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MODELING AND CONTROL OF A SOFC-GT HYBRID SYSTEM WITH SINGLE SHAFT CONFIGURATION

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ABSTRACT

This article focuses on issues related to control and operability of a Solid Oxide Fuel Cell (SOFC) - Gas Turbine (GT) hybrid system with single-shaft GT configuration. The models of all the components of the hybrid system are developed and integrated to constitute the hybrid system. An autonomous power grid is modeled as load. The main control objectives considered are control of Fuel Utilization (FU) in the SOFC and SOFC solid temperature during dynamic operation of the hybrid system.

INTRODUCTION

In the foreseeable future, fossil fuels including natural gas will be a major source of energy. With today's increasing concern about global warming and climate change, there is an incentive to investigate natural gas power processes that operate efficiently, thus emitting less per kWh produced, and also power production processes with CO_2 capture capabilities. It is widely accepted that fuel cells are power sources that will become increasingly important, due to high efficiency, low levels of pollution and noise, and high reliability. One of the most promising fuel cell technologies is the Solid Oxide Fuel Cell (SOFC), due to its solid state design and internal reforming of gaseous fuels, in addition to its high efficiency [1]. The SOFC converts the chemical energy of a fuel directly to electrical energy. Since SOFCs operate at high temperatures (about 1000^0 C), natural gas can be used directly as fuel. The electrical efficiency of a SOFC can reach 55%. Another significant advantage of the SOFC is that since it operates at high temperature and its efficiency increases when pressurized, and it naturally lends itself as a heat source for a gas turbine (GT) cycle. The combined (hybrid) cycle can theoretically have an overall electrical efficiency of up to 70% with a power range from a few hundred kWs to a few MWs. The main applications of the hybrid system include remote area power supply and distributed power generation.

There are several models available in literature for the SOFC-GT hybrid system [2], [3], [4], [5]. In [6], a dynamic model of grid connected SOFC model is developed. However, the SOFC-GT hybrid system with single shaft configuration is integrated in an autonomous power system. The reason for procuring an integrated model is to obtain a comprehensive understanding of the operability of the system which has close dynamic interactions between the power generation system and the local grid. Further, the hybrid system consists of tightly integrated dynamic subsystems with strict operating criteria making the control design more challenging in terms of disturbance rejection, part load operation and in particular start-up, shut down and load shedding. Suitable system actuation must be chosen, good control structures must be devised, and good controllers must be designed. As a basis for all these tasks, control relevant models must be developed for the subsystems, and for the total system. Such models should have limited complexity to allow for the necessary analysis, and at the same time should include the important dynamic interactions.

In this paper we present an integrated model of a SOFC-GT hybrid system with a power grid connecting to an electrical load. The process is described on a system level and modeling of each component is discussed briefly. The model is subsequently used to perform analysis of system dynamics and

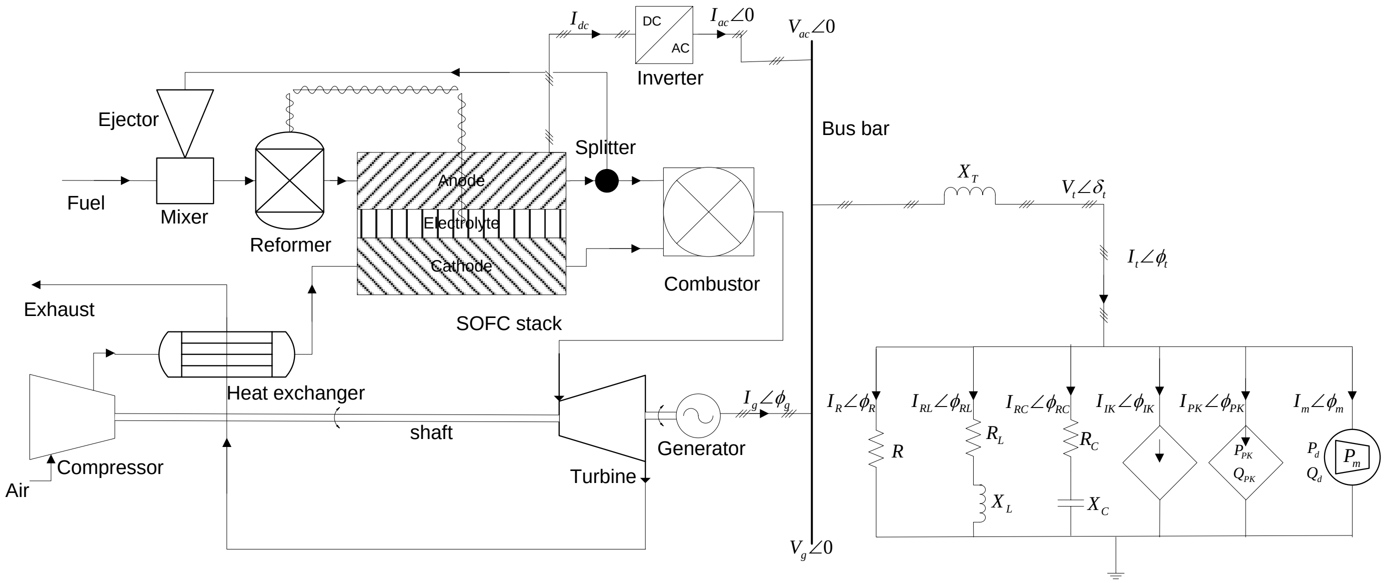

Figure 1: SOFC-GT hybrid system with single shaft configuration in an autonomous power system

optimize system design. A simple control design is proposed and assessed through a set of simulation scenarios.

PROCESS DESCRIPTION

A schematic diagram of the integrated system where the hybrid system is connected to the load by a bus bar is shown in Figure 1. Methane (fuel) is mixed with a part of anode flue gas and is partially steam reformed in pre-reformer generating hydrogen. The heat required for endothermic reformation reactions in the pre-reformer is supplied from the SOFC stack through radiation. The gas mixture from the pre-reformer is fed to the anode volume of the SOFC, where the remaining part of the methane is reformed. Compressed atmospheric air is heated in a recuperative heat exchanger and is used as an oxygen source at the cathode side of the SOFC. In the SOFC, electrochemical reactions take place and DC voltage is produced. The rate of the electrochemical reactions depends on the current. A part of the anode flue gas is recycled to supply steam to the pre-reformer. The remaining part of the anode and cathode flue gases is supplied to a combustion chamber where the unused fuel is combusted.

The hybrid system considered here uses a single shaft GT configuration. The combusted gas mixture is expanded in a gas turbine which is coupled to a compressor and an alternator through a shaft. The expanded gas mixture is used to heat up the compressed air in a heat exchanger. The DC power from the SOFC stack is fed to an inverter which converts DC to AC with a fixed frequency. The inverter and the generator are connected to a local grid, which is connected to a six branch electric load. Both the SOFC stack and the generator supply the electric load demand on the grid. The load sharing between the SOFC stack and the generator cannot be controlled when there is a load change on the grid. Typically 60-70% of the total power is supplied by the SOFC stack.

MODELING

All the models of the system are modeled in the modular modeling environment gPROMS [7]. The detailed modeling of each component of the system can be found in [8], [9]. A brief description of the each model is presented below.

SOFC stack

It is assumed that all the SOFCs in the stack operate at identical conditions. A zero-dimensional SOFC model is developed with no regard to the geometry of the cell. The model developed is a lumped one, which includes dynamic molar balances of all the species both in anode and cathode volumes separately. It includes an energy balance treating the whole SOFC as a single volume to model the temperature dynamics of the SOFC solid mean temperature. There is a radiation from the SOFC to the pre-reformer. The voltage developed across the cell is modeled using Nernst equation, the operating cell voltage is calculated by considering both ohmic and activation losses.

In [10], the low complexity SOFC model is evaluated against a detailed model developed in [5], [11]. The comparisons indicate that the low complexity model is good enough to approximate the important dynamics of the SOFC and can hence be used for operability and control studies.

Pre-reformer

The pre-reformer is modeled as a Continuously Stirred Tank Reactor (CSTR). Mass balances of all the species are included dynamically and energy balance is implemented to model the pre-reformer temperature dynamics. The steam required for the steam-reforming is provided by the recycle flow of the anode flue gas. The heat required for the endothermic reforming reaction is obtained by the radiation heat from the SOFC stack.

Combustor

In the combustor, the unused fuel is burnt in presence of oxygen coming from the cathode outlet. The operating conditions will always be such that there is surplus oxygen available for complete combustion due to the fact that air mass flow rate is much larger than the fuel mass flow rate. In the combustor, the fuel can be methane, hydrogen or carbon monoxide or a mixture of these fuels. As the combustion process is rapid it is modeled as an instantaneous process.

Heat exchanger

A very simple model of a counter-flow heat exchanger is used, in which the amount of the heat exchanged depends on the heat transfer coefficient of the exchanger wall and also on the average temperature difference between the hot and cold streams. A first order transfer function describes the dynamics of the temperatures of both the streams.

Gas turbine cycle

The compressor and turbine models are based on steady state performance map characteristics [12]. The map is modeled using polynomials of 4th and 5th order for reduced mass flow, pressure and efficiency as functions of reduced shaft speed and operation line. A shaft model accounts for the dynamics of the rotating mass in the gas turbine system.

Electrical components

A simple model of inverter is used to convert DC electric power from the SOFC stack to AC, which is given to an autonomous grid. The grid side voltage is maintained constant at 230V by using the inverter controllers and the dynamics of these controllers are neglected. An AC-AC frequency converter with 95% efficiency is assumed to be connected to the alternator to convert the varying frequency of the alternator to the grid frequency. The operating voltage of the alternator is controlled to the grid voltage by controlling the field current in the alternator. The electric load connected to the gird is represented by six parallel branches with different components in each branch. It is categorized into 4 types of loads; constant impedance, constant current, constant power and induction motor load. The constant impedance, constant current and constant power load represent the residential loads such as lights, water heaters, ovens etc. The induction motor load is considered to represent an industrial load. The constant impedance load is represented by the first three branches with resistive, inductive and capacitive loads. The fourth and fifth branches represent the constant current and constant power loads respectively. The sixth branch represents the induction motor load. The total load current is the sum of the currents from the inverter and the alternator.

CONTROL DESIGN

The nominal state of the system is given in Table 1. At the steady state if there is any disturbance in any of the variables in the system, then it would disturb the power balance across the shaft in the GT cycle. Further the shaft speed will either accelerate or decelerate depending on the disturbance and it would make the system unstable. In order to make the system stable the shaft speed is to be controlled. The alternator current is manipulated in order to make the power balance satisfied, thus making the system stable. This is accomplished by using Proportional and Integral (PI) controller 1 as shown in Figure 2. Generally there are two ways of operating the hybrid system; constant shaft speed operation and variable shaft speed operation. Here variable shaft speed operation is considered as it has got advantages [13].

Table 1: Nominal state of the system

Variable	Value
SOFC current	263 A
Fuel flow rate	0.0072 kg/s
SOFC temperature	1206 K
SOFC voltage	0.67 V
Stack power	205 kW
Generator power	76.8 kW
Air flow rate	0.462 kg/s
AU	0.235
FU	0.85
Recycle ratio	0.53
Reforming degree	0.29
I_t	1248 A
V_t	222 V
Induction motor slip	0.1

As the hybrid system is connected to an autonomous power grid, it is to be operated in part load operation, as the electric load changes with time. During the part load operation, the hybrid system has to supply the power exactly needed by the grid. As the main source of the power in the hybrid system is the fuel flow, fuel flow must be controlled to match the power demand in case of any load changes. Since it is not always possible to know the load in advance, any load change is treated as a disturbance. As the bus bar voltage is fixed when there is a load change, the current and the FU in SOFC vary. The FU cannot be varied too much since it may cause uneven temperature and voltage distributions inside the cell [12]. Hence FU is taken as a controlled variable, where it is assumed that a perfect observer is available to estimate FU, as it cannot be measured directly during the dynamic changes. PI controller 2 is designed to control the FU using fuel mass flow as input, in case of any load change as shown in Figure 2.

A load change can affect the SOFC temperature to change beyond the material constraints [1] [12]. Hence the SOFC temperature should be controlled during the load changes. The SOFC temperature can be controlled by varying the air mass flow entering the cathode. The air mass flow entering the cathode can be varied by varying the shaft speed. All these things are accomplished using the cascade controller as shown in Figure 2. The PI controller 3 is used to control the SOFC temperature to a reference point by varying the shaft speed reference point to the PI controller 2. The PI controller 2 varies the alternator current to make the shaft speed equal to the reference point set by the PI controller 3.

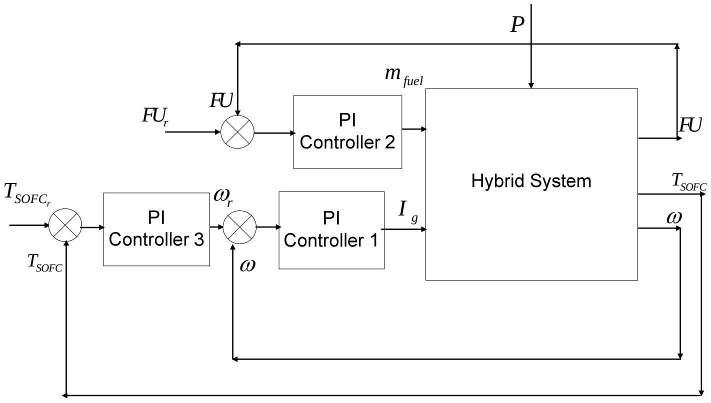

Figure 2: Control structure

SIMULATION

To evaluate the proposed control structure, the following scenario is used. The system is run at steady state for two minutes. After two minutes the following disturbances are given in the different elements of the electric load on the grid is decreased from 100% to 60% in a ramp fashion for 10 sec duration. After 30 minutes, the load is increased by 8% in a step. During the simulation different power profiles are shown in Figure 3. The FU, Air Utilization (AU) and cell voltage profiles during the simulation are shown in Figure 4. Also, different temperature profiles during the simulation are shown in Figure 5.

When there is a load decrease of 40% from the nominal state, both the SOFC stack and the alternator power are decreased at the new steady state value. From Figure 3, it is clear that the stack reacts faster compared to the alternator, as the fuel flow to the stack is decreased by the PI controller 2. At the nominal state the alternator power share is approximately 27.1% in the total power and when the load is decreased, it is maintained at 27% at the new steady state as well. When the load decreased, the fuel flow rate is decreased as in Figure 5, the current is decreased, hence the number of electrochemical reactions that take place decrease. Hence less oxygen is required and the AU is decreased (see Figure 4), even though the air mass flow rate is decreased (see Figure 5), as the former effect dominates. The FU is maintained at 0.85 (see Figure 4) by the PI controller 2 by manipulating the fuel flow rate, though there is a dip for a small time due to sudden change in the SOFC current due to the load disturbance.

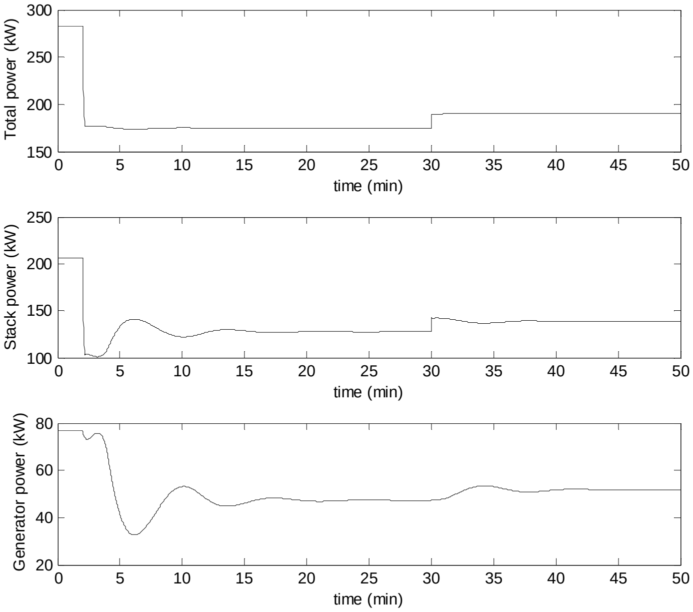

Figure 3: Different power profiles during the simulation

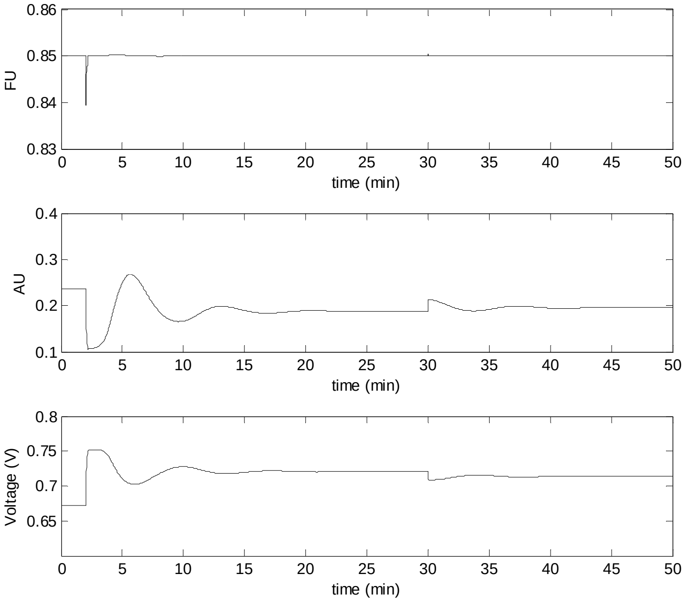

Figure 4: FU, AU and voltage profiles during the simulation

Since the current is decreased, the ohmic loss is reduced. But the open circuit voltage is reduced as the partial pressure of hydrogen is reduced in the cell. As the current is reduced a lot, this effect is dominated and the cell voltage is increased at the new steady state (see Figure 4).

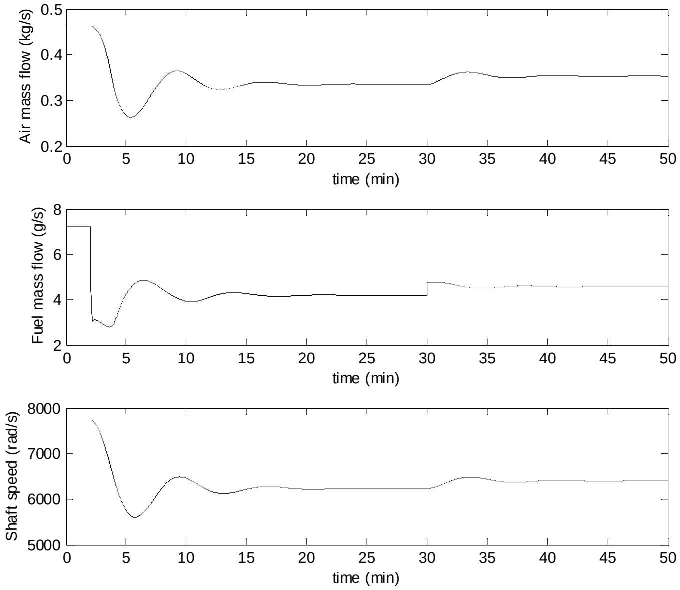

Figure 5: Air and fuel mass flow rates and shaft speed profiles during the simulation

As the fuel flow rate is decreased, the quantity of the fuel burnt in the combustor is decreased and TIT is reduced at the new steady state value (see Figure 6). When the power is reduced, which will have an effect on SOFC temperature to decrease, and PI controller 3 acts to decrease the air mass flow rate by reducing the shaft speed (see Figure 5). The SOFC temperature is varied by only a maximum of 8^0C during the dynamic change and at the steady state it is controlled at the nominal value.

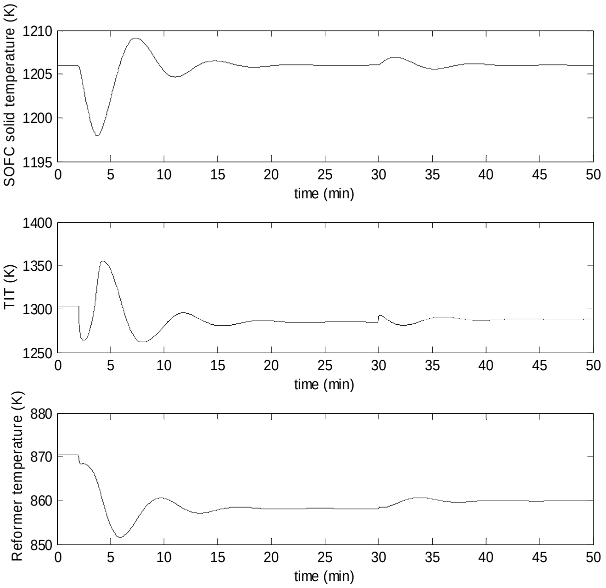

Figure 6: Different temperature profiles during the simulation

For a small step increase after 30 minutes, all the variables act in the opposite direction compared to the case where there is decrease in the load.

CONCLUSIONS

An integrated model of a SOFC-GT hybrid system in an autonomous power system is developed with a relatively low complexity, but including the important dynamics required for a control design. A simple control design is proposed which would stabilize the system and includes controls for FU and SOFC temperature in case of any disturbance in the load connected to the hybrid system.

Future work will focus on the optimization of set points for the all the PI controllers during part load operation by minimizing the fuel input into the system. Also an extension of the proposed control structure for start up and shut down operations of the hybrid system.

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