

Dynamic Voltage Support and Stabilization in Renewable Energy Systems Using Hydrogen

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Abstract

Integration of renewable energy sources into electrical grids introduces power quality challenges and system instability due to the intermittent nature of renewable generation. Although hydrogen is commonly used as an energy storage medium, this paper proposes its use as a dynamic support unit for grid stabilization and power balancing. The proposed system consists of a photovoltaic (PV) system, a Proton Exchange Membrane (PEM) electrolyzer, and a fuel cell integrated through a dynamic voltage control strategy. MATLAB/Simulink simulations demonstrate that the proposed system effectively restores the DC bus voltage to the nominal steady state following severe transient disturbances. Specifically, during power deficits when the voltage falls below 380 V, the fuel cell is activated to supply electrical power, whereas the electrolyzer operates during surplus power conditions above 420 V to absorb excess generated energy. The results demonstrate that the proposed hydrogen-based system enhances voltage stability, improves grid reliability, and provides effective dynamic support for renewable energy integration.

Keywords

Hydrogen Integration, Renewable Energy Integration, Electrolyzer, Fuel Cell, Energy Storage Systems (ESS), Grid Stability, Electrical Grid

1. Introduction

The world is transitioning toward utilizing lower-carbon energy sources, rather

than fossil fuels, which represents a fundamental shift in the industrial era [1]. There are multiple drivers behind this shift; however, the most prominent driver is the decrease in greenhouse gases in order to mitigate the effects of climate change [2]. Additionally, there is enhanced global energy security, and long term sustainable economic growth will create incentives to continue on this path. To meet climate objectives, the world will have to alter how it generates, distributes, and consumes energy [3].

Renewable energy presents a feasible option for future generations, primarily due to the advancements in technology related to solar and wind energy. According to the European Union, over 50% of the electricity generation in Europe needs to come from renewable sources to achieve 2030 objectives, and this has to grow to 80% in 2050 [4]. Nevertheless, utilizing these renewable sources has been shown to negatively impact the reliability and stability of the electrical grid, primarily due to natural variations and interruptions in renewable energy production [5].

Integrating renewable energy resources into the grid creates many technical challenges [6]. Traditional power plants generate electricity with spinning turbines that inherently maintain stability in the electrical grid. Renewable energy connects to the electrical grid with electronic devices that do not inherently stabilize the electrical grid, increasing the probability of frequency fluctuations when something fails [7]. Renewable energy is also intermittent; the sun sets, and the wind stops. As a result, there are mismatched quantities of electricity being generated and consumed. Furthermore, our transmission lines were not designed for renewable-rich areas and become congested with all of the renewable energy created in those areas, much like a highway during rush hour. Excess clean energy is wasted by utility companies, because they cannot move the energy to where it is needed [5]. These three issues, low inertia, frequency instability, and transmission congestion, clearly indicate that there is a need for new flexible solutions now to keep the electrical grid reliable as we transition to cleaner forms of energy.

Conventional Battery Storage Systems have been very successful in terms of effectiveness; however, Hydrogen-Based Energy Storage Systems provide an alternative to conventional battery storage systems that will provide additional flexibility with regard to dynamic load management capabilities over long durations of Renewable Integration [8]. Hydrogen storage utilizes the excess renewable energy to generate hydrogen through electrolysis and then uses the hydrogen stored to produce electricity via a fuel-cell resulting in improved overall system efficiencies [9]. Hydrogen is essential for integrating renewable energy by providing storage and transportation capabilities [10].

In addition to energy storage capabilities, hydrogen-based systems can provide dynamic support to power grids. According to [11], hydrogen units offer functions like frequency regulation, voltage management, and load balancing that enhance grid resilience and make it easier to integrate distributed energy resources. Additionally, hydrogen-based systems can assist in minimizing transmission

losses by localizing energy storage and subsequently enhancing system efficiency and reducing congestion [12].

The expansion of sustainable energy systems relies on green hydrogen's ability to act as an alternative clean energy source and a dynamic load that supports grid reliability. Research has shown that a shift is occurring with regard to renewable-powered electrolysis as a path to achieve carbon neutrality and replace traditional (conventional) steam methane reforming [13]. Although green hydrogen offers numerous advantages environmentally; it will be difficult for large scale use due to the expense of producing hydrogen and intermittent renewable generation. This requires the development of adaptive control strategies to increase hydrogen's operational flexibility within the grid.

Incorporating hydrogen into decentralized hybrid networks is an important step. According to [14], this study showed that a hydrogen-based hybrid networked power supply can reduce reliance on non-renewable fuels and improve overall networked power balance. However, round-trip efficiency and control complexity are current constraints on hydrogen control, necessitating improvements in system architectures and dynamic management strategies.

The operation of dynamic loads, such as electrolyzers, can be controlled by applying diversion control logics, which are well-established in the literature [15]. In this context, when excess renewable energy is available, PWM modulation of surplus renewable energy drives electrolysis in hydrogen systems; thereby enabling the absorption of real-time renewable variability and maintaining grid stability. Scaling this concept to commercial/industrial applications will require advanced power electronics interfaces and predictive control methods to address the rapidly changing nature of renewable input.

The main contributions of this paper are summarized as follows:

- The presented paper redefines the operational model for hydrogen systems. Instead of viewing them in a conventional manner as simply a load or as a long-term backup generator, this study will propose using the hydrogen system as an active dynamic continuous compensator to help with changes in the grid by providing critical support. This methodology maximizes grid efficiency and reliability and minimizes voltage fluctuation.
- A complete system model will be developed in MATLAB/Simulink to test the proposed system. The simulation aims to verify the system's capability to mitigate rapid voltage fluctuations, ensuring stable grid operation and superior power quality.

2. Methodology

2.1. Photovoltaic (PV) System Integration

The primary energy generator in the proposed PV network will be a Solar Photovoltaic (PV) system. PV systems are capable of providing clean and renewable energy. However, the fluctuating nature of irradiance and temperature creates in-

intermittent output levels with PV systems. Therefore, PV systems cause fluctuations in the power supplied through the system. These power fluctuations negatively affect the stability of the system. Thus, an effective and quick method of compensating for these power fluctuations must exist in order to keep the grid voltage within reasonable operation parameters. The electrical behavior of the PV system is governed by the following source current [16]:

$$(I_{\text{source}}) - \left(\frac{e^{-v}}{1.2 \times 0.026} - 1 \right) \times 10^{-12} = \frac{V}{R_L} \quad (1)$$

where I_{source} represents the source current that the PV system generates, V (and v) are the output voltages, and R_L is the load resistance. The numerical constants used in the equation relate to the ideality factor of the diode (1.2), the thermal voltage (0.026 V), and the reverse saturation current (10^{-12} A).

2.2. Hydrogen as a Dynamic Electrical Unit

In response to the potential instability caused by PV system, this paper develops hydrogen-based dynamic electrical units. This approach utilizes both the electrolyzer and fuel cell as dynamic compensators that actively compensate for the instability created by the PV system. By rapidly switching from consuming excess generated power to supplying additional necessary power, the hydrogen system provides a means of dynamically stabilizing the grid voltage and thereby improving overall power quality. The individual PEM cells are connected in a series stack to get the desired voltage levels. The cell has a very low nominal voltage, so a series configuration naturally raises the voltage closer to the 400 V DC bus requirement. In a parallel configuration, very high currents at low voltages would be present, which would substantially increase the thermal losses and would make the power electronic converter design for this prototype much more challenging [17]. The main equations of the PEM electrolytic stack are Equations (2) - (7):

$$V_s(t) = OCV_s + V_{an,s}(t) + V_{cat,s}(t) + R_{el,s}(t) \cdot I_s(t) \quad (2)$$

$$I_s(t) = I_{an,s,1}(t) + I_{an,s,2}(t) = I_{cat,s,1}(t) + I_{cat,s,2}(t) \quad (3)$$

$$\frac{dV_{an,s}(t)}{dt} \cdot C_{an,s}(t) = I_{an,s,1}(t) \quad (4)$$

$$\frac{dV_{cat,s}(t)}{dt} \cdot C_{cat,s}(t) = I_{cat,s,1}(t) \quad (5)$$

$$V_{cat,s}(t) = R_{cat,s}(t) \cdot I_{cat,s,2}(t) \quad (6)$$

$$V_{an,s}(t) = R_{an,s}(t) \cdot i_{an,s,2}(t) \quad (7)$$

Equation (2) is the equation for the calculation of the real voltage of the PEM electrolytic stack, Equation (3) are the currents balance equations at the circuit main nodes, Equations (4) and (5) are the current equations for the capacitive

anode and cathode branches, Equations (6) and (7) are the voltage equations for resistive anode and cathode branches [18].

The parameters of the PEM electrolytic stack equation are defined as follows:

- $V_s(t)$ and $I_s(t)$ represent the stack real voltage and current, respectively.
- OCV_s is the open-circuit voltage of the stack.
- $V_{an,s}(t)$ and $V_{cat,s}(t)$ are the overvoltages at the anode and cathode.
- $R_{el,s}(t)$ is the equivalent ohmic resistance of the electrolyte.
- $I_{an,s,1}(t)$ and $I_{cat,s,1}(t)$ are the currents flowing through the capacitive branches of the anode and cathode, respectively.
- $I_{an,s,2}(t)$ and $I_{cat,s,2}(t)$ are the currents flowing through the resistive branches.
- $C_{an,s}(t)$ and $C_{cat,s}(t)$ denote the equivalent double-layer capacitances at the anode and cathode.
- $R_{an,s}(t)$ and $R_{cat,s}(t)$ represent the equivalent activation and concentration resistances at the anode and cathode.

2.3. Dynamic Voltage Control Strategy

A specific control logic called the Dynamic Voltage Control Algorithm for Hydrogen Systems was developed in order to manage the dynamics of the hydrogen system. This algorithm continues to monitor grid operating conditions and determine whether or how the hydrogen components should operate in order to stabilize the network. The logical progression of this approach is shown in the flow chart provided in **Figure 1**.

When the DC bus voltage climbs above a set limit, it means there's more renewable energy being generated than the grid actually needs at that moment. This usually occurs on sunny days when solar panels are producing plenty of power, or at times when electricity demand drops and there aren't enough loads to consume what's being generated. When that takes place, the system is designed to store the excess power, rather than waste it. The control logic activates the electrolyzer to draw additional electricity from the DC distribution bus to convert it into hydrogen. This method maintains stable voltages while collecting clean energy.

A low DC bus voltage implies that the system is not in equilibrium. The sudden rise in demand or diminishing solar power output could be a reason for this concern. The control system will immediately energize the fuel cell at this moment. The previously stored hydrogen is converted back into electricity and supplied on the DC bus to step-up the voltage and support the load. The system responds in milliseconds and adapts to rapid changes.

Control logic will use a predetermined dead band from 380 - 420 volts which represents that both units are off during steady state operating conditions. By design simultaneous operation of the electrolyser and fuel cell is prevented to avoid converting electrical energy back into chemical energy through the hydrogen cycle.

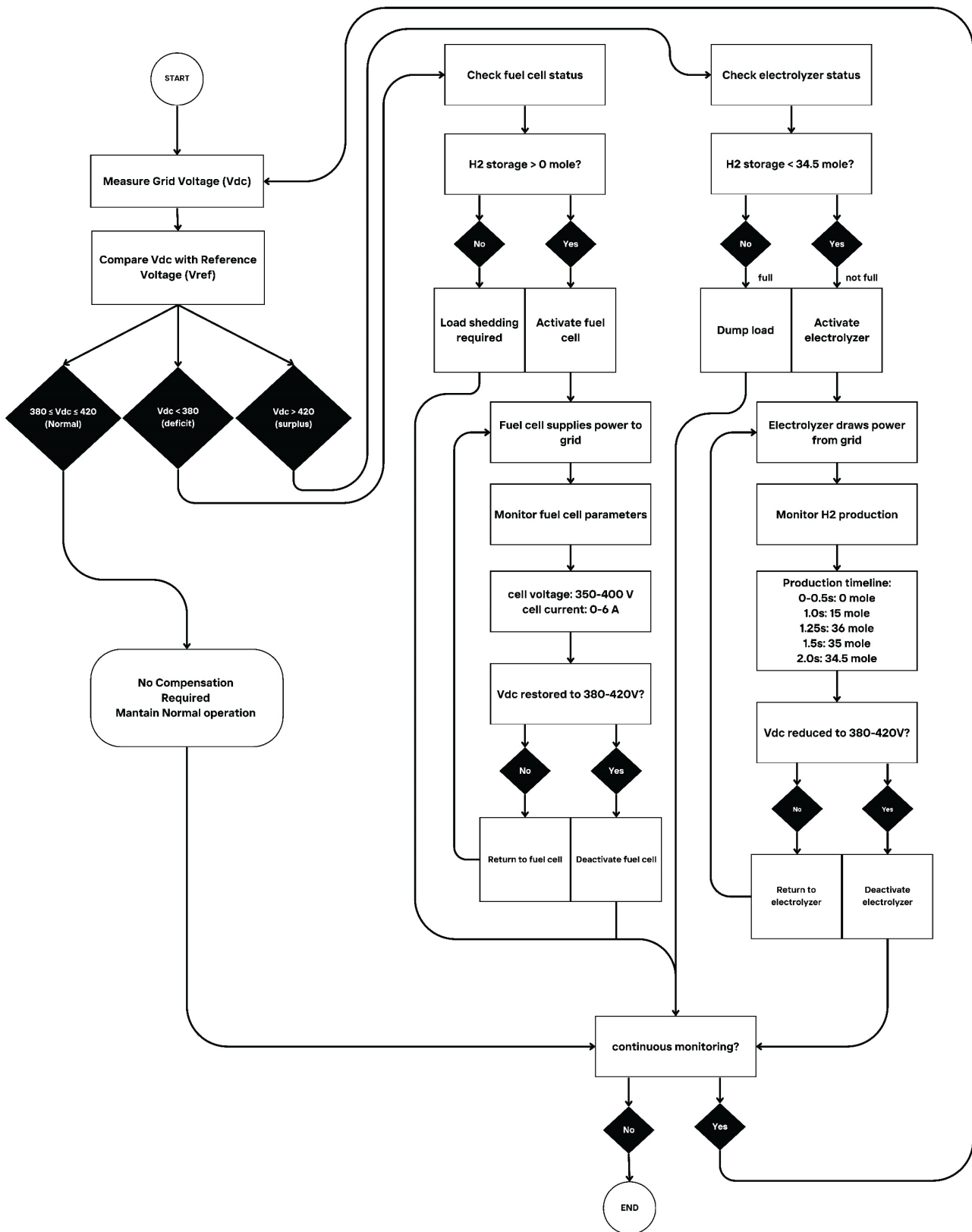


Figure 1. Dynamic voltage regulation algorithm for hydrogen systems.

3. Simulation Setup

To evaluate the feasibility of the proposed dynamic voltage control method, the system model and control strategies were developed and simulated using MATLAB/Simulink (R2023b) software. In order to accurately capture the fast transient response characteristics of both the power electronics and the hydrogen energy systems, a discrete simulation type was used with a sample time of 5×10^{-6} s through the use of the *powergui* block. All simulations were executed on a laptop equipped with an AMD Ryzen 5 processor, 8 GB of RAM, and running a 64-bit Microsoft Windows operating system.

The Inverter-Interfaced PV Generation System is connected to a power transformer and transmitted across a transmission line. At the far end of the transmission line is the load. Based upon the method structure described in this paper, the simulation was developed to assess the viability of the proposed dynamic voltage control. The architectural concepts and operational parameters are adapted from [14]. As such, the focus of this particular configuration is to simulate practical conditions for renewable energy-based grids. The hydrogen system is added to the original model as a dynamic component to maximize grid efficiency, reliability, and minimize voltage fluctuation.

Table 1. System simulation parameters.

Parameter	Value
Power System Components	
PV Array Rated Power	100 kW
PEM Electrolyzer Rated Power	16 kW
Fuel Cell Rated Power	16 kW
Converter Switching Frequency	10 kHz
Line Data (C , L)	20 μ F, 10 mH
Hydrogen Storage & Control	
Nominal DC Bus Reference (V_{ref})	400 V
Control Deadband (Thresholds)	380 V - 420 V
Max Hydrogen Storage Capacity	40.0 mol
PI Controller Gains	$K_p = 0.5$, $K_i = 0.001$
Simulation Setup	
Simulation Sample Time	5×10^{-6} s
Time-Scaling Assumption	2.4 s sim. $\approx$ 12 h real-time

Beginning with the simulated MicroGrid architecture and its electrical components that form part of the DC bus; there is a PV simulator representing the intermittent nature of solar power. There is also a Proton Exchange Membrane (PEM) Electrolyzer acting as a controllable active load for the Hydrogen compen-

sator unit. Finally, a PEM Fuel Cell represents a dynamic voltage source. The nominal voltage of the system is in the range of 380 - 420 Volts. A buffer and intermediate storage unit exists for hydrogen and has a max capacity constraint of 40 moles.

The key innovation is a dynamic voltage regulation controller embedded in the system which translates the previously described flowcharts' logic into control outputs for converter switching duties. The controller serves as the central intelligence unit for the system with respect to the DC bus voltage V_{dc} . Therefore, it will continually monitor the value of V_{dc} . If V_{dc} increases above the nominal value, the controller directs an appropriate amount of power from the DC bus to the electrolyzer so as to be able to absorb the excess energy. If V_{dc} decreases, then the controller will instruct the fuel cell to supply additional energy to the DC bus. As such, both hydrogen systems are capable of responding immediately to changes on the electrical grid.

The proportional-integral (PI) control strategy was chosen for this application as it will help filter out high frequency switching noise. The PI controller has built-in anti-windup protection for the integration portion that prevents the integral from saturating during a severe fault condition. **Table 1** represents the simulation parameters of the system.

4. Results

The simulation system was built with Simulink. It represents traditional PV systems that include Battery Energy Storage Systems (BESSs) which have a physical relationship between energy storage capacity (kWh) and power output capability (kW). The chemical process associated with charging/discharging batteries is equivalent to the electrical process of delivering power from the battery; therefore, it is impossible to independently scale each of these. Therefore, in order to increase the period of time that the system can remain off-grid, such as during prolonged periods of low light, additional battery modules must be added proportionally to the required time. Since this approach results in a larger than necessary amount of power capability being specified to meet the longer term energy needs, long-term, large-capacity energy storage becomes economically impractical.

Electrolysis and a hydrogen cell were added as shown in **Figure 2**. In a hydrogen-based system, the power that can be produced by a system is determined solely by the amount of energy that has been absorbed by the conversion elements (the electrolyzer and fuel cell) to convert the chemical energy into electrical; conversely, the stored energy in a system is independent of the size of the storage tanks. These results were scaled on the simulation time basis, so that 2.4 seconds on the simulation time basis would equal 12 hours of actual time.

As shown in **Figure 3**, the DC voltage is stable at around 380 V. Between 0.6 s and 1.0 s, the voltage increases to about 440 V indicating excess electrical power from renewable sources (PV). Then, the voltage drops rapidly to around 340 V for various reasons, including sudden load increase. After 1.6 s, the voltage stabilizes near 380 V, illustrating that system control restores the power balance.

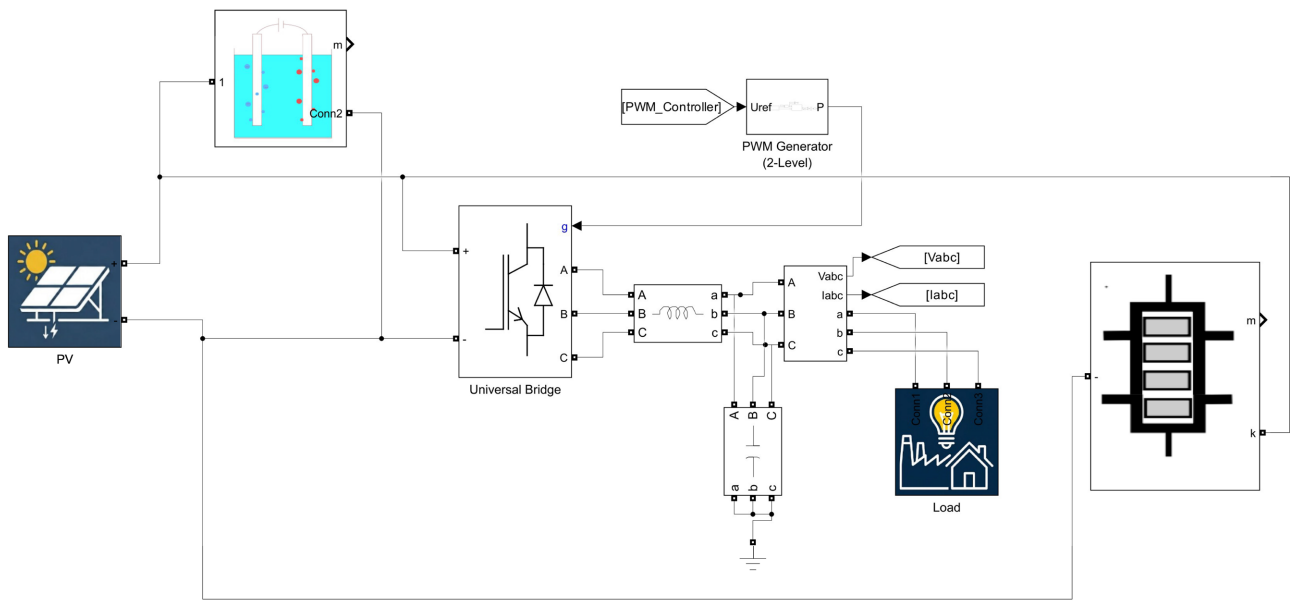


Figure 2. Schematic diagram of the proposed hydrogen-integrated microgrid architecture.

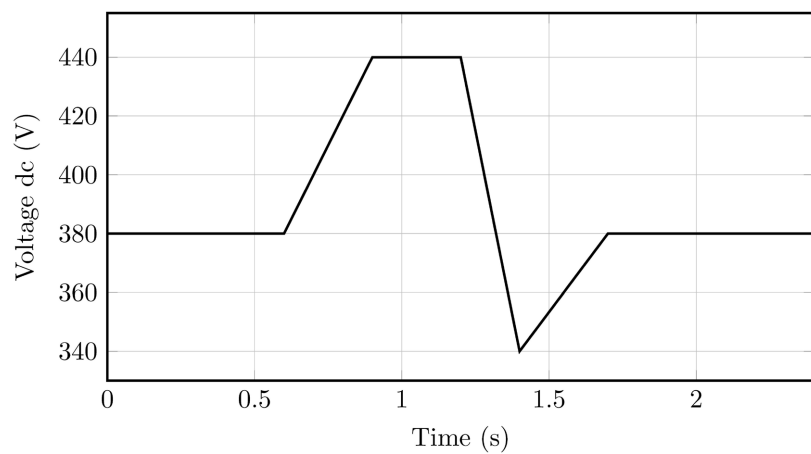


Figure 3. Response of the DC bus voltage.

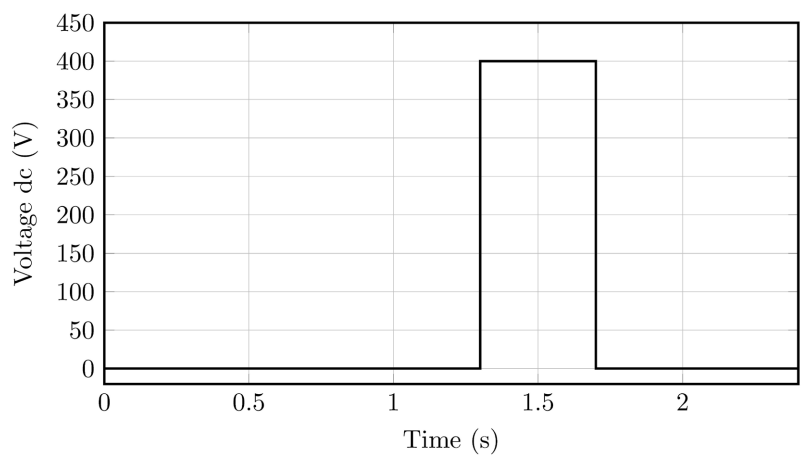


Figure 4. Dynamic voltage response of the fuel cell.

Figure 4 illustrates when the fuel cell is activated. At around 1.3 s the fuel cell rapidly increases to 400 V, indicating that the fuel cell started working. The fuel cell supplied power to support the grid when the DC grid voltage dropped as shown in **Figure 3**. After that, the voltage returns to zero, meaning that the fuel cell shuts down when the grid voltage stabilizes.

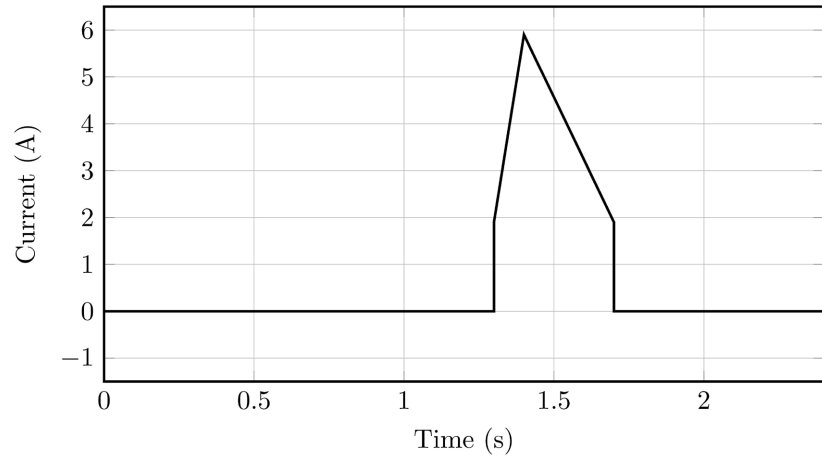


Figure 5. Current of the fuel cell.

Figure 5 shows that the fuel cell produces current only during the overload demand period. At around 1.3 s, the current rapidly increases to about 6 A, meaning the fuel cell started operating. Then, it decreases until it reaches zero.

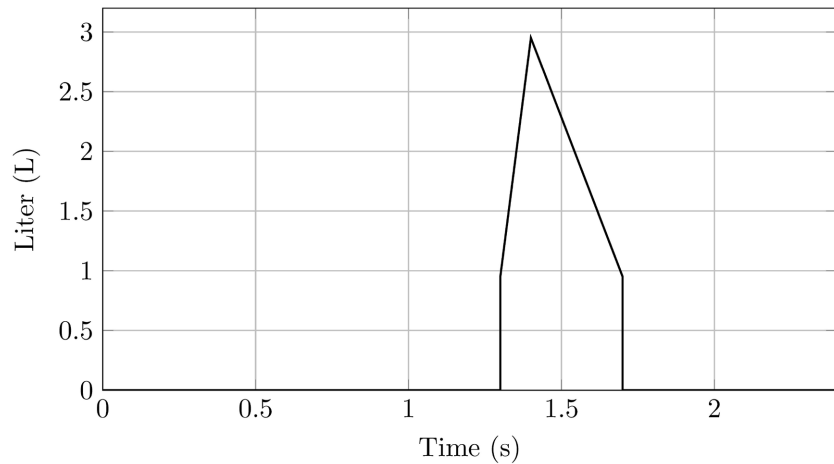


Figure 6. Hydrogen consumption rate.

In **Figure 6** the result shows that from 0 to around 1.3 s, hydrogen consumption is zero because the fuel cell is not supplying power. After that, the hydrogen flow increases significantly to about 3 Liter/min. After reaching the peak (3 Liter/min), it gradually decreases until it returns to zero. So, the result shows that hydrogen is consumed only during the overload demand period.

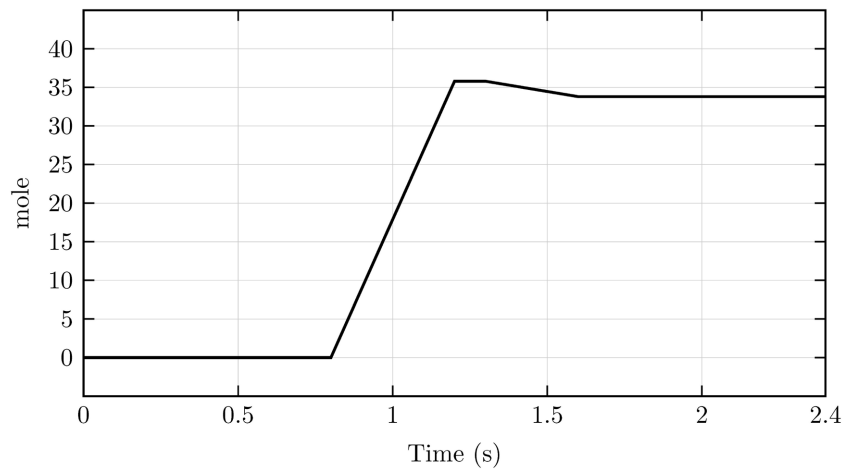


Figure 7. Hydrogen production by the PEM electrolyzer.

Figure 7 shows the amount of hydrogen produced in moles over time. From 0.75 seconds to 1.25 seconds, hydrogen production increases significantly to approximately 36 moles, indicating activation of the electrolyzer due to the increasing DC power supply voltage in **Figure 3**. Subsequently, hydrogen production gradually decreases as it begins to be consumed by the fuel cell.

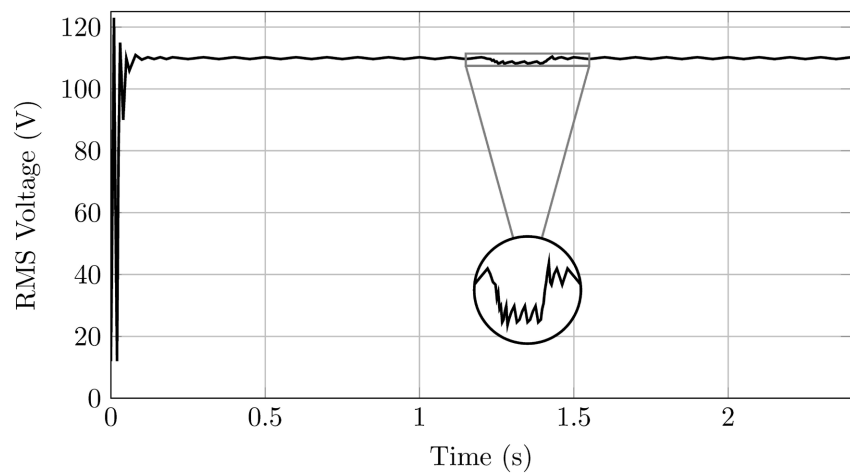


Figure 8. Load RMS voltage.

In **Figure 8**, the first large fluctuations are the transient state of the microgrid because of the system startup and load steps. During this severe transient period, the control system dynamically adjusts the power flow, so that the high frequency oscillations can be effectively damped [19]. After a short time, the voltage reaches a stable steady-state of 110 V. The minor fluctuations and the slight voltage dip visible in the RMS profile represent the system's dynamic adjustment period as the fuel cell begins supplying current to the load to effectively damp the instability and restore normal operation.

The system was subjected to an extreme transient overvoltage of about 440 V

as well as to a significant under voltage condition which decreased to 340 V. The fast response of the dynamic strategy allowed for a recovery to the normal operating conditions with a peak overshoot in approximately 0.2 seconds. Hydrogen production reached its highest value of 36 moles during the simulation of the surplus periods. Meanwhile, the highest hydrogen consumption flow rate during the deficit conditions was around 3 liters per minute.

The results demonstrate the efficiency and reliability of integrating hydrogen production and analysis in electrical networks. When there is excess power, the electrolyzer uses it to produce hydrogen and store it in chemical form. When the voltage drops due to increased demand, the fuel cell converts the produced hydrogen into electricity to power the grid. Overall, integrating hydrogen into the grid is considered a clever solution, as it can be used as a source or load depending on grid conditions. The large initial investment in building both the electrolyzer and the fuel cell represents an additional obstacle to their adoption as alternatives to lower-cost battery solutions. Furthermore, although many companies have successfully developed systems that provide adequate long-term performance, the relatively high cost of replacement components and ongoing service costs represent significant barriers to commercialization.

5. Conclusion

The paper was able to develop and validate a hybrid power network model in the MATLAB/Simulink environment which utilized hydrogen as the main active dynamic stabilization component. Hydrogen was transitioned from being considered an inactive energy reserve and instead became an active device with the aid of a custom-made Dynamic Voltage Control Algorithm. As such, the proposed control strategy kept the DC bus voltage at levels necessary to allow for normal operation. In addition to acting as a dynamic load through electrolysis, it also acted as a fast response source by using its fuel cell capabilities. These two functionalities resulted in significant improvements in overall grid performance as well as grid stability. In addition to reducing real time energy mismatches, reducing transmission loss and relieving grid congestion, these functions provided an improved means of managing high performance power. Therefore, the paper established a scalable, reliable framework for future power management systems, providing a fundamental structure for incorporating flexible hydrogen technologies into future carbon neutral based energy infrastructure networks. In the future, we will conduct a comprehensive comparison of different energy storage including experimental validation, to allow for quantitative evaluation of how well each technology responds during a transient event, and which technology is most reliable under those conditions.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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