Simulations of a flexible 100 kW_{el} PEM Fuel Cell power plant for the provision of grid balancing services

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Abstract. The continuous growth of non-programmable renewable energy resources penetration leads to unpredictable oscillations of the net load faced by dispatchable power plants, hindering the reliability and stability of the electric grid and requiring additional flexible resources. The EU project GRASSHOPPER focuses on MW-scale Fuel Cell Power Plant (FCPP) based on low temperature PEM technology. The project aims to setup and demonstrate a 100 kW_{el} PEM FCPP, flexible in power output and designed to provide grid support. This work presents a dynamic simulation model of the FCPP, developed to simulate plant flexible operation and identify the best management strategy, aiming at optimizing the efficiency while reducing the degradation rate. Cold start up simulations, according to a warm-up procedure limiting stack degradation, result in a time to operation equal to 26 minutes. A sensitivity analysis is performed to determine which parameters mostly influence the warm-up duration, showing that it is possible to reduce start-up time substantially (e.g. down to 3 minutes with component preheating). On the other hand, simulations at variable load along the entire range of operation (20-100 kW_{el}), according to grid balancing requirements, show that the plant is able to ramp up and down between the minimum to the maximum load in about 40 seconds.

1 Introduction

Power generation has experienced in the last years a continuous growth of renewable energy sources (RES) penetration, as required to meet the greenhouse gas emissions reduction targets set by most industrialized countries [1]. New installations have been mainly based on non-programmable resources (wind and solar photovoltaics) whose discontinuous and uncertain generation profile leads to unpredictable oscillations of the net load faced by the other dispatchable power plants, hindering the reliability and stability of the electric grid. Additional flexible resources are therefore necessary in the power system, able to rapidly face the unbalances.

In this framework, the EU project GRASSHOPPER [1] investigates the use of MW-scale Fuel Cell (FC) power plants based on low temperature Polymer Electrolyte Membrane (PEM) technology for the provision of balancing services to the electric grid. Indeed, the fast ramp rate and the load following capability characterising this kind of systems make them a possible source of flexibility for the provision of grid ancillary services. The technical feasibility of large MW-size PEM FC power plants has already been well demonstrated, for example in the DEMCOPEM-2MW project (FCH-JU 2015) [3]. GRASSHOPPER project

aims at demonstrating the dynamic operation capability, realizing the next-generation modular FC Power Plant (FCPP) unit targeting stationary application in the MW scale grid stabilization. The project is setting up a 100 kW_{el} PEM FC pilot unit, demonstrating flexibility in power output to provide grid support. The FCPP design will be cost-effective, targeting an estimated CAPEX below 1500 €/kW_{el} (at a yearly production rate of 25 MW_{el}), as required to enter the markets as a competitive player. Joint development of MEA, stack and system design is thus a primary focus. The flexible demand-driven operation will be demonstrated with a gross power set point range between 20 kW_{el} and 100 kW_{el} and a ramp-up rate delivering 50 kW_{el} within 20 seconds and 100 kW_{el} within 60 seconds.

In this work, a dynamic simulation model of the GRASSHOPPER pilot plant is presented. The model allows to simulate plant warm-up and variable load operation to identify the best management strategy, optimizing the efficiency while reducing the expected FC degradation rate.

2 FC power plant layout

The layout of GRASSHOPPER 100 kW_{el} FC pilot power plant is shown in **Fig. 1**.

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Fig. 1 - Grasshopper 100 kW_{el} FC power plant layout.

The stack is supplied with humidified pure hydrogen and air. Humidification is obtained through packed-bed shower-type humidifiers, that act also as scrubbers removing the impurities from the gas. The stack operating temperature, relevant for degradation and efficiency, is controlled by the flow rate of coolant, a glycol-water mixture flowing through a dedicated loop. The thermal power is partially recovered to heat up the water used for hydrogen and air humidification and partially dissipated by a dedicated cooler. A valve, located at cathode outlet, allows to control air backpressure. Air ratio to stoichiometry is controlled by regulating the rotational speed of the compressor. Excess hydrogen is recirculated through a liquid ring compressor and hydrogen ratio to stoichiometry is controlled with a bypass system. Fresh hydrogen is supposed to be available at sufficiently high pressure (above 4 bar), thus it can be simply injected into the system through a controlled valve.

The simultaneous control of backpressure, stack temperature, air and hydrogen ratio to stoichiometry and relative humidity will allow to optimize the system performance and limit FC stack degradation.

3 FC plant dynamic model

A dynamic model of the 100 kW_{el} FC power plant is developed with the software Simulink. For each plant component, a model able to solve mass and energy balances during variable load operation is built, as described in the following paragraphs. Fluid properties are calculated for gases with the hypothesis of ideal gas and ideal gas mixture, for water and water-coolant mixtures considering ideal liquids with constant specific heat. Component models are then combined together to build the entire system model and PI-type controllers are implemented for the control of system operation.

3.1 FC stack model

The single cell model is developed with a lumped-volume approach, based on performance data available from detailed simulations. Since the FC model has a modular structure, the stack lumped model considers several identical cells, electrically connected in series to form a fuel cell stack. This approach allows to reproduce large scale effects, as required by system simulation, without a detailed description of the internal phenomena in a single cell.

The model receives as input reactants and coolant flow rate, composition, temperature and pressure at FC inlet, and the set-point current density. The model then solves mass and energy balances to determine flow rate, composition, temperature and pressure of reactants and coolant fluid leaving the FC stack. Gas build-up effects in cells channels are neglected, both by a fluid-dynamic and mass inertia point of view, since the volume of the channels is negligible with respect to the volume of other system components (i.e. humidifiers), where mass accumulation is allocated. Temperature dynamic is taken into account through the heat capacity of the stack, that is lumped in the bipolar plates. Constant heat transfer coefficients and no heat losses to the environment are assumed. Pressure drops in the cells channels are linearly dependent on the reactants and coolant fluid volumetric flow rate at stack inlet, assuming laminar flow conditions.

FC voltage and gross electrical power are calculated on the basis of semi-empirical current-voltage polarization curves. These curves are obtained from a simplification of the theoretical polarization curve equations, where the $V(i)$ equation coefficients are regressed on detailed datasets as reported in [4]. The resulting curves take into account voltage dependence on backpressure, air ratio to stoichiometry, air relative humidity and temperature. Voltage dynamic due to the charge and discharge of the cell double layer are included in the model. However, being typical values found in literature for the double layer capacitance between 0.01 and 0.05 F/cm² [5], the settling time associated to this phenomenon results lower than 1 second, much faster than other important dynamic effects such as those associated to the thermal inertia.

3.2 Air compressor model

The air blower is modelled through the machine performance maps, allowing to compute the volumetric flow rate of processed air, its temperature gain and the compressor electric consumption, given the required pressure gain and the rotational speed. The model neglects mass accumulation and temperature dynamics of the working fluid and of the machine. Since this would affect the start-up time, it is assumed that the compressor is switch on in advance and it reaches thermal equilibrium before the simulation starts. Dynamic effects connected to the mechanical inertia of the machine, that slow down the rotational speed variation, are instead included with the same approach proposed in [6]: compressor rotational speed is determined by a balance between the torque generated by the electric motor and the torque required by the compressor.

3.3 Air supply manifold

The air supply manifold model gathers the volumes of all the supply line components, allowing to simulate air build-up in the supply line. The resulting lumped volume is located between the air compressor and the air humidifier.

Assuming constant temperature in the manifold itself and ideal gas behaviour, the manifold model solves mass balances to compute how the pressure of the air in the supply line varies over time. The air flow rate entering the manifold volume is imposed by the air compressor while the air flow rate leaving the manifold volume is set by the pressure drops in the components located downstream and, mainly, by the backpressure valve located at cathode outlet.

Air flow through the valve is modelled as a compressible-fluid one-dimensional isentropic flow through an orifice, with the assumption of subcritical pressure ratio. An empirical discharged coefficient takes into account deviation from one-dimensional flow [7].

3.4 Humidifier model

In the packed-bed shower-type humidifier, the gas (air or hydrogen) is introduced at the bottom of the packed-bed column and flows upwards, increasing its humidity thanks to the evaporation of the water that flows downwards. Residual liquid water accumulates in the tank at column bottom; it is then heated up and pumped back to the humidifier column top.

The model considers two sections: the packed-bed column and the water tank. For each part, a lumped volume approach is considered.

The packed bed column model determines flow rates, composition, temperature and pressure of gas and water leaving the column by solving mass and energy balances, given the inlet streams properties. According to industrial experience, it is assumed that the gas always leaves the column in thermal equilibrium with the sprayed water and fully saturated (humidifier effectiveness 100%). No water drops are entrained by the gas stream leaving the humidifier thanks to a demister installed at the top of the column. Temperature dynamic in the humidifier column is not included in the model, being negligible with respect to temperature dynamic in the humidifier tank. The packed-bed has a void fraction equal to 90% of its volume. However, the air humidifier model does not consider gas build-up in the packed-bed column, since the volume of all the components of the air supply line are gathered in the air manifold. On the contrary, the H₂ humidifier model includes gas build-up possibility in the packed-bed column. In this case, the flow rate of moist hydrogen leaving the humidifier is imposed by the liquid ring compressor which recycles the stack anode exhaust and the inlet flow rate of fresh hydrogen is regulated in order to control the pressure in the humidifier, and consequently the FC anode backpressure.

The bottom water tank model solves mass and energy balances, considering water accumulation and temperature dynamic. The thermal inertia is associated to the heat capacity of the accumulated water, being the heat capacity of the tank walls negligible (< 5%). Perfect mixing in the water tank is assumed.

3.5 Liquid ring compressor model

A stationary model is set up for the liquid ring compressor, since it works within a narrow range of

rotational speed. The compression process is divided into two sequential steps: compression of the hydrogen stream and mixing with the water stream. Constant isentropic and mechanical efficiencies are assumed to compute the electrical power consumption. Mixing of compressed hydrogen and liquid water in the liquid ring compressor is modelled as an adiabatic process.

3.6 Heat exchangers

All the heat exchangers in the plant are counter-current plate-type heat exchangers. Since the plate heat exchanger has a modular structure and the hot and cold fluids are assumed to be equally distributed among the channels, it is modelled as a sequence of identical sub-units. This sub-unit includes a single plate and half of the adjacent cold and hot channels. The heat transferred, the temperature of the plate itself and the temperature of the outlet streams are calculated, discretizing the unit along the direction of the channels (1D-model). For each control volume resulting from the discretization procedure, mass and energy balances are solved assuming a uniform temperature for the plate, neglecting heat transfer by conduction along the flow direction (due to the relatively small thermal gradients and the necessity to avoid more complex iterations which would impact the simulation speed) and heat losses to the environment. Temperature dynamic is related to the heat capacity of the heat exchanger materials, while fluid mass accumulation in the channels is neglected. Constant values for water and coolant heat capacities as well as for the heat transfer coefficients are assumed. The thermal resistance of the plate is neglected. Pressure is assumed to vary linearly with the volumetric flow rates.

3.7 Pumps

A steady state model is realised also for the pumps. The model computes the electric consumption of the pump, as well as pressure and temperature of the outlet fluid assuming constant isentropic and mechanical efficiency.

3.8 Pipelines

The model of pipelines, connecting the plant components, includes calculation of pressure drops and transport delay. Pressure drops in the pipes are computed as a function of the volumetric flow rate. Transport delay, representing the time that the fluid takes to go from one component to the next one, is simulated through a time delay that depends on pipe length, diameter and volumetric flow rate. The assumption of incompressible fluids is introduced (air accumulation, as already mentioned, is concentrated in the air supply manifold volume, while hydrogen accumulation is concentrated in the hydrogen humidifier volume). The heat capacity of the pipeline system is not included in the model since it results negligible with respect to the heat capacity of the other plant components.

4 Dynamic simulations

Preliminary simulations are performed to investigate the system performance during cold start up and variable load operation, in order to simulate the provision of grid ancillary services.

4.1 Cold start up

Cold start up is simulated to understand how long does it take the plant to reach nominal operating conditions when started after a long shut-down period.

It is assumed that the plant is off and all the components and the cooling fluid are at ambient temperature (20°C). The FC plant is switched on and the power demand is increased according to a warm up procedure, defined to allow the plant itself to reach the nominal point (detailed in **Table 1**) as fast as possible while maintaining all the operating parameters within a range of values defined to limit cells degradation.

Table 1. Plant nominal operating point

Parameter	Nominal value
Current density	1 A/cm ²
Stack temperature	65°C
Coolant temperature gain over the stack	10 °C
Air ratio to stoichiometry	2
Hydrogen ratio to stoichiometry	1.5
Air backpressure	1.35 bar
Average air relative humidity	100%
Average hydrogen relative humidity	100%

Warm up initial state considers that the air compressor is switched on at its nominal power (giving the nominal air ratio to stoichiometry at nominal operating conditions) and the backpressure valve is regulated to obtain the nominal air backpressure. The coolant flow rate is set at the nominal value aiming at fast heating of humidifiers. The liquid ring compressor is also operated at its nominal point.

The FC is switched on at its minimum load, with a current density of 200 mA/cm², equal to 20% of the nominal value. The current density is then increased up to the nominal value, with a rate of increase limited by two temperature constrains (defined to limit cell degradation): for each average temperature of the coolant along the stack and for each temperature of the air at stack inlet, a maximum current density is allowed to keep the membrane correctly humidified.

When current density, reactants humidify and stack temperature reach their setpoint, controls are activated to keep, respectively, reactants ratio to stoichiometry, reactants humidity and coolant temperature at the desired values. The external cooler is activated to remove the excess heat.

Fig. 2 shows how the current density varies over time during plant warm up. The average temperature of the coolant over the stack and the temperature of the air at stack inlet are shown in the same figure.

The current density remains at the minimum value for about 450 seconds (> 7 minutes), when the average coolant temperature reaches the minimum value that allows the current to increase. The system reaches the nominal current in 1560 seconds (26 minutes). It takes another 15 minutes for all parameters to reach the nominal point, as shown in **Fig. 3**, being hydrogen ratio to stoichiometry and hydrogen relative humidity the last parameters to reach the nominal point.

Fig. 2 – Current density, average coolant temperature and air temperature at FC inlet over time in cold start up.

Fig. 3 – Relative humidity, ratios to stoichiometry and average coolant temperature profile over time during cold start up vs. setpoints.

Air and fuel ratio to stoichiometry have their maximum at start up, when the current density is at the minimum. Then, they decrease when the current density increases.

Immediately after start up, when the stack is cold, air relative humidity is above 100% while hydrogen relative humidity is about 100%. Then, while increasing the current density, both air and hydrogen average relative humidity decrease because the stack temperature increases faster with respect to the humidifiers temperature, influencing the gas water content at stack inlet (air and hydrogen leave the humidifiers at the same temperature of the sprayed water, saturated with water). Finally, the humidifiers

temperature increases and the average relative humidity reaches the 100% setpoint.

A sensitivity analysis has been performed to determine which parameters mostly influence the warm-up duration. Firstly, a sensitivity analysis on the initial temperature is performed: it is indeed possible that ambient temperature is higher in summer or that the warmup procedure starts from a higher temperature because the plant remained off only for a short period. Then, by the FC point of view, an analysis is performed to assess the impact of the cells overall heat transfer capacity and of the cells heat capacity. Finally, at a system level, the analysis focuses on the impact of (i) the length of the pipes connecting the components, (ii) the amount and initial temperature of the water in the humidifiers (mainly in the air humidifier, since the current ramp up depends on the air temperature at stack inlet) and (iii) the overall heat transfer capacity in the heat exchangers used to heat up the humidifier water.

The cases under investigation and the associated time required for the current density to reach 1000 mA/cm² are reported in **Table 2**, in comparison with the reference case.

Table 2 - Sensitivity analyses: warm up duration and percentage reduction with respect to the reference case.

Case	t [min]	Δt [%]
Reference case	26.0	-
Initial temperature 30 °C	12.8	-50.8%
Initial temperature 40 °C	3.2	-87.7%
Doubled cells overall heat transfer coefficient	25.5	-1.9%
Halved cells heat capacity	24.8	-4.6%
Halved pipes length	23.8	-8.5%
Halved amount of water in the humidifiers tanks	16.9	-35.0%
Initial temperature of water in humidifiers tanks 30°C	15.0	-42.3%
Initial temperature of water in humidifiers tanks 40°C	6.6	-74.6%
Doubled overall heat transfer coefficients in heat exchangers for humidifier water	25.3	-2.7%

Results show that, when the system is kept at higher temperature, the start-up time significantly reduces, reaching the nominal current density in 12.8 and 3.2 minutes when started from 30°C and 40°C respectively. Indeed, the current density remains constant at 200 mA/cm² for 7.5 minutes in the reference case, for 1.3 minutes when the system starts from 30°C while it can increase immediately when it starts from 40°C. The reason is the thermal inertia of the water in the humidifier tanks, that takes about 4 minutes to heat up from 20°C to 30°C, subtracting heat from the coolant fluid and delaying the current increase.

Looking at the FC stack parameters, the impact on the start-up time of the cells overall heat transfer capacity and of the cells heat capacity are not significant.

On a system level, impact of the length of the pipes connecting the plan components is quite limited. On the contrary, a reduction of 50% in the amount of water in the humidifier tanks have an important impact on the start-up time, with a reduction slightly below 10 minutes. Indeed, in this case a lower amount of heat would be transferred from the coolant fluid to the humidifiers water tanks in order to reach the target air temperature. Thus, the current density could increase faster because both coolant and humidifiers temperature, and consequently the air temperature at stack inlet, also increase faster. The strong impact of the heat duty required by the water in the humidifiers tanks on the start-up time is confirmed by the 11 minutes start-up time reduction in the case where the humidifier water temperature at the beginning of the warm up procedure is 30°C, i.e. 10°C higher with respect to the reference case. This time reduction is only 2.2 minutes less with respect to the time reduction obtained by increasing the temperature of all the system components to 30°C, showing the effectiveness of heating up only the water in the humidifier tank to speed up the warm up process.

Finally, a change in the overall heat transfer coefficients in humidifiers heat exchangers does not affect significantly the warm up time. It has to be highlighted that, in this case, the current increase rate is always limited by the coolant temperature rise, since more heat is transferred to the water in the humidifiers tanks and the air temperature increases faster at the expense of the average coolant temperature. For the same reason, the current density remains constant at the initial 200 mA/cm² for a longer time with respect to the reference case (660 seconds instead of 450 seconds).

4.2 Load following operation

In order to provide ancillary services, the FC power plant must operate dynamically, following the load request within few minutes. Thus, the plant will operate most of the time at partial load and the plant optimization has to consider operation at any current density.

Simulation following a hypothetic fluctuation of the load are performed. The gross power generated by the FC power plant is varied every 15 minutes, analysing the entire range of operation for the stack, from 20 kW_{el} to 100 kW_{el}, as depicted in **Fig. 4**.

Fig. 4 – FC gross power demand profile

Fig. 5 shows how the stack gross power, the current density and the voltage vary over time, proving that the system is able to follow the load demand. In **Fig. 6**, details on performance at stepwise power changes from 20 kW_{el} to 100 kW_{el} and from 100 kW_{el} to 20 kW_{el} are presented. The rate of change of the FC gross power is limited at 2 kW_{el}/s, to limit stack degradation while

respecting the desired ramp target (ramp-up rate delivering 50 kW_{el} within 20 seconds and 100 kW_{el} within 60 seconds). To avoid air and fuel starvation, flow rates of air and fuel at FC stack inlet are increased few seconds before current ramp-up and only at the end of current ramp-down. Both in ramp-up and ramp-down the system takes about 40 seconds to reach the power setpoint.

Fig. 5 – FC current density, voltage and gross power profile during variable load operation.

Fig. 6 – FC gross power profile for step-wise changes from nominal to minimum load (left side) and from minimum to nominal load (right side).

Preliminary design evaluations provide gross and net plant efficiency up to 64% and 49% respectively (see Fig. 7). The net efficiency at minimum load operation (~ 42%) is negatively influenced by the air compressor baseload; indeed the air ratio to stoichiometry is controlled through the compressor rotational speed only when the plant operates close to the nominal load, while moving to lower load the compressor reaches its minimum power and air purge is required. The adoption of a compressor controllable over the entire range of plant operation would increase the plant net efficiency. Further improvements will come from design optimization and experience from the pilot unit.

Fig. 7 – FC gross efficiency and plant net efficiency profile during variable load operation.

5 Conclusions and future work

A dynamic model of a 100 kW_{el} PEM FC power plant has been developed, including sub-models of the main plant components. Simulations of plant cold start-up and load following operation have been performed.

Preliminary cold start-up simulations show that the system reaches the nominal current density in 26 minutes when started from 20°C. However, when the system is kept at higher temperature, the start-up time significantly reduces, being 12.8 and 3.2 minutes when started from 30°C and 40°C respectively. A sensitivity analysis shows that the components which more significantly limit the plant dynamic are the humidifiers. Thus, possible options to reduce the start-up time are decreasing the amount of the water in the humidifier tanks, decreasing the humidifiers size or preheating the water.

Simulations of plant variable load operation show that the system is able to follow the power demand and is able to ramp up and down between the minimum and the maximum load in 40 seconds, fully reaching the target set by the project.

These simulations results contribute to determine the plant preliminary operating strategy and allows to identify the more critical aspects and investigate possible evolutions of the design.

During the first period of operation of the 100 kW_{el} GRASSHOPPER pilot plant, experimental operational data will be collected and used to validate the model, aiming at gaining further insight on the plant dynamics and also at optimizing the system for MW-scale.

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