

Grid Integration of Fuel Cell Vehicles: A Review of V2G System Design and Control

Sudhir Gore¹, Dr. Nilesh Bodne², Dr. Kiran Kimmatkar³

Department Of Electrical Engineering, Vidarbha Institute Of Technology Uti, Umrer Road,, Nagpur, , Maharashtra, India

Abstract This This comprehensive review examines the design, simulation, and analysis of a Fuel Cell Vehicle-to-Grid (FCV2G) system—an emerging technology that enables hydrogen-powered fuel cell vehicles to supply electricity directly to the utility grid. The paper evaluates the complete power conversion chain modelled in MATLAB/Simulink: a Proton Exchange Membrane Fuel Cell (PEMFC) electrochemical model, a PI-controlled DC-DC boost converter, a Sinusoidal Pulse Width Modulation (SPWM)-driven full-bridge DC-AC inverter, and an LC output filter for harmonic suppression. Simulation results confirm a DC-DC conversion efficiency of 93.75% at 0.76 duty cycle and a DC-AC conversion efficiency of 95.4%, yielding a high aggregate power conversion quality. The system handles a 10 kW fuel cell stack feeding domestic loads at 220 V/50 Hz, routing surplus energy to the grid and supplementing deficits during peak demand. This review contextualizes the contributions within the broader V2G literature, provides detailed discussion of each subsystem with original block diagrams, critically analyses limitations, and outlines future research directions for advancing FCV2G deployment.

Keywords: Fuel Cell Vehicle (FCV), Vehicle-to-Grid (V2G), Proton Exchange Membrane Fuel Cell (PEMFC), DC-DC Boost Converter, PI Controller, SPWM Inverter, Power Electronics, Renewable Energy, Grid Integration, MATLAB/Simulink

1. INTRODUCTION

- accelerating global transition toward low-carbon energy systems has placed the electrification of transportation at the forefront of both engineering research and public policy. Electric vehicles (EVs), in their various forms, represent not merely a shift in transportation fuels but a potential revolution in how distributed electrical energy is stored and managed. Among the most consequential manifestations of this potential is Vehicle-to-Grid (V2G) technology—the ability of a parked or idle vehicle to discharge energy back into the utility grid, effectively functioning as a mobile distributed energy resource [1,2].

V2G technology was first systematically proposed by Kempton and Letendre [3] in the late 1990s and has since attracted extensive research attention. However, the vast majority of V2G studies have focused on Battery Electric Vehicles (BEVs), whose lithium-ion battery packs provide a convenient bidirectional energy buffer. BEV-based V2G introduces well-documented concerns: battery degradation

from frequent deep cycling, limited energy density constraining discharge duration, and the inherently finite state of charge that limits a vehicle's ability to sustain grid support over extended periods [4,5].

Fuel Cell Vehicles (FCVs), by contrast, generate electricity electrochemically from hydrogen fuel rather than drawing down a stored charge. As long as hydrogen is supplied, a fuel cell can produce power continuously—making FCVs fundamentally more suitable for sustained V2G operation than BEVs. The only byproduct of fuel cell operation is water, and modern PEMFC stacks achieve high power densities with rapid cold-start capability [6,7]. Studies have demonstrated that FCVs can outperform BEVs during extended grid-stress events, such as prolonged peak demand periods or large renewable output drops, precisely because they are not capacity-constrained in the same way [8].

The paper by Navya Surya Praveena and Uday Ashish presents a MATLAB/Simulink simulation of a complete FCV2G power conversion interface, from the electrochemical fuel cell model through a DC-DC boost converter and DC-AC inverter to grid-compatible AC output, controlled by a PI strategy. This review synthesizes and critically evaluates those contributions, embeds the work within the current state of the literature, provides annotated block diagrams for each subsystem, and identifies directions for future research..

II LITERATURE REVIEW

2.1 Origins and Evolution of Vehicle-to-Grid Technology

The concept of using parked vehicles as distributed energy resources was formalized by Kempton and Letendre [3] and later elaborated by Kempton and Tomic [9], who provided the first quantitative framework for V2G economic viability. Their analyses showed that vehicles spend roughly 95% of their lifetime parked—an enormous untapped energy reservoir. This insight catalyzed a generation of V2G research spanning power electronics, control systems, grid economics, and transportation engineering.

Early V2G implementations focused almost exclusively on BEVs and plug-in hybrid electric vehicles (PHEVs). Brooks [10] demonstrated prototype BEV-to-grid power injection, while Tomic and Kempton [11] quantified the revenue potential of V2G ancillary services—frequency regulation in particular—showing that V2G participation could offset

vehicle ownership costs. These foundational studies established the technical and economic framing that continues to shape the field.

2.2 Fuel Cells in Vehicle-to-Grid Applications

The integration of fuel cells with grid support functions was explored early by Lipman et al. [12], who evaluated stationary fuel cell systems for combined heat and power (CHP) and grid backup. The extension to mobile FCVs as grid assets was a natural evolution: Kissock [13] noted that hydrogen vehicles operating in V2G mode could provide regulation services with lower lifecycle degradation than BEVs, since fuel cell stacks degrade primarily with operating hours rather than with charge cycles.

Oldenbroek et al. [14] provided one of the first detailed analyses of FCV2G at fleet scale, demonstrating that a coordinated fleet of hydrogen fuel cell buses could supply significant grid ancillary services while maintaining transportation function. Their results highlighted the value of fuel cells' continuous generation capability for frequency regulation markets, which require fast and sustained power response. Inci et al. [15] subsequently examined active and reactive power control strategies for grid-connected fuel cell systems, showing that careful inverter control can enable both real and reactive power injection—expanding the grid service portfolio of FCVs.

More recently, Mebarki et al. [16] analyzed PEM fuel cell vehicle energy efficiency across realistic drive cycles, providing empirical efficiency data that inform power conversion design. Bi et al. [17] proposed novel high-gain DC-DC converter topologies specifically targeting fuel cell voltage step-up requirements, while Al-Saffar and Ismail [18] developed converters with minimized input ripple to protect fuel cell membranes from current pulsations that accelerate degradation.

2.3 DC-DC Power Conversion for Fuel Cells

The DC-DC boost converter is the critical interface between the low, variable fuel cell output voltage and the stable high-voltage DC bus required by the downstream inverter. Hasaneen and Elbaset Mohammed [19] provided a foundational design and simulation methodology for DC-DC boost converters in this context. The converter must simultaneously provide high voltage gain, low input ripple (to protect the fuel cell), and high efficiency across wide load ranges.

The conventional single-switch boost converter used in the reviewed paper is well-established but has known limitations at high duty cycles (above approximately $D = 0.7$), including switch stress, diode reverse-recovery losses, and efficiency degradation [20]. Advanced topologies—interleaved boost converters, coupled-inductor converters, switched-capacitor converters—have been proposed to address these limitations while achieving voltage gains of 5:1 or greater [21]. The duty cycle of $D = 0.76$ reported in the paper is notably high, approaching the boundary where standard boost converter efficiency degrades significantly, making the reported 93.75% efficiency a notable result warranting experimental validation.

2.4 Inverter Control and Grid Synchronization

The DC-AC inverter and its control system are responsible for generating a grid-synchronized AC waveform and managing real and reactive power injection. Sinusoidal PWM (SPWM) is the classical approach used in the reviewed paper, while more advanced techniques including Space Vector PWM (SVPWM) and hysteresis current control have been shown to offer lower harmonic distortion and faster dynamic response [22].

Grid synchronization is typically achieved through a Phase-Locked Loop (PLL), which tracks the grid voltage phase and frequency in real time. The reviewed paper does not explicitly discuss the PLL implementation, which is a notable gap in the described control architecture. Celik et al. [23] provide a detailed treatment of grid-connected fuel cell inverter control including PLL design, harmonic compensation, and islanding detection—aspects critical for safe real-world V2G deployment.

Anderson et al. [24] addressed fuel cell system design and control for transport applications, noting that the inverter control strategy significantly influences fuel cell operating point stability. Poorly designed inverter control can introduce low-frequency oscillations in the DC bus that stress the fuel cell membrane and reduce its lifetime. The PI controller's ability to suppress these oscillations in the reviewed system is demonstrated by the stable output voltage waveforms.

2.5 PI and Advanced Control Strategies

Proportional-Integral (PI) control is the dominant approach in industrial V2G power converters due to its simplicity, robustness, and well-understood tuning methods [25]. The PI controller eliminates steady-state error through the integral term while the proportional term provides immediate dynamic response. Larminie and Dicks [26] note that PI control is well-suited to the relatively slow dynamics of PEMFC thermal and electrochemical processes, though it may struggle with faster electrical transients.

Advanced control strategies studied in the V2G context include Model Predictive Control (MPC), which optimizes control actions over a prediction horizon to minimize a cost function—enabling simultaneous regulation of voltage, current, and power factor [27]. Fuzzy logic controllers have also been proposed for fuel cell systems because of their ability to handle the non-linear, parameter-uncertain fuel cell dynamics without an explicit mathematical model [28]. Adaptive PI controllers that adjust gains in real time based on operating conditions have shown promise for maintaining performance across the full fuel cell operating range [29]

III. SYSTEM ARCHITECTURE

FCV2G system follows a four-stage power conversion chain, as illustrated in Fig. 1 below. The PEMFC stack generates variable low-voltage DC, which is stepped up by the boost converter to a stable 220 V DC bus, converted to AC by the full-bridge inverter, filtered by the LC stage, and injected into the grid via a transformer. Power flow is bidirectionally managed: surplus power goes to the grid when domestic demand is below FCV capacity, and the grid supplements when demand exceeds it

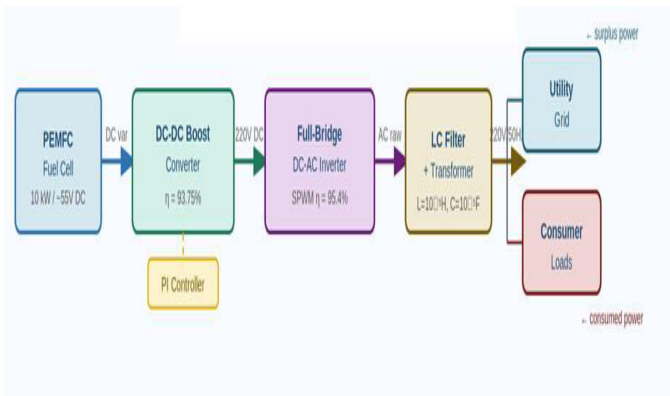


Figure 1: FCV2G System Power Conversion Chain – PEMFC to Grid Interface

Electrochemical Framework

The fuel cell model implemented in MATLAB/Simulink is based on the well-established PEMFC dynamic model of Purkrushpan and Peng [34], which captures the key electrochemical and thermodynamic phenomena governing stack voltage output. The output stack voltage V_{fc} is expressed as the Nernst (open-circuit) voltage minus the sum of three loss voltage terms:

$$V_{fc} = V_{nernst} - (V_{con} + V_{act} + V_{ohmic})$$

The Nernst voltage accounts for operating temperature (T_{fc} in Kelvin) and the partial pressures of hydrogen (P_{H2}) and oxygen (P_{O2}), with the standard reference voltage $E_0 = 1.229$ V. Concentration losses (V_{con}) arise from mass transport limitations at high current densities; activation losses (V_{act}) represent the kinetic energy barriers of the electrode reactions; and ohmic losses (V_{ohmic}) account for membrane and contact resistances R_M and R_C . This formulation is well-validated against experimental PEMFC data in the literature

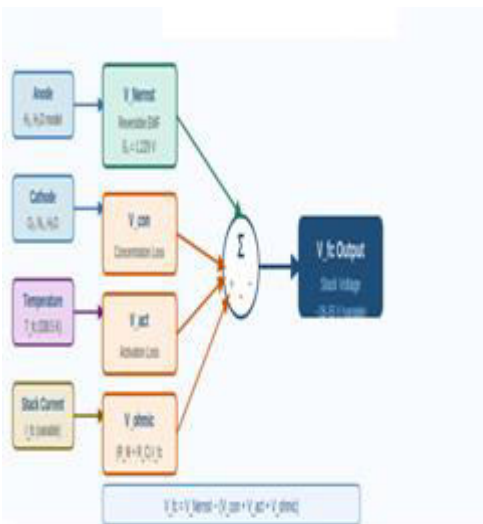


Figure 2: PEMFC Electrochemical Voltage Model – Signal Flow from Inputs to Stack Voltage Output

Anode and Cathode Sub-Models

The model separates anodic and cathodic dynamics: the anode block captures hydrogen partial pressure dynamics and water production, while the cathode block models oxygen consumption, nitrogen dilution, and cathode-side water activity. This separation, consistent with the approach of Khan and Labal [35], improves simulation fidelity and enables independent analysis of each electrode's contribution to overall performance—important for optimizing fuel utilization and membrane humidification.

Fuel Cell Parameters

Key simulation parameters include: anode volume $V_a = 6.495$, cathode volume $V_c = 12.96$, active cell area $A_{fc} = 232.0$ cm², $N = 35$ cells in series, operating temperature $T = 338.5$ K, Faraday constant $F = 96485$ C/mol, and mole fractions $Y_{H2} = 0.99$, $Y_{O2} = 0.21$, $Y_{N2} = 0.79$. The hydrogen and oxygen inlet flows are $K1 = 7.034 \times 10^{-3}$ and $K2 = 7.036 \times 10^{-3}$ mol/s respectively.

Dynamic Load Response

The stack is tested under a variable load profile using resistances ranging from 0.175Ω to 5Ω over 100 seconds. Results confirm the expected inverse current-voltage relationship: at approximately 28 seconds, current peaks near 160 A while voltage drops to approximately 26 V, consistent with significant ohmic and concentration losses under high current density. Peak power reaches approximately 5 kW. This nonlinear characteristic underlines the necessity of the downstream boost converter for voltage stabilization.

. DC-DC Boost Converter Design

Design Rationale

The fuel cell's variable, low-magnitude DC output (typically 20–60 V under load) cannot directly drive a grid-tied inverter, which requires a stable, elevated DC bus voltage. The DC-DC boost converter performs this voltage conditioning role. Its gain is given by $1/(1-D)$, where D is the duty cycle; at $D = 0.76$, the converter achieves a nominal gain of approximately 4.17, stepping up a 55 V fuel cell voltage to the required 220 V DC bus [



Figure 3: DC-DC Boost Converter with PI Closed-Loop Control – Inductance, Switching, and Feedback Path

Converter Parameters and Performance

The converter is designed with inductance $L = 10^{-3}$ H, capacitance $C = 10^{-4}$ F, and switching frequency 5 kHz. At

equilibrium, the duty cycle stabilizes at $D = 0.76$, and the converter achieves a DC-DC conversion efficiency of 93.75%. Output voltage ramps up smoothly and settles near 200 V, while the output current stabilizes at approximately 65 A. The fuel cell input voltage correspondingly stabilizes near 55 V, demonstrating effective PI regulation of the boost converter duty cycle.

PI Controller

The PI controller minimizes the error between the 220 V reference and the measured DC bus voltage, generating a modulated duty cycle signal. Parameters used are proportional constant $K_p = 0.6$, integral constant $K_i = 8$, and loop gain $K = 0.007$. The integral term eliminates the steady-state voltage error while the proportional term provides fast transient response. As Larminie and Dicks [26] note, the relatively slow electrochemical dynamics of PEMFCs make PI control a well-matched and practically sufficient strategy for converter regulation.

This case is similar to case 1 and 2 in section 1. Here also the effect of UG frequency drop is studied for the proposed system with ANN controller. At $t = 2$ sec, UG frequency drops from 50 to 49 Hz. ANN based controller also performs current and power limiting properties as evident from waveforms. When waveforms of ANN based controller and PI based controller is compared head to head, we can observe that

IV. CONCLUSION

This review has provided a comprehensive analysis of the FCV2G system designed and simulated by Navya Surya Praveena and Uday Ashish, contextualizing their contributions within the broader landscape of V2G research spanning over two decades. The work demonstrates the technical feasibility and high efficiency of integrating fuel cell vehicles with the utility grid through a well-designed power conversion chain.

The key contributions of the reviewed study are: (i) a complete MATLAB/Simulink simulation framework covering PEMFC electrochemical modelling, DC-DC boost conversion with PI control, and full-bridge DC-AC inversion with LC filtering; (ii) dynamic load testing revealing the nonlinear current-voltage-power characteristics of the PEMFC stack; (iii) quantified conversion efficiencies of 93.75% (DC-DC) and 95.4% (DC-AC) demonstrating the viability of the power conversion chain; and (iv) demonstration of surplus power routing to the grid and deficit supplementation—the core V2G operating modes.

The fundamental advantage of FCVs over BEVs in V2G applications—continuous power generation as long as hydrogen is available—is well-supported by both the simulation results and the broader literature reviewed here. Addressing the identified gaps, particularly bidirectional operation, realistic grid modelling, PLL-based synchronization, and techno-economic analysis, will be essential for translating these compelling simulation results into deployable FCV2G infrastructure. As hydrogen infrastructure matures and green hydrogen costs decline, FCV2G technology is poised to become a significant

contributor to grid flexibility and renewable energy integration.

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