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Effect of a SOFC plant on distribution system stability

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Abstract

When connected in small amounts, the impact of distributed generation (DG) on distribution system stability will be negligible. However, if its penetration level becomes higher, distributed generation may start to influence the dynamic behavior of the system as a whole. This paper presents a mathematical representation of a solid oxide fuel cell plant that is suitable for use in distribution system stability studies. The model is applied to a distributed utility grid that uses a solid oxide fuel cell plant as distributed resource. Examinations include transient stability and voltage stability of the system.

Keywords: Distributed generation; Power system dynamic stability; Solid oxide fuel cell (SOFC); Transient stability

1. Introduction

Distributed generation (DG) is electricity generation sited close to the load it serves, typically in the same building or complex. The DG embraces a palette of technologies in varying stages of availability, from entrenched to pilot. It is sometimes called a “disruptive” technology because of its potential to upset the utility industry’s apple cart.

Most likely, fuel cells will be a dominant DGs [1,2]. These DGs are dynamic devices and when connected to the distribution system they will affect its dynamic behavior. Hence, several researchers are working to develop dynamic models for these components [3–10].

This paper develops a generic dynamic model for a grid-connected SOFC plant. The model is defined by a small number of parameters and is suitable for planning studies.

The steady-state power generation characteristics of the plant are derived and analyzed. Understanding the transient behavior of SOFC is important for control of stationary utility generators during power system faults, surges and switchings.

Voltage regulation is one of the main problems in the distribution systems, especially at the much far-end load and in the rural areas. Voltage regulation and maintaining the voltage level are well-known problems in the radial distribution network. Several techniques have been applied by implementing many devices in the distribution network to solve these problems. The most common devices and techniques used are transformer equipped by load tap changer, supplementary line regulators installed on distribution feeders, shunt capacitor switched on distribution feeders [11] and shifting transformers towards the load center [12]. A multiple line drop compensation voltage regulation method that determines tap positions of under-load tap changer transformers is proposed in [13] to maintain the customers’ voltages within the permissible limits.

The model derived is based on the main equations. It is developed in the Laplace domain and transient simulation is done using a software developed based on the MATLAB package.

The paper is structured as follows. Section 2 presents a review of transient stability. Some basic concepts of voltage stability are introduced in Section 3. Section 4 describes the SOFC model. Section 5 briefly discusses the utility-connected inverter control. Section 6 depicts some simulation results. Finally, conclusions are presented in Section 7.

2. Transient stability

Transient stability is a term applied to alternating current (ac) electric power systems, denoting a condition in which the various synchronous machines of the system remain in synchronism, or in step each other. Conversely, instability denotes a condition involving loss of synchronism, or falling out of step [14].

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Nomenclature

Fuel cell

E_0	ideal standard potential
F	Faraday's constant
I_{fc}	fuel cell current
K_{H_2}	valve molar constant for hydrogen
K_{H_2O}	valve molar constant for water
K_{O_2}	valve molar constant for oxygen
K_r	constant, $K_r = N_0/4F$
N_0	number of cells in series in the stack
P	real power
P^*	set point for the real power
p_i	partial pressure
q_{fc}^{in}	input fuel flow
q_{fc}^{r}	fuel flow that reacts
r	ohmic loss
$r_{H\text{–}O}$	ratio of hydrogen to oxygen
R	universal gas constant
T	absolute temperature
T_e	electrical response time
T_f	fuel processor response time
U	fuel utilization
V_{fc}	fuel cell voltage
τ_{H_2}	response time for hydrogen flow
τ_{H_2O}	response time for water flow
τ_{O_2}	response time for oxygen flow

Inverter

$\boldsymbol{E}$	load bus voltage
$\boldsymbol{E}^*$	set point for the load bus voltage
L_T	inductance
Q	reactive power
Q^*	set point for the reactive power
$\boldsymbol{V}$	inverter output voltage space vector
X_T	reactance $= L_T\omega$
δ_p	angle between ψ_v and ψ_e
δ_p^*	angle reference
δ_p^*	flux vector associated with $\boldsymbol{V}$
ψ_e	flux vector associated with $\boldsymbol{E}$
ψ_v^*	flux-vector reference

Distribution network stability

$D_x f$	system Jacobian
H	inertia constant
P_e	electrical power output, in p.u.
P_i	initial load
P_L	active load at a bus
P_m	mechanical power, in p.u.
P_{nL}	load distribution factor
P_0	active power base load
$\boldsymbol{x}$	state variables
ΔP_L, ΔQ_L	changes in load demand
δ	rotor angle, in electrical radian
λ	changes in the system loading
ω_0	nominal speed, in electrical rad/s

Hence, for a simplified intuitive description of transient stability, a power system may be regarded as a set of synchronous machines and of loads interconnected through the transmission network. Under normal operating condition, all the system machines run at the synchronous speed. If a large disturbance occurs the machines start swinging with respect to each other, their motion being governed by differential equations. Depending upon the power system modeling, the number of such first-order differential equations is lower bounded by twice the number of system machines, but may be orders of magnitude larger.

DG units normally supply power to the local load centers but the excess power could also be exported to the regional power grid, adding to the capacity and stability of the grid system.

The key to interconnection is the safety of the people who have to clear faults on the line, and protecting the DG generator from feeding into a low-impedance fault. A fault will knock DG off the system, requiring it to be resynchronized with the grid. There are various means to enhance the transient stability performance of the distribution systems [15–17].

Fast valving is one of the most effective and economic means of improving the stability of a power system under large and sudden disturbances. Fast valving schemes involve rapid closing and opening of thermal turbine valves in a prescribed manner to reduce the generator acceleration following a severe fault [18].

During steady-state operation of a power system, there is equilibrium between the mechanical input power of each unit and the sum of losses and electrical power output of that unit. The problem arises when there is a sudden change in the electrical power output due to a severe and sudden disturbance. The severity is measured by drop of this power to a very low or to zero value and a consequential sudden acceleration of the machines governed by the swing equation:

$$\frac{2H}{\omega_0}\frac{d^2\delta}{dt^2} = P_m - P_e \tag{1}$$

where δ is the rotor angle, in electrical radian, P_m the mechanical power, in p.u., P_e the electrical power output, in p.u., H the inertia constant, in MW s/MVA, ω_0 the nominal speed, in electrical rad/s.

From (1), it is apparent that the decrease in the mechanical power has the same impact on the rotor angle swings as that of increase in the electrical power output. Fast valving has a function of reducing the mechanical power input to the turbine and so the generated power.

A change in load demand (ΔP_L, ΔQ_L) causes corresponding change in both bus voltage magnitude and the power output of the generator. The voltage magnitude value is calculated in the power flow analysis. The change in the generator's active power output results in system frequency variations through the swing equations.