MODERNIZATION OF HYBRID POWER SUPPLY NETWORKS USING HYDROGEN GENERATORS

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Abstract – This paper investigates the modernization of combined power supply networks through the integration of hydrogen generators. Hydrogen technologies are evaluated as efficient solutions for energy storage, load balancing, reserve capacity provision, and enhancing system flexibility. A comprehensive review of contemporary hydrogen generator models -Including alkaline, proton exchange membrane, and solid oxide electrolyzers – highlights their respective advantages and limitations. A combined power supply system model incorporating a hydrogen generator was developed using the Simulink environment. This model integrates renewable energy sources, a hydrogen storage electrolysis system, and a fuel cell for electricity generation. Simulation results validate the system's ability to maintain stability and provide uninterrupted power supply under variable demand, peak loads, and main source failures. The findings underscore the viability of hydrogen technologies for modern power grids, emphasizing their potential to enhance sustainability, reliability, and operational efficiency. The proposed model offers a foundation for further research and practical implementation of hydrogen-based systems in energy networks.

Keywords: Hydrogen Generator, Energy Storage, Electrolysis, Simulink Modeling, Power Supply Stability.

1. Introduction

Modern energy is undergoing a transformation associated with the implementation of the Smart Grid concept, which aims to integrate renewable energy sources (RES) into centralized and decentralized power grids. This process creates new challenges, such as reducing the stability of networks due to the variability of solar and wind generation. In such conditions, the role of energy storage devices, which can compensate for the imbalance between electricity production and consumption, becomes crucial [1–3].

Energy storage devices allow for smoothing peak loads, which helps to avoid grid overloads and reduce dependence on traditional thermal power plants. Among the available storage technologies, lithium-ion batteries, supercapacitor-based systems and hydrogen generators stand out. While batteries are mainly used for short-term balancing of networks, hydrogen generators demonstrate advantages in long-term energy storage and providing backup power in emergency situations. In addition, hydrogen is an environmentally friendly source of energy: when it is burned or used in fuel cells, only water is formed, which helps reduce greenhouse gas emissions [4–8].

Hydrogen generators are one of the promising technologies for energy storage and production that can significantly improve the operation of combined power grids. They allow for the efficient use of renewable energy sources by storing excess electricity in the form of hydrogen, which can then be used to generate electricity when needed. This provides flexibility and reliability of the system, as hydrogen generators can quickly respond to changes in electricity demand.

Such generators store excess electricity from renewable sources during periods of low demand and use it during periods of peak loads, which helps maintain the stability of the electricity supply and distribute the load on central power plants. The use of hydrogen generators guarantees a reliable power reserve, which is critical in emergency situations or when the main sources of electricity are disconnected, ensuring the continuity of supply to consumers. In addition, hydrogen generators contribute to the reduction of greenhouse gas emissions, since hydrogen is a clean fuel that produces only water when burned, thus contributing to the reduction of the environmental impact of the energy sector.

Hydrogen generators allow the efficient use of excess electricity generated by renewable sources during periods of low demand. This electricity is converted into chemical energy, which is stored in the form of hydrogen. During peak hours, hydrogen is used to generate electricity through fuel cells or turbines. This solution provides increased system flexibility: hydrogen generators respond quickly to load fluctuations, compensating for sudden demand

[9, 10]. In addition, hydrogen provides backup power in the event of an emergency shutdown of the main sources.

A hydrogen generator, also known as an electrolyzer, is a device that splits water molecules ($2H_2O$) into hydrogen ($2H_2$) and oxygen (O_2). Water electrolysis can be considered a reversible process for producing hydrogen, which can then be used in fuel cells. From an electrochemical perspective, fuel cells undergo reactions that convert the chemical energy of hydrogen into a direct electrical current, while a hydrogen generator can convert electrical energy back into chemical energy stored in water and vice versa [6]. There are two types of electrolysis: alkaline and PEM (proton exchange membrane). An equivalent circuit for one PEM-based electrolyzer is shown in (Fig. 1). It is important to note that PEM cells are more reversible devices for hydrogen systems compared to alkaline electrolysis. In addition, they have numerous advantages, such as smaller size and weight, lower power consumption, and lower operating temperatures [7, 8].

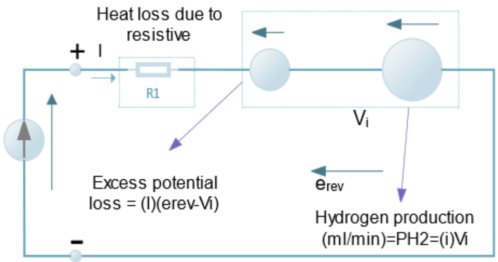


Figure 1: Equivalent circuit of a single PEM electrolyzer

Modern hydrogen systems are used in various scales and configurations, reflecting the versatility of their application in combined power grids [11–15]. The following main approaches to the implementation of hydrogen systems are known:

- Distributed hybrid systems;
- Centralized high-power electrolyzers;
- PEM electrolyzers in local networks;
- Solid-state oxide electrolyzers (SOE).

Distributed hybrid systems combine hydrogen generators and other energy storage devices, in particular batteries. Hydrogen provides long-term energy storage, while batteries are used for operational demand balancing. Their advantage is to ensure multi-level flexibility of the power system, the optimal combination of short-term and long-term energy storage. Meanwhile, such systems have a high cost due to the need to use several types of storage devices and the complexity of management due to the integration of heterogeneous components [2, 3].

Centralized high-power electrolyzers involve the creation of large hydrogen production plants that are used to support national power grids or industrial facilities. They provide significant amounts of hydrogen production and storage and the possibility of using it for decarbonization of industry (e.g. steel or ammonia production). The disadvantage is the need for a developed infrastructure for transportation and storage of hydrogen and significant energy costs for conversion and transportation [4].

PEM electrolyzers in local networks are the most popular technology for integration into local energy networks due to their compactness, high efficiency and low operating temperatures. The advantage of their application is fast start-up and shutdown, lower energy consumption compared to alkaline electrolyzers. They are suitable for operation in small networks and microgrids. The limitations of the use of PEM electrolyzers are the higher cost compared to other technologies and the relatively short service life of the membranes [6–8].

SOEs are high-temperature devices that demonstrate impressive efficiency in energy conversion, especially when operating in combination with thermal sources [9, 10]. They have the highest efficiency among existing electrolyzers, as well as the ability to be used both for hydrogen production and for reverse electricity generation. Among the disadvantages, it should be noted the high cost of manufacturing and the need for high temperatures for operation (800–1000°C).

The purpose of this paper is to develop and model a combined power plant with a hydrogen generator in the Simulink environment, which will provide integration of renewable energy sources, capacity reservation and adaptive load management. To achieve the goal, the task is to analyze existing models of hydrogen systems, study their advantages and disadvantages; develop a system model in the Simulink environment, which will include a hydrogen generator, renewable energy sources and other network components; simulate the operation of the system under conditions of variable load and emergency shutdown of the main sources of electricity; assess the effectiveness of the model in terms of stability of operation, cost-effectiveness and environmental impact.

This study will substantiate the benefits of implementing hydrogen technologies in modern power grids, will contribute to increasing the stability and reliability of power supply, and will create a basis for further developments in the field of renewable energy integration.

2. Electrolysis Modeling in Hydrogen Generators

For modeling electrolysis based on proton exchange membrane, an equivalent circuit was developed in the Matlab/Simulink environment. In hydrogen production, special equations designed for normal conditions were developed to obtain current-voltage characteristics and implemented in the Matlab/Simulink environment. For modeling the electrolysis process, [16, 17]:

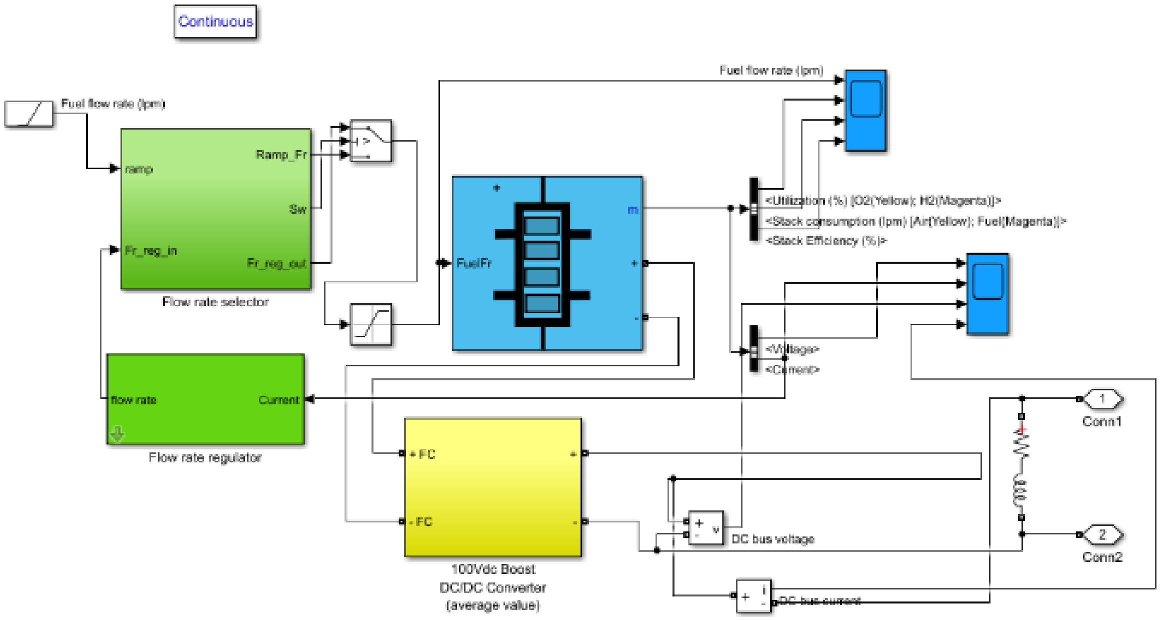


Figure 2: Model of a hydrogen generator in Matlab/Simulink

$$V = IR_i + e_{rev}. \tag{1}$$

The given equation indicates a simple equivalent circuit model for a PEM electrolyzer, which is characterized by an initial resistance R_i and a reverse potential e_{rev}. Ideal potential V_i (electrochemical) is calculated by the equation:

$$V_i = \frac{\Delta G}{2F}, \tag{2}$$

where ΔG indicates the change in the Gibbs free energy of hydrogen gas (in Joules per mole), and F represents the Faraday constant (96.487 Coulombs per mole). If water is in the liquid state, then the change in ΔG for any given temperature T (in degrees Celsius) can be calculated by [8]:

$$\Delta G = 285840 - 163.2 \cdot (273 + T). \tag{3}$$

The value of V_i is calculated at nominal operating conditions, which include a room temperature of 20°C and a pressure of 1 atmosphere. It is 1.223 V and is important for electrolysis and hydrogen production processes. This value is also related to electrochemistry and can be calculated from the ideal gas expression, which is given by:

$$V_m = \frac{R(273+T)}{P}, \tag{4}$$

where R and P represent the ideal gas constant (0.082 L atm·K^{-1}·mol^{-1}) and pressure, respectively. The hydrogen production rate is denoted as V_H (ml/h) and is given by the ratio to the input current I (A):

$$V_H = V_m(I)\left(\frac{10^3 ml}{l}\right)\left(\frac{60s}{min}\right)\left(\frac{I\frac{C}{s}}{2F(C)}\right) =$$
$$= V_m(10^3)(60)\frac{I}{2F}. \tag{5}$$

According to formula (6), the electrochemical energy of hydrogen per second is calculated P_{H2} which is equal to V_H [11]:

$$P_{H2} = V_m(10^3)(60)\frac{I}{2F}\frac{2FV_i}{V_m(10^3)(60)} = V_1 I. \tag{6}$$

From the above equations it follows that the useful power released by the electrolyzer depends on the input current I and the ideal voltage. The input electrical power P, which is consumed in the electrolyzer and is a function of V_H, is determined by [9]:

$$P = VI = I^2R_i + Ie_{rev} = (V_m\frac{2F}{10^3(60)})^2R_i +$$
$$+(V_H\frac{2FV}{V_m 10^3(60)})e_{rev}. \tag{7}$$

The reverse potential erev, relative to the ideal voltage V_i, is calculated as 1.476 V. The resistance R_i of the PEM subsystem is also 0.326 Ohm at a temperature of 20°C and a pressure of 1 atm. To simplify and define the input data of the I-V model as a function of pressure and temperature according to [11]:

$$V(T,P) = IR_i + e_{rev}(T,P). \tag{8}$$

As a result of the calculations, a model was created in Matlab / Simulink, shown in Fig. 2. The DC/DC voltage converter block is shown in Fig. 3. Parameters of the hydrogen generator block is shown in Fig. 4.

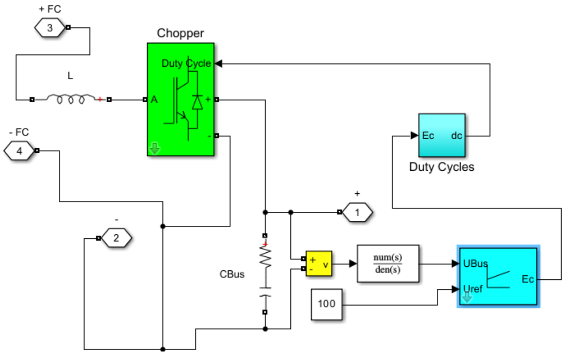


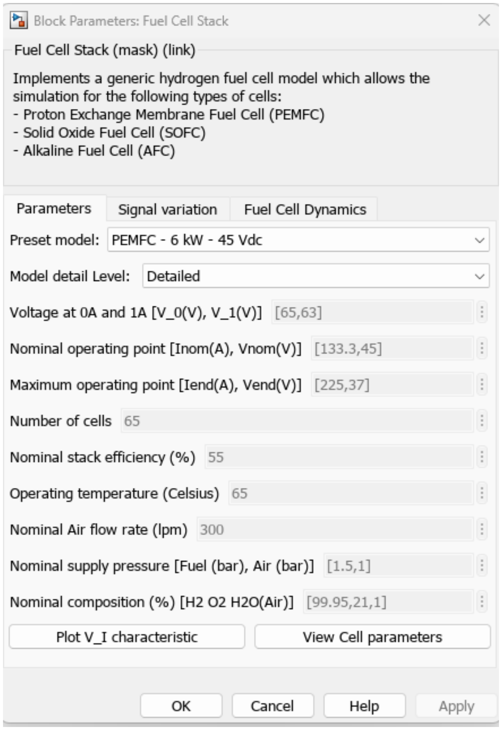
Figure 3: DC/DC voltage converter block in Matlab/Simulink

The model on Fig. 2 of a hydrogen generator is designed to simulate the process of hydrogen production via electrolysis, allowing detailed analysis and optimization of its performance within a power system. This model represents the key components and dynamics of an electrolyzer, which splits water into hydrogen and oxygen using electrical energy. The hydrogen generator model receives DC power, supplied by renewable energy sources such as solar panels or wind turbines, and converts this energy into hydrogen through electrochemical reactions. The model incorporates a range of input parameters, including the voltage and current applied to the electrolyzer, to simulate the energy conversion process accurately. It also include thermal effects, efficiency characteristics, and the operational constraints of the system, ensuring realistic behavior under varying conditions.

The DC/DC voltage converter block on Fig. 3 is a dynamic simulation model used to represent the operation of a converter that adjusts the voltage level from one DC value to another. It is a critical component in power electronic systems, commonly employed in renewable energy systems, electric vehicles, and other applications requiring efficient power management. This block simulates the behavior of various DC/DC converter topologies, such as buck (step-down), boost (step-up), or buck-boost converters, depending on the system's requirements.

Key parameters for the converter block include input and output voltages, switching frequency, duty cycle, and component specifications like inductor and capacitor values. These parameters are adjustable to match specific design goals and operational conditions. The block dynamically responds to changes in input voltage, load conditions, and control signals, accurately simulating real-world performance.

By integrating the DC/DC voltage converter block into a larger system model in Matlab/Simulink, one can analyze and optimize the converter's performance, evaluate efficiency, study transient and steady-state behavior, and design effective control strategies. This makes it an indispensable tool for developing and validating energy systems that rely on precise DC voltage conversion.


Block Parameters: Fuel Cell Stack

Fuel Cell Stack (mask) (link)

Implements a generic hydrogen fuel cell model which allows the simulation for the following types of cells:
- Proton Exchange Membrane Fuel Cell (PEMFC)
- Solid Oxide Fuel Cell (SOFC)
- Alkaline Fuel Cell (AFC)

Parameters | Signal variation | Fuel Cell Dynamics

Preset model: PEMFC - 6 kW - 45 Vdc
Model detail Level: Detailed
Voltage at 0A and 1A [V_0(V), V_1(V)] [65,63]
Nominal operating point [Inom(A), Vnom(V)] [133.3,45]
Maximum operating point [Iend(A), Vend(V)] [225,37]
Number of cells 65
Nominal stack efficiency (%) 55
Operating temperature (Celsius) 65
Nominal Air flow rate (lpm) 300
Nominal supply pressure [Fuel (bar), Air (bar)] [1.5,1]
Nominal composition (%) [H2 O2 H2O(Air)] [99.95,21,1]

Figure 4: Parameters of the hydrogen generator unit

The results of the simulation charts are shown in Fig. 5 and 6. The **fuel flow rate** represents the rate at which fuel is delivered to the system, serving as a critical parameter that influences power output and overall performance [17–23]. The **utilization percentages** of oxygen (O_2: Yellow) and hydrogen (H_2: Magenta) indicate how efficiently these gases are consumed within the process, providing insight into the system's operational efficiency [24]. Similarly, **stack consumption rates** (L/min), categorized as air (Yellow) and fuel (Magenta), reflect the volumetric consumption of these inputs, which is crucial for evaluating the efficiency of hydrogen generation [25].

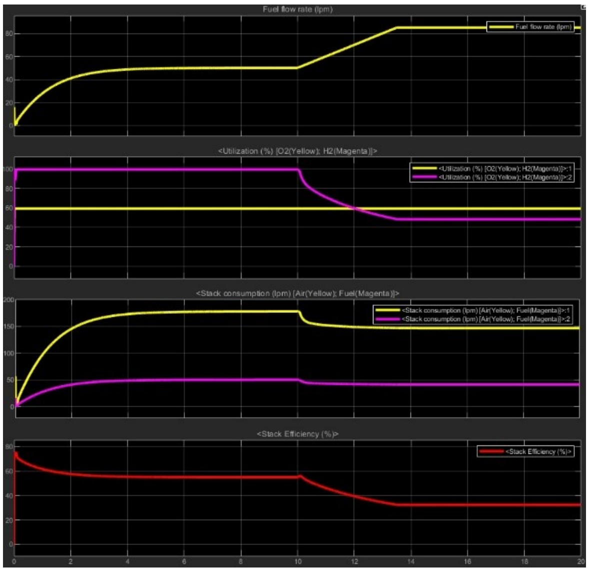


Figure 5: Model simulation charts of oxygen consumption and utilization, fuel and air

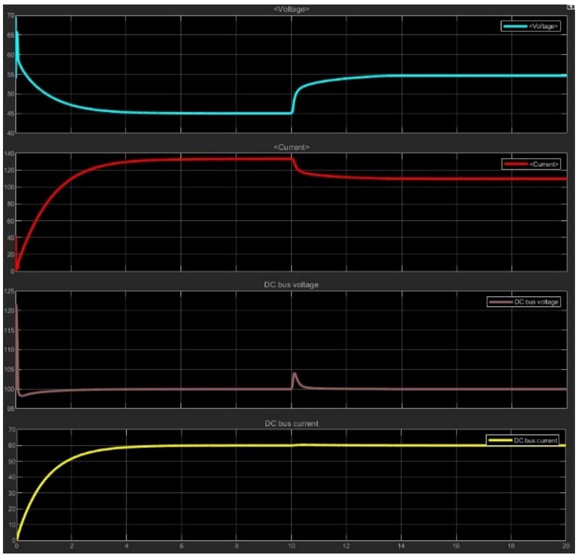


Figure 6: DC bus current and voltage simulation charts

Finally, **stack efficiency** measures the system's capability to convert fuel into electrical energy, accounting for energy losses and other factors, making it a key indicator of overall performance.

The voltage and current chart on Fig. 6 indicates the change in these parameters in the system over time. The change in voltage and current is within acceptable limits, which indicates the normal functioning of the system. These changes are associated with changes in the load and the operation of the system's control devices. These charts indicate the correctness of the model calculations and the efficiency of the system. The system operates as expected and meets the specifications that have been established. The absence of anomalous indicators and deviations from expected values allows us to conclude that the modeling is correct and the system is operating correctly.

3. Model of a Hybrid Power Plant with a Hydrogen Generator

Gaseous or liquid hydrogen can be stored in tanks using a variety of methods, with physical hydrogen storage being one of the most commonly utilized approaches [6]. In Matlab/Simulink, a dynamic module for the tank is created to store gaseous hydrogen produced by an electrolyzer, which can be expressed as [10]:

$$P_b - P_{bi} = z \times \frac{N_{H2} R T_b}{M_{H2} V_b}, \tag{9}$$

where P_b represents the tank pressure (measured in Pascals), P_{bi} is the initial pressure of the storage tank (Pascals), R is the universal gas constant (J/kmol·K), T_b is the operating temperature (K), V_b is the tank volume (m^3), T is the temperature, and Z is the compression ratio, which is a function of pressure:

$$Z = \frac{PV_m}{RT}. \tag{10}$$

In this context, P and V_m indicate the pressure and molar volume, respectively. The model calculates the pressure in the tank using the relationship between the hydrogen flow rate and the tank. This is implemented in Simulink environment for the purpose of storing and supplying hydrogen to a fuel cell or other systems [8].

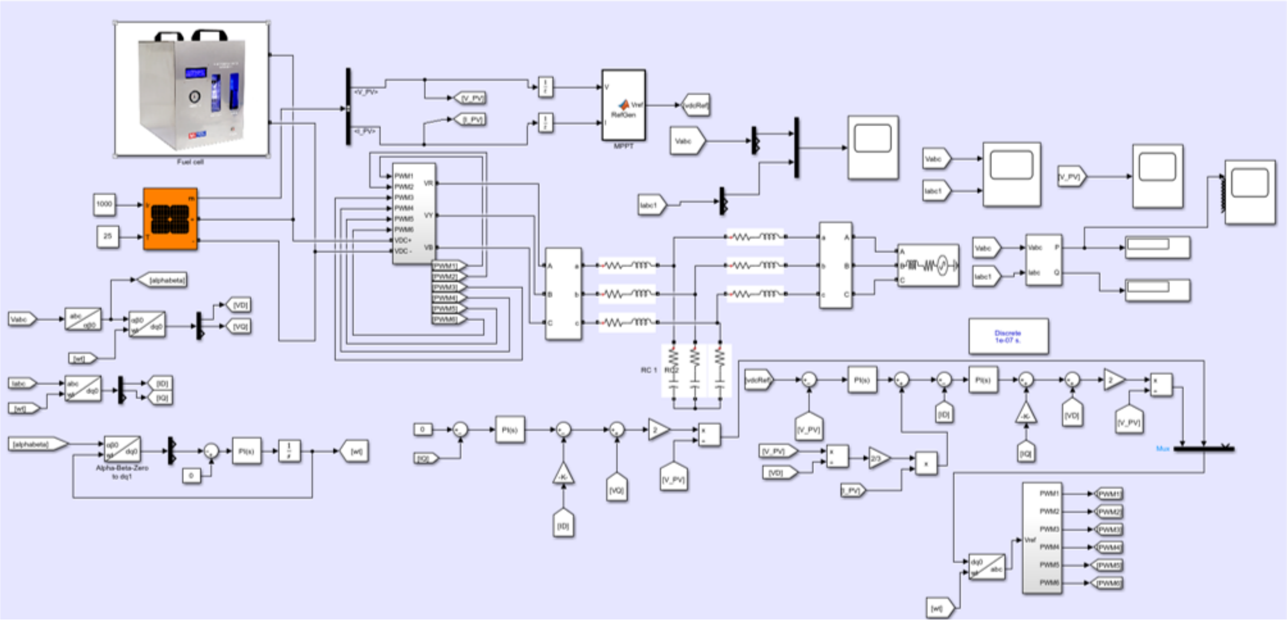


Figure 7: Hybrid model of a power plant with a hydrogen generator in Matlab/Simulink

Table 1: Simulation parameters in Matlab/Simulink

Simulation Parameter	**Value**
Solver	VariableStepAuto
RelTol	1e-3
Refine	1
MaxOrder	5
FixedStep	1e-7
ZeroCross	on

Modules for photovoltaic solar panels, a DC/DC step-down converter, an electrolyzer, and a hydrogen tank have been created and integrated, and they interact well with each other. This system allows for the simulation of various scenarios [16–20]. The important parameters for the simulation in the Matlab/Simulink environment are presented in Table 1.

The scheme of the hybrid model of a power plant with a hydrogen generator in Matlab/Simulink is shown in Fig. 7. The developed simulation model of a solar power plant includes the following components: solar module, DC/DC converter (charge controller), hydrogen generator, storage battery, and electrical load.

All component models are made as separate subsystems in the Matlab/Simulink software environment, and they have the property of mass stacking.The properties of the *Function Block Properties/MPPT* block in the Matlab/Simulink hybrid model scheme are given in below script.

```
function Vref = RefGen (V,I)
Vrefmax = 907.5;
Vrefmin = 0.0;
Vrefinit = 750;
deltaVref =1;
persistent Vold Pold Vrefold;
dataType = 'double';
if isempty(Vold)
    Vold = 0;
    Pold = 0;
    Vrefold = Vrefinit;
end
P = V * I;
dV = V - Vold;
dP = P - Pold;
if dP ~=0
 if dP<0
        if dV<0
            Vref = Vrefold + deltaVref;
        else
            Vref = Vrefold-deltaVref;
End
else
        if dV<0
            Vref = Vrefold - deltaVref;
        else
Vref = Vrefold + deltaVref;
        end
    end
else Vref = Vrefold;
end
if Vref >= Vrefmax | Vref <= Vrefmin
    Vref = Vrefold;
End

Vrefold = Vref;
Vold = V;
         Pold = P;
```

The Simulink model on Fig. 7 represents a hybrid power plant system that integrates solar energy and hydrogen generation technologies to ensure efficient energy management and sustainable operation. It consists of key subsystems that play vital roles in energy conversion and storage processes. The solar module converts sunlight into electrical energy using photovoltaic cells, serving as the primary renewable energy source for the system. The DC/DC converter, or charge controller, regulates the voltage and current output from the solar module, optimizing energy transfer to downstream components such as the hydrogen generator and storage battery. This ensures compatibility between the solar module's output and the system's requirements while maintaining stable operation.

The hydrogen generator converts electrical energy into hydrogen through electrolysis, providing an alternative energy storage medium particularly suited for long-term storage or high-capacity needs. The storage battery stores surplus electrical energy for immediate use or backup during periods of low solar output, balancing the power flow and ensuring a steady energy supply to the load, which represents the system's energy consumption demands. Additionally, the model includes a Duty Cycles block that manages the switching behavior of the DC/DC converter, dynamically adjusting duty cycles to optimize energy flow based on input conditions and system requirements.

A flow rate selector controls the distribution of energy between the hydrogen generator and the storage battery, prioritizing energy allocation based on real-time production and consumption patterns. Together, these components enable the simulation of energy harvesting, conversion, storage, and consumption processes under real-world conditions, such as fluctuating solar irradiance, varying load demands, and energy storage limits.

The modular design of the model supports mass stacking, allowing for scalability and the integration of additional components. By providing detailed simulation capabilities, the model allows researchers and engineers to analyze performance, optimize efficiency, and develop strategies for implementing sustainable hybrid power systems in real-world applications.

Photovoltaic inverters play a key role in converting electricity from solar panels into AC for the grid. Using a single-stage inverter with MPPT and a grid current regulator with high filtering efficiency thanks to the LCL filter assembled from IGBT switches [6].

The inverter is controlled using the synchronous reference system theory. The voltage between the lines is converted into alpha-beta voltages, which are used to determine the current using a PLL (phase locked loop) and further converted to dq voltages through the Clark transform [10].

The inverter currents are converted to the alpha-beta domain, and further converted to the dq domain allows the active and reactive currents to be determined. These data are used to control the controller that regulates the voltage.

The Subsystem "A" model is a three-phase bridge inverter model used in the implementation, consisting of 6 IGBT switches with 6 input signal ports for the PWM (pulse-width modulation) signal. Its switching frequency is 10 kHz, and two parallel-connected input bus capacitors of 500 µF each. This entire scheme is reflected in the subsystem, where a three-phase measuring unit VI is used to monitor the inverter current [21–23].

4. Results and Discussion

The modeling results are presented in Fig. 8–11. The chart (Fig. 8) shows the instantaneous values of voltages V_{abc} and I_{abc}. The current I_{abc} is represented by the blue waveform on the chart, which reflects the fluctuations and noise in the current. The voltage V_{abc} is represented by the yellow waveform, which is sinusoidal and indicates a stable and synchronized voltage.

The current phases stabilize and become synchronized with the voltage phases, which indicates the efficiency of the control system and its ability to compensate for initial disturbances. This is important for ensuring power quality and reliability of power supply. The system can withstand and compensate for instabilities.

Analysis of the behavior of the voltage V_{abc} and current I_{abc} charts (Fig. 9) showed that the voltage V_{abc} waveform is sinusoidal and synchronized between phases, which indicates a healthy system without significant harmonic distortions.

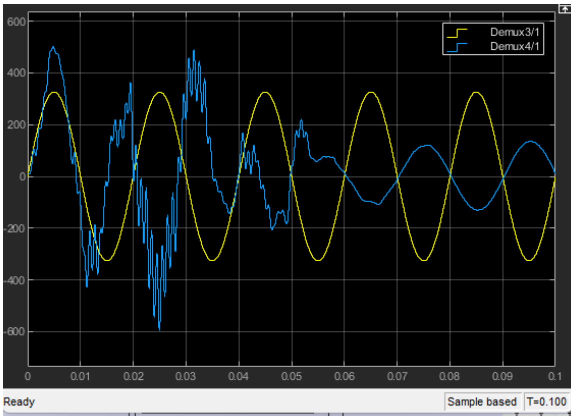


Figure 8: Simulation chart of signals I_{abc} and V_{abc}

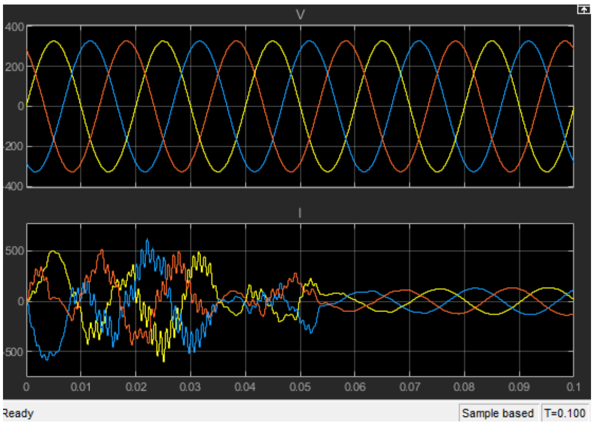


Figure 9: Result of analysis of three-phase voltage and current system

The current I_{abc} waveform (Fig. 10) indicates the presence of transients and minor load instability in the system. By conducting the phase relationship between voltage and current, we obtain that the voltage and current phases are synchronized, which indicates the efficient operation of the system. The stability of the amplitude of both voltage and current is important for the reliability of the electrical system. In general, the behavior of the charts can be assessed as good, since the voltage V_{abc} waveforms are stable and sinusoidal, and the current I_{abc} waveforms show minor deviations, which are subsequently normalized.

The chart (Fig. 11) shows the voltage variation of the solar panels over time. The *Y*-axis is labeled from 0 to 800, indicating voltage levels. The *X*-axis represents time. The yellow line on the chart shows the incremental value. This chart indicates that the solar panel is operating at varying efficiency over the measured period. The voltage drop is caused by a decrease in sunlight intensity, (due to cloud cover or obstructions to the light). The incremental voltage increase reflects the recovery of light intensity. This is an important step in understanding the performance of solar panels and their suitability for environmental conditions.

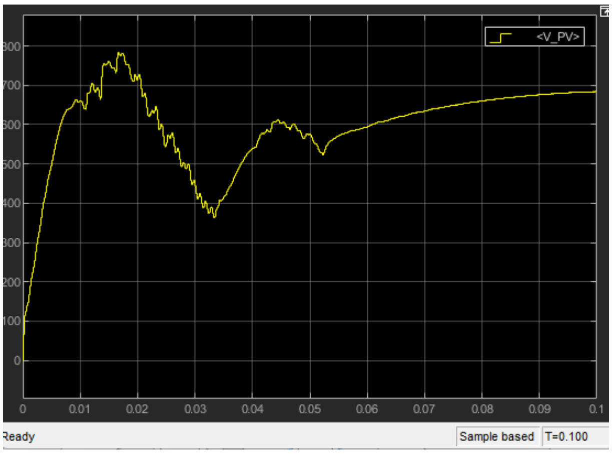


Figure 10: Solar Panel Voltage Chart

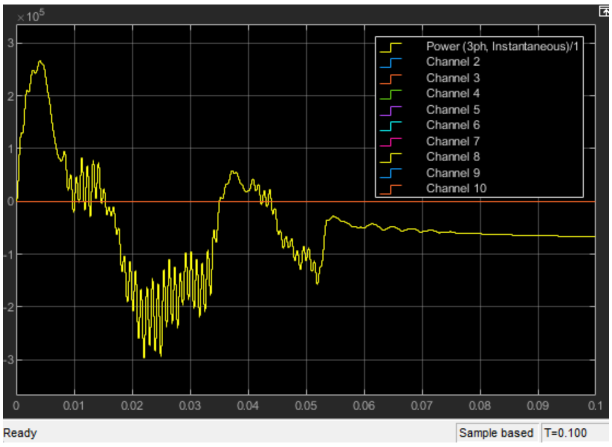


Figure 11: Instantaneous Power Chart

The chart shows significant power fluctuations, with sharp peaks and dips visible between 0.01 and 0.05 on the *X*-axis before stabilizing near zero.

These fluctuations can indicate transients in the system, such as short-term overloads in equipment operation. Stabilization of the chart near zero indicates that the system is returning to normal operation after the transient occurs. This is important for analyzing the reliability and stability of the electrical system, as well as for identifying and resolving potential problems.

The simulation results demonstrated that the developed energy system is highly adaptable and capable of operating effectively across a range of modes. During periods of low electricity demand, the surplus power generated by the system was efficiently redirected to the hydrogen generator. Here, the process of electrolysis was carried out to produce and accumulate hydrogen for future use. This operational strategy ensures that excess energy is stored rather than wasted, thereby enhancing the overall efficiency of the system. In contrast, during periods of peak energy demand or unforeseen shutdowns of the primary electricity sources, the system seamlessly transitioned to utilizing the stored hydrogen in a fuel cell. The fuel cell provided a reliable and stable supply of electricity, ensuring uninterrupted operation even under challenging conditions. This functionality was validated through the analysis of system operation schedules, which clearly reflected its ability to maintain consistent performance. Moreover, the system exhibited a high degree of efficiency and stability in responding to abrupt changes in energy demand. These results highlight the robustness of the system's design, showcasing its potential as a versatile and sustainable solution for modern energy management challenges. The advantage of the model was the reduction of the load on traditional energy sources in critical conditions, which contributed to increasing the overall reliability of the power grid. In addition, the use of hydrogen generators provided environmental benefits - the simulation confirmed the reduction of dependence on fossil fuels.

However, certain technical and economic limitations were identified. For example, the efficiency of the PEM electrolyzer depended on operating conditions, and the cost of its implementation remained quite high due to the need for infrastructure for hydrogen storage.

Nevertheless, the results suggest that such a system could be a promising alternative for grid modernization with renewable energy integration. Further research should focus on improving the energy balance and reducing capital costs.

5. Conclusions

A model of a combined power supply system integrating a hydrogen generator was developed in the Simulink environment. The study focused on the interaction between key components of the system, including renewable energy sources (solar panels and a wind turbine), a hydrogen generator based on a PEM electrolyzer, and a fuel cell. A distinguishing feature of the model was its adaptive control mechanism, which enabled efficient balancing of energy production and consumption under varying load conditions.

The simulation results confirmed the model's adequacy and its capability to effectively balance electricity within the network. The generated simulation charts demonstrated stable system performance, particularly in storing excess energy as hydrogen and utilizing it during peak demand. System efficiency was achieved through the hydrogen generator's rapid response to fluctuations in energy demand and the model's high operational flexibility.

These findings highlight the potential of hydrogen-based systems to enhance the stability, reliability, and environmental sustainability of power grids. The developed model serves as a robust foundation for further research, optimization of energy systems, and the integration of hydrogen technologies into real-world energy infrastructures.

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