Journal of Power Sources 381 (2018) 30–37

Contents lists available at ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

Power ramp rate capabilities of a 5 kW proton exchange membrane fuel cell system with discrete ejector control

K. Nikiforow*, J. Pennanen, J. Ihonen, S. Uski, P. Koski

VTT Technical Research Centre of Finland Ltd, P.O. Box 1000, FI-02044 VTT, Finland

HIGHLIGHTS

- Ejector-based PEMFC system power ramp-rate capabilities were studied.
- Fuel supply manages a 50%–100% power ramp in 0.1 s even in low-volume systems.
- Air supply with 2.5 initial stoichiometry manages a 50%–93% power ramp in 1.0 s.
- Air supply with 7.0 initial stoichiometry manages a 50%–93% power ramp in 0.1 s.

ARTICLE INFO

Keywords:
PEMFC system
Power ramp rate
Dynamic behavior
Ejector
Fuel supply
Air supply

ABSTRACT

The power ramp rate capabilities of a 5 kW proton exchange membrane fuel cell (PEMFC) system are studied theoretically and experimentally for grid support service applications.

The fuel supply is implemented with a fixed-geometry ejector and a discrete control solution without any anode-side pressure fluctuation suppression methods. We show that the stack power can be ramped up from 2.0 kW to 4.0 kW with adequate fuel supply and low anode pressure fluctuations within only 0.1 s.

The air supply is implemented with a centrifugal blower. Air supply ramp rates are studied with a power increase executed within 1 and 0.2 s after the request, the time dictated by grid support service requirements in Finland and the UK. We show that a power ramp-up from 2.0 kW to 3.7 kW is achieved within 1 s with an initial air stoichiometry of 2.5 and within 0.2 s with an initial air stoichiometry of 7.0. We also show that the timing of the power ramp-up affects the achieved ancillary power capacity.

This work demonstrates that hydrogen fueled and ejector-based PEMFC systems can provide a significant amount of power in less than 1 s and provide valuable ancillary power capacity for grid support services.

1. Introduction

Proton exchange membrane fuel cells (PEMFCs) are seen as a valid alternative to diesel generators in backup power and grid balancing applications both in the kW- and MW-range. The main advantages of a PEMFC in these applications are start-up reliability, low start-up costs, ability to respond rapidly to load changes, zero local emissions, and low noise level.

The need for backup power and grid balancing services increases with the amount of variable renewable energy (VRE) in the grid. In particular, the inherent inertia of the system decreases as the penetration of conventional synchronous generators decreases in power systems [1]. The decrease in inertia is mainly due to increasing wind and photovoltaic (PV) solar power generation or electricity imports via high voltage direct current (HVDC) links.

Decreased inertia deteriorates the stability of the power system in case of disturbances. Inertia determines the lowest momentary frequency occurring within a few seconds after a major system frequency disturbance, which typically is caused by the loss of a large power plant or significant transmission connection.

The decrease of inherent inertia can be offset in a number of ways, e.g., keeping a sufficient amount of synchronous generation online in the system and thus curtailing non-synchronous generation or limiting imports via HVDC connections, adding rotating masses like synchronous condensers into the system, or establishing a market for inertia and thus promoting implementation of synthetic inertia. Synthetic inertia could be obtained from non-synchronous units (e.g., wind power plants, solar PV, batteries) by modulating the power output in a manner similar to how synchronous units provide power as inertial response [2]. In Europe, transmission system operators (TSOs) could require non-

* Corresponding author.
E-mail address: kaj.nikiforow@vtt.fi (K. Nikiforow).

https://doi.org/10.1016/j.jpowsour.2018.01.090
Received 1 September 2017; Received in revised form 26 January 2018; Accepted 30 January 2018
Available online 08 February 2018

synchronous Power Park Modules (PPM) to be capable of providing synthetic inertia. This requirement could be applied to PPMs with capacities of a few to tens of megawatts and above depending on the synchronous system [3,4]. Neither inertia requirements nor inertia as an ancillary service is yet widely used.

Inertia is related to the rate of change of frequency (RoCoF) immediately after a disturbance. Frequency containment disturbance reserves (FCR-D) determine the following steady frequency [2,5]. Frequency indicates the balance between system load and power generation and, thus, both power generation and loads can be used for FCR-D.

Historically, load shedding – i.e. fast tripping of loads – has been the means for rapid handling of severe low frequency disturbances due to loss of power supply. In Finland, for example, a tendering for load shedding is employed for system protection because of to the 1600 MW nuclear power production unit that is expected be online in 2019 and will affect the Nordic power system operation security.

In the UK's Enhanced Frequency Response (EFR) market [6], reserve capacity must be activated fully within 1 s and be able to sustain support for a minimum 15 min. Batteries have proven to be a very cost effective way to provide a fast response in the UK EFR tender. The feasibility and applicability of similar fast frequency response systems has been investigated by local authorities, e.g. in Australia [7] and in Texas, U.S [8].

In addition to load shedding and batteries, system protection and EFR could also be implemented by fast generation control reserves with similar control characteristics, i.e., an ability to provide power within 1 s. This creates a new opportunity for fuel cells and, in particular, for PEMFCs, which can achieve a very high power ramp rate.

In Finland, a significant amount of hydrogen is produced as a by-product in chlorine and sodium chlorate factories [9], and the quality of that hydrogen is sufficient for use as fuel in PEMFCs [10]. Using this hydrogen in PEMFC power plants operating at partial load, a significant rapid load response could be provided. However, the ability of PEMFC power plants to provide this ancillary service should be proven by verifying their power ramp rate capability.

A number of factors limit the power ramp rate of hydrogen fueled PEMFC systems, including air supply, fuel supply, and power electronics. These limitations are dependent on the system design and operation. Therefore, the power ramp rate capability can be improved by optimizing the system design and operation.

Air supply is well known to limit the power ramp-up rate in PEMFC systems. In principle, there are three issues: the dynamic capability of the blower/compressor, the gas manifold volume, and the time lag of the control system. Corbo et al. analyzed a 20 kW_e PEMFC system using different air supply strategies. By applying excess air at low loads, a 20%/s power ramp rate was achieved [11]. However, the use of excess air flow rate reduces system efficiency by adding blower power consumption and increases system cost through the need of a more efficient humidifier. In another study, Corbo et al. showed that 10%/s power ramp rate is possible (with minor issues) starting from room temperature [12]. Danzer et al. studied and modeled the control of cathode air excess and pressure in a pressurized PEMFC, showing that with an observer-based multivariable control, a 50%/s power ramp rate is possible [13]. However, the inertia of the compressor was not considered because a mass flow controller supplied the air. The study of Danzer et al. also illustrates that maintaining the cathode pressure close to set-point might be challenging during transients. In pressurized systems, not only does the cathode pressure need to be controlled but also the anode pressure, thus adding complexity. Matraji et al. studied the control of a compressor by modeling and employing a Hardware-In-Loop test bench [14]. According to their results, it takes up to 9 s to increase the air flow rate from 0 to 100%. This long duration may be due to the high inertia of the twin-screw compressor and the limited power of a compressor motor. Based on the literature study, at least a 20–30%/s power ramp rate is possible without extra measures at the air supply side.

The fuel supply also limits the power ramp rate, especially when the system is pressurized and an ejector is employed for anode gas recirculation. In a pressurized system, the anode pressure needs to be controlled to avoid a too high pressure difference over the membrane, leading to possible limitations in power ramp rate. When an ejector is applied, the ejector primary pressure control will further complicate the management of the anode pressure, especially if discrete flow control is applied [15]. Anode gas recirculation is applied in PEMFC systems for fuel humidification and to avoid local fuel starvation [16,17].

A third limitation for the power ramp rate is the thermal management, especially when the stack power density is high. The power densities of present day PEMFC stacks are in the range of 3 kW/dm^3 [18]. When the power is increased from the minimum to the maximum level, the cooling demand may increase up to 5 kW per kilogram of stack mass. This would lead to a temperature increase rate of 2–4 °C/s.

The transients in reactant supply or temperature can also lead to severe degradation of the catalyst layer, as reviewed by e.g. Banerjee [19]. Pei and Chen have reviewed the main factors affecting the lifetime of PEMFC in vehicle applications, and reactant starvation during fast transients is one of the issues [20].

To date, PEMFC systems hydrogen fuel ramp rate capabilities have not been studied, only the air supply capabilities. In addition, in these air supply studies, the focus has been on the time scale of several seconds, not 0.2–2 s, which are needed in many applications, including ancillary services for TSOs.

The present work studies the hydrogen fuel supply ramp rate capabilities of a PEMFC system with an ejector with discrete control. The capabilities of an ejector-based system are studied for the first time without using any anode pressure fluctuation mitigation methods during the transient, such as anode purge [15]. In addition to the fuel supply, the air supply ramp rate capabilities are studied. The work focuses on determining the maximum power increase achievable with a PEMFC system operated at partial load, with the power increase executed within 0.2 or 1–2 s after the request, as suggested by the requirements for ancillary power applications.

2. Methods

2.1. PEMFC system description

Fig. 1 shows the simplified schematic of the PEMFC system employed in this work. The fuel was supplied through a fixed-geometry ejector (E), employed for anode gas recirculation. The ejector primary pressure was controlled using a setup of three solenoid valves and three flow restrictors (EPC), enabling fuel supply at seven discrete flow rates. The fuel supply in the present setup limits the maximum PEMFC power to approximately 4 kW. The load current was fine-tuned to compensate for the possible small variation in fuel supply rate and to maintain a constant anode pressure during steady state operation. Air was supplied with a blower (B) and humidified with a membrane humidifier (MH). A coolant pump (P) recirculated de-ionized water through the stack and through a liquid-liquid heat exchanger (HEX). The PEMFC system was controlled with National Instruments CompactRIO hardware, which was programmed with LabVIEW software. A complete description of the system can be found in previous work [15].

The control software was adopted for the current work, firstly by a higher data acquisition rate (100 Hz), which was triggered prior to a power transient and maintained for 10 s. Secondly, the experiments conducted in this work – the study of system ramp rate capabilities and the control of anode pressure during power transients – relied on exact timing of the fuel valve (in EPC), the air blower, and the electronic load control. Therefore, the control routine was updated to achieve accurate control, with the timing error of 1 ms or below.