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GA-based robust LQR controller for interleaved boost DC–DC converter improving fuel cell voltage regulation

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ABSTRACT

Proton Exchange Membrane Fuel Cell (PEMFC) is one of the most promising technologies for sustainable energy production due to the high power density, low operative temperature and more convenient use for several applications. Nevertheless, the high generated current that characterizes PEMFC requires a specific power conditioning. In addition, specific controller must be designed to fit with system operative points changing associated with the variation of this high current. To deal with this challenge, in this paper, an electrochemical system composed of a Proton Exchange Membrane Fuel Cell (PEMFC) feeding via two phases IBC has been proposed and investigated. For robustness, the used IBC for fuel cell voltage regulation is controlled by linear quadratic regulator (LQR). Then, genetic algorithms technique is applied to optimize the LQR controller parameters giving optimal control coefficients and can if necessary be adjusted according to each working situation change. The model of the entire system is studied using Matlab/Simulink environment. The simulation's comparative standard and robustness results both demonstrate that the proposed GA-based LQR controller outperforms the conventional PI in terms of performance metrics (overshoot reduction: between 58.93% and 97.09%; response time reduction: between 56.40% and 77.00% and ripple reduction: between 84.00% and 94.86%).

1. Introduction

The availability of existing central power generation is not sufficient to meet the growing demand for batteries for use in new electric cars. Many private sectors invest huge money to meet out their contingent loads under power cut and also to cater peak load demand locally using conventional diesel or gas turbine generators. The use of conventional means of power sources are getting limited due to their inefficient and untidy operation. The Private sectors and Utilities are now concentrating on green power technologies with accrued benefits on account of their cleanliness, modularity, high efficiency and reliability. Among the different green power technologies (wind power, photovoltaic, micro turbine, fuel cells, . . . etc.), the fuel cell based distributed generation is considered as one of the most promising technology due to high operating efficiency (40–60%), reliability and higher potential capability [1,2]. The distributed generation in fact offers enhanced voltage support, reduced transmission, distribution losses, improved reliability and power quality. In this case, the fuel cell based can be placed anywhere in the system to upgrade system integrity, reliability and efficiency [3].

The Proton Exchange Membrane (PEM) fuel cell technology is the best candidate for residential and commercial applications due to low operating temperature, quick start up and high power density. The open circuit voltage of the single cell is in the range of 0.8–1.2 V. To get higher operating voltage and power; many cells can be stacked and connected in form of cascaded series and/or parallel connection. Normally, the fuel cell stack available in the market gives operating voltage in the range of 26 V–50 V. These stacks are now widely used in portable devices, automotive industry, residential and stationary power needs. This importance can not preclude the fact that they are unsuitable for abrupt load changes due to the slow response of their underlying electrochemical and thermodynamic processes. In this context, the use of a power conditioning

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Nomenclature

D	Duty cycle
D'_d	Complementary duty cycle
E_{cell}	One cell open circuit voltage
I_{L1}	Inductance 1 current
I_{L2}	Inductance 2 current
I_{load}	Load current
L	Inductance
P_{H_2}	Oxygen pressure
P_{O_2}	Hydrogen pressure
R_{ohm}	Internal membrane resistance
T_{FC}	Fuel cell operative temperature
t_m	Membrane thickness
$V_{act-cell}$	Voltage associated activation losses
V_c	Capacity voltage
$V_{conc-cell}$	Voltage associated with concentration losses
$V_{fc-cell}$	Fuel cell produced voltage
$V_{ohmic-cell}$	Voltage associated with ohmic losses
λ_m	Humidity level
σ_m	Membrane conductivity

Abbreviations

PEMFC	Proton Exchange Membrane Fuel Cell
IBC	Interleaved boost converter
DC	Direct current
LQR	Linear quadratic regulator
GA	Genetic algorithms

stage to adapt the energy sourced to the load demands and to extract the maximum power available becomes inevitable [4].

The DC–DC converter is the central part of the fuel cell power conditioning unit to control delivered power/voltage. Knowing that one fuel cell can deliver approximately around 1 V, the fact of putting a lot of cells on series to reach the desired voltage level is not practical due to some mechanical constraints [5,6]. Many studies choose as a conditioning unit, the DC–DC boost converter as a conditioning unit, due to its reduced components number and simplified control techniques [7]. Other works focus on multilevel converter to get high voltage/power quality with less components constraint [8]. Isolated converters are also used to provide safety for loading devices and improve system efficiency [9].

PEMFC is generally characterised by high current generation which require the use of oversized coils in the power converter to support it. In the hand, large current ripple is not desired since it affects the PEMFC membrane decreasing its operational life time [10,11]. To overcome this challenge, the interleaved boost DC–DC converter (IBC) is proposed [12–16]. With an appropriate phase number and duty cycle level, the current ripples can be practically curved into zero. In the other hand, IBC can also be used to increase the power level, reduce the inductors size and minimize the current stress on the power switches [17–22].

Several controllers are widely used for IBC topology like PI and state feedback techniques, among them: adaptive controller [23], sliding mode fuzzy PID controller [24], neural network controller [25], PSO-based fuzzy controller [26], adaptive sliding mode controller [27], etc. Both of the IBC converter and PEMFC show highly nonlinear behaviour making linear controllers not effective. With IBC controller, the system is expected to operate around a particular point (duty-cycle) to benefit from current and voltage ripples cancelling (for two-phase IBC, the optimal duty-cycle is 0.5). For this reason, the IBC model can be linearized around this functioning point making it able to be controlled via controller like linear quadratic regulator [28]. In addition, the terminal voltage of PEMFC depends highly on some parameters like hydrogen pressure in anode, air pressure in cathode, air humidity level and operating current value. Conventional controllers have simple and efficient structure but still not robust against the variation of external parameters cited above. Linear quadratic regulator LQR is a robust control technique that gives optimal control for linear systems with a given weighting matrices Q and R [29]. Nevertheless, choosing optimal weighting matrices for specific control conditions is not always easy and it is possible only after many simulation tests. Genetic algorithms method is selected to find out optimal LQR weighting matrices due to its advanced characteristics as parallelism, liability, robustness and the ability to optimize multi-objectivities problems [30].

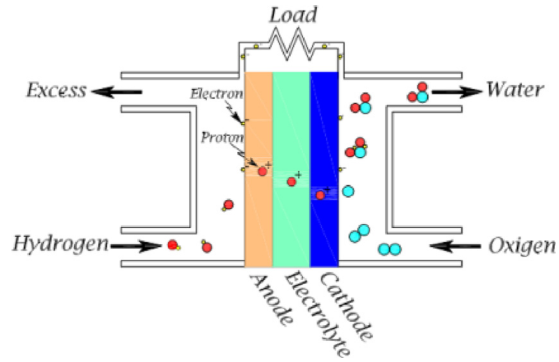

Fig. 1. Scheme of one cell's internal process.

In this paper, an electrochemical system composed of a PEMFC with two phases IBC converter has been proposed and investigated. Fuel cell voltage regulation is assured thanks to robust genetic algorithm-based linear quadratic regulator GA-LQR via an IBC converter. The model of the entire system is built and simulated using Matlab/Simulink environment to check the effectiveness of chosen power topology (current ripples) and the optimized control technique (voltage regulation).

The remainder of the paper is organized as follows. In Section 2, the fuel cell, the interleaved boost converter as well as the LQR modelling are detailed; while Section 3 presents the proposed GA-based LQR controller implementation. The simulation comparative results and discussions are presented in Section 4. Section 5 stated the main conclusions of our this work.

2. Material and methods

This section describes the modelling of the PEM fuel cell, the interleaved boost converter as well as the LQR controller used in this study.

2.1. PEM fuel cell modelling

A PEMFC consists of an electrolyte sandwich between two electrodes. The electrolyte has a special property that allows positive ions (protons) to pass through while blocking electrons. Hydrogen gas passes over one electrode, called anode, and with the help of a catalyst, it is separated into electrons and hydrogen protons [8,9], as shown in Fig. 1.

The chemical reaction that described this process is:

$$2H_2 \rightarrow 4H^+ + 4e^- \quad (1)$$

The protons pass through the electrolyte towards the cathode, and the electrons close the circuit through the electric load, performing the electric activity. In the cathode, the protons and