Electrical Power and Energy Systems 60 (2014) 190–202

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Sliding mode based feedback linearizing controller for grid connected multiple fuel cells scenario

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ARTICLE INFO

Article history:
Received 7 November 2012
Received in revised form 15 December 2013
Accepted 18 February 2014
Available online 28 March 2014

Keywords:
Distributed generation
Feedback linearization
Fuel cell
Master–slave control
Sliding mode control

ABSTRACT

The energy demand is growing at a fast rate around the globe. The conventional power generation technologies may not meet the environmental constraints. Hence, a Solid Oxide Fuel Cell based power generation unit is considered as distributed generating source here, in this paper. An integrated operation of two units is done with a master–slave control strategy. Voltage source converters are used to interface nonconventional energy sources with grid, in general. However, these systems are highly nonlinear and coupled systems. Hence conventional PI controller will not give satisfactory performance for changing operating conditions and uncertain load changes. Hence, feedback linearization scheme has been formulated, which uses nonlinear transformation by means of diffeomorphism mapping to convert nonlinear models into linear models. Sliding mode control technique has been incorporated in the feedback linearized control to address the issues of uncertainty and to add robustness to the control algorithm. The developed control algorithm is tested for different dispatches, load uncertainties, decoupling of control variables and finally the variable grid frequency within a small band.

1. Introduction

The role of distributed generators (DGs) in a power system is increasing at a fast rate due to the increase in energy demand and environmental constraints. Among the available varieties of DGs, fuel cell is one of the promising choices. Due to the delay involved in its hydrogen production cycle, it cannot respond to the load transients immediately. To overcome the inability to handle the transients, fuel cell needs to be augmented with some quick responding storage elements like battery/capacitor as energy buffers. Solid Oxide Fuel Cells (SOFCs) can be used with a wide range of hydrocarbon based fuels. It has a relatively higher operating temperature, by which efficient power conversion can be achieved. Both the simple-cycle and hybrid SOFC systems have demonstrated higher efficiencies among the DGs, which have combined merits of minimal air pollutant and greenhouse gas emissions. These are few among the factors which made the SOFC an attractive emerging fuel cell technology for stationary power generation in the range of few kW to few hundreds of kW [1].

The dynamic modeling of a fuel cell with integrated reformer controller has already been carried out in the literature for quite a long time. Reformer regulator controls the quantity of hydrogen that is to be converted from the hydrocarbon, based on the power to be supplied. The model of the fuel cell based on the electrochemical reactions considering optimal, maximum and minimum utilizations of hydrogen has been developed in [2], where first of all, the reference fuel cell current is derived from the power order. The current so derived is restricted within a band based on the maximum and minimum utilizations of available hydrogen and further used to decide the hydrogen reference considering its optimal utilization. The demerit of this approach is the presence of a sluggish control loop. However, in actual scenario, fuel cell hydrogen reference can be directly decided by the power reference or by the total current required by the load. The fuel cell has been modeled as a voltage source, whose magnitude is governed by the kinematics of the electrochemical reactions and pressure differences between hydrogen and oxygen gases in [3]. This approach results in fuel cell current output which is dependent on the load circuit rather than the hydrogen availability. To overcome the modeling limitation of [3], authors have addressed the issue of fuel cell current in [4], limiting it according to maximum and minimum utilizations with respect to available hydrogen. This modeling is valid with an assumption that sufficient amount of hydrogen is available for the reaction to take place even under the transients which may not be true in practical scenario, since the hydrogen has to be fed at its designed pressure for the reaction to take place. With the above assumption the overall electrical efficiency will effectively drop

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http://dx.doi.org/10.1016/j.ijepes.2014.02.007
0142-0615/

Nomenclature

q_{H_2}	hydrogen (H_2) flow rate at reformer outlet (kmol/s)	V_{fc}	net fuel cell voltage
$q_{methane}$	methane (CH_4) flow rate at reformer inlet (kmol/s)	I_{fc}	fuel cell current
τ	time constant of reformer	D_{Bfc}	duty cycle of fuel cell converter
C_v	conversion factor (kmol of H_2 to kmol of CH_4)	D_{bb}, D_{Bb}	duty cycle of battery for buck, boost operations
E	no load voltage of each fuel cell	m_a	modulation index
E^0	ideal standard potential of each fuel cell	v_m	amplitude of modulating wave
N	number of cells in a fuel cell stack	v_{cr}	amplitude of carrier wave

down due to continuous operation of compressors for maintaining the pressure of hydrogen. It also introduces kinetic sluggishness. Another limitation of the model presented in [4] is that instead of considering the overall time delay from the fuel input to the electrical output, the time delay introduced due to the filtering circuit is considered as the fuel cell response delay time. Moreover, the control of hydrogen production based on steady state load conditions is not considered in [4]. To improve the models proposed in [2–4], in this paper the fuel input to the fuel cell is regulated based on total power feeding. The dynamics of fuel cell from the fuel input to the electrical output are included. Fuel cell output current has been regulated to avoid starvation and under utilization of hydrogen.

The output of the fuel cell is dc in nature, which is to be processed by the power processing unit in order to suit the load requirement. The power processing unit can be an integrated dc/dc converter with a dc/ac converter. In general, the dc/ac converter is a voltage source converter (VSC) due to unmatched merits with other types of dc/ac converters. Because of the multivariable structure and highly coupled nonlinearity of the VSC based power systems, it is not an easy task to achieve ideal control effects with general control philosophies. Hence, nonlinear control theories based on the input–output linearization have been developed over recent years and applied to different application domains. Coming to the power system aspects, in [5], a fuel cell based DG supplying grid is considered, in which the load as well as the grid is connected on the same bus. In such a case, application of feedback linearization technique is more or less same as that of VSC based system analysis without any intermediate tapping of power. The linearization has been reported for VSC interfaced doubly fed induction machine in [6–8], for HVDC systems in [9–11], for voltage tracking in dc/dc converter in [12], for robust tracking in plug-in vehicles in [13] and for power system oscillation damping in [14–18]. When the VSC based system is connected to the load/grid with some intermittent tappings of power, one cannot apply the feedback linearization discussed in these literatures directly, since all the current and voltage equations will get transformed into complex equations depending on the number of tappings in between, starting from the VSC end to the last load/grid point. In [19] almost a similar system as that of [5] is analyzed; with photo voltaic cell as source. In both [5,19], the system is having load as well as grid at same voltage levels. In general the grid voltage is higher than that of load voltage level. Even though, these papers address some critical issues, they are silent about the coordinated multi unit operation and their integration with the loads and the grid. In [20], using the linearization technique the system dynamic response has been made independent of operating condition. However, the effect of variation and uncertainties in parameters is not considered.

The DGs capability for the load disturbances with micro turbine as the source is analysed in [21] and the voltage regulation issues with DGs are addressed in [22,23]. Even though the capacity of the DG is small, it can support the grid, if it remains connected during the disturbances. This can be achieved only through a robust control technique. The aforesaid disturbances include different power quality problems such as voltage disturbances and frequency deviations; in particular when the DG is connected to the grid through a VSC. In the recent past, voltage disturbances have been addressed in few literatures, however the frequency disturbances remain unexplored.

The system considered in this paper consists of two fuel cell based captive power plants (CPPs) synchronized with the grid to meet the demand of the grid as well as the local load, and will be controlled by the master–slave control strategy. The grid and local loads are at two different voltage levels and hence at two different buses. Master unit has a central controller for the entire DG system and decides the power that is to be injected by the (all) other DG(s). As mentioned before, the master decides the slave's injection to the grid; the concept of deregulation can easily be incorporated into the system just by modifying the control commands and there by the dispatches. Each DG unit is responsible for meeting their own local loads under any circumstances. In this paper, a nonlinear mathematical model of the VSC based CPP system(s) is established in the synchronous reference frame. Feedback linearization is used to transform the nonlinear system into a linear one. As mentioned earlier, the feedback linearization is sensitive to parameter variations, uncertainties and exogenous inputs [24]. To overcome these limitations, sliding mode control (SMC) has been incorporated in the feedback linearized controller, which can also handle the problems of discontinuous operation of the switching devices. Several computer simulations are carried out for different load sharing controls between master and slave units. The developed control algorithm has been tested for load uncertainty, decoupling of control variables and variable grid frequency conditions. The control algorithm developed is compared with conventional PI control for their performance efficacy.

In this paper, Section 2 describes the modeling of the system considered includes modeling of SOFC, Battery along with a brief discussion of dc/dc and dc/ac converters. The control algorithm has been described in Section 3. It includes the formulation and application of feedback linearization and sliding mode control to the system considered, along with the stability analysis and design criterion. Section 4 describes the principle of master–slave control strategy. Results and discussions are given in Section 5 with concluding remarks in Section 6.

2. System modeling

Each CPP unit consists of a fuel cell integrated with battery, working as a grid connected DG along with a variable local load. The schematic block diagram of system considered along with its basic control structure is shown in Fig. 1. Output of the fuel cell is dc in nature which is further processed by power processing unit in order to meet the required voltage and power levels based on the application. When a fuel cell is feeding power to the grid, it is advantageous to choose the topology of current fed dc/dc