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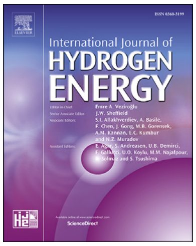

Real-time AC voltage control and power-following of a combined proton exchange membrane fuel cell, and ultracapacitor bank with nonlinear loads

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ABSTRACT

The nonlinear loads create a wide range of current harmonics in the system. Such loads can make distortions on the output voltage profile, influence on the fuel cell (FC) performance, and endanger safe operation of the FC unit. In this paper, new strategies for power-following and AC voltage control have been developed. The proposed system consists of the ultracapacitor (UC) bank and proton exchange membrane fuel cell (PEMFC) supplying nonlinear AC loads. The power tracking strategy is based on the Fourier analysis of total load demand. The Fourier analysis is used as an effective tool to eliminate destructive effect of current harmonics on the PEMFC output current. To supply the nonlinear AC loads under sinusoidal voltage with the fast response, a dynamic model for the inverter control loop is also presented. This model is used to enhance the input reference tracking and reject input/output disturbances. The simulation outcomes confirm the desirable PEMFC performance against nonlinear load disturbances. In addition, the output AC voltage is kept sinusoidal and has low deviations under nonlinear load variations.

Introduction

The FC is an energy provider device that converts the chemical energy into electricity and can be used for fixed and movable applications [1–3]. It has several benefits compared to conventional power providers like internal-combustion engines or batteries. The FC has higher efficiency than diesel engines, works silently, and produces clean energy without pollution. It has more specific energy (energy per unit weight) than batteries, and has a low maintenance cost [4–6]. Therefore, those benefits make the FC an exciting industrial area for large-scale power production [7–9]. The FC can be used for many applications such as distributed generation (DG), emergency power systems (EPS), hybrid-electric vehicles (HEV), and uninterruptible power supply (UPS) [10–14]. Therefore, it is receiving significant commercial investment as a future energy technology. There are different types of FCs that are classified based on the type of electrolyte. Each type has different characteristics that make it appropriate for specific applications. Due to the low working temperature (80–100 °C) and fast start-up, the PEMFC is suitable for residential and industrial applications [15–19].

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However, despite mentioned benefits, the FC suffers from its native limitations e.g., oxygen and hydrogen starvations [1,4,15,20,21]. Oxygen starvation happens when the partial pressure of oxygen collapses below a critical level inside meander of the airflow in the FC cathode [1,22,23]. The hydrogen starvation causes a low value of the hydrogen mole fraction in the anode [1,24]. Those phenomena are created by the transient current of the FC and can completely damage the FC stack [1].

The UC provides an enormous amount of energy, almost immediately, which cannot be supplied by other conventional techniques [25,26]. The UC system has a lot of benefits such as extremely low internal resistance, quick and deep charging and discharging, the wide range of operating temperature, low-priced, and simple structure [27–30]. Therefore, it is developed for different purposes and considered in the large range of applications.

Recently, different control strategies and topologies have been presented for integration of the UC and FC for stand-alone applications [11,25,27–31]. The UC bank can be integrated in series or parallel with the FC system [11,27,32]. In the parallel structure, both of the FC unit and UC bank are directly connected to the DC link capacitor via DC/DC converters. Then, the DC link is connected to the AC side by a DC/AC inverter. In the series arrangement, the FC power plant is connected to the UC bank via a DC/DC converter. Then, the UC bank directly connects to the AC side by DC/DC converter and DC/AC inverter. In the series structure, the FC output power flows through three converters to supply the AC load. Therefore, it has lower efficiency than the parallel form [11,27]. As well, the parallel integration has more flexibility for matching of the load dynamics [11,27,32]. In Ref. [25] decentralized load-tracking of the hybrid FC and UC bank under linear load variations is presented. The FC and UC bank are connected in parallel. Then, decentralized controllers are design for the hybrid system to enhance the system performance. In Ref. [27], a new dynamic model and design methodology for the UC bank integrated in parallel with the FC is presented. This model is used for relatively low-voltage in the stand-alone residential applications. The presented model demonstrates good performance under linear load changes. In Refs. [33–35], the direct integration of the UC bank with the FC power plant without dc/dc converter is illustrated. The presented models are used for supplying of the AC linear loads. Because of the high energy per unit of weight of the UC bank, the DC/DC converter is eliminated. The presented models are appropriate for relatively low-voltage applications with DC link voltage up to 50 (V) [27,33–35].

The suggested models are analyzed under linear load demand. The nonlinear loads directly influence on the DC and AC sides of the hybrid system. Therefore, effects of nonlinear loads on the FC performance and output AC voltage must be evaluated.

The nonlinear loads create a wide range of current harmonics. They can create nonlinear voltage drop in the system. This issue directly influences the output voltage waveform and can create the voltage distortions. As well, the harmonic currents can change the amplitude of the PEMFC output current, frequently. The FC output current represents as an input disturbance to the FC subsystems such as anode flow, cathode flow, stack voltage, and the membrane hydration models [1]. So, it can make harmful effects on those subsystems and create oxygen and hydrogen starvations. Therefore, the nonlinear loads can endanger safe operation and shorten the life of the FC stack.

In this paper, new control strategies for the power sharing and voltage control of the PEMFC/UC system under nonlinear loads are developed. A power sharing mechanism between the PEMFC and UC is performed based on the fast Fourier transform (FFT) of the total load demand. The FFT is used to eliminate destructive effects of the current harmonics on the FC output current. As well, a dynamic model for optimal control of the AC voltage is presented. The main targets of the presented model are the input reference tracking and the input/output disturbance rejection. All simulation outcomes are achieved by MATLAB/SimPowerSystems software.

This paper organized as follows: Section 2 illustrates the PEMFC dynamic model. Section 3 presents the UC bank model. In section 4, the system topology and the control strategy are presented. Simulation and results are shown in section 5. Finally, the conclusions are presented in section 6.

Dynamic model of a PEMFC

In this paper, the used PEMFC is realized in the MATLAB/Simulink software. This FC model is presented in the SimPowerSystems toolbox of MATLAB. It is modeled as a controlled voltage source as shown in Fig. 1 [1,2,27]. The PEMFC parameters used in the presented model are as follows:

B, C: PEMFC constants.
CV: Conversion factor (hydrogen per methane).
E: Nernst instantaneous voltage [V].
E_0: No load voltage [V].
F: Faraday's constant [C/kmol].
I_{FC}: FC system output current [A].
K_3: Proportional-Integral gain.
K_{H2}: Molar constant of hydrogen valve [kmol/(atm.s)].
K_{H2O}: Molar constant of water valve [kmol/(atm.s)].
K_{O2}: Molar constant of oxygen valve [kmol/(atm.s)].
K_r: Modeling constant [kmol/(s.A)].
N_0: Number of series FCs.
P_{H2}: Partial pressure of hydrogen [atm].
P_{H2O}: Partial pressure of water [atm].
P_{O2}: Partial pressure of oxygen [atm].
q_{H2}: Hydrogen molar flow [kmol/s].
q_{O2}: Input molar flow of oxygen [kmol/s].
q_{meth}: Flow rate of methane [kmol/s].
$q_{H_2}^{req}$: Required hydrogen flow to supply the output load [kmol/s];
R: Universal gas constant [(1 atm)/(kmol.K)].
R_{int}: Internal resistance of the FC [Ω].
r_{H_O}: Hydrogen/oxygen flow ratio
T: Absolute temperature [K].
U: Utilization rate.
V_{cell}: Output voltage of the FC system [V].
τ_1, τ_2: Time constants of the reformer [s].
τ_3: Time constant of the PI controller [s].
τ_{H2}: Time constant of hydrogen [s].

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