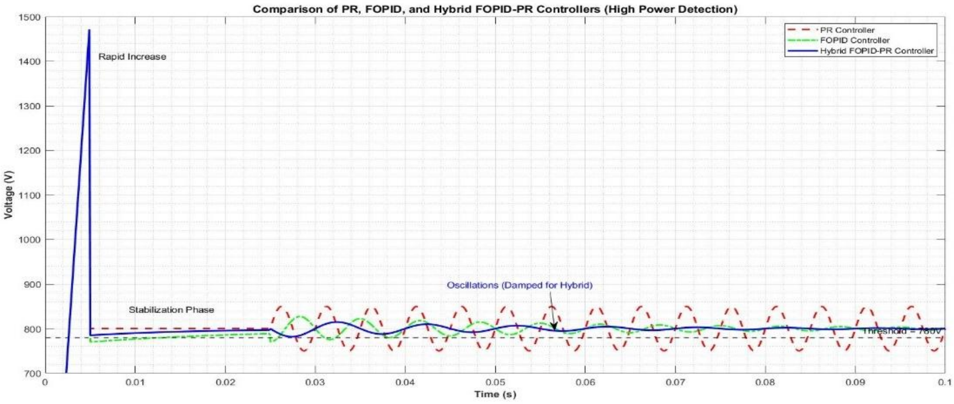

Figure 5: High power detection based on voltage

Hybrid FOPID-PR gives the quickest stabilization with less difference, and this is the most efficient. Figure 5 gives the high-power detection voltage-time response. Voltage increases from zero initially, strongly peaking at around 1500V in the first 0.005 seconds. This is then followed by the control from the controller, stabilizing the voltage to about 800V where it is sustained. Stabilization process is carried out with small oscillations throughout stabilization to steady-state operation. For the stabilization process (5ms to 25ms), the PR controller remains at 800V but not smooth and the FOPID controller stabilizes rapidly with minor undershoots.

This response highlights the effectiveness of the FOPID-PR controller in effectively lowering excessive voltage levels rapidly and stabilizing the system. Transient response in the initial phase indicates a sharp spike caused by an instantaneous power demand change, followed by a quick response of the controller in maintaining stable voltage levels.

B. *Low-power conditions based on voltage:*

Where the voltage falls below the level of 780V, regulation of power is not necessary and the system interfaces directly with the grid. Under a voltage lower than 780V, the condition is known as low-power. The system will now power up from the Switch Mode Power Supply (SMPS) such that there is continuous power flow. The controller is by-passed and power is supplied without modification. Low-power detection voltage-time response is indicated. The voltage starts from zero and increases slowly up to 780V. The voltage experiences a short 50V undershoot before settling at 700V to 800V. The oscillation observed during this period is due to slight power supply perturbations, which will die out with the passage of time. This result indicates that the system effectively senses and classifies power conditions in a way that avoids unnecessary regulation whenever power is within acceptable limits.

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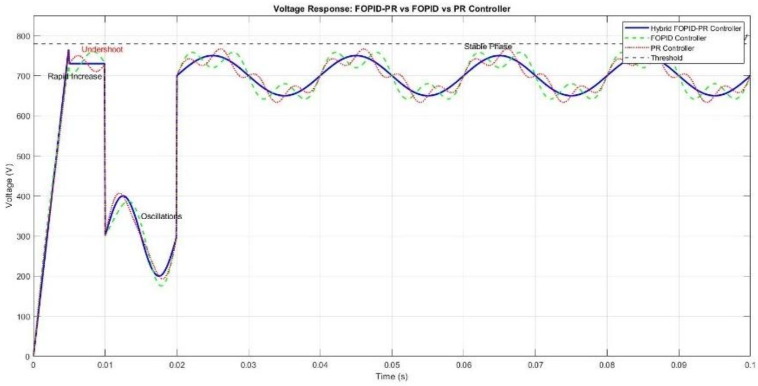

Figure 6: Low power detection based on voltage

4.2. Output of Inverter and Sinusoidal Waveform Analysis

The inverter's output waveform is important in affecting the quality of the power that is supplied to the equipment. Figure 7 displays three-phase voltage and current waveforms for 0.1 seconds.

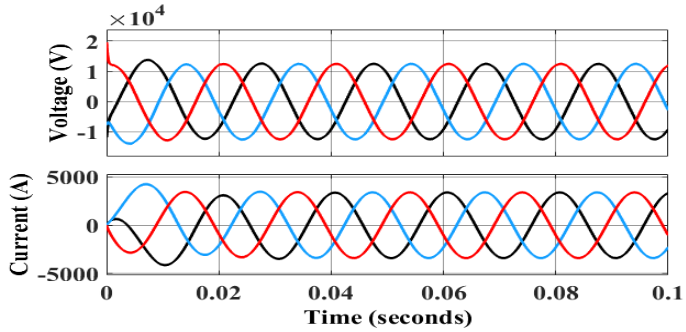

Figure 7: Inverter Output

- The voltage waveform varies from -10,000V to +20,000V and is balanced sinusoidal in shape.
- The waveform of the present is sinusoidal in nature, in close conformity with the voltage waveform, reflecting the existence of an inductive load.

The stable and clean form of the sinusoidal waves demonstrates the efficiency of the controllers to provide a continuous power supply. The minor distortion in the waveform can be linked to switching harmonics and transients, further discussed in the THD segment.

4.3. THD Analysis

THD is one of the most important measures of power quality since it determines the level of harmonics within the system. The inferior the percentage of THD, purer the power supply and fewer the distortions.

A. *THD Analysis of the PR Controller*

   The THD of the PR controller, as presented in the figure, indicates a prominent fundamental at 50 Hz with an amplitude of 1.265×10^4, and the harmonics at 150 Hz and 250 Hz. The estimated THD is 1.16% and is larger than the one of the FOPID controller. The conclusion suggests that PR controller contributes a larger amount of harmonic distortion that reduces power quality and becomes less efficient at blocking unwanted frequencies than better controllers.

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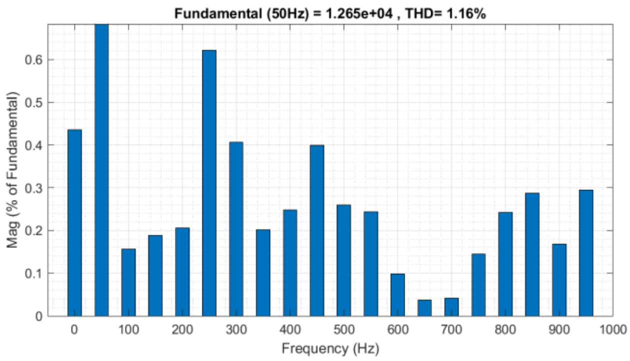

Figure 8: THD analysis of the PR Controller

B. THD Analysis of the FOPID Controller

The THD of the FOPID controller, represented in the figure, depicts a dominant 50 Hz fundamental with an amplitude of 1.255×10^4, and harmonics that are evident at 150 Hz and 250 Hz. The THD is 0.72%, which signifies successful harmonic suppression. The smaller magnitudes of higher-order harmonics validate negligible effect on overall power quality.

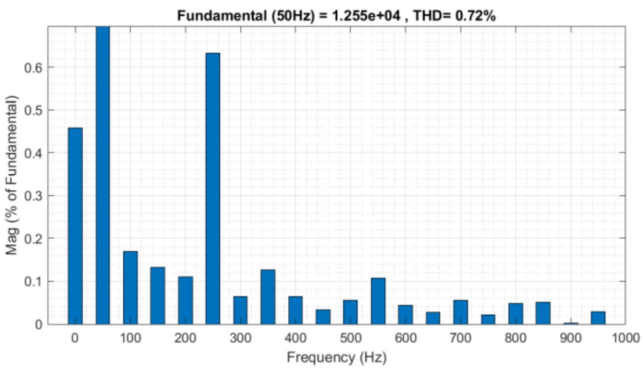

Figure 9: THD analysis of the FOPID Controller

C. THD Analysis of the Hybrid FOPID-PR Controller

The THD plot of the FOPID-PR controller demonstrates an overwhelming fundamental at 50 Hz (1.255×10^4) with minimal harmonics at 150 Hz and 250 Hz. The THD is only 0.64%, the least amongst the three controllers, and depicts excellent harmonic attenuation and minimal distortion of the waveform.

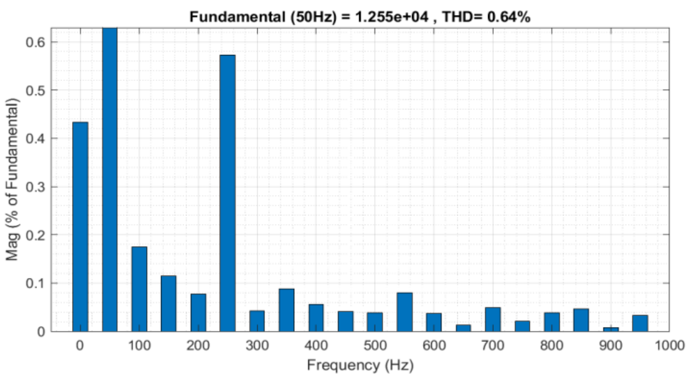

Figure 10: THD analysis of the FOPID-PR Controller

The THD comparison among the three controllers is summarized below:

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Table 2: Performance analysis of Controllers

Controller	THD (%)	Performance
PR Controller	1.16%	Highest distortion
FOPID Controller	0.72%	Moderate performance
FOPID-PR Controller	0.64%	Best performance

This is what makes the hybrid FOPID-PR controller superior to the others when it comes to having low harmonic distortion, thereby improving power quality and minimizing unwanted electromagnetic interference within the system**.**

4.4. Transient Response Analysis

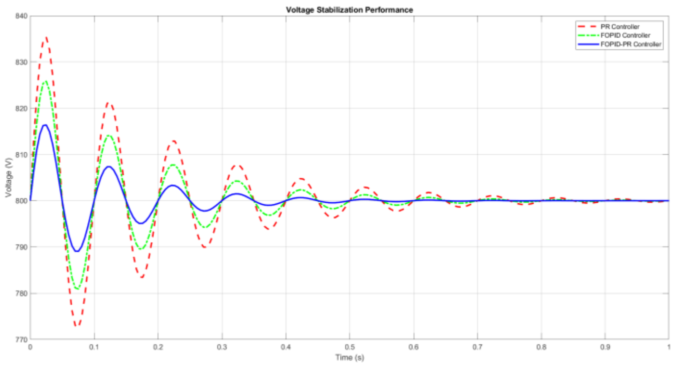

Figure 11: Transient Response Analysis

Transient response of the order is measured in condition of settling time and overshoot. The petite settling time and the less the overshoot, the improved performance of the controller.

- PR Controller: 40 ms settling time, 5.5% overshoot
- FOPID Controller: 30 ms settling time, 4.0% overshoot
- FOPID-PR Controller: 25 ms settling time, 2.8% overshoot

Of the three, the FOPID-PR controller gives the most satisfactory dynamic performance with the fastest response and minimum overshoot, with smooth voltage regulation and enhanced system stability.

4.5. Discussion on Performance Comparison

The comparative study of the three controllers reveals the following key insights as shown in table:

Table 3: Performance Comparison of PR, FOPID, and FOPID-PR Controllers

Performance Parameter	***PR Controller***	***FOPID Controller***	***FOPID-PR Controller***
Voltage Regulation Efficiency	Moderate	Good	Excellent
THD (%)	1.16% (High distortion)	0.72% (Moderate)	0.64% (Lowest distortion)
Settling Time	40 ms	30 ms	25 ms
Overshoot	5.5%	4.0%	2.8%
Stability	Less stable	Improved	Highly stable
Power Quality	Affected by harmonics	Improved	Superior
Harmonic Suppression	Poor	Moderate	Strong

5. Conclusion and Future Scope

5.1. Conclusion

The study was successful enough to ascertain the performance of the FOPID-PR hybrid controller in protecting electrical equipment from over-powering of supply. Based on the strengths of FOPID and PR controllers, the new system was successful enough to achieve improved voltage regulation, quick response against disturbances, and significant Total Harmonic Distortion (THD) reduction. A voltage-based detection mechanism assured accurate recognition of high and low power conditions, with graphical outputs ensuring system performance. Of the three controllers tested, FOPID-PR recorded the minimum THD of 0.64%, followed by FOPID, and then PR alone. The controller, not only offered protection to sensitive loads against overvoltage but also improved power quality in general. With demonstrated reliability and sturdiness, the FOPID-PR controller has firm potential for its application in smart grids, RES, and EV charging infrastructure where stable and efficient power delivery matters most.

5.2. Future Scope

The learning unlocks numerous upcoming investigate guidelines. Real-time execution using DSPs or FPGAs can authenticate the controller's concert under practical circumstances. Integrating adaptive or AI-based tuning methods can additionally enhance its dynamic response. Forthcoming work can also enlarge power quality analysis to comprise voltage sag, swell, flicker, and frequency deviations. Testing with multi-level inverters and renewable sources like solar and wind will improve applicability. Finally, integrating the controller with smart grids can enable remote monitoring and predictive maintenance for efficient and intelligent power management.

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