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# Modeling and Reactive Power Control of Wind and Fuel Cell Technologies in Distribution Networks

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**Abstract.** An integrated scheme of wind and fuel cell renewable energy technologies in distribution networks for electrical energy generation from renewable resources is digitally simulated and presented in this paper. The integrated system has four key subsystems or components to supply the required electric loads. The first subsystem includes the renewable generation sources from Wind turbines and fuel cell stacks. The second represents the added inverter between the Fuel cell collection DC bus and the point of common coupling PCC with the AC distribution network. The third device is the static synchronous compensator STATCOM to provide the required reactive power for voltage regulation at the bus of PCC. The fourth subsystem comprises mainly of two PI controllers. The first controller main function is to regulate the hydrogen flow to the fuel cell, while the second one is used to control the switching action of the STATCOM converter for injecting the required reactive power. The integrated system and the associated subsystems are fully validated for efficient operation under normal or fault conditions using the Matlab/Simulink/Sim-Power software environment.

## Key words

Dispersed Generation, Wind Farm Modeling, Fuel Cell Modeling, STATCOM.

## 1. Introduction

Recently the problem of global warming is the concern of different countries to reduce the emission of harmful gases due to electricity generation by burning fossil fuels. Therefore, extensive research and investment are already done for efficient utilization of clean renewable energy as suitable alternative energy. Among the renewable resources wind, solar and fuel cells are growing in importance and gain the interest of energy researches. As green renewable energy resources, wind and fuel cells have gained substitution potential for conventional fossil fuels . In this regard, the cost of electricity generated by wind energy has been continuously decreasing during the last decade. These cost reductions are due to new manufacturing technologies, large capacity, more efficient and more reliable wind turbines [1-4]. On the other hand, the wind speed variation is dependent on environmental conditions. Therefore, in order to ensure renewable energy diversity and effective utilization more than one renewable energy source are combined to form a coordinated and hybrid integrated energy system [5]. Integrated distributed generation is a valid alternative solution fordistributed generation. Thereby, the distribution grid is hybridizing wind energy and hydrogen fuel cells from natural gas. Recently, the generation cost of fuel cells is declined due to industrial development of the membrane and electrolyte technology. The implementations of fuel cell technology are still limited to hybrid electric vehicles. Some researchers are dealing with the power system application of fuel cell and its interactions with the different system components. When such distributed generators are connected to distribution system, it is important to check the technical constraints of the voltages at system buses and power flows along system lines. Therefore, the interaction of fuel cell with wind turbine and power system components, as well as switching electronic devices are essential to keep these constraints within their permissible levels[6-7]. Wind turbine will generally operate in normal conditions with voltage level between 90 and 105% and frequency between 49-51 Hz. Thepenetrations of distributed generation may violate these operation constraints. Therefore, the active and reactive power supplied to the distribution network should be continuously controlled to regulate the voltage and frequency of the system. Under fault conditions, the wind turbine would experience large voltage variations. The amplitude and duration of these variations will determine whether the wind turbine should be disconnected or kept in operation during fault conditions. FACTs devices such as STATCOMs can provide the required reactive power for voltage regulation and assist wind farms to continue in supplying active power for certain time during fault conditions [8]. The main objective of this paper is to simulate the integrationof wind turbines and fuel cell stacks into the medium voltage distribution system and investigate effect of using STATCOM to stabilize the voltage levels in the studied system. The Matlab/ Simulink software packages used to model the distribution system including the described distributed generators.

## 2. Distribution system description

The schematic diagram of the system under study is shown in Fig (1). It consists of 22 kV network, twelve 600 kW wind turbines and 30 fuel cells each of 80 kW. The average wind speed is 10 m/s at 40 m above ground level. The wind turbines are connected to the network through 800 kVA, 690V/22kV transformers. Each four wind turbines are connected to one feeder consequently there are three groups of wind turbines each group has the same wind speed. The turbines are coupled to induction generators and have fixed capacitors, rated speed of 11 m/s and active stall power control. Local loads are included in the system with total active and reactive power of 8 MW and 6 kVAR, respectively.

The pressure and temperature inside the fuel cell are 2 atm and 80 $^{o}$C, respectively.The fuel cells are connected to the grid through DC/AC inverters. In the first stage the fuel cell is coupled to the inverter through 60V/380V transformer. After inversion the fuel cell stack which contains 6 fuel cells, is connected to the distribution network through 380V/22 kV transformer.

The voltage variations of the distribution network can be recorded due to wind speed fluctuation in the case of installing fixed capacitor for induction generator excitation. Therefore, this system needs additional source of reactive power by installing STATCOM at the point of common coupling to enhance system performance.

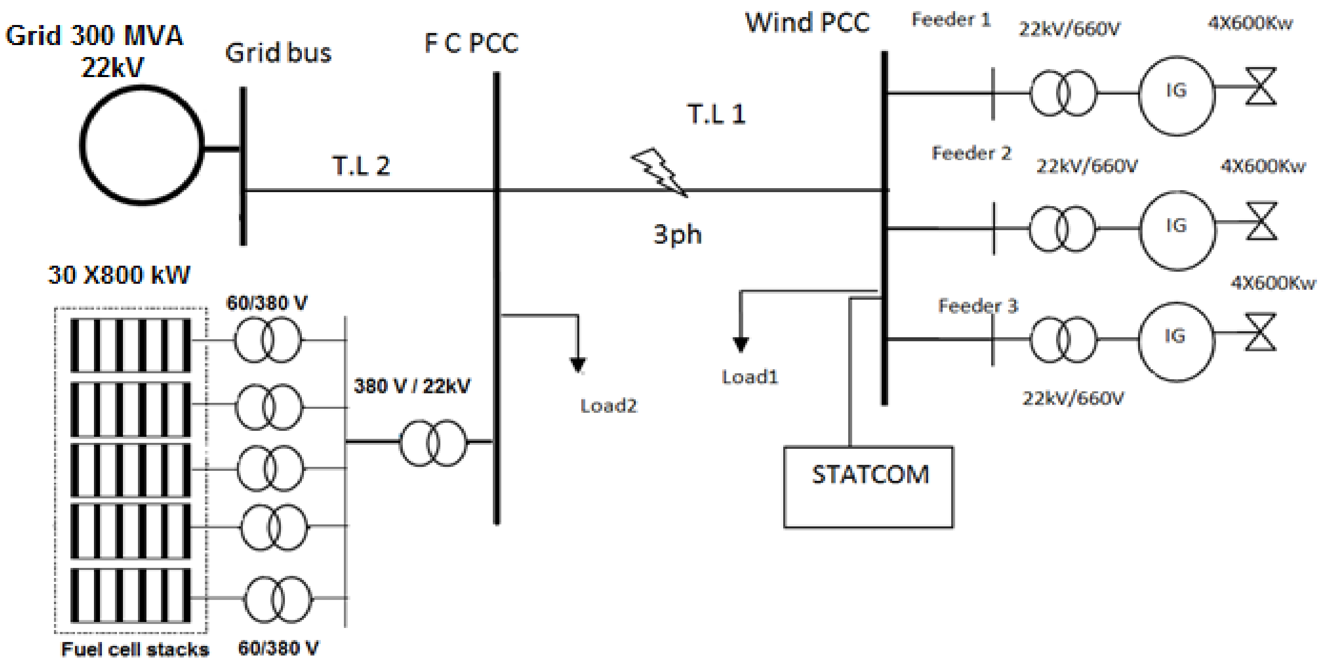


Fig. (1): Schematic diagram of system under study.

## 3. Fuel cell model

Each individual fuel cell unit in the stack has two electrodes, one positive (anode) and one negative (cathode). The reactions responsible for producing electricity take place at these electrodes. The electrolyte in the cell carries electrically charged particles from one electrode to the other. Thereby, the electrolyte permits only the appropriate ions to pass between the anode and cathode [9].Fuel cells have a non-linear characteristic that can significantly influence system operation due to chemical reaction polarization. The three fuel cell polarization losses can be summarized as Irreversible/activation polarization loss, Concentration polarization loss, and Ohmic or resistance polarization.

The activation polarization is directly related to the rates of electrochemical reactions and can be described by the general form of the Tafel's equation [9, 10].

$$\eta_{act} = \frac{RT}{\alpha nF} ln \frac{i}{i_o} \qquad (2)$$

Where; $\eta_{act}$ is the activation losses, $\alpha$ is the electron transfer coefficient of the reaction at the electrode, $i_o$ the exchange current density and n is the number of electrons transferred per mole of fuel cell. The ohmic losses can be expressed by applying Ohm's law as follows: [9, 10].

$$V_{ohm} = iR_{fc} \qquad (3)$$

Where;
$V_{ohm}$ is the ohmic voltage drop, i is the fuel cell current and $R_{fc}$ is the total cell resistance.

As a reactant is consumed at the electrode by electrochemical reaction, there is a loss of potential due to the inability of the surrounding material to maintain the initial concentration of the bulk fluid. As results this produces concentration losses which can be expressed by:

$$\eta_{conc} = \frac{RT}{nF}\ln(1 - \frac{i}{i_L}) \qquad (4)$$

Where; $\eta_{conc}$ is the concentration loss, $i_L$ is the limiting current and F is Faraday constant.

The above mentioned activation and concentration polarization can exist at both the positive (cathode) and negative (anode) electrodes in fuel cells. Therefore, the total losses at these electrodes are the sum of $\eta_{act}$ and $\eta_{conc}$ as follows [9, 10];

$$\eta_{anode} = \eta_{act,a} + \eta_{conc,a} \qquad (5)$$

And; $\eta_{cathode} = \eta_{act,c} + \eta_{conc,c}$ (6)

Then the total voltage;

V cell = E cathode – $\eta_{cathode}$ – ( Eanode + $\eta_{anode}$) – i $R_{fc}$ (7)

## 4. Wind energy conversion

The extracted power of wind turbine depends on three main factors: available wind power, the power curve of the machine and the ability of the machine to respond to wind fluctuation. The expression for power produced by the wind is given by [3, 5& 8].

$$p_m(u) = \frac{1}{2} C_p(\lambda, \beta)\rho\pi R^2 u^3 \qquad (8)$$

Where;
ρ is the air mass density, *R* is the wind turbine radius , *u* is the wind speed,*Cp* is the power coefficient representing the fraction of power extracted from the aerodynamic power , β represents the wind turbine pitch angle and the tip speed ratio λ is defined as;

$$\lambda = \frac{R\omega}{u} \qquad (9)$$

Where; ω is the rotor speed and the power coefficient Cp is expressed by:

$$C_p(\lambda, \beta) = C_1\left(\frac{C_2}{\lambda_i} - C_3\beta - C_4\right)e^{\frac{c_3}{\lambda_i}} + C_6\lambda \qquad (10)$$

$$1/\lambda = 1/[l + 0.08\beta] - 0.035/[\beta^3 + 1] \qquad (11)$$

The coefficients C1 to C6 are [5]:

$C_1$=0.5176, $C_2$ = 116, $C_3$=0.4, $C_4$=5, $C_5$=21 and $C_6$ = 0.0068. Constant zero pitch angles are assumed.

## 5. STATCOM model

Three phases, three-level of STATCOM can be constructed by using twelve switching devices and eighteen diodes. In this configuration, the number of levels refers to the positive and negative voltage levels including zero which appear in the STATCOM output line voltage when very large capacitors are used on the dc side. The inverter is connected to the supply system via three-phase transformer. The equivalent circuit of STATCOM represents as a DC-side capacitor, an inverter, and a series inductance in the three lines connecting to the transmission line. Thisinductance accounts for the leakage of the actual power transformers, and a resistance in series with the AC lines to represent the inverter and transformer conduction losses.STATCOM operates in two modes either inductive or capacitive mode depending on the difference of the voltage levels at PCC and the fundamental component of the inverter output. By neglecting the harmonic components generated by switching pattern, the switching function of the STATCOM can be changed according alpha(α) , the phase angle which relates the phase difference between pwer system volatge at PCC and the inverter output voltage of [11-12].

## 6. Control strategy

The main objective of the control strategy is to regulate the voltage at the PCC for both wind energy farm and the fuel cell stacks when the distribution system is subjected to short circuit faults or various operation disturbances.
For fuel cell stack, the PID-controller is used to control $H_2$ flow rate in order to regulate the fuel cell output voltage. The overall control scheme adopted for FC grid-connected inverters block diagram is illustrated in Figure 2.b.
The reactive power exchange between STATCOM and the distribution system is controlled by the phase angle between the AC system bus and the fundamental inverter voltage (α). Figure 2.b shows the proposed reactive power control by using STATCOM. The output of used PI controller is fed to sinusoidal pulse width modulation (SPWM) to generate the switching pulses for the three level inverter of the STATCOM. The goals in the controller design process include both transient excursion suppression and good regulations in steady-state operation. By transformation the measured three phase voltages and currents of the PCC bus to d-q frame that gets voltage and current in d-q frame, measured voltage vector is being used to assign the amount of STATCOM current to get the desired angle control **α** (output of the PI controller) that added to the phase angle of the terminal voltage of the PCC .The root locus techniques used to obtain the parameters of the PI controller based on linear model according to [8].

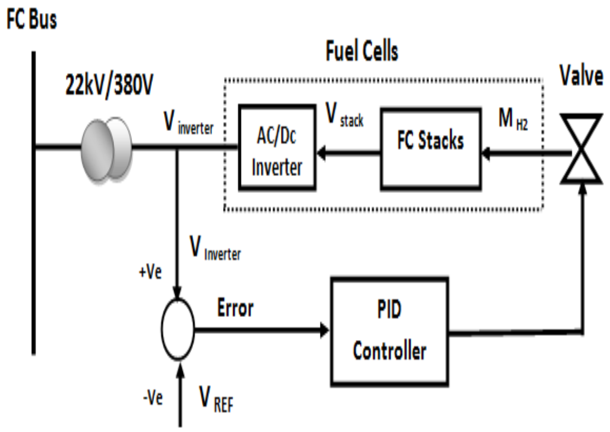


Fig. 2. a.: Fuel cell control block diagram

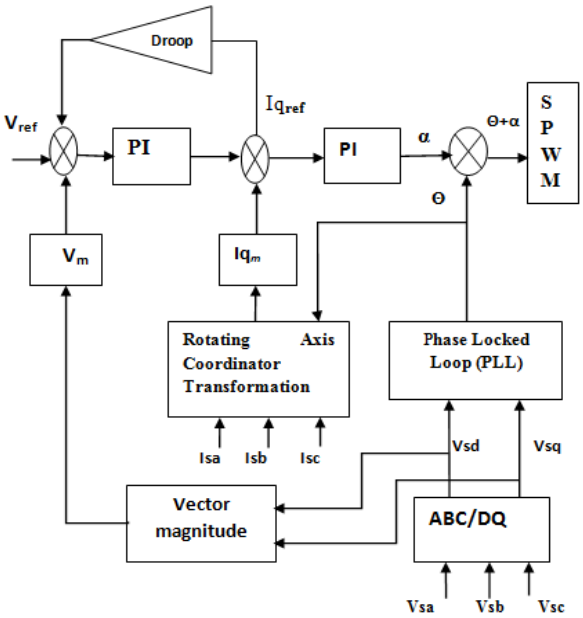


Fig. b.: STATCOM control block diagram

## 7. Simulation results

Power system simulation with the distributed wind and fuel cell generation is carried out by using MATLAB/Simulink to study the system performance at variable wind speed and three-phase short circuit fault . Three phase fault is applied at the mid-point of the line connecting the two PCC of the wind farm and fuel stack. This fault is initiated at 0.7 sec and cleared after 200 msec. The used wind speed time series of the three turbine groups is given in Fig. (3).

The generation system may be hardly affected by short circuit fault due to voltage instability which may lead to complete shutdown of the generating units. The capability of these units to reach their stable state after tripping the fault depends mainly on the system demand to reactive power. As shown in Fig. (4), the dynamic response of the Grid voltage and at PCC is stable due to the effective reactive power control of the installed STATCOM. Similarly,the phase angle between the PCC bus and inverter voltage bus is displayed in Fig. (5a). The effectiveness of the STATCOM control strategy is verified as the STATCOM current response follows its reference value as compared in Fig. (5b). In addition, STATCOM voltage and current are presented in Fig. (6).The voltage response ofthe fuel cell stack is shown in Fig. (7). The simulation results validate the robustness of the control scheme for hydrogen flow rate of fuel cell stack to ensure maximum utilization and voltage stabilization of the stack.Moreover, the active and reactive power supplied by fuel cell stack are displayed in Figures (8 and 9), respectively. It should be noted that recent economic analysis show that the revenue due to selling avoided natural gas and $CO_2$ in the international market could compensate relatively greater generation cost of the wind energy conversion.

The current fuel cell cost is higher than the conventional generating units. The manufacturers have the goal to reduce this cost through higher production rates and continued improvement in design and technology. As fuel cell operates efficiently and cleanly, economical incentives include sale of avoided natural gas and carbon credit could reduce the generation cost of fuel cells significantly. As a result, Wind/fuel cell based hybrid system could substitute the traditional power sources in near future.

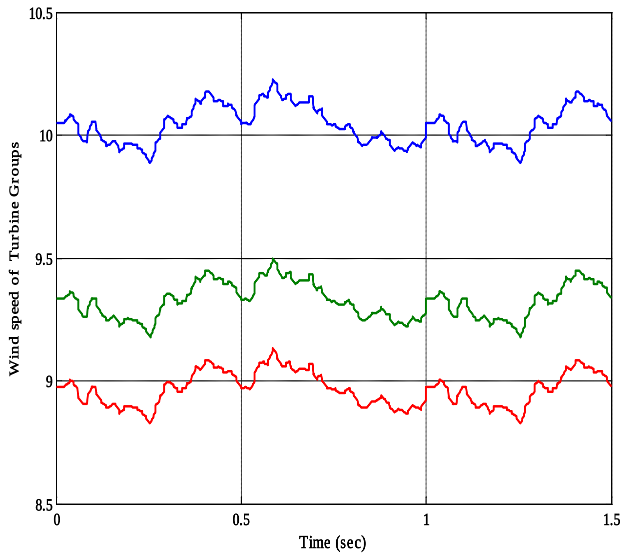


Fig. (3): Wind speed of wind turbine groups

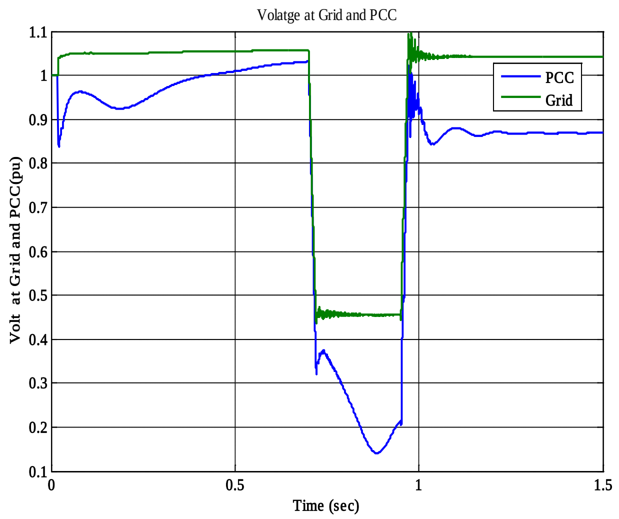


Fig. (4): The dynamic voltage response of Grid and PCC

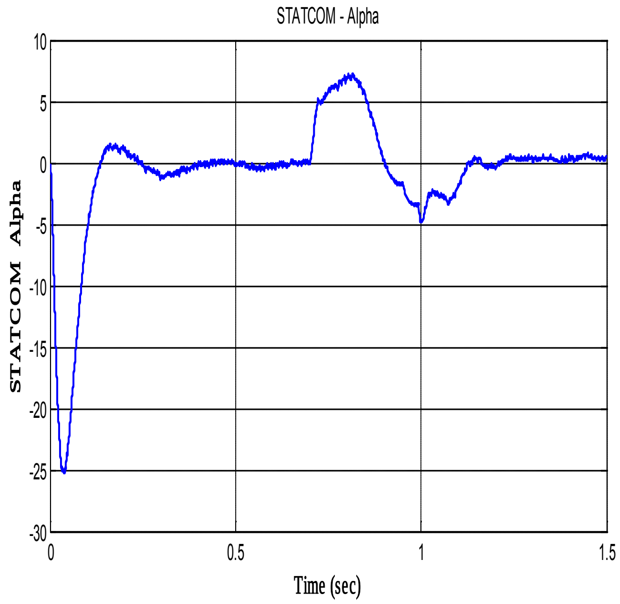


Fig. (5a) Variation of STATCOM alpha

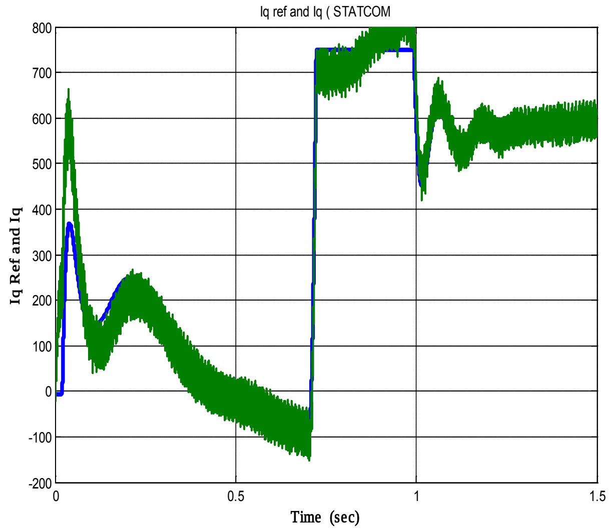


Fig.(5b): STATCOM current Iq and Iqref

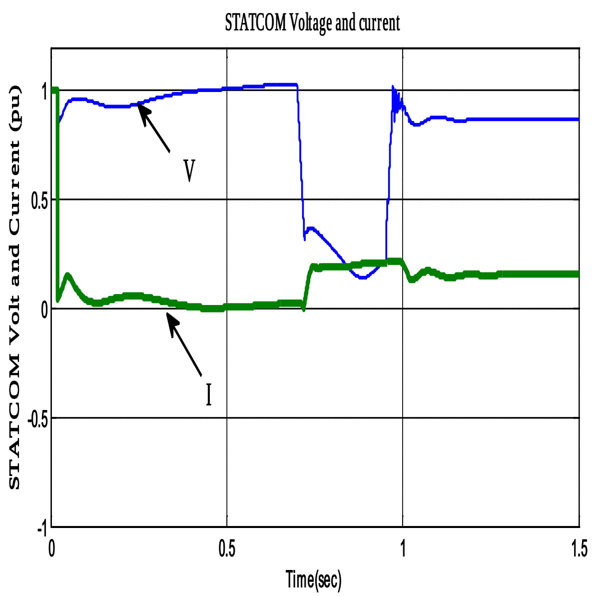


Fig. (6) STATCOM Voltage and current in p.u

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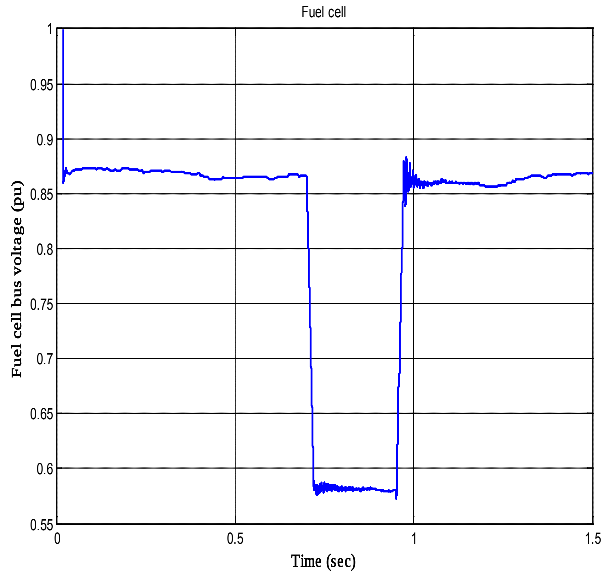


Fig.(7): Voltage dynamic response at the fuel cell bus in p.u.

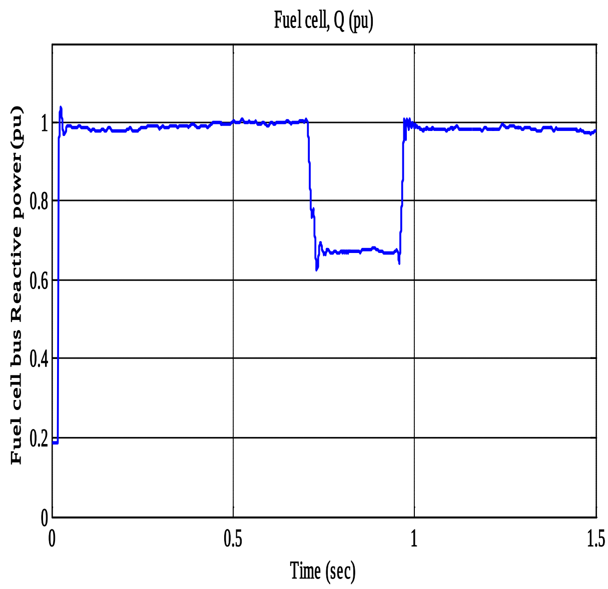


Fig. (8) : Variation of reactive power supplied by fuel stack

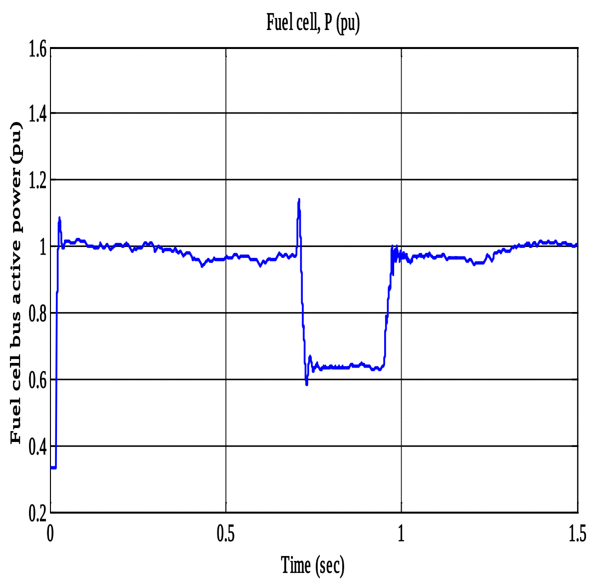


Fig. (9): Variation of power supplied by the fuel stacks

## 8. CONCLUSIONS

The paper presents an integration of wind energy conversion and fuel cell stacks to distribution grid for efficient renewable energy utilization as clean sources of electricity generation. The integrated scheme consists of dispersed wind turbines and fuel cell groups as well as STATCOM to enhance the system performance under varying operating or fault conditions in additinal to Fuel cell controler to regualte the bus volatge.

The integrated system is digitally simulated and validated using the Matlab/Simulink. The operation of STATCOM and Fuel Cell controller schemes for hybrid green renewable energy utilization is validated under short circuit fault condition and wind speed variations. The STATCOM was used to improve the dynamic behavior of the system, fast recover of reactive power and increase the ability to withstand severe disturbances that will decrease time of station shutdown.

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