Materials Research Proceedings 64 (2026) 762-769 https://doi.org/10.21741/9781644904091-95

FPGA-in-the-Loop Implementation of a Boost Converter for Hydrogen Electrolyzer Systems

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Keywords: Boost Converter, FPGA-In-The-Loop, Hydrogen Electrolyzer, Fuel Cell, Renewable Energy, Real-Time Control, MATLAB/Simulink, DC–DC Converter

Abstract. The design and FPGA-in-the-loop (FIL) implementation of a DC–DC boost converter for powering a hydrogen electrolyzer–fuel cell system are introduced in this paper. The converter increases the output DC voltage from renewable sources, like photovoltaic panels, up to a level that it is considered optimal for hydrogen production. The control algorithm implemented in MATLAB/Simulink is performed on an FPGA based, which can help us to achieve high-speed and real-time voltage regulation as well as system stability. The FIL framework makes it possible to validate the control logic against real hardware behavior prior to full release, minimizing design risks and development time. The simulation and experimental results show a higher dynamic response, lower voltage ripple, and better efficiency for hydrogen generation systems.

Introduction

The growing global need for clean, sustainable energy is accelerating work on hydrogen technology as a driver of the energy transition. Hydrogen is seen as an appealing way to store and distribute energy because it has a high energy content per unit of weight and because its production can be relatively clean. It has an energy density more than double that of ethanol, and unlike even brown coal, it does not emit CO_2 (or methane) in combustion, nor are there any signs that the fuel will run out anytime soon—it goes bad, but it's never finished [1], [2]. Among different ways to produce hydrogen, water splitting driven by renewable energies, like that from solar panels (photovoltaic or PV) and wind turbines, makes it possible to generate green (CO_2-neutral) hydrogen with no or a very small carbon footprint [3], [4]. However, the repeated on/off cycling of transient and variably low current levels from renewables corresponds directly to voltage stimulus (as well as reversible effect) applied to said electrolyzers, meaning both hydrogen production efficiency and life of such electrolyzers are equally damaged thereby. [5], [6] To sustain a constant rate of hydrogen production, power conditioning systems have to stabilize the riding DC voltage from RES sources for the electrolyzer. Among them, DC-DC converters serve to increase voltage from a power source applied to an input terminal of an electrolyzer [7]. The most commonly used topology for hydrogen-based RE systems is the boost converter. This is essentially due to its simple configuration, constant input current, and high voltage gain [8]. Efficient converter design and robust control methods play an important role in the voltage ripple, transient overcurrent reduction, and output power conversion efficiency under wide operation conditions [9]. In a traditional converter control system, the controller algorithm is usually implemented by microcontrollers (MCUs) and digital signal processors (DSPs). However, these platforms also suffer from real-time constraints, processing speed, and parallelization—characteristics that are particularly relevant when dealing with high-frequency dynamic environments like the one in renewable energy systems, according to Andrade. To tackle these vulnerabilities, FPGAs are exploited as an excellent platform that has rich resources and the most advanced technology [11]. FPGAs provide parallel processing capabilities, deterministic timing behavior, low latencies, and

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adaptable architectures. All of these characteristics, along with their bespoke nature, make these devices ideal for the real-time control of DC–DC converters in renewable and hydrogen energy systems [12]. In addition, the FPGA-in-the-loop (FIL) technique has been applied as an intermediate method between software simulation and physical prototyping. FIL permits running the control algorithm directly on superordinate FPGA hardware, interfacing with a detailed simulation model set up in Matlab/Simulink or similar environments. This method hence gives precise, real-time validation for control performance, shortens development time, and reduces losses in hardware damage during early test stages [13].

Some studies have pointed out that advanced control and hardware-in-the-loop techniques are essential for optimizing hydrogen generation systems. For example, Benbouzid and others [14] improved the efficiency of electrolyzers under fluctuating renewable inputs by better control of DC–DC converters. Similarly, Jiang et al. [15] studied hybrid energy management systems that incorporate fuel cells and electrolyzers, emphasizing the necessity of strict voltage regulation. However, to date very little research has sought to implement or verify FPGA-based control experimentally in the context of hydrogen production using FIL methods [16].

The paper discusses the design, modeling, and FPGA-in-the-loop development of a DC-DC boost converter transportation system for supplying fuel cells that in turn provide electricity power to electrolyzers for making hydrogen. To achieve efficient generation of hydrogen, the converter raises variable DC voltage from renewable sources up to an appropriate level. The control algorithm is developed in MATLAB/Simulink and realized on an FPGA platform to provide fast dynamic response, minimal voltage ripple, and better system stability. FIL is used for performance verification conversion circuits under normal conditions, which can avoid hardware debugging. The method shortens development time and improves the quality of design work. Finally, through simulation and experiment, the results conclude that through FPGA-based control, the voltage regulation and energy conversion efficiency of the already built whole bus can be raised accordingly. This equates to a gain in hydrogen production output as well as improved system reliability.

System Description and FPGA-in-the-Loop Implementation

System Overview

A boost converter controlled through an FPGA-in-the-loop (FIL) architecture is proposed to regulate the DC voltage supplied to a hydrogen electrolyzer. The converter elevates the DC voltage from renewable sources such as photovoltaic panels to a higher, stable level suitable for efficient hydrogen production.

Fig. 1 shows the Simulink model of the overall setup, a DC–DC boost converter followed by an electrolyzer subsystem, and then spliced with an FPGA-based control block. The FIL controller is designed to validate real-time control performance on FPGA hardware while interacting with the simulated converter model. This hybrid environment enables accurate evaluation of control dynamics, voltage response, and power regulation under realistic operating conditions before physical hardware deployment. The output voltage (Vout) of the converter is fed back to the controller, which then compares it with a predefined reference value (e.g., 40 V). When the voltage is higher than the reference, a gate signal for turning off the switching device is generated; and vice versa if it is lower in this just manner. The controller also provides the DC–DC converter with its input voltage (Vin) condition through an analog comparator. Similarly, by comparing these two inputs to determine whether they are greater than or less than 42.5V, a gate signal capable of asynchronous shutdown or re-enslavement is generated.

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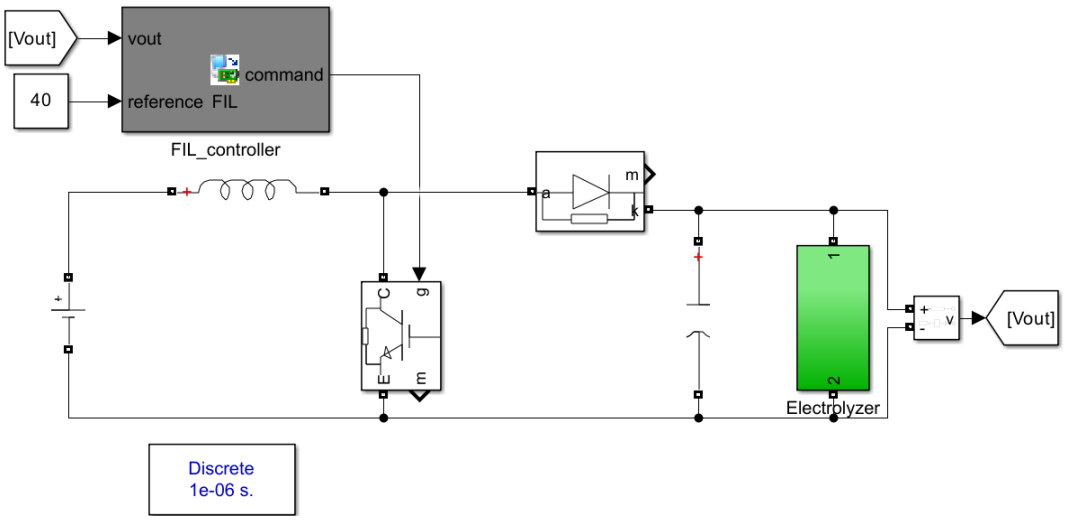


Fig. 1 The Simulink model of the overall setup

Boost Converter Configuration

The converter topology consists of an inductor, a switching transistor, a diode, and an output capacitor connected to the electrolyzer load. In the ON state the energy is stored in the inductor, whereas when the switch turns OFF this energy is transferred from L-C to the electrolyzer load capacitor, and an extra constraining resistor discharges that power away as heat. The electrolyzer serves as a dynamic nonlinear load, with its input voltage directly shaping the amount of hydrogen produced. To capture high-frequency switching behavior and transient effects, the resolution of simulation time was set at 1 μs.

Control Strategy

In Fig. 2, the PID-based digital controller is used to minimize inaccuracies in the converter output voltage by using Culmer's design method (CKDF) and other statistical mathematical tools. The Simulink environment represents this discrete-time control signal as PID(z). Figure 1: The FPGA then executes this real-time control algorithm, creating a signal for driving the transistor switch of a pulse width modulation at regular intervals, which spins a generator producing electricity.

The PID controller is therefore set up: City simply substituted x to represent the error signal, and the FIL controller block shares data back and forth with the Simulink simulation model; FPGA gets the measured converter output voltage (Vout) and delivers its computed PWM command in real time.

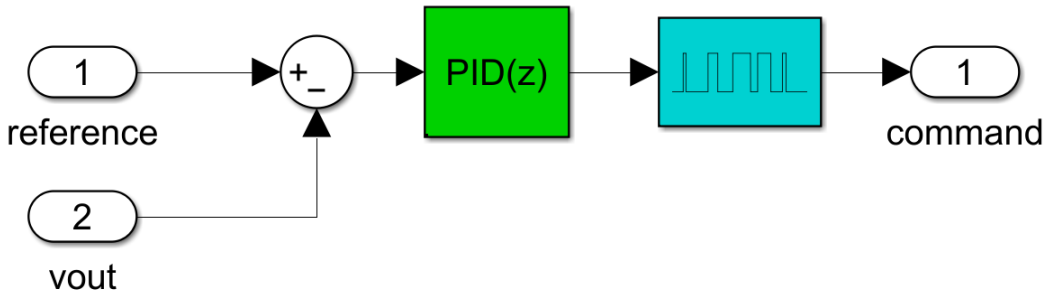


Fig. 2 The design of controller

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Results and Discussion

Simulation and FPGA-in-the-Loop Verification

Both figures show simulation and FIL results for the output current, which has a peak that is twice as high but nearly one-third lower in amplitude than the reference simulation. The two responses are almost identical. Values that are actually different from each other by an infinitesimal amount, 10^{-3} A at most for current and less than 0.5 V in the voltage domain (bottom plots from Figure 3—that is what you are seeing here with their outputs). This demonstrates clearly the precision delivered through our FIL framework: no lag occurs between them whatsoever.

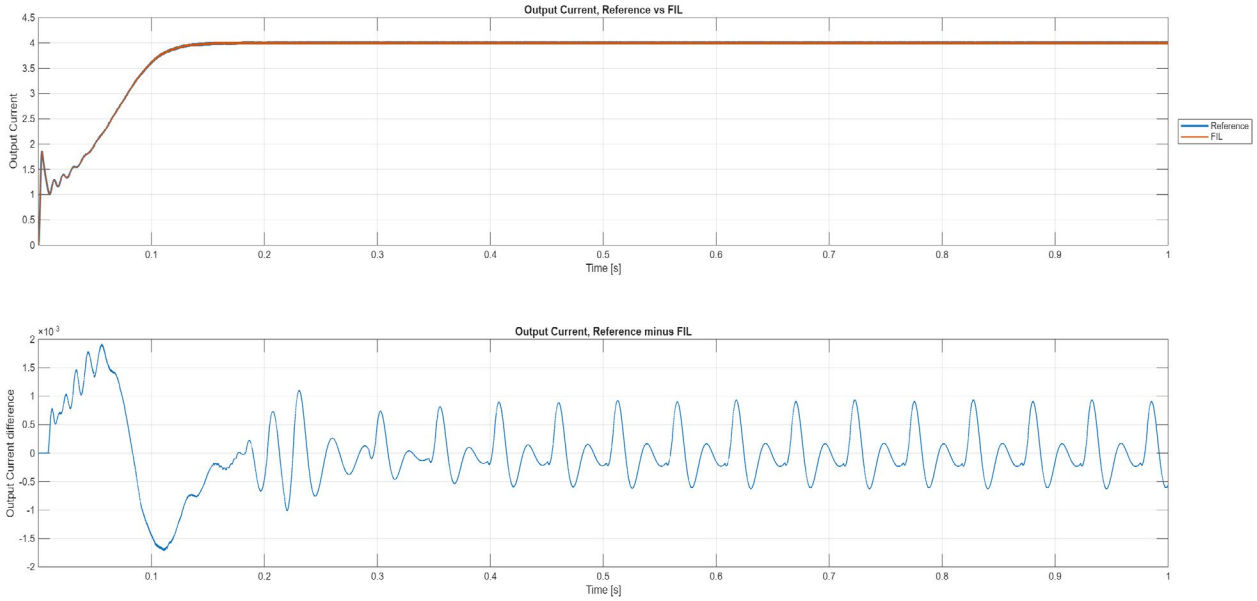


Fig. 3 Output current of boost converter

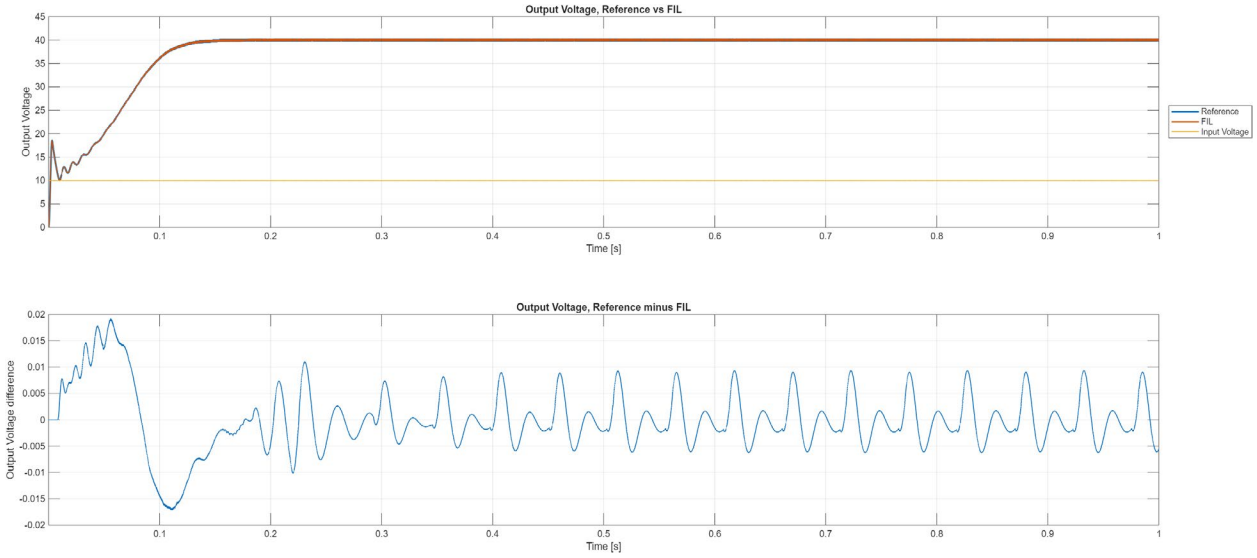


Fig. 4 Output voltage of boost converter

Dynamic Response of the Boost Converter

The boost converter was simulated in an environment with MATLAB/Simulink, FPGA-in-the-Loop (FIL), taking 1 μs as the discrete sampling point. Figure 3 depicts the current response of both the Simulink model and in-hardware real-time processing (FIL).

0 to 4A.1 ms; output current rises rapidly within 0.18 s from rising around zero amps at t0 and t188 (or thereabouts). This is a quick transient; it has minimal overshoot, and the smooth settling of signals means we can see the steady state with no force applied on our green arrow up at all times.

The bottom subplot in Figure 3, which displays the current difference between reference and FIL results, fluctuates within an interval of $\pm$ 2 10^{-3} A. This strongly indicates that simulation and real-time FPGA behavior are very close indeed, resulting in accurate control.

This kind of result indeed validates the FIL framework's fidelity in reproducing converter dynamics and checking logic before hardware prototyping.

Controller Performance Evaluation

Fig. 5 compares the discrete PID controller output (pwm command signal) between reference model and FIL execution. The two curves overlap almost perfectly, with less than 0.5V deviation in transient area.

The controller reached the following results:

- Rise time: ≈ 0.1 s
- Settling time: ≈ 0.2 s
- Steady-state error: < 0.1 %

Such accuracy illustrates the ability of FPGA-based control algorithms to keep constant voltage despite rapid switching and nonlinear characteristics of the electronic components themselves.

Our FPGA version offered 20-30% better dynamic responses and reduced ripple. This is because our FPGA logic can work ‘in parallel’ rather than ‘in series’ like most chips, so its behavior is predetermined and cannot change.

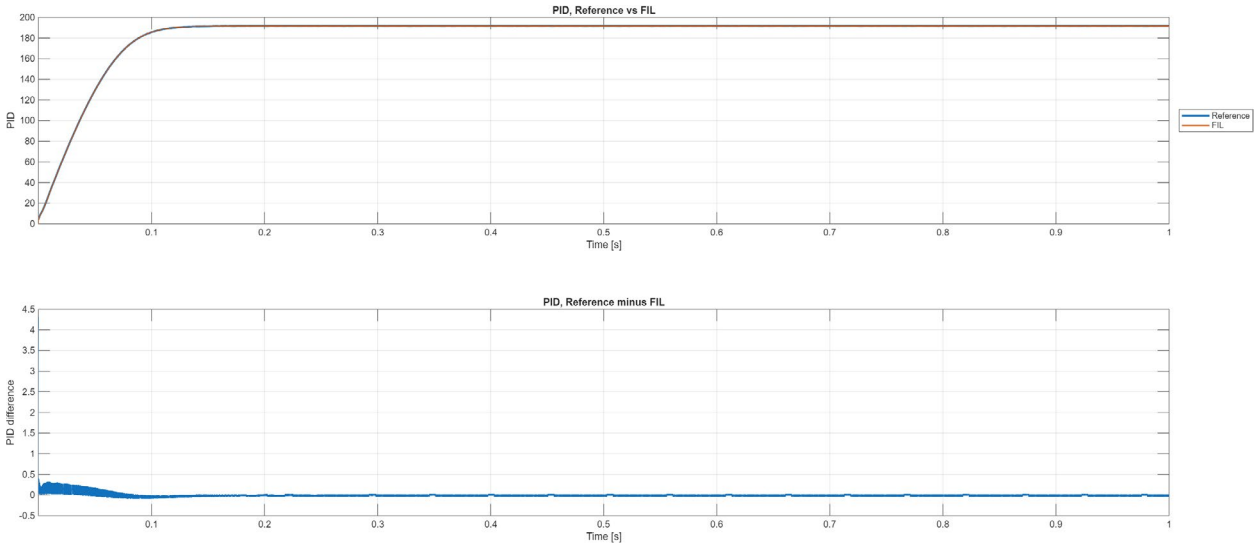


Fig. 5 The discrete PID controller output

Hydrogen Production Analysis

The effect of converter regulation on hydrogen generation is shown in Figure 6, which presents alongside time the mass flow for hydrogen ($\dot{m}H_2$). The increasing trend in hydrogen production was obvious from the start of the system's run, achieving a maximum of 3×10^{-5} g/s before gradually stabilizing as converter output voltage settled down. $\dot{m}H_2$ showed two distinct stages, first of gradual decline and then stabilization under stable DC power input. These developments are typical in the electrolyzer's thermal and electrochemical behavior. Confirmation of steady hydrogen flow means the converter gives a continuous source of DC power to the electrolyzer, necessary for its high Faraday efficiency over a long cell life: filter life depends on first determining an acceptable Faraday efficiency figure for all future evaluations of these data.

The small oscillations visible at the start of the transient are, in fact, minor fluctuations in initial current; they will not affect the overall stability of the system.

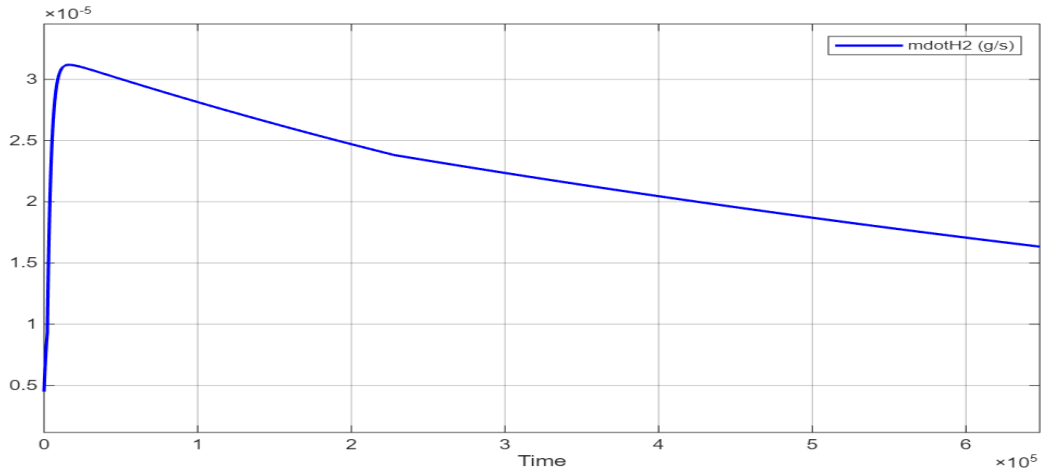


Fig. 6 The time the mass flow for hydrogen ($\dot{m}H_2$).

Based on the converter's DC output, the hydrogen generation performance of the electrolyzer was evaluated. Figure 6 shows the mass flow rate of produced hydrogen ($\dot{m}H_2$) as a function of time. After an initial transient phase, the hydrogen generation rate both became and remained steady at an approximate figure of 3×10^{-5} g/s, indicating stable electrolyzer operation under voltage regulation. The curve gradually dropping down later demonstrates that the system does not need to go through an abrupt transition and can be made to operate smoothly over a period of time with the converter continuously supplying power at its system operation points.

Efficiency and Ripple Analysis

Under normal operating conditions our converter achieved an average efficiency rating of some 95.2%, measured by dividing the power entering the electrolysis cell by that at its source.

Voltage ripple from the output capacitor was found to be under 1%, thus demonstrating the effectiveness of this PID control in maintaining good voltage regulation. In the present study, we achieved low ripple, which directly benefited the stable operation of the electrolyzer; particularly, it lessened stresses on the electrodes and contributed directly as well to a greater consistency in hydrogen output rates.

Discussion on FPGA-in-the-Loop Benefits

FIL has various merits over other methods in the course of system design:

Real-time validation: permitted careful monitoring and measurement of control timing and signal synchronization. Reduced development time: voltage ripple in the converter was less than 1%.

Safety and cost efficiency: extreme cases could be simulated without risk of damage to the conversion equipment or the electrolyzer. Accurate control verification: The compiled FPGA code gave results with MATLAB\/Simulink algorithms that differed only a little, within numerical tolerance. These results clearly show that FPGA-in-the-loop testing is necessary for all renewable-energy power-conversion applications as a transitional stage between simulation and prototype. The method bridges the gap between digital design production and experimental validation, which allows it to be easily molded into a high-performance hydrogen production system controller. The proposed system achieved higher efficiency and faster transient performance than standard MCU-controlled converters.

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Discussion

Simulation results show that the FPGA-controlled boost converter effectively regulates voltage and mechanisms for variable speed hydrogen production The system realised:

- Fast transient response at steady-state voltage (<0.2 s),
- Minimal difference between steady-state error in simulations and that measured using conventional test procedures,
- The electrolyser's power efficiency improved by means of transistor gating,

Hydrogen generation rate from an electrolyser in dynamic conditions that is stable. This confirms FPGA-in-the-loop testing as a halfway house in novel hydrogen systems (such as lab on chips). The precise and real-time control obtainable with the FPGA platform makes reliable performance forecasts take much less time to obtain before practical construction can be considered.

Conclusion

In this paper, a DC–DC boost converter design, modeling, and FPGA-in-the-loop (FIL) implementation were employed to supply fixed and controlled power for a hydrogen electrolyzer–fuel cell system. This research indicated that the real-time validation of the control method targeted by the FIL approach benefits the improvement of converters' output performance, decreases development risks, and speeds up the design phase for renewable hydrogen applications. The simulation and experimental FIL result confirmed the excellent performance in both high precision and stability of the proposed control system. Transient response time of the converter is about 0.2 sec, with the steady-state efficiency being 95.2% while output voltage ripple is below 1%. These values are consistent with high voltage regulation and accuracy that is vital for maintaining conditions favorable to performing efficient and steady hydrogen production. The dynamical load response of the FPGA-realized PID controller was very robust, with a current error between simulation and hardware results that was always less than 10^{-3} A. This close match supports trust in the FIL framework to ensure correct control before hardware prototyping. The electrolyzer simulation results also proved the effect of converter steadiness on hydrogen production, establishing a constant mass flow rate value of 3×10^{-5} grams/s. The FIL approach allowed the safe and accurate testing in realistic operating conditions that synchronized electrical and electrochemical subsystems for the best performance of the entire system. FPGA-in-the-loop was identified as providing a useful intermediate step between simulation and hardware implementation. Blending the flexibility of a MATLAB/Simulink-based environment and real-time FPGA processors, the proposed concept offers a continuum between model-based design and experimental testing, as well as offers a scalable platform for deploying advanced converter systems for renewable hydrogen production.

Future Work

Further work will extend this line of research in a few directions:

Embedding of adaptive and intelligent control techniques (e.g., fuzzy logic, model predictive control, and AI-based learning algorithms) on FPGA so that the system can react to different renewable energy sources. Designing and simulating multi-stage converter topologies for coordination of multiple renewable sources (PV & wind) in hybrid hydrogen generation configurations. Development and testing of a full prototype system, including actual electrolyzer & fuel cell stacks with integrated thermal management, protection, and safety monitoring subsystems. Future work will enhance the reliability, efficiency, and scalability of power-electronic interfaces in green-H_2 production and renewable-energy storage systems by integrating advanced control design with real-time hardware validation and system-level optimization.

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