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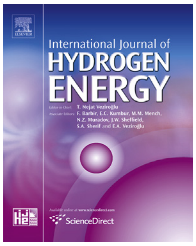

Dynamic modeling and dynamic responses of grid-connected fuel cell

Yanxia Yang, Xu Luo, Chaohua Dai*, Weirong Chen, Zhixiang Liu, Qi Li

School of Electrical Engineering, Southwest Jiaotong University, Chengdu 610031, Sichuan Province, China

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ABSTRACT

The active distribution network (ADN) is a new effective approach to facilitate connecting distributed generation (DG) to the network, where the DG is controlled to support the system stability during various kinds of disturbances. Fuel cell is one of the most important DGs, however there are still many issues left to be solved in order to meet the requirements of the ADN, such as dynamic modeling, dynamic responses to power systems, especially during voltage dip, system fault, etc. In the existing grid-connected fuel cell researches, most of the dynamic models did not consider air compressor and its parasitic power consumption. Hence, a dynamic model of grid-connected proton exchange membrane fuel cell (PEMFC) is presented by considering dynamic modeling of the air compressor and its parasitic power consumption. Based on the model, the mutual influences between power system and fuel cell are analyzed when the fuel cell is synchronously grid-connected. The dynamic responses of the fuel cell and its low voltage and fault ride-through capability are studied when the power system fault or voltage dip occurs. Finally, based on the dynamic simulation of the typical power systems with a PEMFC, the theoretical basis and guiding suggestions are presented for grid-connection, dynamic operation, and off-grid of fuel cells.

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Introduction

Due to the world energy crisis, more and more attention has been focused on energy conservation, green energy and sustainable development. To take full advantage of resources and the regulatory capacity of distributed generations (DGs), active distribution network (ADN) has become a new hot topic of research in recent years. The so-called ADN [1,2] is referred to as a novel type of smart distribution network (SDN) with flexibility of network structure to support large-scale grid-connected DGs with active control ability, which is considered as a new technology accessing to the distribution network that follows the virtual power plants and micro-grid to support large-scale DGs.

Fuel cell (FC) is referred to as one of the important DGs of the 21st century in many existing distributed generation technologies. With the current status of the increasing power shortage, the grid-connected fuel cell has gradually become a big trend. Among them, there is growing interest to use proton exchange membrane fuel cell (PEMFC) [3] as power generation devices due to its high energy conversion efficiency, low operating temperature, fast response, good stability, no pollution, low noise characteristics, and so on.

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* *Corresponding author.*
E-mail address: daichaohua@swjtu.edu.cn (C. Dai).

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Nomenclature

ADN	active distribution network
DG	distributed generation
FC	fuel cell
PEMFC	proton exchange membrane fuel cell
SDN	smart distribution network
V_{cell}	fuel cell stack voltage (V)
E_{Nerst}	Nernst instantaneous voltage (V)
V_{act}	activation overvoltage (V)
V_{ohmic}	ohmic overvoltage (V)
V_{con}	concentration overvoltage (V)
T_{fc}	temperature (K)
P_{H_2}	hydrogen partial pressures (kPa)
P_{O_2}	oxygen partial pressures (kPa)
ζ_i	constants utilized in the modeling of activation voltage
I_{st}	fuel cell stack current (A)
C_{O_2}	dissolved oxygen concentration in the interface of the cathode catalyst (mol cm^{-3})
R_{ohmic}	internal ohmic resistance (Ω)
R_M	equivalent membrane impedance (Ω)
R_c	contact resistance between the membrane and electrodes (Ω)
γ_M	resistivity of the Nafion series
A	stack area (cm^2)
λ	water content of the membrane
B	constant utilized in modeling the concentration overvoltage
J	current density (A cm^{-2})
	C equivalent capacitance (F)
J_{cp}	dynamic behavior of the compressor speed (kg m^2)
ω_{cp}	compressor speed (rad/s)
τ_{cm}	compressor motor torque (N m)
V_{cm}	compressor motor voltage (V)
τ_{cp}	required compressor torque(N m)
R_{cm}	motor constants (Ω)
k_t	motor constants (N m/A)
k_v	motor constants (V/(rad/s))
η_{cm}	motor mechanical efficiency (%)
γ	air specific heat ratio
C_p	air specific heat (J/kg k)
η_{cp}	compressor efficiency (%)
P_{sm}	pressure inside the supply manifold (kPa)
P_{atm}	atmospheric pressure (kPa)
T_{atm}	atmospheric temperature (K)
W_{cp}	air flow rate through compressor (kg/s)
R_a	air gas constant (J/kg k)
V_{sm}	supply manifold volume (m^3)
$W_{sm,out}$	supply manifold exit flow (kg/s)
P_{ca}	cathode pressure (kPa)
R	universal gas constant (J/mol K)
M_a	molar mass of air (kg/mol)
M_{O_2}	molar mass of oxygen (kg/mol)
V_{ca}	cathode volume (m^3)
$W_{ca,in}$	cathode inlet air mass flow rate (kg/s)
$W_{ca,out}$	outlet flow of the cathode (kg/s)
$W_{O_2,rct}$	cathode mass flow of oxygen consumed by the reaction(kg/s)
$W_{ca,in}$	cathode inlet air mass flow rate(kg/s)
M_v	molar mass of steam (kg/mol)
Φ_{atm}	relative humidity of the ambient environment
$P_{atm}^{(T_{atm})}$	saturation pressure at room temperature(kPa)
P_{atm}	atmospheric pressure (kPa)
$K_{sm,out}$	supply manifold flow coefficient (kg/s Pa)
$P_{sat}^{(T_{atm})}$	aaturation pressure at T temperature (kPa)
$W_{ca,out}$	outlet flow of the cathode (kg/s)
OER (λ_{O_2})	oxygen excess ratio
P_{net}	net power of the fuel cell system (W)
VSI	three-phase voltage-source inverter
PWM	pulse-width-modulation

However, there have been more studies on modeling and control of wind power and photovoltaic power generation so far [4–6], and relatively few on grid-connected fuel cell systems in power system community. The dynamic models for both PEMFC and solid oxide fuel cell were proposed in Ref. [7], where the impact of fuel utilization rate and the time-varying pressure of various reactants are considered, and according to the efficiency of applied cells and analysis on generation economy, it is suggested to control fuel utilization rate within the range from 0.7 to 0.9. A decoupling hysteretic control method of grid-connected fuel cell for active and reactive power was proposed in Ref. [8], where a 6 kW FC system model was established. In Ref. [9], a double-loop control strategy for grid-connected fuel cell was proposed and simulation studies under the conditions of three-phase short-circuit fault, voltage dip and mutational load were conducted.

In the above-mentioned references, the air compressor dynamic model and its parasitic power consumption were not considered in the grid-connected FC dynamic models. However, for the active control of reactive power and voltage in ADN, it is necessary to change the compressor speed to accommodate the fuel cell power output regulation. Because air compressor belongs to mechanical inertia equipment, its response time constant may seriously affect the dynamic response of fuel cell to electric power system and can not be ignored especially when fuel cell is connected to ADN. Meanwhile, in terms of the high-power fuel cell, especially ones of over 100 kW, the parasitic power may account for over 20% of the total power output, among which the main part is consumed by the air compressor. Hence, the fuel cell model without air compressor dynamic model and its parasitic power consumption could not truly reflect the dynamic response of fuel cell to power system.

In order to study voltage and power output characteristics of fuel cell and the mutual influence between fuel cell and distributed network, a dynamic model of grid-connected PEMFC is presented by considering the air compressor dynamic model and its parasitic power consumption in this paper. The power performance of the PEMFC is investigated along with the effect of model

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