Operational Analysis and Intelligent Supervisory Control of a Hybrid Renewable Energy System with Hydrogen Energy Storage

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Abstract

Hybrid renewable energy systems (HRES) integrating multiple renewable energy sources together with advanced energy storage technologies are becoming increasingly important for ensuring reliable, flexible, and sustainable energy supply under variable operating conditions. This study investigates the operational behavior of an HRES combining photovoltaic, wind, and biomass generation with lithium-ion batteries, electrolyzers, hydrogen storage, and fuel cells. The proposed system architecture enables coordinated short-term and long-term energy balancing by combining fast-response battery storage with hydrogen-based energy storage for utilization of surplus renewable energy and reserve electricity generation during deficit periods. Renewable generation and electricity demand forecasting were performed using a bidirectional Long Short-Term Memory (Bi-LSTM) neural network model trained on time-series operational data. The developed supervisory control framework dynamically coordinates battery charging/discharging, electrolyzer operation, hydrogen storage utilization, and fuel cell activation according to changing renewable generation and load demand conditions. The results demonstrate that the integrated HRES configuration effectively improves energy balancing, reduces renewable energy curtailment, and enhances system operational stability under stochastic renewable generation conditions. The proposed framework enables efficient utilization of renewable energy resources while supporting low-emission and flexible operation of modern distributed energy systems. The study confirms the potential of intelligent predictive control approaches for improving the operational performance and reliability of complex hybrid renewable energy systems integrating hydrogen-based energy storage technologies.

Keywords

Hybrid renewable energy systems, HRES operation, hydrogen energy storage, electrolyzer, fuel cell, renewable energy integration, intelligent energy management, Bi-LSTM forecasting.

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