Vector Control of Fuel Cell Based Grid Connected Inverter

Prabodha Kumar Rath^{1,*} and Kanhu Charan Bhuyan²

¹Lecturer, Department of Electrical Engineering, College of Engineering and Technology, Bhubaneswar, Odisha, India

²Asst. Professor, Department of Instrumentation and Electronics, College of Engineering and Technology, Bhubaneswar, Odisha, India
E-mail: prabodharath85@gmail.com; kanhu2006@gmail.com

*Corresponding Author

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Abstract

Electrical energy consumption increases day by day so we should find alternative means to generate electrical energy to meet the demand in addition to existing conventional generation facilities. For this distributed generation (DG) will definitely going to take a key role in the energy supply. Presently various technologies are available as DG, they are micro-turbines, photovoltaic cells system, fuel cells system and wind energy systems. Out of these technologies fuel cell have becoming more popular due to its characteristics like cleanliness, portability and suitability for electricity and heat generation. In this paper, model of Solid Oxide Fuel Cell (SOFC) is presented. As fuel cells operate at lower voltages so there is a need of DC-DC boost converter to boost. Then the boosted voltage inverted by using DC-AC converter known as grid-connected inverter in order to inter connect to the utility grid. The control strategy of this model is vector control (VC) method. VC method is use for the generation of DC-AC converter switch pulse. *MATLAB/SIMULINK* is used to validate the modeling and simulation of fuel cell generation and power conditioning unit.

Keywords: Fuel Cell (FC), Vector Control (VC), Boost Converter, Distributed Generation (DG), Shunt Filter.

1 Introduction

Now-a-days throughout the world the use of electrical energy is much more in comparison electrical energy use in last few decades. Production of electrical energy mainly depends on fossil fuel. So to meet the demand of electrical power we are consuming huge amount of fossil fuel which has limited existence in nature and also inject harmful gases to the environment resulting in green house effect. Therefore to meet the electrical energy demand we should use the renewable sources of energy like wind energy, solar energy, biomass power etc [1, 4]. Notable progress in electric market deregulation and new rules in terms of environmental pollution leads to use of distributed generation. There is a significant rise in use of renewable sources of energy due to its clean power generation property and also due to awareness among the people about the harmfulness of conventional sources of energy and due to shortage of power generation. The use of renewable sources of energy leads to healthy environment and meeting the energy demand in a better way and researchers are working very hard to fulfill the above requirements [2].

A large portion of renewable energy comes from solar power and wind power. The biggest demerit of these sources of energy is there variable nature. Solar power is only available during day time and wind tends to blow intermittently. As storing of electrical energy is a difficult task so excess renewable energy produced cannot be stored for future use. So to overcome the demerits of solar power and wind power fuel cell is use to generate electrical energy [17].

A fuel cell is a device which is use to convert stored chemical energy to electrical energy. An electrochemical process, which is an efficient process, is take place for conversion of fuel to electrical energy. There are many advantages of fuel cells over wind power and solar power generation. They are: high efficiency at any load, fuel cell can be placed any site in distribution network (but solar power and wind power generation unit cannot), lower maintenance and longer life, zero greenhouse gas emission [5].

The motive of this paper is to propose and present the experimental results of a grid-connected three phase FC system using vector control scheme. In this paper FC is use to produce electrical power. As the generated power is at low voltage level by using boost converter electrical power at higher voltage

level is produced. The proposed three phase grid-connected FC system can operate either in grid connected or stand-alone mode [3].

The paper is organized as follows:

Section 2 provides an introduction to the FC system. A single line diagram of the proposed system is provided with detailed explanation of each element associated with the system.

Section 3 provides the operating principle of proposed system.

Section 4 presents the vector control method for grid connected inverter.

Section 5 provides the simulation results of the proposed system. The steady-state condition is established and operational performance and stability of the system is studied.

2 Components of The System

The single line diagram as shown in Figure 1 is the representation of a FC connected to grid through inverter system. The system consists of many equipment such as FC, DC-DC boost converter, DC-AC converter i.e. inverter, filter, control unit and grid. In the following subsection the description of some important components of the proposed system and their function given.

2.1 Fuel Cell

A FC is an electrochemical cell in which the chemical energy from a fuel converted into electricity through an electrochemical reaction of hydrogen fuel with oxygen or another oxidizing agent. FC may be explained as source of electric power which never becomes dead as long as hydrogen and oxygen are supplied. The hydrogen is supplied directly or indirectly produced by reformer from fuels such as natural gas, alcohols, or gasoline.

Figure 1 Block diagram of fuel cell based grid connected inverter.

There are various type of FCs are there and as we focus on efficiency, low emissions, low cost solid oxide fuel cell is best among them.

The principal components of SOFC include an anode gas flow field, an anode gas diffusion layer, an anode catalyst layer, a cathode catalyst layer, a cathode gas diffusion layer, and a cathode gas flow field. Oxygen is supplied to cathode gas flow field and it diffuses through the gas diffusion layer and infuses into cathode catalyst layer and fuel cell membrane. At the same time, hydrogen gas is supplied to the anode gas flow field, where it to enters into fuel cell through anode gas diffusion layer and catalyst layer. A chemical reaction takes place between hydrogen and oxygen, due to which there is transfer of H^+ ion through the fuel cell from anode side to the cathode side and producing water as waste product [7].

The electrochemical reactions within the SOFC can be written as,

In practice, the ideal reversible electromotive force of the SOFC is reduced by various potential losses within the fuel cell. The terminal voltage V_{FC} of the fuel cell is

$$V_{FC} = V_o - V_{act} - V_{ohm} - V_{conc} \quad (4)$$

Here V_o is open circuit voltage, V_{act} is activation loss, V_{ohm} is Ohmic loss and V_{conc} is concentration loss.

When fuel cell circuit is open, the reversal potential is given by the equation

$$V_o = N_o \left\{ E^o + \frac{RT}{2F} \left(\ln \frac{P_{H_2} P_{O_2}^{0.5}}{P_{H_2O}} \right) \right\} \quad (5)$$

N_o is number of cells in stack, E^o is standard reversible cell potential (1.2 V), R is universal gas constant (8314 J/(k mol K)), T is absolute temperature (1273 K), F is faraday's constant (96487 C/mol), P_{H_2} , P_o and P_{H_2O} are partial atmospheric pressure of H_2 , O_2 and H_2O .

The polarisation curve of SOFC provides the fuel cell output voltage as a function of the current density in steady state.

Figure 2 V-I characteristic of a single FC.

The activation losses at the anode and cathode side are given by

$$V_{act} = -[\xi_1 + \xi_2 T \xi_3 T \ln(c_{O_2}) + \xi_4 T \ln(i_{FC})] \quad (6)$$

ζ represents the parametric coefficients for cell model.

At the vapour-liquid interface, the dissolved oxygen concentration (mol/cm³) is obtained from Henry's law as.

$$c_{O_2} = \frac{P_{O_2}}{5.08 \times 10^6 e^{-\left(\frac{498}{T}\right)}} \quad (7)$$

The Ohmic voltage loss produced within the fuel cell as a result of the electrical resistance of the SOFC material (ceramic material) is given by.

$$V_{ohm} = (0.01605 - 3.5 \times 10^{-5} T + 8 \times 10^{-5} j) j \quad (8)$$

Meanwhile, the concentration polarisation loss caused by the inability of the oxygen and hydrogen gases to diffuse at a sufficient speed through the porous components of the cell is given by.

$$V_{con} = -B \ln \left(1 - \frac{J}{J_{max}} \right) \quad (9)$$

B is the work status constant of the fuel cell and J_{max} is the maximum cell current density (Acm⁻²).

For a fuel cell stack containing N number of fuel cells, the output voltage V_{stack} and the power P_{stack} are represented as

$$V_{stack} = NV_{FC} \quad (10)$$

$$P_{stack} = V_{stack} I_{FC} \quad (11)$$

Figure 3 P-I characteristics of fuel cell.

I_{FC} is fuel cell current. The result obtained from the simulation for power verses current density of fuel cell model is shown in Figure 3.

The fuel cell efficiency can be expressed as

$$\eta = \mu_f \frac{V_{FC}}{1.48} \quad (12)$$

The result obtained for fuel cell efficiency from the simulation is shown in Figure 4.

2.2 DC-DC Boost Converter

The process that changes one DC voltage to a different DC voltage is called DC-DC conversion. A boost converter is a DC-DC power converter that steps up the input voltage to a higher output (load) voltage [8]. It is a converter which consists of two semiconductors (a diode and a transistor) and one energy storage element inductor. To reduce voltage ripple, filters made of capacitors are normally added to such a converter's output (load-side filter).

Figure 4 Efficiency-current characteristics of fuel cell.

For DC-DC boost converter the relationship between input voltage and output voltage is

$$V_{FC} = \frac{V_{FC(DC)}}{1 - d} \quad (13)$$

Here V_{FC} is the output voltage of boost converter, $V_{FC(DC)}$ is the input voltage to boost converter and d is the duty cycle.

2.3 DC-AC Converter

A DC-AC converter or inverter is an electronic device or circuit that converts direct current (DC) to alternating current (AC). The input voltage, output voltage and frequency, and overall power handling depend on the design of the specific device. The inverter does not produce any power; the power is provided by the DC source. For designing of inverter circuit fully controlled power electronic switches are used so that we don't extra commutation circuit for switching off of the switches. To control the switching action of switches pulse width modulation technique is used [6].

2.4 Shunt Filter

Three-phase harmonic filters are shunt filter which are used in power system to reduce the distortion in voltage and for power factor correction as they provide reactive power at fundamental frequency. Due to power electronic converters, which are non linear in nature, harmonic currents or harmonic voltages, are injected into power system and the order of harmonics high as the PWM switching frequency of the semi-conductor switches (like MOSFETs, IGBTs) is high. Shunt filters reduce distortion by diverting harmonic currents in less impedance paths. Harmonic filters are designed to be capacitive at fundamental frequency, so that they could produce reactive power required by converters. To get an acceptable distortion, many units of filters of different types are connected in parallel. High-pass filters are used to filter out the high-order harmonics. A special type of high-pass filter, the C-type high-pass filter, is used to provide reactive power and avoid parallel resonances. It also allows filtering low order harmonics (such as 3rd), while keeping zero losses at fundamental frequency.

3 Control Scheme of Grid Connected Inverter

The control system of the proposed grid connected fuel cell system is comprised of a faster vector controller. Where, the vector controller is completed

Figure 5 Vector control system of VSC-HVDC system.

by additional controllers which provide the references for the vector controller. Thus, the vector controller is the inner loop and additional controller is the outer loop. In this paper, the additional controllers will be referred to as the outer controllers. The outer controllers include the DC voltage controller, the reactive power controller or the frequency controller. Even if both current and voltage control schemes are possible, current control is generally preferred for its better dynamic characteristics and inherent over-current limitation capabilities. When current control is used, grid current and inverter output currents are measured and compared with reference signals; the current errors are used as inputs to the PWM modulator, which then provides the required switching signals.

The AC filters connected to the system behave as pure capacitors at fundamental frequencies. Hence in the mathematical model presented here, the filter resistances and inductances can be neglected. The voltage across the transformer, the current to the filter and the voltage across the source impedance can be obtained in three phase instantaneous form as follows:

The voltage across source impedance is

$$V_{ac}(t)_{abc} - V_s(t)_{abc} = R_s i_s(t)_{abc} + L_s \frac{d}{dt} i_s(t)_{abc} \quad (14)$$

The current through the filters is

$$i_s(t)_{abc} - i_t(t)_{abc} = C_f \frac{d}{dt} V_s(t)_{abc} \quad (15)$$

The voltage across the transformer is

$$V_s(t)_{abc} - V_c(t)_{abc} = R_T i_t(t)_{abc} + L_T \frac{d}{dt} i_t(t)_{abc} \quad (16)$$

The above equations in can be converted into $\alpha\beta$ frame as follows:

$$\frac{d}{dt}i_s(t)_{\alpha\beta} = -\frac{R_s}{L_s}i_s(t)_{\alpha\beta} + \frac{1}{L_s}\{V_{ac}(t)_{\alpha\beta} - V_s(t)_{\alpha\beta}\} \quad (17)$$

$$\frac{d}{dt}V_s(t)_{\alpha\beta} = \frac{1}{C_f}i_s(t)_{\alpha\beta} - \frac{1}{C_f}i_t(t)_{\alpha\beta} \quad (18)$$

$$\frac{d}{dt}i_t(t)_{\alpha\beta} = -\frac{R_T}{L_T}i_t(t)_{\alpha\beta} + \frac{1}{L_T}\{V_s(t)_{\alpha\beta} - V_C(t)_{\alpha\beta}\} \quad (19)$$

By using the transformation angle $\emptyset$ derived from the phase locked loop (PLL), the above equations are further transferred to the synchronously rotating dq- reference frame, using Park's transformation, as follows:

$$\frac{d}{dt}i_s(t)_{dq} = -\frac{R_s}{L_s}i_s(t)_{dq} - j\omega i_s(t)_{dq} + \frac{1}{L_s}\{V_{ac}(t)_{dq} - V_s(t)_{dq}\} \quad (20)$$

$$\frac{d}{dt}V_s(t)_{dq} = \frac{1}{C_f}i_s(t)_{dq} - \frac{1}{C_f}i_t(t)_{dq} - j\omega V_s(t)_{dq} \quad (21)$$

$$\frac{d}{dt}i_t(t)_{dq} = -\frac{R_T}{L_T}i_t(t)_{dq} - j\omega i_t(t)_{dq} + \frac{1}{L_T}\{V_s(t)_{dq} - V_C(t)_{dq}\} \quad (22)$$

the dq-current component through the transformer can be given by,

$$\frac{d}{dt}i_t(t)_d = \omega i_t(t)_q + \frac{V_s(t)_d - V_C(t)_d}{L_T} - \frac{R_T}{L_T}i_t(t)_d \quad (23)$$

$$\frac{d}{dt}i_t(t)_q = -\omega i_t(t)_d + \frac{V_s(t)_q - V_C(t)_q}{L_T} - \frac{R_T}{L_T}i_t(t)_q \quad (24)$$

The proposed simulation model consists of reactive power controllers at inverter side. The outer controller generates the reference values of the dq-current components for inner current controllers. The inner controller gains are higher when compared to the outer controller to ensure the stability of the complete system. A reactive power controller is obtained from equation

$$i_q^* = \frac{2}{3} \frac{Q_{ref}}{V_s} \quad (25)$$

Here, Q_{ref} is reference reactive power.

For accurate control of the reactive power, in combination with a feedback loop an open loop is used.

$$i_q^* = \frac{2}{3} \frac{Q_{ref}}{V_s} + \left(K_1 + \frac{K_2}{s} \right) (Q_{ref} - Q_{actual}) \quad (26)$$

Where, K_1 and K_2 are the proportional and integral gains respectively of the reactive power controller.

Figure 6 DC voltage control.

3.1 DC Voltage Control at Inverter Side

The inverter controller controls the DC link voltage of the system. DC voltage controller consists of outer control loop (Figure 6) where the reference DC voltage (V_{dc}^*) is compared with actual DC link voltage (V_{dc}) and error is fed to the PI-controller which generates the output in the form of reference current (I_d^*). This reference current is compared to the actual d-current component (I_d) of the AC system in inner current control loop (Figure 6). The output is in the form of voltage which is then compared to d-component of system voltage (V_d) and cross-coupling term to get the output in the form of voltage (V_d^*).

3.2 Reactive Power Control at VSC₂

The reactive power flowing between inverter and load system is controlled by reactive power controller at inverter. The reactive power controller consists of outer and inner current control loops as well. In the outer current control loop, reactive power reference (Q^*) is compared with the measured system reactive power (Q). The error is then passed through the PI-controller which gives output of reference current (I_q^*). This q-component of the current controls the reactive power flow in the system so it is used as a reference current for the inner current controller and compared with q-component of measure AC current (I_q). The error (E_{Iq}) gives voltage after passing through PI-controller. This voltage is then compared to the q-component of voltage (V_q) and cross coupling term to get the controller output voltage (V_q^*).

Figure 7 Reactive power control.

Figure 8 Inner controller loop.

4 Simulation Results

The fuel cell unit is connected to a DC-DC boost converter to get the required voltage level to connect it to the utility grid via the DC-AC inverter whose switching action is controlled by vector control method. The fuel cell connected to grid system is modeled in MATLAB/Simulink R2010a and Simulations are also performed to verify the simplified model.

Some assumptions are taken in this system:

- The switching loss of the power electronics switches is zero.
- The three phase transmission system is ideal.
- The reactive power is zero.

In the Simulink model of the proposed system its control system use sinusoidal PWM method of frequency 1350 Hz, the model is simulated with a time

Table 1 Parameters of fuel cell based grid connected inverter system

S.L.	Parameters	Value
1	Inverter Output Frequency (f)	50 Hz
2	Filter Inductance (L)	0.0095 H
3	DC link voltage	180 V
4	Switching Frequency of PWM	1350 Hz
5	Load Resistance (R _{Load})	100 Ohms
6	Filter Rating	490 VAR

of $7.406\mu\text{s}$. By using a small time step it is possible to observe the system performance in detail during transient state and steady state conditions. The Table 1 presents the system parameters and its ratings.

From the following Figure 9 it is clear that the output voltage of FC unit after the DC-DC boost converter which is the DC link voltage is settled to 188 V after 0.12 sec from starting.

The following Figure 10 shows the output three phase voltage of the DC-AC converter, from this it is clear that the voltage profile settled to its steady state value 0.57 pu at 0.12 sec.

The following Figure 11 shows the output three phase current waveform of the inverter unit, from this it is clear that the current settled to its steady state value at 0.1 sec.

From above voltage and current waveforms it is clear that both contain many distortions so we couldn't connect the inverter output to grid directly. We should filter out the distortion from the voltage and current.

The following Figure 12 shows the three phase voltage after the filtration process and from this it is clear that we get three phase sinusoidal output voltage with less distortion.

Figure 9 Fuel cell output voltage (V).

Figure 10 Inverter output voltage (pu).

Figure 11 Inverter output current (pu).

Figure 12 Inverter output voltage (pu) after filter.

The FFT analysis gives the THD content of voltage is 3.43% which is shown in following Figure 13.

The following Figure 14 shows the three phases current after the filter and from this it is clear that we get three phase sinusoidal output current with less harmonic content.

The FFT analysis gives the THD content of current is 3.8% which is shown in following Figure 15.

Figure 13 FFT analysis of voltage.

Figure 14 Inverter output current (pu) after Filter.

Figure 15 FFT analysis of current.

5 Conclusion

A model of the solid oxide fuel cell (SOFC) connected to grid through inverter was developed in MATLAB 2010a. A DC-DC boost converter with closed loop control feedback system has been built to increase the voltage level so that it could be connected to grid. A three phase DC-AC inverter has been designed and connected between the SOFC-load systems. Vector control technique along with sinusoidal pulse width modulation method is used for the switching of inverter effectively. The characteristics waveforms of voltage and current for the proposed system have been obtained and from the waveforms it is cleared that the parameters have faster response time, lower overshoot and less oscillation. The phase-phase voltage measured from the system and its THD is studied and it is found that harmonic content is very less.

This designed system could be used as a distributed generation system. As the system based on fuel cell so there is no bad effect on the environment that's why it could be used widely to meet the power demand efficiently.

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Biographies

Prabodha Kumar Rath received the B.Tech. degree in Electrical Engineering from Institute of Technical Education & Research, Bhubaneswar, Odisha, India in 2008 and the M.Tech. degree in Power System & Power Electronics specialization from Institute of Technical Education & Research, Bhubaneswar, Odisha, India in 2014. He is currently working as a faculty in Electrical Engineering dept. in CET, Bhubaneswar. His research interests include modeling and control of renewable energy systems and applications of Power Electronics system.

Kanhu Charan Bhuyan, received his B.Tech. degree in Electronics and Instrumentation Engineering from College of Engineering and Technology (Affiliated to Biju Patnaik University of Technology), Odisha, India in 2003 and his M.Tech. degree in Control and Automation specialization from IIT, Delhi, India in 2005. He received his Ph.D. degree from NIT, Rourkela, India in 2014. He is currently working as an Assistant Professor at Instrumentation and Electronics department, College of Engineering and Technology, Bhubaneswar. His current research interests in modeling of photovoltaic cell, fuel cell and control strategies of various power converter and renewable power generation systems.