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Stability analysis of an off-grid hybrid power plant for hydrogen production

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Abstract. A 500 kW off-grid hybrid system based on renewable energies (PV and Wind) is designed to produce green hydrogen. This energy system includes a Battery Energy Storage System (BESS) to improve the grid stability. To control the power plant two strategies are assessed. First, a variable-load control is applied to the electrolyser, while the BEES control (with hysteresis) ensures that the power is not less than the minimum admissible in the electrolyser. A second control is developed to minimize electrolyser degradation. In this case, the electrolyser operates at constant power, allowing only very slow voltage variations.

Key words. Off-grid hybrid system, grid stability, power plant control.

1. Introduction

The main issue with renewable energies is that they are not always available. Solar panels work best on long, sunny summer days [1], while wind turbines perform better in the spring and winter when there is more wind. Because of this, it is interesting to combine solar and wind energy into hybrid systems.

The goal of hybrid systems is to improve efficiency by using both energy sources together, ensuring that if one source is low or not available, the other can still meet energy needs. A key challenge with combining renewable energy sources is the need to store extra power when more energy is produced than is needed.

Isolated hybrid systems with renewable sources are therefore an attractive solution for small-scale clean energy production in isolated locations [2], for grid-connected operation in other contexts and also for new application as hydrogen production. Frequency stability is ensured by balancing power generation and consumption. Therefore, the power plant stability requires, at each instant of time, to control the available energy according to the consumption, with the added difficulty of the unpredictability of renewable generation. The objective of the primary control frequency is, as fast as possible, to restore the balance between generation and load and the grid frequency is thus stabilized. Likewise, synchronous generators (SG) are equipped with automatic voltage regulators to handle with voltage changes caused by load fluctuations. Renewable generation does not participate in frequency regulation; its control is a grid-following control, limited to follow the voltage signal generated by the SG.

When powering a hydrogen generating plant, the fundamental objective of the spinning reserve (SR) is to smooth the supply voltage to mitigate natural fluctuations in renewable energy, to ensure operation remains above production minimums, (10% for PEM electrolysers and 40% for alkaline electrolysers), and to guarantee the power supply for auxiliary equipment (motors, pumps, etc.). The length of time the plant must be powered determines the size of the primary reserve. SR is usually based on synchronous generator sets; though it can also be covered by BESS.

In this work, a 500 kW hydrogen generating plant powered by a hybrid off-grid energy system based on wind and photovoltaic generation is considered. The system has been modelled and evaluated in MATLAB-Simulink. Based on the technical limitations of the electrolyser, two management strategies for producing green hydrogen are proposed and assessed. The plant is completed with a BESS. The first control of the electrolyser is a variable-load control with hysteresis in the BESS. The BESS ensures that the generated power is not less than the minimum power admissible in the electrolyser. The second strategy operates at constant power, allowing slow variations to adapt to the available renewable energy.

2. Hydrogen electrolyser

Green hydrogen is produced from renewable electricity through a water electrolysis process. The most mature and commercialized technologies for low temperature hydrogen electrolysers are Alkaline electrolysis (AEL) and Proton exchange membrane (PEM). Alkaline electrolysis has been applied for large-scale hydrogen production in the MW-scale but has disadvantages such as low current density, environmental pollution, impurities in the produced gas and slow response to power changes [3]. PEM-based electrolysis has significant advantages over AEL electrolysers: are smaller in size and weight, consume less energy, produce high purity hydrogen and can operate at higher pressures. Also, PEM electrolyser responds quickly to power fluctuations due to the rapid movement of protons through the polymer membrane [4],[5].

A. Electrolyser as an electrical load

In an isolated grid with renewable sources that feeds a hydrogen electrolyser, it is important to know the active power consumption profile of the electrolyser in order to manage the plant resources. The electrolyser stack is formed by connecting multiple electrolytic cells in series and parallel. The active power consumption of the stack depends on the limitations of the technology used. Table I shows the main characteristics of commercial electrolyser technologies[6].

Table I. – Electrolyser technology characteristics [6]

Parameter	*Alkaline*	*PEM*
Cell voltage [V]	1.8-2.4	1.8-2.2
Current density [A/cm^2]	0.2-0.4	0.6-2.0
Operating pressure [bar]	<60	<80
Operating Temperature [°C]	60-80	50-80
Minimum HE power consumption P_{SG} [%*]	10-40	0-10
Cold start-up time [6]	<60 min	<20 min
Warm start-up time [5]	1-5 min	<10 s [5]

*of electrolysis stack rated power.

To evaluate the behaviour of an isolated network that feeds an electrolyser, the electrical model of the electrolyser should be able to show its static and dynamic behaviour. During dynamic operation, the parasitic capacitance between the anode and cathode affects the rate of change of the voltage and over-voltages appear in the transient state which are extinguished in the steady state [7]. For this purpose, an equivalent circuit of the electrolyser formed by voltage sources, resistors and capacitors based on the equivalent circuit for potential energy storage is used [8],[9]. The equivalent simplified circuit that models the electrical behaviour of a PEM cell is shown in the Fig. 1. The RC parallel circuits represent the dynamics of the cathode ($\boldsymbol{R_1}$, $\boldsymbol{C_1}$) and the anode ($\boldsymbol{R_2}$, $\boldsymbol{C_2}$). The ohmic losses in the membrane are represented by the resistor $\boldsymbol{R_{int}}$, while $\boldsymbol{V_{int}}$ indicates the reversible voltage and reproduces the power converter into hydrogen.

In addition, the electrolyser has auxiliary systems for its operation, such as the water pump and H_2 compressors, O_2 extractor, heaters among others as it is shown in Fig. 2 [10]. All of these supporting subsystems are part of the Balance of the Plant (BoP). In this work, these auxiliary subsystems are modelled as a constant power load.

B. Electrolyser operation states

The electrolyser can work in different states: cold (all equipment turned off), standby (hot waiting to produce) and production. The flexibility of plant operation is determined by the acceptable load range (which includes the minimum load and overload capacity), the load gradients, the start-up time (both hot and cold), as well as the standby losses and cold consumption.

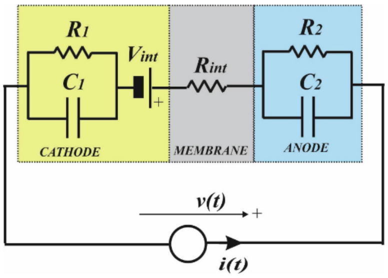

Fig. 1. Equivalent PEM cell circuit [9].

Table II. – Equivalent PEM cell circuit values.

Element	Value
$\boldsymbol{V_{int}}$	402.084 V
$\boldsymbol{R_{int}}$	0.2515 Ω
$\boldsymbol{R_1}$	0.1595 Ω
$\boldsymbol{R_2}$	0.0797 Ω
$\boldsymbol{C_1}$	0.7865 F
$\boldsymbol{C_2}$	0.7865 F

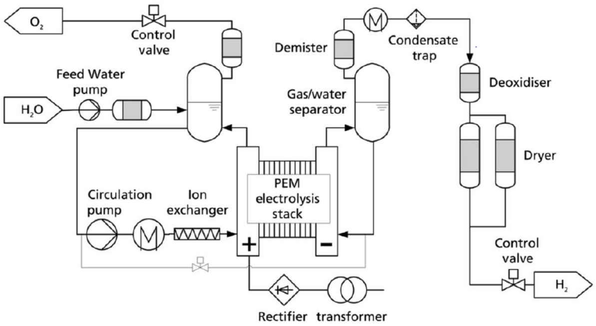

Fig. 2. Example of layout of a complete PEM hydrolyser system [10].

In the cold state (without any hydrogen production), the electrolyser power consumption is minimal and mainly due to the control, measurement, and protection systems. In the standby state, the electrolyser is suitable for operation (with appropriate temperature and pressure), but hydrogen production is not occurring. It is recommended to inject a maintenance current of 1% of the nominal input current to avoid accelerated cell degradation [11],[12]. Finally, in the production state, PEM electrolysers have a theoretical operating range from 0 to 100% [4]; however, a minimum production threshold of 5% is typically imposed [13].
Cold start-up involves initiating the system from ambient temperature and pressure conditions. The start-up time ranges from 5 to 20 minutes for PEM technology and several tens of minutes for AEL technology (Table I) [14]. Hot start-up begins from the standby state, with a start-up time of less than 10 seconds (Table I). Finally, the shut-down process depends on ambient temperature conditions and the status of the H_2 and O_2 systems. The same duration as the cold start-up time has been considered.

C. Effects of dynamic loads

PEM electrolysers can operate with a ramp rate of 10% of nominal power per second [13], limited by thermal management, pressure, continuous voltage across the electrolyser and the response time of external plant control systems. Also, faster ramp rates increase the cell degradation. In case of PV, changes can reach up to 60% of the nominal power within 1 second [15]. Additionally, PEM electrolysers exhibit a flexible operating range from 5% to the rated value. This flexibility enables PEM systems to better utilize energy from renewable sources. However, failure to comply with these current ramping rates and time constraints may lead to accelerated aging due to degradation of the membrane, catalyst layer, bipolar plates, and other components. Likewise, load fluctuations result in additional losses that may cause hot spots, further contributing to cell aging and other adverse effects [16]. Therefore, plant control system must take into account the dynamic behavior of the electrolyser in order to avoid significant efficiency losses [17] and accelerated its ageing.

3. Off grid hybrid power plant for H_2 production

A. Off-grid hybrid power plant

The off-grid hybrid power plant model proposed for H_2 production is shown in Fig. 3. A three-phase synchronous generator (SG) is considered for emergency backup and there is no connection to the grid. The SG model is a synchronous generator with salient poles, 400 V line voltage and 125 kVA. The wind generators (250 kW) use two-level inverters with a grid-following control, while PV (500 kW) and BESS are connected through DC-DC converters to the DC bus. The AC-DC converter is bidirectional (250 kW). Power sizing procedure is not discussed in this paper; this issue is a decision which depends on the resources available at the site.

A BESS is used to support the dynamic loads caused by intermittent power generation. The equivalent rated load of the electrolyser plant is 500 kW ($\boldsymbol{P_{H2}}$), the power (DC) allocated to hydrogen production ($\boldsymbol{P_{H2,prod}}$) is 425 kW, while the power (AC) required for auxiliary equipment ($\boldsymbol{P_{H2,aux}}$) is 75 kW. In addition, there are three-phase loads representing other electrical requirements such as industrial machines, pumps, lighting and others.

The control has a modular scheme, based in seven levels or layers, which functionalities are:

- Layer 1: Input data adaptation
- Layer 2: Sources and loads definition
- Layer 3: Spinning reserve management
- Layer 4: Activation of sources and loads
- Layer 5: Calculation of sources load factor
- Layer 6: Safety measures
- Layer 7: Output data adaptation

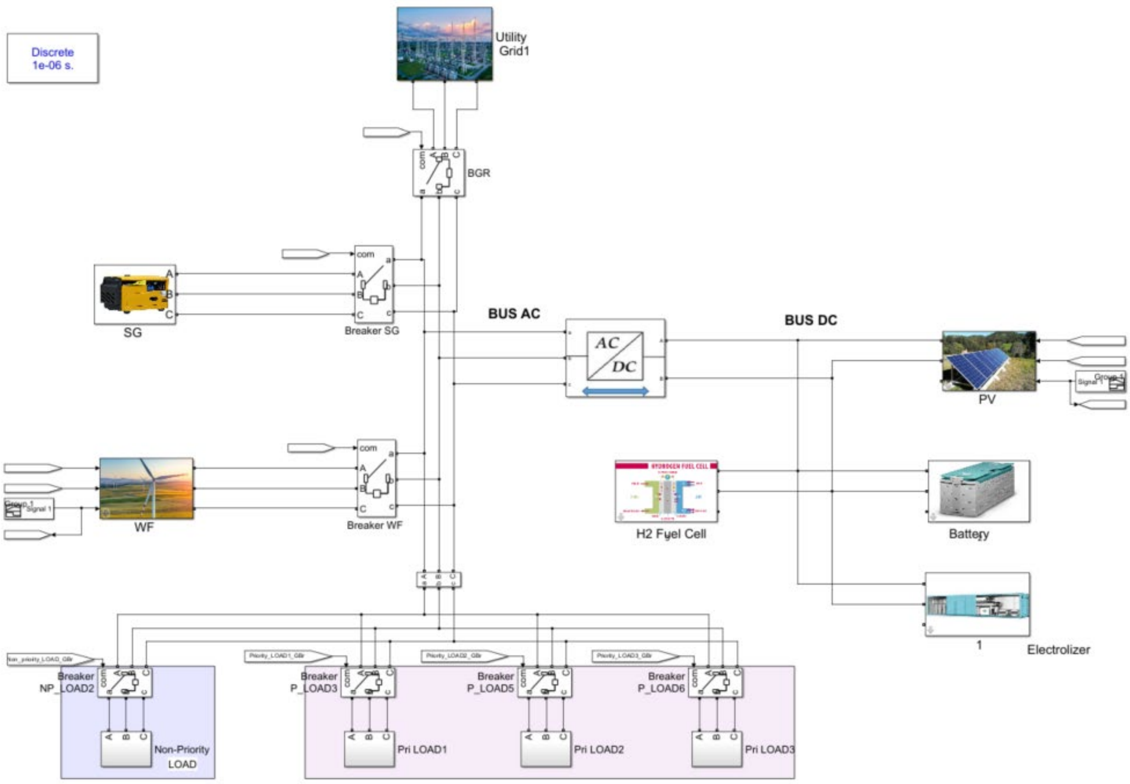

Fig. 3. Proposed off-grid hybrid power plant.

B. Technical limitations

Technical constraints are critical for achieving optimal integration of the electrolyser within an isolated power generation plant. The maximum consumption is limited by the rated power, while the minimum consumption is constrained to ensure the safe operation of the electrolyser; hence, operation must cease below this threshold.

An unplanned shutdown may be triggered either by an input to the control system (e.g., manual push button) or by an interlock due to an abnormal operating condition. The adopted control actions are primarily determined by the fail-safe positions of the process automatic valves, the disconnection setpoints of other control devices, and the tripping settings of electrical circuit breakers. These scenarios are intrinsic to the electrolyser operation.

An additional cause may be caused by a blackout, which is unlikely when the plant is grid-connected—at least in developed regions—but may occur more frequently in islanded installations. A common scenario is the transient passage of clouds, which inevitably causes a sharp drop in power output and may lead to shut down the electrolyser. Power fluctuations induce repeated temperature changes in the electrolyser from low to high; moreover, such temperature cycling accelerates degradation of the electrode and membrane. Fluctuating currents within the electrolyser lead to variations in both temperature and gas pressure [18]. Therefore, the electrical system must remain stable and exhibit slow response dynamics to accommodate the natural variability of renewable sources.

C. Electrolyser Requirements

Proper electrolyser operation requires to satisfy intrinsic safety conditions related to its minimum and maximum power consumption. During the Cold state, power consumption is neglected. In Standby mode, the consumed power to maintain pressure and temperature corresponds to $\boldsymbol{P_{H2,aux.}}$. Finally, during production mode, the minimum required power should cover both the partial load threshold (5% of $\boldsymbol{P_{H2}}$) and auxiliary systems ($\boldsymbol{P_{H2,aux.}}$), while the maximum power is constrained by the rated power plant. In production mode, the power ramp rate must not exceed 10% of $\boldsymbol{P_{H2}}$. Additionally, the system must ensure supply for cold start and shutdown procedures (Table I). Moreover, to maximize electrolyser lifespan, the power demand during cold state until the next scheduled operating cycle must be covered [11]. The power limits are summarized in Table II.

Table II. – Technical operating limits of the electrolyser

State	$P_{DC,min}$ (kW)	$P_{DC,max}$ (kW)	$P_{AC,min}$ (kW)	$P_{AC,max}$ (kW)	ΔP_{max} (kW/s)
Cold	0	0	-	-	0
Standby	0	0	75	75	0
Production	22	425	75	75	42.5

D. BESS as spinning reserve

SG acts as emergency backup (secondary reserve), therefore its usage is minimized. A BESS [19] is used as spinning reserve (SR). The SR is designed to cover the demand in case of PV or wind generation loss. The plant control system (PLC) estimates at every instant the SR needs (every 24 s) based on the demand and the intrinsic safety constraints of both the electrolyser and the plant, sending operating setpoints to each device.

For sizing the BESS system, the following operation requirements are established:

- The BESS must be able of transitioning the electrolyser from full-load operation to minimum production and keep it for a while ($\boldsymbol{E_{prod,min}}$).
- The BESS must ensure the availability of the required energy ($\boldsymbol{E_{shutdown}}$) to safely shutdown the electrolyser.
- The energy required to remain in cold mode ($\boldsymbol{E_{cold}}$).
- To avoid fluctuations, the BESS must be able to support the loss of this generation to maintain voltage stability—e.g., during a cloud passage—thus it must sustain production for a few minutes ($\boldsymbol{E_{stab}}$).

The battery capacity $\boldsymbol{E_{BEES}(kWh)}$ is thus sized according to:

$$\boldsymbol{E_{BEES}} > \boldsymbol{E_{stab}} + \boldsymbol{E_{prod,min}} + \boldsymbol{E_{shutdown}} + \boldsymbol{E_{cold}} \qquad (1)$$

4. Case Studies

A. Plant Control with Variable Load

The stability is evaluated for both the DC microgrid for hydrogen production and the AC microgrid. The PEM electrolyser can operate under variable load, which facilitates hydrogen production in isolated systems powered by renewable energy, although rapid voltage variations can negatively impact its durability.

In variable load mode, a hysteresis based control strategy is implemented in the BESS. The BESS must act when the generated power falls below the minimum power required for production, equal to a $\boldsymbol{P_{H2,aux}}$+ $\boldsymbol{P_{DC,min}}$ (97 kW), which corresponds to a DC voltage of 465 V. The BESS disconnect when the electrolyser reaches 10% of its nominal power ($\boldsymbol{P_{H2,aux}}$+ $\boldsymbol{P_{DC,10\%}}$ = 117.5 kW), which corresponds to a DC voltage of 518 V. Moreover, the plant uses an MPPT (Maximum Power Point Tracking) system to extract the maximum power from renewable generation. The case study considers a sudden drop in renewable output at t = 5 s, lasting for 10 s. The power plant response obtained in MATLAB-Simulink is shown in Fig. 4.

When the available renewable generation drops below 97 kW, BESS as backup supplies the minimum power required to sustain hydrogen production and its auxiliary systems. Once the renewable generation (through MPPT) is able to inject 10% of the nominal current (at t = 17.1 s), BESS stops supplying power. The response of hydrogen production $\boldsymbol{P_{H2}}$ (blue curve), from 5 s onwards, follows a similar slope to the loss of renewable generation. However, when renewable production is recovered (red curve) the slope from the second 18 s onwards is slower. This is due to the dynamics of the MPPT whose reaction is in the order of seconds.

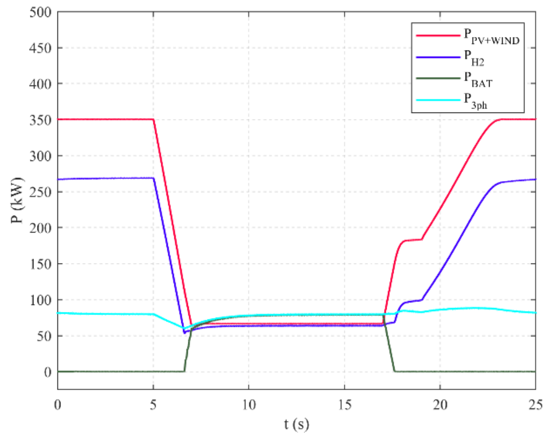

Fig. 4. Power distribution in the hybrid stand-alone plant.

B. Plant Control at Constant Voltage

PEM electrolysers powered by renewable energy are subject to frequent power and temperature fluctuations at the cell level [20]. Cathodic catalyst degradation occurs due to current—and hence voltage—variations. Although the specific factors that can accelerate degradation remain unclear, it is proposed to operate at constant power, with slow variation, to match the operating ranges of renewable energy production.

The microgrid control designed to maintain the electrolyser voltage at a constant value consists of two main components: a PI controller with voltage and current control loops in the Boost converter of the solar plant, and a PI controller with a voltage control loop for the battery, which compensates for energy deficits e.g. when irradiance drops and the solar plant cannot provide full power.

When renewable energy production becomes insufficient, DC voltage decreases. If it falls below 690 V, the battery supplies the missing energy, therefore voltage can back to 695 V. Once the voltage increases enough to exceed 705 V, the battery disconnects. A hysteresis band is implemented in the BESS control to prevent repeated switching within a short period. For this reason, the connection occurs at 690 V and disconnection at 705 V. Additionally, there is a hysteresis mechanism in the charge control. To prevent the battery from discharging slightly due to internal resistance upon reaching 100% state of charge and subsequently recharging repeatedly, the system applies a similar hysteresis strategy. The battery remains in standby mode until the state of charge falls below a defined threshold before allowing charging again.

Fig. 5 illustrates the plant behavior under constant power control when the generation is lower than the rated power. During the event, a generation loss of over 80% is observed (from 350 kW down to 67 kW). At 350 kW, the system operated at 615 V. BESS is activated when the voltage drops below 610 V and stops operating when it recovers to 625 V. Voltage stabilization occurs in less than 1 second. The BESS compensates for the generation loss and maintains approximately constant hydrogen production, avoiding significant pressure or temperature variations.

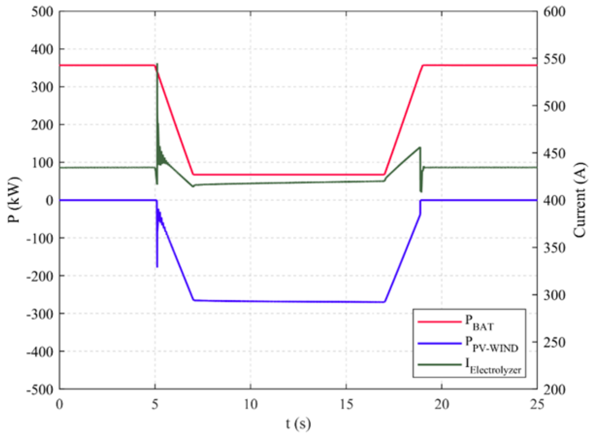

Fig. 5. PV-WIND and battery powers and electrolyzer's current.

5. Conclusions

This study analyzes the behavior of an off-grid hybrid plant for green hydrogen production under different proposed strategies. The power system consists of renewable energy sources (PV and Wind), a Battery Energy Storage System (BESS), and a synchronous generator only as emergency backup for auxiliary loads. The entire system has been modeled and evaluated using MATLAB-Simulink. The electrical model of the electrolyser includes its equivalent circuit and that of the auxiliary systems.

The plant control strategies have been designed based on the technical limitations of the electrolyser. The first control approach considers the variable load capacity of the electrolyser, implementing hysteresis control in the BESS. This ensures that the generated power remains above the minimum admissible threshold in the production state. Additionally, a Maximum Power Point Tracking (MPPT) algorithm is applied to extract the maximum power from the renewable generation. As a result, hydrogen production follows the fluctuations of renewable generation, resulting in a highly variable voltage profile.

Several studies indicate that these variations in current and voltage accelerate the degradation of the electrolyser. Therefore, a second control strategy has been developed to operate at constant power, allowing slow variations to adapt to the available renewable energy. This second strategy also demonstrates improved overall plant efficiency.

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