Passivity-based control for an Isolated DC Microgrid with Hydrogen Energy Storage System (O-10H)

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1. Introduction

Currently, there is considerable interest in promoting technologies for the clean production of hydrogen from renewable energies resources (RES) for later use in transport or energy storage [1]. In this framework, the production of the carbon-free “green hydrogen” via electrolysis of water from wind and/or photovoltaic energy is seen as one of the most viable and promising way.

On the other hand, it is well known that the integration of renewable energy resources in energy systems has imposed several challenges, considering the uncertain and variable energy production. As a result, it may happen that energy balance cannot be guaranteed, which would affect the stability of the power grid. In the last decades, a lot of research in the field of hybrid energy storage systems (ESS) has been made to deal with excess or deficit of energy at different rates and successfully integrate RES into the electrical grid. In this framework, the present work proposes combining short-term battery energy storage system (BESS) and long-term hydrogen-based energy storage system (HESS) to deal with excess or deficit of energy and successfully integrate RES into the electrical grid. The system studied has a typical structure of electric-hydrogen hybrid refueling station [2]. It consists of a DC bus connected to an external electrical network and renewable generation, storage, demand and hydrogen production systems. The integration of the electrolyzer and the fuel cell in the DC Microgrid (MG) is carried out controlling the duty cycle of the power converters with Interconnection and Damping Assignment control (IDA-PBC). This technique has gained popularity in recent decades because it assigns a desired port-controlled Hamiltonian structure (PCH) to the closed loop while ensuring a desired dynamic behavior [3].

The main objective of the control strategy is to ensure the supply of electrical energy to the loads, quality in the electrical variables of the network and safety operation condition of the components. Representative simulation results under demanding conditions verify the effectiveness of incorporate hydrogen energy storage systems with IDA-PBC for this class of problems.

2. Microgrid

An isolated DC MG with typical structure of hydrogen refueling stations is proposed, Fig 1 [2]. It has a single DC bus in which energy storage devices, renewable energy resources and loads are connected directly or through interfacing parallel converters. The ESS devices consist of BESS and HESS, both connected to the bus by bidirectional DC-DC converters. As mentioned before, the HESS system is essentially composed of an electrolyzer (EL) and a fuel cell (FC). The EL generates hydrogen using the energy available from RES and is sized in order to dispatch a possible hydrogen demand and supply the FC. The FC uses available hydrogen when the energy from the RES is not enough to compensate the power demanded by the loads. Finally, the RES are constituted of a PV array and a wind turbine (WT) generator, both has its own Maximum Power Point Tracking (MPPT) controllers and converters associated. The power exchange between the ESS, RES and the load is ensured by controlling the power converters. Each DC/DC converter is controlled by a standard pulse width modulation (PWM) that generates the switching signals. Therefore, the control variables to carry out the objective are the duty cycles of those converters. In order to design a control that guarantee a correct balance of power on the DC bus and quality of its electrical parameters, a complete mathematical model of the proposed DC MG is developed.

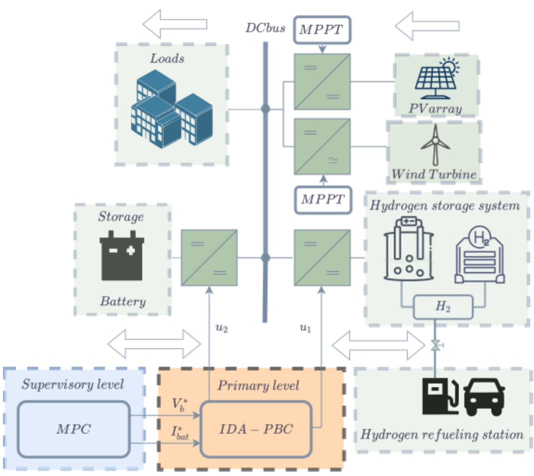

Fig. 1. Isolated DC MG scheme with a typical structure of electric-hydrogen hybrid refueling station.

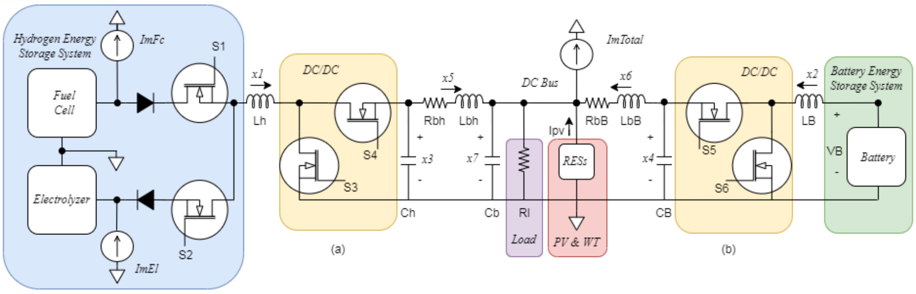

Fig. 2 Electrical diagram with the variables involved of the MG.

2.1 *Hydrogen energy storage system*

In this subsection, the characteristic curve, voltage V_h versus current I_h, of the HESS is modeled. This function is computed as a five-order polynomial equation of the piecewise function, expressed as follows:

$$V_h(I_h) = \begin{cases} V_{fc} = (I_h + I_{mfc}) \\ V_{el} = (-I_h + I_{mel}) \end{cases} \quad (1)$$

where V_{fc} and V_{el} are the voltages of the FC and EL respectively. The maintenance currents I_{mfc} and I_{mel} are also taken into account which are the minimum currents at which the FC and EL will operate to guarantee their availability. Therefore, the current of the HESS I_h is the difference between the current of the FC or the EL with its respective maintenance current. It is important to highlight that both maintenance currents, whose sum is I_{mtot}, are fed by current sources coming from the bus.

Electrolyzer: The EL modeled in this work is of the alkaline type, consisting of a NiO diaphragm and two activated electrodes immersed in KOH electrolyte. The cells of the EL, of bipolar design, are connected in series and the EL voltage V_{el} [4]:

$$V_{el} = N_e \frac{r(T_e)}{A_e} I_{el} + N_e \left[V_{rev} + s(T_e) \log\left(\frac{t(T_e)}{A_e} I_{el} + 1 \right) \right] \quad (2)$$

where N_e is the number of cells connected in series, I_{el} is the EL current, T_e is its operating temperature, A_e is the area of each cell, V_{rev} is called the voltage necessary to produce electrolysis if the process is reversible or ideal and finally $r(T_e)$, $t(T_e)$ and $s(T_e)$ are temperature-dependent parameters specific to each EL. The temperature is considered to be kept constant by external control.

Fuel cell: Proton-exchange membrane fuel cell (PEMFC) is considered in this work. Its voltage V_{fc} can be expressed:

$$V_{fc} = N_{fc} \left[V_o - b \log\left(\frac{I_{fc}}{A_{fc}} \right) - R_{fc} \left(\frac{I_{fc}}{A_{fc}} \right) \right] \quad (3)$$

where N_{fc} is the number of cells connected in series, I_{fc} is the FC current, A_{fc} is the area of each cell, V_o is the open circuit voltage of each cell, b is the so-called slope of *Tafel*, R_{fc} is the resistance of each cell [4].

2.2 *Battery energy storage system*

In the MG, a lead-acid battery bank is connected by a bidirectional converter to the bus. The battery voltage is:

$$V_B = E_o - \frac{Q\,K}{Q - \int I_B\,dt} + A e^{-B \int I_B\,dt} - I_B R_B \quad (4)$$

where E_o is a constant voltage, K is the polarization voltage, Q is the capacity of the battery, I_B is its current, $\int I_B\,dt$ is the actual battery charge, A is called the amplitude of the exponential zone, B is the exponential zone time constant inverse and R_B the internal resistance.

3. Nonlinear model

In this section, the aforementioned DC MG is modeled. The state variables involved, shown in Fig.2, are:

$$[x_1; x_2; x_3; x_4; x_5; x_6; x_7] = [I_h; I_B; V_{Ch}; V_{CB}; I_{bh}; I_{bB}; V_b]$$

with I_h the HESS current, I_B the battery current, V_{Ch} and V_{CB} the output voltage of the converters, I_{bh} and I_{bB} the output currents of the converters and finally, V_b the capacitor or bus voltage.

The vector of control variables is $[\mu_h; \mu_B] = [1 - U_h; 1 - U_B]$ where U_B is the duty cycle of the battery converter and U_h that of the HESS converter. The system of equations that represents the microgrid is:

$$\begin{aligned} \dot{x}_1 &= \frac{1}{L_h}[V_h - x_3\mu_h] \quad ; \quad \dot{x}_5 = \frac{1}{L_{bh}}[x_3 - x_5 R_{bh} - x_7] \\ \dot{x}_2 &= \frac{1}{L_B}[V_B - x_4\mu_B] \quad ; \quad \dot{x}_6 = \frac{1}{L_{bB}}[x_4 - x_6 R_{bB} - x_7] \\ \dot{x}_3 &= \frac{1}{C_h}[x_1\mu_h - x_5] \quad ; \quad \dot{x}_7 = \frac{1}{C_b}\left[x_5 + x_6 + I_{net} - \frac{x_7}{R_L}\right] \\ \dot{x}_4 &= \frac{1}{C_B}[x_2\mu_B - x_6] \end{aligned} \quad (6)$$

where I_{net} is the net current between that generated by the RES and that consumed by the maintenance currents. Then, the equilibrium of the system $x^* = [x_1{}^*; x_2{}^*; x_3{}^*; x_4{}^*; x_5{}^*; x_6{}^*; x_7{}^*]$ can be expressed as:

$$x^* = [\frac{1}{\mu_h{}^*}\left(\frac{V_d}{R_L} - I_{net} - \mu_B{}^* x_2{}^*\right); x_2{}^*; (V_d + x_5{}^* R_{bh}) \\ ; (V_d + x_6{}^* R_{bB}); x_1{}^*\mu_h{}^*; x_2{}^*\mu_B{}^*; V_d] \quad (7)$$

with V_d the voltage reference of the DC bus. The control variables at equilibrium are:

$$[\mu_h{}^*; \mu_B{}^*] = \left[\frac{V_h(x_1{}^*)}{x_3{}^*}; \frac{V_B(x_2{}^*)}{x_4{}^*}\right] \quad (8)$$

4. IDA-PBC

Given the nonlinear system $\dot{x} = f(x, u)$ where $x \in \mathbb{R}^n$ is the vector of states, $u \in \mathbb{R}^m$ is the control action with $m < n$. The control objective is to find the state-feedback $u = \beta\,(x)$, such that the closed-loop dynamics:

$$\dot{x} = [J_d(\beta\,(x)) - R_d]\nabla H_d \quad (9)$$

Where H_d is a desired smooth energy function that has a local minimum at the equilibrium point x^*. The positive semi-definite matrix $R_d = R_d{}^T \geq 0$ represents the desired damping or dissipation. The interconnection structure is captured in the $n \times n$ skew-symmetric matrix $J_d(u) = -J_d(u)^T$ which, in this particular case, depends on the control variable. In this context, the equilibrium x^* is locally stable and it will be asymptotically stable if the largest invariant set under closed-loop dynamics contained in $\{x \in \mathbb{R}^n | \nabla H_d{}^T R_d \nabla H_d = 0\}$ is equal to $\{x^*\}$ [3].

The desired energy function is given by $H_d = \frac{1}{2}(\tilde{x}^T Q \tilde{x})$ and the diagonal matrix $Q = diag[L_h; L_B; C_h; C_B; L_{bh}; L_{bB}; C_b]$.

The dissipation variable $r_2 > 0$ corresponding to the state x_2 is incorporated to add damping to the system. Therefore, the proposed control variables are as follows: with ${x_2}^* \neq 0$

$$\begin{cases} \mu_h = \dfrac{R_L V_h}{[(R_{bh}+R_L){x_7}^* - I_{net}R_{bh}R_L - R_{bh}R_L{x_2}^*\mu_B]} \\ \mu_B = \dfrac{-{x_7}^* + \sqrt{{x_7}^{*2} + 4{x_2}^* R_{bB}(V_B + r_2{x_7}^*(x_2 - {x_2}^*))}}{(2{x_2}^* R_{bB})} \end{cases} \quad (10)$$

and with ${x_2}^* = 0$

$$\begin{cases} \mu_h = \dfrac{R_L V_h}{[(R_{bh}+R_L){x_7}^* - I_{net}R_{bh}R_L]} \\ \mu_B = \dfrac{V_B}{{x_7}^*} + r_2 x_2 \end{cases} \quad (11)$$

As there could be uncertainty in the system parameters, the need to have null steady state error in the battery current and the importance of keeping the bus voltage close to the nominal value, it is necessary to add integral action to the IDA-PBC. Since the feedback interconnection of dissipative and observable zero-state systems is Lyapunov stable, it is proposed the new control variables:

$$\begin{cases} {\mu_h}' = \mu_h + k_h \int (x_7 - V_d)\, dt\, ; k_h > 0 \\ {\mu_B}' = \mu_B - k_B \int (x_2 - {x_2}^*)\, dt\, ; k_B > 0 \end{cases} \quad (12)$$

5. Results

Simulation results of the system with IDA-PBC subject 24 hours profiles of irradiance, wind speed and load consumption are considered. In Fig. 3(a) is presented the irradiance power P_{PV} profile throughout the day, in Fig. 3 b) is shown the power profile of the wind turbine P_{WT}. Finally, in Fig. 3(c) the power load consumption profile P_L is depicted. Figure 4 shows the simulation results of the model with the control strategy under the aforementioned realistic profiles. In particular, in Fig. 4a) and in Fig. 4(b) are presented the power curves of the FC and EL respectively. When the power of the RES is not enough to supply the loads, then the power of the fuel cell P_{fc} is such that it generates the power demanded by the load and the power of the EL operating in maintenance mode. Also, in Fig. 4b) the power P_{el} of the EL is observed, which satisfies the balance together with the power variations of RES, while the FC is in maintenance mode. Finally, Fig. 4c) shows the bus voltage V_b which reaches the desired value in the steady state V_d due to the IDA-PBC with integral action.

6. Conclusions

In this work, IDA-PBC control strategy for an isolated DC microgrid with hydrogen-electric hybrid storage system is proposed. The IDA-PBC guarantees a correct power balance and ensures asymptotic stability of the closed-loop system with strongly non-linear characteristics. In addition, it has robustness and flexibility to modify the interconnection, the damping and the desired energy function of the system. The results of the simulation under demanding conditions showed a good system response and show the benefits of incorporating hydrogen-based storage in isolated DC MG with RES penetration.

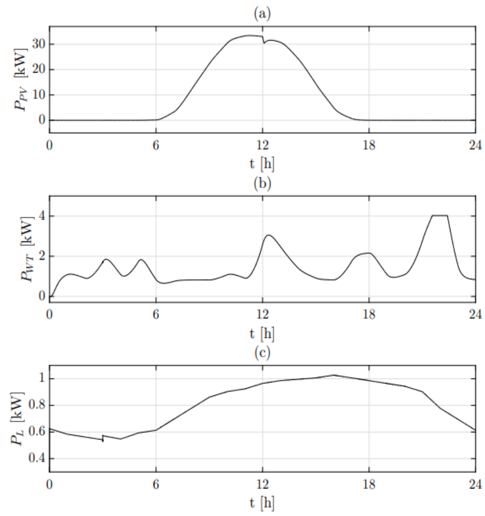

Fig. 3 24 hours profiles of: (a) Power irradiance, (b) Power of wind turbine and (c) Load power consumption.

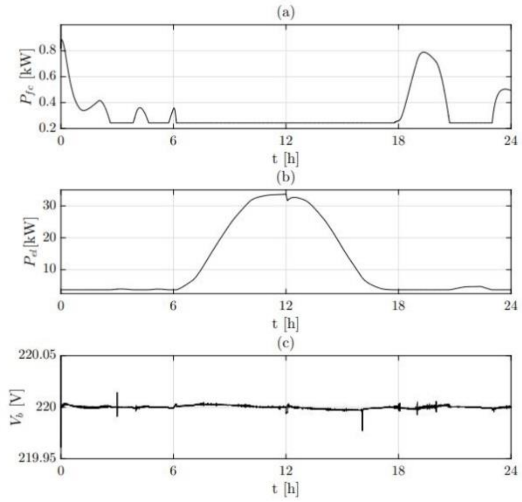

Fig. 4 (a) FC power (b), EL power, (c) Bus voltage.

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References

[1] Zhou, Ying, et al. Green hydrogen: A promising way to the carbon-free society. *Chinese Journal. of Chemic. Eng.* (2022).

[2] Zhang, Xue, et al. Transform from gasoline stations to electric-hydrogen hybrid refueling stations: An islanding DC microgrid with electric-hydrogen hybrid energy storage system and its control strategy. *International Journal of Electrical Power & Energy Systems* 136 (2022): 107684.

[3] R. Ortega, A. Van Der Schaft, Interconnection and damping assignment passivity-based control of port-controlled hamiltonian systems, *Automatica* 38 (4) (2002) 585–596.

[4] P. Rullo, L. Braccia, P. Luppi, D. Zumoffen, D. Feroldi, Integration of sizing and energy management based on economic predictive control for standalone hybrid renewable energy systems, *Renewable energy* 140 (2019) 436–45