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Real-Time Control for Wind-Hydrogen Systems: Prioritizing Hydrogen Generation and Ancillary Services with Site Data

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***Abstract:** Green hydrogen has emerged as a cornerstone in achieving carbon neutrality, especially within the power and industrial sectors. This study focuses on the integration of wind energy and electrolyzer-based hydrogen production to enhance grid resilience and support frequency regulation. A novel control strategy for managing DC link voltage in electrolyzer-assisted wind turbines is proposed, enabling fast frequency response under varying wind conditions. Utilizing real-world wind speed and grid frequency data from Jamogadrani, Madhya Pradesh, this work evaluates the hydrogen production potential and frequency correction capabilities of the hybrid system. Key findings include the economic and operational viability of prioritizing hydrogen production while supporting grid stability. This paper outlines a pathway for integrating such hybrid systems into India's renewable energy framework, addressing challenges in frequency regulation and maximizing the utility of renewable resources. The study provides a foundation for policy shifts and technological advancements needed for the successful deployment of wind-hydrogen systems.*

***Keyword:** Wind farms, Green Hydrogen, Frequency Regulation, Electrolyzer Control, Renewable Energy Grid Integration.*

I. INTRODUCTION

Green hydrogen is emerging as a pivotal solution in the global push for carbon neutrality, especially within the power and industrial sectors. According to the International Energy Agency (IEA), global demand for hydrogen could increase sixfold by 2050, with green hydrogen expected to comprise 520 million tons of the total hydrogen supply [1]. An optimum control strategy for hydrogen production from wind energy has been discussed in the latest reports [2]. Its production and its related issues are addressed [3]. This demand surge is driven by hydrogen's potential to decarbonize sectors such as power generation, refining, steel, and fertilizer production [4]. In line with the Paris Climate Agreement and Nationally Determined Contributions (NDCs), many nations have committed to reducing emissions, with hydrogen production emerging as a cornerstone of these efforts. India, through its National Green Hydrogen Mission, aims to produce 5 million tons of green hydrogen annually by 2030 [5]. This initiative aligns with India's renewable energy goal of achieving 500 GW of installed renewable capacity by 2030 [6], necessitating significant innovation and investment in hydrogen production and grid integration technologies [7].

Wind energy has emerged as a promising renewable energy source for green hydrogen production [8]. Studies show that integrating wind energy with electrolysis systems can enhance energy utilization by leveraging surplus wind power for hydrogen production [9]. For instance, standalone wind farms equipped with hydrogen generators using maximum power point tracking (MPPT) have demonstrated technical feasibility and economic viability [10]. Such systems not only contribute to decarbonization goals but also reduce curtailment losses by utilizing excess energy, thus enhancing the overall value of renewable resources [11].

Despite its advantages, wind energy alone cannot withstand frequency ride-through events due to its dependency on variable wind conditions. The electrolyzer-fuel cell combination helps maintain the DC link voltage; however, its response time ranges from 0.5 to 200 seconds [12]. Hydrogen-based systems, when combined with energy storage technologies, offer promising solutions for stabilizing frequency and voltage. Advanced strategies, such as multicellular inverters and current control mechanisms for electrolyzers, enable quicker regulation of the DC link voltage and improve system stability under fluctuating conditions [13].

Traditional frequency regulation, typically performed by synchronous generators, requires rapid responses to maintain grid stability. While wind turbines can contribute to ancillary services, their response latency (ranging from 1.2 to 4 seconds) limits their efficacy for immediate frequency correction [14]. Furthermore, wind turbines in India operate under a "Must Run" mandate which means any renewable energy plant must keep on operating in India if there is energy resource available to it. Plants that are operational under this "must-run" status will not be able to comply with frequency supports as they keep operating on Maximum Power Point Tracking (MPPT) complicating their use in frequency correction services. This highlights the critical need for innovative solutions that balance renewable energy integration with grid stability [15].

Addressing these challenges requires a paradigm shift in the operational mandates of wind farms. A promising approach in Evolves designating

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specific wind turbines for hydrogen production and frequency support as primary objectives, with power generation as a secondary objective. Such a strategy would enable wind farms to act as Frequency Containment Reserves (FCRs), contributing to grid resilience while advancing green hydrogen production [16].

In this paper, we propose a novel control strategy for electrolyzer-assisted wind turbines designed for fast frequency response under highly variable wind conditions [17]. By managing the DC link voltage effectively [18], the proposed system enhances frequency regulation while maintaining hydrogen production efficiency [19]. Using real-world wind and grid frequency data from Jamogadrani, Madhya Pradesh [20], we analyze hydrogen production potential and frequency correction opportunities [21], offering a practical evaluation of the system’s capabilities [22].

i. *Key Contributions The novelty and key contributions of this paper are as follows:*

- **Primary Hydrogen Production Mandate:** Proposes a new operational model where wind turbines are primarily used for hydrogen production and frequency regulation, with power generation as a secondary objective.
- **Advanced Control Strategy:** Introduces a DC link voltage control mechanism tailored to electrolyzer-assisted wind farms, enhancing fast frequency response under varying wind conditions.
- **Real-World Application:** Uses site-specific data from Jamogadrani, Madhya Pradesh, for a practical evaluation, setting a precedent for assessing hydrogen and frequency regulation potential based on local wind and grid characteristics.
- **Enhanced Grid Resilience:** Suggests a pathway for a future policy where certain wind farms are designated as Frequency Containment Reserves, contributing both to renewable integration and grid stability.

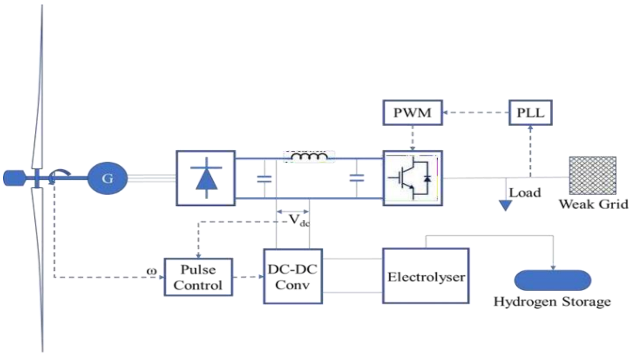
The remainder of the paper is structured as follows. Section II provides a detailed description of the methodology, including the wind-hydrogen hybrid system's modeling framework and electrolyzers' control strategy. Section III discusses the results obtained from simulation studies and real-world data analysis, highlighting hydrogen production potential and frequency regulation performance. Section IV presents a comprehensive discussion of the implications of the proposed strategy on grid stability and green hydrogen integration. Finally, Section V concludes the paper, summarizing the findings and suggesting directions for future research.

II. METHODOLOGY AND MODELING

The idea behind modeling the wind system is to verify the performance of test-setup in wind variations of arbitrary type and later extending the analysis to actual wind speeds from a site location. The simulation gives variations in every parameter of the model concerning varying wind conditions. These variations are repeatable and hence serve as the reference for making an empirical relationship or lookup table for real-time analysis.

A. Wind Electrolyser Hybrid System

Fig. 1 shows all the blocks present in a wind-hydrogen hybrid generator. The wind turbine used is type 4 with a Permanent Magnet Synchronous Generator (PMSG). Being the type 4 wind turbine system, there are two convertors i.e., grid side and machine side convertor. The DC link is provided with a type filter for harmonic filtration in voltage. The inverter is then connected to a grid and a load. The grid is weak with an X/R ratio of 2. The voltage of the grid is 380 V. Hydrogen electrolyzer is fed using a DC-DC buck converter. The wind turbine blades are controlled for pitch for speed variation. There are three PMSGs considered with 3.2 MW capacity each. The Machine side converter is kept uncontrolled. This is purposely kept to allow maximum infeed of wind energy available (concerned with no power curtailment and must run status of renewables). The control of the DC-DC buck converter takes care of any excessive wind gust coming by allowing more current to flow towards the Electrolyser thereby absorbing excessive torque generated. This maintains the required power infeed at the grid side.



[Fig.1: Block Diagram of Wind-Electrolyser Hybrid System]

B. Buck Converter Control

Fig 2. Implements the buck converter control strategy. The purpose of this control strategy is to generate the duty reference and finally the pulses as per the set duty ratio. The controller primarily generates the difference between the duty ratio. For this, there is a maximum allowable duty ratio fixed as constant and the online duty ratio is obtained by the ratio of the present DC link voltage with reference DC link voltage to be set on the DC link. The PI controller wants to minimize this error therefore it sets the reference for pulse generation. Here is the first stage of control. In the next stage of control, a signal is added to prevent the rise in the speed of the turbine. This care is taken to overcome a shortcoming of this controller most simply. The PI controller may seldom give zero duty ratio which disconnects the Buck converter from the load side. The disconnection of the Buck converter develops a huge voltage.

Across the inductor thereby reflecting it on the DC link. In other words, the disconnection of the Buck converter towards the load side pushes all the energy to the source side. This momentary rise in DC link available energy increases its voltage. The Machine side converter sees the higher voltage on the other side causing it not to conduct current in the forward direction.

This causes the disconnection of the machine side with the grid side. As there is no flow of energy from the machine

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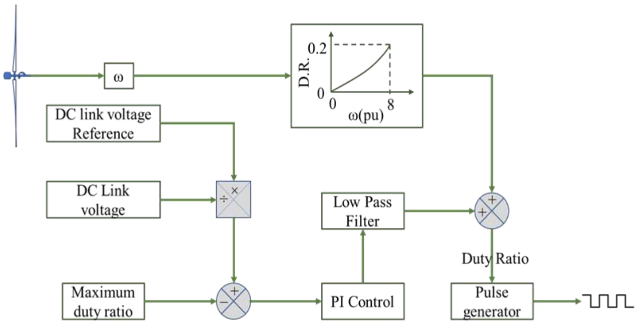
side to the grid side in this case, it abruptly causes to increase in the speed of the turbine. This rise in speed cannot be quickly controlled by the blade pitch control causing the condition of dynamic imbalance to prevail.

As a measure of the solution, the controller does not allow the buck converter to disconnect from the electrolyzer load under any condition. This can be achieved by putting in some extra references for the duty ratio. These extra references are generated from a lookup table implemented between the required duty ratio v/s turbine rpm in pu. Therefore, this addition of duty ratio prevents the turbine from over-speeding hence can be called over-speed protection of the turbine. Keeping the electrolyzer always connected with the DC link will not allow voltage development across the buck converter inductor, thereby preventing the rise in DC link voltage.

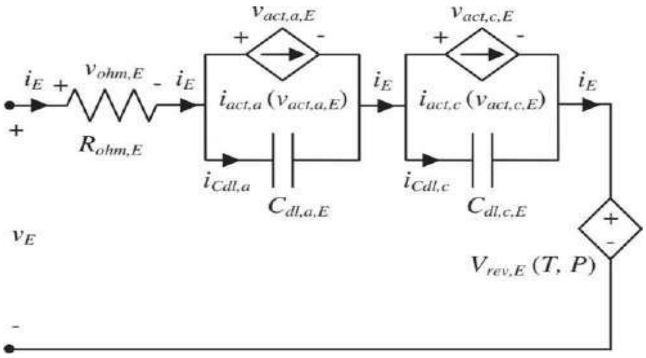


[Fig. 2: Buck Converter Control Strategy]

C. Modeling and Scaling Up of Electrolyzer

The electrolyser is modelled as per [10]. An electrolyte is an electrical apparatus to obtain basic elements from the electrolyte. An alkaline water electrolyzer uses an alkaline solution as an electrolyte medium to perform electrolysis. The reference gives the miniature kW range model for the electrolyzer, while the model used in this paper is a scaled-up version of the same post its static and dynamic validation. Fig 3 shows the component-wise electrical equivalent elements of electrolyzer cells connected. VE (source voltage) can be expressed as the sum of voltages over the ohmic component of the cell, activation over-voltages on the cathode as well as anode and reversible thermodynamic processes. The source current is denoted by iE and capacitors are modeled for reproducing the double-layer effect.

$$V_E = V_{ohm} + V_{act,a,E} + V_{act,c,E} + V_{rev} \quad \dots \quad (1)$$



[Fig.3: Static and Dynamic Model of Alkaline Water Electrolyser]

Scaled-up model parameters are tabulated in Table 1. The paper did not feel any need to model the storage for hydrogen as the outlet pressure of the electrolyzer will be as per the designed pressure as tabulated in Table 1.

Table 1: System Specification For 5mw Hydrogen Electrolyser

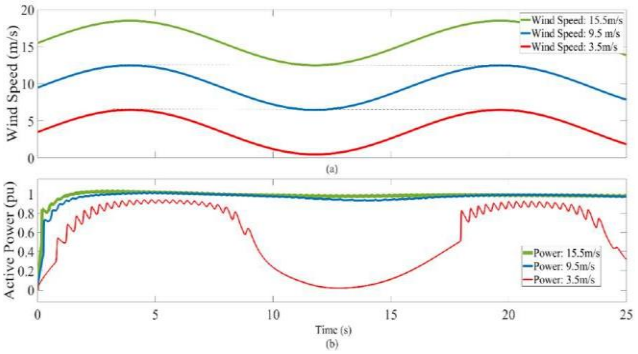
Specification	System Data	Simulated Data
Rated H_2 output	500 Nm^3/h	504 Nm^3/h (As per scaled-up model)
Rated O_2 output	250 Nm^3/h	-
Design Pressure	22 Bar	-
Rated Pressure	20 Bar	25 Bar (Operating Pressure)
Design Temperature	100°C	-
Rated Operating Temperature	90 ± 5°C	95°C (Operating Temp)
No. of Cells	4000	4000
Electrolyte Conc. (KOH Soln)	26–30%	30%
Rated DC Current & Volts	535A & 9400V	528A & 9450V
DC Power	6 MW	5.88 MW

III. RESULTS AND DISCUSSION

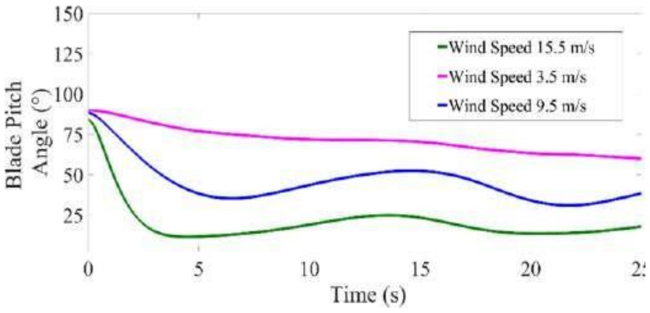
A. Comparative Performance of Wind-Hydrogen Hybrid Setup

The Wind-Hydrogen setup is tested for wind speed variations. These variations are chosen by considering the mean speeds of 3.5 m/s, 9.5 m/s, and 15.5 m/s. Around these mean speeds, the sinusoidal variation of ±3 m/s with 1rad/sec variation is implemented. Such variation of speed covers the total spectrum of real-time wind speeds. The variations implemented within a small period also show the sturdiness of the model and control setup reliability in that it does not go into anti-windup issues. Wind speeds are shown in Fig 4. The corresponding power generated from the wind turbine is shown in Fig 4. b. as per the typical power to wind speed curve of the wind turbine.

Fig 5. Show the variation in blade pitch angle of wind turbine blades. The initialization of blades is done from 90 Degrees. Thereafter as the wind speed rises, the blade pitch reduces to maintain maximum rated torque. It can be noticed that when the wind speed in all three cases, reaches its maximum, the minimum blade pitch angle is seen which denotes the inverse relationship of wind speed to blade pitch angle to maintain shaft torque.



[Fig.4: (a) Wind Speed Variations (b) Active Power Generated with the Wind Speed Variations]



[Fig.5: Blade Pitch Angle of Wind Turbine in All Three Cases]

It can be noticed in Fig 6 that all the parameters of Voltages and current dip during 10 to 16 seconds. This is the period when the wind speed is below the cut-in speed of the wind turbine. There is also drastic recovery seen in all the parameters as the wind speed corrects itself. There is also a step load increment made at 21 sec and released at 22 Sec. During this load increment, it can be seen that the DC link voltage remains constant, which denotes the potency of DC link voltage control implemented via Buck Converter to control DC link voltage.

In Fig 7. The output power from the inverter can be seen varying in the same trend with the influence of turbine power generated. However, the control is designed to support hydrogen production primarily. Therefore, the output power from the inverter is chopped at 2.75 MW if there is no deviation from the wind speed side and grid side.

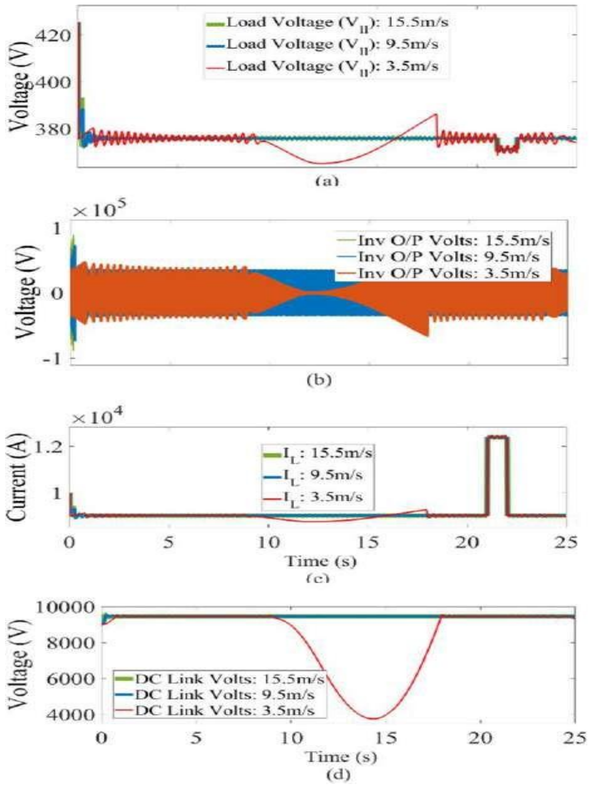
The grid side frequency is captured using PLL. It is for 3.5 m/s wind speed range when the frequency harmonics are seen in Fig 8. Some magnified images also show the discourse of frequency progression at various time intervals. For the load increment case at 21-22 seconds, all of the wind speed cases have responded for frequency correction using the droop response.

[!htbp]

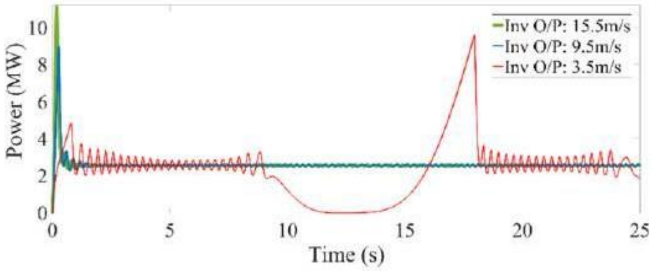
Hydrogen production is again limited by the power available on the shaft of the turbine. Fig 9 shows cases of the production rate variation of Hydrogen through an electrolyzer. To obtain this amount of hydrogen, the power consumed by the electrolyzer is shown in Fig 10. (c). Fig 10 shows the corresponding currents and voltages after the DC-DC buck converter. It can be noticed the power consumed by the electrolyzer is around 6 MW in conditions of shaft power availability, however, once the power is not sufficiently available on the shaft, the power consumed by the electrolyzer is proportionally reduced to satisfy the grid conditions. Although Fig 7. shows the power output profile from the inverter, for the 3.5 m/s wind speed case as flatulating, the mean lies around 2.75 MW which satisfies this desired operation from the controller.

B. Scaled-Up Model for Grid

The model is then stretched to operate on the real-time frequency and wind speed data. The year-round 100 m wind speed data is taken from Jamogadrani, Madhya Pradesh, India. Western Region Load Dispatch Centre (WRLDC), Grid India, releases the ongoing frequency data with some excursions if any observed out of band. The frequency data from Grid India is collected to identify mean and standard deviations. Using those mean and standard deviations, the frequency data is generated. Our model has to operate keeping both i.e., grid. frequency and wind speed into consideration. Fig 11. Shows the frequency and wind speed profile for the 50th to 90th minute on the first day of the year. Such details are available with year-round frequency and wind speed. The hybrid plant design must support the grid in occasions of frequency below 50 Hz and must reduce the output power if the frequency is above 50 Hz. Also, the plant must divert power towards the hydrogen electrolyzer based on the power availability from the wind side.



[Fig.6: (a) Load Voltage in Grid (b) Inverter Output Voltage (c) Line Current After Inverter (d) DC Link Voltage]



[Fig.7: Inverter Output Active Power]

Fig 12. Showcases the production of hydrogen concerning wind speed variation. It is evident that if the wind speed falls, corresponding hydrogen production also reduces proportionally to maintain the grid side infeed as per the frequency variation. This power adjustment is done while keeping the DC link voltage consistently the same as shown in an earlier section. Fig 13. Shows that hydrogen production follows the inverse behavior to grid power infeed from the plant. As per the frequency, if there is no need to inject power into the grid, that extra power is diverted to the electrolyzer to produce hydrogen, thereby making the plant a hydrogen-producing priority.

From the data analysis, the total wind and electricity generation potential for this setup in the given location is 9.5 gm/s and 14 MU from an 8.23MW capacity wind turbine and 5 MW hydrogen electrolyzer. In the per kWh capacity, the hydrogen potential of the site ranges from 490-500 gms/kWh of installed capacity with the same setup.

IV. DISCUSSION

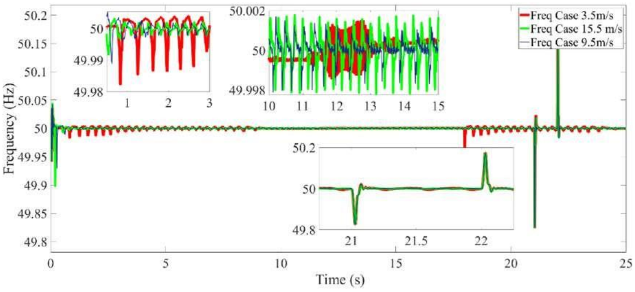
The proposed wind-hydrogen hybrid system offers distinct advantages over existing models and strategies, particularly in the context of India's growing renewable energy (RE) landscape. This section discusses the superiority of the model, emphasizing its simplicity, computational efficiency, and alignment with the National Green Hydrogen Mission.

A. Simplicity and Ease of Implementation

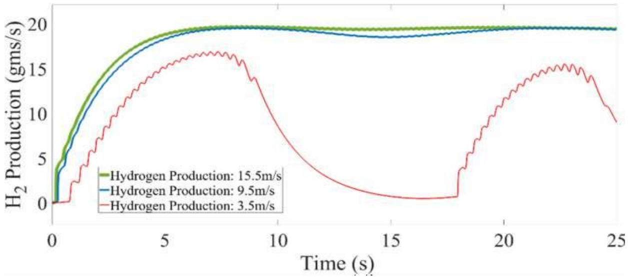
The model is designed with simplicity at its core, avoiding unnecessary complexities in control and optimization. Unlike many existing strategies that rely heavily on intricate optimization algorithms to manage power distribution between hydrogen production and grid delivery, our model leverages a straightforward controller. This eliminates computational burdens while ensuring efficient and real-time operation. The ease of applying this model makes it highly suitable for India's rapidly expanding renewable sector, where practical and scalable solutions are essential.

B. Efficient Power Diversion Without Computational Overhead

The controller in our model efficiently handles the diversion of power between hydrogen production and grid delivery without requiring additional optimization processes. This not only simplifies implementation but also reduces operational delays. By dynamically allocating power based on available wind energy and grid frequency conditions, the model ensures Optimal performance. The lack of reliance on complex algorithms enhances its reliability and adaptability, especially in scenarios with fluctuating wind speeds and grid demands.



[Fig.8 Grid Frequency Profile]



[Fig.9: Hydrogen Production]

C. Exclusion of Fuel Cells and Related Complexities

A major highlight of the model is the exclusion of fuel cells, which are typically used in similar setups for frequency response or power delivery. Managing fuel cells requires precise control of thermodynamic parameters such as pressure, temperature, and flow rates, which significantly increases system complexity and costs. In contrast, our strategy directly diverts power to hydrogen production and grid support, bypassing the need for fuel cells. This ensures the quickest possible response to grid frequency deviations while avoiding the operational challenges associated with fuel cell technologies.

D. Uncontrolled Rectification at the Machine End

As shown in Fig. 1, the model employs uncontrolled rectification at the machine end, a design choice that significantly reduces system complexity. Conventional systems often incorporate additional controls at this stage, which can increase both implementation challenges and costs. By removing the need for controlled rectification, the model simplifies the energy conversion process while maintaining its primary objectives of hydrogen production and ancillary grid support. Any excess power generated at the machine end is safely allocated for hydrogen production, ensuring resource optimization without adding further control requirements.

E. Prioritization of Hydrogen Production and Grid Support

The model's design philosophy prioritizes hydrogen production and ancillary grid support over direct power generation. This approach aligns seamlessly with India's green hydrogen mandate and renewable energy goals. By allowing flexibility in power allocation, the model supports dynamic grid requirements while ensuring hydrogen production remains a constant focus. This prioritization not only supports grid stability but also enhances the economic viability of the system by maximizing the utilization of surplus wind energy.

F. Suitability for India's Growing Renewable Energy Sector

India's renewable energy landscape is characterized by rapid growth and increasing complexity, necessitating solutions that are scalable, efficient, and aligned with policy mandates such as the National Green Hydrogen Mission. The proposed model meets these requirements by offering a low-complexity, high-performance solution that integrates seamlessly into existing renewable energy frameworks. Its adaptability to varying wind conditions and grid demands makes it particularly well-suited for deployment in India's diverse geographical and operational contexts.

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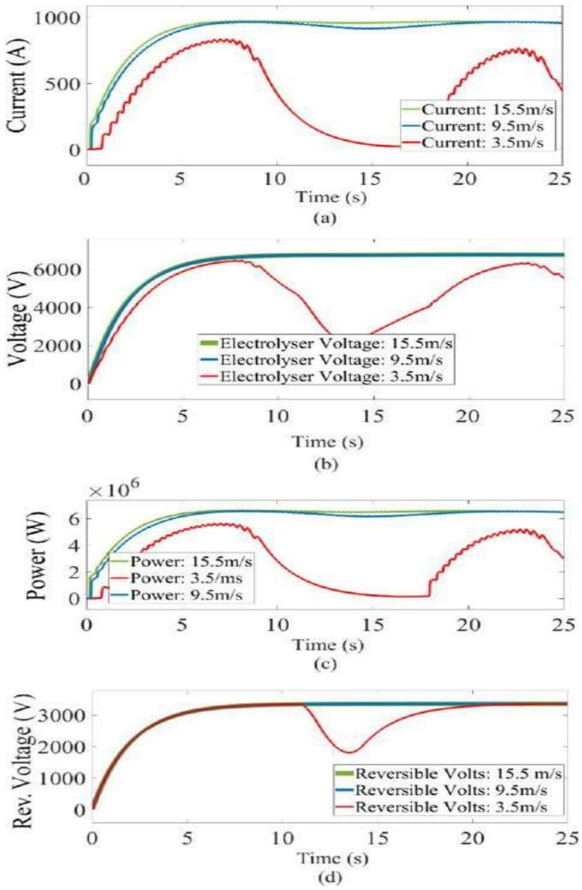
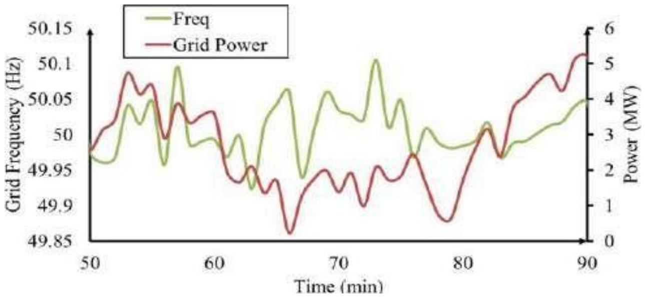
V. CONCLUSION

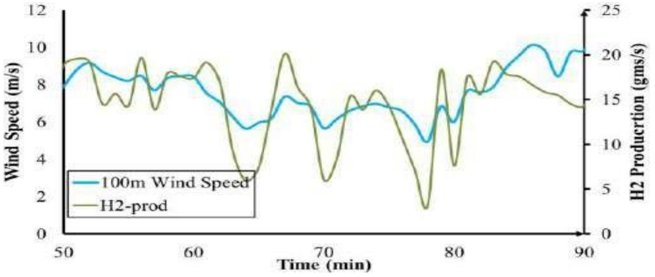
The proposed wind-hydrogen hybrid system demonstrates the feasibility of integrating hydrogen production and frequency regulation into wind farm operations. By employing a tailored DC link voltage control strategy, the system effectively manages frequency deviations while optimizing hydrogen production. Using real-world data, the study highlights. The potential of hybrid systems to contribute significantly to grid stability and green hydrogen objectives. The results underscore the importance of policy and operational adjustments, such as designating selected wind farms for frequency containment and hydrogen production. Future work should focus on scaling these findings to larger grids and exploring advanced control algorithms to further enhance system responsiveness and economic viability. This approach aligns with global climate commitments and positions wind-hydrogen hybrids as a strategic solution for sustainable energy transitions.



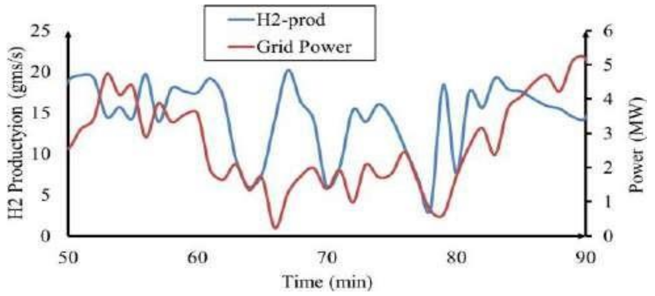
[Fig.10: (a) Electrolyser Current (b) Electrolyser Input Voltage (c) Power Consumed (d) Reversible Voltage]



[Fig.11: Power Delivery Towards Grid Frequency Deviation with the Real-Time Data]



[Fig.12: Hydrogen Production Based on Real-Time Wind Speed Data]



[Fig.13: Hydrogen Production and Grid Power Infeed by Wind-Hydrogen Hybrid Plant]

DECLARATION STATEMENT

After aggregating input from all authors, I must verify the accuracy of the following information as the article's author.

- **Conflicts of Interest/ Competing Interests:** Based on my understanding, this article has no conflicts of interest.
- **Funding Support:** This article has not been sponsored or funded by any organization or agency. The independence of this research is a crucial factor in affirming its impartiality, as it has been conducted without any external sway.
- **Ethical Approval and Consent to Participate:** The data provided in this article is exempt from the requirement for ethical approval or participant consent.
- **Data Access Statement and Material Availability:** The adequate resources of this article are publicly accessible.
- **Authors Contributions:** The authorship of this article is contributed equally to all participating individuals.

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