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Parametric analysis of the steady state and dynamic performance of proton exchange membrane fuel cell models

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ABSTRACT

Proton exchange membrane fuel cells (PEMFCs) are devices that attract the interest for a variety of applications including portable devices, transportation and stationary power. Several models are available in the literature concerning PEMFCs with different modelling approaches. In this paper, two representative dynamic models are examined, one using an electrical equivalent and one based on semi-empirical equations. Moreover, an enhanced model based on semi – empirical equations and a simplified transfer function representation for the dynamic response is proposed. All models can be easily incorporated in power system simulation software. Scope of this paper is to present a parametric analysis method in order to determine the ability of each model to represent accurately the steady – state as well as the slow and fast dynamics of a PEMFC. The influence of each specific parameter is investigated and the tuning procedure is described. Finally, simulation results are presented and the adaptability of all models is evaluated.

1. Introduction

Fuel Cells (FCs) are promising devices for electricity production due to their high efficiency, modularity and low to zero emissions, depending on the fuel type. Their application ranges from power generation and vehicle propulsion to portable electronic devices, whereas their power output varies from a few watts to several megawatts [1]. FCs can also be used as a solution to the problem of electric power storage, related to the trend of higher renewable energy penetration in power grids [2].

Several PEMFC models have been proposed in the literature with various degrees of detail, considering the FC physical, electrochemical and thermal mechanisms as well as the FC dynamic performance and response during changes in load, gas pressure and temperature. The models found in the literature can be divided into two main categories: the physical models and the electrical equivalents.

The physical models are usually based on several approaches considering the analytical or semi-empirical mathematical equations [3–14]. A common approach is to represent the steady-state losses with semi-empirical equations and the dynamic behaviour with mass and energy balance equations. The more elaborate models use two or three dimensional diffusion equations in order to represent the pressure dynamics [15,16], while the less complicated adopt a one dimensional approach concerning the mass and energy balance equations [1,4]. Generally, these models require the knowledge of certain structural and operational parameters and in most cases also experimental measurements, in order to define the modelling parameters of the semi-empirical equations.

The electrical equivalent models usually represent the same semi – empirical equations with the physical models using passive elements as well as active electrical elements [17–19]. Electrical equivalents with passive elements are also available in the literature based on Electrochemical Impedance Spectroscopy (EIS) [20] or Current Interrupt techniques [21]. These models are generally less complicated and can be easily incorporated in power system simulation tools. Information considering certain operating parameters, such as changes in the pressure and in the temperature is not generally included. However, in Refs. [22] and [23] more detailed and complex models are presented, taking into account the mass flows, temperature changes and the humidity using the corresponding electrical equivalent circuits.

In power system simulations, detailed FC models demand significantly high computational power, in order to investigate the

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performance of large number of FC units included in a power grid. To overcome the computational effort simplified models can be used presenting high accuracy, especially for the simulation of fast transients, in order to represent the interactions of the FC system with the Power Conditioning Unit (PCU) and the power system.

In this paper three simplified dynamic models, suitable for power system modelling, are analyzed and implemented in Matlab/Simulink [24]. Similar investigations conducted already in the literature are limited only for the steady-state operating condition [25–27]. The models included in this study are an electrical equivalent circuit model, proposed by Yu et al. [4], a generic physical model based on manufacturer data, proposed by Njoya et al. [5] and an enhanced model combining features from different modelling approaches. The enhanced model is based on semi-empirical equations for the steady-state losses [1,6–9] and on a transfer function to simulate the dynamic response of the overall PEMFC system [10,11,13]. In this work, the transfer function approach of the model is further improved in order to accurately simulate fast transients [10].

Scope of this paper is to investigate the performance of the models for steady −state as well as for fast and slow dynamics, covering the whole operating spectrum of PEMFCs. Therefore, a systematic parametric analysis in order to investigate the model tuning capabilities and the influence of the model parameters is presented. Furthermore, a methodology to extract the model parameters from measurements is proposed, based on parameter estimation techniques and empirical parameter tuning guidelines. The accuracy of the calculated FC dynamic responses is evaluated using experimental results carried out in a Nexa™ Power Module, 1.2 kW by Ballard Power Systems as well as with published experimental results [28,29].

2. FC models in the literature

One representative model for each main category, namely, of the electrical equivalent models and physical models, is described briefly. For both models presented, constant temperature in the FC, ideal gases, well hydrated membrane and no water management issues are assumed. Both models follow simplified approaches and are suitable for the design and wide-level studies of interactions of power converters and power systems [5,17].

2.1. Electrical equivalent circuit model

The model proposed by Yu and Yuvarajan [17] is an electrical equivalent model incorporating a diode and two transistors to describe the static conditions, whereas a capacitor and an inductor are used to model the FC system dynamics. All the above components can be easily implemented in typical power system simulation software. This model has been originally implemented in PSpice, whereas in this paper the Matlab/Simulink® software is used, due to detailed electrical element models available in the Simscape™ library. The circuit parameter estimation procedure differs from the original [17], since in this case the inductor and capacitor ohmic losses as well as the transistor resistances are also taken into account.

The corresponding circuit, shown in Fig. 1 can be used for the steady-state and the dynamic analysis of the PEMFC and includes junction diode D_S, bipolar junction transistors (BJTs) Q_1 and Q_2, capacitor C_1, inductor L_S and resistors R_1 and R_2.

The steady-state behaviour is represented by taking into account the voltage changes using a diode D_S for the activation polarization. Activation losses are expressed by the Tafel equation, which is similar to the characteristic diode equation given in (1) [1,17].

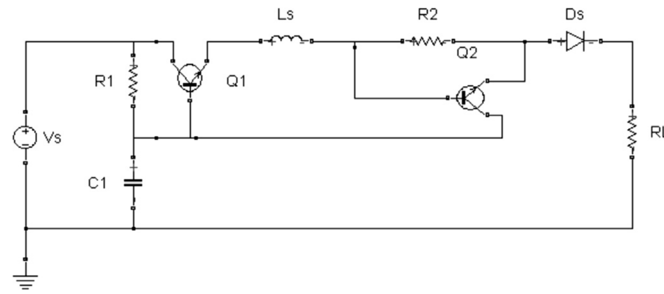

Fig. 1. Electrical equivalent circuit model implemented in Matlab/Simulink.

$$V_D = nV_T \ln\left(\frac{I_D}{I_S}\right) \quad (1)$$

where V_D is the diode voltage drop, n is the emission coefficient constant, V_T is the thermal voltage of the diode, I_D and I_S are the diode and the saturation currents, respectively.

All resistances contribute to the ohmic polarization, either as electrical elements or as block parameters. The concentration polarization is modelled using Q_1, Q_2 and R_1, R_2. The voltage output decreases with an exponential rate similar to the semi-empirical equation of the concentration polarization, shown in (2) [17]:

$$V_o = V_S - R_2 I_o - V_{BE} - R_1 I_{CS} e^{R_2 I_o / V_T} \quad (2)$$

where V_S is the circuit dc voltage input, I_o is the load current and V_T is the thermal voltage of the transistor.

Linear resistor R_1 determines the rate of voltage change in the concentration overvoltage area of the V–I characteristic. Capacitor C_1 represents the charge double layer phenomenon at the FC membrane, while the inductor L_S represents the undershoot caused by load changes.

2.2. Generic model

The model proposed by Njoya et al. [5] is included in the SimPowerSystems library of Matlab/Simulink and is suitable for the simulation of the FC steady-state and dynamic behaviour. The model is developed with the objective to be easily integrated in electrical systems simulation software using only a few data from manufacturer datasheets as inputs. It is suitable for the design and simulation of vehicular, portable and stationary power generation systems.

Physical modelling techniques are combined with electrical components, taking into account the activation and ohmic losses. The activation irreversibility is modelled by a first order transfer function, including the stack settling time, while the ohmic irreversibility by an ohmic resistance referring to the electrode and electrolyte resistance. The main feature of this model is that certain parameters can be varied such as the operating temperature, the fuel and air pressure, the fuel composition and the flow rate of the reactants. Therefore, the auxiliary units of the FC system and the respective controllers regulating the inputs can be easily implemented. Additionally, the ohmic stack resistance is assumed constant and the modelling of concentration polarization is omitted.

Another important characteristic of the model is that when the airflow rate varies, the effect of oxygen depletion can be simulated, resulting in an undershoot in the stack voltage, by specifying the FC response time, peak oxygen utilization and the corresponding voltage undershoot. The outputs of the model include various physical operating quantities apart from the electrical.