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***Abstract*—The increasing need of cost-effective and large-scale energy storage systems is motivating a strong focus on the deployment of hydrogen based conversion and storage. Hence, the potential of achieving fast dynamic response and high efficiency of electrolyzers makes them attractive to support the mitigation of reliability and stability threats due to the inherent variable power supply from renewables. Suitable dynamic models of new combined solutions, i.e. renewable generation with electrolyzers, are urgently needed to properly characterize and mitigate such threats. Therefore, this paper presents an EMT real-time simulation model of an electrolyzer connected to an offshore 20 MW DC wind power generation system. The envisioned power electronic layout along with the necessary controlling actions are explained in detail. Two modes of electrolyzer operation are proposed the master and slave mode. Based on whether hydrogen production is the priority or grid power injection is priority, the controlling action of the proposed model can be switched. The proposed model is developed as a building block for the study and design of multi-gigawatt scale offshore wind power plants, with stability support from electrolyzers.**

***Index Terms*—Electrolyzer, EMT model, high-power dual active bridge converter, large-scale energy systems, real-time digital simulation, wind generator**

I. Introduction

An inherent characteristic of renewable energy systems is the intermittent nature. As such sources are not controlled by mankind, measures have to taken to compensate for the variation in injected power due to environmental change [1]. This is done with the help of storage systems [2]. Energy storage is generally achieved in the form of chemical energy storage or batteries - a technology that has seen significant development in recent years especially with the deployment of lithium ion batteries [3]. The world's largest battery storage system currently has a capacity of 750 MW/3,000 MWh [4]. While such systems can help in grid scale storage requirements, there are various challenges associated with the wide scale deployment of such storage systems. In [5], a very comprehensive study is presented on the various challenges that are associated with grid scale lithium ion battery storage. Challenges like battery cycle life, fire safety, recycling, limited raw materials etc. have to be dealt with before such battery storage systems can be used for grid scale storage.

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Of late, there has been a shift of interest to hydrogen as a means of power conversion and storage, also considering the use of hydrogen for production of electrical energy [6]. As such, the efficient production of clean hydrogen has become one of the key goals for future renewable rich grids [7]. In the recent years researchers have extensively investigated electrolyzers and their improved integration to the grid [8]. In addition to the significant ongoing research efforts, there has been an exponential growth in the installation of electrolyzers in the recent years [9]. Currently, electrolyzer plants in the range of 100s of MW are already operational and many more are scheduled to start operation in the near future [10], [11]. In such a scenario, researchers and organizations are investigating deeper into the scope of incorporating electrolyzers with renewable energy systems. In the European regions around the North Sea, many wind energy projects are coming up which plan to utilize the tremendous wind energy potential available in the region [12]. Such offshore and onshore projects are looking into hydrogen as an option for storage and even transfer of power.

Based on the placement location, electrolyzers are classified into three types - offshore, onshore and in-turbine types [13]. While each of the types have their own advantages and disadvantages, this paper focuses on the in-turbine type electrolyzer. In-turbine electrolyzers can be preferable because the losses incurred in transmission of hydrogen is relatively lower as compared to transport of electrical power [14], There have been researches carried out on wind turbine and electrolyzer integration [15], [16]. However, such interaction with DC wind generators and DC collection are scarce. DC wind power generation is another area researchers are looking into off late [17]. This paper presents the model of a 20 MW DC wind generator with connection to in-turbine type electrolyzer, and proposes the use of electrolyzer to smooth out disturbances due to wind speed variations. The paper is organized as follows. Section II gives a description of the proposed system, Section III explains the proposed power management methodology. The converter controls are explained on Section IV, the simulation results are furnished in section V and the paper is concluded in Section VI.

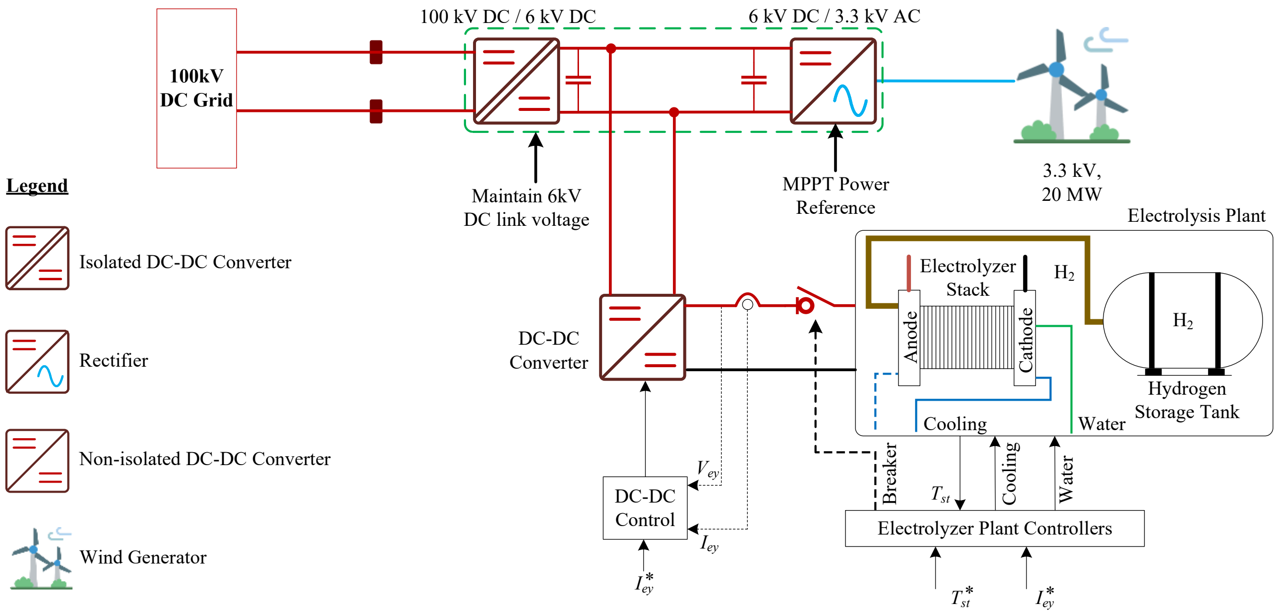

Fig. 1. Schematic diagram of the proposed DC wind energy system with in-turbine electrolyzer.

II. Description of the Proposed System

The schematic diagram of the proposed DC wind energy system with in-turbine electrolyzer is shown in Fig. 1. The paper considers a permanent magnet synchronous generator for wind power generation. Focus is laid on the power electronic conversion process involved and thus machine dynamics are not discussed. The electrical output of the wind power generator is converted to 6 kV DC with an AC to DC converter and in the subsequent stage, an isolated DC-DC converter steps up the DC from 6 kV to 100 kV and feeds the power into the HVDC grid. An electrolyzer is interfaced to the 6 kV DC bus via a DC-DC converter. The electrolyzer plant controllers are responsible for controlling the water intake for hydrogen production, temperature of the electrolyzer stacks and also the breaker that connects the electrolyzer to the wind power generation system.

III. Proposed Power Management Methodology

The in-turbine electrolyzer consumes power from the wind power generator based on factors like availability of wind power and power required to be fed to the HVDC grid. Based on these, the operation is classified into two modes, (a) electrolyzer in master mode and (b) electrolyzer in slave mode. These modes are explained as follows.

A. Electrolyzer in Master Mode

In this mode hydrogen production is given priority and the electrolyzer is provided with the reference for hydrogen production. Thus, the electrolyzer consumes power as per the requirement to meet the hydrogen production demand and the balance power is fed to the HVDC grid. In this case, the power fed to the HVDC grid is expressed by the following equation.

$$P_{HVDC} = P_{gen} - P_{ely}, \tag{1}$$

where, P_{gen} is the power generated by the wind generator and P_{ely} is the power consumed by the electrolyzer.

In the proposed system, the AC-DC converter of the wind generator injects the maximum available power to the common DC bus. The electrolyzer draws the power as per the reference in this mode and the balance power is automatically fed to the HVDC grid. Therefore no additional power management action is necessary.

B. Electrolyzer in Slave Mode

In this mode, the power fed to the HVDC grid is given priority. It is fixed at a certain reference and the balance power is fed to the electrolyzer. In this mode, the hydrogen production varies based on the variation of available wind power. Thus, power consumed by the electrolyzer is expressed by the following expression.

$$P_{ely} = P_{gen} - P_{HVDC} \tag{2}$$

In this mode, the grid reference power injection is maintained by setting the current reference of the electrolyzer with the help of a PI controller which maintains constant power injection to the grid. The difference between the actual grid power and the reference is calculated and fed to a PI controller through a rate limiter. The PI controller limits are set as per the maximum and minimum possible power current levels for the electrolyzer. Fig. 2 shows the power control action achieved in this manner.

The power flow diagram and the power management flowchart is shown in Fig. 3.

IV. Converters and Controls

Many power converters are operational to ensure smooth operation of the complete system under study. There are also

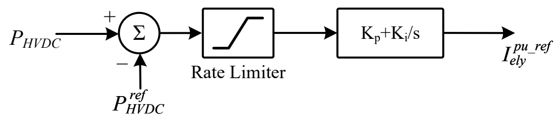

Fig. 2. Control diagram for generation of electrolyzer p.u. current reference in slave mode.

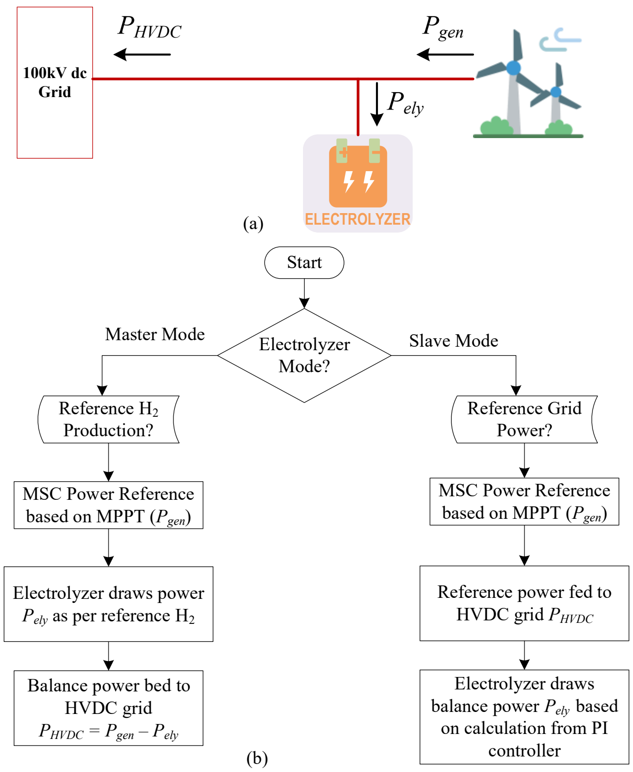

Fig. 3. Power management in the proposed model. (a) Power flow diagram. (b) Flowchart for power management.

controllers for the flow of fluids in the electrolyzers and breakers. The controlling action of each of these are discussed as follows.

A. Wind Generator AC-DC Converter

This converter is also known as the machine side converter or MSC. It operates as a current-controlled voltage source converter converting the AC power available at the wind generator output to DC. It also utilizes a maximum power point tracking (MPPT) strategy to extract maximum power from the wind generator. The standard control procedure for wind generator AC-DC converter was followed, as described in numerous literature [18], [19]. Therefore, an overview of the adopted control method is presented. The MPPT control is achieved through the control of the electrical torque of the permanent magnet synchronous generator (PMSG), which is controlled by manipulating the quadrature axis stator current (i_{sq}). The power output of the wind generator is proportional to the cube of the wind speed, and the maximum mechanical torque is proportional to the square of the turbine rotor speed. The control system utilizes a proportional integral (PI)

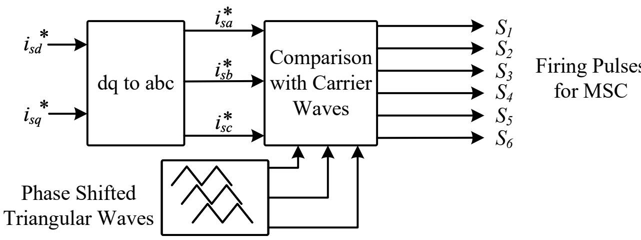

Fig. 4. Firing pulse generation for MSC.

controller in the outer loop to control the quadrature axis stator current based on the error between the measured torque and the torque reference. The system dynamics are represented in the d-q frame of reference, allowing for easier control of the PMSG. The inner control loop involves PI controllers to regulate the reference terminal voltages (v_{sd} and v_{sq}) based on the desired changes in stator currents. The modulation signals for the converter are obtained by converting the d-q axis stator currents to abc axis and then comparing them with a triangular carrier wave to generate the switching pulses for the converter. Fig. 4 illustrates the process of firing pulse generation for the converter.

B. Wind Generator DC-DC Converter

This converter steps up the 6 kV DC voltage to 100 kV for injection into the HVDC grid. This is an isolated DC-DC converter which consists of two full bridges and an high frequency isolation transformer for voltage step-up. It is also called the grid side converter or GSC as it interfaces the wind power generation system to the HVDC grid.

The power flow through the isolated DC-DC converter is governed by Equation 3, which takes into account parameters such as the turns ratio of the isolation transformer (n), the firing angle delay between the primary and secondary side bridges (δ), DC link voltage (V_{DC}), HVDC grid voltage (V_{HVDC}), switching frequency (f_{GSC}), and isolation transformer inductance (L_{DC-DC}).

$$P_{DC-DC} = \frac{n\delta(1-\delta)V_{DC}V_{HVDC}}{2f_{GSC}L_{DC-DC}} \quad (3)$$

When the MSC operates to feed in the maximum available power to the DC link, this power is automatically transferred to the HVDC grid through the isolated DC-DC converter. The converter adjusts the firing angle delay (δ) between the primary and secondary side bridges to maintain the common DC link voltage.

The control strategy involves using a PI controller to adjust the firing angle delay (δ) based on the error between the reference voltage and the actual voltage of the common DC link. This control action ensures that the common DC link voltage is maintained at the desired level.

Firing pulses for the switches of the isolated DC-DC converter are generated based on the adjusted firing angle delay (δ). These pulses are utilized to control the switches of the primary and secondary side bridges, ensuring proper

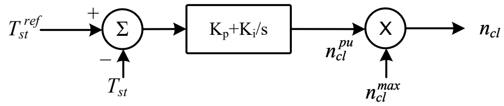

Fig. 5. Control diagram for electrolyzer temperature controller.

operation of the converter and regulation of the common DC link voltage.

C. Electrolyzer DC-DC Converter

This converter steps down the DC voltage from 6 kV DC bus of the wind generator for the electrolyzer stacks. The electrolyzer stacks operate at a voltage level of 0.315 kV DC. If the power input to the electrolyzer fluctuates or hydrogen production varies, a robust control system is needed for the buck converter to adjust the terminal current and voltage accordingly. Since the electrolyzer follows its polarization curve, its terminal voltage significantly affects the current flow and thus hydrogen production. To ensure the desired hydrogen production rate, a cascade dual-loop control method is used for the buck converter. The outer loop controls the input current to the electrolyzer and generates a voltage reference for the terminal. A maximum value selector ensures the terminal voltage stays above a minimum threshold. The inner loop controls the terminal voltage by adjusting the buck converter output through pulse width modulation.

D. Electrolyzer Water Controller

The water controller of the electrolyzer maintains the continuous supply of water to meet the requirements of the electrolysis process as per the set rate of hydrogen production. The water consumption rate is directly proportional to the stack current and can be expressed as follows [20].

$$n_{H_2O}^{rate} = N_s \frac{I_{st}}{2F} \tag{4}$$

where, n_{H_2O} is the moles of water consumed, N_s is the number of electrolyzer cells connected in series and F is the Faraday's constant. As hydrogen production is based on the stack current, the current control has to be taken into account to decide the required water flow rate. Thus, the electrolysis stack water requirement can be expressed as a function of the rated stack current, I_{st}^{rated}, the per unit reference current reference (I_{pu}^{ref}) and the water utilization factor (U_{H_2O}). This is expressed as follows.

$$n_{H_2O} = N_s \frac{I_{st}^{rated}}{2F} \times \frac{1}{U_{H_2O}} \times I_{pu}^{ref} \tag{5}$$

E. Electrolyzer Temperature Controller

The electrolyzer temperature controller controls the flow of coolant fluid. A stack temperature monitor measures the stack temperature and this is compared with the reference temperature. The error is fed to a PI controller and the required rate of flow for coolant liquid is obtained. The control diagram is shown in Fig. 5 [20].

TABLE I
SIMULATION PARAMETERS

Parameters	Values
Wind generator rated power	20 MW
Rated wind speed	12 m/s
Rated generator voltage	3.3 kV
DC link voltage	6 kV
HVDC grid voltage	100 kV
MSC switching frequency (f_{MSC})	2 kHz
GSC switching frequency (f_{GSC})	5 kHz
Rated power of the electrolyzer system	7 MW
Electrolyzer rated voltage	0.315 kV
No. of electrolyzer stacks in parallel	30

F. Electrolyzer Breaker Control

The electrolyzer breaker control is used to shut down the electrolyzer in case a water starvation is detected. This is done to safeguard the electrolyzer cells from potential damage. The breaker can also be activated if there is a need to switch off the electrolyzer for power management based on wind speed and grid power requirements.

V. SIMULATION AND TESTING

The EMT model of the wind power generation system, along with the in-turbine electrolyzer, is developed using RSCAD software and simulated in a real-time digital simulator. While conventional PMSG wind power generation models are already available in RSCAD library, the DC power generation model was developed with alterations to the existing models. The simulation assesses the system's behavior under various scenarios, validating the proposed control strategies and system operation in both the master and slave modes of the electrolyzer. The simulation parameters are given in Table I.

Fig. 6 shows the simulation results obtained for an increase in hydrogen production from the electrolyzer under the master mode operation. Fig. 6(a)-(f) respectively show the wind speed, wind generator power output, hydrogen production from electrolyzer, power consumed by the electrolyzer, power injected to the HVDC grid and common DC bus voltage. The wind speed is kept constant at 12 m/s. Thus the wind power generation is constant as seen in Fig. 6(b). In this mode of operation hydrogen production is given priority. Thus the hydrogen production reference is given and the system adjusts accordingly. The hydrogen production reference is increased from 6 moles/s to 8.5 moles/s. This corresponds to an increase in power consumption by the electrolyzer and the power consumption increases from 4 MW to 7 MW. These two are observed in Fig. 6(c) and (d). As the wind power generated is consumed by the electrolyzer, when the electrolyzer consumes more power, the power injected to HVDC grid reduces a similar amount from 16 MW to 13 MW. This is seen in Fig. 6(e). During the transition, the common DC bus voltage of the wind generator (Fig. 6(f)) experiences a negligible oscillation and that does not affect the operation of the system.

Fig. 7 depicts the same parameters as described in Fig. 6, yet under a scenario of changing wind speed while maintaining

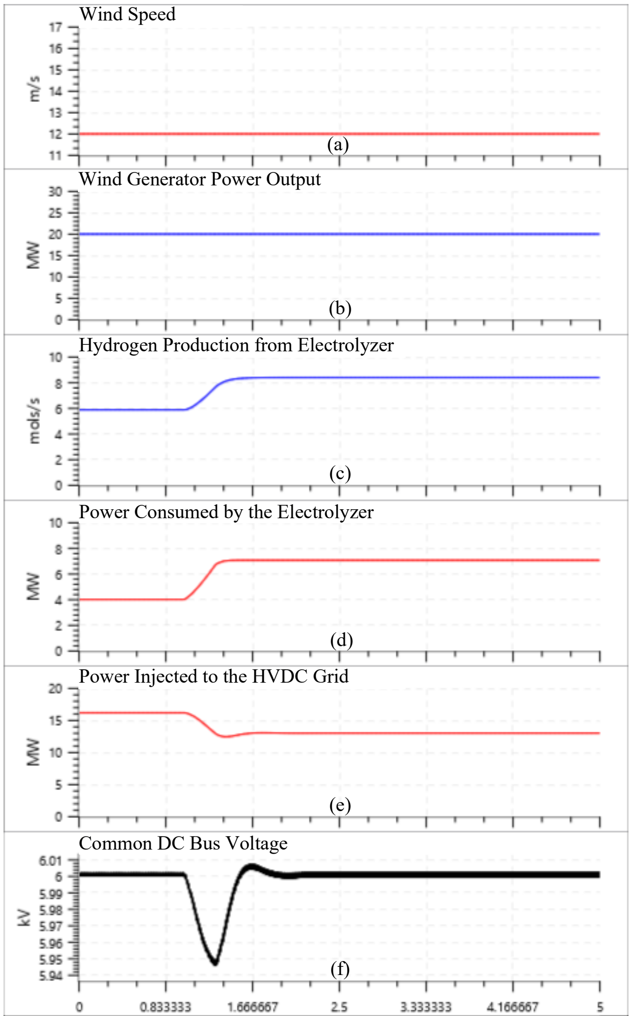

Fig. 6. Simulation results for increase in hydrogen production under master mode operation. (a) Wind speed. (b) Wind generator power output. (c) Hydrogen production from electrolyzer. (d) Power consumed by the electrolyzer. (e) Power injected to the HVDC grid. (f) Common DC bus voltage.

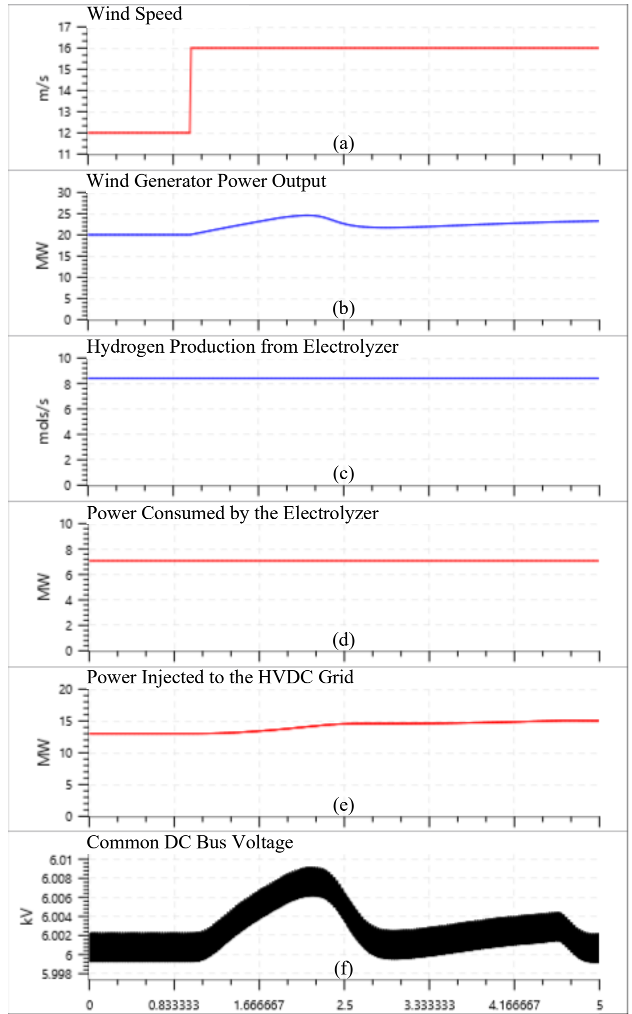

Fig. 7. Simulation results for increase in wind speed under master mode operation. (a) Wind speed. (b) Wind generator power output. (c) Hydrogen production from electrolyzer. (d) Power consumed by the electrolyzer. (e) Power injected to the HVDC grid. (f) Common DC bus voltage.

a constant hydrogen production reference. The wind speed is increased from 12 m/s to 16 m/s. A step increase in wind speed is emulated even though such changes are not generally seen in the real world. This is done to test the system under extreme circumstances. The increased wind speed has a corresponding increase in power generation from 20 MW to 22 MW. While the increase in power is lower than what may be expected, it must be noted that the system is rated at 20 MW and performance is tested above the rated values. The hydrogen production is constant at 8.5 moles/s and the power consumed by the electrolyzer is also constant at 7 MW. The increased power generation increases the power injected to the HVDC grid from 13 MW to 15 MW. The common DC bus voltage of the wind generator again sees negligible oscillation. The results show the isolation of hydrogen production from disturbances appearing from wind speed variations.

Fig. 8 shows the simulation results for electrolyzer operating in slave mode of operation. In this, the grid power injection is given the reference and based on the available power, the electrolyzer adjusts the power intake for hydrogen production. The reference power injection to the HVDC grid is kept constant at 15 MW and the system is subjected to a wind speed change from 11 m/s to 15 m/s. As the wind speed increases, the power generated by the wind generator increases to 22 MW, a seen in Fig. 8(b) . This is sensed by the electrolyzer power reference controller and the current reference to the electrolyzer increases accordingly. Thus the hydrogen production also increases along with increase in power consumed by the electrolyzer as seen in Fig. 8(c) and (d), respectively. The power injected to the HVDC grid is maintained constant at 15 MW and there is negligible disturbance in the wind generator common DC link voltage. These are seen in Fig. 8 (e) and (f), respectively. The ripple in the DC link voltage is seen to increase slightly to around 3 V. This amounts to a ripple of around 0.05%, which is under acceptable limits. The wind speed variation is unable to affect the power injection to the

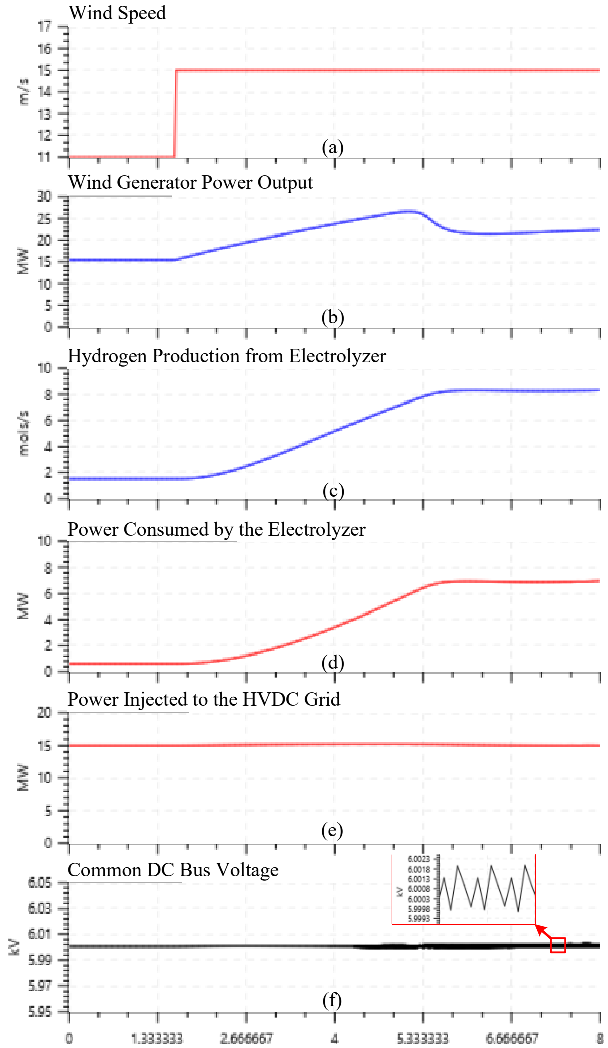

Fig. 8. Simulation results for increase in wind speed while under slave mode operation. (a) Wind speed. (b) Wind generator power output. (c) Hydrogen production from electrolyzer. (d) Power consumed by the electrolyzer. (e) Power injected to the HVDC grid. (f) Common DC bus voltage.

grid. This verifies the operation of the electrolyzer in the slave mode.

VI. Conclusions

A 20 MW DC wind power generator with in-turbine electrolyzer model is presented. The electrolyzer power consumption is controlled to mitigate the disturbances in power injection due to changing wind speed. Two modes of power flow to the electrolyzer are presented - the master mode where the primary reference is the production of hydrogen and the slave mode where the priority is injection of power to the HVDC grid. The power flow control in the master mode is straight forward with the electrolyzer drawing the required power and the grid getting the rest. In the slave mode, the grid power reference is determined and based on that, the reference current for the electrolyzer is determined with the help of a PI controller. In this mode the power variations due to the wind speed variation is absorbed by the electrolyzer and the grid is isolated from such disturbances. Real time digital simulation results are furnished validating the operation of the proposed system and control strategies. The proposed system is envisioned as a building block of a large DC wind energy harnessing plant with electrolyzer integration for the production of green hydrogen along with control to mitigate stability threats.

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