ABSTRACT

PAL, SHRUTI. Modeling and Performance Evaluation of Grid-Connected SOFC System. (Under the direction of Dr. Subhashish Bhattacharya).

Fuel Cell(FC) energy-based systems are a growing source of Distributed Generation (DG) and are connected to the Power Distribution System. This research focuses on understanding the behavior of the Solid Oxide Fuel Cells (SOFC) as distribution system for constant fuel utilization topology. The SOFC model is based on electrochemical and thermal equations and the processing of fuel (H_2 and O_2) through Steam Methane Reforming of natural gas. The goal is to understand the behavior of the distribution system and understand and mitigate the problems caused by the integration of the SOFC to the utility grid. The results discuss the behavior of the distribution system under various load requirements and the implementation of protection of the SOFC and the grid.

The complete system along with the SOFC system along with appropriate Power Conversion System (PCS) is implemented on the Real-Time Digital Simulation (RTDS) platform for constant fuel utilization topology. The PCS is equipped with advanced supervisory control scheme to adhere to IEEE 1547 requirements for utility grid applications. The focus of the paper is on IEEE 1547 standards for soft based systems.

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Modeling and Performance Evaluation of Grid-Connected SOFC System

by
Shruti Pal

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CHAPTER

1

INTRODUCTION

With the increase in power demands and the spatiotemporal factor of renewable sources, the demand for secondary power sources like fuel cells has gained mass recognition. Fuel Cells (FC) are getting recognition in the power distribution system due to their higher efficiency, zero or low emission of pollutant gases, and abundant fuel supply (4). Among the several FCs, the commercialized is Proton Exchange Membrane FCs (PEMFC) because of their compact setup and lower operating temperature. The PEMFC applications can be seen in the vehicle and commercial applications (5), (7).

The other actively researched FC are Solid Oxide Fuel Cells (SOFC). The primary difference between PEMFC and SOFC is their operating temperature. The SOFC operate at higher temperature (600°C to 1000°C). The commercialisation of these cells is challenging due to their high operating temperature. There is extensive research going on to analyze and solve the problems caused by powering the grid by SOFC for low problem applications. Sedghisigarchi and Feliachi (6), have analyzed the dynamics of distribution systems that contain fuel cells and have enhanced the stability of these systems by controlling the fuel cells.

The FC power generation depends on either of the two topological factors, constant fuel utilization, and constant fuel flow rate (8). In this report, constant fuel utilization topology

is explored to understand power generation. This thesis report focuses on the modeling of the generation of H_2 from steam reforming methanation of natural gas (8) for planar geometry. The fuel given to the cells is methane and dry air at room temperature. FCs are connected in series to meet the voltage demands and in parallel to meet power demands. FC operates at low DC voltage, and to supply to the grid, the DC power has to be converted to AC using power electronics converters as shown in Figure 3.1. The work in (3) discusses the control of SOFC plant in a grid-connected system for constant fuel utilization method using a z-source inverter for DC- AC conversion.

Figure 1.1: Solid oxide fuel cells integrated to the utility grid using a 3 phase power electronic system.

Hardware-in-the-loop (HIL) real-time digital simulation is implemented to emulate the behavior of the real hardware and validate the physical system. The environment is designed to test the controller design thus offering benefits such as the reduction in cost, validation of controller with the physical system before complicating the hardware design as well as flexible debugging for the controller.

Figure 1.2: Load connection diagram for per phase

Implementation of grid support functions (GSF) is supported [3, 6] by standards for EPS-DER interconnection at PCC, e.g. California Public Utilities Commission Rule 21 and Hawaii Rule 14H [1, 2], as well as updates to UL1741 Supplement SA and ongoing revisions to IEEE 1547 [4, 5] as some of the initial work towards this area. It is encouraged by the utilities with a growing trend, as mentioned in the new guidelines from standards. 4 Figure. 4. Reference diagram for load connection at PCC For integration of DER with the Area EPS, there are certain requirements to follow and restrict disturbances at the node of Point of Common Coupling (PCC). Some of these requirements include grid synchronization, voltage and frequency maintenance [4, 5], power quality (allowable under THD limits).

Modelling of individual DER i.e. inverter (front end converter) system is demonstrated and impact on PCC is analyzed. Specific grid support capabilities of DER provided in IEEE 1547 are implemented.

The thesis primarily focuses on designing and validating a robust real time simulation environment for converters interconnecting SOFC with the grid. This report can be used as a template for early design stage evaluations of grid-connected SOFC model with a controller designed for both the boost converter and VSI. The impact on SOFC is analyzed due to load unbalance. Specific grid support capabilities of DER provided in IEEE 1547 is implemented. The system is implemented and Real-time simulations are performed on OPAL RT platform used in HIL testing for controller validation.

Chapter 2 discusses about modeling the SOFC cell and the balance of Plant. Chapter 3

talks about the power conversion system required to inject SOFC power to grid. IEEE 1547 standards for PCC voltage are covered in chapter 4. Chapter 5 shows the implementation of system on RTDS platform and results are discussed in chapter 6.

CHAPTER

2

MODELING OF SOFC SYSTEM

SOFCs convert the chemical energy of hydrogen to electrical energy. The hydrogen required for the cells can be generated by various methods such as natural gas, gasoline or diesel, etc. Using natural gas is the most efficient method for generating hydrogen-rich gas. Though the fuel cells are compact and can be maintained, the problem is the generation of hydrogen rich gas. There are several processes for the generation of hydrogen gas, the most efficient being the steam reforming (SR) process.

Compared to other types of fuel Cells, the SOFC operates at high temperatures 700 deg C to 1000 deg C. The two geometries in research are planar and tubular. Although tubular SOFCs are more developed than planar SOFCs, the planar has attracted researchers due to their compact size, efficiency, and power density despite problems caused by higher temperatures. The DC current (I_{fc}) is generated due to flow of $2e^-$ from anode to cathode as shown in figure 2.1, thus generating electrical energy.

Figure 2.1: Working principle of the Solid Oxide Fuel Cells

Although H_2 is responsible for the generation of electrical energy, it is not the main fuel to the SOFC system. The purified H_2 for the generation of energy is extracted from natural gas. The generation of H_2 for the FC stack is an important aspect of the paper and is discussed thoroughly in this section. The complete system is shown in figure 2.3.

Figure 2.2: The block diagram of SOFC system

2.1 FC stack

Planar SOFCs are divided into 5 parts: Fuel channel, a positive electrode (anode), electrolyte, a negative electrode (cathode), and air channel. Considering an adiabatic system, the molar flow rate entering the fuel channel of the SOFC is the same as the molar flow rate exiting the CPOx. The flow rate is assumed to be evenly distributed to the number of cells connected in series as would be expected under ideal operational conditions. The SOFC converts the chemical energy of H_2 and O_2 into electrical energy according to the well-known oxidation of H_2 to H_2O . The modeling of the positive electrode, electrolyte, and negative electrode (abbreviated PEN) is discussed under the electrochemical sub model; the fuel channel and air channel are modeled in a mass balance sub-model. SOFC stack contains three main parts: Positive electrode (anode), Electrolyte, and Negative electrode (cathode), collectively known as PEN. The chemical reactions producing electrical energy occur in the PEN, as shown in figure 2.1.

Planar SOFCs are divided into 5 parts: Fuel channel, positive electrode (anode), electrolyte, negative electrode (cathode) and air channel as seen in Fig. 2.3. Considering an adiabatic system, the molar flow rate entering the fuel channel of the SOFC is the same as the molar flow rate exiting the CPOx. The flow rate is assumed to be evenly distributed

to the number of cells connected in series as would be expected under ideal operational conditions. The input to fuel channel are the molar flow rate of CH_4 , CO , CO_2 , H_2 , H_2O and N_2 .

Figure 2.3: Sub models of SOFC system

$$N_{in,f} = \frac{1}{N_{cell}} N_{out,fuel}^{CPOX} \quad f \in (CH_4, CO, CO_2, H_2, H_2O, N_{2f}) \quad (2.1)$$

The input to air channel is output of the manifold. O_2 in air channel reacts in cathode.

$$N_{in,a} = \frac{1}{N_{cell}} X_{a,air} N_{out,air}^{manifold} \quad a \in (O_2, N_{2a}) \quad (2.2)$$

The modeling of the positive electrode, electrolyte, and negative electrode (abbreviated PEN) is discussed under the electrochemical sub model; the fuel channel and air channel are modeled in a mass balance sub-model.

2.1.1 Electrochemical sub model

The SOFC voltage (V_{fc}) is given by:

$$V_{fc} = V_{NERST} - V_{act} - V_{conc} - V_{ohmic} \quad (2.3)$$

The internal EMF (E_{NERST}) is the open circuit voltage of the fuel cell and is given by:

$$V_{NERST} = N_{cell} \left(E_o + \frac{RT}{nF} \ln \left(\frac{p_{H_2} p_{O_2}^2}{p_{H_2O}} \right) \right) \quad (2.4)$$

p_{H_2} , p_{H_2O} and p_{O_2} are the partial pressures of H_2 , H_2O and O_2 respectively.

Figure 2.4: Implementation of NERST equation in MATLAB/Simulink

The activation loss (V_{act}) is due to the energy barrier to be overcome for the electrochemical reaction to occur and is given by the Butler-Volmer equation as follows.

$$V_{act} = \frac{RT}{n\alpha F} \ln(\beta + \sqrt{\beta^2 + 1}) \quad (2.5)$$

$$\beta = \frac{i_{fc}}{i_o}$$

Figure 2.5: Implementation of Activation voltage loss in MATLAB/Simulink

The concentration loss (V_{conc}) reflects over the potential due to the species diffusion between the reaction site and the bulk flow in the gas channels and is given by following equation,

$$V_{conc} = -\frac{RT}{nF} \ln\left(1 - \frac{i_{fc}}{i_L}\right) \quad (2.6)$$

Figure 2.6: Implementation of concentration voltage loss in MATLAB/Simulink

V_{ohmic} is the ohmic loss due to the internal resistance in the SOFC.

$$V_{ohmic} = r I_{fc} \quad (2.7)$$

V_{fc} is the output voltage of the connection to the power electronic circuit. I_{fc} is the fuel cell current. It acts as feedback to get the molar flow rate of methane and dry air depending on the requirement.

Table 2.1: The constants used in the fuel cell voltage and losses calculation

Open circuit voltage	Eo	1.1 V
Gas constant	R	8.314 kJ/mol
Number of electrons participating in the reaction	n	2
Electron coefficient of the reaction	α	0.5
Ohmic resistance	r	0.126 Ω
Limiting current density	i_L	3 A/ cm^2

The SOFC voltage as per electrochemical submodel is a non linear function of fuel

partial pressure, PEN temperature, current density as in the composite function.

$$V_{fc} = f(i_{fc}, p_{H_2}, p_{O_2}, p_{H_2O}, T) \quad (2.8)$$

2.1.2 Mass Balance Sub-Model

The concentration of species and the bulk pressures of the fuel channel and the air channel are calculated in the mass balance sub-model. The CO entering the SOFC is further converted to hydrogen through water gas shift (WGS) reaction, and the steam reformation (SR) and WGS occur due to the high temperature of the SOFC. The reactions determine the composition of fuel flow and the partial pressures of species. The moles of species are calculated below:

The CO entering the fuel channel is further converted into hydrogen through the water shift reaction with the aid of a catalyst, thus making it as a fuel instead of poisonous gas. Due to high temperature, a methanation process can be applied to produce H_2 .

The amount of CH_4 reacting in SR reaction can be calculated using SR reaction rate and is given by the equation:

$$r_{SR} = 0.04274 p_{CH_4} \exp\left(\frac{-82000}{RT}\right) \quad (2.10)$$

$$p_{CH_4} = \frac{N_{CH_4}}{N_{sf}} P_{fuel}, N_{sf} = N_{CH_4} + N_{CO} + N_{CO_2} + N_{H_2} + N_{H_2O} + N_{2,f} \quad (2.11)$$

$$P_{fuel} = P_{fuel}^1 + \sum \frac{N_{out,sf} M_{sf}}{\alpha_{sf}} \quad (2.12)$$

The partial pressure of H_2 and H_2O are given by fuel channel and partial pressure of O_2 is given by air channel. The partial pressure of the gases are given by the equation:

$$p_{H_2} = \frac{N_{out,H_2}}{N_{out,fuel}} P_{fuel} \quad (2.13)$$

N_{out,H_2} , $N_{out,fuel}$ are the molar flow rate of hydrogen and total molar flow rate of the fuel stream. When the cells are connected in parallel, the pressure of each fuel outlet changes.

The partial pressure of O_2 and H_2O can be calculated similarly.

Table 2.2: The constants used in the mass balance sub model

Equilibrium constant (WGS reaction)	k_{WGS}	0.01
Fuel channel temperature	T	800 g C
area of the cell	A	$0.04 m^2$

Table 2.3: Flow of gases through fuel channel

	CH_4	CO	CO_2	H_2	H_2O	N_{2f}
Entering SOFC	$(1 - \beta)N_{fuel}$	$x N_{fuel}$	$y N_{fuel}$	$2x N_{fuel}$	$2y N_{fuel}$	$0.78 N_{air}$
SR reaction	$-\emptyset$	$\emptyset$	0	$-\emptyset$	$3\emptyset$	0
Anode reaction	0	$-\Omega$	Ω	Ω	Ω	0
WGS reaction	0	$-\Omega$	Ω	Ω	Ω	0
Total	$-\emptyset$	$\emptyset - \Omega$	Ω	$3\emptyset + \Omega - \frac{I_{fc}}{2F}$	$\emptyset + \Omega - \frac{I_{fc}}{2F}$	0
Exiting SOFC	$(1 - \beta)N_{fuel} - \emptyset$	$xN_{fuel} + \emptyset - \Omega$	yN_{fuel}	$2xN_{fuel}$	$2yN_{fuel}$	$0.78N_{air}$

Table 2.4: Flow of gases through air channel

	O_2	N_2
Entering SOFC	$0.21N_{in,air,a}$	$0.78N_{in,air,a}$
Cathode	$\frac{I_{fc}}{4F}$	0
Total	$\frac{I_{fc}}{4F}$	0
Exiting SOFC	$0.21N_{in,air,a} - \frac{I_{fc}}{4F}$	$0.78N_{in,air,a}$

2.2 Balance of Plant

The Balance of Plant (BOP) consists of natural gas fuel storage (Fuel Tank), fuel valve controlled by its controller, the processor (CPOx) that reforms natural gas to hydrogen. The manifolds are represented by the first-order lag model.

2.2.1 Fuel flow Controller

The topology used here is constant utilization. This means that mass flow rates of Methane and air changes as per the load requirement. The mass flow rates of Methane and dry air can be calculated as shown in equation 2.14. The natural gas entering the fuel system is controlled by the current drawn from the SOFC stack. The SOFC voltage can be either controlled by constant fuel utilization or constant fuel flow rate topology. A constant fuel utilization topology results in exceedingly small deviation in fuel cell voltage due to change in fuel cell current and such small voltage changes can be easily handled by the power converter connected to the SOFC and hence the SOFC is operated under constant fuel utilization (or current control) topology. The assumed input to the fuel cells is Methane and dry gas at room temperature, which is fed to a first-order controller to emulate the slower dynamics of chemical reactions followed by Methane and air fed to the CPOx. In contrast, the air is fed to the SOFC cathode.

- N_{cell} : number of cells connected in series to meet the required output voltage.
- Fuel utilization (u) : $0.7 < u < 0.9$, if $u < 0.7$: not enough fuel flow to maintain fuel cell voltage. $u > 0.9$: may damage the cell due to overutilization.
- Oxygen to Carbon ratio: The moles of oxygen getting consumed per one mole of carbon. It defines the moles of methane reacting in CPOx.

- Dry air fed to the fuel controller is a mixture of all the gases (N2 and O2). O2 will participate in the reaction but N2 will not.

$$\begin{aligned}
 N_{fuel} &= \frac{N_{cell} I_{fc}}{u F (8 - 4 O_2 C)} \\
 N_{air} &= \frac{N_{cell} I_{fc} O_2 C}{u F (8 - 4 O_2 C X_{O_2,air})} \\
 N_{in,air,a} &= \frac{N_{cell} I_{fc}}{4 F X_{O_2,air}}
 \end{aligned} \tag{2.14}$$

Figure 2.7: Implementation of molar flow rate of methane to be processed in CPOx in MATLAB/Simulink

Figure 2.8: Implementation of molar flow rate of dry air to be processed in CPOx in MATLAB/Simulink

Figure 2.9: Implementation of dry air required in fuel cell in MATLAB/Simulink

Table 2.5: The constants used in the fuel flow controller equations

Number of Cells	N_{cell}	1
Oxygen to Carbon ratio	O_2C	0.62
Fuel Utilization	u	0.85
Faraday's constant	F	96486
Composition of O_2 in air	$X_{O_2,air}$	0.21

2.2.2 Gas Supply Manifolds

Gas supply manifolds are responsible for even distribution of gases. For any change in load, the fuel flow rate changes, and the fuel and air distribution takes time for equilibration. This causes a delay in the system, which must be accounted for in a robust and quantitative control scheme. Specific times of reaction and equilibration are collectively modeled using first-order dynamics and appropriate time constants in manifolds, as shown in equations

(1) and (2). The subscripts 'f' and 'a' are used to distinguish the air entering the CPOx and the air channel. The input to the gas supply manifolds is natural gas (CH_4) and air from the fuel flow controller with the dynamic behavior of the system dependent on these time constants.

$$\begin{aligned} N_{in,CH_4}^{CPOX} &= \frac{1}{s\tau_{CH_4} + 1} N_{in,CH_4} \\ N_{in,air}^{CPOX} &= \frac{1}{s\tau_{air,f} + 1} N_{in,air,f} \end{aligned} \quad (2.15)$$

$$N_{in,air,a}^{cathode} = \frac{1}{s\tau_{air,a} + 1} N_{in,air,a} \quad (2.16)$$

2.2.3 CPOx

The purified hydrocarbons react with steam in the fuel processor. The two types of reactions occurring in CPOx are given in equation (3). A mixture of CO and H_2 (syngas) is generated via POx reaction. The reaction enthalpy of TOx is high, increasing the temperature of the syngas flowing out of the CPOx. For the reactions to occur, the amount of CH_4 reacting should be greater than the O_2 entering the CPOX thus consuming O_2 completely during the process.

The heat generated from TOx reaction is enough to increase the temperature (750°C-800°C) of CPOX. The species exiting the CPOX are CH_4 , CO, CO_2 , H_2 , H_2O and N_2 . The molar flow rates of the species exiting CPOX can be calculated based on the reaction. Assuming that 'x' molar concentration of CH_4 reacts in POX and 'y' molar concentration of CH_4 reacts in TOX and ' β ' molar concentration of CH_4 reacts in CPOX, the sum of x and y can be written as β as seen in equation 2.18. One mole of CH_4 consumes 0.5 moles of O_2 and 0.5 moles of O_2 in POX and TOX respectively. It is assumed that O_2 is completely consumed in CPOX, so equation 2.19 gives a relation between x and y.

$$x + y = \beta \quad (2.18)$$

$$0.5x + 2y = O_2C \quad (2.19)$$

Figure 2.10: Implementation of the amount of CH_4 used in POx and TOx in MATLAB/Simulink

β is the percentage of CH_4 reacting in the fuel processor. It is dependent on the ratio of oxygen to carbon ratio and CPOx temperature. β is calculated as

$$\begin{aligned} \beta &= 1 - (1 - 0.5\beta_1)(1 - \tanh(\beta_2(O_2C - 0.5))) \\ \beta_1 &= \min[2, 0.0029T_{CPOX} - 1.185] \\ \beta_2 &= 0.215 + \exp(3.9 \times 10^{-8}(T_{CPOX} - 600)^3) \end{aligned} \quad (2.20)$$

Figure 2.11: Implementation of the amount of CH_4 used in the CPOx

Solving the equations and , mass flow rate of all the species are calculated as in following equations.

$$N_{out,CH_4}^{CPOx} = (1 - \beta)N_{in,CH_4}^{CPOx} \quad (2.21)$$

$$N_{out,CO}^{CPOx} = xN_{in,CH_4}^{CPOx} \quad (2.22)$$

$$N_{out,CO_2}^{CPOx} = yN_{in,CH_4}^{CPOx} \quad (2.23)$$

$$N_{out,H_2}^{CPOx} = 2xN_{in,CH_4}^{CPOx} \quad (2.24)$$

$$N_{out,H_2O}^{CPOx} = 2yN_{in,CH_4}^{CPOx} \quad (2.25)$$

N_2 being inert gas doesn't take part in reaction. So the mass flow rate of N_2 exiting CPOx is same as entering CPOx. Subscript 'f' and 'a' are added to distinguish between mass flow rate of fuel and air channel.

$$N_{out,N_2f}^{CPOx} = N_{in,N_2f}^{CPOx} \quad (2.26)$$

Table 2.6: The species entering and exiting the oxidisation controller

	CH_4	O_2	CO	CO_2	H_2	H_2O	N_{2f}
Entering CPOx	N_{fuel}	$0.78N_{air}$	0	0	0	0	$0.21N_{air}$
POx	-x	-0.5x	x	0	2x	0	0
TOx	-y	-2y	0	y	0	2y	0
Total	$-\beta$	$-O_2C$	x	y	2x	2y	0
Exiting CPOx	$(1 - \beta)N_{fuel}$	0	xN_{fuel}	$2xN_{fuel}$	yN_{fuel}	$2yN_{fuel}$	$0.78N_{air}$

Figure 2.12: Implementation of Table 2.6 in MATLAB/Simulink

CHAPTER

3

GRID CONNECTED SYSTEM

Figure 3.1: Solid oxide fuel cells integrated to the utility grid using a 3 phase power electronic system.

SOFCs are used to power the utility grid in this paper. As SOFCs operate at low DC voltage and power the AC load, a power conditioning unit is required to convert DC power to AC power. The most suitable PCU is selected based on application and SOFC behavior.

Voltage Source Inverter(VSI) is a DC-AC converter and is used for power conversion. The SOFC voltage varies over a small change in feedback current, so the conventional VSI is not enough to control the output voltage. A DC-DC boost converter is connected to keep the input voltage of VSI constant and will be discussed in this paper. Another method is to use a Z-source inverter, and these inverters are specially designed with voltage boosting capability (3).

Table 3.1: Grid parameters

Number of Cells	400
Rated Output Power	10 kW
Grid voltage (Line to line)	480
Grid frequency	60 Hz
DC bus voltage	1000 V
Switching frequency	2 kHz

3.1 Boost converter

As discussed, the SOFC voltage may vary depending on the load requirement, temperature variation, dynamic disturbances, etc. A boost converter is needed to boost up and control the output voltage. As a boost controller can operate with duty cycle = 0.7 with good efficiency, the number of SOFC cells connected in series reduces. The working principle of the boost converter is discussed in this section. The components are selected to keep the ripple of both the output voltage and input current under 10%. The frequency of the converter is f_s .

Figure 3.2: Step up DC-DC converter when switch is ON

Figure 3.3: Step up DC-DC converter when switch is OFF

The switch is ON for t_{on} time.

$$\begin{aligned}
 D &= \frac{t_{on}}{T_s} \\
 V_L &= V_{fc} \quad \Rightarrow \quad L \frac{d}{dt} i = V_{fc} \\
 i_c &= -\frac{V_{dc}}{R} \quad \Rightarrow \quad C_{dc} \frac{d}{dt} v_{dc} = -\frac{V_{dc}}{R}
 \end{aligned} \tag{3.1}$$

The switch is OFF for t_{off} time,

$$\begin{aligned}
 D' &= \frac{t_{off}}{T_s} \\
 V_L &= V_{fc} - V_{dc} \quad \Rightarrow \quad L \frac{d}{dt} i = V_{fc} - V_{dc} \\
 i_c &= i_L - \frac{V_{dc}}{R} \quad \Rightarrow \quad C_{dc} \frac{d}{dt} v_{dc} = i_L - \frac{V_{dc}}{R}
 \end{aligned} \tag{3.2}$$

The inductor voltage and capacitor current are zero for one cycle at a steady state. The relationship between output parameters and input parameters are calculated based on the above equation.

$$\begin{aligned}
 V_L &= L \frac{d}{dt} i_L = D(V_{fc}) + D'(V_{fc} - V_{dc}) = 0 \quad \Rightarrow \quad V_{dc} = \frac{V_{fc}}{1-D} \\
 i_c &= C \frac{d}{dt} V_{dc} = D(-\frac{V_{dc}}{R}) + D'(i_L - \frac{V_{dc}}{R}) = 0 \quad \Rightarrow \quad i_L = \frac{V_{dc}}{D'R}
 \end{aligned} \tag{3.3}$$

3.1.1 Components design

Inductor

$$\begin{aligned}
 L \frac{d}{dt} i_L &= (V_{dc} - V_{fc}) \\
 L \frac{\Delta i}{\Delta t} &= (V_{dc} - V_{fc}) \\
 L &= \frac{(V_{dc} - V_{fc})}{\Delta i f_{sw}}
 \end{aligned} \tag{3.4}$$

Putting the values in the above equation, the value of inductor is 240mH.

DC capacitor

$$\begin{aligned}
 C_{dc} \frac{d}{dt} v_{dc} &= -\frac{V_{dc}}{R} \\
 C_{dc} \frac{\Delta v_{dc}}{\Delta t} &= -\frac{V_{dc}}{R} \\
 C_{dc} &= \frac{V_{dc}}{R f_{sw} \Delta v_{DC}}
 \end{aligned} \tag{3.5}$$

With switching frequency = 2000 Hz, the resistor value = 2000 Ω and the voltage ripple is 5%, the value of capacitor 10uF

3.1.2 Transfer function

Due to non-linear components, small-signal modeling is used for the AC equivalent modeling of the boost converter. The parameters are a combination of DC values and AC values. Applying small-signal approximation in equation 3.3, the relationship between the output voltage and duty cycle can be represented by the following transfer function (1).

Using small ripple approximation, the signals are part of the dc value and small-signal and can be represented in the following way.

$$\begin{aligned}
 v_{fc}(t) &= V_{fc} + \hat{v}_{fc}(t), \hat{v}(t) \ll V \\
 v_{dc}(t) &= V_{dc} + \hat{v}_{dc}(t), \hat{v}_{dc}(t) \ll V_{dc} \\
 i(t) &= I + \hat{i}(t), \hat{i}(t) \ll I \\
 d(t) &= D + \hat{d}(t), \hat{d}(t) \ll D \\
 i_L(t) &= I + \hat{i}(t), \hat{i}_L(t) \ll I_L
 \end{aligned} \tag{3.6}$$

Applying inductor volt-time balance

$$\begin{aligned}
 <v_L(t)>_{Ts} = d(t)v_{fc}(t) + d'(t)(v_{fc}(t) - v_{dc}(t)) \\
 L\left(\frac{dI_L}{dt} + \frac{d\hat{i}_L(t)}{dt}\right) &= (D + \hat{d}(t))(V_{fc} + \hat{v}_{fc}(t)) + (D' - \hat{d}(t))(V_{fc} + \hat{v}_{fc}(t) - V_{dc} - \hat{v}_{dc}(t))
 \end{aligned} \tag{3.7}$$

Putting DC terms equal to zero and neglecting second order terms

$$L \frac{d}{dt} \hat{i}_L = \hat{v}_{fc} + D' \hat{v}_{fc} + \hat{d} V_{dc} \tag{3.8}$$

Applying capacitor charge balance

$$\begin{aligned}
\langle i_c(t) \rangle_{T_s} &= d(t) \left(-\frac{v_{dc}(t)}{R} \right) + d'(t) \left(\frac{i_L(t)}{n} - \frac{v_{dc}(t)}{R} \right) \\
C \left(\frac{dV_{dc}}{dt} + \frac{d\hat{v}_{dc}(t)}{dt} \right) &= (D + \hat{d}(t)) \left(\frac{V_{dc}}{R} + \frac{\hat{v}_{dc}(t)}{R} \right) + (D' - \hat{d}(t)) \left(I_L(t) + \hat{i}_L(t) - \frac{V_{dc}}{R} - \frac{\hat{v}_{dc}(t)}{R} \right)
\end{aligned} \tag{3.9}$$

Putting DC terms equal to zero and neglecting 2nd order terms we get

$$C \frac{d}{dt} \hat{v}_{dc} = \frac{\hat{v}_{dc}}{R} + D' \hat{i}_L - \hat{d} I_L \tag{3.10}$$

From equation 3.8 and 3.10, the small signal model can be derived as follows

Figure 3.4: Small signal model of boost converter

Output to control transfer function

$$G_{vd}(s) = \frac{\hat{v}_{dc}(s)}{\hat{d}(s)} \Big|_{v_{fc}(s)=0} \tag{3.11}$$

$$G_{vd} = \frac{V_{dc}}{D'} \frac{sL - (D')^2 R}{LCRs^2 + sL + (D')^2 R} \tag{3.12}$$

3.1.3 Controller design

The fundamental control idea is to regulate the output voltage of the step-up DC-DC converter. This is typically achieved by sensing the output DC voltage and then comparing it with the given reference voltage ($V_{dc,ref}$) as shown in Fig. 3.6. The voltage error will be

compensated using a controller in a digital or analog platform.

Figure 3.5: Control model of step up DC-DC converter

Figure 3.6: Control model of step up DC-DC converter

The error voltage ($V_{err} = V_{dc,ref} - V_{dc}$) is controlled so that the error is close to zero. The controller's output is compared to the triangular waveform of high frequency, and the pulse

generated is input to the switch(Q1).

The relationship between the output voltage and the duty cycle is given by the equation 3.12. A simple PI controller is used to control the output voltage of the boost converter. The cutoff frequency of the boost controller is designed at 0.08 Hz. The slow response of the controller will not affect the overall response time of the system as the reaction takes a few minutes to attain equilibrium in SOFC. The bode plot of the boost controller is shown in Figure 3.7(1).

Figure 3.7: bode plot of boost converter without and with PI controller

3.2 Voltage Source Inverter

The DC-AC converters convert DC power to AC power as per utility grid requirements. A line to line RMS voltage rating of 480V requires at least 800V DC link voltage. The model is designed with a 5% voltage drop in filter and 1000V DC link voltage. The filter on the AC side can be L, LCL, or higher order. A simple inductive (L) filter as shown in figure 3.8.

Figure 3.8: Schematic of 2 level 3 phase Voltage Source Inverter

The maximum capacity of the system can be found on the nameplate. The relationship between rated power, voltage and current is given by

$$S = \sqrt{3} V_{L-L(rms)} I_{L(rms)} \quad (3.13)$$

3.2.1 Frame Transformation

The three phase (abc) quantities are converted to two mutually perpendicular components (dq) which rotate with angular velocity ω . This is achieved by Clarke's transformation and Park's transformation.

Clarke's transformation

Figure 3.9: Clarke's transformation

The Clarke's transformation transform three phase quantities to stationary two phase quantities ($\alpha\beta$).

$$\begin{bmatrix} \alpha \\ \beta \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \quad (3.14)$$

Given the positive sequence of grid voltage as

$$\begin{aligned} V_a &= V_m \sin(\omega t) \\ V_b &= V_m \sin(\omega t - \frac{2\pi}{3}) \\ V_c &= V_m \sin(\omega t + \frac{2\pi}{3}) \end{aligned} \quad (3.15)$$

$$\begin{aligned} V_\alpha &= V_m \sin(\omega t) \\ V_\beta &= -V_m \cos(\omega t) \end{aligned} \quad (3.16)$$

$$V = V_{\alpha} + j V_{\beta}$$

$$V = V_m e^{j(\omega t - 90^{\circ})}$$
(3.17)

Figure 3.10: Implementation of Clarke transformation in MATLAB/Simulink

Park's transformation

Figure 3.11: Park's transformation

$$\begin{bmatrix} d \\ q \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta) \\ \sin(\theta) & -\cos(\theta) \end{bmatrix} \begin{bmatrix} \alpha \\ \beta \end{bmatrix} \quad (3.18)$$

Figure 3.12: Implementation of Park transformation in MATLAB/Simulink

A PLL with reference frequency generates the reference angle by phase-locking with the sensed grid voltage. All the sensed 3-phase variables are converted to the equivalent synchronous DQ-reference frame. In the synchronous reference frame, the fundamental component of all the variables behaves like DC parameters. The inverter is operating at unity power factor, so the reactive power and current are taken to be zero for the simulation. The grid voltage is the purely active power source, and the grid voltage in q- axis = 0. The inverter voltage should be in the same phase as the grid voltage (2).

Figure 3.13: Control block diagram of (PLL) for unity power factor

Figure 3.14: Implementation of PLL block in MATLAB/Simulink

3.2.2 Control of VSI

To regulate the power flow of the DC-AC converter, it is necessary to measure the output of AC currents and grid voltages. The grid parameters are transformed from ABC to DQ. The grid voltage measurements are generally used as inputs for a Phase Locked Loop (PLL) for estimating the phase and frequency information of the utility grid. Single or multiple current regulators can be used in tandem with a PLL to regulate the AC power flow between the utility grid and the power conversion unit. The current controllers generate DQ voltage

references, which are converted to 3 phases and are compared to generate a pulse, as shown in figure 3.16.

Figure 3.15: Per phase equivalent diagram of 2 level 3 phase inverter

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = R \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + L \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} V_{ga} \\ V_{gb} \\ V_{gc} \end{bmatrix} \quad (3.19)$$

The grid voltage and current are transformed to 2 phase (DQ) using Clarke's and Park's transformation.

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} R & -\omega L \\ \omega L & R \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + L \frac{d}{dt} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} V_{gd} \\ V_{gq} \end{bmatrix} \quad (3.20)$$

The relationship between grid current and the reference DQ voltage is given in the Equation 3.19.

$$\begin{aligned} V'_d &= (R + sL)i_d & \Rightarrow & & V'_d &= V_d + \omega L i_q - V_{gd} \\ V'_q &= (R + sL)i_q & \Rightarrow & & V'_q &= V_q - \omega L i_d - V_{qd} \end{aligned} \quad (3.21)$$

Equation 3.21 represents two SISO systems, each of which is identical. The d-axis SISO system alone is considered in the following explanations. The same methodology can be applied to the q-axis SISO system also (2).

Figure 3.16: Control algorithm of 2 level 3 phase Voltage source Inverter

Knowing the plant transfer function, $G(s) = \frac{1}{(R+sL)}$ from equation (29), the controller is designed so the overall system is first-order low pass filter as shown in figure 3.17. The relationship between reference current and A simple PI controller is designed in the synchronous reference frame (DQ) to control the current of the grid-connected system. The cut-off frequency of the controller is set to be 10% below the switching frequency. The time constant is given by $\tau = \frac{1}{f_c}$.

For fundamental component control, the two proportional-integral (PI) controllers are used in the system for both d-axis and q-axis. Feed-forward terms can be used to decouple the two current controller dynamics. The d-axis current controller regulates the active component of the fundamental grid current to this reference and generates the d-axis voltage component of the converter voltage. The q-axis current controller regulates the reactive component of the fundamental grid current.

The d-axis current is compared to its reference current and generates the d-axis voltage component of the converter voltage. Unity power factor (UPF) is achieved by keeping the q-axis current at zero.

Figure 3.17: d-axis current controller of 2 level 3 phase VSI

$$\begin{aligned}
 \frac{(K_p + \frac{K_i}{s})(\frac{1}{R+sL})}{1 + (K_p + \frac{K_i}{s})(\frac{1}{R+sL})} &= \frac{1}{\tau s + 1} \\
 (K_p + \frac{K_i}{s}) &= \frac{L}{\tau} + \frac{R}{\tau s} \\
 K_p &= \frac{L}{\tau} \quad K_i = \frac{R}{\tau}
 \end{aligned} \tag{3.22}$$

The switching frequency f_{sw} selected for the model is 2kHz, and the bandwidth ($\frac{1}{\tau}$) for the controller is 100Hz. The value of L and R are designed as discussed above. The values of K_p and K_i are calculated using these parameters. The current controller compared the reference current to the actual current and passed through the controller. The controlled output is V_d . The feedforward terms $\omega L I_q$ and V_{gd} are added to get actual V_{d_ref} . Similarly, the current in the q axis is controlled to give V_{q_ref} . This voltage in the DQ reference frame is converted to ABC frame (V_{abc_ref}) and is compared to the triangular waveform to get gate signals.

Figure 3.18: Implementation of d-axis current controller in MATLAB/Simulink

Figure 3.19: Implementation of q-axis current controller in MATLAB/Simulink

CHAPTER

4

IEEE 1547

4.1 Load connection

Figure 4.1: Load connection diagram for per phase

A load is connected in parallel to the grid to emulate the behavior of the system under abnormal conditions. The grid-connected inverter with load is shown in the figure. The point of Common coupling (PCC) is the point where grid load is connected to the power generation. We are interested in finding out the active, reactive, and apparent power flow at the PCC.

4.2 Phasor diagram and power flow

Figure 4.2: Phasor diagram

$$P = \frac{V_{grid}}{\omega L} \times V_{inv} \times \sin(\theta) \quad (4.1)$$

$$Q = \frac{V_{grid}}{\omega L} \times (V_{inv} \cos(\theta) - V_{grid}) \quad (4.2)$$

$$pf = \cos(\theta) = \frac{V_{inv} \sin(\theta)}{V_{load}} \quad (4.3)$$

For unity power factor

$$\begin{aligned} V_{inv} &= \sqrt{(V_L^2 + V_{grid}^2)} \\ \theta &= \tan^{-1}\left(\frac{V_L}{V_{grid}}\right) \end{aligned} \quad (4.4)$$

4.3 IEEE 1547

The PCS (an example realization shown in Fig 5) will be equipped with an advanced supervisory control scheme to adhere to IEEE 1547 requirements. This is an aspect that previously has not been implemented for SOFC based PCS.

There can be several different types of grid abnormalities such as grid voltage sag, swell, grid frequency deviation, etc.

The SOFC based PCS typically should remain interconnected to the utility grid even during grid abnormalities. IEEE 1547 defines a range of supervisory control requirements for grid-tied systems. These conditions are required to protect the PCS and distributed generation system under grid abnormalities. They also cover performance requirements, power capabilities, power quality, and islanding issues. The grid operating conditions are bound to vary due to variations in the load. These regulations are used to improve grid synchronization, voltage sag/swell, and frequency variation. Some of these conditions are discussed below.

4.3.1 Voltage - Reactive power mode

The injection/absorption of reactive power is defined by the PCC voltage. For abnormal voltage conditions, reactive power shall be provided subject to DER capacity and is required to be back to normal operation, when voltages become normal. If the PCC voltage is reduced, the reactive power is injected into the grid to increase the PCC voltage and absorbed if the PCC voltage is increased. The relationship between PCC voltage and reactive power should be followed as per Figure 4.3.

Table 4.1: PCC voltage and the reactive power requirements (Volt-Var mode) as per IEEE 1547

V		Q	
V1	$V_{REF} - 0.08V_N$	Q1	44 % of S, injection
V2	$V_{REF} - 0.02V_N$	Q2	0
V3	$V_{REF} + 0.02V_N$	Q1	0
V4	$V_{REF} + 0.08V_N$	Q2	44 % of S, absorption

Figure 4.3: PCC voltage and the reactive power requirements (Volt-Var mode) as per IEEE 1547

4.3.2 Active - Reactive power mode

The injection/ absorption of reactive power is provided to the grid based on the active power as per Figure 4.4. If the active power is absorbed by the grid, reactive power will be injected to compensate for the power of the grid and vice versa.

Table 4.2: Active power and the reactive power requirements (Watts-Var mode) as per IEEE 1547

P		Q	
P1	$0.2P_{rated}$	Q1	0
P2	$0.5P_{rated}$	Q2	0
P3	P_{rated}	Q1	44% apparent power is absorbed
$P1'$	$0.2P'_{rated}$	$Q1'$	0
$P2'$	$0.5P'_{rated}$	$Q2'$	0
$P3'$	P'_{rated}	$Q3'$	44% apparent power is injected

Figure 4.4: Active power and the reactive power requirements (Watts-Var mode) as per IEEE 1547

4.3.3 Frequency - Active power mode

The active power is injected into the grid based on frequency variation. The full active power is injected for frequency less than the operating frequency. As the frequency increases, the active power reduces linearly till it is constant as shown in Fig 4.5.

Figure 4.5: Active power and frequency requirements as per IEEE 1547

4.4 Supervisory Control

The grid-connected inverter is controlled by injecting and absorbing active and reactive power to the grid. The PLL block is used to control the reference and actual parameters. The PCC voltage for the unity power factor is aligned with the direct component of the rotating voltage vector thus locking the phase. Once the phase is locked, the 3 phase inverter operates normally. The PCC voltage changes due to load connected in parallel with the grid, causing a sag or swell in PCC voltage. As per IEEE 1547, the lag or swell in PCC voltage will lead to the voltage compensation by either injecting or absorbing reactive power as per Figure 4.3.

4.4.1 Under voltage detection

The PCC voltage three-phase voltage is converted to a DQ frame. The Q axis voltage is zero for the unity power factor and the D axis voltage is compared with the reference voltage. The ratio depicts the percentage of sag or swell. As the load is purely inductive, there is a sag in PCC voltage.

$$V_{ratio} = \frac{V_d}{V_{d,ref}} \quad (4.5)$$

Table 4.3: Detection Logic

Logic	V_{ratio}	Reactive Power (Q)
Logic 1	$0.9 < V_{ratio} < 0.92$	44%Q
Logic 2	$0.92 < V_{ratio} < 0.98$	k%Q
Logic 3	$0.98 < V_{ratio} < 1.02$	0
Logic 4	$1.02 < V_{ratio} < 1.08$	-k%Q
Logic 5	$1.08 < V_{ratio} < 1.10$	-44%Q

Figure 4.6: Under voltage detection algorithm implemented in MATLAB/Simulink

CHAPTER

5

REAL TIME HIL SIMULATION PLATFORM

5.1 Subsystem representation

Figure 5.1: Subsystem model in opal-RT

5.2 Master subsystem

The Master subsystem is the main block and is the solver, performing all the calculations. It consists of an eHS block, analog, and digital control blocks. The input parameters from the console are given to the controller through a communication block called the OpComm block. The eHS solver block emulates the operation of FPGA. It uses the bitstream files to assign ports and peripherals for signals during run time.

Figure 5.2: Grid connected SOFC system implemented in Master subsystem

5.2.1 Switching model in FPGA

The switching frequency is 2kHz. The switching model is running at 1us time step allowing high-frequency stimulation with good data acquisition. The FPGA block consists of a boost converter and 3 phase voltage source inverter. The gate pulse for both inverter and boost converter is modeled in the CPU block. The fuel cell voltage input to the boost converter is calculated in the CPU.

Figure 5.3: Inverter model with grid and load on FPGA

5.2.2 SOFC emulation in CPU

The SOFC is emulated in the CPU of the Master subsystem. The input to the block is I_{fc} and the output are fuel cell voltage and voltage losses. The V_{fc} is the input to the FPGA block as can be seen in Figure 5.2. The voltage losses are sent to the console subsystem for the measurement. The SOFC block consists of a fuel flow controller, CPOx, fuel cell as per the equations discussed in Chapter 2.

Figure 5.4: SOFC implementation in Master subsystem subsystem

5.2.3 Boost controller

The boost converter is controlled through the PI controller to maintain a constant output voltage. A saturation block with a minimum value of zero and the maximum value of 0.8 is added after the controller to keep the modulated value within the range. A PWM generator block compares the modulated value with a triangular waveform to get pulse signals for the boost converter.

Figure 5.5: Boost converter controller implemented in CPU subsystem

5.2.4 VSI controller

The 3 phase voltage and current from FPGA is converted to dq frame. The dq reference voltage from current controller are converted to abc waveform and the gate pulses are obtained by comparing the modulated signals with triangular waveform. The gate pulses are input to FPGA block.

Figure 5.6: controller of VSI implemented in CPU subsystem

5.2.5 Supervisory control

The block injects or absorbs the active power and reactive power according to the three conditions as discussed in Chapter 4.

Figure 5.7: Supervisory control implemented in CPU subsystem

CHAPTER

6

RESULTS & DISCUSSION

The SOFC is modeled using all the equations and is implemented in opal-RT. This type of modeling becomes important since this will allow us to study the interactions between the SOFC system as well as the PCS. The SOFC with power electronic converters will be implemented in FPGA, and the controller will be implemented and validated in OPAL-RT CPU as depicted in Fig 2. The OPAL-RT systems are available in the NC State FREEDM laboratories.

Once the fundamental models of the BOP and SOFC are developed and integrated with the electrical system models through the opal RT platform, interplays between these various systems can be explored and investigated for specific applications. In the next section, we describe a few applications of the SOFC in the range of 5kW to 25 kW. Power electronics solutions will be provided and explored based on the specific application, considering the integrated modeling approach described above, and they will be validated experimentally for compatibility with the SOFC.

Table 6.1: Parameters of the grid connected system

Symbol	Representation	Value
N_{cell}	number of cells	400
P	Power of the system	10kW
V_{grid}	Grid voltage	480 V
V_{dc}	DC voltage	1000 V
f_{sw}	Switching frequency	2 kHz
f_g	Switching frequency	60 Hz
u	fuel utilization	0.85
τ_{CH_4}	fuel response time	5 minutes
r	Ohmic losses	0.126 Ω
E_o	ideal standard potential	1.1 V
T	temperature of FC stack	1023 K

6.1 Behavior of SOFC

The primary focus of the research is to understand the behavior of SOFC. The results discussed in this section are for a single cell. The SOFC voltage decreases with an increase in current as can be seen in Fig. 6.1. At zero current, there is no loss in the SOFC, therefore the voltage is 1.1 times the number of cells connected in series. The sudden voltage drop can be seen is due to the activation loss. After that, a linear decrease in cell voltage is seen. This is due to ohmic losses. The cell voltage drops sharply when the load current density reaches the maximum current density that can be generated by the fuel cell. The sharp voltage drop is due to the concentration losses. There is a slight variation in the fuel cell voltage concerning current for different time constants of chemical reactions.

Due to change in the load, the current increases from 1A to 2A at $t = 600$ seconds as seen in Fig. 6.2 (c). The effect of change in current and time constant of manifolds can be seen in the Figure 6.2, 6.4. 6.5 and 6.6.

The SOFC voltage reduces till $t = 600$ seconds due to the first-order lag of the manifolds. At $t = 600$ seconds, SOFC voltage reduces because of the SOFC current. As the current increases, the demand for the fuel increases and can be seen in Fig 6.2 (b).

Figure 6.1: V_{fc} vs I_{fc}

(a)

(b)

(c)

Figure 6.2: Variation in SOFC voltage and fuel flow rate on changing the SOFC current.

Figure 6.3: NERST Voltage

Figure 6.4: Concentration Voltage losses

Figure 6.5: Activation Voltage losses

Figure 6.6: Ohmic voltage losses

6.2 Utility grid connection

The SOFC is connected to power the utility grid and the results are discussed in the following section. For the unity power factor, the q axis current is maintained at zero and the grid current is aligned with the d axis current.

6.2.1 Inverter parameters

Magnitude of voltage vector

The grid is connected to the system and the results are discussed. For the unity power factor, the q-axis current is maintained at zero and the d-axis demand current is changed from 4A to 8A at $t = 10$ seconds. The results are discussed in this section.

Figure 6.7: Grid voltage in dq axis

Inverter current in both d and q axis

Figure 6.8: Inverter current in d-axis

Figure 6.9: Inverter current in q axis

Active Power and reactive power

The active power is the power supplied to the grid, as a result positive power. The reactive power is zero due to zero demand reactive current.

Figure 6.10: Active and reactive power

6.2.2 Boost converter parameters

The DC voltage is constant at 1000 Vots as required by VSI, thus the boost controller is working. The DC current is changes as current required by inverter as seen in Fig. 6.12. The reduction in current is due to the cascaded load resistor.

Figure 6.11: Boost converter voltage for grid connected system

Figure 6.12: Boost converter current for grid connected system

6.2.3 SOFC parameters

The SOFC output current (I_{fc}) is related to DC by the duty cycle. The duty cycle of the boost converter is approximately 0.6. By this relationship, the SOFC current change can be seen in Fig 6.14.

Figure 6.13: SOFC current for grid connected system

Figure 6.14: SOFC voltage for grid connected system

6.3 IEEE 1547 results

6.3.1 Reactive Power Control

The reactive load is added in parallel with the grid, introducing disturbance at PCC voltage. The reactive power is injected at point B to increase the PCC voltage. The voltage ratio is 0.96 and injected current = 0.65A.

Figure 6.15: Detection of sag in PCC voltage

Grid Voltage in dq axis

Figure 6.16: Grid voltage in dq axis for reactive power compensation

Inverter current in dq axis

Figure 6.17: Inverter current in d axis for reactive power compensation

Figure 6.18: Inverter current in q axis for reactive power compensation

Active and reactive power

The reactive power is injected as can be seen in the following graph. The active power is negative because the power is given to the grid from SOFC.

Figure 6.19: Active and reactive power for reactive power compensation

SOFC parameters

Figure 6.20: SOFC voltage for reactive power compensation

Figure 6.21: SOFC current for reactive power compensation

6.3.2 Active Power Control

The reactive power is controlled based on the active power as per IEEE guidelines. Reactive power is injected if active power is absorbed and is absorbed if active power is generated. The reactive power is 44% of the rated for rated active power.

Active and Reactive Power

The active power is injected at point A and reactive power is absorbed. Grid current increases as a result of an increment in active power.

Figure 6.22: The active power in injected the grid and reactive power is absorbed as per Table 4.2

Inverter current in dq axis

Figure 6.23: Inverter current in d axis to inject active power

Figure 6.24: Inverter current in q axis to inject active power

SOFC parameters

Figure 6.25: SOFC voltage to inject active power

Figure 6.26: SOFC current to inject active power

6.3.3 Frequency regulation

Active power is controlled based on the frequency for DER with 50% loading. The active power reduces on increasing the frequency. The frequency of the system changes from 60 Hz to 59 Hz at $t = 12$ seconds. The controller is set to ON at $t = 8$ seconds.

Grid voltage in dq axis

Figure 6.27: Grid voltage in dq axis for variation in frequency

Inverter parameters

The active power is controlled based on the frequency at $t = 8$ seconds. On reducing the frequency, the active power is increased as seen in Figure 6.28. The reactive power remains zero.

Figure 6.28: Variation in active power with grid frequency as per IEEE 1547

Figure 6.29: Inverter current in q axis for variation in grid frequency as per IEEE 1547

Figure 6.30: Inverter current in q axis for variation in grid frequency as per IEEE 1547

SOFC parameters

Figure 6.31: SOFC voltage for variation in grid frequency as per IEEE 1547

Figure 6.32: SOFC current for variation in grid frequency as per IEEE 1547

6.4 No load condition

The SOFC will go into no-load condition if the power converter shuts down due to a fault scenario (VSI in the case of a grid-connected system). The feedback current to SOFC reduces to zero. The supply of fuels needs to be cut in this case. But due to the slow dynamics of BOP, the fuel reduction will take time. The SOFC voltage follows the dynamics of BOP and might take minutes to a couple of hours to reduce to zero depending on the fuel cell. If the voltage is not stored, it may damage the components. An energy storage device (typically

a battery) can generally be integrated into the intermediate DC link using a dc-dc power conversion system as shown in Figure 6.33.

Figure 6.33: Energy storage system added to the SOFC based PSC to handle system fault scenarios.

The DC converter is disconnected in the example to show the behavior of SOFC with no load. The current reduces to zero (current non zero due to ohmic resistance of the cell). The SOFC voltage remains 440 V. There is a need for the energy storage device to dump the power in case of an abrupt shutdown.

Figure 6.34: SOFC current at No Load condition

Figure 6.35: SOFC voltage at No Load condition

Figure 6.36: SOFC power at No Load condition

CHAPTER

7

CONCLUSIONS & FUTURE WORK

7.1 Summary of Results

7.1.1 SOFC

SOFC voltage is dependent on the dynamics of chemical reactions. The effect can be seen with different time constants. The FC stack and power electronics system is fast. But the supply of fuel to the fuel cell depends on the speed of reactions in the processor (CPOX). The load (resistor) is connected to the SOFC model and the fuel cell voltage is plotted for ramp current and step currents. The effect of temperature is also discussed. To meet the power demand of the grid, 400 fuel cells are connected in series. The control modes have been tested and their performance in terms of providing grid support in the occurrence of Undervoltage and frequency variation has been demonstrated.

7.1.2 Support Features of grid

The control modes are sufficient to bring back the normal operation of PCC voltage. The active power is controlled in case of frequency variation as discussed. The reactive power is

injected/absorbed according to the PCC voltage. The reactive power is injected/absorbed based on the absorption /generation of active power. The FC power is varied as per load power demand.

The inverter connected to the grid is subjected to voltage sag condition. The drop in voltage is controlled by injecting the reactive power as specified in IEEE 1547 section of voltage reactive power control. A smooth detection of the voltage is made possible by maintaining the linear V-Q characteristics for reference set point.

A control scheme is implemented to inject active power to the grid as per the frequency.

The SOFC model is implemented in opal-RT with the controller designed in CPU and the power conversion system in FPGA.

7.2 Conclusions

The model is not an exact emulation of the physical SOFCs. But the modeling has given an idea about the behavior of the fuel cells and their applications for commercial use.

The modeling of SOFC is done with many assumptions. The SOFC modeling didn't take into account the variations in the temperature due to the reactions. This will change the transient behavior of the SOFC. It might impact the load too abruptly. The reaction rates are not exact and I have taken less time due to limitations in capturing results. As a result, the SOFC steady-state will take time.

Challenges faced

Due to the limited accessibility of the lab, it was difficult to solve opal-RT-related issues.

Limitation

SOFC has been modeled considering the system to be completely adiabatic. The temperature of the fuel channel, air channel and PEN is kept same. The compressor and heat exchanger are not implemented in the modeling irrespective of being the most important components in the system.

Some of the issues of IEEE 1547 that are not covered include cases of unbalanced sag and swell conditions. The PLL design is limited to detect the magnitude of the voltage only for balanced sag.

7.3 Future Work

- Implementation of Controller in loop for SOFC modeling.
- Comparison between SOFC and PEMFC performances using the opal-RT platform.
- Implementation of energy balance sub-model in the fuel cell and the impact of temperature variations in the performance.
- Fault testing and Low voltage ride through cases.
- Testing the SOFC system for data center applications.

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APPENDICES

APPENDIX

A

ACRONYMS

A summary of all acronyms is documented in Table A.1.

Table A.1: A summary of acronyms used in alphabetical order.

Acronym	Abbreviation
Solid Oxide Fuel Cell	SOFC
Proton exchange membrane fuel cell	PEMFC
Real Time Digital Simulation	RTDS
Future Renewable Electric Energy Delivery and Management	FREEDM

APPENDIX

B

VARIABLES

A summary of all variables is documented in Table B.1.

Table B.1: A summary of common meteorological variables and their abbreviations in alphabetical order.

Variable	Abbreviation
Fuel utilization	u
Faraday's constant	F
Oxygen to Carbon ratio	O_2C
Universal gas constant	R
Temperature of fuel channel	T
exchange current density	i_o
limiting current of the cell	i_L
Ohmic resistance of the fuel cell	r
The downstream pressure of fuel exhaust	P_{fuel}
SR reaction rate	r_{SR}