State Machine for efficient operation of an on-site green production hydrogen refueling station (P-8H-V)

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1. Introduction

Hydrogen is a convenient way of storing the intermittent nature of renewable energy surplus generation in such a way that it can be released at a later place or time in a controlled manner, which is the definition of an energy vector [1]. In particular, hydrogen can be used in transportation, given its relatively high volume energy density at high pressures.

The first retail hydrogen refueling station was opened in Torrance, California, in 2011, and it is still in service [2]. Ten years later, 685 hydrogen refueling stations were in operation worldwide and 252 additional ones were planned [3]. One of them is going to be located in Zaragoza, Spain, and as the one at Torrance, it will generate hydrogen from renewable sources in situ.

In order to manage this kind of stations, a control system is needed, to optimize energy transfer and ultimately maximize the economic output of the facility. This is a problem open to a variety of options [4,5]. In the present case, various electric supply, storage and consuming systems need to be controlled as well. The control being designed is based on a state machine that rules the operation of the different devices of the installation, providing satisfactory results for various scenarios.

There is a general lack of work in the literature describing the operation strategies of an on-site green production refueling hydrogen station. This work presents a flexible control oriented model that is used to develop a controller for H_2 distribution as well as a day-ahead predictive deterministic algorithm for grid connected production. Results have been validated through simulation.

2. System description and model

2.1 System description

The studied green hydrogen production and service station is shown in Fig. 1, where the blue arrows represent hydrogen flows. It is designed to supply hydrogen to Heavy Duty fuel cell Vehicles (HDV) and Light Duty fuel cell Vehicles (LDV).

H_2 source is based on small electrolyzers incorporated inside solar panels, which have two working modes logically exclusive: irradiance mode and grid mode. In irradiance mode, we can assume a linear relationship between the direct beam irradiance input and the produced hydrogen flow rate output. Grid mode permits to bypass the solar energy source to electricity coming from the utility grid, but can only give discrete hydrogen production levels.

The hydrogen station consists of a total of 7 tanks at 4 different pressure levels: low (2 barg), mid (45 barg), high 1 (500 barg) and high 2 (1000 barg). Hydrogen flow rate is controlled by 3 compressors and 5 hydrogen flow rate valves. Compressors are shown as grey triangles and flow valves as ⋈. Their reference signals are shown in red in Fig. 1 (*Ci_EN* for enable signal of compressor *Ci* and *FV_ii* for hydrogen flow rate reference of the valves). S1 and S2 are controlled selectors. Demand is considered a disturbance which indicates that a vehicle has arrived and needs to be served. The signals used for demand are D_HDV and D_LDV, respectively.

H_2 is supplied to LDV and HDV with 700 barg and 350 barg target pressures, respectively. H_2 can also be stored in Multiple Element Gas Containers (MEGCs) to be sold to the end-user.

2.2 System model

A model of the system has been developed in Matlab Simulink with Ode23s as time-variable step solver. The main model assumptions are:

- H_2 is considered as an ideal gas with compression factor correction implemented using a 2-D lookup table.
- Temperature is considered constant at 298 K.
- Heat, pressure or H_2 losses are not considered.
- Gas compression is thermally stable (ideal H_2 coolers are implicitly considered)
- Output compressors flow rate is linearly dependent on input pressure, only ON/OFF control logic is possible.
- Direct expansion flow rate (i.e. tank to vehicle or tank to MEGCs) is considered constant at 180 kg/h.
- MEGCs are considered as an infinite volume tank.
- Vehicles H_2 demmand is fixed. Every day 2 HDV and 1 LDV need to be served. HDV arrive every 12h starting at 08:00h and LDV arrive at 14:00h. All vehicles come with empty tanks.
- The linear relationship between input direct beam irradiance and H_2 flow rate (ω) is 10.11 (kgH_2/h)/(1000 W/m^2).
- The only discrete continuous level in grid mode considered is 3.74 kg/h.

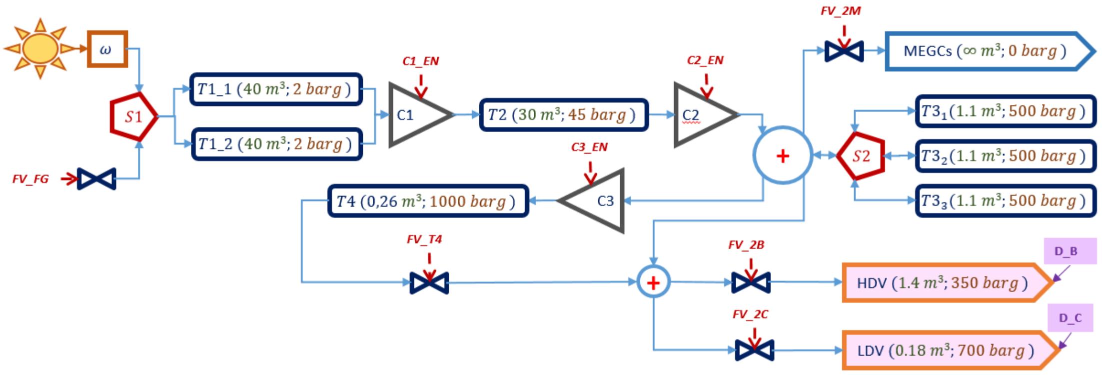

Fig. 1: System topology diagram

3. State machine and predictive algorithm

3.1 State Machine for H_2 distribution strategy

Strategy for H_2 distribution along the different pressure buffer tanks has been developed with a finite state-machine using the Stateflow toolbox of Matlab Simulink. The strategy purpose is to guarantee fast direct expansion service as much as possible (service from T3_i or T4). For that, ordered emptying/filling processes become relevant since tank's capacity is a system constraint. Notice that in direct expansion, flow rate is larger than 0 only if a pressure drop between tanks exists. For this reason, in T3_i, the implemented strategy prioritizes filling first the tank with highest pressure and emptying first the tank with lowest pressure.

The strategy for H_2 distribution is described in the decision tree of Fig. 2. This strategy will define at each time every control decision variable except for S1.

3.2 Predictive algorithm

A day-ahead deterministic algorithm has been developed to guarantee demmand supply, which has been implemented in Stateflow environment, too. The algorithm will determine at each time step the S1 state (0 for irradiance mode and 1 for grid mode) based on the predicted irradiance and price profiles.

In order to determine S1, the algorithm will compute each day at 00:00h the difference between the potential day-ahead production in irradiance mode (considering only irradiance hours above IRTH) and the target daily H_2 production. If the result is negative, the difference will be covered with FV_FG along the minimum energy cheapest hours with irradiance below IRTH.

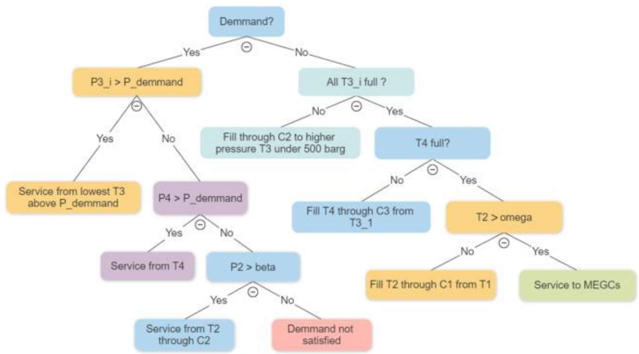

Fig. 2: Decision tree for H2 distribution strategy

4. Results

A complete year has been simulated with the described model. An averaged year direct beam irradiance profile is obtained from meaned hourly data from 2007 to 2016 at Zaragoza, Spain. The energy price timeseries are hourly values of 2021 in Spain. Simulation parameters are the following:

- Irradiance threshold (IRTH): 370 W/m^2.
- Minimum daily target service: 67 kg/day of H_2.
- Omega and Beta values are set at 15 barg.

Simulations have been run in a HP Z2 Tower G5 Workstation (i7-10700 CPU and 16 GB of RAM). Complete simulation elapsed time in rapid accelerator mode: 18 minutes.

4.1 Complete year simulation

In Fig. 3 and Fig. 4, results for the averaged year simulation are presented. Pressure values of all tanks are shown as well as vehicles tank pressure. A service will be checked as completed if its maximum pressure is 350 barg for HDV and 700 barg for LDV, which corresponds to 30 kg and 7 kg supplied H_2, respectively.

As it can be seen in Fig. 3.5, the output of our distribution strategy and our predictive strategy has correctly supplied all HDV along the complete year simulation, which is the first purpose of our distribution strategy, since T3_i are always prioritized in the filling process. Also important to notice is the trend of T2 (Fig. 3.3) to stay in low pressure levels, almost never above 50% capacity. In Fig. 3.6 we can appreciate that T4 has never been used for HDV service. In Fig. 3.8, we see the switch S1 state, directly related with the system inlet H_2 flow rate in Fig. 3.1.

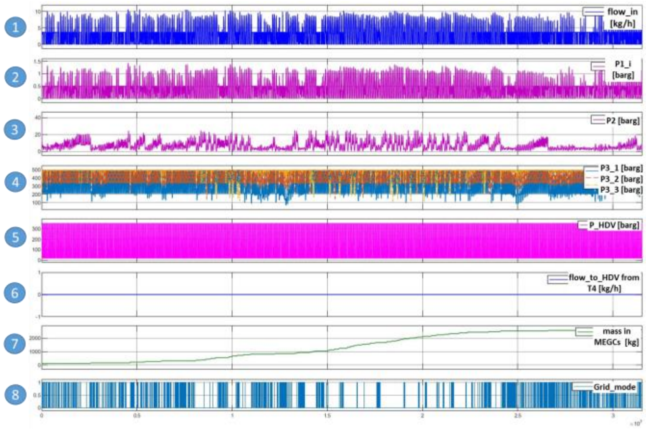

Fig. 3: All year simulation results

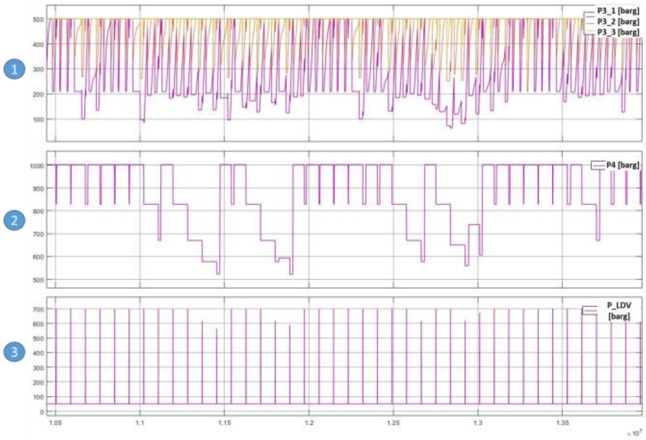

Fig. 4: May section with LDV detail results

Fig. 4 show a zoomed view of the results around May in which LDV demmand has not been completed. As it can be seen in Fig. 4.3, some services have been abandoned below 700 barg. The reason is the low T4 pressure level, even under 700 barg, at some service start times (note that T4 is the only tank that can end the service from 500 barg to 700 barg). This is because our predictive algorithm does not take in to account the state of charge of the different tanks, only the total daily input H_2 mass to the system.

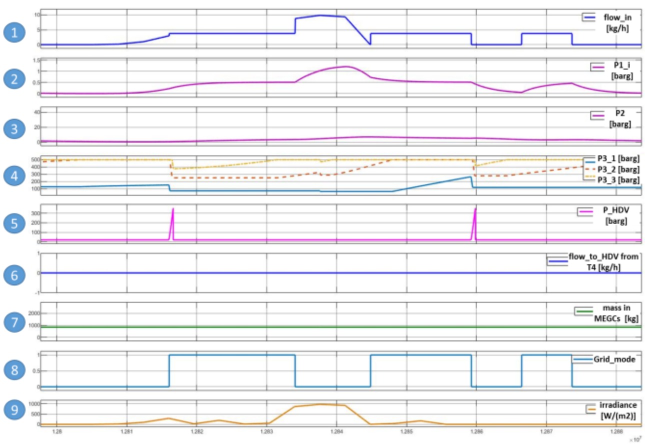

Fig. 5: A day of May results

In Fig. 5, a day of May is shown, where the sequence of filling and emptying T3_i tanks can be appreciated, together with all diferent equilibrium points. Moreover, the S1 grid mode effect with its associated constant input flow rates are shown in Fig. 5.1.

5. Conclusions and future work

In this work a flexible and fast simulation model of a hydrogen station has been developed, based on a real system with many control variables. An algorithm for H_2 distribution has been designed and implemented into a finite state machine. Moreover, a predictive algorithm has been created. Both algorithms have been validated through simulation showing promising results. The distribution state machine implemented has achieved to correctly follow the decision tree of Fig. 2, respecting equilibrium points in direct tank expansion cases and filling/emptying priority order. This model serves as a quick and flexible simulation testbench for component dimensioning (tanks and compressors) and control strategy testing. The preliminar predictive algorithm presented has correctly served all HDV along a year data and almost all LDV.

Model improvements could be implemented such as compressor electric variable consumption and other parasite comsumptions, pressure drops, thermal inestability in compression, variable service flow rate, minimum input pressure for compressors, etc. Also a photovoltaic and battery on-grid system and some grid power constraints could be added. The presented preliminar predictive algorithm could be improved in the following ways: consideration of information about the state of the system (not only daily production fulfillment but also service fulfillment in account of expected vehicle arrival time), FV_FG and IRTH values could be variable and decided by the algorithm, a forecasted data uncertainty treatment could be done and finally, the algorithm could also exploit, to decrease cost, some of the above model mentioned changes.

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