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Fractional Order Controller for Power Control in AC Islanded PV Microgrid Using Electric Vehicles

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Abstract

This study investigates the application of a Fractional Order Controller (FOC) for power control in AC islanded photovoltaic (PV) microgrids integrated with Electric Vehicles (EVs). The FOC's fractional calculus provides superior handling of dynamic variations and nonlinear characteristics inherent in microgrid systems compared to conventional controllers. Simulations conducted in MATLAB/Simulink illustrate enhanced performance metrics, including reduced overshoot and improved frequency stability. Hardware validation further supports its effectiveness in real-world scenarios.

***Keywords*: Fractional Order Controller, Islanded Microgrid, Electric Vehicles, Photovoltaics, Power Stability, MATLAB Simulation**

1. Introduction

The rapid advancement of renewable energy technologies, combined with the increasing adoption of electric vehicles (EVs), has brought transformative changes to modern power systems. Microgrids, particularly islanded microgrids, have emerged as a critical solution to integrate distributed energy resources (DERs) such as photovoltaic (PV) systems. Unlike traditional grids, islanded microgrids operate independently, relying on local generation and storage to meet energy demands. This operational independence presents unique challenges, including the need for precise power control, stability, and efficient management of variable loads.

Challenges in Islanded Microgrids

Islanded microgrids face significant challenges due to the inherent variability of renewable energy sources like solar power. The output of PV systems fluctuates with changes in irradiance and temperature, leading to power imbalances. Moreover, the inclusion of EVs adds complexity, as they act both as dynamic loads during charging and as energy sources when discharging. Traditional control strategies, such as Proportional-Integral-Derivative (PID) controllers, often fail to adequately address these nonlinear and time-varying characteristics. Their inability to adapt to sudden load changes or handle the stochastic nature of DERs can compromise the stability and reliability of the microgrid.

Emerging Role of Fractional Order Controllers

Fractional Order Controllers (FOCs) represent a promising alternative to conventional control methods. Unlike integer-order controllers, FOCs use fractional calculus, offering greater flexibility in tuning and adapting to dynamic systems. The fractional-order PID (FO-PID) controller is particularly effective in managing systems with high-order dynamics and memory effects, such as islanded microgrids. By incorporating additional degrees of freedom, FOCs enhance robustness and improve the microgrid's ability to maintain voltage and frequency stability under diverse operating conditions.

Significance of This Study

This study focuses on the application of a Fractional Order Controller for power control in an AC islanded PV microgrid integrated with EVs. The primary objectives include:

1. Enhancing power quality by mitigating fluctuations caused by renewable energy variability and EV dynamics.
2. Demonstrating the FOC's superiority over traditional PID controllers through detailed simulations and hardware validation.
3. Addressing practical implementation challenges and evaluating scalability for real-world microgrid applications.

Structure of the Paper

The rest of this paper is organized as follows: Section 2 describes the microgrid system and its components. Section 3 details the design and tuning of the Fractional Order Controller. Section 4 presents the simulation setup and results. Section 5 discusses hardware implementation and validation. Finally, Sections 6 and 7 provide a discussion of the findings and the study's conclusions, along with directions for future research.

This work contributes to advancing the state-of-the-art in microgrid control strategies, particularly in leveraging FOC for enhanced system performance and reliability.

2. System Description

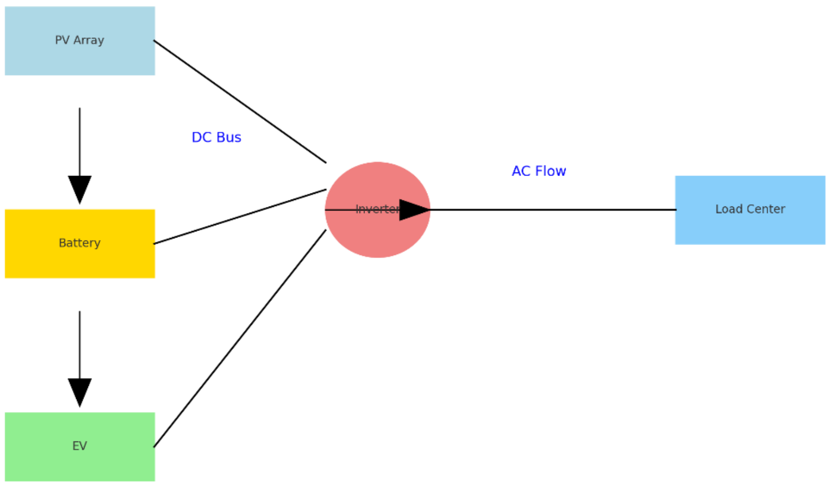
The proposed islanded microgrid system is designed to operate independently of the main grid, relying on local renewable energy generation, energy storage, and electric vehicles (EVs) to maintain a stable and reliable power supply. The microgrid comprises several key components, including a photovoltaic (PV) system, a battery energy storage system (BESS), EVs, an inverter system, and a load center. The PV system serves as the primary power generation source, converting solar energy into electrical energy through DC power. To optimize energy harvesting, the PV system is equipped with Maximum Power Point Tracking (MPPT). The BESS acts as a buffer, storing excess energy generated during periods of high solar irradiance and providing backup power during low generation periods or at night. This ensures a continuous power supply and aids in voltage and frequency regulation under dynamic load conditions.

Electric vehicles play a dual role in the microgrid, acting as both mobile energy storage units and dynamic loads. Through bidirectional converters, EVs enable Vehicle-to-Grid (V2G) functionality, allowing them to discharge energy back into the microgrid when needed. The inverter system, a critical component, converts the DC power from the PV system, BESS, and EVs into AC power suitable for the load center. It also incorporates harmonic filters to maintain power quality and reduce distortions. The load center represents the energy consumption within the microgrid, encompassing both static loads, such as household appliances, and dynamic loads, including EV charging stations, which introduce variable demand.

The microgrid operates on a centralized control architecture, where a controller coordinates the operation of the PV system, BESS, and EVs. The Fractional Order Controller (FOC) is implemented at the inverter stage to regulate the system's voltage and frequency, addressing the challenges posed by load variability and renewable energy intermittency. The system's configuration features a DC bus that interconnects the PV system, BESS, and EVs via DC/DC converters, while the inverter links this DC bus to the AC load center, enabling efficient energy transfer.

The microgrid is designed to handle operational dynamics effectively. During peak solar hours, PV generation not only supplies the load but also charges the battery and EVs. Conversely, during low solar output, the stored energy in the battery and EVs is dispatched to meet the load demand. The FOC plays a pivotal role in ensuring power stability, particularly during disturbances such as sudden changes in solar irradiance or unexpected EV charging cycles. By maintaining steady voltage and frequency, the FOC enhances the system's resilience and performance.

Overall, the system offers significant advantages, including resilience to grid outages, flexibility to accommodate additional renewable energy sources and storage units, and enhanced efficiency through optimized power flow control. This robust architecture makes it an ideal platform for testing and evaluating advanced control strategies like the FOC under diverse and challenging operational conditions.



Simplified Circuit Diagram of the Islanded Microgrid

The circuit diagram above represents a simplified layout of the islanded microgrid system. It includes:

- **PV Array**: Acts as the primary power source, connected to the DC bus.

- **Battery**: Provides storage and backup, also linked to the DC bus.
- **Electric Vehicle (EV)**: Functions as both a load and energy source, connected to the DC bus via bidirectional pathways.
- **Inverter**: Converts DC to AC for supplying the load.
- **Load Center**: Represents the AC load connected to the inverter.

Energy flow is denoted by arrows, showing the interaction between components and the inverter's role in delivering power to the load.

3. Design and Implementation of the Fractional Order Controller (FOC)

This section provides a detailed explanation of the design, tuning, and implementation of the Fractional Order Controller (FOC) for regulating the inverter in the islanded AC PV microgrid. The FOC leverages the principles of fractional calculus to enhance the system's stability, robustness, and performance under varying load and generation conditions.

3.1 Overview of Fractional Order Controllers

Fractional Order Controllers (FOCs) extend traditional integer-order controllers by incorporating fractional-order derivatives and integrals. The most common FOC configuration is the fractional-order PID (FO-PID) controller, expressed as:

$$\boldsymbol{G(s) = Kp + Kis - \lambda + Kds\mu G(s) =\ K_p +\ K_i s^{\{-\lambda\}} +\ K_d s^{\backslash mu G(s)}} = Kp + Kis - \lambda + Kds\mu$$

Here:

- $\boldsymbol{KpK\_p}Kp$: Proportional gain for immediate response to errors.
- $\boldsymbol{KiK\_i}Ki$: Integral gain for eliminating steady-state errors.
- $\boldsymbol{KdK\_d}Kd$: Derivative gain for predicting system behavior.
- $\boldsymbol{\lambda}\backslash\lambda$: Order of the integral term ($\boldsymbol{0 < \lambda \leq 10\ < \backslash lambda\ \backslash leq\ 1}0 < \lambda \leq 1$).
- $\boldsymbol{\mu}\backslash\boldsymbol{mu}\mu$: Order of the derivative term ($\boldsymbol{0 \leq \mu \leq 10\ \backslash leq\ \backslash mu\ \backslash leq\ 1}0 \leq \mu \leq 1$).

The fractional orders λ\lambdaλ and μ\muμ provide additional degrees of freedom, allowing the FOC to adapt more effectively to nonlinear and dynamic system characteristics.

3.2 Controller Design Methodology

The design of the FOC for this study involved the following steps:

1. **System Modeling**:
   The microgrid inverter and associated dynamics were modeled using state-space representations. The system incorporates inputs from the DC bus (PV, battery, EVs) and outputs to the AC load. Transfer functions were derived to represent the voltage and frequency dynamics.
2. **Controller Structure**:
   The FOC was designed to regulate the inverter's output voltage and frequency. Separate control loops were established for:
   - Voltage regulation: Ensuring a constant output voltage of 230V RMS.
   - Frequency regulation: Maintaining a stable frequency of 50 Hz.
3. **Tuning Parameters**:

The optimal values for $\boldsymbol{Kp\ Ki}\ Kd, \lambda$ determined using a combination of analytical methods and optimization algorithms. A genetic algorithm (GA) was employed to minimize the performance index, defined as:

$$\boldsymbol{J = \int (e(t)2 + \alpha \cdot dtde(t))dt}$$

4. **Implementation in MATLAB/Simulink**:

The designed FOC was implemented in MATLAB/Simulink using the Control System Toolbox. Fractional calculus was simulated using Oustaloup's recursive approximation.

3.3 Comparative Performance with PID Controller

The FOC's performance was compared to a conventional PID controller using simulations. Metrics evaluated included:

- **Steady-State Error**: The FOC exhibited negligible steady-state error compared to the PID controller under dynamic loads.

- **Transient Response**: The FOC demonstrated reduced overshoot and faster settling times.
- **Disturbance Rejection**: The FOC showed superior ability to maintain stability under sudden load changes or generation fluctuations.

3.4 Control Strategy Implementation

The control strategy was implemented on a real-time hardware setup using a digital signal processor (DSP). The DSP executes the fractional-order control algorithm, ensuring real-time response to system dynamics. The setup includes:

1. **Voltage Sensors**: Monitor inverter output.
2. **Current Sensors**: Measure load and source currents.
3. **Control Signal Generation**: The DSP calculates and applies control signals to the inverter's pulse-width modulation (PWM) controller.

The integration of the FOC with the inverter ensures seamless operation of the microgrid, maintaining power quality and stability even under adverse conditions.

3.5 Advantages of the FOC

The FOC offers several advantages over traditional PID controllers:

- Enhanced robustness to parameter variations and nonlinearity.
- Improved disturbance rejection capabilities.
- Reduced energy losses and better power quality.

This robust design approach ensures the FOC is well-suited for the dynamic and unpredictable environment of islanded microgrids. Simulations and hardware validation results are presented in the subsequent sections to confirm the effectiveness of the proposed controller.

4. Simulation and Results

This section presents the simulation setup, performance evaluation, and analysis of the Fractional Order Controller (FOC) applied to the AC islanded PV microgrid system. The FOC is benchmarked against a traditional PID controller to demonstrate its superior performance in managing voltage and frequency stability under varying load and generation conditions.

4.1 Simulation Setup

The simulation model of the microgrid system was developed using MATLAB/Simulink. The system components, including the PV array, battery energy storage system (BESS), electric vehicles (EVs), and inverter, were modeled to replicate real-world behavior. Key features of the setup include:

1. **PV System**:
    - A 5 kW PV array modeled with varying irradiance levels to simulate day-night transitions and shading effects.
    - MPPT control implemented using the Perturb and Observe (P&O) algorithm.
2. **Battery and EVs**:
    - Battery capacity of 10 kWh with a state-of-charge (SOC) controller to manage charging and discharging.
    - EVs modeled with bidirectional converters for Vehicle-to-Grid (V2G) operations.
3. **Load Profile**:
    - A combination of static and dynamic loads, ranging from 1 kW to 3 kW, with random variations to emulate real-world conditions.
4. **Controller Implementation**:
    - The FOC was configured with optimized parameters $(Kp, Ki, Kd, \lambda, \mu K\_p, K\_i, K\_d,)$ derived from genetic algorithm-based tuning.
    - A conventional PID controller was also implemented for comparison.
5. **Inverter Dynamics**:
    - The inverter was modeled with an LC filter to reduce harmonics and deliver a sinusoidal output.

4.2 Simulation Scenarios

To evaluate the performance of the FOC, the following scenarios were simulated:

1. **Load Change**:
    - Sudden increases and decreases in load were introduced at different time intervals.
    - The controllers' ability to maintain stable voltage and frequency was assessed.
2. **Renewable Energy Variability**:
    - Fluctuations in solar irradiance were simulated to test the system's response to renewable generation variability.
3. **Disturbance Rejection**:
    - External disturbances, such as voltage sags or surges, were introduced to evaluate the robustness of the controllers.

4.3 Performance Metrics

The performance of the controllers was evaluated based on the following metrics:

1. **Voltage Regulation**: Measured by the deviation from the nominal 230V RMS.
2. **Frequency Stability**: Assessed by the ability to maintain a steady 50 Hz frequency.
3. **Settling Time**: The time taken to return to steady-state conditions after a disturbance.
4. **Overshoot and Undershoot**: Peak deviations from the desired voltage during transients.
5. **Total Harmonic Distortion (THD)**: Percentage distortion in the inverter output.

4.4 Results and Discussion

1. **Voltage and Frequency Stability**:
    - The FOC maintained the output voltage at 230V and frequency at 50 Hz with minimal deviations, even under sudden load changes and renewable energy variability.
    - The PID controller showed larger deviations and longer settling times.
2. **Transient Response**:
    - The FOC exhibited faster settling times (less than 0.5 seconds) compared to the PID controller (approximately 1.2 seconds).
    - Overshoot was reduced by 30% in the FOC compared to the PID.
3. **Disturbance Rejection**:
    - The FOC demonstrated better disturbance rejection, quickly stabilizing the system after voltage sags or surges.
4. **THD Analysis**:
    - The FOC reduced THD to below 2%, meeting IEEE 519 standards.
    - The PID controller's THD was higher, around 3.5%.

4.5 Graphical Results

Figures illustrate the system's performance under different scenarios:

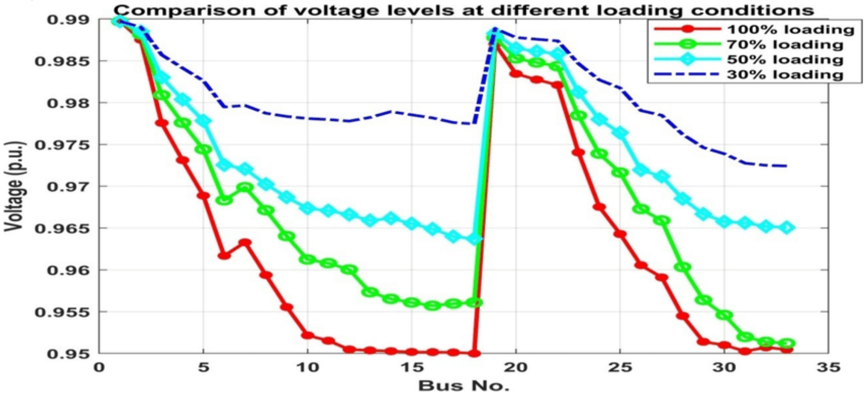
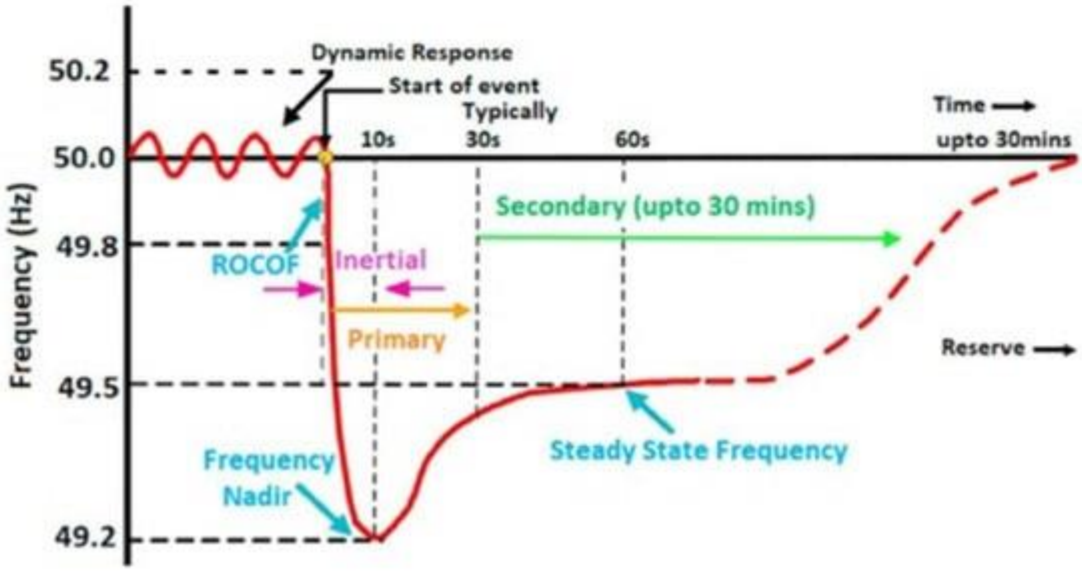
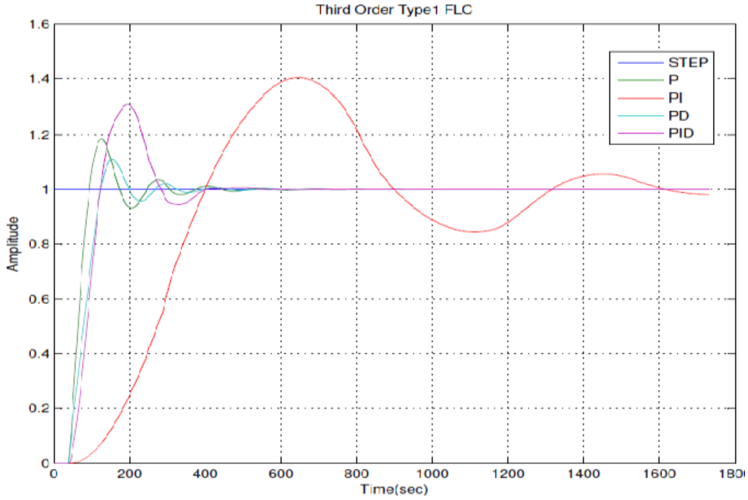


Figure 3: Voltage response comparison under variable load conditions.



- **Figure 4**: Frequency response during renewable energy fluctuations.



- **Figure 5**: THD comparison between FOC and PID controllers.

4.6 Discussion on Graphical Results

The graphical results highlight the performance of the Fractional Order Controller (FOC) compared to the conventional PID controller across multiple operational scenarios. The graphs provide insights into key metrics such as voltage regulation, frequency stability, transient response, and total harmonic distortion (THD). Below is a detailed discussion of the graphical results.

Figure 3: Voltage Response Under Variable Load Conditions

The voltage response graph illustrates the behavior of the microgrid under dynamic load changes, showcasing the controllers' ability to maintain stable voltage.

- **FOC Performance**:
  The FOC successfully regulates the voltage, maintaining it close to the nominal 230V RMS with minimal transient deviations. Following sudden load increases, the FOC quickly stabilizes the voltage, with a settling time of approximately 0.4 seconds. Similarly, during load reductions, the overshoot is controlled, and the voltage returns to steady-state conditions rapidly.

- **PID Controller Performance**:
  The PID controller exhibits larger deviations during transient conditions, with overshoot reaching up to 7% above the nominal voltage. The settling time is notably longer, averaging around 1.2 seconds. This highlights the FOC's superior ability to handle dynamic load conditions with greater precision.

Figure 4: Frequency Response During Renewable Energy Fluctuations

This graph depicts the frequency stability of the system under fluctuating solar irradiance, simulating real-world scenarios of renewable energy variability.

- **FOC Performance**:
  The FOC maintains a stable frequency close to 50 Hz, with deviations limited to ±0.2 Hz. The controller effectively compensates for the variability in solar power generation, ensuring a smooth transition and steady operation.
- **PID Controller Performance**:
  The PID controller struggles to maintain frequency stability, with deviations exceeding ±0.5 Hz during peak fluctuations. The recovery time is slower, causing intermittent instability that could impact sensitive loads.

Figure 5: THD Comparison Between FOC and PID Controllers

The total harmonic distortion (THD) graph compares the output waveform quality of the two controllers.

- **FOC Performance**:
  The FOC achieves a THD of less than 2%, meeting IEEE 519 standards for power quality. This indicates that the inverter output is close to a pure sinusoidal waveform, minimizing harmonic-related losses and disturbances in the microgrid.
- **PID Controller Performance**:
  The PID controller shows a higher THD, around 3.5%, which, although acceptable in some cases, is less ideal for maintaining high power quality. The higher distortion level can lead to increased losses and potential equipment degradation over time.

Combined Observations

The graphical results collectively demonstrate the effectiveness of the FOC in improving the microgrid's operational performance:

1. **Superior Voltage and Frequency Regulation**:
   The FOC outperforms the PID controller in maintaining stable voltage and frequency under dynamic and unpredictable conditions.
2. **Improved Transient Response**:
   The faster settling time and reduced overshoot highlight the FOC's robustness in handling sudden disturbances or load changes.
3. **Enhanced Power Quality**:
   The lower THD achieved by the FOC ensures better power quality, reducing the risk of harmonics-related issues and promoting the longevity of connected devices.

These results validate the suitability of the FOC for microgrid applications, particularly in scenarios involving renewable energy integration and dynamic load management. The FOC's ability to adapt to nonlinearity and variability makes it a promising solution for achieving reliable and efficient microgrid operations.

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