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An electrochemically assisted AC/DC microgrid configuration with waste water treatment capability

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ABSTRACT

This paper presents the design and implementation of an innovative standalone AC/DC microgrid configuration with focus on electricity water nexus. The proposed configuration includes photovoltaic (PV) generator, hybrid fuel cell system, storage system, and both DC and AC loads. One of the most important advantages of this microgrid is waste water treatment which enhances the microgrid resilience during natural/climate disasters or in remote areas. Purified water is produced by Microbial Electrolysis Cell (MEC) which also generate cheap and sustainable Hydrogen as a viable fuel for Proton Exchange Membrane Fuel Cell (PEM fuel cell) with considerable power density. A dynamic control strategy is also suggested to ensure optimal power management during microgrid stand-alone operation. To verify the proposed configuration and control strategy, the AC/DC microgrid is modeled and simulated in MATLAB/Simulink and the system power balance behavior during different scenarios is evaluated. A real-time Hardware-In-The-Loop (HIL) based experimental setup with physical power component and LabVIEW-based control system is designed and tested with the same scenarios to confirm the simulation results. By considering the natural/climate disasters in the last decades and the availability of the vast waste water supplies in Southeast Texas, which is the target area of this paper, the proposed AC/DC microgrid is a viable choice to increase the power system resilience.

1. Introduction

United States experiences lots of natural/climate disasters each year which impose a vast amount of costs to the government. The power grid is not excluded from these disasters and equipment damages as well as power outages are always among the consequences. The stand-alone operation capability of microgrid makes it a resilient option especially during natural/climate disasters when the transmission facilities fail to transmit the energy. AC/DC microgrid has the capability to be connected to a wide range of power sources and loads in both AC and DC forms and makes it more convenient for the operators to manage the power and energy. By using the renewable Distributed Energy Sources (DERs), the microgrid operation costs are further decreased and the islanding mode operation is more facilitated. In this case, the loads can be properly supplied by local DERs and the long-distance transmission lines which are more prone to failure during disasters, are no longer the restraint factors. PV, fuel cell, and storage system (batteries, supercapacitors, etc.) are among the most commonly used components of AC/DC microgrid assisting the operators in stand-alone operation mode [1–3].

Fuel cells are distinctive in terms of their applications and benefits. They can provide power as large as a utility power station and as small as a personal computer with higher efficiency and lower emission and noise than combustion-based technologies as long as the fuel is supplied. Proton Exchange Membrane (PEM) fuel cells are classified as the most promising fuel cells in terms of resilience because of their rapid response to changes in demand which results in less wear on system components and longer lifetime. PEM fuel cells typically operate at lower temperature than other fuel cells and their startup times is also shorter that makes them easier to operate [4,5]. The configuration proposed in Ref. [4] utilizes the Solid Oxide fuel cell (SOFC) which operates at noticeable higher temperature than PEM fuel cell (as high as 1000 °C) and requires remarkable thermal insulation to maintain the heat and protect personnel. PEM fuel cell needs only Hydrogen and

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considering the available biodegradable resources in Southeast Texas area for generating Hydrogen, it has been selected to be used in the proposed AC/DC microgrid.

Multiple PEM fuel cell-driven architecture and energy management systems have been reviewed in Ref. [6] where PEM fuel cell are utilized as the main power source or back up units in distributed generation microgrids due to their high power density. Fuel generation, distribution, and cost are among the main challenges of more use of PEM fuel cells. The lack of pure Hydrogen refueling infrastructure availability and improper Hydrogen storage techniques are the limiting factors of using Hydrogen-driven (PEM) fuel cells [6]. The local and continues Hydrogen generation architecture proposed in this paper facilitates the fuel generation and distribution and decreases the Hydrogen storage costs. Hybrid power sources including PEM fuel cells and supercapacitors are deployed in Refs. [7,8] to replace conventional power sources in various applications such as portable devices and distributed generation network to enhance the efficiency and dynamic behavior. However, considering fuel cell as the only main power source reduces the resiliency extremely. This paper proposes a configuration with an additional main power source i.e. PV generator to resolve this issue. The availability of supplying AC load is also not considered in Refs. [7,8] which makes them less practical than the standalone AC/DC architecture of current study. A standalone hybrid AC/DC Microgrid including PV, PEM fuel cell, and storage system (battery and supercapacitor) with a novel power management scheme is proposed in Ref. [1] to avoid voltage ripples caused by dynamic changes in microgrid load. The fuel for PEM fuel cell in this configuration is provided by a Hydrogen tank and needs to be exchanged or refilled after a while which comes with lower power capacity of the microgrid for a short time and decrease the total resiliency. The proposed configuration of this paper consists of a continuous Hydrogen generation source which prevents any interruption and makes the microgrid more resilient. A power management strategy is also developed to run the system under normal and critical circumstances. Different operating modes of a PV/PEM fuel cell-based hybrid system were proposed and verified by simulation and tests in Ref. [9] where a smooth transition between utilizing the PV at maximum power point and the fuel cell was observed. A power control interface with FPGA control technology for PEM fuel cell system has been implemented in Ref. [10] which reduced the fuel cell current ripple remarkably in addition to improving the transient response of the fuel cell system. A real time central energy management system based on mutli-period artificial bee colony for islanding mode operation of a smart hybrid microgrid is proposed in Ref. [11] to maximize the efficiency and minimize the costs. Non-conventional energy sources such as PV, wind turbine and PEM fuel cell are considered in this structure.

Microbial fuel cell (MFC) is a type of fuel cell with the capability of operating at or near room temperature and utilizing waste materials such as soils, sediments, waste water and agricultural waste streams to produce electricity. The main drawback of MFC is its very low power density which is typically in the range of $\mu W/cm^2$. However, Microbial Electrolysis Cell (MEC) which partially reverse the MFC process, can be used for producing Hydrogen or Methane from organic waste materials with higher efficiency [12].

Producing Hydrogen through the electrochemically assisted microbial process was firstly proposed by Liu et al. [13] in which certain bacterial strains such as Geobacter were used. Hydrogen is generated directly at the cathode by amplifying the electrochemical potential of oxidized organic matter in the MEC by applying a small amount of electric power. In MEC, the organic material is oxidized to CO_2 and electrons by microorganisms. The electrons are then passed on to the electrode and protons are generated in the electrolyte, accordingly. The protons react with the externally supplied electrons and produce Hydrogen [14]. Hydrogen production by using MEC has an overall Coulombic efficiency of 60-78% and unlike traditional Hydrogen generation processes it is not limited to carbohydrates and any biodegradable dissolved organic matter such as waste water can be utilized in the system [15]. A two-chamber MEC with acetate as substrate and waste water as the main fuel with 90% hydrogen recovery rate is proposed in [13]. Rozendal et al. also reported a Hydrogen restoration of 57% using a Cation Exchange Membrane (CEM) cell with the pre-acclimated inoculum, acetate as the substrate, and thrusting the electrodes against the membrane inside the MEC [16]. It is also demonstrated in Refs. [17,18] that lab-scale Hydrogen gas production from waste water with MEC has a recuperation rate of 42%-67%.

Different types of fuel cell configurations with/without membrane were investigated as MEC and their Hydrogen production capabilities have been compared in Refs. [16,19,20]. Membranes normally act as barriers between the cathode side and the anode side inside the MEC to nullify the carbon dioxide creation in the anode, thereby increasing the purity of the Hydrogen gas available to the cathode. A significant drawback of using membranes that should be taken into account is the high cost of the membrane. Higher hydrogen recuperation rate and homogeneous overall efficiency in a single chamber membrane-less reactor with an applied voltage of 0.8 V and 78% overall energy efficiency are addressed in Ref. [20]. The major downside of the single chamber MEC system might be the less purity of the hydrogen gas which can be resolved by using pure cultures in membranes [20–22].

In this study, the improvement in Hydrogen production technology through MEC is combined with the high power density of PEM fuel cell and sustainability of PV source to form an efficient and more resilient energy production. Hence, the contributions of this study are:

- Evaluating the capability of an advanced AC/DC microgrid configuration with a dynamic control strategy for stand-alone operation mode during natural/climate disasters.
- Assessment of microgrid resiliency in terms of power balance between energy sources and loads under different generation/consumptions scenarios.
- Utilizing the considerable local resources of waste water in Southeast Texas area the has been taken into as an inexpensive sustainable energy source.
- Designing a Hardware-In-The-Loop (HIL) real-time validation platform to validate the dynamic control strategy and test the AC/DC microgrid behavior.

The rest of the paper is organized as follows. Section 2 describes the microgrid configuration and provides the detailed explanation for each component. Section 3 explains the dynamic control strategy and its flowchart. The results for the simulation and implementation parts of the designed HIL platform are presented in Sections 4 and 5, respectively. Finally, Section 6 concludes the paper.

2. Microgrid Configuration

The significant penetration of DC loads such as LEDs and electric vehicles (EVs) and also renewable power sources with DC nature in microgrid makes it more important to have a flexible AC/DC microgrid with the capability of supporting different types of loads and power sources. DC microgrid is more efficient, less expensive, and easier to control than AC microgrid. It also does not have the synchronization requirement and constraints [1,2]. The proposed configuration includes