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Development of the Structure and Operating Algorithm of a Micro Hydropower Plant with a Battery-Based Ballast Load

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Abstract. Micro hydropower plants (micro-HPPs) play a significant role in providing reliable and sustainable electricity to remote and rural areas. However, one of the main challenges in micro-HPP operation is maintaining stable voltage and frequency under variable load conditions. Traditional ballast load controllers dissipate excess energy as heat, leading to efficiency losses. This paper proposes an improved structural configuration and operating algorithm for a micro hydropower plant with a battery-based ballast load. The proposed system combines an electronic load controller with a battery energy storage system to absorb surplus power, enhance energy utilization, and stabilize operating parameters. The developed control algorithm ensures frequency regulation, optimal battery charging and discharging, and reliable operation of the asynchronous generator. Simulation-based analysis demonstrates that the proposed approach significantly improves overall system efficiency, power quality, and operational flexibility.
Keywords: micro hydropower plant, ballast load, battery energy storage, electronic load controller, frequency regulation.

Introduction. Micro hydropower plants are among the most promising renewable energy sources for decentralized power supply, particularly in mountainous and rural regions with small rivers or irrigation canals. Their advantages include high reliability, long service life, and minimal environmental impact. Despite these benefits, micro-HPPs often operate under fluctuating consumer loads, which directly affects generator speed, output frequency, and voltage stability.

In conventional micro-HPP systems, excess generated power is dissipated through resistive ballast loads controlled by an electronic load controller (ELC). Although this method provides effective frequency regulation, it results in energy losses and reduced overall efficiency. With the increasing demand for energy efficiency and flexibility, integrating energy storage systems into micro-HPPs has become an important research direction.

This study focuses on the development of a micro-HPP structure incorporating a battery-based ballast load and the design of an operating algorithm that ensures stable operation, efficient energy utilization, and improved power quality.

The proposed micro-HPP structure consists of the following main components:

- Hydraulic turbine
- Asynchronous generator
- Electronic Load Controller (ELC)
- Battery Energy Storage System (BESS)
- Bidirectional DC–DC converter
- Inverter and local AC load

The asynchronous generator converts mechanical energy from the turbine into electrical energy. The ELC continuously monitors generator frequency and voltage. When consumer load decreases and surplus power appears, instead of fully dissipating this energy in a resistive ballast, the controller redirects a portion of the excess power to the battery system.

The battery energy storage system acts as an active ballast load, absorbing surplus energy during low load periods and supplying energy back to the system during peak demand or transient disturbances. This hybrid approach significantly reduces thermal losses and increases the utilization of renewable energy.

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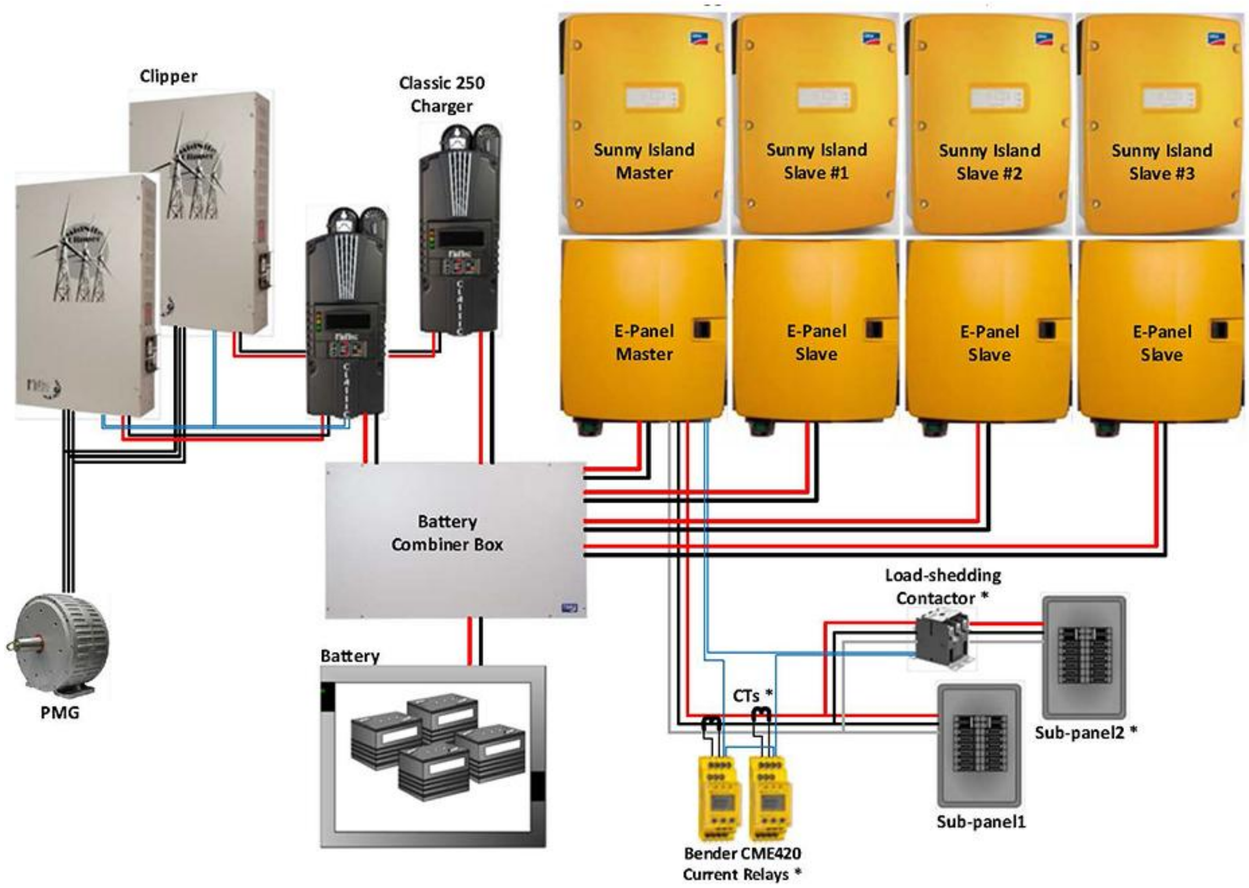

Fig. 1. Structural Diagram of a Micro Hydropower Plant with Battery-Based Ballast Load and Inverter System

Operating Algorithm of the Proposed System

The operating algorithm of the micro-HPP with a battery-based ballast load includes the following stages:

1. **Monitoring Stage**. The controller continuously measures generator frequency, voltage, load power, and battery state of charge (SOC).
2. **Normal Operation Mode**. When generated power matches consumer demand, the battery remains in standby mode, and the system operates similarly to a conventional micro-HPP.
3. **Surplus Power Mode**. If generated power exceeds load demand, the controller prioritizes battery charging. The charging current is regulated based on SOC limits and frequency deviation.
4. **Frequency Stabilization Mode**. If battery charging capacity is insufficient or the battery reaches maximum SOC, excess power is partially diverted to a resistive ballast load to maintain frequency stability.
5. **Deficit Power Mode**. During sudden load increase or transient disturbances, the battery discharges to support the generator, reducing frequency deviations and improving dynamic response.

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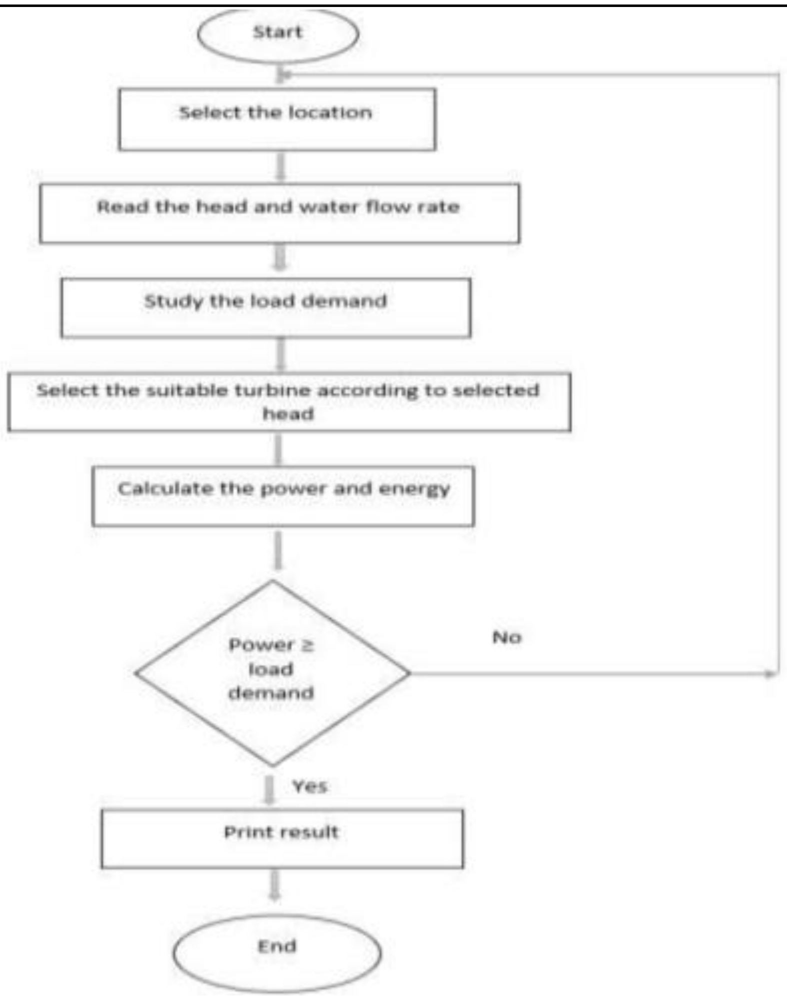

Fig.2. Advanced Operating Algorithm Block Diagram

This algorithm ensures smooth transitions between operating modes and prevents overcharging or deep discharging of the battery.

Results and Discussion

Simulation results show that the proposed system maintains frequency deviations within ±1% under rapid load changes, compared to ±4–5% in conventional ballast-only systems. Battery integration reduces energy losses in the ballast load by up to 60%, leading to higher overall efficiency.

Additionally, the system demonstrates improved voltage stability and enhanced reliability during short-term load fluctuations. The use of battery-based ballast control also enables partial energy storage for later use, which is particularly beneficial for isolated microgrids.

Conclusion

This paper presented the development of a structural configuration and operating algorithm for a micro hydropower plant with a battery-based ballast load. The proposed approach combines conventional electronic load control with battery energy storage to improve frequency regulation, energy efficiency, and operational flexibility. The results confirm that integrating batteries as an active ballast load is an effective solution for modern micro-HPP systems, especially in off-grid and rural applications. Future research will focus on experimental validation and optimization of battery sizing and control parameters.

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