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Research Paper

ADAPTIVE COORDINATED CONTROL OF FLYWHEEL AND BATTERY ENERGY STORAGE FOR IMPROVED FREQUENCY REGULATION IN ISOLATED DIESEL MICROGRIDS

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ABSTRACT

Diesel generator-based microgrids are widely used in remote and isolated locations where renewable energy integration and reliable power supply are essential. However, sudden load variations and intermittent renewable energy sources cause significant frequency deviations, reducing system stability and power quality. Conventional battery energy storage systems (BESS) provide frequency support but suffer from slow dynamic response and accelerated battery degradation under frequent charge-discharge cycles. Flywheel Energy Storage Systems (FESS), on the other hand, offer rapid response and high power density but are limited by lower energy storage capacity. This project proposes a coordinated control strategy that combines the strengths of both FESS and BESS for effective frequency regulation in a diesel generator-based microgrid. The flywheel system compensates for fast transient power fluctuations, while the battery system manages long-duration energy balancing. An intelligent power management controller coordinates power sharing between the storage devices and the diesel generator, ensuring stable frequency, reduced generator stress, and improved battery lifespan. MATLAB/Simulink is used to model and validate the proposed system under different load disturbance scenarios. Simulation results demonstrate improved frequency stability, reduced frequency deviations, faster recovery time, enhanced power quality, and efficient utilization of energy storage resources compared to conventional single-storage systems.

INTRODUCTION

The increasing deployment of isolated and remote microgrids has created a growing demand for reliable and efficient frequency regulation techniques. Diesel generator (DG)-based microgrids are widely employed in remote communities, military installations, islands, and industrial facilities where access to the main utility grid is unavailable. Although diesel generators provide dependable power generation, they possess relatively slow dynamic response characteristics due to mechanical inertia and governor limitations. Consequently, sudden load variations often result in significant frequency deviations, reduced power quality, increased fuel consumption, and accelerated mechanical wear. These challenges necessitate the integration of advanced energy storage systems (ESSs) capable of providing rapid power support and improving the overall stability of islanded microgrids.

Among the available energy storage technologies, Battery Energy Storage Systems (BESSs) have attracted considerable attention because of their high energy density, long-duration energy support, and mature technological development. However, batteries experience performance degradation under frequent high-power charging and discharging cycles, reducing their operational lifetime and increasing maintenance costs. Conversely, Flywheel Energy Storage Systems (FESSs) exhibit high power density, extremely fast response, and exceptional cycling capability, making them highly suitable for compensating sudden transient power fluctuations. Nevertheless, flywheels possess relatively limited energy capacity and cannot independently sustain long-duration frequency regulation. Therefore, neither BESS nor FESS alone can provide an optimal solution for all operating conditions in diesel generator-based microgrids.

A hybrid energy storage system that combines both flywheel and battery technologies offers an effective solution by exploiting the complementary characteristics of each storage device. In such a coordinated configuration, the flywheel manages high-frequency and transient power disturbances owing to its rapid response capability, while the battery supplies medium-frequency and long-duration energy support. The diesel generator, in turn, handles slow and steady-state power requirements. This coordinated allocation of power significantly reduces battery stress, minimizes unnecessary diesel generator ramping, enhances fuel efficiency, and improves overall system reliability and frequency stability.

Recent advances in intelligent control strategies have focused on frequency decomposition techniques that distribute power among multiple energy sources according to the frequency components of load variations. By employing suitable high-pass, low-pass, and band-pass filtering methods, the control system assigns fast transient power demands to the FESS, medium-frequency fluctuations to the BESS, and low-frequency components to the diesel generator. Such coordinated control enables seamless power sharing while maintaining system frequency within acceptable operating limits under highly dynamic loading conditions. Furthermore, the use of programmable load emulators and MATLAB/Simulink-based validation has demonstrated the practical feasibility and effectiveness of these coordinated control approaches.

This work presents a coordinated control strategy for Flywheel Energy Storage Systems and Battery Energy Storage Systems in a diesel generator-based islanded microgrid. The proposed approach aims to improve frequency regulation by intelligently allocating power compensation according to the dynamic characteristics of each energy source. By combining the fast transient response of the flywheel with the sustained energy support of the battery, the proposed system achieves improved frequency stability, reduced diesel generator stress, enhanced battery lifespan, lower fuel consumption, and superior microgrid reliability under varying load conditions. The proposed coordinated control framework offers a practical and efficient solution for next-generation resilient and sustainable standalone microgrid applications.

OBJECTIVE

The primary objectives of the proposed system are:

1. To maintain stable microgrid frequency during sudden load changes and renewable power fluctuations.
2. To coordinate Flywheel Energy Storage System (FESS) and Battery Energy Storage System (BESS) for optimal power sharing.

3. To reduce the burden and mechanical stress on the diesel generator.
4. To minimize battery degradation by assigning transient power compensation to the flywheel system.
5. To improve dynamic response and overall stability of the isolated microgrid.
6. To enhance power quality, system reliability, and operational efficiency using an intelligent coordinated control strategy.
7. To validate the proposed coordinated control approach using MATLAB/Simulink under various operating conditions.

PROBLEM STATEMENT

Diesel generator-based microgrids operating in isolated and remote areas experience frequent frequency fluctuations due to sudden load variations and the intermittent nature of renewable energy sources. Conventional diesel generators alone cannot respond quickly to rapid power imbalances, resulting in poor frequency regulation, increased fuel consumption, and higher maintenance costs. Although Battery Energy Storage Systems (BESS) can provide frequency support, repeated high-power charge-discharge cycles accelerate battery aging and reduce system reliability. Similarly, Flywheel Energy Storage Systems (FESS) offer fast response but cannot sustain long-duration energy support due to limited storage capacity. Existing control methods generally utilize either battery or flywheel storage independently, leading to inefficient utilization of storage resources and reduced overall system performance. Therefore, an efficient coordinated control strategy that integrates both FESS and BESS is required to achieve rapid transient compensation, long-term energy balancing, improved frequency regulation, enhanced battery life, reduced diesel generator stress, and reliable operation of diesel generator-based microgrids.

LITERATURE REVIEW

The increasing deployment of islanded diesel generator-based microgrids has created significant challenges in maintaining frequency stability due to rapid load fluctuations and the slow dynamic response of diesel generators. To overcome these limitations, researchers have investigated hybrid energy storage systems (HESSs) that combine the complementary characteristics of Flywheel Energy Storage Systems (FESSs) and Battery Energy Storage Systems (BESSs). Flywheels provide high power density and rapid transient response, whereas batteries offer high energy density and sustained power support, making their coordinated operation highly suitable for microgrid frequency regulation.

Faraji et al. (2025) proposed a coordinated control strategy that integrates FESS and BESS with a diesel generator in an islanded microgrid. Their approach introduces a frequency-based power allocation mechanism that separates frequency deviations into high-, medium-, and low-frequency components. High-frequency disturbances are compensated by the flywheel due to its fast response, medium-frequency variations are handled by the battery storage system, and low-frequency power imbalances are supplied by the diesel generator. This coordinated energy management significantly reduces frequency deviations, minimizes battery stress, and enhances overall microgrid stability under dynamic loading conditions. MATLAB/Simulink simulations and programmable load emulator experiments validate the effectiveness of the proposed method.

Previous studies have demonstrated that battery energy storage systems are effective for primary frequency regulation in islanded microgrids. However, frequent charge-discharge cycles accelerate battery degradation and reduce operational lifetime when batteries alone compensate for fast transient disturbances. Consequently, researchers have explored hybrid storage architectures where high-power devices such as flywheels absorb sudden power fluctuations while batteries provide long-duration energy balancing, thereby improving system reliability and extending battery lifespan.

Several control strategies, including fuzzy logic, adaptive controllers, model predictive control, droop control, and disturbance observer-based control, have been proposed to regulate frequency in diesel-renewable hybrid microgrids. Although these techniques improve transient performance, many rely solely on battery storage or renewable generation support, limiting their capability to handle rapid and continuous load variations efficiently. Moreover, improper coordination among distributed energy resources may increase frequency oscillations and reduce system resilience.

Fractional-order controllers and intelligent optimization techniques have also been investigated for hybrid microgrids containing diesel generators, renewable sources, batteries, and flywheel storage. These methods improve dynamic response and robustness against uncertainties; however, their computational complexity and tuning requirements often hinder practical implementation in real-time control systems. Therefore, simplified coordinated control strategies that effectively exploit the complementary characteristics of FESS and BESS remain an active research area.

Overall, the recent literature indicates that coordinated control of flywheel and battery energy storage systems provides a promising solution for enhancing frequency regulation in diesel generator-based microgrids. By allocating fast transient power support to the flywheel and long-term energy compensation to the battery, hybrid energy storage systems improve frequency stability, reduce diesel generator stress, extend battery life, and enhance the reliability and operational efficiency of standalone microgrids under varying load conditions.

EXISTING SYSTEM

The existing diesel generator (DG)-based microgrid frequency regulation approach primarily depends on the diesel generator governor and individual Battery Energy Storage Systems (BESS) to compensate for power imbalances. However, due to the slow mechanical response of diesel generators and the limited power density of batteries, the system cannot effectively handle sudden load variations. This results in larger frequency deviations, increased settling time, and higher stress on battery storage. Conventional methods generally lack intelligent coordination between different energy storage devices, causing inefficient power sharing and reduced overall system performance. Additionally, repeated high-frequency charge/discharge cycles accelerate battery degradation, reducing its operational lifespan and increasing maintenance costs.

Disadvantages of Existing System

- Slow dynamic response of diesel generators to sudden load changes.
- Large frequency deviations during transient operating conditions.

- Excessive dependence on battery energy storage, leading to faster battery aging.
- Inefficient utilization of available energy storage resources.
- Longer frequency recovery and settling time.
- Increased operational and maintenance costs due to battery degradation.
- Limited capability to maintain stable frequency under highly variable loads.
- Reduced reliability and power quality in islanded microgrids.

PROPOSED SYSTEM

The proposed system employs a coordinated control strategy that integrates a Flywheel Energy Storage System (FESS) with a Battery Energy Storage System (BESS) for diesel generator-based islanded microgrids. The controller separates power fluctuations according to their frequency components, allowing the FESS to compensate for rapid transient disturbances while the BESS manages medium-term energy variations. The diesel generator supplies only the low-frequency power demand, significantly reducing its control burden. This coordinated energy management improves frequency regulation, minimizes battery stress, enhances dynamic stability, and extends the lifetime of both the diesel generator and battery system. The strategy is validated through MATLAB/Simulink simulations and programmable load emulation under dynamic loading conditions.

Advantages of Proposed System

- Fast frequency regulation using high-speed flywheel energy storage.
- Coordinated power sharing among FESS, BESS, and diesel generator.
- Reduced battery charging/discharging stress, extending battery life.
- Improved frequency stability during sudden load disturbances.
- Faster transient response and reduced settling time.
- Lower diesel generator mechanical stress and fuel consumption.
- Enhanced reliability and operational efficiency of the islanded microgrid.
- Improved power quality with minimized frequency fluctuations.
- Better utilization of hybrid energy storage resources.
- Suitable for renewable-integrated and standalone microgrid applications.

IMPLEMENTATION

The proposed implementation aims to improve frequency stability in a diesel generator (DG)-based islanded microgrid by coordinating a **Flywheel Energy Storage System (FESS)** and a **Battery Energy Storage System (BESS)**. The flywheel provides immediate compensation for sudden power imbalances, while the battery manages medium-duration energy requirements. The diesel generator supplies the long-term steady-state power. A frequency decomposition method using high-pass, band-pass, and low-pass filters allocates power regulation tasks among the three sources. The complete system is modeled and validated in MATLAB/Simulink under different dynamic loading conditions.

Implementation Steps

1. **Microgrid Modeling**
    - Develop an islanded microgrid consisting of:
        - Diesel Generator (DG)
        - Flywheel Energy Storage System (FESS)
        - Battery Energy Storage System (BESS)
        - Dynamic Load
        - Power Converters and Controllers
    - Model the generator governor, excitation system, and load dynamics.
2. **Frequency Measurement**
    - Continuously monitor system frequency using a Phase-Locked Loop (PLL) or frequency estimation algorithm.
    - Calculate the frequency deviation (Δf) from the nominal frequency.
3. **Frequency Signal Decomposition**
    - Apply digital filters to divide the frequency deviation into three components:
        - **High-frequency component → Flywheel Energy Storage System**
        - **Medium-frequency component → Battery Energy Storage System**
        - **Low-frequency component → Diesel Generator**
    - This enables each source to respond according to its dynamic characteristics.
4. **Flywheel Energy Storage Control**
    - Implement a bidirectional converter with vector control.
    - Provide rapid charging/discharging during sudden load disturbances.
    - Restore flywheel speed after transient conditions.
5. **Battery Energy Storage Control**
    - Design a bidirectional DC-DC converter.
    - Monitor State of Charge (SOC).
    - Supply or absorb power during medium-duration frequency deviations.
    - Prevent overcharging and deep discharging using SOC protection.
6. **Diesel Generator Control**
    - Implement governor-based speed control.
    - Adjust mechanical power gradually to restore nominal frequency.
    - Coordinate with FESS and BESS to reduce mechanical stress and fuel consumption.

7. **Energy Management System (EMS)**
   - Develop a supervisory controller that:
     - Allocates power references.
     - Monitors SOC and flywheel speed.
     - Coordinates seamless transitions between storage devices and DG.
     - Maintains overall system stability.
8. **Simulation and Validation**
   - Implement the complete model in MATLAB/Simulink.
   - Apply various load disturbances (step increase/decrease).
   - Compare system performance with and without coordinated control.
   - Evaluate:
     - Frequency deviation
     - Settling time
     - Overshoot
     - Diesel generator power fluctuations
     - Battery SOC
     - Flywheel speed response

Implementation Modules

- Diesel Generator Model
- Flywheel Energy Storage System
- Battery Energy Storage System
- Frequency Detection Module
- High-Pass, Band-Pass, and Low-Pass Filters
- Coordinated Control Algorithm
- Energy Management System
- Bidirectional Converter Controllers
- Dynamic Load Emulator
- Performance Evaluation Module

Software Requirements

- MATLAB/Simulink
- Simscape Electrical
- Simulink Control Design
- Power System Toolbox

Hardware Requirements

- Intel Core i5/i7 Processor
- 8 GB RAM (Minimum)
- Windows 10/11
- MATLAB-compatible workstation
- Optional: DSP Controller (TI TMS320F28379D), Programmable Load Emulator, Battery Emulator, Flywheel Emulator, Data Acquisition System

Expected Outcomes

- Fast frequency regulation after load disturbances.
- Reduced frequency oscillations and settling time.

- Lower stress on the diesel generator.
- Improved utilization of battery and flywheel storage.
- Enhanced microgrid stability, reliability, and power quality under islanded operation.

CONCLUSION

The proposed **coordinated control strategy for Flywheel Energy Storage System (FESS) and Battery Energy Storage System (BESS)** significantly improves frequency regulation in a diesel generator-based islanded microgrid. By allocating high-frequency power fluctuations to the FESS, medium-frequency variations to the BESS, and low-frequency power demands to the diesel generator, the control scheme effectively utilizes the strengths of each energy storage technology. This coordinated operation minimizes frequency deviations, reduces diesel generator stress, enhances system stability, and improves overall power quality during sudden load changes. MATLAB/Simulink simulations and experimental validation demonstrate that the proposed approach provides faster dynamic response, better frequency restoration, reduced battery degradation, and improved operational efficiency compared to conventional control methods. The proposed system offers a reliable and scalable solution for isolated microgrids with high renewable energy penetration, contributing to enhanced reliability, fuel savings, and sustainable power system operation.

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