PI and Hysteresis Current Controller for Grid-Connected Dynamic State Configuration Model of Solid Oxide Fuel Cell SOFC

Youssef A. Mobarak, Abdullah A. Alshehri

***Abstract:** As the surrounding problems of the states and the requirement to meet out the increasing energy demand are increasing gradually generation of distributed nature system based various types of clean power systems are being erected increasingly to manage the load side energy requirements and reduce the environmental issues. Fuel cell is the latest technology that can use as DG system and solve the above mention issues. In this research work, a grid-connected dynamic state of solid oxide fuel cell (SOFC) system is represented. The fuel cell stack DC voltage needs to be converted and stepped-up to match the load side grid. So, a DC-AC voltage source converter is utilized to for interfacing the fuel cells with the load side grid, and the transformer is installed for increasing the potential level to match the voltage grid. Two types of control strategies are presented (PI and hysteresis current controller) to control and shape the inverter output voltage, hence provides decoupled real and reactive energy. The entire work is modeled in MATLAB/Simulink.*

***Keywords:** Dynamic state, Grid, Fuel Cell, DC –AC inverter, PI controller, Renewable energy*

I. INTRODUCTION

Fuel cell systems play an important role in future energy conversion, with wide range of applications, from centralized and distributed power generation to transportation to portable electronics. Fuel cells have high efficiency, and the ability to be fed by both hydrogen and hydrocarbons such as methanol and diesel. Fuel cells will mainly help in transition to hydrogen economy due to the ease of producing hydrogen from other renewable energy such as biomass. However, hydrogen is able to transform in to other of energy for the final stage use. Hydrogen is the most suitable fuel for use in fuel cells in order to generate electricity. According to the US department of energy, the global market of fuel cells see some increase by four hundred percentage [1-2]. Non movable applications such as co-generation, back-up and distant micro grid power systems, accounted for 80% of the installed fuel cells.

The authors in [3] provided a general model of stand-alone SOFC that help to simulate and understand all parameters that affects the performance of the fuel cell, hence either increase or decrease the energy and efficiency of the fuel cells. Zhu and Tomsovic [4] present simplified slow dynamic state for MT and fuel powered cells. The thermodynamic model of the fuel cells is not included. In addition, a loosely coupled system with practical and active strategy of control is implemented to ensure the capability of the micro turbine and fuel cells, which is proven in this study. Yet, based on the references in [4],[5], Wen et al proposed a power control approach that employs the inverter along with the capacitor [6]. In [7], a dynamic model of SOFC is presented for addressing the issue in distribution system. The work involves the dynamics of the pressures of the reactants and its products, and the control of the converter. Differently, the authors [8] present a predictive model of SOFC stacks for controlling the stack heat based on the least squares based vector machine technique. The predictive model shows a rapid response and better accuracy under different operating temperatures. Colson et al [9] present the model of grid connected fuel cell plant which produces enough power to meet the load demand. The model is tested under short-duration transient to evaluate the system performance.

Wang and Nehrir [11] present a dynamic model and controller design methodology for power pool connected fuel cells distributed generation power monitoring units to control load flow from the Fuel cells to the distribution side using dq transformation. In [12], theory based simulations results of standalone power system network are presented. In [13], abinayasaraswathy et al present different control strategies, such as unchanged current and power control for grid-connected SOFC. Similarly, modelling of SOFC connected power systems are connected at different working conditions is presented in [14]. In addition, an efficient control algorithm is designed for optimal controlling of an auxiliary equipment, such as compressor, valves, fuel containers, separators and humidifiers using waters. Praveen et al [15] proposed work of a fuzzy logic based hybrid sources system for improvement of quality of the power system. While the authors in [16], present a control strategy of the inverter for improvement of quality of the power system in the grid connected SOFC using flux-vector control, where the space-vector pulse width modulation is incorporated by ANN.

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In [17], a power monitoring system for SOFC power plant is proposed for reducing the execution time of the FC-gas-turbine power plant. Allie et al [18] propose two strategies of SOFC model interconnected to utility grid for mitigating the large load disturbance. The two strategies include either using electrical storage component as ultra-capacitor interfaced with DC-DC converter.

Both strategies are effective for load following fuel cell.

Taher and Mansouri proposed a developed control strategy for managing the requirement of real power of the grid while operating the SOFC within its safe operating conditions [19]. Basically, an robust PI optimal controller is used to manage the real power of the grid-connected SOFC and fulfill the operating conditions by using two proportional-gained controllers, one for controlling the utilization factor and the other one is for controlling the pressure difference in the fuel cell. In [20], the authors proposed control strategy of DG for hybrid power source in micro grid the proposed strategy is used for active and reactive power management and control over micro grid operations. The efficacy of the performance of the proposed strategy in load tracking is fast and proven in the simulation results. In [20], a work on predictive control scheme for tracking of power and heat management of fuel cells and gas-turbine for mobile applications is presented. The results through simulations indicates accuracy of the controller design by illustrating the rapid load-tracking while maintain the FC temperature of various stakes within the limits of operating constraints. In, the authors provide few coordinated management strategies of power control of the fuel cell connected micro grid. The first strategy is to allow FC follow inversion scheme, while the other one is to let inverter follows the fuel cell.

The proposed research is significantly important for study of the SOFC for standalone and grid-connected power systems to produce an efficient electrical generation system. Improving the generation system performance and reduces the output oscillations by introducing soft switching converter techniques. Social impacts are expected due to the stabilization of output power and the reduction of cost such as: Application of the fuel cells for homes or applications at the isolated regions far from a grid line. This paper is organized as the FC and SOFC are described and DC/AC inverter are discussed. The simulation results of the proposed model in grid-connected SOFC model. The effect of different measurement results of the output power are discussed as well.

II. FUEL CELLS, TYPES AND OPERATION

A. Fuel Cell Model

It is compulsory to send paper in both email address. It produces power as DC as result of electrochemical actions that is happened in the fuel cell. There are several factors that affects the quantity of energy delivered by a fuel cell, such as fuel cell types, size of the cell, heat produced at which a fuel cell functions, and gasses at high pressure supply to the cell. The power electronic inverter converts DC power to AC power output, and it involves controlling various parameters to meet the needs of applications. Currents inverters and conditioners receive and smoothen the electrical current from the fuel cell to match the required needs of the utility grid. Conversion and conditioning may lead to decrease in system efficiency between 2 to 6 percent. The reactant gases pressure increases, the fuel cells performance improves: hence lots of fuel cells systems require an air compressor, which increases the pressure in many times. A fuel cell has anode and cathode immersed in the electrolyte in between of them. In hydrogen fuel cell, a catalyst enables hydrogen molecules to split into holes and electrons ions and electrons, the negative electrons move via the circuit to create a flow of current, while hydrogen ions will reach the cathode through electrolyte. There several variety of fuel cells are produced and for sale in the market. The change in Gibbs free energy is the accountable for releasing energy of the fuel cell. This modification in Gibbs free energy as the reactants modify to the final products [2].

$$\Delta G_f = G_f \ of \ products - G_f \ of \ reactants \quad (1)$$

For electrochemical reaction, the maximum electrical work at given temperature and pressure to move a charge around the circuit of a voltage E (4) [3].

$$\overline{\Delta g_f} = \overline{g_f} \ products - \overline{g_f} \ reactants \quad (2)$$

$$W = -\Delta G_f = -nFE \quad (3)$$

Where n is the No of electrons, F is Faraday's constant, and E is the terminal voltage of the cell (reversible), or the potential difference across the electrodes.

$$E = -\frac{\overline{\Delta g_f}}{nF} \quad (4)$$

For general reaction as given $jJ + kK \rightarrow mM$ where k moles and j moles and after reaction to will provide m moles of M. Both moles of the products as well as reactants have in more action. This function is the partial pressure of the gas with respect to the rated pressure:

$$a = \frac{P}{P^{\circ}} \quad (5)$$

$$\Delta\overline{g_f} = \Delta\overline{g_f^{\circ}} - RT\ln\left(\frac{a_J^j \cdot a_K^k}{a_M^m}\right) \quad (6)$$

Where P is the gas pressure and P° is the rated pressure, 0.1MPa. Equations (4) and (6) can be combined together to obtain as the Nernst equation [2].

$$E = -\frac{\overline{\Delta g_f}}{2F} + \frac{RT}{2F}\ln\left(\frac{PH_2 \ . \ PO_2^{\frac{1}{2}}}{PH_2O}\right) \quad (7)$$

B. Modeling of SOFC

The system which has solid oxide fuel cell (SOFC) that is interfaced to a three-phase grid through IGBT inverter and transformer, which is shown by the block diagram representation of the fuel cell in figure 1.

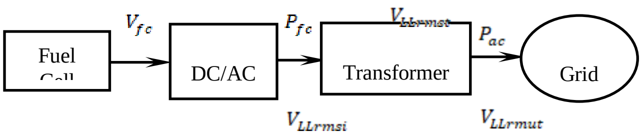


Fig. 1.Model of fuel cell [6]

Where, V_{fc} stack voltage of the fuel cell, V_{LLrmsi} terminal voltage of inverter, V_{LLrmst} Rated Voltage (kV), X_t Leakage, V_{LLrmsu} grid voltage, P_{fc} stack power, and P_{ac} Real power supplied into the grid (kW). In this model, some assumptions have been taking into accounts: The gases of fuel cells are treated as ideal, single pressure is mentioned in the inner side of the electrodes, the heat of the fuel cell is fixed, and the Nernst's equation is applied. The fuel cell output power has power rating of 50 KW, and any value of reference power that is higher than this value, the fuel cell system would show instability in the system's parameters. The basic energy can be obtained by increase the total no of fuel cells, increase voltage based on the material used for fuel cells.

$$P_{fc} \leq 50\ KW \tag{8}$$

Solid oxide fuel cell (SOFC) is the most commonly used among all the fuel cells due to high efficiency, low emission, and quiet operation. It generates electrical power continuously as a gaseous fuel is electrochemically burnt in a continuous manner (energy conversion device). In SOFC, hydrogen is utilized as fuel and oxygen as the oxidant in the electrochemical reaction, which is occur as follow:

$$\text{Anod: } H_2 + \frac{1}{2}O_2^- \rightarrow H_2O + 2e^- \tag{9}$$

$$\text{Cathode: } \frac{1}{2}O_2 + 2e^- \rightarrow O_2^- \tag{10}$$

Overall reaction:

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \tag{11}$$

The output voltage is given as follow:

$$V_{fc} = E - V_{act} - V_{con} - V_{ohmic} \tag{12}$$

The open circuit equation is given as follow:

$$E = N(E_0 + \frac{RT}{2F}\ln\left(\frac{PH_2 \,.\, PO_2^{\frac{1}{2}}}{PH_2O}\right) \tag{13}$$

Where E is the open circuit voltage (Nernst's reversible voltage) of the SOFC when the current density I_{fc} is zero. In this study, only the internal resistance of the FC is considered.

Figure 2 depicts the standard characteristics of solid oxide fuel cell. From the graph it has been identified that even though increase in the load the voltage is drooping. Since the drop is approximately linear in the middle of the graph which is ohmic polarization and best operating region of a fuel cell. Equation 14 indicates the Fuel utilization ratio. Typically, fuel utilization is usually at higher values. The reaction of the flow of fuel is given equation (15) [5]. The fuel cell current is restricted by a certain input of flow of fuel and the fuel utilization value, which is given by equation (16) [5].

$$U_f = \frac{qH_2^r}{qH_2} \tag{14}$$

$$qH_2^r = 2K_rI \tag{15}$$

$$\frac{0.8qH_2}{2K_r} \leq I \leq \frac{0.9qH_2}{2K_r} \tag{16}$$

Pressure of input parameters is given in the equations (17), (18), and (19). The fuel cell current is able to measure, so that the fuel input which can be control the utilization of fuel at 85%, which is the best possible percentage of the fuel utilization.

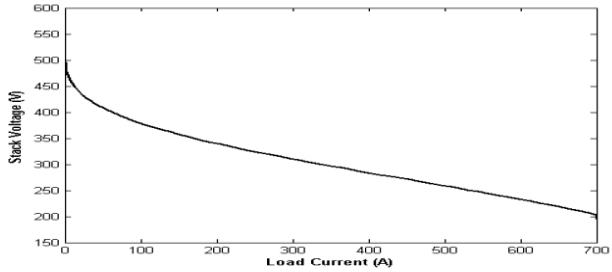


Fig. 2.Solid oxide fuel cell characteristics

The fuel cell amperes is given in equation (20).

$$pH_2 = \left(\frac{\frac{1}{KH_2}}{1+\tau_{H_2^S}}\right)(qH_2 - 2K_rI) \tag{17}$$

$$pO_2 = \left(\frac{\frac{1}{KO_2}}{1+\tau_{O_2^S}}\right)(qO_2 - K_rI) \tag{18}$$

$$pH_2O = \left(\frac{\frac{1}{KH_2O}}{1+\tau_{H_2O}S}\right)(2K_rI) \tag{19}$$

$$I = \left(\frac{I_{ref}}{1+\tau_e S}\right) \tag{20}$$

The reference current is shown in equation (21), the flow of the oxygen and fuel is shown in equations (22) (23).

$$I_{ref} = \left(\frac{P_{ref}}{V_{fc}}\right) \tag{21}$$

$$qH_2 = \frac{2K}{U_{opt}}\left(\frac{1}{1+\tau_f S}\right) \tag{22}$$

$$qO_2 = \frac{qH_2}{r_{HO}} \tag{23}$$

Where: qH_2, qO_2 Fuel flow, and flow of oxygen (mol/s). KH_2, KO_2, and KH_2O, Constant of molar of valve hydrogen, oxygen and water (kmol/s atm). τ_{H2}, τ_{O2}, τ_{H2O}, τ_e, and τ_f Response time for hydrogen, oxygen, water, The block diagram indicates SOFC dynamic state model in Figure 3.

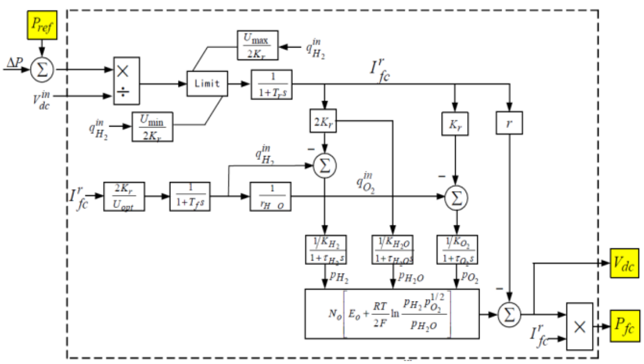


Fig. 3.Model of solid oxide fuel cell [4]

III. POWER QUALITY UNITS

One of the main function of a power conditioning units is to exchange power between two electrical subsystems in a controlled manner. A two level three-phase bridge DC/AC VSI is used as converter to inject AC Power to the grid. The transistor gating signal for the inverter are received from the management of the decoupled system of the apparent power. In this paper, two designed control schemes of the inverter are proposed, the controller generates the reference currents for tracking controller which provides the switching signal for the inverter. The main purpose of the proposed control strategies is to control the real and reactive power independently. A current-controlled pulse width modulation voltage source inverter is used.

The PWM-VSI consists of a semiconductor device (IGBT) with antiparallel reverse diode. Complex power can be managed by varying the phase angle and voltage magnitude. The direction of power is identified based on the difference between the potential and the phase angle of the transformer and utility. However, the proposed model assumes that the Q is zero, in another word, the angle difference is zero in the load side. So only the real power P is controlled. The real and reactive power can be calculated by equation (24), (25). The PLL is utilized for obtaining the angle of phase, from the grid side voltages for dq-abc transformation parameters given by the Figure (4) and the 3 references are made. Each one is compared with the measured grid currents and the errors are fed to the hysteresis current controller.

$$P = \frac{V_{LLrmst}\ V_{LLrmsu}\ \sin\emptyset}{\omega\ L_t} \quad (24)$$

$$Q = \frac{V_{LLrmst}^2 - V_{LLrmsu}\ \cos\emptyset}{\omega\ L_t} \quad (25)$$

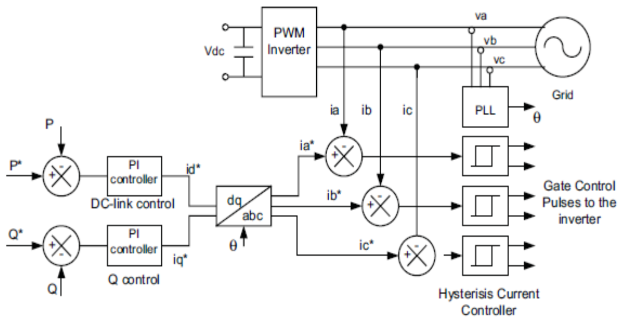


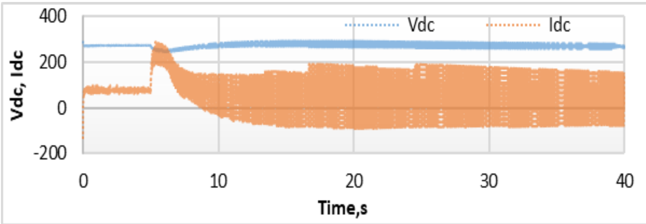
Fig. 4.Proposed inverter control circuit for the FCDG system.

The PI controller is used for the decoupled P-Q control. The PI Controller is injected with the error signal due to the reference real power and measure power in order to manage the angle of the inverter and set the active reference current. A hysteresis current control (HCC) method is created to produce a reference current of compensation for active filter. In this proposed work, the fixed band filter is used as in [4]. In this controller the inverter switches are made off and on to reduce the error to a small value.

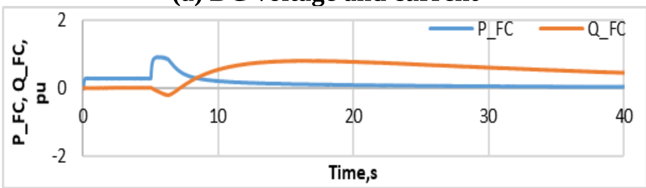
IV. SIMULATION RESULTS

A. Simulation of the fuel cells for the input of step change:

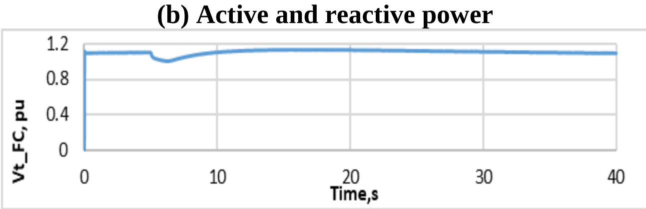
Figure (5) shows the responses of the fuel cells when reduce the number of fuel cell to three hundred at step changes in reference from 0.3 to 1 pu. The high ripple in voltage and current is due to the number of fuel cell cannot compensate for the rated power value of 1 pu. Fig (5.a) shows the reaction response of the FC and the voltage voltage and current, which losses stability. In fig (5.c), the active and reactive power values loss stability when increasing in reference power occur at step time of 5 second. The fuel cell voltage terminals show small voltage drop, then it reaches to a steady state value of 1.1 pu in 25s. In fig (5.d), the partial pressure of gases goes below 0.1 mol/ sec.



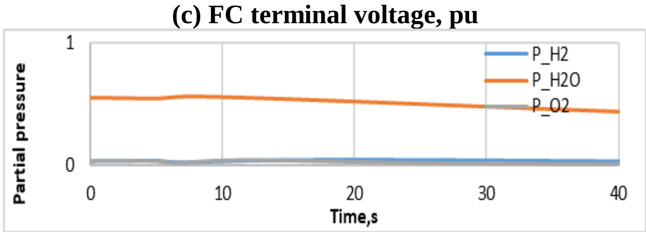
(a) DC voltage and current



(b) Active and reactive power



(c) FC terminal voltage, pu



(d) Partial pressures of air, hydrogen and oxygen

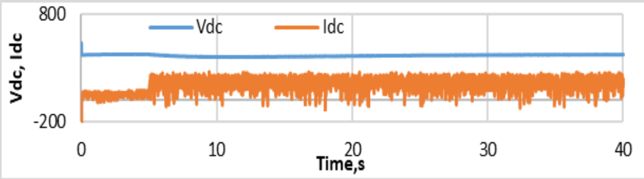
Fig. 5.Response of the fuel cell for step change in active power from 0.3 to 1 pu (50 kw)

B. Simulation results of the fuel cell when reducing the ohmic loss:

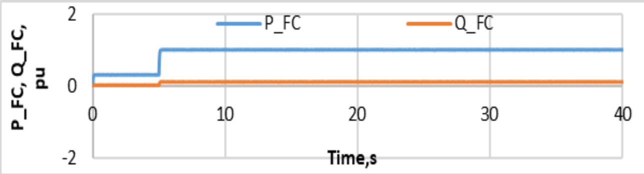
Figure (6) show the parameters results of the fuel cell when decreasing the ohmic loss per cell up to 3.2813e-5 has opposite results. In fig (6.a), the dc voltage shows very low voltage drop, then reaches steady state value of 420 V in 20s, however, the dc current still shows undesired ripple.

The active and reactive power show stable response, moreover the fuel cell terminal voltage shows a very small voltage drop.

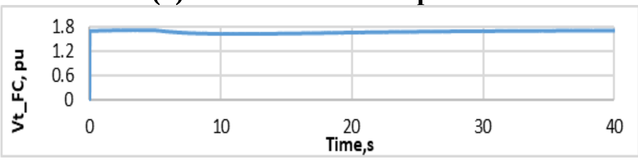
Fig (6.b), (6.c) the show the reaction response of the active and reactive power and the terminal voltage respectively. The gas pressure are almost fixed in values, which is shown in fig (6.d).



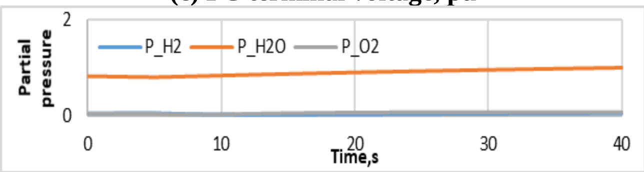
(a) DC voltage and current



(b) Active and reactive power



(c) FC terminal voltage, pu

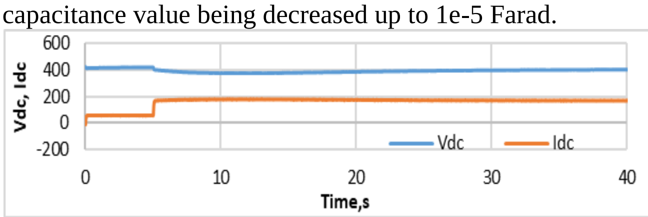


(d) Partial pressures of air, hydrogen and oxygen

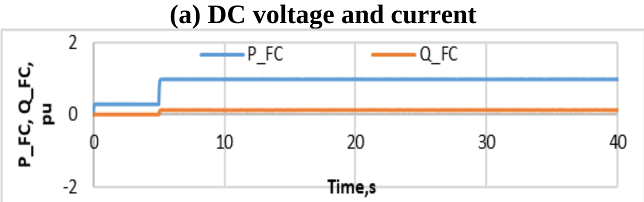
Fig. 6.Response of the fuel cell when decreasing the ohmic loss

C. Simulation result of the fuel cell when decreasing the capacitance value:

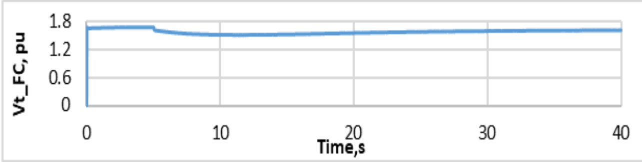
In Fig. (7.a) the dc voltage shows recognizable drop in voltage due to increase capacitance value up to 1e-2, which leads to longer response time to reach steady state value of 400 volts, while the dc current shows a very small noise, and then it takes almost 15s to reach steady state value 170 A. fig (7.b), (7.c), and (7.d) show results as same as when the capacitance value being decreased up to 1e-5 Farad.



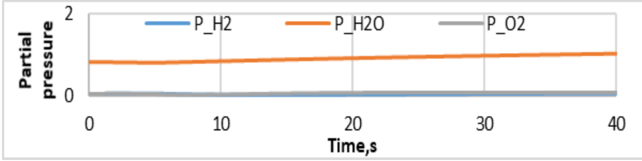
(a) DC voltage and current



(b) Active and reactive power



(c) FC terminal voltage, pu

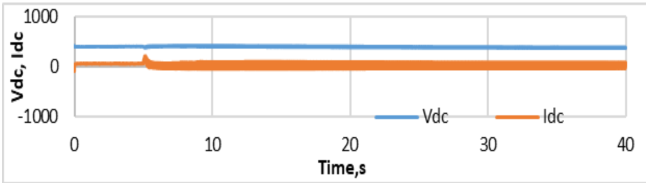


(d) Partial pressures of air, hydrogen and oxygen

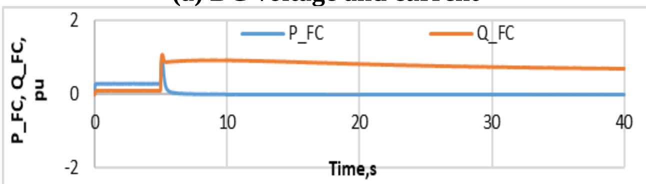
Fig. 7.Response of the fuel cell when decreasing the capacitance value

D. Response of the fuel cell when increasing the inductance:

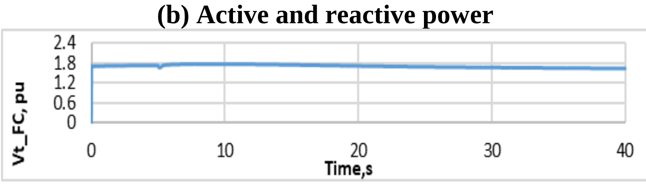
As the inductance value being increased up to1e-2, the dc voltage shows no noise frequency, yet still show high ripple frequency, which is depicted in fig (8.a). similarly, the dc current show high ripple frequency, yet it shows instability when the reference power increased, then reach to steady state in around 25 second. fig (8.b) show how active and reactive power loss stability and active power drop to zero value as result of increasing the inductance. The fuel cell terminal voltage increases up to 1.7 pu, then slightly drop, and reaches to steady state value of 1.6 pu within 25s.



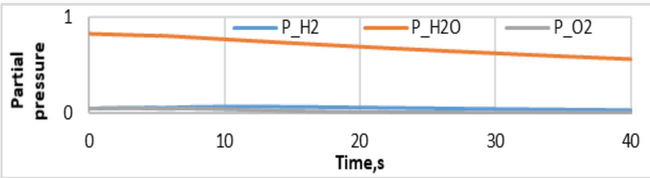
(a) DC voltage and current



(b) Active and reactive power



(c) FC terminal voltage, pu



(d) Partial pressures of air, hydrogen and oxygen

Fig. 8.Response of the fuel cell when increasing the inductance value

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V. CONCLUSION

This research is significantly important for study of the SOFC for standalone and grid-connected power systems is to produce an efficient electrical generation system. Improving the generation system performance and reduces the output oscillations by introducing soft switching converter techniques.

Social impacts are expected due to the stabilization of output power and the reduction of cost such as: Application of the fuel cells for homes or applications at the isolated regions far from a grid line. DC voltage stakes of Fuel cell needs to be converted and stepped-up to get connected with grid. So, a DC-AC voltage source inverter is used to for interfacing the fuel cells with the utility grid, and the transformer to improve the voltage and connected with the bus bar. PI and hysteresis current controller are control and shape the inverter output voltage, hence provides decoupled real and reactive power control.

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