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Sliding Mode Control of the Battery Bank for the Fuel Cell-based Distributed Generation System

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Abstract

The dynamic models for the fuel cell power and the configuration of the fuel cell distributed generation system are shown in this paper. Due to nonlinear characteristics of fuel cell model, the output voltage of fuel cell varies greatly when the load changes. A novel interface is designed to provide a constant output voltage for charging of the battery bank of the fuel cell distributed generation. The thesis presents a sliding mode control design of PEMFC distributed generation system. A cascaded control structure is chosen for ease of control realization and to exploit the motion separation property of power converters. The simulation results confirm the output current and voltage of the PEM fuel cell array converge rapidly to their reference values.

Keywords: *fuel cell, distributed generation, slidng mode*

1. Introduction

The development of renewable energy is increasing world wide because of the growing demand on energy, high oil prices, and concerns of environmental impacts. The development of nonfossil fuels energy production technologies is needed to improve the energy production efficiency and reliability and to reduce the level of pollutions [1]. The new technologies are expected to lower the investment and reduce cost. Distributed generation (DG) is an attractive technology that has been studied by several researches over the past several decades [2]. DG systems are small-scale power generation technologies used to provide an alternative to or an improvement of the traditional electric power system [3]. Distributed generation is generating plant serving a customer on-site or providing support to a distribution network, connected to the grid at distribution-level voltages. The technologies generally include engines, micro turbines, fuel cells and photovoltaic systems.

In recent years, distributed generation systems (FCDG) of the fuel cell generated a lot of interests. A fuel cell is converted to chemical energy directly into electricity energy conversion device. In several types of fuel cells, proton exchange membrane fuel cell (PEMFC) has attractive features, such as high power density, solid electrolyte, low operating temperature, quickly starting, low sensitivity direction and low corrosion [4]. Therefore, the proton exchange membrane fuel cells are a well-conceived candidate for developing distributed generation power systems.

However, from the fuel cell literatures [5, 6], According to our understanding, proton exchange membrane fuel cell has a drawback. It is a great change in output voltage when the load changes. Therefore, we must design a set of interfaces to provide a constant output voltage for FCDG. As a result, a set of power electronic devices and the controller is necessary for proper control performance FCDG. Some of the power converter to the interface and the effectiveness of the fuel cell stack with the utility. Power converters are formed with DC/DC converter and inverter. DC/DC converter achieves higher voltages and smooth DC link.

For the PEM fuel cell-based DG system, the battery bank can be organized by connecting the individual lead-acid batteries together. The terminal voltage and capacity of the battery bank are decided based on demands of the PEMFC-based DG system considered in paper.

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The paper is organized as follows. In section 2, distributed generation system is presented. Next in section 3, Sliding Mode Control of the DC/DC Boost Converter is designed. Finally in section 4, the system is simulated. The conclusions are given in section 5.

2. Distributed Generation System

2.1. Static Model of PEMFC

In PEMFC, the movement of electrons through the external circuit and of protons through the membrane for a single cell generates a voltage difference between the cell terminals. This voltage can be defined by [7]:

$$V_{FC} = E_{nernst} + V_{act} + V_{ohmic} + V_{con} \quad (1)$$

Where E_{nerst} is the thermodynamic potential of the cell and it represents its reversible voltage; V_{act} is known as activation overpotential voltage drop due to the activation of the anode and cathode; V_{ohm} is a measure of ohmic voltage drop; V_{con} represents the voltage drop resulting from the concentration or mass transportation of the reacting gases.

E_{nerst} is described by the Nernst equation. With literature values for the standard-state entropy change, the expression is [8]:

$$E_{nernst} = 1.229 - 8.5\times10^{-4}(T - 298.15) + 4.31\times10^{-5}T \times (\ln P_{H_2} + 0.5\ln P_{O_2}) \quad (2)$$

Where T is the cell operating temperature (K); P_{H_2} and P_{O_2} represent the partial pressures of hydrogen and oxygen (atm), respectively.

Activation overvoltage which is dominant at low fuel cell currents is the combination of cathode and anode activation overvoltages. It is due to sluggish electrode kinetics and described by the Tafel equation, which can be expressed as [9]:

$$V_{act} = \xi_1 + \xi_2 T + \xi_3 T \ln C_{O_2} + \xi_4 T \ln I_{FC} \quad (3)$$

Where I_{FC} is the static current passing through the cell and ξ_{1-4} represents the experimental coefficients depending on each type of cell. Oxygen concentration in the interface between the cathode and the catalyst (mol/cm^3) is given by [10]:

$$C_{O_2} = \frac{P_{O_2}}{5.08\times10^6 \times e^{\frac{-498}{T}}} \quad (4)$$

V_{ohm} represents the voltage drop due to resistance to the transfer of electrons through the electrodes and to the transfer of protons through the membrane. The expression of the voltage drop due to ohmic losses can be given:

$$V_{ohmic} = -I_{FC} R_m \quad (5)$$

The ohmic resistance R_m is given by:

$$R_m = \frac{\rho_m l_m}{A} \quad (6)$$

Where ρ_m is membrane resistivity (Ω.cm) to proton conductivity; lm is membrane thickness (cm); A cell active area (cm^2). Membrane resistivity depends strongly on membrane humidity and temperature.

V_{con} represents the voltage drop resulting from the concentration or mass transportation of the reacting gases. The equation for concentration overvoltage is shown by:

$$V_{con} = B(1 - \frac{I_{FC}}{I_{L\max} A}) \tag{7}$$

Where I_{Lmax} is the limiting current. It denotes the maximum rate at which a reactant can be supplied to an electrode.

The output voltage of the fuel cell stack is $V_{stack} = NV_{FC}$, where N is the number of single cells in stack.

2.2. PEMFC-based DG System

In this section, Figure 1 illustrates a topology of the DG system where the output voltages from fuel cells are not directly fed to the DC/AC inverter but instead are used to charge the battery bank. The charged battery bank then provides the required DC bus voltage to the DC/AC inverter [11]. It is important for the fuel cell-based DG system supplying to the residential and industrial loads to meet the objectives of the work required characteristics.

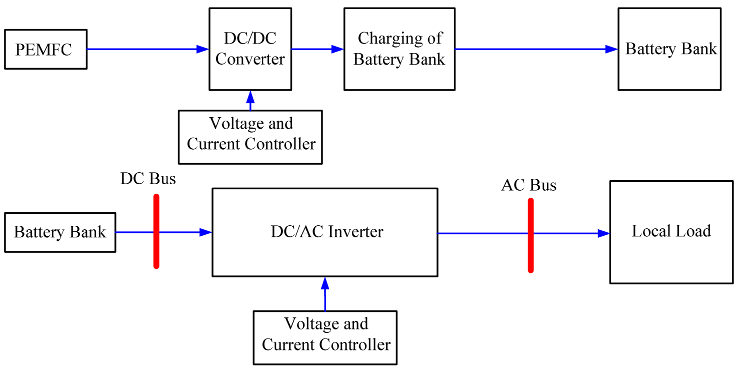

Figure 1. PEMFC DG System

The system should provide constant voltage to single-phase and three-phase loads up to the rated conditions. The DC/DC boost converter, the power storage element, such as lead-acid battery, and the DC/AC single-phase and three-phase inverters are essential elements of the PEM fuel cell-based DG system. The boost converter boosts this voltage to charge the lead-acid battery bank. The desired DC bus voltage needed for proper operation of a single-phase or three-phase inverter is provided from the battery bank.

3. Sliding Mode Control of the DC/DC Boost Converter

3.1. Cascaded Control Structure

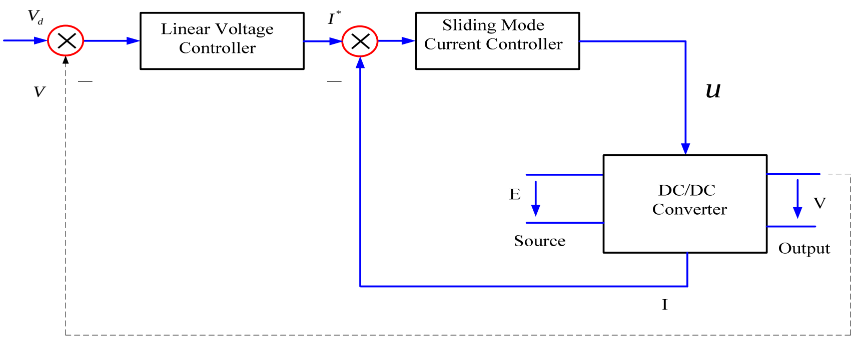

Figure 2. Cascaded Control Structure of DC/DC Converters

Provide for boost converters, the input inductor current and the output capacitor voltage are usually choosed as the state variables. For most converters used in practice, the motion rate of the current is much faster than the motion rate of the output voltage. As can be seen in Figure 2, The control problem can be obtained by using two structure from the cascade control loop: an inner current control loop and an outer voltage control loop. The latter is usually achieved with standard linear control techniques, nevertheless, the current control is carried out using Pulse Width Modulation (PWM) control.

Therefore, we use the sliding mode approach for the control of inductor current. Figure 3 is the general structure of control system for DC/DC converters. The block diagram of the proposed sliding mode control design is shown in Figure 3. Command current compares with the actual current into sliding mode controller. Output voltage of DC/DC is controlled by duty cycle.

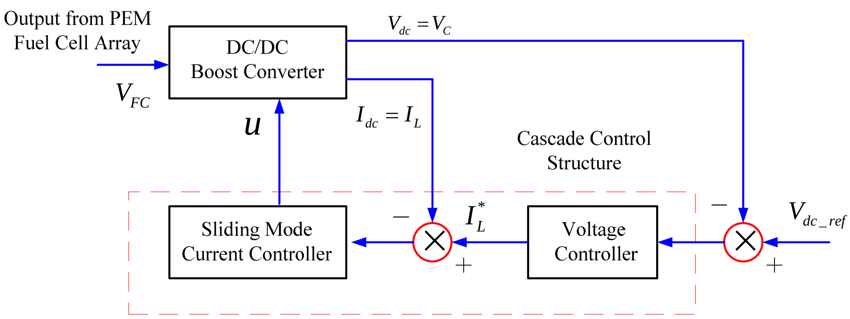

Figure 3. Block Diagram of the Sliding Mode Control Design for the DC/DC Boost Converter

To charge the battery bank, the output voltage of the PEM fuel cell array is stepped up using the DC/DC boost converter. Typical value that it is the output voltage of the PEM fuel cell array is between 50-70V. The voltage is increased to V_{bat}=450V, which is required by the DC bus voltage of the battery.

The DC/DC boost converter topology can be as shown in Figure 4, The inductor current and the capacitor voltage is selected as the state variables of the model. The input V_{FC} is the output of the proton exchange membrane fuel cell array, and *u* is the duty cycle of PWM control.

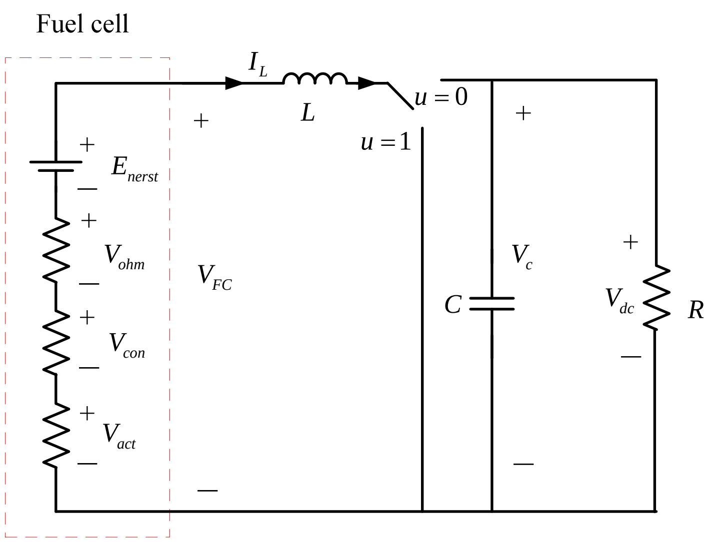

Figure 4. DC/DC Boost Converter

3.2. Sliding Mode Algorithm

The dynamic model of the boost converter based on the state space averaging technique can be rewritten as [12, 13]:

$$\dot{I}_L = -(1-u)\frac{1}{L}V_c + \frac{V_{FC}}{L} \quad (8)$$

$$\dot{V}_C = (1-u)\frac{1}{C}I_L + \frac{1}{R_L C}V_c \quad (9)$$

The control law is executed to regulate the output voltage of the DC/DC boost converter at $V_{dc\text{-}ref}$=450V. The block diagram of the proposed sliding mode control design is shown in Figure 3. The aim of the control design is to achieve a constant output voltage $V_{dc\text{-}ref}$. In other words, the steady-state behavior of the boost converter should be given by:

$$V_C = V_{dc\_ref} \Rightarrow \dot{V}_C = \dot{V}_{dc\_ref} = 0 \quad (10)$$

To design the sliding mode control law, it is assumed that I_L in Equation (8) and can be handled as a control input. The control goal shown by Equation (10) is substituted into the voltage loop equation. I.e. the Equation (9), to yield the desired current as follows:

$$(1-u)\frac{1}{C}I^*_L = \frac{1}{RC}V_C \quad (11)$$

$$\Rightarrow I^*_L = \frac{V_{dc\_ref}}{(1-u)R} \quad (12)$$

To ensure that the actual current I_L exactly tracks the desired current I_L^*, the sliding surface is chosen as:

$$S = I_L - I^*_L \quad (13)$$

To enforce sliding mode in the manifold s = 0 , the control u can be defined as:

$$u = \frac{1}{2}\left[1 - sign(s)\right] \quad (14)$$

The equivalent control of u is derived by solving $\dot{s} = 0$

$$\dot{s} = \dot{I}_L = 0 \quad (15)$$

$$(1-u_{eq})\frac{1}{L}V_C = \frac{V_{FC}}{L} \quad (16)$$

$$\Rightarrow (1-u_{eq}) = \frac{V_{FC}}{V_C} \quad (17)$$

$$\Rightarrow u_{eq} = 1 - \frac{V_{FC}}{V_C} \quad (18)$$

Substituting Equation (18) into Equation (11), we get the desired current as:

$$I^*_L = \frac{V_{dc\_ref}}{R \cdot V_{FC}} \tag{19}$$

V_C is the output voltage of the slow voltage loop. The motion equation of the out voltage is obtained by substituting the equivalent control and desired current into the Equation (16).

$$\begin{aligned} \dot{V}_C &= \left[1-\left(1-\frac{V_{FC}}{V_C}\right)\right] \cdot \frac{1}{C} \cdot (I_L) - \frac{1}{RC} V_C \\ &= \frac{V_{FC}}{V_C} \cdot \frac{1}{C} \cdot (I_L) - \frac{1}{RC} V_C \\ &= -\frac{1}{RC}\left(V_C - \frac{V^2{}_{dc\_ref}}{V_C}\right) \end{aligned} \tag{20}$$

As long as the output voltage of the DC/DC boost converter is higher than the input voltage converter, a sliding mode control law can be performed. This is an imperative requirements to ensure convergence to s=0. In the PEM fuel cell based DG system, required DC bus voltage (450V) is always higher than the output voltage of the PEM fuel cell, the sliding mode control law can always be enforced.

4. Simulation Results

The proposed control algorithm is fed to the DC/Dc boost converter and the system is simulated in Matlab/Simulink. Figure 5, Figure 6 and Figure 7 show the implementation of the sliding mode control for DC/DC converter. In the simulation, the converter parameters are selected as C=250μF, R=60Ω, and L=15mH. The desired output voltage is V_{out}=450V. Figure 5 demonstrates sliding surface stabilized at S=0 quickly. As can be seen from Figure 6 and Figure 7, the output current and voltage of the PEM fuel cell array converge rapidly to their reference values.

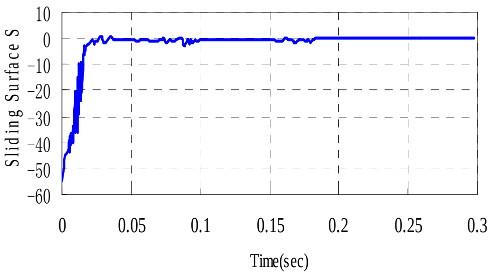

Figure 5. Sliding Surface $S = I_L - I^*_L = 0$

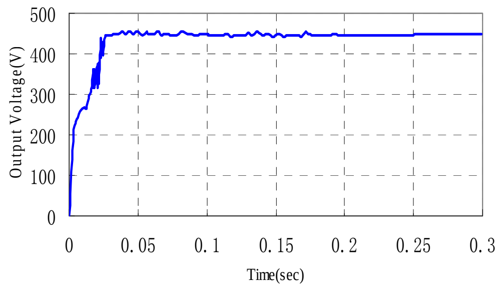

Figure 6. Voltage Response of Sliding-mode-Controlled Boost Converter

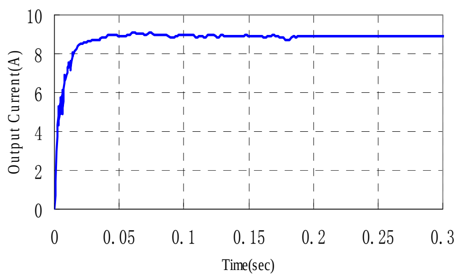

Figure 7. Current Response of Sliding-mode-controlled Boost Converter

5. Conclusion

Using models of the PEM fuel cell array and DC/DC boost converter, the sliding mode control law is designed for boost converter to control its output voltage which it charges the battery bank of the fuel cell distributed generation. This novel interface plan greatly enhances the fuel cell DG capability of serving any kind of AC loads not only single-phase loads, unbalanced loads but also balanced loads.

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