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Design and implementation of partial feedback linearizing controller for grid-connected fuel cell systems

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ABSTRACT

This paper presents an approach to design a nonlinear controller for grid-connected fuel cell (FC) systems in order to provide ancillary services to low or medium voltage power networks. In this paper, these ancillary services mainly refer to the delivery of both active and reactive power from the FC to the grid under different operating conditions. The controller is designed based on the dynamical model of a proton exchange membrane fuel cell (PEMFC) which is developed from the electrical equivalent circuit of a grid-connected PEMFC through a voltage source converter (VSC). Partial feedback linearization technique is then employed to obtain the control laws with an aim of regulating respective currents related to both active and reactive power through the switching action of VSCs. The stability of the internal dynamics of the PEMFC system is also analyzed in this paper as the proposed control scheme cannot be implemented for unstable internal dynamics. A rate limiter is used with the proposed partial feedback linearizing controller to ensure the suitability under the worst-case conditions as well as to prevent the over-modulation in the rate of change of power references. The applicability and performance of the proposed controller is justified on a simple system as well as on a 12-bus balanced test distribution system and the CIGRE low voltage test distribution network under different grid events. The simulation results show the superiority of the proposed controller as compared to the vector controller.

1. Introduction

The integration of renewable energy sources (RESs) is increasingly being pursued in recent years to alleviate pressure on power transmission, deferring in the construction of new transmission lines, and deregulation in the electricity market. These RESs help to reduce the adverse environmental impact of the centralized fossil fuel-based power generation. The distinct advantage of fuel cell (FC) as compared to other RESs (e.g., solar photovoltaic (PV) and wind) is that it can be installed at any place without any geographical restrictions [1].

The FC, an electrochemical device, converts chemical energy of fuel into electrical energy where the byproducts of the chemical reaction are heat and water. The FC has higher efficiency and noiseless operation with lower emissions of oxides (nitrogen and sulfur) [1–3]. FCs can be classified into several types depending on the types of electrolyte used. Different types of FCs include proton exchange membrane fuel cells (PEMFCs), solid oxide fuel cells (SOFCs), molten carbonate fuel cells (MCFCs), phosphoric acid fuel cells (PAFCs), alkaline fuel cells (AFCs), zinc air fuel cells (ZAFCs), direct methanol fuel cells (DMFCs), and photonic ceramic fuel cells (PCFCs) [1,4]. Among these FCs, the application of PEMFC is rapidly increasing in distribution systems because of its high power density, high modularity, low operating temperature, small size, simple construction, zero emission, high efficiency, and low corrosion [2,4–6]. In this paper, a PEMFC system is considered for providing network support in terms of delivering active and reactive power.

The integration of distributed generators (DGs) and energy storage devices associated with the assemble of loads can be controlled locally or centrally, e.g., microgrids[7]. Microgrids can operate autonomously or in the grid-connected mode with the implementation of suitable control methods where synchronous generators are rarely used [8]. The voltage and frequency stability become critical due to the lack of inertia of RESs in distribution networks and the intermittent characteristics of RESs. Since the frequency and voltage fluctuations lead to the mismatches in active and reactive power, the PEMFC should have the capability to appropriately support active and reactive power. The PEMFC requires power electronic interfaces for the grid integration and the switching characteristics of these interfacing units are nonlinear [8,9]. The

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nonlinearity becomes severe when the power from the RESs fluctuates and the system configuration varies due to any external disturbance along with the variations in loads. In the design of linear controllers, these nonlinearities are not taken into consideration and these controllers also have the limited operating regions around the equilibrium point [8,10–12]. Thus, the controllers need to be designed based on a model which can capture the aforementioned nonlinearities while ensuring appropriate active and reactive power support [8].

A two-level control strategy is considered in [13] for a hybrid power generation system. In [13], a supervisory control scheme is implemented in the upper level for selecting power references and a sliding mode controller is used in the lower level, where the DC-DC converter is only capable of sharing active power from the sources. A two-stage power conditioning system is presented in [14] for a FC-based microgrid. The two-stage converters have some drawbacks such as large size, high cost, and relatively inefficient [15]. A proportional integral (PI) controller is employed in [16] for controlling both active and reactive power supply in a grid-interfaced FC system. A vector control scheme is proposed in [17] for PQ control in a grid-interfaced PEMFC system. The PI controller has slow convergence and poor disturbance rejection capability. Moreover, there exist steady-state errors with PI controllers if a sinusoidal reference needs to be tracked [15] and the gains need to be adjusted with changes in operating conditions [18]. In [15], a proportional regulator (PR) controller is used for a single-phase grid-connected FC system to inject active and reactive power. However, the gain of this type of controller is also required to be modified with the changes in operating conditions. A model predictive control approach is proposed in [19] for optimizing operational costs and durability of the fuel cell system in a grid-connected microgrid. The model predictive controllers encounter several drawbacks such as difficulties with operation, high maintenance cost, and lack of flexibility. In [20], a time-scale separation redesigned scheme is considered to design a robust controller for grid-connected fuel cell system. The controller in [20] cancels the uncertainties associated with the real and reactive power controller. However, the approach to prevent over modulation is not presented and also the redesigned scheme uses PI-based control approach. To alleviate these drawbacks, this paper proposes a nonlinear partial feedback linearizing control scheme for injecting active and reactive power into the three-phase grid from a PEMFC system. In order to solve the over modulation issues in partial feedback linearizing controller a proposal for selection of DC-bus voltage level and limit the rate of change in active power reference is also presented.

In this paper, a dynamical model of the grid-connected PEMFC system is developed using the electrical equivalent circuit of the PEMFC where the parameters for the equivalent circuit are estimated through the current change method. The partial feedback linearizing technique is then applied for controlling the switching sequence of the inverter. The *dq*-axes components of the grid currents are regulated to control the amount of active and reactive power injection into the grid and these regulations are performed through the derivations of control laws. The stability of the internal dynamics of the PEMFC system is ensured before implementing the controller. Since the proposed linearization scheme is independent of the operating points, it assures stable operation of the grid-connected PEMFC over a wide operating region. A criteria for the selection of DC-bus voltage level for the VSC system is presented in the paper. It is shown that if the DC-bus voltage is maintained within the specified limit, the maximum amplitude of the modulation index can always be kept within the unity value using a rate limiter under both steady-state conditions and sudden changes in load conditions. The rate limiter limits the rate of change of active power references to be followed by the partial feedback linearizing controller. The effectiveness of the proposed control approach is demonstrated through the simulation results on three different systems: a small system, a 12-bus test distribution system, and the CIGRE low voltage distribution test network.

The organization of the remaining sections are as follows. The dynamical model of PEMFC system is developed in Section 2. In Section 3, the applicability of the partial feedback linearization approach is justified while the controller design is presented in Section 4. The selection of the DC-bus voltage for the proposed controller is given in Section 5 and the controller performance is evaluated and compared with the vector controller in Section 6. Finally, concluding remarks are addressed in Section 7 along with the directions for the future research.

2. Dynamic modeling of PEMFC

An equivalent circuit model of the PEMFC is required to describe its electrical behaviors and interactions with the power electronic interfaces [1,4,21]. The current change method is adopted in this paper to select the parameters of the PEMFC equivalent circuit [4]. The V-I curve of the equivalent circuit model is given in Fig. 1 and it is assumed that the PEMFC system operates

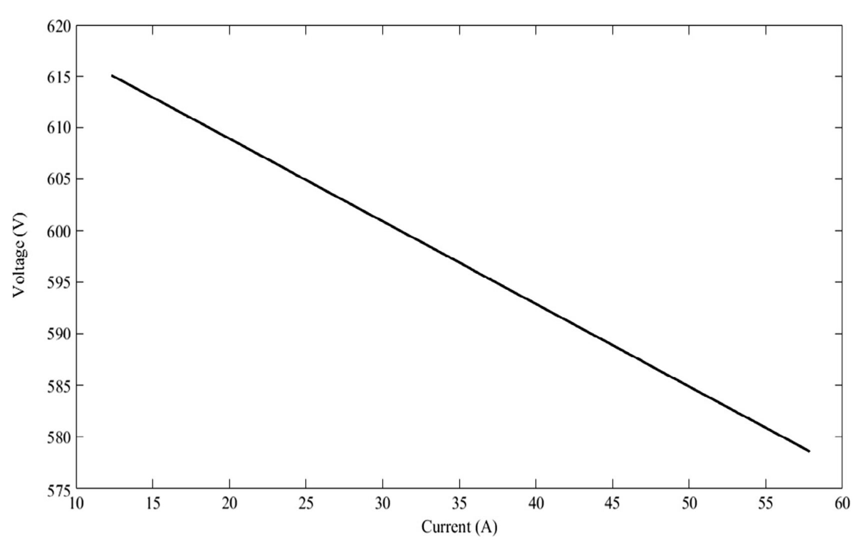

Fig. 1. V-I curve of the PEMFC equivalent circuit model.