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Fuel Cell – Ultra Capacitor hybrid system for Grid Connected Applications

P.Vijayapriya[1], D. P. Kothari[2], M. Kowsalya[1]
[1]Vellore Institute of Technology, University, Thiruvalam Road, Vellore
[2]MVSR College of Engineering, Hyderabad
Corresponding author, e-mail: pvijayapriya@vit.ac.in, dpk0710@yahoo.com

Abstract

Fuel cells are considered as one of the most promising devices for standalone/grid connected distributed generations due to its cleanliness, modularity and higher potential capability. In the present energy scenario, Fuel cells combined with other renewable technologies are gaining attraction. This paper focuses on the combination of Fuel Cell (FC) and Ultra-Capacitor (UC) systems for sustained power generation. Model of Proton Exchange Membrane (PEM) Fuel Cell have been developed in the MATLAB/Simulink Environment. To supply the required hydrogen moles, Electrolyzer model was developed. Hydrogen storage tank was modeled such that the generated moles of hydrogen from the electrolyzer are stored in the storage tank and the fuel cell receives the required amount of hydrogen moles from the storage tank rather than the electrolyzer. The combined system was synchronized to the grid and when the load demand exceeds the capacity of the fuel cell system, then the additional power is supplied by the grid thus ensuring continuity of supply to the load.

Keywords: *fuel cell, ultra capacitor, electrolyzer, hydrogen storage tank, grid connected*

1. Introduction

In order to move towards a sustainable existence in our critically energy dependent society, there is a continuing need to adopt environmentally sustainable methods for energy production, storage, and conversion. The use of fuel cells in both stationary and mobile power applications can offer significant advantages for the sustainable conversion of energy. Benefits arising from the use of fuel cells include efficiency and reliability, as well as economy, unique operating characteristics, planning flexibility and future development potential. By integrating the fuel cells in series with renewable energy storage and production methods, sustainable energy requirements may be realized.

There are many challenges and technical hurdles in realizing this, but however the fuel cell community must face this in order to be widely used in the distributed generation market. The first challenge is that fuel cells could contribute to the establishment of a distributed generation market if they become more economically competitive with current technologies. The key challenge is to produce an ideal hydrogen-fuelled engine (a fuel cell) that can cost-effectively produce power in the hydrocarbon-based economy of today. This is the most significant technical challenge with regard to integrating fuel cell systems with available infrastructure, reducing their capital cost through volume manufacturing, and achieving widespread use in various sectors.

Different models of PEM Fuel Cell (Polymer Electrolyte Membrane Fuel Cell) is available in literature [1-8] that are suitable for electric power generation purposes in which some are very simplified electrical model that can be used in designing a control system [2-[4]. In [5], Caisheng Wang et al developed dynamic model for PEM fuel cells which includes double layer charging effect and thermodynamic characteristics that could be used in control related studies. Kodjo Agbossou et al [6] discusses about the activation loss, ohmic loss and concentration loss with the help of polarization curves. Ali et al [7] proposed a dynamic model that modularizes the fundamental thermal-physical behavior of a fuel cell and developed a modular block that exhibits most of the fuel cell properties and incorporates essential physical and electrochemical processes that happens along its operation. Another dynamic model that is suitable for determining control strategy was developed by Gorgun [8] that will ensure efficient

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and reliable operation of the electrolyzer. Also the model can be integrated with renewable energy system models to design, analyze and optimize sustainable energy systems. Alejandro et al [9] developed both Simulink and prototype model of PEM fuel cell oriented towards control and operation optimization and can be used as tool for design of Fuel Cell based system. In [10], A. Kirubakaran et al discusses about regulation of the fuel cell terminal voltages with a simple DC/DC boost converter interfaced with PEM fuel cell system. It was observed that the design of simple DC/DC boost converter gives better performance for varying loads thereby increasing its life span. El Sharkh et al [11] analyzed how active and reactive power output of a standalone PEM Fuel cell power plant is controlled and verified the result by using the model to predict the response of power plant under two different load conditions. Per Unit mathematical model using dq0 reference frame theory was developed by Shailendra et al [12] to define the power flow limits that can be supplied by the fuel cell power plant. Soedibyo [13] utilized Genetic Algorithm method to determine the optimal capacities of hydrogen, wind turbines and micro-hydro unit according to the minimum cost objective functions. M.Uzunoglu et al [14] modeled a wind/FC/UC hybrid power system for a grid-independent user with appropriate power flow controllers. The proposed system can be used for non-interconnected remote areas or isolated cogeneration power systems with non-ideal wind speed characteristics. The additional hydrogen moles generated are stored in hydrogen for future use and the model does not describe how this can be utilized.

2. Research Method

In this paper, a grid connected fuel cell/Ultra capacitor model is designed to meet the load requirements. The Fuel cell takes hydrogen from the electrolyzer directly until the threshold voltage, while after that, the hydrogen storage supplies hydrogen to the Fuel Cell thus utilizing the stored hydrogen for meeting the load requirements

2.1. Fuel Cell – Ultra Capacitor Dynamic Model

For sustainable existence in the energy deficient society, we should adopt to sustainable methods of energy production, conversion and storage. Fuel cells finds a strong place in sustainable energy conversion that offers greater advantages for both mobile and stationary power appliances. Reliability, efficiency, flexibility and future development potentials are some of the benefits of using fuel cell technology for distributed generation. The main disadvantage is the cost and the availability or extraction of hydrogen. Of the different types of fuel cells available, PEM fuel cell is promising technology for distributed generation.

The polarization curve for the PEM fuel cell is obtained from the sum of the Nernst's voltage, the activation over voltage, and the ohmic over voltage. Assuming constant temperature and oxygen concentration, the fuel cell output voltage may be expressed as:

$$V_{cell} = E + \eta_{act} + \eta_{ohmic} + \eta_{trans} \tag{1}$$

Where:

$$\eta_{act} = -B\ln(CI_{fc}) \tag{2}$$

$$\eta_{ohmic} = -R_{\text{int}} I_{fc} \tag{3}$$

$$\eta_{trans} = me^{nI_{fc}} \tag{4}$$

Now, the Nernst's instantaneous voltage may be expressed as:

$$E = N_O \left[E_O + \frac{RT}{2F} \log\left[\rho H_2 \frac{\sqrt{\rho O_2}}{\rho H_2 O} \right] \right] \tag{5}$$

Where:

$$\rho H_2 = \frac{1/KH_2}{1+\tau_{H_2}s}(qH_2 - 2K_rI) \tag{6}$$

$$\rho O_2 = \frac{1/KO_2}{1+\tau_{O_2}s}(qO_2) \tag{7}$$

$$\rho H_2O = \frac{1/KH_2O}{1+\tau_{H_2O}s}(qH_2O) \tag{8}$$

The MATLAB and Simulink based Fuel cell system model developed in this paper using the above equations is shown in Figure 1 and the output voltage waveform is shown in Figure 2.

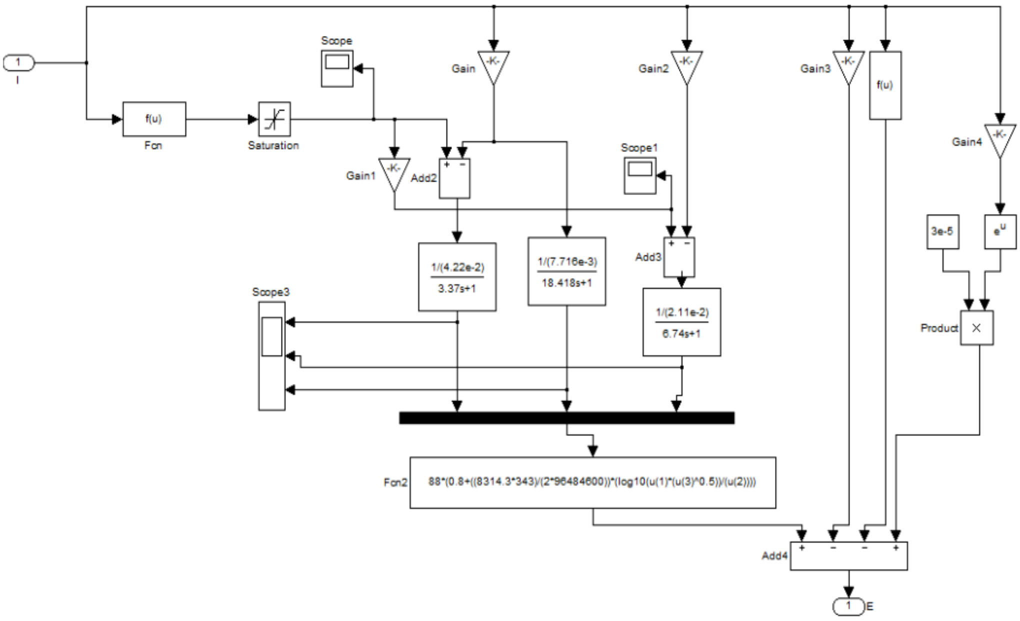

Figure 1. Simulink Model of the Fuel Cell System

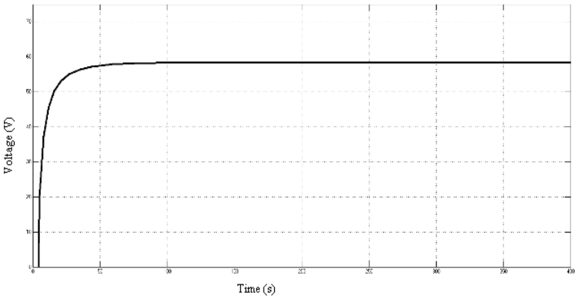

Figure 2. Output Voltage of PEMFC

As seen from the graph, the fuel cell system takes a few seconds to reach load demand level, hence it has a little poor load following characteristic. This delay in load following is mainly caused by the reformer due to gas processing response.

Therefore, for grid connected operation a battery or charged ultra-capacitor can be used in conjunction with the fuel cell system to meet the load requirement during transient period.

UC provides lowest cost per Farad, extremely high cycling capability, and are environmentally safe. The capacitance of UCs may vary from a few Farads to several thousand Farads per cell. Because of the above mentioned unique characteristics, UCs are utilized for a wide range of applications. The UC model that has been implemented in MATLAB/Simulink is shown in Figure 3 and its characteristics is shown in Figure 4

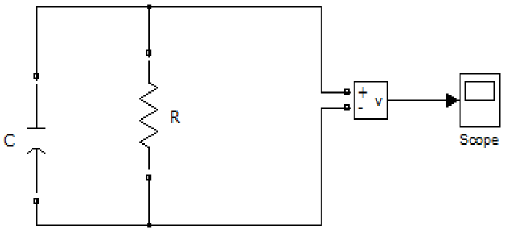

Figure 3. UC Model

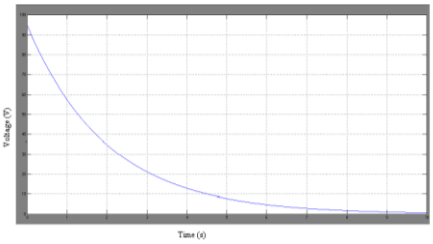

Figure 4. UC Characteristics

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On simulating the combined Fuell Cell – UC system, shown in Figure 5, the transient of the output voltage is much reduced when compared to Fuel cell operating alone thus enabling this system to take up load dynamically. Here the output voltage shown in Figure 6 is the output of the boost converter connected to the combined system.

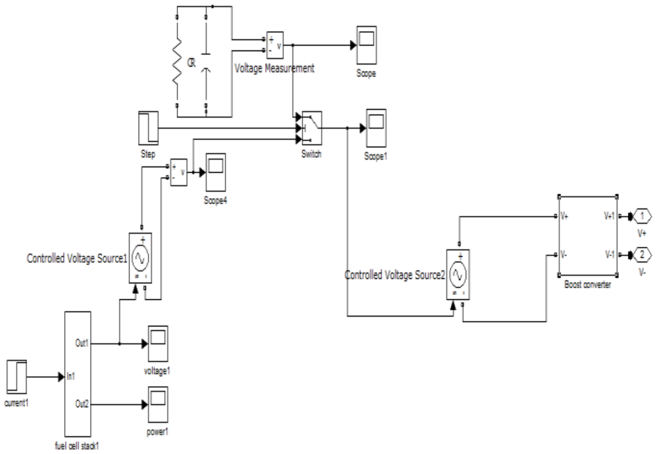

Figure 5. Combined Fuel Cell – UC System

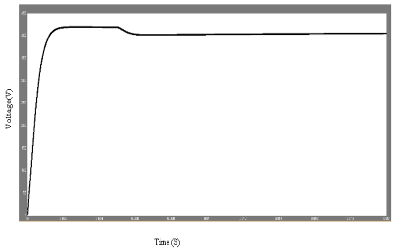

Figure 6. Output of the Combined System with Boost Converter

2.2. Electrolyzer Model

Electrolyzers are devices that produce pure hydrogen and oxygen to meet the requirements of different users. Among the various types of electrolyzers, PEM electrolyzers are very simple and compact. Besides they ensure high purity and efficiency at high current density levels. PEM electrolyzers, use electromotive force to break the bond between the hydrogen and oxygen in the H2O when dc voltage is supplied. The membrane separates the H2 from the O2. The electrochemical reaction of water electrolysis is given by:

$$H_2O(\ell) + electrical\ energy \rightarrow H_2(g) + 1/2O_2(g) \quad (9)$$

According to Faraday’s law, hydrogen production rate of an electrolyzer cell is directly proportional to the electrical current in the equivalent electrolyzer circuit.

$$N_{H2} = \frac{\eta_F n_c i_e}{2F} \tag{10}$$

The ratio between the actual and the theoretical maximum amount of hydrogen produced in the electrolyzer is known as Faraday efficiency. Assuming that the working temperature of the electrolyzer is 40 ◦C, Faraday efficiency is expressed by:

$$\eta_F = 96.5 \exp\left(\frac{0.09}{i_e} - \frac{75.5}{i_e^2}\right) \tag{11}$$

According to the Equation (10) & (11), a simple electrolyzer model is developed using Simulink, which is illustrated in Figure 7.

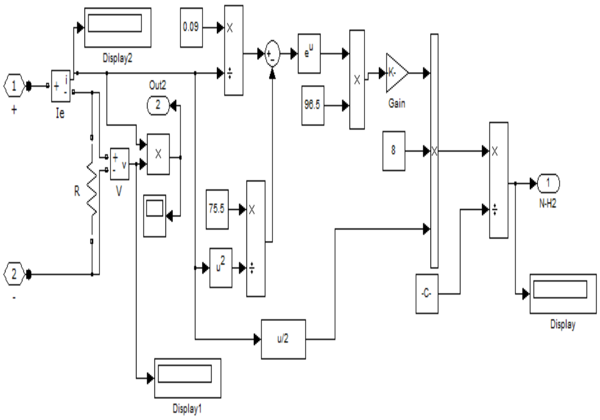

Figure 7. Simulink Model of Electrolyzer

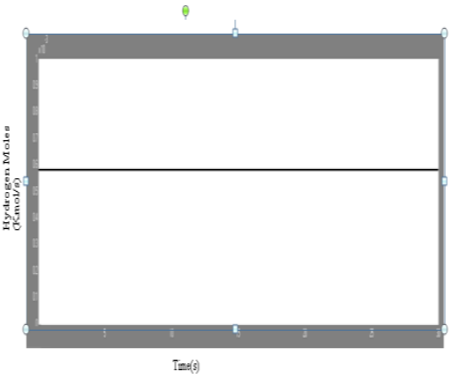

Figure 8. Electrolyzer Output

In this model, the electrolyzer works on the operating point 45 A–50V. Therefore, the dc bus of the electrolyzer is fixed at 400V and eight electrolyzer units are used in series (45 A–400 V) to produce the hydrogen. The output of the model is shown Figure 8.

2.3. Hydrogen Storage Tank Model

The hydrogen storage tank model is based on Equation (12) and it directly calculates the tank pressure using the ratio of hydrogen flow to the tank. The produced hydrogen is stored in the tank, whose system dynamics can be expressed as follows:

$$P_b - P_{bi} = z\frac{N_{H_2} R T_b}{M_{H_2} V_b} \tag{12}$$

The Simulink model of the hydrogen storage model is depicted in Figure 9. Neither the compression dynamics nor the compression energy requirements are accounted for in our calculations. All auxiliary power requirements such as pumps, valves, fan and compression motors were ignored in the dynamic model.

The amount of hydrogen moles consumed by the FC system is proportional to the power drawn from the FC system. It is evident that the hydrogen storage tank pressure decreases with time as more and more hydrogen extracted from the storage tank because the load increases. The pressure variation of storage hydrogen according to load is illustrated in Figure 10.

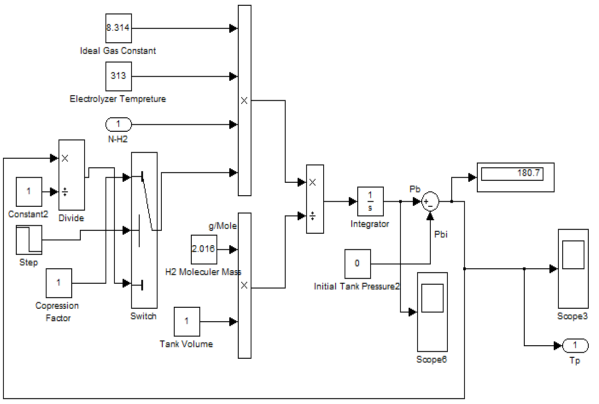

Figure 9. Simulink Model of Hydrogen Storage Tank

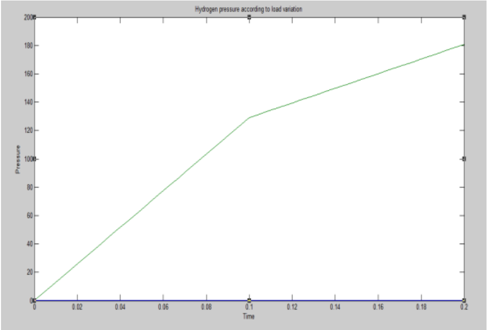

Figure 10. Hydrogen Tank Pressure Variation

In the previous literature, the excess amount of hydrogen (amount of hydrogen produced by hydrogen and the amount consumed by the fuel cell) is stored in the tank and how this stored hydrogen is used in case of deficiency is not illustrated as there is no feedback path from the storage tank to the fuel cell

In this model, the hydrogen moles developed by the electrolyzer is stored in the hydrogen storage tank, and the fuel cell draws the necessary amount of hydrogen from the storage tank directly. The hydrogen storage tank subsystem converts the pressure back to hydrogen moles to be given to Fuel cell. However during the initial transient period till the Fuel cell reaches 90V, the Electrolyzer directly supplies the hydrogen moles to the Fuel cell because, the pressure in hydrogen tank would not be sufficient to deliver the required moles to the Fuel Cell. The Simulink model of the subsystem is shown in Figure 11.

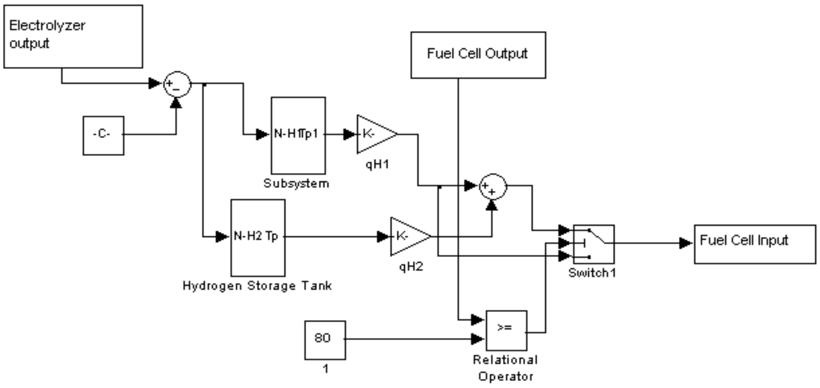

Figure 11. Complete Hydrogen Storage Tank System

3. Results and Analysis

DC output of the Fuel Cell is converted to AC using a IGBT inverters by generating appropriate gate signals. To remove harmonics in the converted AC signal, LC filter is used. The Simulink model of the complete system is shown in Figure 12.

This complete system is designed to meet the upto 2 kW load only. When the load exceeds more than 2kW, control circuit makes grid automatically switched ON and both system and grid satisfies the demand. In control circuit, the load side power is compared with reference 2kW. When the relational operator input is 1 then the signal is given to the circuit breaker while all other times there are no signal to the circuit breaker.

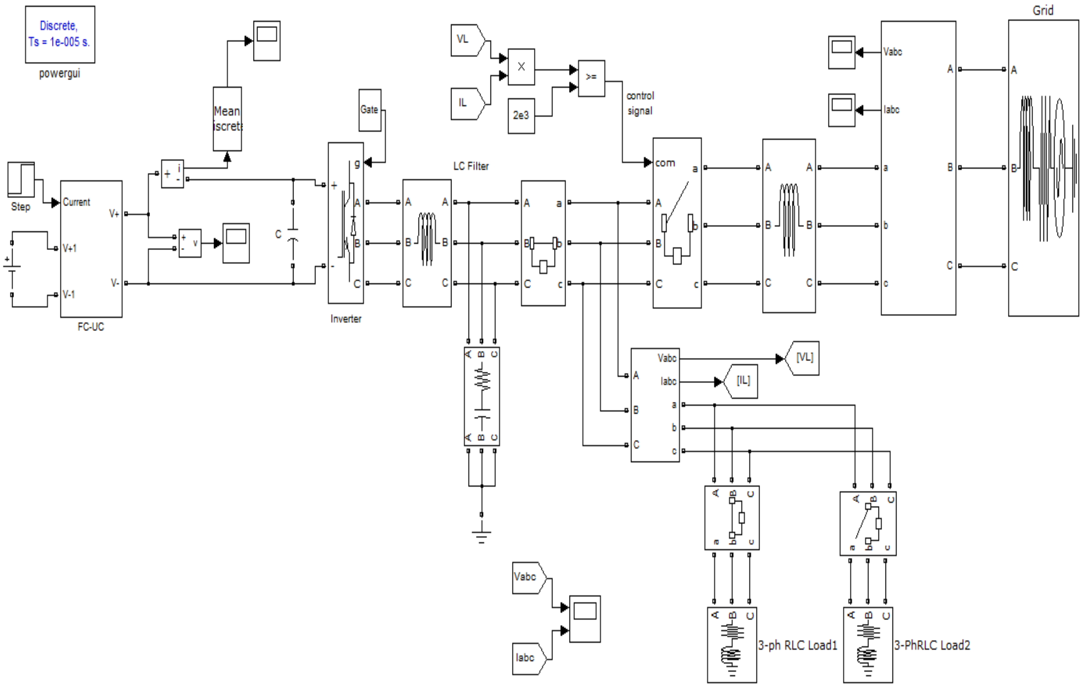

Figure 12. Complete Simulink Model of the Proposed System

Initially upto 0.1 sec, a load of 2 kW is added and the Fuel Cell is supplying the required load power. At 0.1 sec another load of 2.5Kw is added and hence the Grid also supplies power to the load along with the Fuel cell system. Figure 13, shows the waveform of voltage and the current of the load. As seen clearly, the load current has increased at 0.1 sec.

Figure 14 shows the grid current. It is evident from the Figure 14 that, upto 0.1 sec, grid current is zero or no power is drawn from the grid as the Fuel cell power is sufficient to meet the load.

When the load is increased at 0.1 sec beyond the capacity of the Fuel cell, then the required additional power is taken from the grid as evident from Figure 14.

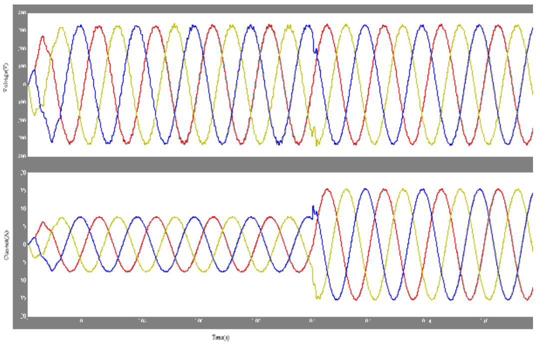

Figure 13. Load Voltage and Load Current

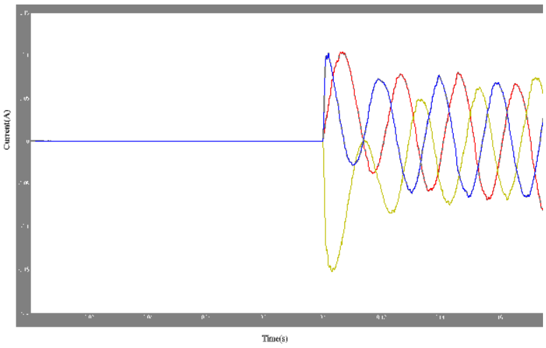

Figure 14. Grid Current

4. Conclusion

The dynamic model of Fuel Cell has been developed and it is observed that due to inherent property of fuel cell, there is a delay in output voltage. To avoid this problem charged Ultra Capacitor is connected in parallel with the FC Stack. Electrolyzer and Hydrogen Storage tank were also modeled which is responsible to supply the hydrogen fuel to fuel cell as per load variation and storage of hydrogen during surplus generation. Unlike the Electrolyzer and Hydrogen storage tank models reported in the literature, for few seconds until the system voltage reaches the threshold limit, the electrolyzer directly supplies hydrogen moles required by the Fuel Cell and the remaining is stored in the hydrogen tank, while after that, the electrolyzer stores all the generated hydrogen moles in the tank and the storage tank supplies the required hydrogen moles to the fuel cell. As the system is Grid connected, when the load demand is more than the capacity of the Fuel cell system, then the excess power is delivered by the Grid thus ensuring continuity of supply to the load.

Table 1. Operational Parameters of PEMFC–Electrolyzer Model

Parameters	Symbol	Value	Unit
DC output voltage of FC system	Vcell	-	V
Nernst instantaneous voltage	E	-	V
No load voltage	Eo	0.6	V
Activation over voltage	η_{act}	-	V
Ohmic over voltage	η_{ohmic}	-	V
Voltage loss due to mass transfer & concentration loss	η_{trans}	-	V
Slope of Tapel line	B	0.04777	A^{-1}
Constant to simulate ohmic loss	C	0.0136	V
Internal resistance of FC	R	0.00303	Ω
Fuel cell system current	I_{fc}	-	A
Constants derived from experiments	m, n	-	-
Number of series fuel cells instack	No	80	-
Universal gas constant	R	8314.47	$(JKmolK)^{-1}$
Absolute temperature	T	343	K
Faraday's constant	F	96484.6	$CKmol^{-1}$
Hydrogen partial pressure	ρH_2	-	atm
Oxygen partial pressure	ρO_2	-	atm
Water partial pressure	ρH_2O	-	atm
Hydrogen value molar constant	KH_2	$4.22e\text{-}^{5}$	Kmol (atm s)-^{1}
Hydrogen time constant	τ_{H2}	3.37	S
Hydrogen flow that reacts	qH_2		Kmol s^{-1}
Modeling constant	Kr	$1.8449e^{-6}$	$Kmol(SA)^{-1}$
Stack current	I		A
Oxygen value molar constant	KO_2	$2.11e\text{-}^{5}$	Kmol (atm s)-^{1}
Oxygen time constant	τ_{O2}	6.74	S
Input molar flow of oxygen	qO_2		Kmol s^{-1}
Water value molar constant	KH_2O	$7.716e^{-6}$	Kmol (atm s)-^{1}
Water time constant	τ_{H2O}	18.418	S
Molar flow rate of water	qH_2O	-	Kmol s^{-1}
Produced hydrogen moles per second	NH_2	-	Mol s^{-1}
Faraday efficiency	η_F	-	-
Number of electrolyzer cells in series	n_c	8	-
Electrolyzer current	i_e	-	A
Pressure of tank	Pb	-	Pa
Initial pressure of tank	Pbi	-	Pa
Compressibility factor as a function of pressure	Z	-	-
Molar mass of hydrogen	MH_2	2.016	$Kgkmol^{-1}$
Volume of tank	Vb	1	m^3

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