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Load-following mode control of a standalone renewable/fuel cell hybrid power source

Nicu Bizon *

University of Pitesti, 110040 Pitesti, 1 Targu din Vale, Arges, Romania

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A hybrid power source (HPS), fed by renewable energy sources (RESs) and fuel cell (FC) sources, with an energy storage device (ESS) to be suitable for distributed generation (DG) applications, is proposed herein. The RESs could be a combination of photovoltaic (PV) panels and wind turbines (WT) based on common DC-bus, which are used as the primary DC source. The FC operates as a backup, feeding only the insufficiency power from the RESs based on the load-following strategy. The battery/ultracapacitor hybrid ESS operates as an auxiliary source for supplying the power deficit based on dynamic power balance strategy (the transient power – mainly via the ultracapacitors stack, and the steady-state power – mainly via the FC and batteries stack). If the FC stack is designed and operates based on average load-following strategy, then the ESS will operate in charge-sustaining mode during a load cycle. This feature permits to optimize the batteries stack capacity and extend its life time as well. The ultracapacitors stack can be designed considering the peaks of RESs power on DC-bus and the imposed window for its state-of-charge (SOC). This FC/RES/ESS HPS is ideal to be used for standalone plug-in charge station (PCS) or as DG system grid connected. In the last case, which is not analyzed here, the energy management unit (EMU) that communicates with smart grid will establish the moments to match the HPS power demand with grid supply availability, stabilizing the grid. Using load and RES power profiles that have a higher dynamic than in reality, the HPS operation is shown based on an analytical analysis and the appropriate Matlab/Simulink® simulations.

1. Introduction

A FC/RES/ESS HPS for a PCSs or DG systems grid connected will use the FC and RES systems in relation with a reversible ESS in order to cope with the dynamic load profiles or grid power demands via controlled power converters [1,2]. If the HPS operates into a stand-alone system, then the FC system is used as a backup system that is fueled from a limited hydrogen tank [3] or via an electrolyzer, used as a long-term storage system [4]. The ESS can be implemented using the ultracapacitors [5], batteries [1,6], or both technologies operating in an active hybrid ESS topology [7]. The hydrogen can be produced from water by electrolysis, and until now the water is abundantly available on Earth. The hydrogen can be stored for use with the intermittent and seasonal RES technologies, being one of the most attractive options as energy carrier [8]. In the last decade there have been many proposed technical projects in the development of FC/RES HPSs, mainly based on PV panels and WTs [2,8]. Consequently, the literature in this area has been focused on sizing [2], performance [6], economics [9], and power flow management [5], with high attention paid to dynamic behavior of energy sources [10] and the appropriate control aspects [11].

The control loops, in this paper, are designed with consideration to the time constants of the energy sources. Thus, the load-following control loop is designed to feed the proton exchange membrane (PEM) FC system based on average power balancing strategy. Because the RESs have substantially different power–current characteristics, each RES will be integrated in the FC/RES HPS via a power converter. Thus, each RES will supply the common DC-bus in an energy harvesting mode if a maximum power point (MPP) tracking controller will be used. Also, the PEMFC is a nonlinear dynamic system and must be integrated in the FC/RES HPS via a power converter, which will operate the PEMFC at MPP. It is known that the energy efficiency is dependent on operating conditions [12], so the MPP depends mainly by the fueling [13], the temperature [14] and the humidity [15]. The FC power can be controlled by the fueling rates, which are considered to be the system maneuvering or energy inputs [16]. Moreover, the FC efficiency depends by the anode and cathode pressures, which can be considered to be the system dynamics' state variables [17].

Thus, it is challenging to design the control loops to operate the PEMFC system efficiently and sustainably. It is known that the fuel flow cannot follow the current steps because this will essentially

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* Tel.: +40 348 453 201/722 895624; fax: +40 348 453 200.
E-mail addresses: nicubizon@yahoo.com, nicu.bizon@upit.ro

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lead to the degradation of the stack lifetime, brought by the apparition of the fuel starvation phenomenon [18]. Therefore, if utilizing fuel cell in dynamic applications, then it is mandatory that the FC current slopes will be limited as response to the sharp load profiles [18–20]. Besides the use of constant rate limiters [18], some adaptive techniques are proposed in the literature such as the use of the wavelet transform [19] or use of the Extremum Seeking Control (ESC) [20] for analyzing the dynamic load profile to evaluate the appropriate profile of the FC current. As it is known, the air flow control is one of the most important control methods for maintaining the stability and reliability of a fuel cell system, which can avoid starvation or saturation of the oxygen [18,21]. The air flow is controlled by the fuel cell processor based on different control strategies in order to match the optimal oxygen excess ratio [22]. Nonetheless, to shown the advantages of the fuel flow control in the load following loop, this paper considers a constant air flow corresponding to nominal value of 50 lpm. In this case, the PEMFC will always have enough oxygen, operating in the region between oxygen starvation and oxygen saturation. However, if the air flow is too large, the net power will decrease due to the excessive power demanded by the air compressor. This aspect of maximize the net power based on both fuel rates will be considered in the following work, where a one input – two outputs ESC is proposed. Here a one input – one output ESC scheme is used [23].

Beside the RESs above mentioned, the PEMFCs are considered to be the most promising alternative among next DG systems due to their high energy density and clean energy [24]. On the other side, the RES technologies have recently attracted specialists' attention, being intensively investigated to solve current energy crisis [2].

Note that the PV power flow is influenced by several factors, including irradiance, temperature, shading, degradation, mismatch losses, soiling, etc [25]. Also, the uncertainty in the WT power flow is very large due to the inherent variability in wind speed [26]. So, the RES power flow fluctuates depending on weather conditions, and this issue must be solved based on power balancing strategy considering the difference power and battery voltage value [27]. Here the FC power reference is also computed based on power balancing strategy, but in a different control way. Thus, a fuzzy logic controller is used to implement the intelligent energy management strategy proposed. Note that a excellent review of main energy management strategies of PEMFC hybrid systems is shown here, too. All strategies are based on an optimal reference power signal that is calculated by minimizing a cost function. In this paper the reference power (which is the difference power that must be supplied by the PEMFC) is processed to obtain the reference fuel flow rate for the hydrogen. As it was mentioned before, there are many proposed techniques to compute the fuel flow rates. Because fuel cell is supplied with gas through pumps, valves and compressors, large time constants are involved in such signal processing blocks. Therefore, in the hybrid FC system, the PEMFC will operate in nearly steady state conditions and ultracapacitors will function during transient load demand [18] or variation of the RES power [27]. Also, in this paper it is proposed a control to regulate the DC bus voltage through the power delivered by the fast energy storage device, the ultracapacitors [18]. To better stabilize the DC bus, a small battery is used. This battery will operate in the charge sustaining mode based on the load following strategy.

It is know that fluctuating power causes frequency deviations and reduction in reliability of the smart grid when a large power flow, from several RES HPSs, is used [28]. Due to the high variability of available RES power flow, the batteries used in RES/ESS HPS can operate in the irregular cycles, under partial charge/discharge mode [25,26]. In turn, this can also have a detrimental effect on battery lifetime [29,30], so an average charge sustained mode is proposed for the batteries stack used in this FC/RES/ESS HPS architecture.

However, limited by their inherent time response, the PEMFC stack has a long start-up time and limited slope to instantaneous power demands [13]. Thus, combining FC with ESS will obtain a FC/ESS HPS architecture that makes the best use of the merged technologies [31]. In the FC/battery HPS, the FC system is controlled to satisfy load average power requirements, but the battery, on the other hand, is used to serve high pulse power requirements in short intervals. Consequently, the battery/ultracapacitor hybrid ESS topology is required to make face to a pulsed load [1]. Furthermore, the ultracapacitor stack is used to regulate the DC-bus based on a semi-active hybrid ESS topology [1].

The overall energy efficiency of the FC/RES/ESS HPS could be maximized by identifying the best degree of hybridization [32] and the appropriate energy management strategy of multiple sources and loads [33]. The challenge for the EMU design based on the load-following strategy is to enhance the performance of all technologies working together and to minimize fuel consumption while reducing system degradation.

What remains of this paper is organized as follows. The second section presents the RES/FC HPS architecture and defines the control loops used for (I) the FC power control, (II) DC-bus voltage, and (III) RES energy harvesting. Also, some design considerations are briefly shown. The third section details the used models for all blocks from the RES/FC HPS architecture. The forth section introduces the power balancing strategies and compares two of them that are based on grid-following and load-following concept. The features of the load-following strategy applied to the RES/FC HPS architecture are highlighted through the simulation, some of the obtained results being shown in next section. Finally, some conclusions are given related to the RES/FC HPS architecture under load-following strategy.

2. RES/FC HPS architecture

The purpose of this paper is to demonstrate that load-following EMU strategy is feasible and flexible, offering robust design options to control the power flow and improve the operation of the whole RES/FC HPS (see Fig. 1).

2.1. The FC control

The FC system powers the DC bus via a DC–DC power converter that boosts the FC voltage. The FC system usually operates between the maximum efficiency point and maximum power point (MPP) for both high efficiency and reliability [12]. If energy harvesting mode is selected to operate the FC system, then the boost converter is necessary to be appropriately controlled based on MPP tracking control loop. The MPP tracking controller based on advanced ESC proposed in [23] offers high performances in both search speed and tracking accuracy indicators. The MPP ESC generates the reference current, I_{ref}, by processing the FC power signal to extract the gradient signal to the MPP point [23]. The hysteretic controller is chosen as current-mode controller because it is robust and quite simple to design [23].

The PEMFC systems can operate efficiently and durable if the fueling rates are appropriately controlled [34,35]. A dynamic PEMFC model that sufficiently represents its dynamics is necessary to validate the proposed control loops [36].

The PEMFC air flow can be adjusted by robust control of a compressor [37], but it is also known that the FC power can be directly regulated by controlling the hydrogen feed [34]. The hydrogen and oxygen (or air) feeds will be adjusted to stoichiometrically match