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Integration of a hybrid fuel cell-battery system to a distribution grid

Christina N. Papadimitriou*, Nicholas A. Vovos

University of Patras, Department of Electrical and Computer Engineering, Power Systems Laboratory, 26500 Rion, Greece

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ABSTRACT

In order to integrate a proton exchange membrane type (PEM) fuel cell system (FCS) combined with a battery bank to a distribution grid; this paper proposes a local controller based on fuzzy logic. The proposed system provides primary frequency control and local bus voltage support to the local grid. This opposes the passive distributed generation of the present that do not provide auxiliary services, such as back-up power, voltage support and reliability of supply as they operate under constant power factor equal to 1 at all times. During network disturbances, the distributed generations of the present are disconnected until normal operation is reestablished. When the distributed generation penetration is high this may lead to system instability. The microgrid concept is the effective solution for the control and quality improvement of grids with high level of DG penetration. So, the proposed system, also, can be an active controllable microsource of a microgrid in the future that cooperates with other microsources in order to cover the local load demands for active and reactive power either under grid-connected mode or under islanding operating mode. In cases where the distribution grid (working as microgrid) is forced to operate in islanded mode, the hybrid system provides the demanded active and reactive power. The FCS is connected to a weak distribution grid so that the system performance is studied under the worst conditions. The simulation results are obtained using MATLAB software under a severe step load change where the grid is still connected and under islanded operation. In both cases the system presents a good performance.

1. Introduction

In the next decade the penetration of distributed generation (DG) in the distribution grid is expected to play an important role in the power generation. Until now, penetration of DG in conventional systems is limited so that the systems overcome emergency situations with the usual procedure followed by the traditional Power Systems. Also, in weak distribution grids high DG penetration results in voltage rise problems, as thoroughly explained in [1], due to the distribution system operator (DSO) policy for DG to “fit and forget” requiring only operation at a fixed power factor. This policy fails to integrate the DG to the system and exploit its capability to mitigate such effects. Also, under remote fault conditions the DG is disconnected until the system recovers, due to safety concerns and the risks associated with an islanded system [2,3]. It is a strong belief, though, that DG in the form of one independent unit or in the form of a cluster of cooperating units (microgrid) can provide ancillary services such as reserves and voltage support under local disturbances and also play a significant role in islanded operation, providing the demanded active and reactive power by the critical loads. This can be achieved by the control of the DGs electronic interface to the main grid and the energy storage plants.

Efforts have been made in the past so that DG contributes in primary frequency control [4,5]. In Ref. [4], a FCS without a reformer is initially trying to supply demand power and in a second case a FCS with a reformer is combined with wind turbines that compensate the slow response of the FCS, trying to attain power equilibrium. The FCS has slow response, whether a reformer exists or not mainly because of the time delay of the system supplying air and the manifold dynamics. In Refs. [6,7], hybrid systems of fuel cell-battery have been presented and efforts have been made in order to regulate the fuel cell and the battery bank power to the dc side demand. In these cases, the hybrid systems operate in stand-alone mode without interfacing with an ac system.

In order to integrate DG to the grid, this paper proposes a fuzzy based local controller for a proton exchange membrane type (PEM) fuel cell system (FCS) combined with a battery bank providing primary frequency control and local bus voltage support. Under this operating philosophy, DG must support the grid during local distur-

Abbreviations: PEM, proton exchange membrane (fuel cell type); FCS, fuel cell system; DG, distributed generation; DSO, distribution system operator; MC, microsource controller; MGCC, microgrid central controller; DMS, distribution management systems; PCC, point of common coupling; MFs, membership functions; VSI, voltage source inverters; Fcs1–5, fuzzy controllers 1–5; IGBT, insulated gate bipolar junction transistor; PWM, pulse width modulation; PI, proportional integral; SCC, short circuit capacity.

* Corresponding author. Tel.: +30 210 6423465; fax: +30 2106423465.
E-mail addresses: chpapad@upatras.gr, chpapanetwork@gmail.com (C.N. Papadimitriou).

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bances, as central generation supports high voltage systems in the transient period. In the control scheme presented here the hybrid system power covers both the ac and dc side power demand. This is because the FCS has been designed to operate both when the distribution system is connected to the mean voltage level of the grid and when it is disconnected from the grid and operates in stand-alone mode (as a part of a microgrid in the future). The microgrid concept is the effective solution for the control of grids with high level of DG penetration. The majority of the DGs comprising a microgrid are also controllable. So, in order to achieve the full benefits from the operation of the controllable distributed generation, a hierarchical control system architecture comprising three control levels can be envisaged in a future microgrid. The microsource controller (MC) uses local information to control the voltage and the frequency of the microgrid in transient conditions. The microgrid central controller (MGCC) optimizes the microgrid operation and the distribution management systems (DMS) optimizes multiple MGCC which are interfaced in. As the proposed controller in this paper is based on local information it will comprise the first layer MC of the FCS-battery system in the future microgrid. The battery bank delivers power only in the transient period and in steady state the FCS provides the overall power needed. The control has been designed to provide the system either partially with the demanded active and reactive power in case of a load change in grid-connected mode or the whole demanded energy in case of grid disconnection. The latter happens either due to a remote fault that has taken place at the mean voltage side or because the islanding operation mode is desirable for microgrids in some cases. After the fault is cleared the controller synchronizes the FCS with the main grid and the electrical connection is restored. In order to study the worst-case scenario, it is assumed that the point of common coupling (PCC) that the hybrid system is connected to, through a line to the distribution grid has low short circuit capacity. The system configuration is similar to this of a microgrid. So, a satisfactory operation of the hybrid system reassures its successful integration into a microgrid in the future. The response of the system is simulated firstly under a severe step load change under grid connected mode and secondly when a change to islanded operation mode is caused by an upstream supply outage, using MATLAB software. It is expected that in steady state the DSO should coordinate DG to optimize operation minimizing active power losses and maintaining flat voltage profile.

In the following section, the proposed hybrid system is described and analyzed. In Section 3 the local controller and its components are analyzed thoroughly. The simulation results are obtained and analyzed in Section 4. In Section 5, a study about the active power and voltage magnitude interaction is presented and the last section concludes the paper.

2. System description and modeling

The configuration of the system is shown in Fig. 1. The hybrid system of this study is consisted of a proton exchange membrane type (PEM) fuel cell system (FCS) and a battery bank. The adopted mathematical model of the FCS is fitted to this paper requirements. The FCS includes the following four main flow systems that are responsible for four main transient phenomena:

1. Hydrogen supply system to the anode
2. Air supply system to the cathode
3. De-ionized water as a coolant
4. De-ionized water to the humidifier of the membrane.

It is assumed in our study that for the first flow system a compressed hydrogen tank is available and that the hydrogen flow in the anode is adjusted according to the air flow in the cathode through a valve. For the second flow system, the "Chopper 2" (Fig. 1) controls the supplied dc power to a dc motor that drives a compressor which controls the air flow in the cathode. Therefore the rate of change of the power at the output of the FCS is limited by the overall inertia of the compressor and the motor. In our case, the study period of the system lasts for a few seconds. So, for the third subsystem it is assumed that the temperature of the fuel cell stack remains constant (80 °C) as the thermal dynamics are very slow with a time constant of about 10^2 s. Different operation temperatures of the FC lead to different polarization curves. If a fuel cell operates at higher temperatures, the shape of the voltage/current density graphs changes. In particular, the initial fall in voltage as current is drawn from the cell is remarkably less and the graph is more linear. In addition, there may be a higher current density at which the voltage falls rapidly, as with lower-temperature cells. In order to determine the desired operation temperature the following is taken in mind: operating temperatures of over 60 °C are desirable because they reduce losses, especially when the cathode activation voltage drops. Also, it makes economic sense to operate the fuel cell at maximum possible power density, even if the extra weight, volume, cost, and complexity of the humidification system are taken into account. With larger cells, all these are proportionally less important. On the other hand, in real systems, it is very difficult to arrange proper FC humidification at temperatures above 80 °C unless the system is pressurized to about 2 bar or more or else the system will dry out. Typical operating temperature of a PEM type FC is 80 °C and this value is chosen as the initial temperature for the simulated FCS. About the fourth system, it is assumed that the membrane of the model is fully humidified as the membrane hydration has a transient phase of about 10 s [8]. It has to be mentioned, that the air flow dynamics and the humidity management define the FCS response. By assuming that the membrane is fully humidified, the designed controller for the second subsystem can be safely decoupled from the humidity. Also, the "double-layer charging effect" has been neglected taking into account that the time constant is merely 10^{-19} s [9]. The FCS is designed to be self-powered meaning that every auxiliary component of the FCS must be supplied by the FCS power particularly including the air supply system. At the output of the FCS, the "Chopper 1" is connected so that the dc voltage is boosted [10,11] and the FCS's output is regulated, without exceeding the FCS capabilities. The battery bank is connected in order to support the dc voltage, to keep its deviations into certain limits and to support FCS's performance under fast load changes as FCS dynamics are slow. The hybrid system interfaces with the ac-side system through a voltage source inverter (VSI) so that the active and reactive power can be controlled independently. An L-C filter is located at the VSI output followed by a step-up transformer. The transformer is connected to the point of common coupling (PCC) with a 2 km distribution line where a passive load and an induction motor are connected at the low voltage side of the distribution grid.

3. Fuzzy local controller

The four main flow subsystems that were briefly mentioned in the previous section and the auxiliary subsystems that are beyond the scope of this paper, establish a non linear FCS. The non linearity of the system and some key points of great significance for the system efficiency and performance are outlined below and justify the application of a fuzzy based intelligent control. Firstly, it is significant for the compressor motor controller (Chopper 2) to have a good dynamic response during fast load changes, so that the FCS voltage does not drop dramatically leading to oxygen starvation. Secondly, the "Chopper 1" controller has to act simultaneously