Enhancing Distribution System Resiliency Using Grid-Forming Fuel Cell Inverter

Preprint

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Enhancing distribution system resiliency using grid-forming fuel cell inverter

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***Abstract*—Legacy inverters interfacing distributed energy resources are traditionally grid-following (GFL) in nature. GFL assets typically follow real power and reactive power set points. Recently, inverters with grid-forming (GFM) capability have gained attention because GFM assets can increase the resiliency of the distribution system under stressed conditions. These GFM inverters can use photovoltaics, batteries, or fuel cells as their energy source. In this paper, we present information on inverters interfacing fuel cell assets, specifically with GFM capability. By introducing a fuel cell-powered GFM coupled with hydrogen production and storage, the GFM can continuously provide GFM activities during periods of low renewable resource availability and/or during power outages exceeding typical electric battery duration. Finally, we present information on the need for updates to interconnection and interoperability standards that can be leveraged by utilities for including fuel cell inverters in their asset mixes.**

***Keywords*—Fuel cells, fuel cell inverters, microgrids, grid-following inverters, grid-forming inverters.**

I. INTRODUCTION

Traditionally, the inverters used to interface distributed energy resources (DERs) including solar, batteries, and fuel cells are grid following (GFL) in nature. GFL inverters follow real power and reactive power set points decided by either a local autonomous controller or a remote controller such as a microgrid controller. In the recent years, multiple challenges in the distribution system have increased the need for grid-forming (GFM) inverters that can interface a wide variety of energy resources [1]. These GFM inverters are becoming critical assets for power systems to enable the replacement of existing rotating machines and provide grid services, such as grid resiliency and black starts [2]. If existing DERs can act as reliable long-term GFM assets, grid operators can reduce parallel investment costs in GFM assets, operations costs, and emissions. Hydrogen assets (fuel cells) have the potential to successfully replace rotating machines and act as a voltage and frequency master by leveraging the long-duration and seasonal energy storage capabilities of hydrogen technologies. Fig. 1 shows the use of hydrogen technologies in a microgrid setting. Compared to PV or batteries, sustainable access to hydrogen can enable the GFM fuel cell inverters to maintain voltage and frequency in an islanded microgrid setting.

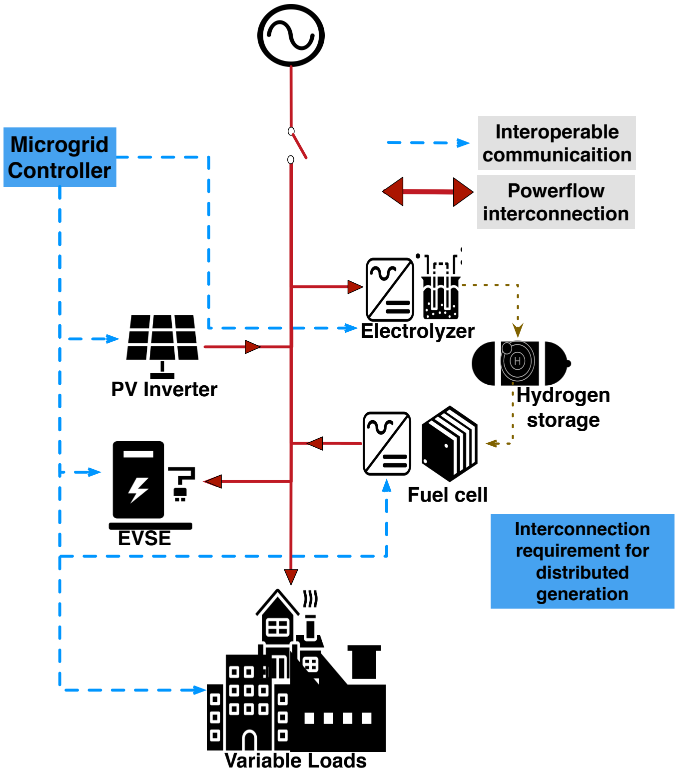

Fig. 1. Use of hydrogen assets in a microgrid setting

GFM assets are traditionally used as a voltage-frequency

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master in an islanded microgrid. These GFM assets can operate in two modes: GFL mode and GFM mode. In GFL mode, these assets will follow the real power and the reactive power set points; in GFM mode, these assets will follow the voltage and the frequency set points. Traditionally, diesel generators or natural gas-based generators are widely used to act as a voltage-frequency master. But many utilities are aiming to replace these assets with GFM inverters supported by photovoltaics (PV), batteries, or fuel cells. Because these GFM assets need a long-term reliable energy source, fuel cells are a reasonable and viable choice to support GFM requirements in microgrid use cases.

But some challenges facing the widespread deployment of GFM fuel cell inverters need to be addressed. Specifically, in this paper, we aim to focus the discussion on the interconnection and interoperability requirements of GFM fuel cell inverters. Currently, state-of-the-art fuel cell inverters follow the general interconnection and interoperability requirements of DERs. Following these interconnection and interoperability requirements can be expensive for grid operators because these requirements were built with PV and battery energy storage systems (BESS) in mind. Because fuel cells have different operational requirements, these requirements need to be appropriately modified for grid operators to use them. Lack of specific standards for fuel cell-supported GFM inverters can lead to increased costs incurred by grid operators. These additional steps can also increase the operational costs of these assets. In our paper, first, we present a background on fuel cells and their unique requirements of operations. This is followed by a quick discussion on GFL and GFM inverter controls. And, finally, we present the interconnection and interoperability standards available for use with fuel cell inverters and the necessary updates that might need to be made for interfacing fuel cells.

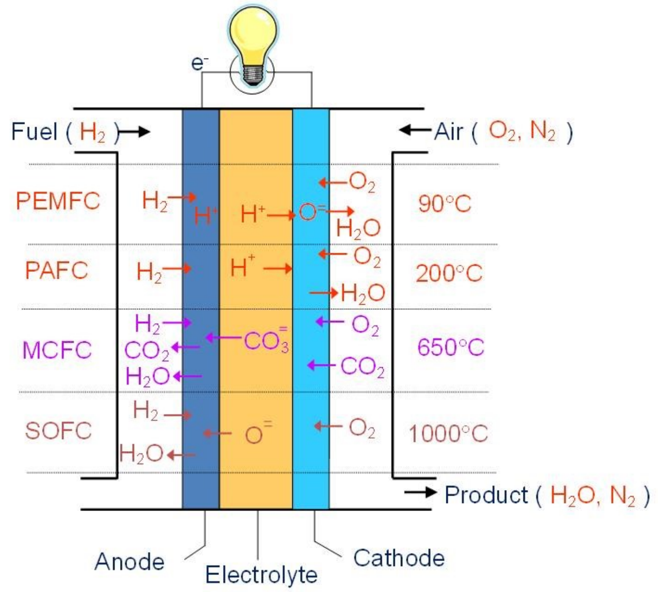

Fig. 2. Schematic showing the general fuel cell electrochemical configuration: four types of commercially available fuel cells, a summary of the fundamental electrochemical reactions, and typical fuel cell operating temperature. Fuel cells include the low-temperature PEMFC, typically used in mobile or backup power applications, and three intermediate and high-temperature fuel cells, typically used for stationary generation in electricity only and CHP applications

II. FUEL CELL STORAGE

Fuel cells are electrochemical devices that directly convert fuel energy into electricity. The general operating principle is depicted in Fig. 2 [3]. Fuel (depicted as hydrogen) is separated from an oxidant (depicted as air) by an electrolyte layer. The electrolyte is permeable to select ions that are formed by adding or removing electrons to select fuel or oxidant chemical species passing through the fuel cell. The ion is driven through the electrolyte by an electromotive force that also drives electrons through an external circuit, providing direct current electricity. Fig. 1 depicts four fuel cell types that are commercially available today, along with the chemical species that are critical to fuel cell operation. These fuel cells are combined with fuel and oxidant processing and preparation systems and with power electronics to convert the fuel cell DC output to AC, forming a fuel cell system.

This energy conversion process has three distinct advantages over combustion-based systems: 1) Fuel cells are governed by the Nernst potential, not the Carnot efficiency, meaning that a fuel cell can typically achieve much higher fuel-to-electricity conversion efficiencies ($>50\%$) than a combustion-based engine [4]. 2) Fuel cell efficiencies achieved at the megawatt scale are maintained at the watt scale. And 3) by avoiding combustion processes, fuel cells produce little to no criteria pollutant emissions [5], enabling safe operation in and around population centers.

Stationary fuel cell systems are most commonly used in DER applications [6] for backup, load-following, and baseload power. In load-following and baseload power instances, the proximity of a fuel cell system allows for combined heat and power (CHP) operation through integration with a building domestic water, space, or process heating system, potentially boosting system efficiency to greater than 80% [5]. These fuel cells have historically been powered using conventional natural gas that is reformed on-site into hydrogen [4]; however, increasing interest in hydrogen as a renewable energy carrier [7], [8] has led to industry efforts to develop pure hydrogen fuel cell systems. Prior work has shown fuel cells as being a critical component in reducing emissions in a distribution system [9], suggesting that the hydrogen fuel cell will be a fundamental component in distributed applications that require firm power.

III. FUEL CELL CHARACTERISTICS

Two defining fuel cell characteristics are the electrolyte and cell operating temperature. These are depicted in Fig. 2 by showing the chemical species necessary for fuel cell operation and the typical operating temperatures. The four fuel cells are the proton exchange membrane fuel cell (PEMFC), the phosphoric acid fuel cell (PAFC), the molten carbonate fuel cell (MCFC), and the solid oxide fuel cell (SOFC). Note that sulfur and sulfur-containing compounds have been observed to damage these four fuel cell types and should be removed from any fuel inlet stream. PEMFCs use a polymer electrolyte and are characterized by relatively low operating temperature, high power density, and fast dynamic response. This type of fuel cell is most commonly used in mobile applications, but it is also used to provide backup generation for communication networks and other remote critical loads. An experimental example of a PEMFC providing emergency backup power in a data center application is shown in Fig. 3, which was originally presented in [10]. Fig. 3 shows the dynamic response of a 10-kW PEMFC integrated with a small battery pack when faced with a step increase in electrical demand that requires the PEMFC to change from 0% to 100% output at 10 seconds.

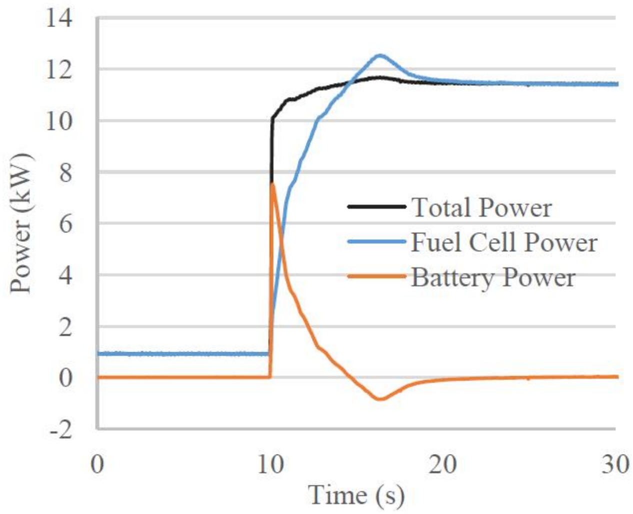

Fig. 3. Experimental results from a PEMFC/battery hybrid system responding to a step increase in electrical demand from 0 kW to 9 kW at 10 seconds. This experiment simulates a step increase in PEMFC electrical load during a power outage, demonstrating a fast response time that is complimented by integration with a battery system.

Two critical limitations for the PEMFC are input fuel requirements and fuel cell stack lifetime. PEMFCs require nearly pure hydrogen as a fuel input. On-site reformation of natural gas to hydrogen, followed by hydrogen purification is possible but reduces system efficiency to 30% or less because of reformation heat input requirements. Reformation byproducts, particularly carbon monoxide, that are not removed from the fuel stream will poison the fuel cell, reducing fuel cell capacity. PEMFCs also have a relatively short life span of less than 10,000 operational hours [11]. Because of these limitations, PEMFCs are most commonly used in applications where pure hydrogen can be stored on-site or on-vehicle or where dynamic response requirements override efficiency goals and when intermittent operation is expected. PEMFCs are available with capacities from less than 1 kW to more than 100 kW.

PAFCs use liquid phosphoric acid as the electrolyte. PAFC systems also require pure hydrogen, but they are more fuel tolerant than PEMFCs. The expected operational life span for a PAFC regularly approaches 40,000 hours [5]. Commercially available systems are typically used for stationary generation, with PAFC modules being offered in the range from 100 kW to 400 kW. PAFC systems can operate dynamically [12] but have slower response characteristics than PEMFCs; however, PAFCs are typically used to provide load-following or baseload power, and they are less likely to be required to perform a cold-start in response to an adverse electrical event.

MCFCs uses a molten carbonate salt suspended in a ceramic matrix as the electrolyte. These systems reach fuel-to-electrical conversion efficiencies for the fuel cell system of 40% to 50%. The high operating temperature enables better thermal integration with natural gas-reforming processes, preserving system efficiency when using natural gas. Additionally, MCFC systems are more tolerant to non-hydrogen fuel species, such as carbon monoxide. MCFCs are available in the megawatt range and are used almost exclusively as baseload generation.

SOFCs use a solid metal oxide electrolyte that becomes ionically conductive at high temperatures. SOFCs have many of the same benefits of MCFCs, including fuel flexibility and excellent thermal integration with fuel processing systems. SOFCs, however, regularly achieve fuel-to-electrical conversion efficiencies exceeding 50% while achieving operational life spans of 10 years or more. SOFC systems are capable of dynamic operation, as shown in Fig. 4 [13]. Fig. 4 shows the dynamic response of a 2.5-kW SOFC system to a dynamic load, showing the potential for the system to respond quickly to step changes in load.

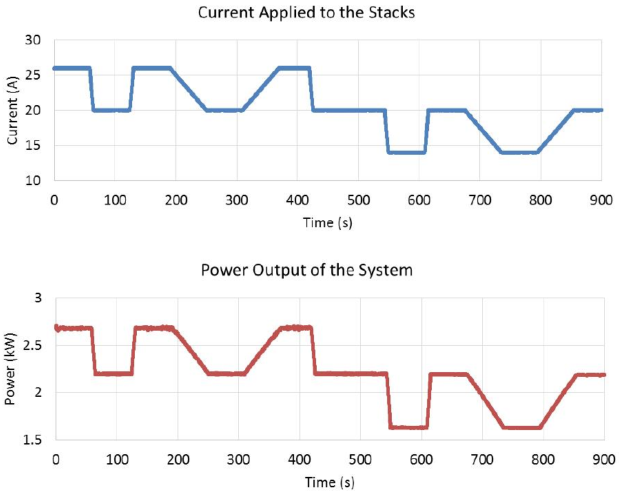

Fig. 4. Experimental results showing a 2.5-kW SOFC system dynamically responding to a dynamic load. Experimental results were developed during the evaluation of the SOFC for data center operation.

Despite the results shown in Fig. 4, SOFC systems are typically operated as a baseload generator. This is partly because fuel cell manufacturers deploy SOFCs under power purchase agreements, but it is also a result of concerns over system thermal cycling and accelerated fuel cell degradation. Additional technology development is necessary to guarantee appropriate SOFC life span under dynamic operating conditions and/or limited dynamic operation to adverse events that reduce access to other electrical sources. Further system development is required to ensure minimal system degredation due to dynamic operation. These systems must be modified to ensure desired operation under pure hydrogen inlet conditions. SOFC system capacities range from the single to hundreds of kilowatts.

In modern fuel cell applications, fuel supply is provided through existing gas infrastructure or through a dedicated fuel storage and supply system (e.g., stored hydrogen for a backup

TABLE I. OVERVIEW OF FUEL CELL AND ELECTROLYZER CHARACTERISTICS. FUEL CELL SYSTEM EFFICIENCY IS FUEL-TO-ELECTRICITY CONVERSION EFFICIENCY. ELECTROLYZER SYSTEM EFFICIENCY IS ELECTRICITY-TO-HYDROGEN CONVERSION EFFICIENCY.

System Type	**Electrolyte Type**	**Operational Temperature (oC)**	**System Efficiency (% LHV)**
PEMFC	Polymer	65–85	30% with natural gas, >50% with hydrogen
PAFC	Liquid phosphoric acid	150–200	35%–45%
MCFC	Lithium, sodium, and/or potassium carbonates	650	40%–50%
SOFC	Yittria stabilized zirconia	700–1000	>50%
Low-temperature electrolyzer	Alkaline acid or polymer	80	60%
High-temperature electrolyzer	Yittria stabilized zirconia	>700	>60%

PEMFC, or syngas or biogas). In applications where firm, low-carbon power is required, a fuel cell system powered using renewable hydrogen could meet all requirements at lower cost than intermittent renewables paired with electric batteries; however, establishing a clean and reliable supply of hydrogen is essential to meeting operational requirements. One emerging paradigm suitable for meeting these needs is the power-to-gas concept [14], where excess or low-cost renewable electricity is used to create hydrogen in an electrolyzer. The operating principle of an electrolyzer is essentially the same as a fuel cell but in reverse. Instead of fuel input, electricity and water are fed to the system, which splits a water molecule into hydrogen and oxygen. Because the process involves the transfer of an ion across the electrolyzer, the two gas species are separated, and the hydrogen can be captured and stored for later use, such as reconversion to electricity in a fuel cell.

Ideally, any fuel cell system could be operated in reverse to produce hydrogen; however, aside from SOFC systems, lower-temperature fuel cell systems are poor candidates for reverse electrolysis operation because of mismatched catalysts to support water splitting and ion transfer [15]. In this application, a separate low-temperature electrolyzer designed for water splitting can be adopted to support hydrogen production. SOFC systems, however, operate at sufficiently high temperatures to overcome barriers to reverse operation [16], efficiently generating hydrogen. This form of reversible SOFC operation has been experimentally demonstrated [17], providing a proof of concept of a single system operating as both a fuel cell and an electrolyzer. In both the high- and low-temperature fuel cell and electrolyzer scenarios, the power-to-gas concept can aid in system integration with intermittent renewables while firming electricity service during adverse events. Critically, this system must be integrated with a zero- or low-carbon source of electricity, such as on-site renewables, to ensure zero- or low-carbon hydrogen production. Table I presents a summary of the fuel cell technology and electrolyzer technology available for use.

IV. USE OF FUEL CELL INVERTERS IN MICROGRID OPERATION

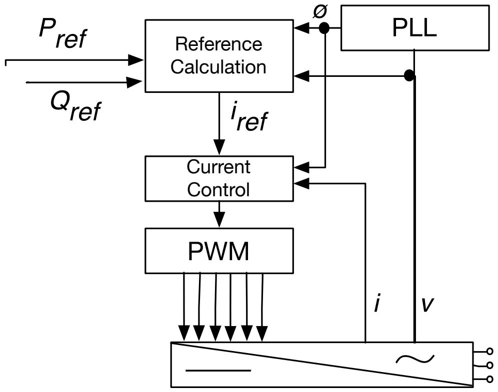

Fig. 5. Controls used in GFL inverter.

Microgrids allow parts of distribution systems to connect to and disconnect from the main grid due to either planned or unplanned islanding cases. Microgrids achieve this primarily by the use of a reliable GFM asset. Rotating machine-based assets usually form the grid during islanded mode of operation. And inverter-based DERs followed active and reactive power (PQ) set points from a microgrid controller. Fig. 5 presents the typical controls used in GFL inverters. GFL inverter controls convert PQ set points to a current reference point, and these current reference points are used to generate pulse-width modulation (PWM) signals for the inverter [18]. Recently, inverters interfacing storage systems were used to maintain voltage and frequency. BESS have been successfully integrated in the field with GFM inverters. One such droop-based GFM controls is shown in Fig. 6 [2]. But using BESS GFM assets to support microgrids for long-term operation can require bulk batteries and can increase the cost of the installation. Based on this requirement, GFM inverters interfacing fuel cells can enable long-term, reliable islanded operation because they only requires larger hydrogen storage and access to hydrogen fuel.

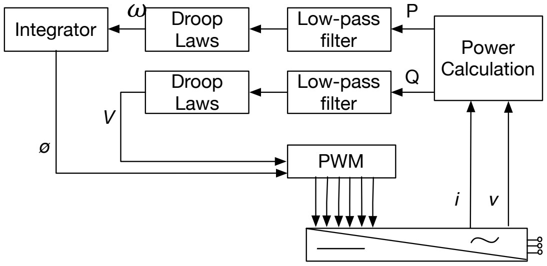

Fig. 6. Controls used in droop-based GFM inverter.

V. INTERCONNECTION STANDARDS

Interconnection standards typically dictate the requirements and procedures that should be followed by assets while connecting to the power system. Such interconnection standards establish transparent processes for stakeholders to follow during their deployment. The current state of the art in standards are IEEE 1547, Interconnection of DERs and Electricity Supply Systems by the Canadian Standards Association, and UL 1741. These interconnection standards were written primarily for PV inverters and BESS inverters and with the field experiences of these devices. Hydrogen-sourced fuel cell inverters are unique because of the unique requirements of hydrogen resources (for example, ramp rate limitation, unique black-start requirements).

Interconnection standards need to consider two key factors for GFM inverters interfacing fuel cells:

1) Ramp rate: Fig. 3 shows the ramp rate of a fuel cell set point with an auxiliary battery. In the absence of an auxiliary battery, the ramp rates of the devices can be slow for a GFM asset. Using auxiliary energy devices is a research topic of interest, and in the near future, the ramp rates can be improved to match PV or battery systems; thus, ramp rates can be critical for fuel cell GFM inverters because these can cause instability in the system.
2) Lack of bidirectionality: Novel reversible fuel cells are being developed in that lab environment that can absorb electricity to create hydrogen and convert hydrogen to electricity. But, primarily, fuel cells are unidirectional in nature, having the ability to convert hydrogen fuel to electricity and thus form the grid.

VI. INTEROPERABILITY STANDARDS

Interoperability is a critical component to enable the sensing and control of field assets at a reasonable price [19]. Interoperability standards dictate proper communications between the different intelligent electronic devices. Interoperability standards such as International Electrotechnical Commission (IEC) 61850 and Distributed Network Protocol (DNP) 3 detail the data model, information model, and proper communications among the assets. Currently, IEC 61850 7-420 covers DERs in its documentation, but it does not address the recent advancement in fuel cells. In the past, GFL inverters have been the focus of the standards. This is being changed as more GFM inverters are being integrated into the system. Similar to interconnection standards, interoperability standards need to consider a couple of key factors for fuel cell GFM inverters:

1) Hydrogen asset information: GFMs inverter can use either traditional fuel cells or reversible fuel cells. Depending on the type of fuel cell used, the data model needs to handle the critical information from the field devices to a client (microgrid controller or advanced distribution management system).
2) Supplemental power devices: In addition to the information on the hydrogen assets data model, the client communicating with the field devices might also need to know the status of the supplemental power devices used with the fuel cells.

VII. CONCLUSIONS

This paper presented background on fuel cells and fuel cell characteristics that need to be considered for use in distribution systems with microgrids as critical GFM assets. The work here also presented background on interconnection requirements and interoperability requirements presented by multiple standards for standardized installation and operation in the field. As next steps, we plan to run power-hardware-in-the-loop experiments and controller-hardware-in-the-loop experiments with a fuel cell inverter that can operate in GFL mode and GFM mode. We hope that our work presented here and our next steps will enable GFM fuel cell inverters to be a key asset in microgrids.

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