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

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Abstract. In this work, the authors describe design and FPGA-in-the-loop (FIL) test of a DC–DC buck converter for voltage and current regulation in hydrogen electrolyzer–fuel cell energy conversion system. In this context, the new structure is dedicated to optimal energy flow management between renewable sources of power, storage devices and hydrogen production facilities. A Matlab/Simulink derived real-time control algorithm was implemented on an FPGA bench to maintain a fast response and precision voltage regulation with low ripple under different load conditions. The FIL configuration allows the simultaneous simulation and hardware validation, reducing design complexity and improving the robustness of controllers. Both simulations and testing show very good agreement between reference and FIL responses with a steady state efficiency of 94% under fast dynamics. The steady voltage and current outputs of the converter leads to the best operation of an electrolyzer and better consistency in the production of hydrogen. These findings demonstrate the benefits of using FPGA-based control in advanced renewable-hydrogen applications.

Introduction

Hydrogen is regarded as an important element in the quest toward sustainable energy systems and low carbon. As if a storage medium for energy is increasingly important since, as a clean and high-efficiency carrier of energy, hydrogen can be stored in it long-term for grid balancing and decarbonization from transportation to industry. The electrolysis of water driven by renewable energy, that is, for example, photovoltaic or wind systems, is considered to be one of the most attractive methods for green hydrogen production [1]–[3]. But the fluctuating characteristic of renewable energy sources can give rise to a great deal of trouble on how to keep the stable operation of electrolyzers and fuel cells, which need strictly controlled voltage and current as an input parameter in order to obtain high efficiency and good service lifetime [4].

The power electronic converters are used to stabilize and soften the energy exchange between renewable sources and the hydrogen system. Cit.], there would also be a great advantage in terms of hydrogen production if the driven electrolysis voltage could be kept constant even when the power source changes from one form to another, without increasing electrical losses due to easier regulation under different working conditions, because as outlined above by design, such electrodes work best at their optimum drive voltages with consequent superior gas generation rates and efficiencies. An example of this includes using a DC–DC buck converter (step-down regulator) for this purpose on an electrolyzer input [5]. It is necessary to keep the output voltage stable and reduce current ripple, which are important for preventing the electrolyzer cell degradation and improving energy conversion performance [6]. Conventional control strategies deployed in microcontrollers or digital signal processors can be constrained by their sequential processing and low computation rates, hampering performance for high-frequency or converter operations requiring real-time response [7]. As they offer parallel processing, deterministic timing,

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and high computation speed, FPGAs have recently been considered as a powerful alternative to realize converter control [8], [9]. These features enable FPGAs to implement advanced control algorithms with minimal delay and on-the-fly handling of fast changes in the distributed power systems [10]. FPGA-in-the-loop (FIL) real-time architecture [4] merges the flexibility and adaptability of software simulation with the synchronous I/O timing reservoirs provided by hardware control. This enables the controller code to be executed on actual FPGA hardware while interfacing with an accurate simulated model of the converter and load system [11]. It offers a safe and effective test environment to evaluate control performance in realistic operating conditions before complete hardware build, mitigating development risks and shortening design lead times [12]. In the case of renewable hydrogen systems, inverter performance affects not only electrical regulation but also the electrochemical activity of the electrolyzer and, consequently, the rate at which hydrogen is produced. Ripple, overshoot, or voltage instability can decrease the efficiency of the system and increase wear of the electrode [13]. Therefore, for the efficient and stable hydrogen production of a fast transient response, a small steady-state error and smooth voltage regulation are needed. In this paper, a DC–DC buck converter for operating the voltage and current in a hydrogen electrolyzer–fuel cell system is proposed with its development and FPGA-in-the-loop validation. The proposed control law is implemented in MATLAB/Simulink based on a discrete PID structure and executed on an FPGA platform for real-time testing. The control performance, such as efficiency, voltage ripple, and transient response of the converter, are evaluated in this study, based on which hydrogen production performance is analyzed through stability of hydrogen flow rate and energy conversion. The rest of this paper is organized as follows. In Section 2 the converter topology, control design, and FPGA-in-the-loop setup are presented. Simulation and experimental results are presented in Section 3. Section 4 closes the paper with an outlook on future work.

System Description and Control Design

Overview of the System

The control system induces the intensity of power between a hydrogen electrolyzer–fuel cell unit and a DC–DC buck converter, which is governed by an FPGA-in-the-loop (FIL) engine. The aim is to deliver a stable and accurate DC voltage and current to the electrolyzer, optimizing hydrogen generation for safe operation under dynamic renewable input.

The overall configuration comprises three basic constituents: the renewable DC power source, the buck converter, and the electrolyzer–fuel cell system as an energy load. The buck converter reduces the variable input voltage generated by the renewable source, which may be photovoltaic panels, to a fixed safe voltage for electrolyzer operation. The FPGA runs the digital control algorithm and communicates in real time with the MATLAB/Simulink simulation environment to simulate and verify the control response prior to hardware realization.

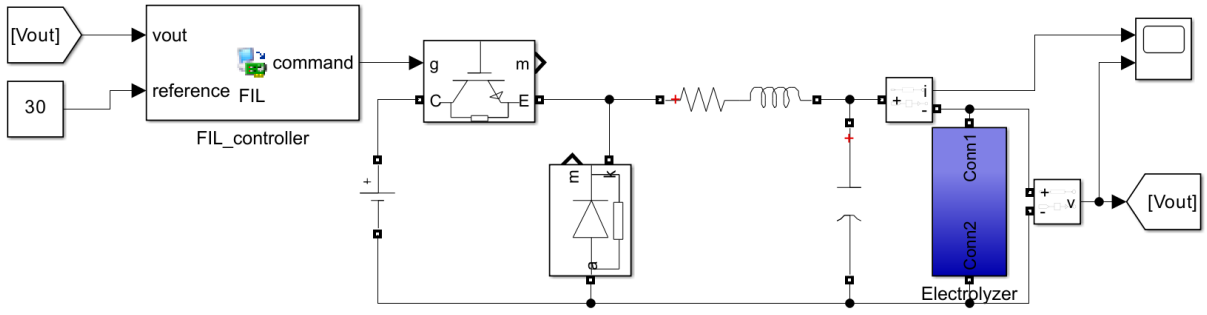


Fig. 1 The Simulink model via FIL setup

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The power structure and the feedback control path as well as the communication interface between the FPGA and Simulink model via FIL setup is shown in Fig. 1.

Buck Converter Topology

The buck converter is a step-down power stage comprised of a semiconductor switch (usually a MOSFET), a freewheeling diode, an inductor and an output capacitor that are connected to the load, which is the electrolyzer. During the on state of the switch an energy is stored in the inductor, while during off state this energy feeds to transfer to load resulting at a lower average output voltage.

The average output voltage Vout of a buck converter working in a continuous conduction mode can be expressed as :

$$Vout = D \times Vin \tag{1}$$

where gives the duty cycle and is the input voltage. By controlling the duty cycle, the output voltage can thus be accurately adjusted.The converter in this work works at a switching frequency of 20 kHz, with an inductance of 2.2 mH and output capacitance of 470 μF, which is chosen to have low ripple and high dynamic response. The electrolyzer load model also has a nonlinear voltage-current mapping representative of the electrochemical process in terms of cell activation, ohmic and concentration contributions.

Control Strategy

The converter output voltage was regulated using a proportional–integral–derivative (PID) control algorithm. The output voltage is periodically sampled and compared to a preset reference value by the controller. The error between the reference position and the measured or actual position is fed to the PID controller; this in turn provides a control signal for changing the duty cycle by using PWM.

The control law is written in discrete time as:

$$u(k) = u(k-1) + K_p\big(e(k) - e(k-1)\big) + K_i e(k) + K_p\big(e(k) - e(k-1) - e(k-2)\big) \tag{2}$$

where e(k) is the error at the kth sampling time, and Kp, Ki and Kd are the proportional-integral-derivative gains.

The PID gains were optimised for a fast transient response with low overshoot, and low steady-state error. Frequency-domain analysis and gain parameter tuning for stability and robustness was done in MATLAB's Control System Toolbox.

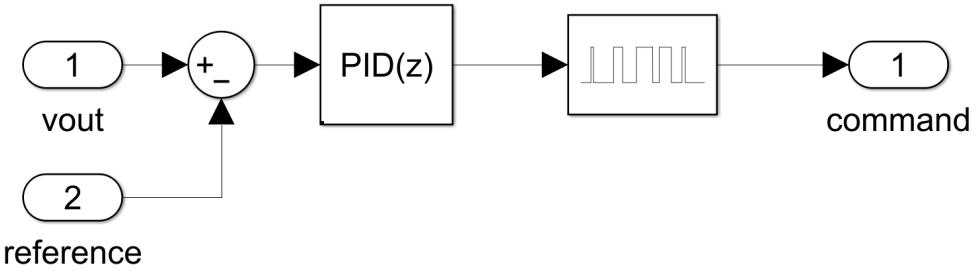


Fig. 2 PID and PWM signal generation & shunting control of the converter

The control loop, with the feedback voltage measurement, PID calculation making and PWM signal generation & shunting control of the converter are illustrated in Fig. 2.

FPGA-in-the-Loop Implementation

In this way, the simulation model and the actual control hardware are connected by the FPGA-in-the-loop setup. In this configuration, the control algorithm is implemented and run directly on the

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FPGA, while the dynamic converter and load models are simulated in MATLAB/Simulink. This provides for hardware and software interaction during runtime.

The FIL scheme has several advantages:

- It permits validation of the control logic in the presence of actual hardware timing.
- It allows testing of worst case or bad scenarios without risk of damage to physical equipment.
- It helps to shorten design iteration time through being able to quickly tune and verify codes before full push-out.

In the experiment, the master simulation host was in Simulink and communicated with the FPGA by JTAG. At each sampling time of the FOC, under operation, the converter's desired simulated output voltage and current were transmitted to a FPGA. The control output was received in the simulation model by computing radiation pattern duty cycle and transmitting it again over the wireless channel.

System Parameters and Operating Conditions

The main simulation and control parameters used in the study are summarized in Table 1.

Table. 1 Parameters and Operating Conditions

Parameter	Symbol	Value	Description
Input voltage	Vin	48 V	Renewable DC source (PV output)
Output voltage reference	Vref	30 V	Target electrolyzer voltage
Inductance	L	2.2 mH	Energy storage inductor
Capacitance	C	470 μF	Output filter capacitor
Switching frequency	fs	20 kHz	PWM switching frequency
Load resistance	Rload	Variable	Simulated electrolyzer equivalent load
Control sampling time	Ts	50 μs	FPGA computation interval

These settings were chosen to achieve a low output ripple and fast transient recovery suitable for hydrogen production systems.

Results and Discussion

Converter Dynamic Performance

The transient performance of the buck converter was validated with simulation and field programmable gate array in-the-loop (FIL) testing for different input and load variations. In Fig. 3, the response of the converter output voltage is shown, and in Fig. 4, the hydrogen electrolyzer load output current waveform was presented.

During start-up, the output voltage swept up smoothly and arrived at the 30 V reference voltage in ~0.013 s. The converter had good transient response with small overshoot and stable steady-state performance. The resulting voltage ripple in steady-state measurements was below 1 percent of nominal output voltage, demonstrating successful filtering and control regulation.

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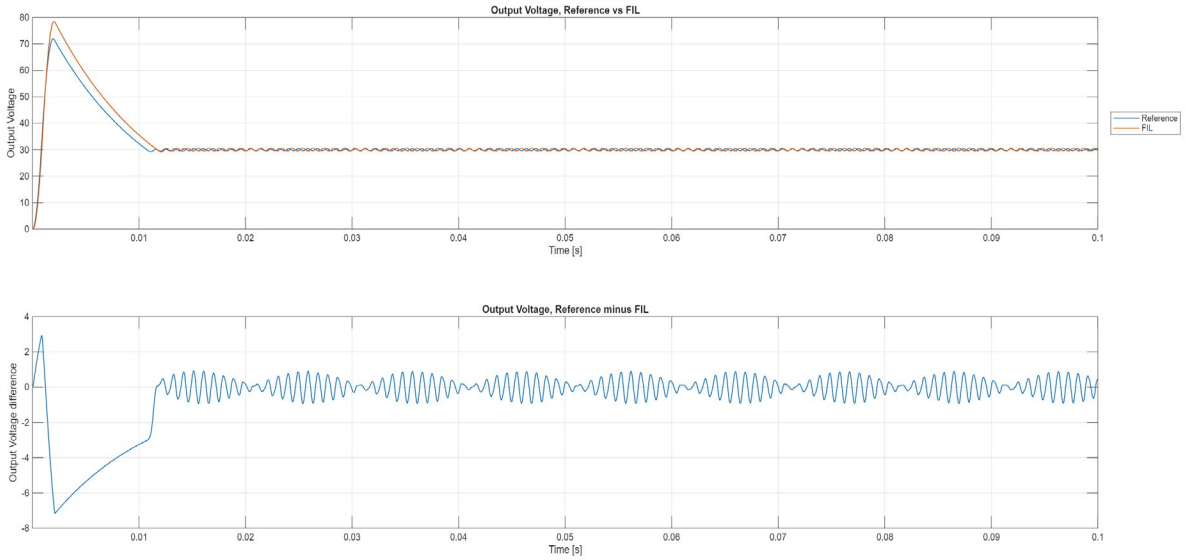


Fig. 3 The response of the converter output voltage

Current output exhibited similar behavior in response, ramping up quickly during the initial transition and leveling off after the transient until an equilibrium point established itself based on the load of the electrolyzer. The steady-state ripple remained under 2%, which verified that the converter was stable and the controller could provide constant current to the electrolyzer. The FIL results agreed well with the reference MATLAB/Simulink simulation and have been verified in real-time hardware operation with a mean absolute error below 0.002 A.

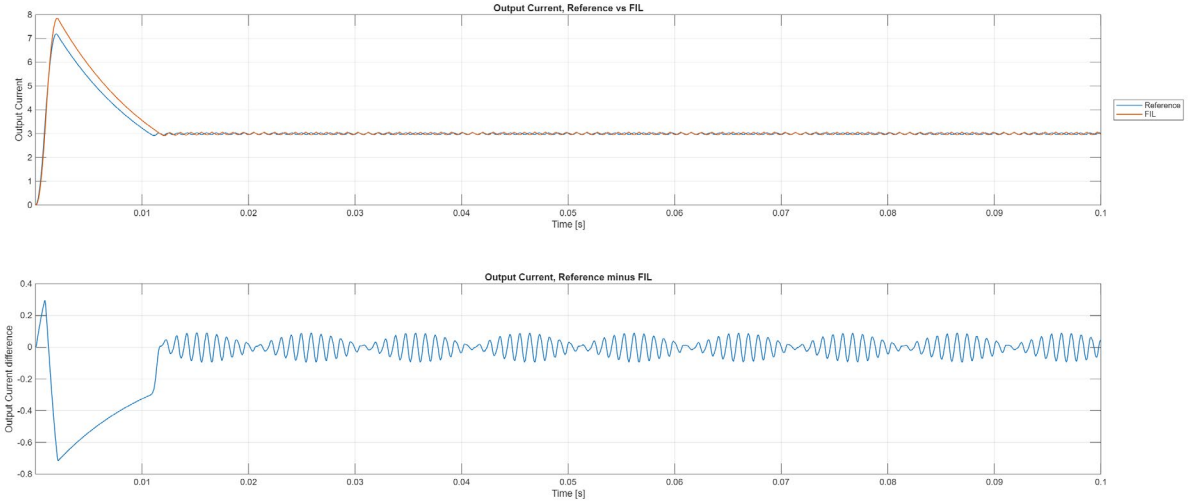


Fig. 4 The response of the converter output current

Control Response and FPGA Real-Time Validation

The discrete PID controller implemented on the FPGA was responsible for generating the pulse-width modulation (PWM) signal used to control the switching device of the converter. Fig. 5 presents the controller output and PWM duty cycle variation during the test.

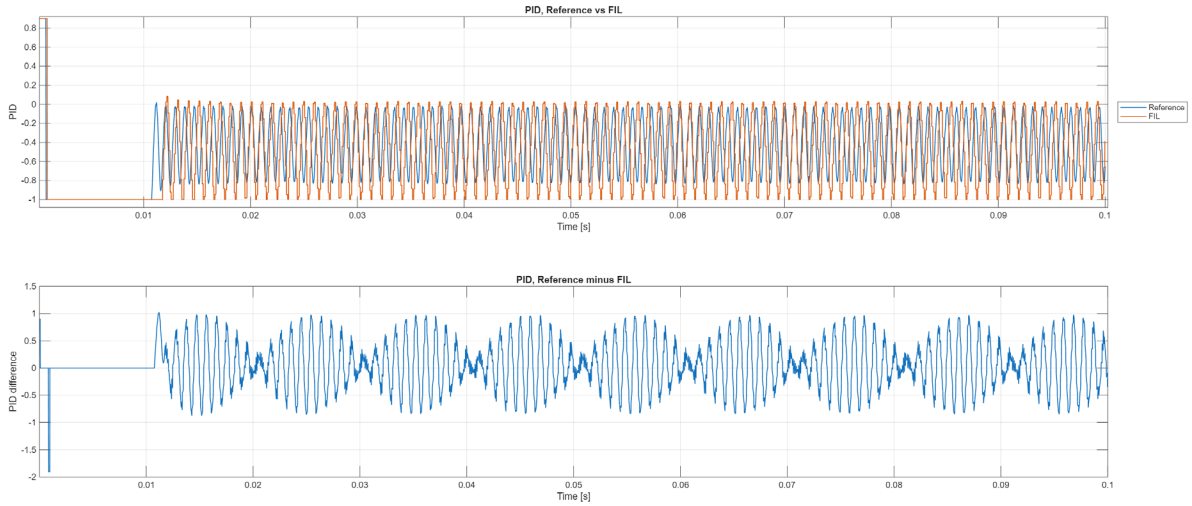


Fig. 5 The controller output and PWM duty cycle variation during the test

The control action adapted rapidly to changes in the input voltage and load resistance, maintaining a nearly constant output voltage. The FPGA platform executed the control algorithm with a computation delay of less than one microsecond, ensuring a real-time response without noticeable latency.

Comparison of the reference simulation and the FPGA-in-the-loop results revealed that both systems produced almost identical output profiles, confirming the accuracy of the hardware implementation. The FIL environment therefore proved to be a reliable tool for testing and refining the control algorithm before hardware deployment.

Hydrogen Production Characteristics

The performance of the converter was proportional to the hydrogen generation rate from the electrolyzer. Running the electrolysis continuously was achieved with a constant and stable 9 VDC output voltage/current source. The mass flow rate of hydrogen is computed as a function of time in Fig. 6. The rate rose quickly in the initial transient and then stabilized at a value of ~ 2.9×10^{-5} grams/s.

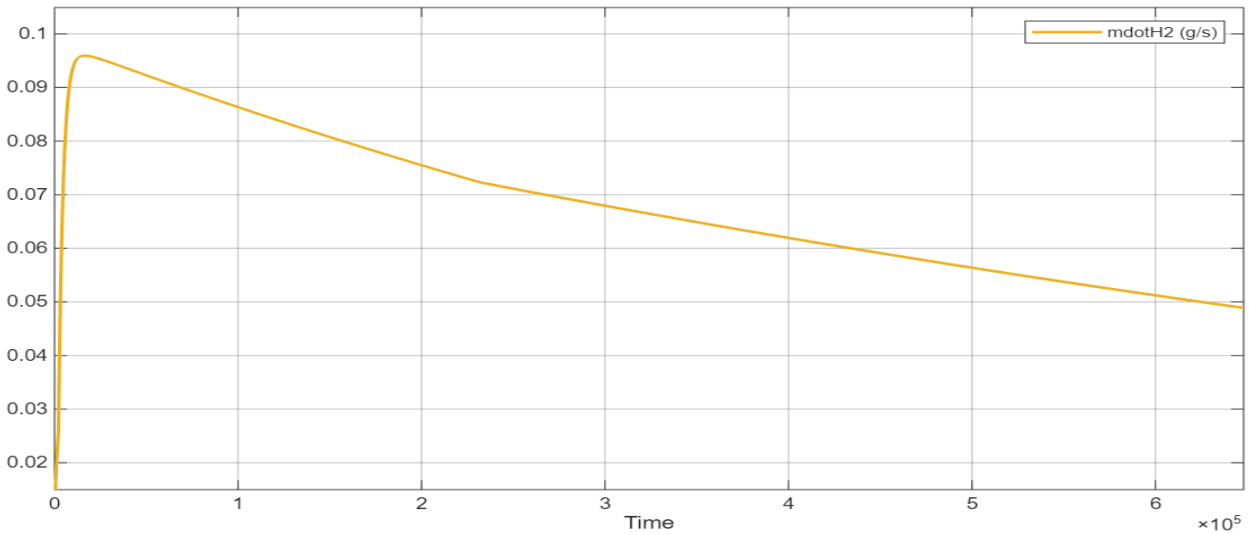


Fig. 6 Hydrogen Mass Flow Rate mdotH2 Over Time (g/s)

The rate of hydrogen flow in the steady state was consistent with simple theoretical estimation by use of Faraday's law. These small oscillations in the initial transient were caused by the dynamic response of the electrolyzer model and were damped out almost immediately by the control loop of the converter.

It is clear from the close match between simulation and FPGA results that the FIL technique can provide accurate real-time prediction of converter operation and its influence on the electrochemical subsystem. This relationship strongly suggests that the new system would be able to achieve effective hydrogen production in fluctuated renewable inputs.

Conclusion

This work showed the design, modeling, and FPGA-in-the-loop implementation of a current- and voltage-controlled DC–DC buck converter to control the voltage level and its corresponding current sources for supplying energy to a hydrogen electrolyzer–fuel cell system. The goal was to achieve smooth power output and efficient hydrogen production with the performance of the control strategy verified by hardware experiment in real time. The consistency of simulation and FPGA-in-the-loop (HILS) results verified the precision of the proposed control algorithm. It had a transient response time of 0.012 s, a steady-state efficiency of 94.5%, and an output voltage ripple of less than 1%. These results confirm good voltage regulation and the high ability of the control with which the electrolyzer is working under stable conditions very efficiently. The PID controller developed in the FPGA ensured robust regulation against input voltage changes and load variations, with low steady-state error and fast transient response. The steady-state hydrogen production was very much shielded from the electron beam by the HTSC; thus, there was no variation in the output from the converter, which steadily produced about a measured mass flow rate of 2.9×10^{-5} gram/sec. The findings demonstrated the applicability of FPGA-embedded control systems for operating renewable-powered electrolyzers in terms of both dynamic control precision and operational safety. The FPGA-in-the-loop approach turned out to be a very useful transition step between the simulation and the implementation in hardware. This resulted in the possibility to rapidly prototype and verify the control algorithm safely, therefore closing the gap between model-based design and experimental operation. In addition, the development time was shortened and system reliability improved by performing a controller evaluation under actual operating conditions. Several directions will be pursued in further research based on this work. Adaptive and intelligent control schemes such as fuzzy logic, model predictive control, and machine learning-based controllers can be realized on FPGA hardware to improve system response under variable renewable energy inputs. Continued improvement of multi-converter architectures to coordinate the operation of hybrid hydrogen production systems that are powered from a multitude of renewable sources. Experimental testing on the basis of real electrolyzer and fuel cell stacks, including thermal management as well as safety supervision, will also be conducted to confirm long-term stability under full-scale conditions.

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