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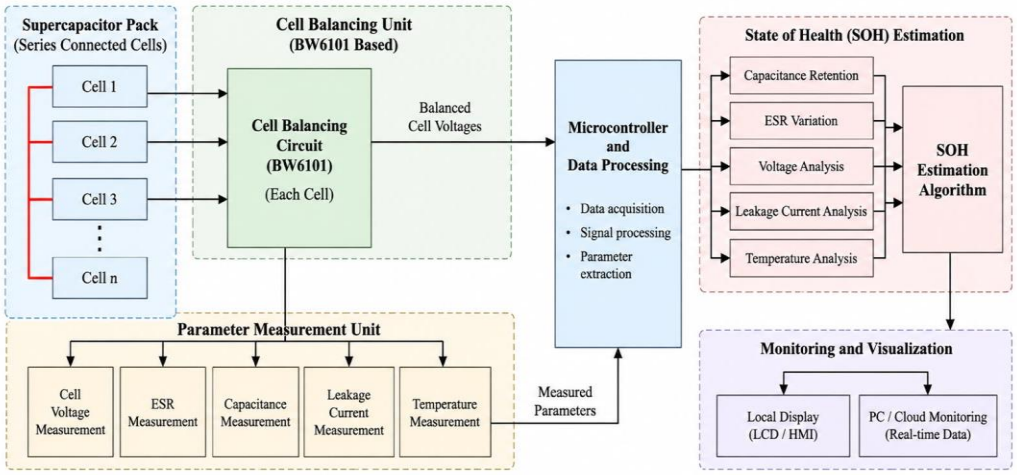
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Integrated Supercapacitor Cell Balancing and Multi - Parameter State of Health Estimation for Hydrogen Fuel Cell Electric Vehicles

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ABSTRACT: Hydrogen Fuel Cell Electric Vehicles (HFCEVs) require efficient energy storage systems to manage transient power demands and improve overall powertrain performance. Supercapacitors are suitable for this purpose because of their high-power density, rapid charge–discharge capability, and long cycle life. However, series-connected supercapacitor cells can experience voltage imbalance due to variations in capacitance, leakage current, temperature, and ageing. In addition to voltage balancing, estimating the State of Health (SOH) of supercapacitors is essential for assessing degradation and maintaining reliable operation. This paper presents a proposed integrated supercapacitor cell balancing and multi-parameter SOH estimation system for HFCEV applications. The system incorporates a BW6101-based balancing circuit and evaluates supercapacitor health using five parameters: cell voltage, Equivalent Series Resistance (ESR), capacitance, leakage current, and temperature. Capacitance retention and ESR variation serve as primary degradation indicators, while voltage, leakage current, and temperature provide supplementary information about cell operating conditions. The acquired parameters are intended to support health assessment through a defined estimation method, with the potential for digital monitoring and remote data visualization. The system is designed to combine cell-voltage balancing with condition assessment, thereby supporting the identification of voltage deviations and possible supercapacitor degradation. Experimental evaluation will focus on balancing performance, parameter measurement, and SOH estimation accuracy. The proposed approach provides a foundation for developing an integrated supercapacitor management system for automotive energy storage applications.



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I. INTRODUCTION

Supercapacitors are used in Hydrogen Fuel Cell Electric Vehicles (HFCEVs) to support peak power demands and regenerative braking. However, series-connected cells may experience voltage imbalance due to variations in capacitance, leakage current, and ageing, reducing efficiency and lifespan.

Existing balancing methods help maintain cell voltage but cannot fully assess degradation. Therefore, this project proposes a BW6101-based cell balancing system with multi-parameter State of Health (SOH) estimation using voltage, ESR, capacitance, leakage current, and temperature. This integrated approach aims to improve cell monitoring, reliability, and supercapacitor pack performance.

II. LITERATURE REVIEW

⇒ *Supercapacitors in Automotive Energy Storage*

Supercapacitors are widely studied for automotive applications due to their high-power density, rapid charge–discharge capability, and long cycle life. They support peak power demands and absorb regenerative braking energy. Naseri et al. [1] reviewed supercapacitor management systems, highlighting the importance of modelling, monitoring, balancing, and protection for reliable operation.

⇒ *Voltage Imbalance and Cell Balancing*

Series-connected supercapacitors may experience voltage imbalance due to variations in capacitance, leakage current, manufacturing tolerances, and ageing. Qu et al. [2] reviewed cell-balancing techniques, including passive methods that dissipate excess energy as heat and active methods that transfer energy between cells. Dedicated balancing ICs offer an alternative implementation, although performance depends on circuit configuration and operating conditions.*Supercapacitor SOH Estimation*

State of Health (SOH) estimation evaluates degradation relative to a healthy reference. Capacitance and Equivalent Series Resistance (ESR) are important indicators because capacitance loss reduces charge-storage capability, while increasing ESR can increase power losses. Reliable estimation requires consistent measurement conditions and suitable reference values [1].

⇒ *Multi-Parameter Health Assessment*

Combining ESR and capacitance with voltage, leakage current, and temperature can provide a broader assessment of supercapacitor condition. However, these parameters are influenced by operating conditions and must be appropriately normalized and interpreted. A combined SOH estimate requires a defined model and validation against reliable reference data.

⇒ *Research Gap and Motivation*

Existing research addresses supercapacitor balancing and management, but voltage balancing alone cannot quantify cell degradation. This work proposes integrating a BW6101-based balancing circuit with multi-parameter SOH estimation using voltage, ESR, capacitance, leakage current, and temperature. The system aims to combine voltage regulation with cell-health assessment, with its effectiveness and novelty to be established through experimental evaluation and comparison with existing approaches.

III. MATERIALS AND METHODS

⇒ *Materials and System Components*

The proposed system integrates supercapacitor cell balancing and multi-parameter State of Health (SOH) estimation for Hydrogen Fuel Cell Electric Vehicle (HFCEV) applications. The main components include series-connected supercapacitor cells, a BW6101-based balancing circuit, voltage and temperature sensors, and suitable measurement and data acquisition hardware. Additional circuits are used to measure ESR, capacitance, and leakage current. A processing unit can acquire the parameters and display the estimated SOH.

⇒ *Proposed System Architecture*

The system consists of four functional blocks: cell balancing, parameter measurement, SOH estimation, and data visualization. The BW6101 circuit addresses cell-voltage imbalance, while the measurement unit acquires voltage, ESR, capacitance, leakage current, and temperature. These parameters are processed using a defined estimation method, and the results are presented through a monitoring interface. Wireless monitoring can be incorporated where implemented.

⇒ Supercapacitor Parameter Measurement

1. Cell Voltage: Individual cell voltages are measured to evaluate operating conditions and balancing performance. Voltage spread is calculated as:

Voltage spread = Maximum cell voltage − Minimum cell voltage.

2. Equivalent Series Resistance (ESR): ESR indicates internal resistance and associated power losses. It can be estimated using a current-pulse method:

ESR ≈ Absolute change in voltage ÷ Absolute change in current.

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3. Capacitance: Capacitance represents charge-storage capability and can be estimated under controlled charging or discharging conditions:

Capacitance (C) = Current (I) × Time interval (Δt) ÷ Voltage change (ΔV).

4. Leakage Current: Leakage current is measured after charging the cell to a specified voltage and allowing a defined settling period. Increased leakage may indicate changes in cell condition.

5. Temperature: Temperature is recorded alongside electrical parameters because it influences ESR, capacitance, leakage current, and ageing behavior.

⇒ *State of Health Estimation*

SOH is assessed by comparing measured parameters with healthy reference values. Capacitance retention and ESR-based indicators serve as the primary degradation indicators, while voltage, leakage current, and temperature provide supplementary information. A combined SOH estimate requires a defined, calibrated model validated against reliable reference data.

⇒ *Experimental Procedure*

The supercapacitor cells are connected to the balancing circuit and measurement hardware. Initial cell voltages and electrical parameters are recorded. The balancing circuit is then operated within component specifications, and cell voltages are measured again. ESR, capacitance, leakage current, and temperature are measured under controlled conditions. The acquired data are processed by the selected SOH estimation method and compared with reference values, where available.

⇒ *Performance Evaluation*

System performance is evaluated using voltage-spread reduction, capacitance retention, ESR variation, leakage current, temperature, and SOH estimation accuracy.

Percentage reduction in voltage spread:

R_v (%) = [(Initial spread − Final spread) ÷ Initial spread] × 100

Capacitance retention:

R^c (%) = (Measured capacitance ÷ Reference capacitance) × 100

SOH estimation accuracy can be evaluated using Mean Absolute Error (MAE) and Root Mean Square Error (RMSE) when reliable reference SOH values are available. These metrics help assess balancing performance and the reliability of the proposed health estimation method.

IV. INFERENCE

The proposed system integrates BW6101-based cell voltage balancing with multi-parameter State of Health (SOH) estimation for supercapacitors in Hydrogen Fuel Cell Electric Vehicles (HFCEVs). By combining balancing with electrical and thermal parameter assessment, the system aims to identify voltage imbalance and potential cell degradation.

⇒ *Cell Voltage Balancing*

Variations in capacitance, leakage current, and ageing can cause voltage imbalance in series-connected supercapacitors. The BW6101-based circuit aims to reduce voltage differences, which can be evaluated by comparing cell voltages before and after balancing. However, balanced voltage alone does not guarantee good cell health, as degraded cells may exhibit increased ESR or reduced capacitance.

⇒ *Multi-Parameter SOH Estimation*

The proposed approach considers ESR, capacitance, leakage current, voltage, and temperature. Increasing ESR and decreasing capacitance can indicate degradation, while leakage current provides information about self-discharge behavior. Voltage helps assess operating conditions, and temperature supports the interpretation of electrical measurements. Considering these parameters together can provide a broader assessment of cell condition than relying on voltage alone.

⇒ *Integration and Performance Evaluation*

Cell balancing regulates voltage distribution, whereas SOH estimation assesses changes in cell characteristics over time. The system should therefore be evaluated separately for

balancing performance and health-estimation accuracy. Voltage-spread reduction, capacitance retention, ESR variation, and leakage current can be measured under controlled conditions. Estimated SOH should be compared with independently established reference values to validate the model.

⇒ *Limitations and Future Scope*

The reliability of the proposed system depends on measurement accuracy, suitable reference values, and a validated SOH estimation method. Future improvements may include testing under different temperatures and charge–discharge conditions, historical data logging, improved estimation models, and wireless or cloud-based monitoring.

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These developments could support more effective supercapacitor condition assessment for automotive energy storage applications.

V. RESULTS AND DISCUSSION

The following tables illustrate the expected presentation of results for the proposed supercapacitor cell balancing and multi-parameter SOH estimation system. The numerical values are hypothetical examples, not experimental measurements.

⇒ *Cell Voltage Balancing*

The illustrative voltage spread decreases from 0.17 V to 0.01 V, corresponding to a 94.12% reduction in voltage imbalance.

Cell	Before (V)	After (V)
Cell 1	2.42	2.49
Cell 2	2.31	2.48
Cell 3	2.38	2.49
Cell 4	2.25	2.48
Voltage spread	0.17 V	0.01 V

Table I. Cell voltages before and after balancing

⇒ *C. Multi-Cell SOH Indicators*

The illustrative data show that Cell 4 has the lowest capacitance retention and the greatest ESR increase

⇒ *Electrical and Thermal Parameters*

Capacitance retention and ESR provide complementary information about degradation. Leakage current and temperature help interpret the cell's operating condition. These individual indicators do not, by themselves, establish overall SOH.

Parameter	Reference	Measured	Indicator
Capacitance	100 F	90 F	90% retention
ESR	20 mΩ	25 mΩ	80% ESR indicator
Leakage current	0.20 mA	0.30 mA	50% increase
Temperature	25°C	30°C	+5°C

Table II. Supercapacitor parameter assessment

relative to the reference. A validated model would be needed to combine these indicators with voltage, leakage current, and temperature into an overall SOH estimate

Cell	Reference C (F)	Measured C (F)	Retention (%)	Reference ESR (mΩ)	Measured ESR (mΩ)	ESR indicator (%)
Cell 1	100	95	95.0	20	21	95.2
Cell 2	100	90	90.0	20	23	87.0
Cell 3	100	85	85.0	20	25	80.0
Cell 4	100	80	80.0	20	28	71.4

Table III. Capacitance retention and ESR-based indicators

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