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AI-Driven Hybrid Supercapacitor–Battery Energy Storage with V2G for Fast Frequency Regulation in Smart Grids — A Review

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ABSTRACT

The rapid integration of renewable energy sources such as solar and wind into modern power systems has introduced significant challenges related to grid stability, especially frequency regulation. Due to their intermittent and unpredictable nature, maintaining a balance between generation and load has become increasingly complex. Hybrid Energy Storage Systems (HESS), which combine batteries and supercapacitors, provide an effective solution by leveraging the high energy density of batteries and the high power density of supercapacitors.Vehicle-to-Grid (V2G) technology further enhances system flexibility by allowing electric vehicles (EVs) to act as distributed energy resources, capable of supplying power back to the grid when required. Additionally, Artificial Intelligence (AI) techniques such as machine learning and reinforcement learning improve system performance through intelligent forecasting, optimization, and adaptive control strategies.This paper presents a comprehensive review of AI-driven hybrid supercapacitor–battery energy storage systems integrated with V2G for fast frequency regulation in smart grids. The study covers system architecture, control strategies, performance metrics, challenges, and future research directions.

Keywords:- Hybrid Energy Storage System (HESS), Supercapacitor, Battery, Vehicle-to-Grid (V2G), Artificial Intelligence, Smart Grid, Fast Frequency Regulation, Reinforcement Learning

1. INTRODUCTION

The transition from conventional fossil fuel-based power systems to renewable energy-based smart grids has significantly transformed the operation and management of electrical networks. Renewable energy sources, particularly solar and wind, are inherently variable and uncertain, leading to frequent fluctuations in power generation. These fluctuations directly affect grid frequency, making frequency regulation a critical issue. Traditionally, synchronous generators provided inertia and frequency support. However, with their reduced presence in modern grids, alternative solutions are required. Energy storage systems have emerged as key technologies to ensure grid stability. Batteries, such as lithium-ion batteries, offer high energy density but are not well-suited for handling rapid power fluctuations due to degradation issues. On the other hand, supercapacitors provide excellent power density and fast response but have limited energy storage capacity. Hybrid Energy Storage Systems (HESS) combine these two technologies to achieve optimal performance

2.SYSTEM ARCHITECTURE OF HYBRID ENERGY STORAGE SYSTEM (HESS)

The system architecture of a Hybrid Energy Storage System (HESS) plays a crucial role in determining its performance, efficiency, and control capability. HESS integrates batteries and supercapacitors through power electronic interfaces to ensure optimal energy management and fast dynamic response. Based on the configuration and control strategy, HESS architectures are broadly classified into three main types: passive, active, and semi-active topologies.

2.1. Passive Topology

Passive topology is the simplest configuration of HESS, where the battery and supercapacitor are directly connected in parallel without the use of any intermediate power electronic converters.

- **Working Principle:-** In this configuration, power sharing between the battery and supercapacitor occurs naturally based on their internal characteristics such as impedance and voltage levels.
- **Advantages:** Simple design and low cost ,High reliability due to fewer components ,No need for complex control systems
- **Limitations:** Lack of precise control over power distribution ,Inefficient utilization of storage components, Possible overloading or underutilization of battery/supercapacitor .Due to limited controllability, passive topology is generally used in low-cost and less critical applications.

2.2 Active Topology

Active topology is the most advanced and widely used configuration in HESS. In this architecture, both the battery and supercapacitor are connected to the DC bus through dedicated DC-DC converters.

- **Working Principle:**

Power electronic converters regulate the flow of energy between the battery, supercapacitor, and the grid/load. A control system determines how much power each component should supply or absorb.

- **Advantages:** Precise control of power sharing ,Improved efficiency and performance ,Better protection of battery from high current stress ,Enhanced flexibility in operation
- **Limitations:** Higher cost due to converters ,Increased system complexity ,Requires advanced control algorithms .Active topology is ideal for applications requiring **fast frequency regulation**, such as smart grids and electric vehicles.

2.3 Semi-Active

Topology-Semi-active topology is a compromise between passive and active configurations. In this system, typically one energy storage device (usually the supercapacitor) is connected through a DC-DC converter, while the other (battery) is directly connected to the DC bus**.**

- **Working Principle:**

The converter controls the power flow of one storage element, while the other operates passively.

- **Advantages:** - Moderate cost compared to active topology ,Improved control compared to passive systems ,Reduced complexity
- **Limitations:** - Limited control compared to fully active topology ,Slightly lower performance than active systems This topology provides a **balanced solution** in terms of cost, control, and performance.

3. ROLE OF ARTIFICIAL INTELLIGENCE

Artificial Intelligence (AI) plays a vital role in enhancing the performance, reliability, and efficiency of Hybrid Energy Storage Systems (HESS) integrated with Vehicle-to-Grid (V2G) technology. Due to the stochastic nature of renewable energy sources and dynamic load variations, conventional control methods are often insufficient. AI-based approaches enable intelligent decision-making, real-time optimization, and adaptive control, making them highly suitable for modern smart grid applications. AI techniques help in forecasting, control, optimization, and energy management, thereby ensuring effective utilization of both batteries and supercapacitors while maintaining grid stability.

3.1 AI-Based Forecasting-

Accurate forecasting is essential for maintaining the balance between power generation and consumption in smart grids. AI-based forecasting techniques analyze historical and real-time data to predict future trends.

a) Load Demand Forecasting-

AI models such as Artificial Neural Networks (ANN) and Deep Learning algorithms are widely used to predict electricity demand. These models consider various parameters such as Historical load data Weather conditions Time of day and seasonal variations .Accurate load forecasting helps in scheduling energy storage systems efficiently and reducing frequency deviations.

b) Renewable Energy Generation Forecasting –

Renewable sources like solar and wind are highly variable. AI techniques improve prediction accuracy by analyzing environmental data: Solar irradiance ,Wind speed and direction ,Temperature and humidity .Deep Learning models, such as Convolutional Neural Networks (CNN) and Long Short-Term Memory (LSTM) networks, are particularly effective for time-series forecasting.

c) Importance of Forecasting-

The Main important points to be noted are Reduces uncertainty in grid operation , Enhances scheduling of HESS and V2G systems ,Improves overall system reliability

3.2 AI-Based Control Strategies

AI-based control strategies enable dynamic and adaptive operation of HESS and V2G systems, ensuring optimal power sharing and fast response to grid disturbances.

a) Reinforcement Learning (RL)

Reinforcement Learning is a powerful AI technique where an agent learns optimal actions through interaction with the environment, Used for real-time energy management ,Adapts to changing grid conditions ,Optimizes charging and discharging cycles RL-based controllers can minimize frequency deviation while extending battery life.

b) Fuzzy Logic Controllers (FLC)

Fuzzy logic controllers handle uncertainty and nonlinear behavior effectively,Uses linguistic rules instead of mathematical models ,Suitable for power sharing between battery and supercapacitor ,Provides smooth and stable control .FLC is particularly useful in systems where precise mathematical modeling is difficult.

c) Genetic Algorithms (GA)

Genetic Algorithms are optimization techniques inspired by natural selection.,used for parameter tuning and optimization ,Helps in minimizing energy losses ,Improves efficiency of HESS operation ,GA can optimize controller parameters and system configurations for better performance.

d) Hybrid AI Techniques

In advanced systems, multiple AI techniques are combined to improve performance:

- ANN + Fuzzy Logic (Neuro-Fuzzy Systems)
- RL + Deep Learning (Deep Reinforcement Learning)

These hybrid approaches provide higher accuracy and adaptability.

3.3 Benefits of AI Integration

The integration of AI into HESS and V2G systems offers several significant advantages:

a) **Real-Time Optimization**-
AI enables continuous monitoring and adjustment of system parameters, ensuring optimal performance under varying conditions.

b) **Reduced Operational Cost-**
Efficient energy management reduces energy wastage, maintenance costs, and battery replacement frequency.

c) **Improved Grid Stability-**
AI ensures rapid response to frequency deviations, thereby maintaining grid stability and reliability.

d) **Intelligent Energy Management-**
AI facilitates smart decision-making for: Charging and discharging cycles ,Power sharing between storage devices ,Integration of renewable energy sources .

e) **Extended Battery Life-**
By minimizing unnecessary charge-discharge cycles and avoiding high current stress, AI helps in prolonging battery lifespan.

4. VEHICLE-TO-GRID (V2G) INTEGRATION

Vehicle-to-Grid (V2G) technology is an advanced concept in smart grid systems where electric vehicles (EVs) are not only consumers of electricity but also act as distributed energy storage units. Through bidirectional power flow, EVs can supply energy back to the grid during peak demand periods and store energy during low demand periods. This capability makes V2G a crucial component in modern energy management systems, especially when integrated with Hybrid Energy Storage Systems (HESS).

4.1 Concept of V2G

V2G enables communication and power exchange between electric vehicles and the power grid. Unlike traditional unidirectional charging, V2G systems allow:Charging Mode (Grid → Vehicle) during off-peak hours , Discharging Mode (Vehicle → Grid) during peak demand .Electric vehicles are connected to the grid via smart chargers equipped with bidirectional converters and communication interfaces.

4.2 Working Principle of V2G System

The working of a V2G system involves the following steps:

1. **Grid Monitoring:-** The system continuously monitors grid conditions such as frequency, load demand, and generation levels.
2. **Decision Making (AI-based):-** AI algorithms determine whether EVs should charge or discharge based on real-time data.
3. **Energy Flow Control:** - During excess generation → EVs are charged ,During high demand → EVs supply energy back to the grid
4. **Communication System:-** Smart communication protocols ensure coordination between EVs, charging stations, and grid operators.

4.3 Components of V2G System

A typical V2G system consists of:- Electric Vehicles (EVs): Act as mobile energy storage units ,Bidirectional Chargers: Enable power flow in both directions ,Power Electronic Converters: Control voltage and current ,Communication Network: Ensures data exchange ,Control System (AI-based): Optimizes charging/discharging decisions

4.4 Benefits of V2G Integration

a) Frequency Regulation-

V2G provides fast response to frequency deviations by injecting or absorbing power, helping maintain grid stability.

b) Peak Load Management-

EVs supply power during peak demand, reducing stress on the grid and avoiding blackouts.

c) Renewable Energy Support-

Excess renewable energy can be stored in EV batteries and used later when generation is low.

d) Economic Benefits-

Reduced electricity cost for users, Revenue generation for EV owners, Lower infrastructure investment for utilities

e) Distributed Energy Resource (DER)-

V2G transforms EV fleets into decentralized energy sources, enhancing grid resilience.

4.5 Role of AI in V2G Integration

Artificial Intelligence enhances V2G performance through:-**Smart Scheduling:** Determines optimal charging/discharging time ,User Behavior Prediction: Ensures EV availability when needed ,Battery Health Management: Prevents excessive degradation ,Grid Optimization: Maintains balance between supply and demand .

5. PERFORMANCE EVALUATION METRICS

Key performance indicators include frequency nadir, settling time, battery degradation rate, energy efficiency, and economic benefits. Simulation studies commonly use IEEE test bus systems for validation.

5.1 Challenges and Research Gaps

Major challenges include accurate state estimation, cybersecurity risks, and scalability of AI models, interoperability standards, and regulatory policies for V2G participation.

5.2 Future Research Directions

Future research should focus on distributed multi-agent control, explainable AI models, real-time hardware implementation, and large-scale pilot demonstrations integrating renewable energy clusters.

6. CONCLUSION

AI-driven hybrid supercapacitor–battery energy storage integrated with V2G represents a transformative solution for fast frequency regulation in smart grids. Hybridization enhances performance and lifetime, while AI improves control adaptability. Further research and real-world deployment are necessary to unlock full potential.

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