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Control of hybrid fuel cell/energy storage distributed generation system against voltage sag

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Fuel cell (FC) and energy storage (ES) based hybrid distributed power generation systems appear to be very promising for satisfying high energy and high power requirements of power quality problems in distributed generation (DG) systems. In this study, design of control strategy for hybrid fuel cell/energy storage distributed power generation system during voltage sag has been presented. The proposed control strategy allows hybrid distributed generation system works properly when a voltage disturbance occurs in distribution system and hybrid system stays connected to the main grid. Hence, modeling, controller design, and simulation study of a hybrid distributed generation system are investigated. The physical model of the fuel cell stack, energy storage and the models of power conditioning units are described. Then the control design methodology for each component of the hybrid system is proposed. Simulation results are given to show the overall system performance including active power control and voltage sag ride-through capability of the hybrid distributed generation system.

1. Introduction

The growing interest in environmental issues, combined with the progress of technologies to couple renewable energy sources to the grid and the liberalization of the energy market have led to a growing share of grid connected distributed generation (DG) [1]. Several technologies are being used in distributed generation applications with variable degree of success. Among those are: wind turbines, small-scale hydropower plants, biomass, micro-turbines, photovoltaic arrays, and fuel cells. A fuel cell is a device that directly converts the chemical energy of fuel to electric energy. Recent advances in the fuel cell technology significantly improved the technical and economical characteristics of this technology [2]. Environmental friendliness, practically noise free operation, and very high efficiency combined with the forecasted shift to gaseous fuels make fuel cells a very sound competitor on the future electricity markets. Fuel cell power generation has been developed in electric power and electric industry fields. Combining fuel cells with energy storages like batteries and supercapacitors makes hybrid distributed generation systems (HDGS) could operate properly under transient conditions in demand power [3]. Hybrid fuel cell/energy storage distributed generation systems can be strategically placed at any site in a power system (normally at the distribution level) for grid reinforcement, thereby deferring or eliminating the need for system upgrades and improving system integrity, reliability, and efficiency. A full-bridge inverter is practically always used for interfacing this green hybrid power source to the utility grid. So the important operation and performance requirements are imposed on HDGS when connected to a utility grid [4]. To support the grid in case of disturbances it will become necessary to keep the distributed generator units connected to the grid. In the wide range of power quality disturbances, the interest focuses on voltage sags, which can severely affect the performance of the voltage source converter (VSC). A voltage sag is a drop in voltage with duration between one half cycle and one minute [5], which is in most cases caused by a short-circuit fault.

In the networks with a large DG penetration level the disconnection will cause serious problem and may result in a large power generation deficit and instability problems. So, the interaction between DG units and the grid during the voltage sag is very important and it must be considered for designing the proper control strategy. Authors have presented in [4], the fuzzy control strategy for fuel cell distributed generation systems to mitigate voltage sag and active power control in distribution systems. However, only symmetrical voltage sag has been considered and supposed that the capacity of the fuel cell distributed generation system is high and it could be used to mitigate the voltage sag like static compensators (STATCOM). In Ref. [3], the intelligent power management strategy has been proposed for hybrid fuel cell/battery energy storage distributed generation systems. The proposed hybrid system in Ref. [3] is very suitable for power management studies. But for power quality studies, there are some limitations to use the battery

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energy storage. There are some reasons that make the use of supercapacitor is better than battery for power quality problem studies [6–8]. Firstly, due to the low power density of the battery it cannot release its charge or discharge fast enough during the voltage sag. Secondly, although batteries are considered to be the main energy storage device for DG application, their cycle and calendar life should still be improved. Lastly, in most of today's DG applications, batteries are placed as an assistant power source [3] to deliver the power for long time. Hence, in this paper a novel control strategy is presented for proper operation of hybrid fuel cell/energy storage distributed generation system during voltage sag. For this purpose, a fuzzy logic control strategy is proposed to manage the power flow between the solid oxide fuel cell and supercapacitor during voltage sag. Based on the dynamic modeling of the hybrid distributed generation system, local controllers are designed to regulate the operating point of power electronic converters, energy storage and fuel cell.

2. Dynamic modeling of hybrid distributed generation system

In this paper, a grid connected HDGS is evaluated. Hybrid fuel cell distributed generation systems, like any DC generating system, need an electronic converter to interface with the AC system. In DG applications, the converter is connected in parallel with the network, in the same way a traditional generator is connected. Fig. 1 shows the block diagram of the HDGS proposed in this paper. As shown in the figure, it consists of a fuel cell, a supercapacitor, DC to DC power converters, a 3-phase DC to AC inverter and an output filter. The mathematical models describing the dynamic behaviour of each of these components are given in Refs. [3,4].

2.1. Solid oxide fuel cell model

Fuel cells are static energy conversion devices that convert the chemical energy of fuel directly into electrical energy. They show great promise to be an important DG source of the future due to their many advantages, such as high efficiency, zero or low emission (of pollutant gases), and flexible modular structure. The model of SOFC power plant used in this study is based on the dynamic SOFC stack model developed and validated in Ref. [9]. The performance of FCs is affected by several operating variables, as discussed in the following. Decreasing the current density increases the cell voltage, thereby increasing the FC efficiency. One important operating variable is the reactant utilization, U_f, referring to the fraction of the total fuel (or oxidant) introduced into a FC that reacts electrochemically:

$$U_f = \frac{q^{in}_{H_2} - q^{out}_{H_2}}{q^{in}_{H_2}} = \frac{q^{r}_{H_2}}{q^{in}_{H_2}} \tag{1}$$

Where q_{H_2} is the hydrogen molar flow.

High utilizations are considered desirable (particularly in smaller systems) because they minimize the required fuel and oxidant flow, for a minimum fuel cost and compressor load and size. However, utilizations that are pushed too high result in significant voltage drops. The SOFC consists of hundreds of cells connected in series and parallel. Fuel and air are passed through the cells. By regulating the pressure level, the amount of fuel fed into the fuel cell stacks is adjusted, and the output real power of the fuel cell system is controlled. The Nernst's equation and Ohm's law determine the average voltage magnitude of the fuel cell stack. The following equations model the voltage of the fuel cell stack:

$$V_{fc} = N_0\left(E_0 + \frac{RT}{2F}\left(\ln\left(\frac{P_{H_2}P_{O_2}^{0.5}}{P_{H_2O}}\right)\right)\right) - rI_{f0} \tag{2}$$

where:

N_0 is the number of cells connected in series;
E_0 is the voltage associated with the reaction free energy;
R is the universal gas constant;
T is the temperature;
I_{f0} is the current of the fuel cell stack;
F is the Faraday's constant.

P_{H2}, P_{H_2O}, P_{O_2} are determined by the following differential equations:

$$\begin{aligned}
\dot{P}_{H_2} &= -\frac{1}{t_{H_2}}\left(P_{H_2} + \frac{1}{K_{H_2}}\left(q^{in}_{H_2} - 2K_r I_{fc}\right)\right)\\
\dot{P}_{H_2O} &= -\frac{1}{t_{H_2O}}\left(P_{H_2O} + \frac{2}{K_{H_2O}}K_r I_{fc}\right)\\
\dot{P}_{O_2} &= -\frac{1}{t_{O_2}}\left(P_{O_2} + \frac{1}{K_{O_2}}\left(q^{in}_{O_2} - K_r I_{fc}\right)\right)
\end{aligned} \tag{3}$$

Where, $q^{in}_{H_2}$ and $q^{in}_{O_2}$ are the molar flow of hydrogen and oxygen and where the K_r constant is defined by the relation between the rate of reactant hydrogen and the fuel cell current:

$$q^{r}_{H_2} = \frac{N_0 I}{2F} = 2K_r I \tag{4}$$

2.2. Supercapacitor model

Supercapacitors store electrical energy by accumulating charge on two parallel electrodes separated by a dielectric material. The capacity represents the relationship between the electric charge stored in the capacitor and the voltage between the two electrodes of the capacitor. The classical equivalent circuit of the supercapacitor is shown in Fig. 2 [10]. The SOC is the only state variable of the energy storage system:

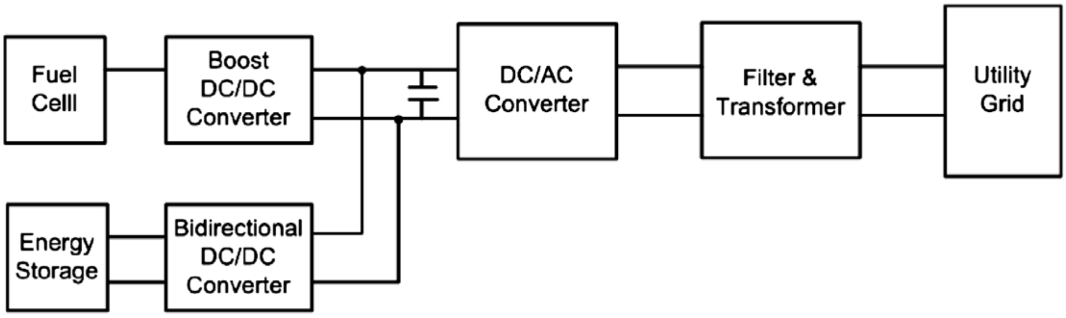

Fig. 1. Proposed structure of hybrid fuel cell/energy storage distributed generation system.