



OPEN ACCESS

EDITED BY

Lei Zhang,
Beijing Institute of Technology, China

REVIEWED BY

Wei Zuo,
Wuhan University of Science and
Technology, China
Chuanyu Sun,
University of Padua, Italy
Jiageng Ruan,
Beijing University of Technology, China

*CORRESPONDENCE

Yu Duan,
✉ tony.duan@changanuk.com

RECEIVED 30 June 2024

ACCEPTED 23 July 2025

PUBLISHED 18 September 2025

CITATION

Duan Y, Li Y, To D, Zhang J, Chen J, Ran H and
Fan M (2025) Advanced online fuel cell stack
water management strategies for fuel cell
stacks in vehicle powertrain control.
Front. Energy Res. 13:1457052.
doi: 10.3389/fenrg.2025.1457052

COPYRIGHT

© 2025 Duan, Li, To, Zhang, Chen, Ran and
Fan. This is an open-access article distributed
under the terms of the [Creative Commons
Attribution License \(CC BY\)](#). The use,
distribution or reproduction in other forums is
permitted, provided the original author(s) and
the copyright owner(s) are credited and that
the original publication in this journal is cited,
in accordance with accepted academic
practice. No use, distribution or reproduction
is permitted which does not comply with
these terms.

Advanced online fuel cell stack water management strategies for fuel cell stacks in vehicle powertrain control

Yu Duan^{1*}, Yu Li², Daniel To¹, Jiaxiang Zhang¹, Jinrui Chen²,
Hongxu Ran² and Min Fan³

¹Powertrain Software, Changan UK R&D Centre, Birmingham, United Kingdom, ²Fuel cell stack Department, Changan Deepal Technical Co, Ltd, Chongqing, China, ³Fuel Cell Department, Changan Advanced Battery Research Institute, Chongqing, China

Effective water management is crucial for the optimal performance and durability of proton exchange membrane fuel cells (PEMFCs) in automotive applications. Conventional techniques like electrochemical impedance spectroscopy (EIS) face challenges in accurately measuring high-frequency resistance (HFR) impedance during dynamic vehicle operations. This study proposes a novel stack water management stability control and vehicle energy control method to address these limitations. Simulation and experimental results demonstrate improved system and powertrain efficiency, extended stack lifespan, and optimized hydrogen consumption. These findings contribute to advancing robust water management strategies, supporting the transition toward sustainable, zero-emission fuel cell vehicles.

KEYWORDS

PEMFC, water management, impedance, temperature, fuel cell stack, powertrain, EIS, DC/DC

1 Introduction

Fuel cells are emerging as a promising technology for clean vehicle powertrains, converting hydrogen's chemical energy into electricity through electrochemical reactions. Among these, proton exchange membrane fuel cells (PEMFCs) are widely used due to their high efficiency and zero-emission characteristics. However, effective water management within the fuel cell stack is essential to maintain optimal performance, efficiency, and durability. Advanced online water management strategies are critical for real-time optimization of these parameters, especially in dynamic operating conditions.

The relationship between fuel cell water management and energy management is foundational to the performance of fuel cell systems. Proper water management directly influences electrochemical reactions, energy efficiency, and system longevity. Below are the critical aspects:

1. Optimal proton exchange membrane (PEM) performance
 - Water's role: PEMFCs rely on hydrated membranes to facilitate proton conduction between the anode and cathode. Insufficient hydration increases ionic resistance, reducing energy efficiency.
 - Energy impact: Inadequate water management can cause dehydration or flooding, disrupting electrochemical reactions and lowering energy output.
 2. Flooding and energy loss
 - Flooding: Excess water at the cathode can obstruct gas diffusion pathways, limiting oxygen supply and energy generation.
 - Energy management: Designs such as optimized gas flow channels and water removal mechanisms prevent flooding, ensuring consistent performance.
 3. Membrane dehydration and durability
 - Dehydration: A dry membrane loses its ability to transport protons efficiently, shortening the fuel cell's lifespan and reducing energy output.
 - Energy trade-offs: Balancing hydration and dehydration improves long-term efficiency and reduces maintenance.
 4. Thermal management interplay
 - Heat and water evaporation: Fuel cells generate heat, influencing water retention. High temperatures can cause excessive evaporation, while low temperatures can result in condensation.
 - Integrated management: Coordinating water and thermal regulation maintains optimal operating conditions for steady energy production.
 5. Energy efficiency and recovery
 - Energy costs of water management: Systems for humidification or water removal require energy, impacting overall efficiency.
 - Energy recovery: Proper water management facilitates waste heat recovery, enhancing system efficiency.
 6. Multi-stack fuel cell systems for high-power applications
 - ❖ Architecture innovations

To meet the growing power needs of heavy-duty vehicles and stationary systems, multi-stack fuel cell setups are becoming more common. Key improvements include the following:

 - Central vs. distributed manifolds: Central manifolds make systems simpler, but a single fault can affect the whole system. Distributed manifolds provide better fault protection and flexibility, although they are more complex.
 - Modular stack design: Allows for easy scaling and quick replacement. Modules can be swapped without changing the entire setup.
 - Thermal management: Shared cooling improves efficiency but requires precise control to avoid hot spots and uneven aging.
 - ❖ Challenges in multi-stack systems
 - Uneven degradation: Thermal and hydraulic imbalances lead to non-uniform aging.
 - Electrical and electromagnetic interference (EMI) issues: Inter-stack electrical management must mitigate interference and ensure safe operation.
 - Packaging constraints: Increased volume and weight require innovative system integration techniques.
 - ❖ Optimal water management in PEM fuel cells for multi-stack
 - Importance of water balance
 - Prevention of membrane dehydration (causing resistance increase) and flooding (blocking reactant access).
 - Critical for performance, durability, and freeze-start reliability.
 - Operating conditions combination analysis
 - Multi-parameter optimization (temperature, humidity, stoichiometry, and pressure).
 - Use of design of experiments (DOE) and response surface methodology (RSM) to map optimal regimes.
 - Integration of real-time sensors and feedback loops for adaptive control.
 - Advanced water management techniques
 - Novel gas diffusion layer (GDL) and microporous layer (MPL) materials to improve capillary transport.
 - Hydrophilic/hydrophobic patterning in flow channels.
 - Anode recirculation and humidity control subsystems.
- Energy management in fuel cells can be optimized by designing effective water management strategies, ensuring steady performance and durability while maximizing output efficiency. EIS plays a crucial role in the development, optimization, and maintenance of these vehicles by providing detailed insights into the performance and health of fuel cell systems. EIS has been employed to analyze the performance, identify the degradation mechanisms, and optimize the operation of the fuel cells. EIS has been used to measure the impedance of the fuel cell over a range of frequencies. Impedance is a complex quantity consisting of a real part (resistance) and an imaginary part (reactance). By applying a small AC signal and measuring the resulting current response, an impedance spectrum was obtained, which can provide detailed insights into various electrochemical processes occurring within the fuel cell.
- EIS has found extensive applications across various electrochemical devices, as detailed in several comprehensive reviews (Yuan X et al., 2007; Tang Z et al., 2020; Meddings et al., 2020). Although EIS is widely employed to analyze the functioning of devices, such as fuel cells and batteries, fuel cells represent the most active area of research. This preference stems from the superior effectiveness of EIS in examining electrochemical characteristics affected by operating variations such as fuel stoichiometry, contamination, flooding, and starvation (O'Rourke et al., 2008; De Beer et al., 2015; Zhang Q et al., 2016). In addition to assessing fuel cell performance under different operational conditions, EIS also plays a crucial role in diagnosing and optimizing materials and components such as membranes, bipolar plates, and gas diffusion layers (GDL), thus enhancing the design and fabrication of membrane electrode assemblies (MEA) (Hink and Roduner, 2013; Baricci et al., 2017; Ihonen et al., 2004). In Tang et al.

(2024a) and Tang et al. (2024b), the temperature sensitivity characteristics of the proton exchange membrane fuel cell under different degradation levels, accelerated durability tests, and temperature sensitivity tests of the fuel cell are first performed, and the temperature characteristics under different degradation states are analyzed by EIS and polarization curve. A temperature sensitivity model considering the states of health (SOH) of the PEMFC is presented. When the operating temperature of the PEMFC at different states of health (SOH) increases from 60 °C to 80 °C, the impedance arc radius changes significantly. Specifically, as both the degradation level and operating temperature of the PEMFC increase, the high-frequency impedance shows a slight increase. This is primarily attributed to the higher operating temperature as the accelerated durability testing does not result in substantial degradation of the PEMFC.

Integrating advanced diagnostics like EIS into the design process further enhances the understanding of how different channel structures affect PEMFC performance under dynamic operating conditions. Gradient sinusoidal-wave fins in cathode channels (Chen et al., 2023; 2024) have been shown to increase water removal and improve oxygen flow, leading to better performance and durability. These insights can guide the development of robust and efficient cathode channel designs tailored to specific applications, such as automotive fuel cell stacks. Some research (Chen et al., 2023; 2024) on optimized designs improved power output and water management while keeping the pressure drop low, achieving a balance between efficiency and stability. Channel shapes and operating conditions worked together to increase fuel cell performance, highlighting the value of combined optimization strategies. A study on multi-objective optimization of proton exchange membrane fuel cells (PEMFCs) using response surface methodology (RSM) and the Non-Dominated Sorting Genetic algorithm II (NSGA-II) focuses on enhancing the performance and efficiency of PEMFCs through systematic design and analysis.

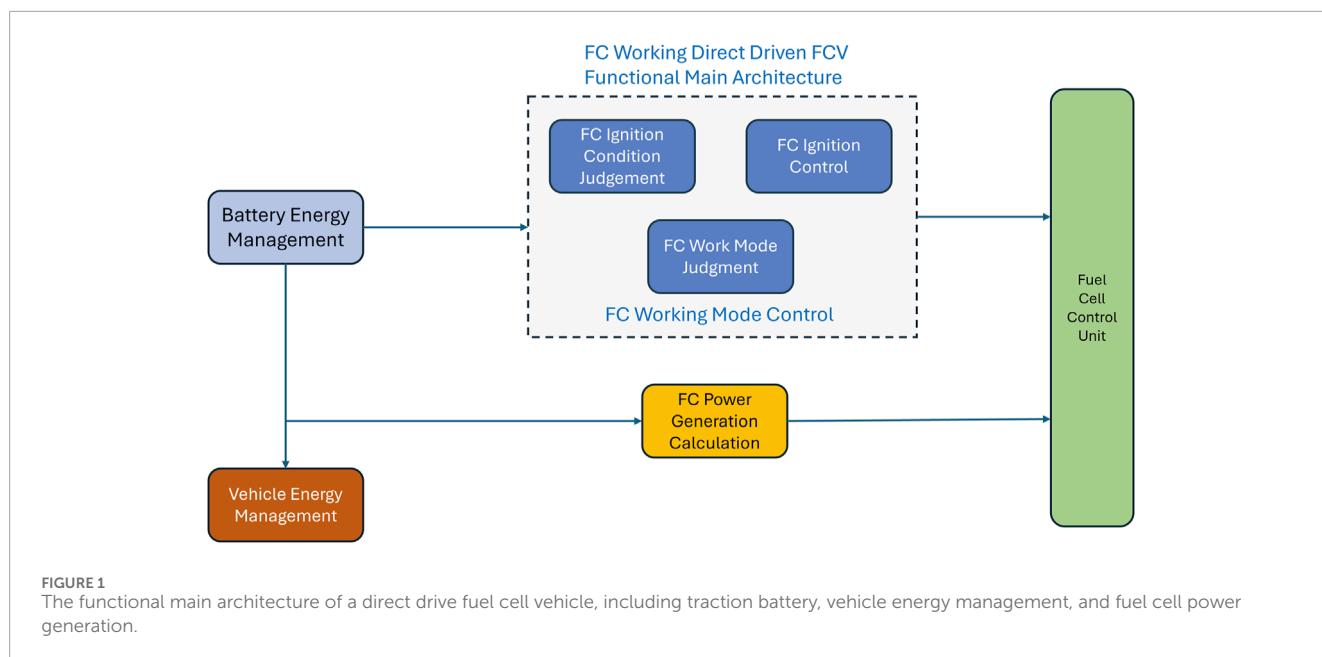
The current study builds on these advancements, investigating how innovative cathode channel designs and water management strategies can increase PEMFC performance, particularly in fuel cell electric vehicles (FCEVs). By addressing the challenges of water and thermal regulation, this research aims to contribute to the development of high-performing, durable, and sustainable fuel cell technologies. PEMFC not only generates water but also generates heat that can lead to power loss. Chen et al. (2023) and Chen et al. (2024) offer important insights into optimizing the design and operating conditions of high-temperature proton exchange membrane fuel cells (HT-PEMFCs), highlighting the importance of integrated management strategies to improve performance and durability in high-temperature environments. These fuel cells depend on materials capable of withstanding elevated temperatures, which help minimize the need for extensive thermal management components.

Energy management systems (EMSs) for fuel cell electric vehicles (FCEVs) are critical control systems that manage power distribution between different power sources, such as hybrid electric vehicles (HEVs). The EMSs for FCEVs are categorized into three main types: rule-based, learning-based, and optimization-based systems (Zhou et al., 2019).

1. Rule-based EMSs: These systems operate based on predefined rules and vehicle state observations. They are heavily reliant on engineering experience and require substantial calibration efforts (Zhao et al., 2022).
2. Learning-based EMSs: Practical implementations of learning-based EMSs include Q-learning (Ihonen et al., 2004), deep Q-learning (Zhou et al., 2019), and a deep deterministic policy gradient (DDPG) (Zhou et al., 2022). However, their application in FCEVs is limited by the restricted computational resources available onboard the vehicle (Ganesh and Xu, 2022).
3. Optimization-based EMSs (OB-EMSs): These systems use optimization techniques to determine the optimal control policy under physical constraints to minimize costs. These methods can be divided into offline and online methods.
 - Offline OB-EMSs: Techniques such as dynamic programming (Zhou et al., 2018), Pontryagin's maximum principle (PMP) (Huangfu et al., 2022), and genetic algorithms (Lu et al., 2020) are used to achieve global optima based on prior knowledge and typically serve as a baseline (Ao et al., 2021).
 - Online OB-EMSs: Methods such as model predictive control (MPC) and an equivalent consumption minimization strategy (ECMS) are designed for real-time control. Unlike MPC, ECMS does not depend on accurate power predictions and achieves long-term performance with a lower computational effort (Chen et al., 2021; Gao et al., 2021).

Lithium-ion batteries have become important power sources for the fuel cell vehicle and new energy vehicles (Etacheri et al., 2011; Feng et al., 2018; Wang et al., 2019). In a fuel cell electric vehicle (FCEV) powertrain, the battery thermal management system (BTMS) manages the heat partitioning while the battery is charging and discharging. Thermal issues can lead to battery fires, accidents, or explosions and have become the bottleneck in the development of the new energy vehicle industry. Some research based on the liquid cooling plate of the LiFePO₄ batteries presented cooling plate design methods. Fu et al. (2024) investigate the effects of filling ratio, filling position, and segment number of the porous medium on the maximum temperature and temperature difference of each cell and the pressure drop of the liquid cooling plate and propose improvements in cooling efficiency.

In the context of fuel cell powertrains, FCEVs are a promising solution for sustainable transportation utilizing hydrogen fuel cells to generate electricity for propulsion. Fuel cell vehicle powertrains represent a sophisticated integration of hydrogen fuel cells, DC/DC boost converters, electric motors, power electronics, and advanced control systems. An adaptive power coordination strategy (APCS) is introduced to determine the maximum efficiency of the fuel cell stack combined with the best efficiency of the FCEV powertrain. Effective water management, thermal regulation, and real-time monitoring using techniques such as EIS are critical for maintaining the performance, efficiency, and longevity of fuel cell systems. With technological advances, FCEVs are poised to become the cornerstone of sustainable and clean transportation. This article describes how the water management of a fuel cell stack is introduced and associated with a fuel cell powertrain.



Combining a fuel cell powertrain with maximum torque per ampere (MTPA) control in an electric motor system can significantly enhance overall efficiency and performance. In addition, a combined maximum efficiency control method and MTPA method were proposed by Amornwongpeeti et al. (2014), Amornwongpeeti et al. (2016), and the method was implemented in this study.

2 Fuel cell powertrain and EIS methods

The fuel cell electric vehicle powertrain system structure and the operation of the fuel cell electric vehicle (FCEV) powertrain system are shown in Figure 1, and the roles of each component are explained.

Fuel cell:

- Hydrogen fuel is converted into electrical energy via electrochemical reactions.
- Acts as the main energy source, powering the vehicle under most conditions.
- Operate most efficiently within a specific power range.

DC/DC converter:

- Connect the fuel cell stack in series to regulate and stabilize the output voltage.
- Ensures that the output voltage of the fuel cell is consistent with the bus voltage, thereby maintaining the system stability.

Battery:

- Functions as auxiliary energy sources to improve the overall efficiency of the powertrain.

- Supplies power to the motor when the demand is low, preventing the fuel cell from operating in low-efficiency regions.
- Supplements power when demand exceeds the maximum output of the fuel cell. Capable of storing energy recovered during braking, which can be used to charge the battery.

2.1 Fuel cell vehicle operation scenarios

Theoretically, the FCEV powertrain system combines the strengths of a fuel cell and battery to create an efficient and flexible power delivery system. The fuel cell serves as the main energy source, providing consistent power under normal driving conditions. The battery acts as an auxiliary source, supplying power during low demand, supplementing the fuel cell during high demand, and storing recovered braking energy. This dual-source strategy ensures optimal efficiency and performance under a range of driving conditions. A fuel cell powertrain converts hydrogen into electricity through a chemical reaction, which then powers an electric motor. The efficiency of a fuel cell powertrain is influenced by several factors, such as fuel cell stack efficiency, power electronics inverter efficiency, and motor efficiency. The total FCEV efficiency varies via different and complex operation scenarios and can be simply defined as follows:

- Low-power demand:
 - ✓ The battery supplies power to the drive motor.
 - ✓ This prevents the fuel cell from operating in its low-efficiency range, thereby increasing the overall system efficiency.
- High-power demand:
 - ✓ The fuel cell provides maximum power output.
 - ✓ The battery supplements the additional power required by the motor drive.

- ✓ Ensuring that the vehicle has sufficient power for acceleration, hill climbing, or other high-demand situations.
- Energy recovery:
 - ✓ During braking or deceleration, the motor drive acts as the generator.
 - ✓ Kinetic energy is converted back into electrical energy, which is stored in the battery.
 - ✓ The recovered energy is used to recharge the battery and improve the overall energy efficiency of the vehicle.

In [Figure 2](#), the FCEV operation in a drive cycle of the new European driving cycle (NEDC) is used as an example to demonstrate how an FCEV operates in different operating modes. Essentially, the necessary power analysis is implemented using mathematical equations to control the power/energy flow more efficiently inside the fuel cell vehicle powertrain. An innovative powertrain method is introduced and combined with the fuel cell stack impedance measurement to optimize the fuel cell vehicle powertrain. Optimal power management of the FCEV in the drive cycle can be achieved through hybrid system integration and energy management systems. Hybrid system integration has been applied in many FCEVs that use a hybrid system that combines a fuel cell with a traction battery. This allows the vehicle to optimize power delivery using the battery for short bursts of acceleration and the fuel cell for steady cruising, thereby enhancing the overall efficiency. Energy management systems, as mentioned by [Li et al. \(2021\)](#) and [Zhang et al. \(2021\)](#), control the flow of electricity between the fuel cell, battery, and electric motor, ensuring that the vehicle operates at optimal efficiency under various driving conditions. The different states and power demands of an FCEV powertrain system are documented in [Table 1](#). The impedance using the EIS method can be an indicator to optimize the fuel cell stack to generate energy efficiently, combined with the best state of charge in the traction battery for the motor control.

If fuel cell water management is not properly handled, several negative effects can arise, significantly impacting the fuel cell's performance, efficiency, durability, and overall reliability. These side effects are as follows:

➤ Membrane dehydration

- Cause: Inadequate hydration due to insufficient water retention in the membrane.
- Effects:
 - Reduced ionic conductivity: The proton exchange membrane (PEM) relies on water for proton transport. A dry membrane increases resistance, reducing the fuel cell's power output.
 - Heat accumulation: Poor hydration exacerbates heat buildup, risking thermal degradation of components.
 - Accelerated wear: Dehydration leads to cracking and physical damage to the membrane, shortening its lifespan.

➤ Flooding of gas diffusion layers (GDLs) or channels

- Cause: Excessive water production or inadequate removal from the cathode side.
- Effects:
 - Blocked reactant flow: Flooded GDLs or flow channels obstruct the supply of oxygen and hydrogen to the reaction sites, reducing the efficiency of electrochemical reactions.
 - Performance loss: Energy generation is compromised, causing voltage drops and unstable operation.
 - Startup issues: In cold conditions, excess water may freeze, leading to startup failures or permanent damage.

➤ Non-uniform water distribution

- Cause: Uneven humidification or inconsistent removal of excess water.
- Effects:
 - Localized dehydration or flooding: Different regions of the fuel cell can experience either dehydration or flooding, leading to uneven performance and accelerated degradation.
 - Cell imbalance: Multi-cell stacks may develop performance inconsistencies, reducing overall efficiency and output.

➤ Corrosion and catalyst degradation

- Cause: Water mismanagement leads to imbalanced operational conditions, promoting side reactions.
- Effects:
 - Electrode corrosion: Water pooling can increase the risk of side reactions, forming reactive oxygen species that corrode electrodes.
 - Catalyst layer damage: Poor water handling exposes catalysts to mechanical stress, chemical reactions, and thermal cycling, reducing their effectiveness.

➤ Thermal management challenges

- Cause: Water evaporation or accumulation affects the thermal equilibrium of the system.
- Effects:
 - Overheating: Dehydrated membranes or inadequate cooling increase the operating temperature, reducing efficiency and potentially damaging components.
 - Energy losses: Excess energy is consumed in compensating for thermal or water imbalances.

➤ Decreased system efficiency and longevity

- Cause: Accumulation of small inefficiencies due to improper water management.
- Effects:
 - Lower power output: The fuel cell cannot deliver its designed energy capacity.
 - Higher maintenance costs: Frequent repairs or replacements are required for damaged components.

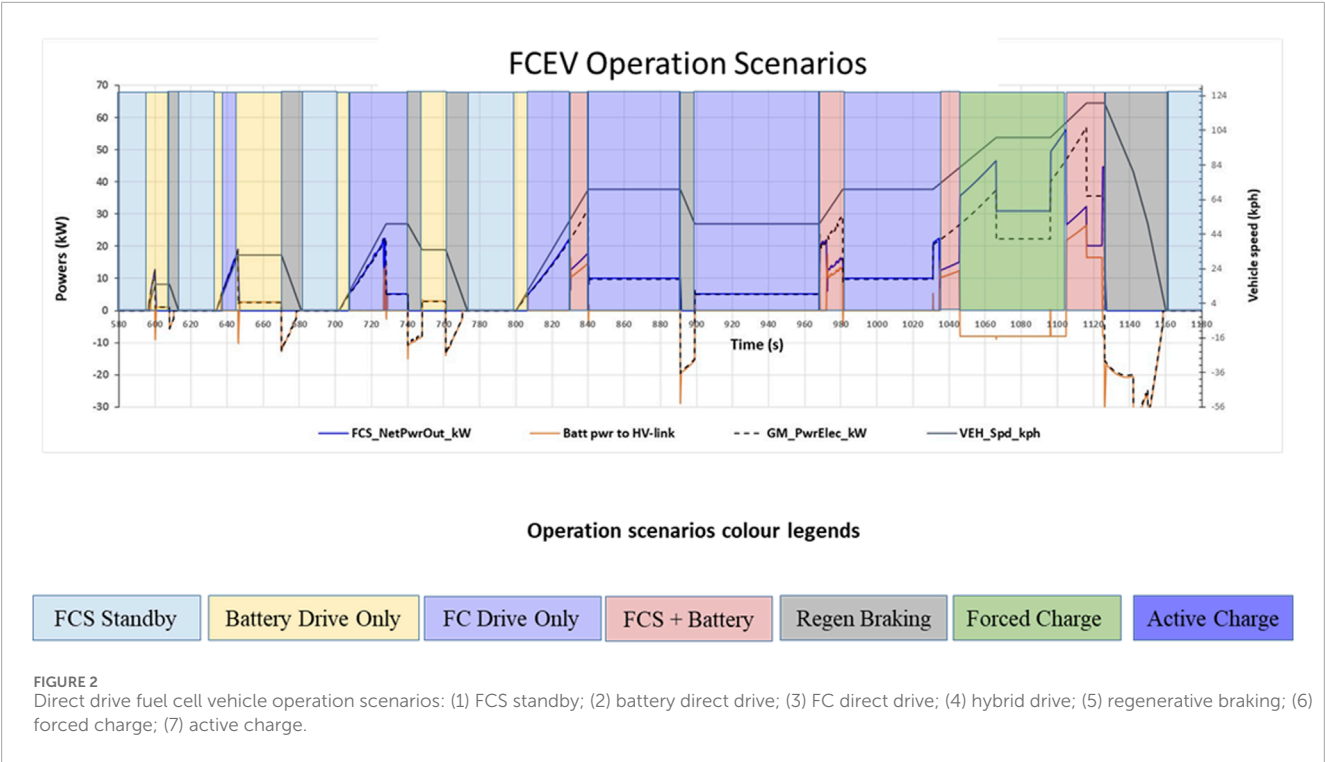


TABLE 1 FCEV power distribution scenarios.

Power demand status	Power distribution scenarios			EIS
Low-power demand	Battery drive	$P_{motor} < P_{battery}$	$P_{fuelcell} = 0$	OFF
Moderate power demand	Fuel cell (FC) drive	$P_{motor} \approx P_{fuelcell}$	$P_{battery} \approx 0$	ON
High-power demand	FC + Battery	$P_{motor} > P_{fuelcell}$	$P_{battery} = P_{motor} - P_{fuelcell}$	ON
Regenerative braking	Active charging	$P_{motor} < 0$	$P_{fuelcell} < 0$	OFF

○ Reduced lifespan: Chronic water-related issues accelerate the degradation of the fuel cell.

Effective water management is crucial for maintaining the delicate balance between hydration and the removal of excess water in fuel cells. Neglecting this balance results in operational inefficiencies, decreased power output, component degradation, and a shortened lifespan, significantly undermining the fuel cell's overall performance.

The key variables of the FCEV power flow are defined in Table 2, and the total power delivered to the motor can be expressed as Equation 1

$$P_{motor} = P_{fuelcell} + P_{battery}, \tag{1}$$

where P_{motor} is the total power required by the drive motor, $P_{fuelcell}$ is the power output from the fuel cell, and $P_{battery}$ is the power output from the battery (positive when discharging and negative when charging). Based on comparisons of the power sources, the scenarios of power distribution can be defined as follows:

- 1. Low-power demand

- 2. Moderate power demand
- 3. High-power demand
- 4. Regenerative braking

2.2 Integrating fuel cell efficiency and MTPA electric motor control

In electric vehicles (EVs) and FCEVs, MTPA control is essential for improving the efficiency and performance of the traction motor, thereby extending the driving range and enhancing the driving experience. The strategy ensures that the motor operates efficiently under various load conditions, contributing to the overall energy efficiency of the vehicle. In Figure 3, the MTPA control strategy for interior permanent magnet synchronous motors (IPMSMs) focuses on achieving maximum torque output for a given current, thereby improving the motor's efficiency and performance. The strategy involves optimal control of the d-axis and q-axis currents, leveraging the motor's magnetic properties to minimize current and maximize torque. The transformation of rotating current (i_d and i_q) to the

TABLE 2 Key parameters for FCEV power-flow modeling.

Symbol	Parameter	Value
m	Vehicle total mass	1895 kg
C_d	Drag coefficient	0.258
A_f	Front area	2.85 m ²
g	Gravity	9.81 N/kg
μ_1	Rolling resistance	0.001
η_{ele}	Efficiency of electric components	0.95
η_{me}	Efficiency of mechanical components	0.95
km/h	Max vehicle speed	180
kW	Electric motor power	175
kWh	HV battery	18.99
kW	Fuel cell stack power	68
V/A	Vehicle electric max voltage/current	400/300

stationary frame approach has been demonstrated for the vector control of the electric machine (Duan and Sumner, 2012). In this research, a lookup table of both fuel cell power and high-frequency impedance via the EIS method is used to optimize the powertrain system output power efficiency. The lookup table can provide the power limit to protect the fuel cell stack even with higher powertrain system efficiency.

In the MTPA strategy, the two-axis stator reference currents are calculated so that the maximum torque per ampere will be achieved. The equation by Duan and Sumner (2012) represents the relationship between the torque and current as Equations 2, 3:

$$\text{MTPA} \propto \frac{T_{ref}}{I_{ref}} \quad (2)$$

$$I_{ref}^2 = I_{ds}^2 + I_{qs}^2 \quad (3)$$

If the reference torque (T_{ref}) is assumed to be constant, then the stator reference current (I_{ref}) should be minimized using the above equations. For a fuel cell powertrain, achieving maximum efficiency involves optimizing both the fuel cell stack and the electric motor control. The field-oriented control of electric machines is used for this optimal control algorithm to achieve the best control and optimized fuel cell stack efficiency. During online EIS impedance measurement, R_s and P_{fc} are involved with MTPA control together to limit any fuel cell stack behaviors that are higher than the range of HFR impedance. In terms of fuel cell stack efficiency improvement, the operation conditions and load match conditions are all considered to maintain optimal conditions, such as temperature, pressure, and humidity, for the fuel cell stack to ensure high efficiency. Using an adaptive power coordination strategy ensures that the fuel cell operates at its peak efficiency point across different load conditions. Figure 4a shows that below

a certain minimum vehicle speed, only the battery is used. If the demanded motor power exceeds the maximum fuel cell power at its operating condition, the battery is used to shown in Figure 4c. The motor charges the battery by regenerative braking. The fuel cell power output is inhibited when the power demand falls below a limit at the operating speed to prevent inefficient operation. If the battery state of charge (SOC) is lower than its minimum allowable value, the fuel cell should provide additional shown in Figure 4b.

2.3 Practical implementation in FCEVs

In a fuel cell electric vehicle (FCEV), the integration of MTPA control within the motor and the efficient operation of the fuel cell stack can lead to significant efficiency gains:

- Enhanced range: By maximizing the efficiency of both the fuel cell and the motor, the vehicle can achieve a longer range on a given amount of hydrogen.
- Improved performance: Efficient torque management through MTPA control provides better acceleration and performance characteristics.
- Energy efficiency: Reduced electrical losses in the motor and optimal fuel cell operation lead to lower overall energy consumption.

The adaptive power coordination strategy (APCS) ensures the efficient use of the fuel cell and battery by prioritizing the fuel cell as the main power source and using the battery as a supplementary source. Regenerative braking is utilized to recover energy and charge the battery. The strategy includes mechanisms to avoid inefficient fuel cell operation and maintain the battery's SOC within safe limits. The fuel cell is the primary power source. The battery is used to provide additional power when needed by the vehicle. The APCS method is followed and shown in Figure 5:

- 1 Minimum vehicle speed:
 - Below a certain minimum vehicle speed, only the battery is used for propulsion.
- 2 Demanded motor power exceeds fuel cell capacity:
 - If the demanded motor power exceeds the maximum power output of the fuel cell under its current operating conditions, the battery supplies the additional required power.
- 3 Regenerative braking:
 - The motor charges the battery through regenerative braking during deceleration or braking events.
- 4 Fuel cell power output inhibition:
 - The fuel cell's power output is inhibited when the power demand falls below a certain limit at the operating speed to prevent inefficient operation.
- 5 Battery state of charge (SOC) management:
 - If the battery's state of charge (SOC) drops below its minimum allowable value, the fuel cell provides additional power to recharge the battery.

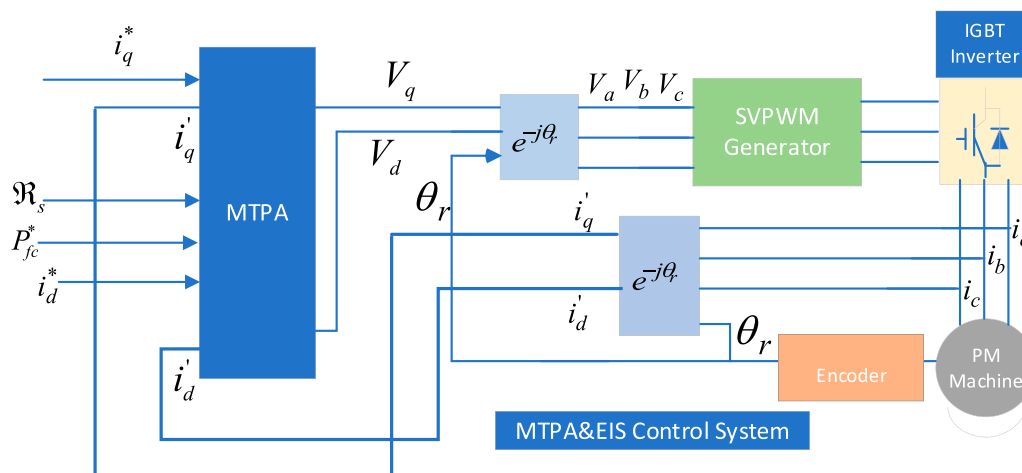


FIGURE 3
MTPA and EIS scheme of vector control for the permanent magnet (PM) machine to optimize the fuel cell stack SOH and vehicle performance.

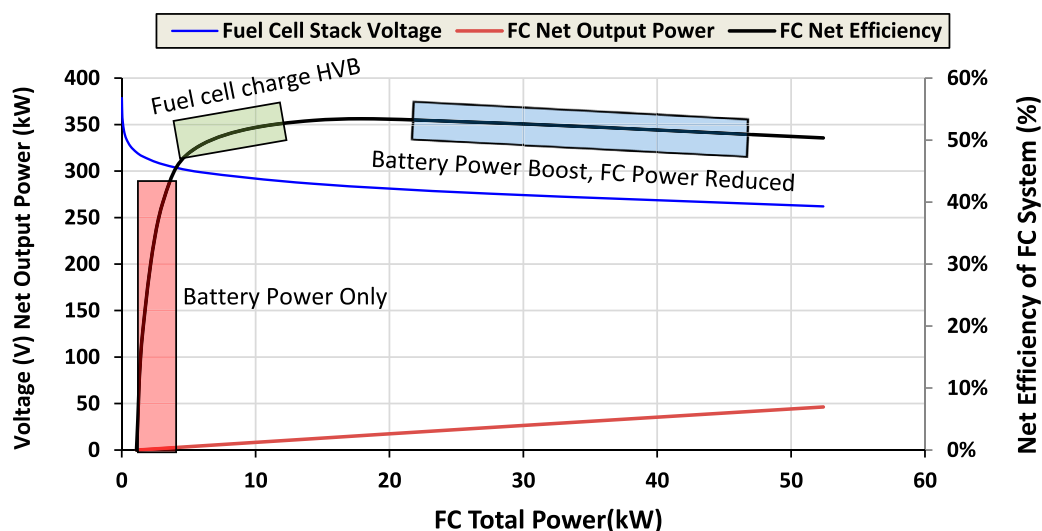
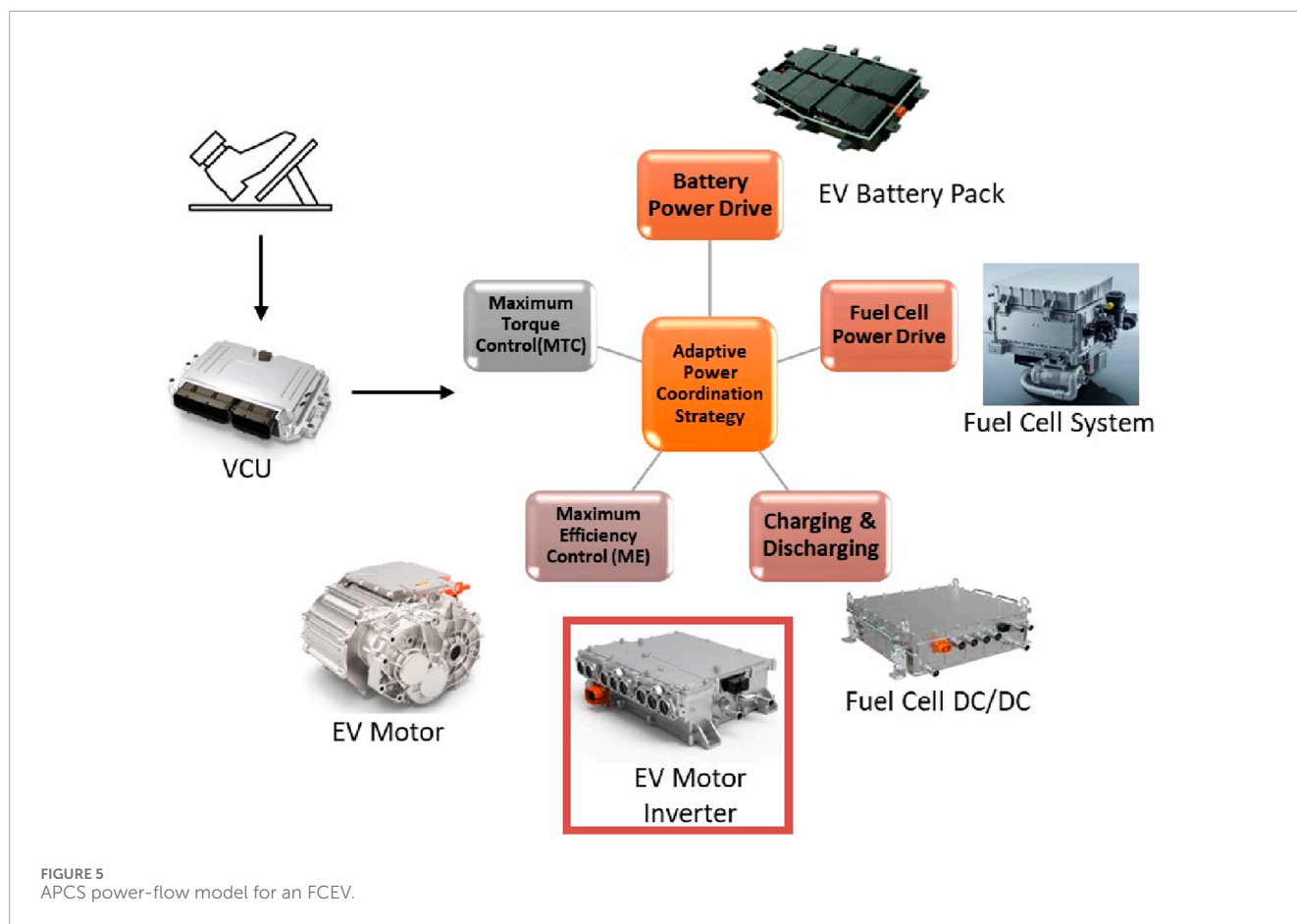


FIGURE 4
Fuel cell stack efficiency analysis at the different power stages: (a) battery only; (b) fuel cell only; (c) hybrid power generation.

In summary, combining a fuel cell EIS powertrain technique with MTPA control maximizes the overall system efficiency. MTPA optimizes the motor's performance by minimizing current usage for required torque, thereby reducing electrical losses. Meanwhile, maintaining high fuel cell stack efficiency ensures that the electrical energy produced from hydrogen is used effectively. Integrating these strategies results in improved performance, extended range, and increased energy efficiency in fuel cell electric vehicles.

FCEV power-flow modeling is the key to understanding the FCEV architecture to improve the vehicle's drivability, durability, flexibility, and functionality. The model contains fuel cell stack control, fuel cell stack water management control, IPSM motor control, energy management control, battery management control,

and vehicle performance control to maximize the system/vehicle efficiency and minimize fuel consumption. The APCS applied in an FCEV power-flow model is shown in Figure 5. The acceleration pedal sends the power demand request. Once the vehicle control unit (VCU) receives the demand request, it will communicate with the controllers of other power sources. For efficient control, this research centralized the energy flow of the APCS method implemented into an EV motor inverter. All the other controllers are at the sub-level of the EV inverter controller. As high bandwidth is required to use an EV inverter, complex algorithms are suitable to be located in this inverter controller. The VCU is used as a high-level commander to supervise vehicle-related control. This novel control method is widely used in the EV motor control platform, especially in the EV powertrain control field.



3 Fuel cell stack water management using EIS methods

Electrochemical impedance spectroscopy (EIS) is a powerful technique used to analyze the electrochemical properties of systems like fuel cells (FC). In EIS, a small sinusoidal perturbation signal, either current or potential, is imposed on the FC stack. The response of the stack, in terms of potential or current, is then measured. There are two primary modes of operation for EIS:

- Potentiostatic mode: In this mode, a potential perturbation is applied, and the current response is measured.
- Galvanostatic mode: In this mode, a current perturbation is applied, and the potential response is measured.

3.1 Differences and applications

The choice between potentiostatic and galvanostatic modes has been extensively studied. Each mode has its specific applications and advantages:

- ❖ Potentiostatic mode: This is typically used when the system under investigation is better characterized as a current source. It allows for precise control of the potential, which is useful in systems where the potential must be accurately controlled or is critical to the system's operation.

- ❖ Galvanostatic mode: This is preferred for systems characterized as voltage sources, such as multi-cell FC stacks with high-power outputs. This mode involves controlling the current and measuring the resultant potential response.

For fuel cell stacks, especially multi-cell stacks with high power, the galvanostatic mode is generally preferred. There are several reasons for this preference:

- Characterization as a voltage source: FC stacks are better characterized as voltage sources. In the galvanostatic mode, the current is controlled, and the voltage response is measured, aligning with the inherent characteristics of FC stacks.
- Avoiding large current changes: Applying a small potential perturbation in the potentiostatic mode can result in large changes in current, especially in high-power stacks. This can lead to the overloading of certain cells within the stack, which might cause degradation or even failure of the entire stack (Amornwongpeeti et al., 2014; 2016).
- System stability: Using the galvanostatic mode helps in maintaining system stability. Small current perturbations are less likely to cause large disturbances in the stack, thereby preventing potential overloads and ensuring the longevity and reliability of the fuel cell stack.

Addressing the deterioration of the membrane is crucial, as it directly affects the performance and longevity of the PEMFC, influencing issues like flooding or drying of the cell. This work

focuses on tackling these specific challenges to enhance the viability of PEMFCs in diverse applications using the EIS. The EIS measures the response of an AC voltage or current on a fuel cell at different frequencies to obtain the impedance spectrum of the system. EIS testing can help analyze:

- Electrochemical processes: Electrochemical reaction dynamics, charge transfer, and diffusion processes at different frequencies.
- Electrode/electrolyte interface behavior: Identifies the characteristic changes between the electrode and the electrolyte interface.
- Impedance element separation: separation and quantification of ohmic impedance, mass impedance, charge transfer impedance, etc.

3.2 EIS theory

The Randles equivalent circuit shown in [Figure 6](#) is widely used in electrochemistry for several important reasons:

1. Simplifies complex systems: It provides a simplified model of complex electrochemical systems, making it easier to analyze and understand the impedance characteristics of electrochemical cells.
2. Characterizes electrochemical processes: The components of the Randles circuit correspond to specific physical and chemical processes:
 - Solution resistance (R_s): Represents the resistance of the electrolyte.
 - Double-layer capacitance (C_{dl}): Represents the capacitive behavior of the electrode-electrolyte interface.
 - Charge transfer resistance (R_{ct}): Represents the kinetics of the electrochemical reactions.
 - Warburg impedance (Z_w): Represents the diffusion of species in the electrolyte.
3. Data interpretation: By fitting experimental impedance data to the Randles circuit, researchers can extract quantitative values for the resistances, capacitances, and diffusion parameters. This aids in the interpretation of experimental results and in comparing different systems.
4. Diagnostics and monitoring ([Yuan et al., 2006](#)): In practical applications, such as battery diagnostics and corrosion monitoring, the Randles circuit helps in identifying and diagnosing issues by analyzing changes in the circuit parameters over time.
5. Predictive modeling: A Randles circuit aids in predictive modeling of electrochemical systems, allowing for the simulation of how a system will behave under different conditions.
6. Versatility: The basic Randles circuit can be modified and extended to include additional elements to model more complex behaviors, making it a versatile tool for a wide range of electrochemical systems.

The Randles model consists of the following components:

- ❖ Solution resistance (R_s): This represents the resistance of the electrolyte solution. It is in series with the rest of the circuit elements and accounts for the ohmic drop in the electrolyte.
- ❖ Double-layer capacitance (C_{dl}): This capacitor models the capacitance at the electrode–electrolyte interface due to the formation of the electric double layer. It is in parallel with the charge transfer resistance.
- ❖ Charge transfer resistance (R_{ct}): This resistor represents the resistance to charge transfer at the electrode interface due to the electrochemical reaction. It is in parallel with the double-layer capacitance.

Overall, the Randles equivalent circuit is a fundamental tool in EIS for analyzing and understanding the impedance of electrochemical systems as [Equations 4, 5](#).

$$Z_\delta = R_d \frac{\tanh(\tau_d j \omega)^\alpha}{(\tau_d j \omega)^\alpha}, \quad (4)$$

$$Z = R_\Omega + \frac{1}{\frac{1}{R_{ct} + Z_w} + j\omega C_{dl}}, \quad (5)$$

where ω is the angular frequency of the applied AC signal, $\omega = 2\pi f$, j is the imaginary unit, and $j^2 = -1$. This equation shows that the total impedance is the sum of the solution resistance and the combined impedance of the parallel Resistor-Capacitor (RC) circuit, representing the double-layer capacitance and the charge transfer resistance.

3.3 Calculation of stack impedance

To calculate the impedance of the fuel cell (FC) stack using electrochemical impedance spectroscopy (EIS), we follow these steps:

1. Perturbation signal: An AC perturbation signal with a single frequency is superimposed on the DC current of the FC stack. This AC signal has an amplitude of i_1 , as shown by the red curve in [Figure 7 \(1\)](#).
2. Stack voltage response: The AC perturbation causes a corresponding perturbation in the stack voltage, with an amplitude of e_1 , represented by the blue curve in [Figure 8 \(1\)](#).
3. Phase difference: The current signal leads the voltage signal by a phase angle ϕ .
4. Impedance calculation:
 - The impedance Z of the stack can be calculated using the amplitude of the voltage and current perturbations and the phase difference between them.
 - The general formula for impedance Z in AC circuits is given by the following [Equation 6](#):

$$Z = \frac{e_1}{i_1} \quad (6)$$

where:

- e_1 is the amplitude of the AC voltage response.
- i_1 is the amplitude of the AC perturbation.

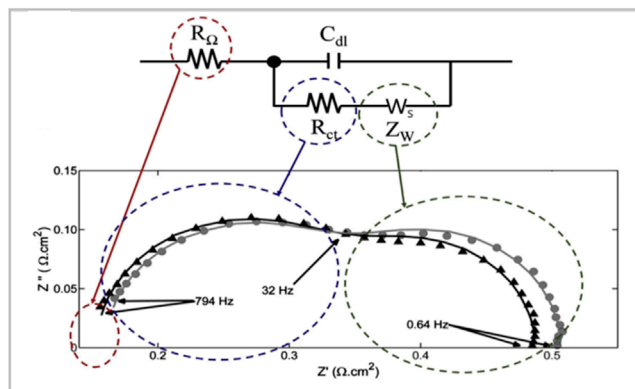


FIGURE 6 Randles equivalent circuit and equations: impedance measurement using real and imaginary axis to present with low and high frequency.

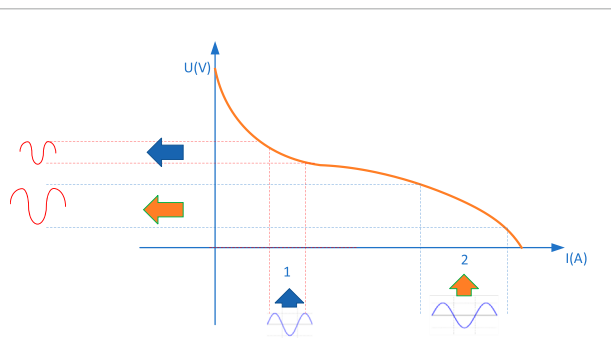
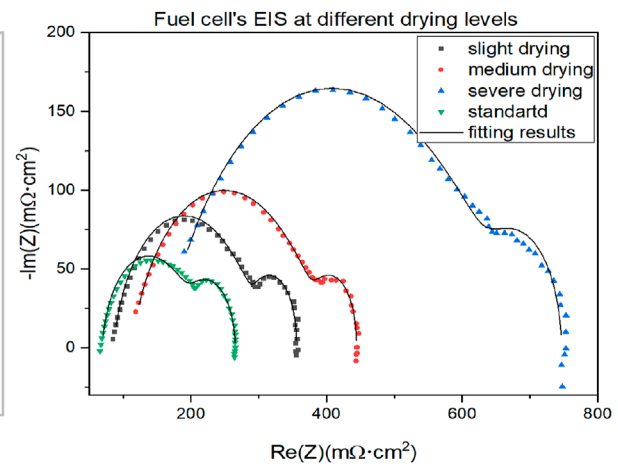


FIGURE 7 EIS implementation by injecting sinusoidal perturbations (1) linear region and (2) non-linear region, adapted from Wasterlain (2010).

5. Complex impedance: Because there is a phase difference ϕ between the voltage and current, the impedance can be expressed in its complex form as Equation 7:

$$Z = \frac{e_1}{i_1} e^{j\theta}. \quad (7)$$

Here:

- j is the imaginary unit.
 - $e^{j\theta}$, represents the phase shift in the form of a complex exponential.
6. Impedance components:
- The impedance Z can be separated into its real and imaginary components:
 - Real part (Resistance, R): $R = |Z| \cos(\theta)$
 - Imaginary part (Reactance, X): $X = |Z| \sin(\theta)$
 - Therefore, the impedance can also be written the Equation 8 as follows:

$$Z = R + jX. \quad (8)$$

7. Amplitude and Phase: Using the measured amplitudes i_1 and e_1 , and the phase angle ϕ , the stack impedance and phase angle can be calculated as follows Equations 9, 10:

$$|Z| = \sqrt{R^2 - X^2}. \quad (9)$$

$$\theta = \tan^{-1}\left(\frac{X}{R}\right). \quad (10)$$

The perturbation signal's frequency can be varied across a wide range, allowing for the formation of an impedance spectrum by measuring the stack impedances at discrete frequency points. These measurements are often graphically represented using a Nyquist plot (Becherif et al., 2018). The parameters R_{in} (internal resistance), which is the high-frequency intercept of the impedance arc, and R_{polar} (polarization resistance), which is the zero/low-frequency intercept of the impedance arc, are critical indicators of the health and performance of a fuel cell stack (Onanena et al., 2010), particularly in a proton exchange membrane fuel cell (PEMFC). The parameters of impedance and resistance mentioned that are extracted from the EIS analysis. A higher R_{in} value indicates increased ohmic losses (Wasterlain, 2010), which could be due to poor humidification of the membrane or other issues in the cell components. A higher R_{polar} value indicates increased polarization losses, which could be due to sluggish electrochemical reactions or poor mass transport. By monitoring these parameters, engineers can assess the health of the fuel cell stack and diagnose issues related to resistance and performance, enabling targeted maintenance and optimization.

4 Experiment and results

The specifications of the fuel cell system and powertrain system test rig include:

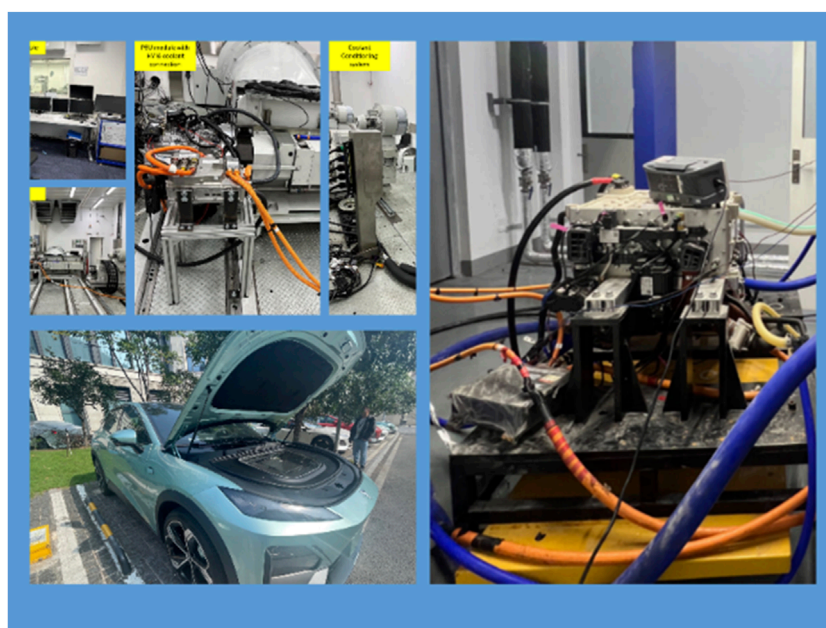


FIGURE 8
Test rig for PEMFC module level, system level, and vehicle level testing.

- Modules: Fuel cell test station, thermal cooling glycol system, battery emulator, motor/inverter, and dyno.
- Components: load devices (test motors), sensors, actuators, interface I/Os definitions, and controllers.
- Measurement instruments: power pressure transducers, thermocouples, flow meters, and a 3-phase AC voltage/current measurement device.
- Operating ranges: temperature: 18 °C–85 °C, hydrogen pressure: 0–3 bar, air flow rate: 0–9k SLPM
- Control system software used: feedback control loop design
- Safety mechanisms: emergency shutdown, over-pressure relief, over-current/voltage/temperature/flow protection, isolation monitoring

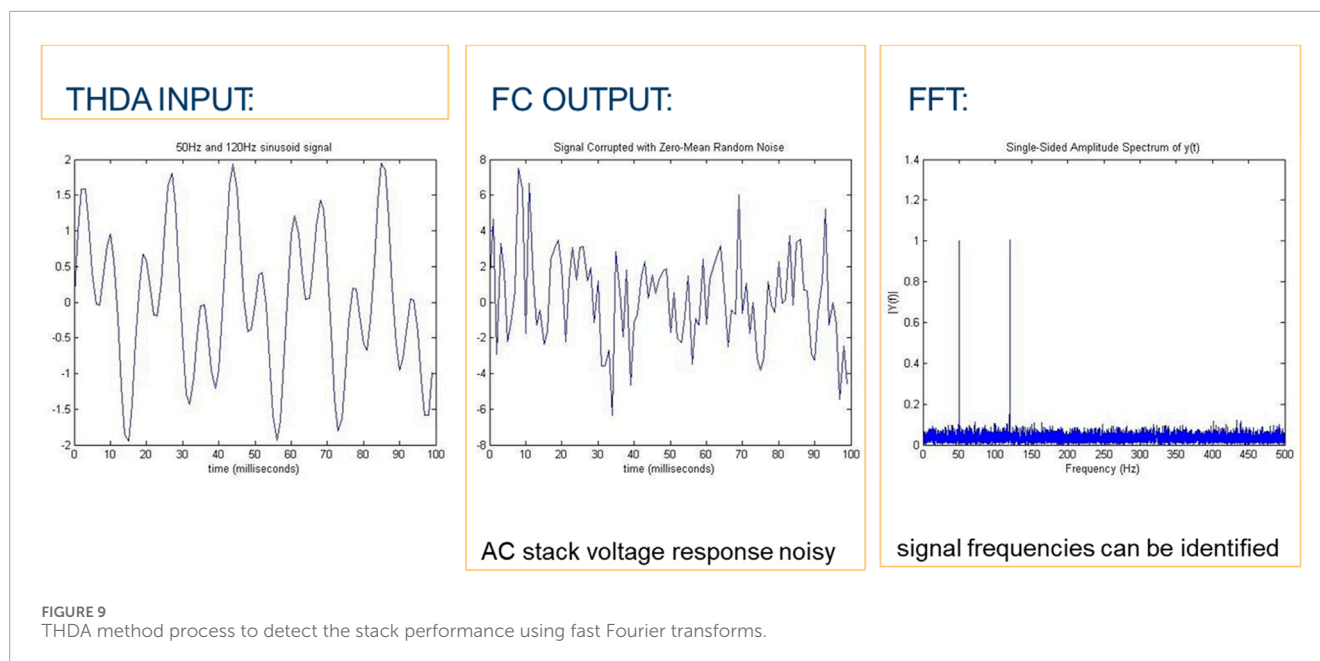
The specifications of vehicle testing protocols are defined to test a vehicle's powertrain efficiency under defined conditions. The test protocols are defined as follows:

- Test type uses Changan's road testing drive cycle
- Environment is on the chassis dynamometer
- Conditions: test temperature is ambient conditions at 20 °C, humidity is approximately 60%–80%, altitude is less than 1,000 m
- Measurement parameters: power output, torque, fuel consumption, and stack impedance
- CLTC drive cycle is used for this test
- The instrumentation used: CAN bus logger and power analyzer to measure both the current and voltage of the powertrain

TABLE 3 Key motor parameters for FCEV MTPA control.

Items	Parameter	Unit
Machine type	PMSM	-
Pole pairs	12	-
Rated speed	6,000	rpm
Rated torque	120	Nm
Rated current	170	A
Rated voltage	350	V
Inductance	0.11	mH
Inertia of moment	0.001	kgc
Motor friction	0.01	N·m/A
Peak torque	190	Nm
Connection type	Y	-
Flux linkage	0.024	Wb

The test motor parameters are shown in Table 3 (Wasterlain, 2010). In this experiment, both the motor in the test bench and the FCEV are the same. The test plan is carried out under simulation testing, test rig testing, and vehicle testing. The test cases were defined differently for simulation and rig/vehicle testing. Some results are shown in the appendix of this article.



4.1 EIS, total harmonic distortion analysis (THDA), and APCS implementations

EIS online measurement is achieved using an additional control board to generate AC signals and implemented in the fuel cell boost DC/DC converter, whose architecture is described by [Becherif et al., \(2018\)](#). Total harmonic distortion analysis (THDA) ([Becherif et al., 2018](#)) was carried out to ensure the measured impedance through EIS is correct. This research aims to use MTPA powertrain control together with online EIS impedance measurement, as shown in [Figure 9](#). The design requirement is detailed below:

1. Efficient operation of a fuel cell stack:

Fuel cell stacks should operate at their optimal efficiency levels during normal vehicle operations to maximize performance and minimize fuel consumption.

2. Conditional operation of the fuel cell control system:

The fuel cell control system can be deactivated when the fuel reactor is not needed to supply energy, conserving power and reducing wear on the system.

3. Battery system energy management:

The vehicle should consume and replenish battery energy within the limits of the battery's capacity and energy consumption parameters, ensuring balanced and efficient use.

4. Controlled battery energy use:

Each instance of battery energy usage and replenishment should fall within a reasonable range, maintaining the battery's health and efficiency.

5. Stable battery power under non-continuous extreme conditions:

During non-continuous extreme conditions, the fuel reactor control system should maintain the battery power at a predetermined threshold without allowing it to decrease, ensuring consistent performance.

6. Smooth power generation requests:

In non-continuous extreme conditions, power generation requests by the fuel cell stack should meet the vehicle's requirements without causing abnormal fluctuations or jumps, ensuring stable operation.

7. Adaptive fuel cell stack (FCS) operating mode:

During non-continuous extreme conditions, the vehicle control unit (VCU) should assess the vehicle's operational status and adjust the fuel cell stack (FCS) operating mode accordingly. This adjustment should maintain normal functionality without causing any abnormal jumps in performance. When the adaptive FCS operating mode operates the fuel cell stack at its point of maximum efficiency, the fuel cell stack power range with the best efficiency is between 5 kW and 15 kW, as shown in [Figure 10](#). Fuel consumption improvement can be achieved, and the test is carried out in the powertrain rig running the NEDC drive cycle as the FCEV powertrain control input.

[Figure 8](#) shows the results of carrying out all testing activities in the fuel cell stack test rig, powertrain test rig, and Deepal S7-F vehicle. The fuel cell stack parameters for the series of tests are listed in [Table 4](#). The testing was conducted under the Changan vehicle testing standard and the national fuel cell stack testing standard.

4.1.1 Offline or periodic EIS measurements

- Are taken under static or steady-state conditions, often during shutdown or controlled operation.

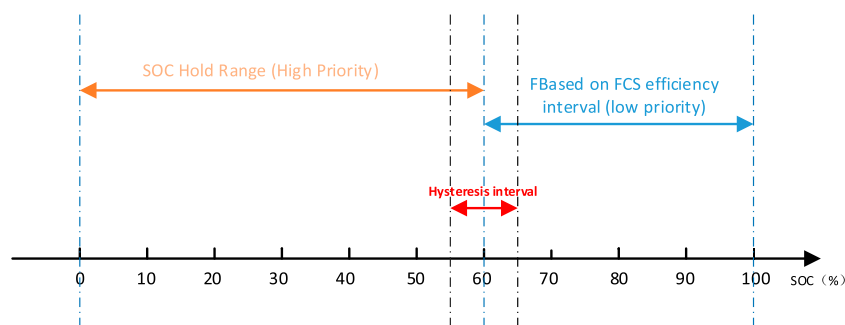


FIGURE 10
APCS efficiency analysis diagram for an FCEV.

TABLE 4 Fuel cell stack parameters.

Items	Parameter	Unit
System insulation resistance	≥ 1.5 ($2 \mu\text{s/cm}$)	M Ω
Fuel cell stack peak power	≥ 67.5	kw
Fuel cell stack maximum efficiency	≥ 60.5	%
Minimum cold start temperature of the fuel cell stack	-30	$^{\circ}\text{C}$
Fuel cell stack durability	$\geq 10,000$	h
Fuel cell stack loading rate	≥ 9	kw/s
Fuel cell stack load reduction rate	≥ 6	kw/s
Normal temperature idle, cool engine start time	12	s
Normal temperature idle, warm engine start time	10	s
Rated heat engine start time at normal temperature	18	s
Fuel cell engine calorific value (max)	82	kw

- Miss transient behaviors such as sudden membrane dehydration or electrode flooding, which develop and disappear quickly during real operation.
- Cannot provide time-resolved insight into failure mechanisms that evolve on dynamic time scales (seconds to minutes).
- Often require manual intervention and stop-test-run cycles, unsuitable for onboard diagnostics.

4.1.2 Advantages of real-time EIS

Real-time EIS enables continuous, *in situ* impedance monitoring during fuel cell operation, providing the following:

1. Detection of transient events:
 - Flooding in the cathode or anode gas channels shows up as low-frequency impedance increases due to mass transport limitations.
 - Membrane dehydration leads to increased high-frequency resistance (HFR) due to reduced ionic conductivity.

- These conditions can occur and resolve within seconds and are only detectable via real-time monitoring.

2. Dynamic health monitoring:

- Allows for early warning systems, adaptive control strategies, or real-time fault correction (e.g., air purging and humidifier control).
- Enables lifetime modeling and condition-based maintenance instead of scheduled replacement.

4.1.3 Computational requirements

To extract useful EIS data in real time, systems must:

- Perform the Fast Fourier Transform (FFT) analysis or equivalent signal processing (e.g., DFT and Kalman filtering).
- Run nonlinear curve fitting (e.g., using ZView-type algorithms or equivalent) to fit impedance spectra to equivalent circuit models.
- Operate at sufficient sampling rates (e.g., 10–100 Hz signals with 100–5 kHz sampling rates).

4.1.4 Implementation complexity

a. Hardware requirements

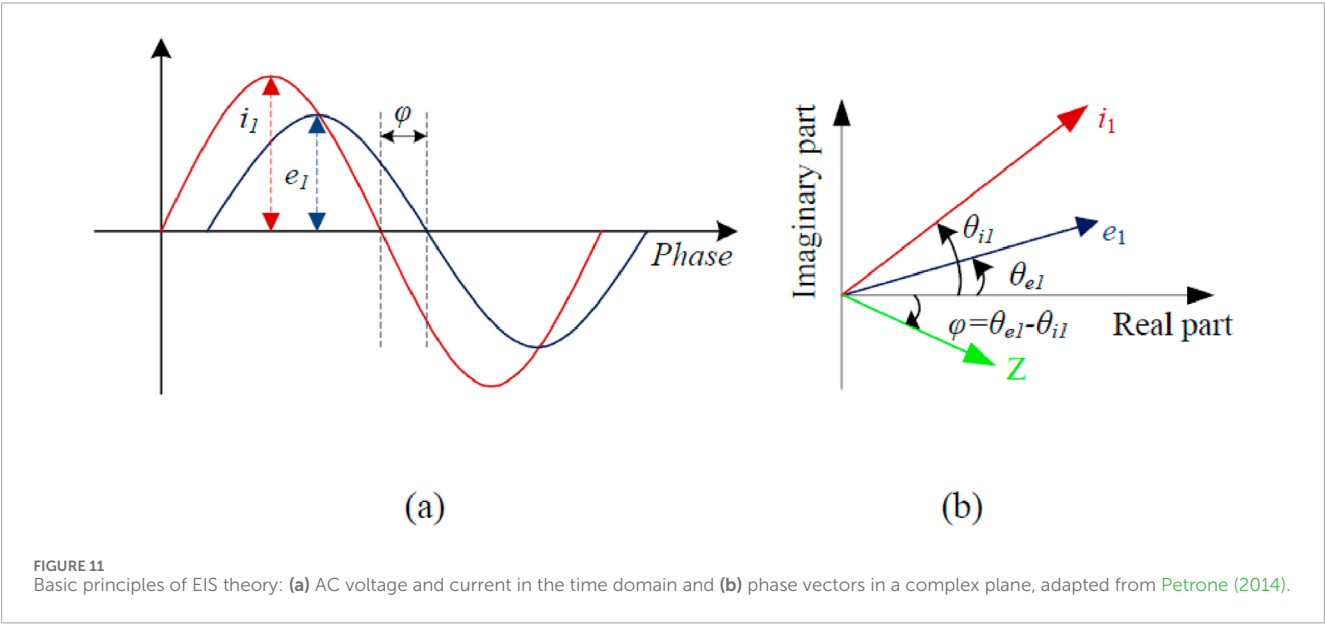
- Perturbation source: Inject a small AC signal (e.g., 10 mV and 100–5 kHz bandwidth) via power converter modulation.
- Measurement: High-resolution voltage/current sensors (ADC ≥ 16 -bit, 10–100 kHz).
- Processing unit: Microcontroller, DSP, or FPGA to handle real-time analysis.

b. Integration challenges

- Must be non-intrusive: Signal injection should not disrupt normal fuel cell operation.
- Must coexist with DC/DC converter control loops (avoiding aliasing or instability).
- Requires EMI shielding and careful grounding to preserve signal integrity.
- Supplementary Table A8 in the appendix shows the comparison of offline and real-time EIS.

TABLE 5 Comparison of scenarios for an overview of powertrain power loss.

Scenario	Primary loss source	Efficiency Trend	Overall loss impact
High speed	Aerodynamic, compressor, and thermal	Efficiency significantly drops	High total power loss
High torque	Electrical resistance	Moderate efficiency drop	Lower power loss than high speed
Without EIS and APCS	Lack of diagnostics and control	Unoptimized efficiency	Uncontrolled total power loss
With EIS and APCS	Good on diagnostics and control	Optimized efficiency	Under controlled total power loss



4.2 Results and analysis

In Figures 11a,b, showing the HFR impedance Nyquist plot, individual increases and decreases can be observed in the numbers, rising from 35 A to 230 A as the current density increases. The main factor contributing to this phenomenon is the moisture content of the membrane. As the current density increases, the water produced by the cathode oxygen reduction reaction (ORR) also increases. In theory, the impact on fuel cell performance can be defined as follows:

- ❖ Optimal moisture level: There is an optimal level of moisture content where the membrane conductivity is maximized without causing flooding.
- ❖ Flooding: At very high current densities, excessive water can flood the electrode, blocking gas transport pathways and reducing the effective area for the ORR.
- ❖ Dry out: At very low current densities, insufficient water production can lead to the membrane drying out, increasing resistance and reducing performance.

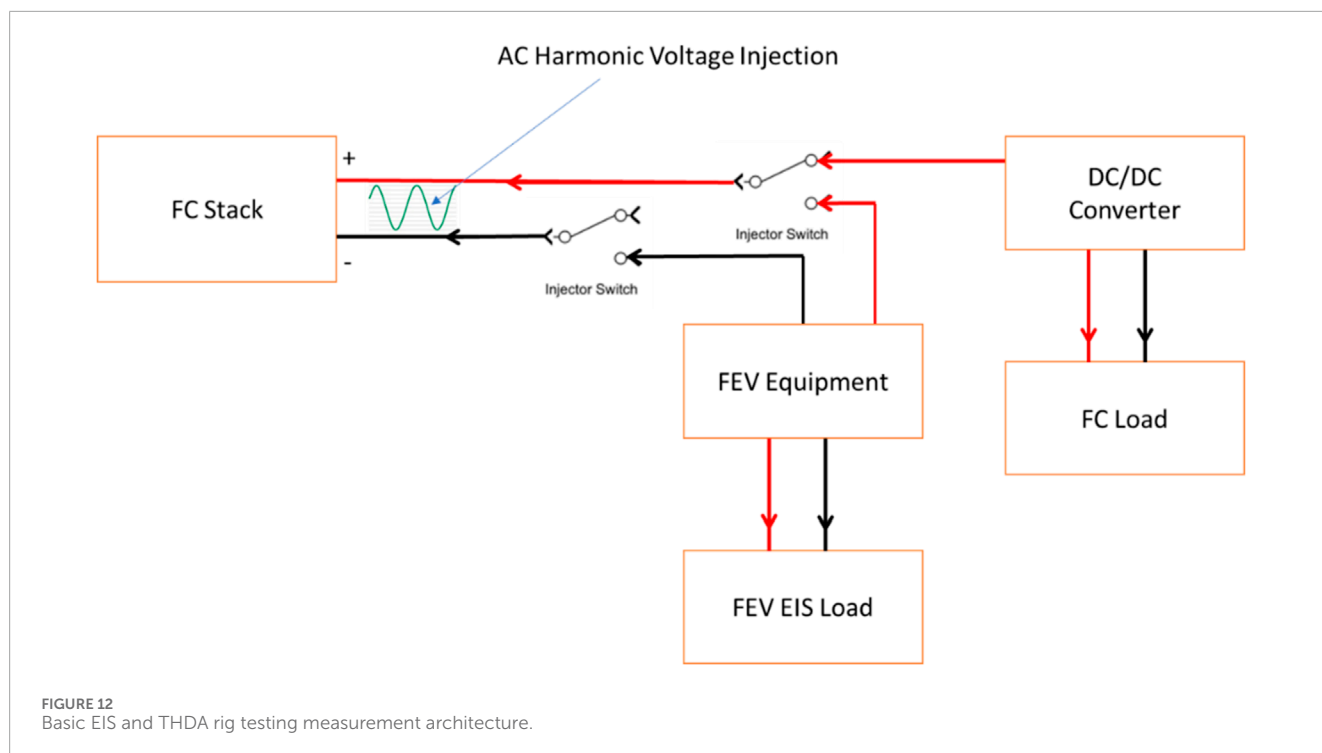
Understanding and managing the balance between current density and ORR is essential for optimizing fuel cell performance and longevity. The relationship between ORR and current density is as follows:

- Increased current density: As the current density increases, the rate of the ORR must also increase to supply the necessary electrons for the reaction. This means more oxygen must be reduced at the cathode.
- Water production: An increase in the ORR rate leads to more water production at the cathode because each ORR event produces water as a byproduct.
- Moisture content: As the current density increases, the moisture content in the membrane also increases due to the higher production of water from the ORR. This can impact the membrane's conductivity and overall fuel cell performance.

The AC perturbation signal has an amplitude of i_1 , represented by the red curve in Figure 11a, and the resulting stack AC voltage has an amplitude of e_1 , represented by the blue curve. The phase value of the current advances that of the voltage by ϕ shown in Figure 11b, shows the corresponding stack impedance in the form of a phase vector. The stack impedance can thus be calculated with its amplitude and phase as:

Humidity plays a crucial role in the performance of proton exchange membrane fuel cells. The EIS data, represented in the Nyquist plot, highlight three key effects of low humidity:

1. Increased high-frequency resistance: The rise in the cell's high-frequency resistance, primarily due to the membrane,



indicates reduced electrolyte (membrane) conductivity at lower humidity.

2. 45° Angle at high frequency: This feature reflects a distributed ohmic resistance coupled with a distributed double layer, suggesting significant ohmic resistance within the catalyst layer.
3. Higher charge transfer resistance: A larger high-frequency impedance arc indicates an increase in charge transfer resistance for the oxygen reduction reaction, further impairing performance.

The architecture in Figure 12 for electrochemical impedance spectroscopy (EIS) and total harmonic distortion analysis (THDA) testing is designed to evaluate the performance and operational characteristics of fuel cells or related powertrain systems. AC signals are generated from a DC/DC converter and injected into the fuel cell stack. The scanned (100–1000 Hz AC signal) feedback from the stack is analyzed using EIS and THDA methods.

The Nyquist plot shown in Figure 13a graphically represents impedance data, with the real component of impedance on the x-axis and the imaginary component on the y-axis. The Bode plot shown in Figure 13b illustrates the relationship between impedance magnitude and phase angle as functions of frequency. The data shows that impedance magnitude decreases at higher current densities, while the injection frequency becomes lower. EIS and THDA are often used in the characterization of fuel cells, batteries, supercapacitors, and other electrochemical devices to assess performance, identify degradation mechanisms, and optimize design or operational conditions.

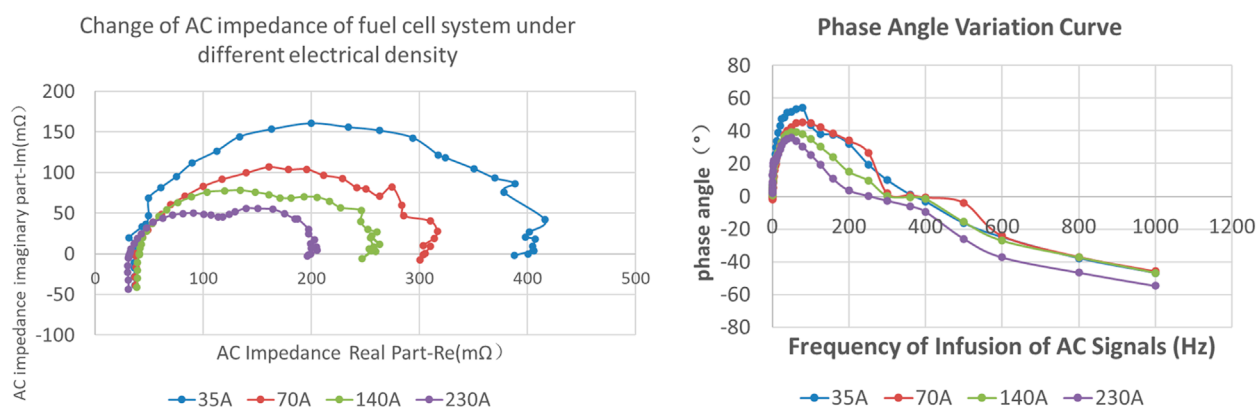
A small sinusoidal signal is superimposed on the stack's operating conditions (current or voltage) using a potentiostat or load tester. The system's response is measured, capturing the fundamental

frequency and its harmonics. In Figure 14, the THDA method is applied to investigate the impedance variations of a stack, which is an alternative way or backup to observe the fuel cell state of health (SOH). In Figure 14, when applied to the fuel cell stack under 35 A load current, the THDA reaches 55%, and the phase angle change decreases to 20°; therefore, EIS and THDA are both well analyzed for the variations of system operation status. In this period, as in the fuel cell stack at the lower power generation period, the efficiency is high while the APCS control method is applied, so this change caused the stack operation to be disturbed.

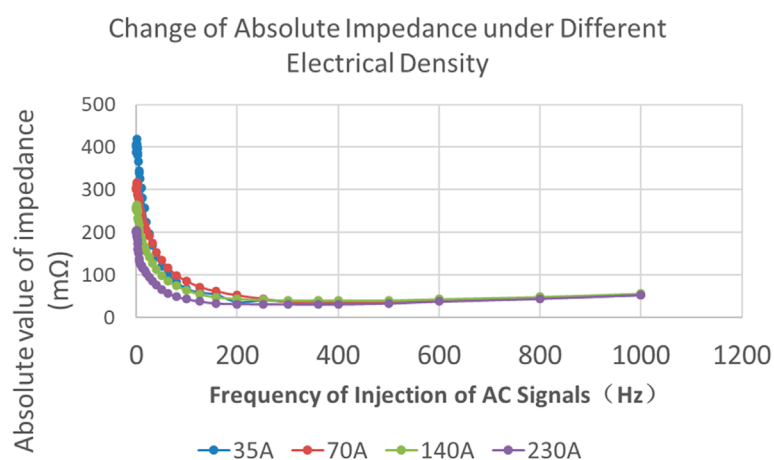
There are some key features for comparing APCS control when using or not using the EIS impedance measurement are shown in Figure 15:

- Efficiency: In the APCS control method, MTPA reduces energy losses, while the fuel cell-battery integration optimizes power generation and consumption.
- Longevity: The reduced load fluctuations on the fuel cell and motor components increase system durability.
- Sustainability: Improved energy utilization lowers hydrogen consumption and extends battery life, contributing to a cleaner, more sustainable vehicle operation.

MTPA control in Equation 11 minimizes the current drawn from the power sources, reducing stress on the fuel cell and extending its lifespan. This integration of fuel cell power generation, battery management, and MTPA motor control using EIS measurement forms the foundation of advanced FCEVs, enabling a smooth and efficient transition to sustainable transportation. Without water management and MTPA, the efficiency map shown in Figure 16 shows reduced high-efficiency regions, increased inefficiencies at high torque and power outputs,



(a)



(b)

FIGURE 13
(a) Nyquist plot and (b) Bode plot under different load currents.

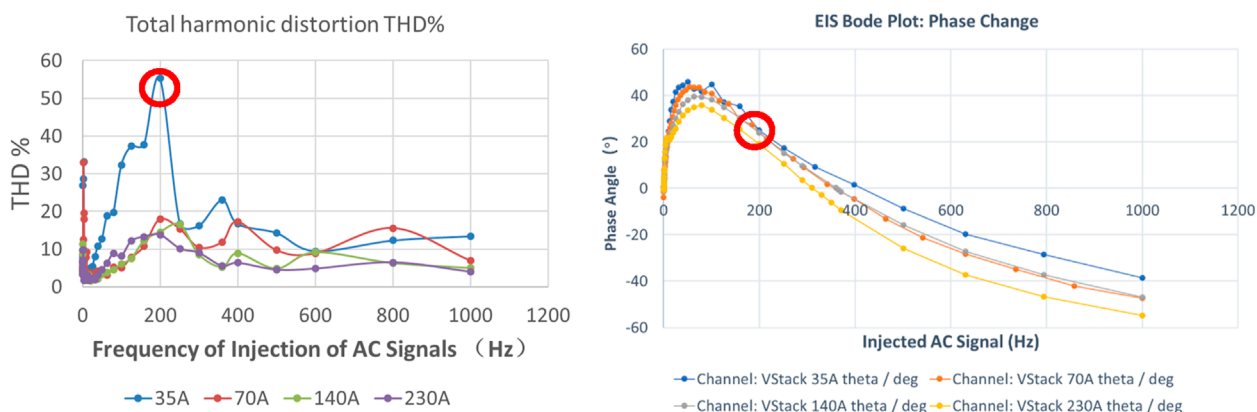


FIGURE 14
THDA and phase angle change plot under different load currents.

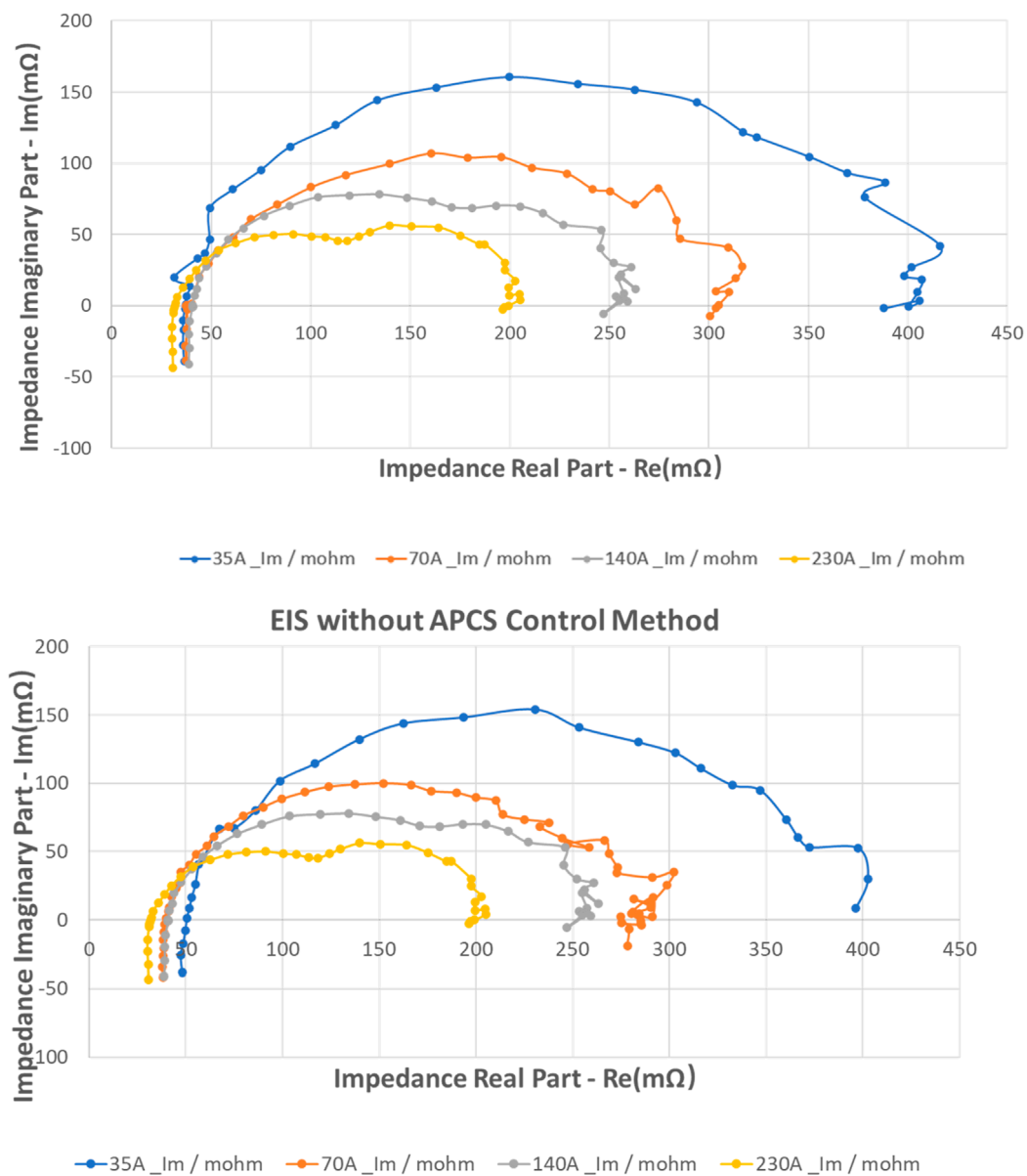


FIGURE 15

(a) Stack impedance measurement under different current densities using APCS and (b) without using APCS control.

and suboptimal performance across varying speeds and loads. Efficiency drops significantly at higher power outputs, where water production and heat generation are excessive. At low-power outputs, dehydration reduces ionic conductivity, further shrinking the efficient operating range.

$$T \propto \psi_m i_q + (L_d - L_q) i_d i_q \quad (11)$$

- T : Torque output
- ψ_m : Permanent magnet flux
- L_d, L_q : Inductances in the d and q axes
- i_d, i_q : Currents in the d and q axes

FCEV vehicle powertrain's performance is compared when using or not using the water management and APCS maximum

efficiency control. Figures 16a,b show that efficiency has been improved after the implementation of both control methods. The vehicle test has shown obvious changes in the powertrain efficiency because the impedance of the stack is under monitoring and control.

The battery charging losses are clarified as internal resistive heat loss, chemical reaction losses, and thermal losses of heat generation when charging at high power. In Figure 17, the maximum charge power is at 34.9 kW, and the maximum power of the fuel cell stack is 67.5 kW. The total energy loss during battery charging using the fuel cell stack with MTPA control can be expressed as follows in Equation 12:

$$\eta_{total} = \eta_{total} \cdot \eta_{DC/DC} \cdot \eta_{battery} \cdot \eta_{motor} \quad (12)$$

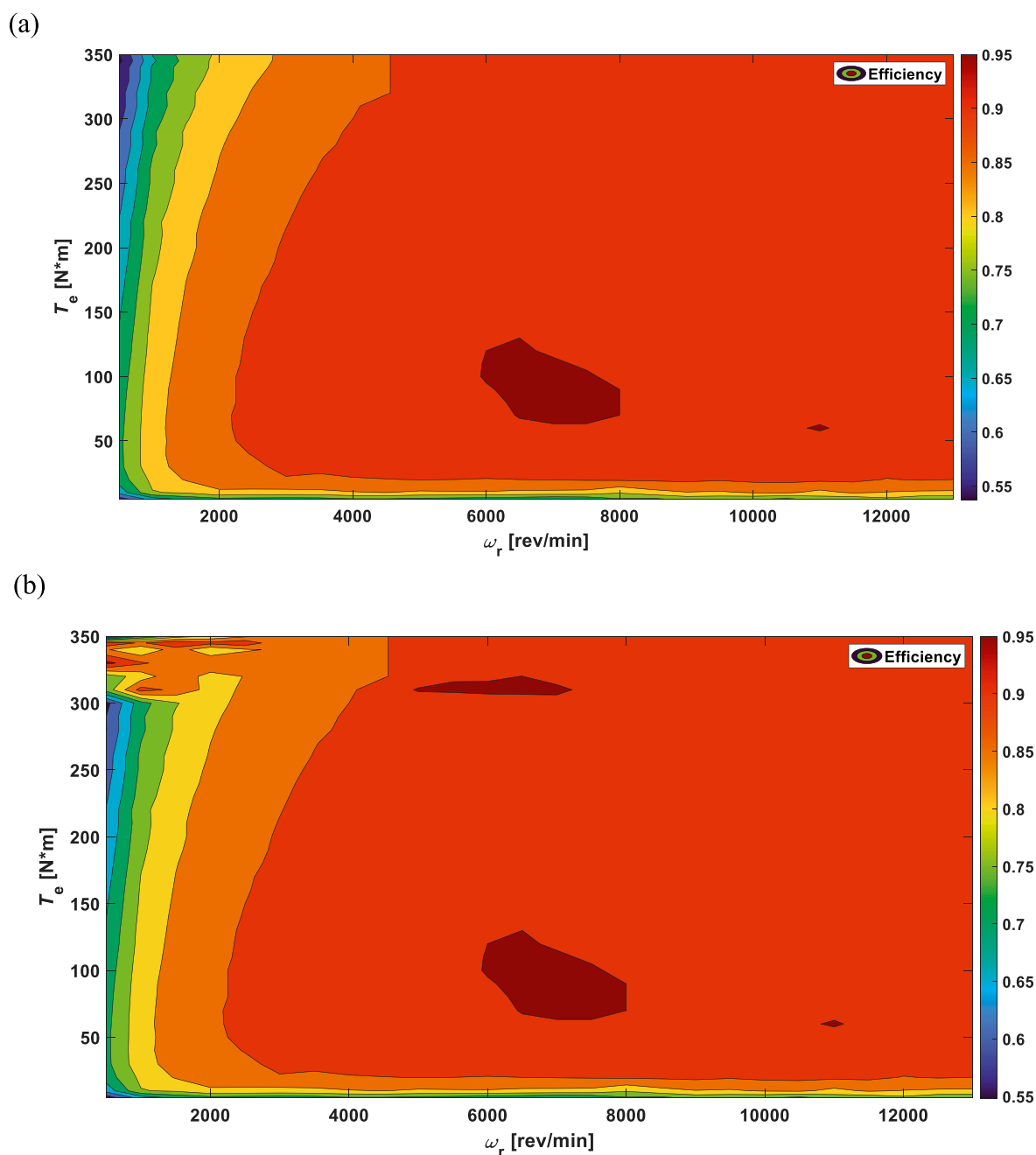


FIGURE 16

(a) FCEV powertrain efficiency map without water management and APCS control and (b) FCEV powertrain efficiency map with water management and APCS control.

High internal resistance in the battery or high-power demand can lead to significant charging losses, impacting range and overall efficiency. Proper MTPA control minimizes motor losses by reducing the current demand for a given torque, indirectly reducing strain on the battery and fuel cell stack. The energy management system (EMS) must ensure that the fuel cell operates at its optimal efficiency point while supplying power for both propulsion and battery charging. The fuel cell stack is generating power while the state of charging (SOC) is less than a certain low range, and the charging event occurs when the vehicle is either accelerating

or maintaining a steady speed. Using batteries with low internal resistance and advanced thermal management will optimize the system efficiency and reduce charging losses. For the MTPA control, ensuring precise motor control will minimize current demand and related losses and improve the entire vehicle powertrain system efficiency.

The hydrogen consumption of a fuel cell stack during the new European driving cycle (NEDC) is a critical metric used to evaluate the efficiency and range of a fuel cell electric vehicle (FCEV). Below is an analysis of hydrogen consumption at various

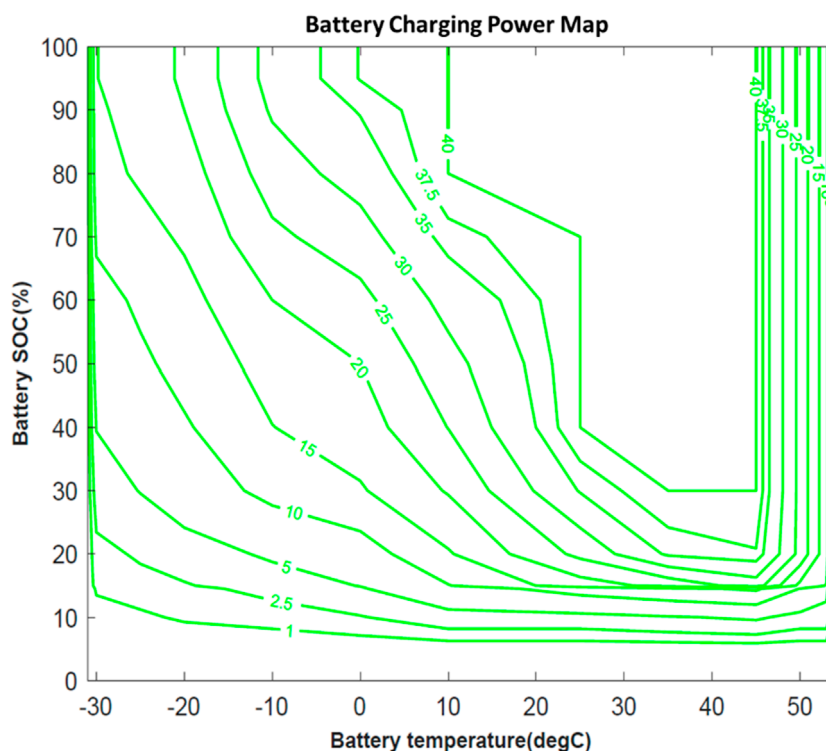


FIGURE 17
FCEV battery charge loss map.

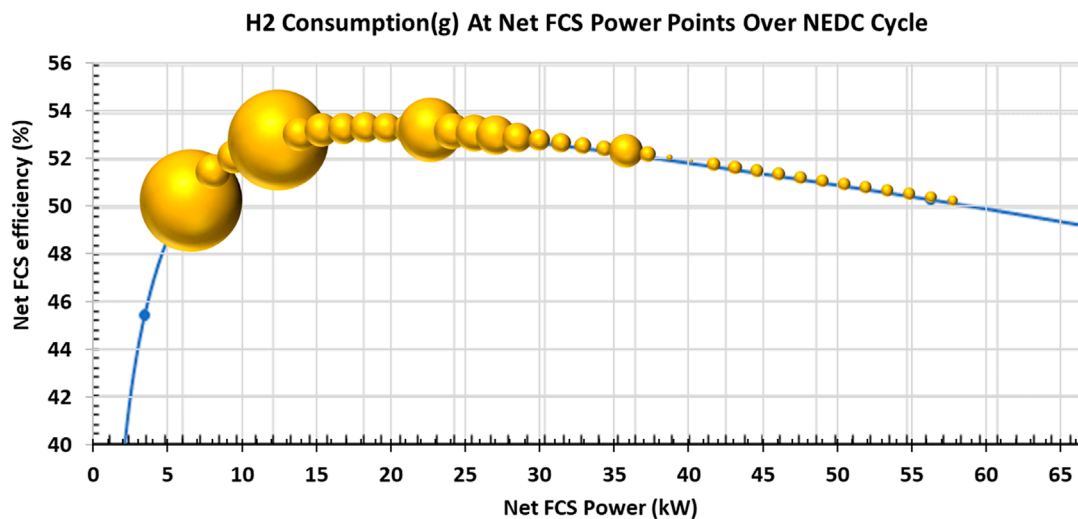


FIGURE 18
Hydrogen consumption at net fuel cell stack power points over NEDC drive cycle.

net power points of the fuel cell stack during the NEDC. In Figure 18, the maximum efficiency of a fuel cell stack is 53.29% when EIS and the APSC/MTPA control method are applied. Fuel cell efficiency is defined as how effectively the system converts hydrogen into electrical power. Higher power points lead to increased hydrogen consumption due to reduced efficiency at high loads. System losses include thermal, electrical, and auxiliary losses (e.g., pumps, fans, and compressors). During

transient operation, power fluctuations during acceleration and deceleration affect overall consumption. The method is to reduce hydrogen consumption and to optimize stack design for better performance across power points and improve fuel cell efficiency.

Energy recovery is used to have regenerative braking to reduce power demand on the fuel cell. Advanced energy management balances power distribution between the fuel cell and the battery.

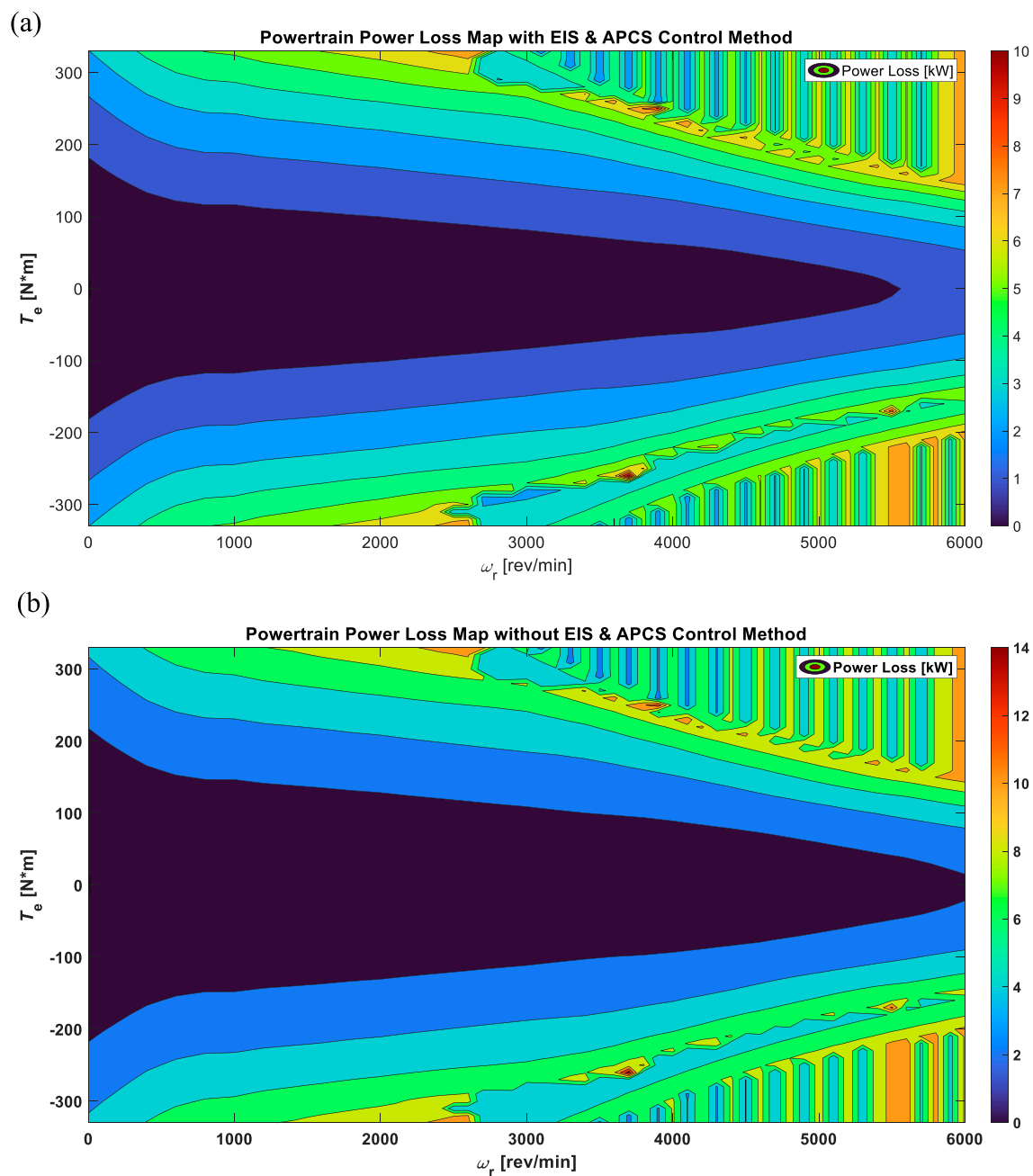


FIGURE 19
(a) Comparison of power loss between EIS and APCS control method and (b) without EIS and APCS control method.

By analyzing hydrogen consumption across the NEDC, this research has refined the fuel cell stacks for better efficiency, extended the range, and optimized performance under varying driving conditions through the various control methods.

4.3 Impact on fuel cell stack power loss

1. High-speed operation

- Loss characteristics: At high speeds, the fuel cell stack experiences increased aerodynamic drag and mechanical losses.

○ Key loss contributors:

- Compressor power: The fuel cell air compressor requires more energy to maintain the necessary airflow, leading to higher parasitic losses.
- Thermal management: Excessive heat generation at high speeds demands greater cooling, further contributing to power loss.
- Efficiency impact: Fuel cell efficiency drops due to higher oxygen demand and reduced polarization curve efficiency.
- Result: High-speed operation leads to higher total power loss.

2 High-torque operation

- Loss characteristics: During high-torque demands (e.g., acceleration or hill climbs), the motor's efficiency decreases due to higher current demands.
- Key loss contributors:
 - Electrical resistance losses in the powertrain.
 - Heat losses in the motor windings and inverters.
- Efficiency impact: Although there is a higher energy demand, the fuel cell operates at a more efficient point on its polarization curve than under high-speed conditions.
- Result: High-torque operation incurs a smaller power loss (by a few kilowatts) than high-speed operation.

3 Total power loss without EIS and APCS methods (shown in Figure 19b)

- Without EIS and the APCS control method:
 - The fuel cell stack lacks precise diagnostics and real-time control optimization.
 - Poor water and energy management significantly worsens system inefficiencies, particularly under dynamic conditions such as high speed and high torque. Power loss has been analyzed using the EIS and APCS methods and found to be minimal within the torque range of -200 Nm to 200 Nm. However, as torque increases beyond this range, power loss rises substantially, with higher torque applications amplifying the losses further. This highlights the critical role of precise control and optimization in mitigating inefficiencies under demanding operational scenarios. Overall power losses remain unmitigated, resulting in lower efficiency and higher hydrogen consumption.

Using advanced methods like in Table 5 can effectively reduce these losses by 45% by enabling better energy allocation, precise water management, and real-time adaptation to operating conditions.

5 Conclusion

Advanced online water management strategies remain central to the efficient, reliable operation of proton exchange membrane fuel cell (PEMFC) systems in automotive powertrains. Real-time diagnostic and control methods—incorporating dynamic algorithms and computational tools—are pivotal for optimizing performance, ensuring system durability, and supporting the broader adoption of clean transportation technologies. Electrochemical impedance spectroscopy (EIS) has proven especially valuable as a real-time diagnostic tool, capable of detecting critical phenomena such as transient flooding and dehydration that conventional offline diagnostics often miss. The incorporation of total harmonic distortion analysis (THDA) within the EIS framework enables continuous monitoring of water dynamics in the fuel cell stack, providing a proactive layer of system protection and performance optimization. The integration of EIS with the adaptive power coordination strategy (APCS) and maximum torque per ampere (MTPA) control further enhances powertrain responsiveness. This approach has led to significant operational improvements, including a 45% reduction in power

loss, a 53.29% increase in efficiency, and a peak battery charging power of 39.4 kW. However, this innovation also introduces computational challenges. Real-time EIS demands increased signal processing capabilities and algorithmic efficiency to ensure viable implementation within embedded automotive systems. These trade-offs must be addressed through optimized hardware-software co-design. Considering recent advancements—such as multi-stack fuel cell systems for high-power applications and novel energy management architectures [e.g., “Progress and challenges in multi-stack fuel cell system for high-power applications: Architecture and energy management”]—the scalable, intelligent control becomes even more important. Additionally, methods for analyzing operating condition combinations to determine optimal water management states [e.g., “Operating conditions combination analysis method of optimal water management state for PEM fuel cell”] underscore the evolving complexity of fuel cell operation and the need for integrated approaches that combine diagnostics, control, and environmental adaptability.

Future research should prioritize the integration of such control-diagnostic methods with multi-stack configurations, explore their applicability across diverse environmental conditions, and assess their compatibility with emerging energy storage technologies. Addressing these challenges will be key to scaling fuel cell technology for high-power, commercially viable applications in next-generation electric vehicles.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

Author contributions

YD: Writing – original draft. YL: Data curation, Validation, Writing – original draft. DT: Validation, Writing – original draft. JZ: Resources, Supervision, Writing – original draft. JC: Formal Analysis, Methodology, Validation, Writing – original draft. HR: Methodology, Software, Writing – original draft. MF: Methodology, Project administration, Writing – original draft.

Funding

The author(s) declare that no financial support was received for the research and/or publication of this article.

Conflict of interest

Authors YD, DT and JZ were employed by Changan UK R&D Centre. Authors YL, JC, and HR were employed by the Changan Deepal Technical Co, Ltd.

The remaining author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated

References

- Amornwongpeeti, S., Kiselychynk, O., Wang, J., Antaloae, C., Soumelidis, M., Thomas, S., et al. (2014). "A combined MTPA and maximum efficiency control strategy for total harmonic distortion analysis." *Int. J. Hydrogen Energy* 39 (9), 4558–4565. doi:10.1016/j.ijhydene.2013.12.180
- Amornwongpeeti, S., Kiselychynk, O., Wang, J., Antaloae, C., Soumelidis, M., and Shah, N. (2016). "A combined MTPA and maximum efficiency control strategy for IPMSM motor drive systems," in *Conference: 2016 international conference on electrical systems for aircraft, railway, ship propulsion and road vehicles and international transportation electrification conference (ESARS-ITEC)*.
- Baricci, A., Mereu, R., Messaggi, M., Zago, M., Inzoli, F., and Casalegno, A. (2017). Application of computational fluid dynamics to the analysis of geometrical features in PEM fuel cells flow fields with the aid of impedance spectroscopy. *Appl. Energy* 205, 670–682. doi:10.1016/j.apenergy.2017.08.017
- Becherif, M., Marie-Cecile, P., Hissel, D., and Zheng, Z. (2018). Determination of the health state of fuel cell vehicle for a clean transportation. *J. Clean. Prod.* 171 (10), 1510–1519. doi:10.1016/j.jclepro.2017.10.072
- Chen, Z., Liu, Y., Ye, M., Zhang, Y., and Li, G. (2021). A survey on key techniques and development perspectives of equivalent consumption minimisation strategy for hybrid electric vehicles. *Renew. Sustain. Energy Rev.* 151, 111607. doi:10.1016/j.rser.2021.111607
- Chen, Z., Zuo, W., Zhou, K., Li, Q., Huang, Y., and Jiaqiang, E. (2023). Multi-objective optimization of proton exchange membrane fuel cells by RSM and NSGA-II. *Energy Convers. Manag.* 277, 116691. doi:10.1016/j.enconman.2023.116691
- Chen, Z., Zuo, W., Zhou, K., Li, Q., Huang, Y., and Jiaqiang, E. (2023). Multi-factor impact mechanism on the performance of high temperature proton exchange membrane fuel cell. *Energy* 278, 127982. doi:10.1016/j.energy.2023.127982
- Chen, Z., Zuo, W., Zhou, K., Li, Q., Yi, Z., and Huang, Y. (2024). Numerical investigation on the performance enhancement of PEMFC with gradient sinusoidal-wave fins in cathode channel. *Energy* 288 (1), 129894. doi:10.1016/j.energy.2023.129894
- De Beer, C., Barendse, P. S., Pillay, P., Bullocks, B., and Rengaswamy, R. (2015). Online diagnostics of HTPM fuel cells using small amplitude transient analysis for CO poisoning. *IEEE Trans. Ind. Electron.* 62, 5175–5186. doi:10.1109/tie.2014.2377131
- Duan, Yu, and Sumner, M. (2012). "A novel current derivative measurement using recursive least square algorithms for sensorless control of permanent magnet synchronous machine," in *Proceedings of the 7th international power electronics and motion control conference*. Haerbin, China: IEEE.
- Etacheri, V., Marom, R., Elazari, R., Salitra, G., and Aurbach, D. (2011). Challenges in the development of advanced Li-ion batteries: a review. *Energy Environ. Sci.* 4 (9), 3243–3262. doi:10.1039/c1ee01598b
- Feng, X., Ouyang, M., Liu, X., Lu, L., Xia, Y., and He, X. (2018). Thermal runaway mechanism of lithium ion battery for electric vehicles: a review. *Energy Storage Mater.* 10, 246–267. doi:10.1016/j.ensm.2017.05.013
- Fu, Z., Zuo, W., Li, Q., Zhou, K., Huang, Y., and Li, Y. (2024). Numerical investigations on liquid cooling plate partially filled with porous medium for thermal management of lithium-ion battery pack. *Publ. Energy* 313, 133926. doi:10.1016/j.energy.2024.133926
- Ganesh, A. H., and Xu, B. (2022). A review of reinforcement learning based energy management systems for electrified powertrains: progress, challenge, and potential solution. *Renew. Sustain. Energy Rev.* 154 (October 2021), 111833. doi:10.1016/j.rser.2021.111833
- Gao, H., Wang, Z., Yin, S., Lu, J., Guo, Z., and Ma, W. (2021). Adaptive real-time optimal energy management strategy based on equivalent factors optimization for hybrid fuel cell system. *Int. J. Hydrogen Energy* 46 (5), 4329–4338. doi:10.1016/j.ijhydene.2020.10.205
- Hink, S., and Roduner, E. (2013). Application of a contact mode AFM for spatially resolved electrochemical impedance spectroscopy measurements of a Nafion membrane electrode assembly. *Phys. Chem. Chem. Phys.* 15, 1408–1416. doi:10.1039/c2cp42843a
- Huangfu, Y., Li, P., Pang, S., Tian, C., Quan, S., Zhang, Y., et al. (2022). An improved energy management strategy for fuel cell hybrid vehicles based on pontryagin's minimum principle. *IEEE Trans. Industry Appl.* 58 (3), 4086–4097. doi:10.1109/tia.2022.3157252
- Ihonen, J., Mikkola, M., and Lindbergh, G. (2004). Flooding of gas diffusion backing in PEFCs. *J. Electrochem. Soc.* 151, A1152. doi:10.1149/1.1763138
- Li, J., Wang, H., He, H., Wei, Z., Yang, Q., and Igic, P. (2021). Battery optimal sizing under a synergistic framework with DQN-Based power managements for organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.
- the fuel cell hybrid powertrain. *IEEE Trans. Transp. Electrification* 8 (1), 36–47. doi:10.1109/tte.2021.3074792
- Lu, X., Wu, Y., Lian, J., Zhang, Y., Chen, C., Wang, P., et al. (2020). Energy management of hybrid electric vehicles: a review of energy optimization of fuel cell hybrid power system based on genetic algorithm. *Energy Convers. Manag.* 205, 112474. doi:10.1016/j.enconman.2020.112474
- Meddings, N., Heinrich, M., Overney, F., Lee, J. S., Ruiz, V., Napolitano, E., et al. (2020). Application of electrochemical impedance spectroscopy to commercial Li-ion cells: a review. *J. Power Sources* 480, 228742. doi:10.1016/j.jpowsour.2020.228742
- Onanena, R., Candusso, L. O. D., Same, A., Hissel, D., and Aknin, P. (2010). Estimation of fuel cell operating time for predictive maintenance strategies. *Int. J. Hydrogen Energy* 35 (15), 8022–8029. doi:10.1016/j.ijhydene.2010.05.039
- O'Rourke, J., Ramani, M., and Arcak, M. (2008). Using electrochemical impedance to determine airflow rates. *Int. J. Hydrogen Energy* 33, 4694–4701. doi:10.1016/j.ijhydene.2008.05.058
- Petrone, R. (2014). *Electrochemical Impedance Spectroscopy for the on-board diagnosis of PEMFC via on-line identification of Equivalent Circuit Model parameters*. Fisciano, Italy: University of Salerno.
- Tang, Z., Huang, Q. A., Wang, Y. J., Zhang, F., Li, W., Li, A., et al. (2020). Recent progress in the use of electrochemical impedance spectroscopy for the measurement, monitoring, diagnosis and optimization of proton exchange membrane fuel cell performance. *J. Power Sources* 468, 228361. doi:10.1016/j.jpowsour.2020.228361
- Tang, X., Shi, L., Zhang, Y., Li, B., Xu, S., and Song, Z. (2024a). Degradation adaptive energy management strategy for FCHEV based on the Rule-DDPG method: tailored to the current SOH of the powertrain. *IEEE Trans. Transp. Electrification* 11, 993–1003. doi:10.1109/tte.2024.3399054
- Tang, X., Yang, M., Shi, L., Hou, Z., Xu, S., and Sun, C. (2024b). Adaptive state-of-health temperature sensitivity characteristics for durability improvement of PEM fuel cells. *Chem. Eng. J.* 491 (1), 151951. doi:10.1016/j.cej.2024.151951
- Wang, Q., Mao, B., Stolarov, S. I., and Sun, J. (2019). A review of lithium ion battery failure mechanisms and fire prevention strategies. *Prog. Energy Combust. Sci.* 73, 95–131. doi:10.1016/j.pecs.2019.03.002
- Wasterlain, S. (2010). *Approches expérimentales et analyse probabiliste pour le diagnostic de piles à combustible de type PEM*. Besancon, France: Université de Franche-Comté.
- Yuan, X., Colin, J., Blanco, M., Wang, H., Zhang, J., and Wilkinson, D. P. (2006). AC impedance diagnosis of a 500 W PEM fuel cell stack Part I: stack impedance. *J. Power Sources* 161, 920–928. doi:10.1016/j.jpowsour.2006.05.003
- Yuan, X., Wang, H., Colin Sun, J., and Zhang, J. (2007). AC impedance technique in PEM fuel cell diagnosis-A review. *Int. J. Hydrogen Energy* 32, 4365–4380. doi:10.1016/j.ijhydene.2007.05.036
- Zhang, Q., Lin, R., Técher, L., and Cui, X. (2016). Experimental study of variable operating parameters effects on overall PEMFC performance and spatial performance distribution. *Energy* 115, 550–560. doi:10.1016/j.energy.2016.08.086
- Zhang, Y., Ma, R., Zhao, D., Huangfu, Y., and Liu, W. (2021). A novel energy management strategy based on dual reward function q-learning for fuel cell hybrid electric vehicle. *IEEE Trans. Industrial Electron.* 69 (2), 1537–1547. doi:10.1109/tie.2021.3062273
- Zhao, X., Wang, L., Zhou, Y., Pan, B., Wang, R., Wang, L., et al. (2022). Energy management strategies for fuel cell hybrid electric vehicles: classification, comparison, and outlook. *Energy Convers. Manag.* 270, 116179. doi:10.1016/j.enconman.2022.116179
- Zhou, W., Yang, L., Cai, Y., and Ying, T. (2018). Dynamic programming for new energy vehicles based on their work modes part ii: fuel cell electric vehicles. *J. Power Sources* 407, 92–104. doi:10.1016/j.jpowsour.2018.10.048
- Zhou, Q., Li, J., Shuai, B., Williams, H., He, Y., Li, Z., et al. (2019). Multi-step reinforcement learning for model-free predictive energy management of an electrified off-highway vehicle. *Appl. Energy* 255 (2019), 113755–601. doi:10.1016/j.apenergy.2019.113755
- Zhou, J., Liu, J., Xue, Y., and Liao, Y. (2022). Total travel costs minimization strategy of a dual-stack fuel cell logistics truck enhanced with artificial potential field and deep reinforcement learning. *Energy* 239, 121866. doi:10.1016/j.energy.2021.121866