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Modelling and Simulation of Photovoltaic Full Cell Hybrid System

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***Abstract*— A hybrid system also called as standalone system supplies electricity to the load without being connected to the electric grid. Hybrid systems have applications in remote and inaccessible areas where the population is living without electricity. In remote and rural areas the grid connection is not technical feasible and also a cost effective option. Therefore, hybrid systems are well suited for such areas. The purpose of this thesis is to model and simulate the different components of a PVFC hybrid system which may fulfill the electric demands for remote and rural areas. Therefore, here a photovoltaic generator and a fuel cell are connected to the load to fulfill the electrical demands to these areas. This hybrid system consists of a photovoltaic generator and a proton exchange membrane fuel cell (PEMFC) coupled together to form a hybrid system which is connected to the load or grid as per the user demand. A simulation software program known as Matlab has been used to simulate the system performance. The system design and performance analysis could thus be achieved through computer modeling and simulation prior to practical realization.**

Keywords*— Dynamic model; Fuel cell; Photovoltaic module; Hybrid system

I. INTRODUCTION

The non renewable sources of energy such as natural gas, petroleum and coal are being depleted rapidly. Also, they cause global problems such as the green house effect and pollution which are posing great danger for our environment and eventually for the entire life on our planet. On other hand, the renewable energy sources such as solar, wind, tidal, geothermal etc are attracting more attention as an alternative energy. The photovoltaic (PV) energy among the renewable energy sources has been widely used in low power applications. Photovoltaic generator converts solar radiation directly into electricity. Photovoltaic generators have a lot of advantages such as being inexhaustible and pollution free, silent, no rotating parts etc. They are replacing electricity generators by other polluting ways.

From an operational point of view, a PV power generation experiences large variations in its output power due to intermittent weather conditions. Those phenomena may cause operational problems at the power station, such as excessive frequency deviations. In many regions of the world, the fluctuating nature of solar radiation means that purely PV power generators for off grid applications must be large and thus expensive. One method to overcome this problem is to integrate the photovoltaic plant with other power sources such as diesel, fuel cell (FC), or battery back-up. The diesel back-up generator for PV power is able to ensure a continuous 24-hour. However, it has a number of significant disadvantages such as noise and exhaust gases pollution. In addition, reasonably reliable diesel back-up generators are available only for the power range above about 5kW, which is too much high for a large number of applications. In the middle and small power range this technology cannot be used in an effective way. The fuel cell beak-up power supply is a very attractive option to be used with an intermittent power generation source like PV power because the fuel cell power system is characterized with many attractive features such as efficiency, fast load-response, modular production and fuel flexibility. Due to the fast responding capability of the fuel cell power system, a photovoltaic-fuel cell (PVFC) hybrid system may be able to solve the photovoltaic inherent problem of intermittent power generation.

Unlike a storage battery, which also represents an attractive back-up option, such as fast response, modular construction and flexibility, the fuel cell power can produce electricity for unlimited time to support the PV power generator. Therefore, a continuous supply of high quality power generated from the PVFC hybrid system is possible day and night. Environmental impacts of the fuel cell power generation are relatively small in contrast to other fossil fuel power sources. Since chemical reactions inside the fuel cell stack are accomplished by catalysts, it requires a low sulphur content fuel. Low-emission characteristics of the fuel cell power system may allow some utilities to offset the costs of installing additional emission control equipment. Moreover, their high efficiency results in low fossil fuel CO_2 emissions, which will help in reducing the rate of global, warming. Therefore, the fuel cell power system has a great potential for being coordinated with the PV generator to smooth out the photovoltaic power's fluctuations.

A. Objective of Study

It has been well-proven that a photovoltaic power source should be integrated with other power sources, whether used in either a stand-alone or grid-connected mode. Stand-alone power systems are very popular, especially in remote sites. The system under study in this dissertation is the modeling and simulation of different components of a PVFC hybrid power system, which is constituted of a photovoltaic generator, a proton exchange membrane (PEM) fuel cell and PCU unit. This system is intended to be a future competitor of hybrid PV/Diesel systems, especially from an environmental point of view (low noise and zero emission) and operational costs point of view [4].The development of appropriate simulation tools will help in dealing with modeling, simulation, and design and energy management of the system understudy. A simulation software program known as Matlab has been used to simulate the system performance. The system design and performance analysis could thus be achieved through computer modeling and simulation prior to practical realization. This dissertation aims towards: Proper data collecting and/or data synthesizing that describes the system operation and the load profile, Visualizing and analyzing the system dynamic behavior using power flow trace overlong-term duration, for example, one year, creating an accurate simulation system model to predict the real performance of the PVFC hybrid system, and then Undertaking detailed analysis of the effect of changes in the system configurations, power conditioning units, and sites to choose an optimal system design. The objective of the study is to reach a design that optimizes the operation of a PVFC hybrid system. All components of this system have been selected for an optimal operation of the complete system. The data of the component models was taken from real projects or manufacturer's data sheet. The component models of the system are verified with component's experimental data to assure the accuracy of these models before being implemented into the system simulation study.

B. Problem Statement

Electricity is extremely versatile, clean, easy to use, and can be turned on or off at the flick of a switch. Electricity has brought enormous social benefits in all areas of life. Currently, many nations already have small-scale solar, wind, and geothermal devices in operation providing energy to urban and rural populations. These types of energy production are especially useful in remote locations because of the excessive cost of transporting electricity from large-scale power plants. A renewable energy system, which we have designed here, is composed of some renewable sources, and targets a small area such as a village. The system supplies energy to rural area by using renewable sources

It is the preferred method of supplying power for many household applications, especially lighting, but connection to the national electrical grid is a rare occurrence in rural areas of the developing and under developed world. In the majority of the worlds' poorer countries it is estimated that significantly less than 5% of the rural population are connected to the national grid. There are many reasons, both technical and economic, which make grid connection unfeasible and these will be looked at briefly in this fact sheet. In urban areas of the developing world grid connection is commonplace. Particularly in remote mountainous areas (such as the Himalayas Region) people often live under extreme conditions. The harsh climate in high-altitudes, limited available natural resources and the remote location of most villages make life challenging.

C. Solution Statement

Hybrid energy systems (HES), which utilize different renewable resources such as wind, solar, biomass, small/micro hydro, with fossil fuel powered diesel/petrol generator to provide electric power, are well suited for remote rural areas. This proposed work a general methodological framework for the formulation of an action plan for the small-scale hybrid energy system for remote area. The action plan is formed on the basis of cost effective modeling for remote rural area that is minimization of energy production cost. Among the renewable energy resources, the energy through the photovoltaic (PV) N effect can be considered the most essential and prerequisite sustainable resource because of the ubiquity, abundance, and sustainability of solar radiant energy. Regardless of the intermittency of sunlight, solar energy is widely available and completely free of cost. Recently, photovoltaic array system is likely recognized and widely utilized to the forefront in electric power applications. It can generate direct current electricity without environmental impact and contamination when is exposed to solar radiation. Use of a PVFC hybrid model provides a potential solution for better energy efficiency while reducing the cost of FC power technology.

Hybrid systems have applications in remote and inaccessible areas where the population is living without electricity. In remote and rural areas the grid connection is not technical feasible and also a cost effective option. Therefore, hybrid systems are well suited for such areas. With increasing concerns about fossil fuel deficit, skyrocketing oil prices, global warming, and damage to environment and ecosystem, the promising incentives to develop alternative energy resources with high efficiency and low emission are of great importance. Among the renewable energy resources, the energy through the photovoltaic (PV) N effect can be considered the most essential and prerequisite sustainable resource because of the ubiquity, abundance, and sustainability of solar radiant energy. Regardless of the intermittency of sunlight, solar energy is widely available and completely free of cost. Recently, photovoltaic array system is likely recognized and widely utilized to the forefront in electric power applications. It can generate direct current electricity without environmental impact and contamination when is exposed to solar radiation. A simulation software program known as Matlab has been used to simulate the system performance. The system design and performance analysis could thus be achieved through computer modeling and simulation prior to practical realization.

II. BLOCK DIAGRAM OF PVFC HYBRID SYSTEM

The block diagram of the PVFC Hybrid system is shown in figure 1 consists of a photovoltaic cell, a fuel cell, an inverter and a DC-DC converter. In this system a photovoltaic cell feeds power into grid through the DC-DC converter and inverter, which step up the voltage level and invert the DC of the photovoltaic cell into AC for the grid. In the absence of solar radiation the fuel cell is the other alternative which continuous the powers supply to the grid.

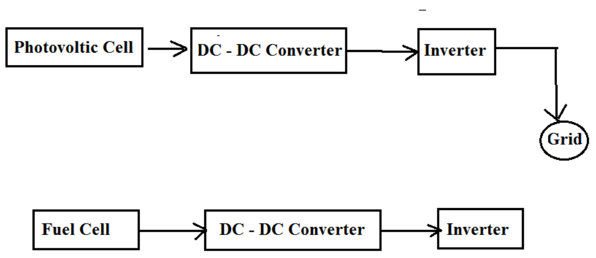

Figure 1. "Block Diagram of PVFC Cell"

III. MODELLING OF COMPONENTS

A. *Modelling of Photovoltaic Cell*

A general mathematical description of I-V output characteristics for a PV cell has been studied for over the past four decades. Such an equivalent circuit-based model is mainly used for the MPPT technologies. The equivalent circuit of the general model which consists of a photo current, a diode, a parallel resistor expressing a leakage current, and a series resistor describing an internal resistance to the current flow, is shown in Figure 2.

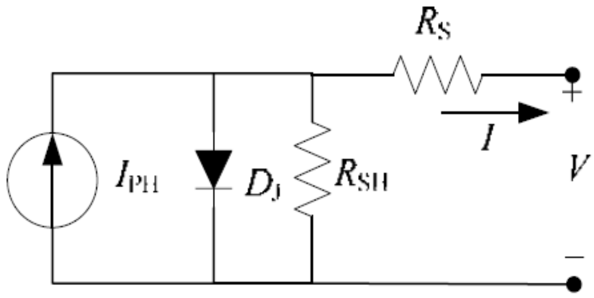

Figure 2. "Electrical model of PV cell"

The voltage-current characteristic equation of a solar cell is given as

$$I = I_{PH} - I_S e^{\frac{q(V+I_{RS})}{kT_C A - 1 - (V+I_{RS})R_{SH}}} \qquad \text{Equation 1}$$

Where I_{PH} is a light-generated current or photocurrent, I_S is the cell saturation of dark current, $q = 1.6 \times 10^{-19} C$ is an electron charge, $k = 1.38 \times 10^{-23} J/K$ is a Boltzmann's constant, T_C is the cell's working temperature, A is an ideal factor, R_{SH} is a shunt resistance, and R_S is a series resistance. The photocurrent mainly depends on the solar insulation and cell's working temperature, which is described as [1],

$$I_{PH} = [I_{SC} + K_I (T_C + T_{ref})]\lambda \qquad \text{Equation 2}$$

Where I_{SC} is the cells short-circuit current at a $25^0 C$ and $1 kW/m^2$, K_I is the cells short-circuit current temperature coefficient, T_{ref} is the cell's reference temperature, and λ is the solar insulation in kW/m^2 [2] . On the other hand, the cell's saturation current varies with the cell temperature, which is described as

$$I_S = I_{RS} (T_C + T_{ref})^3 e^{\frac{qE_G (1/T_{ref} \, 1/T_C)}{k_C A}} \qquad \text{Equation 3}$$

Where I_{RS} is the cell's reverse saturation current at a reference temperature and a solar radiation E_G is the bang-gap energy of the semiconductor used in the cell. An even more exact mathematical description of a solar cell, which is called the double exponential model, is derived from the physical behaviour of solar cell constructed from polycrystalline silicon. This model is composed of a light-generated current source, two diodes, a series resistance and a parallel resistance. However, there are some limitations to develop expressions for the V-I curve parameters subject to the implicit and nonlinear nature of the model. Therefore, this model is rarely used in the subsequent literatures and is not taken into consideration for the generalized PV model [5]. The shunt resistance R_{SH} is inversely related with shunt leakage current to the ground.

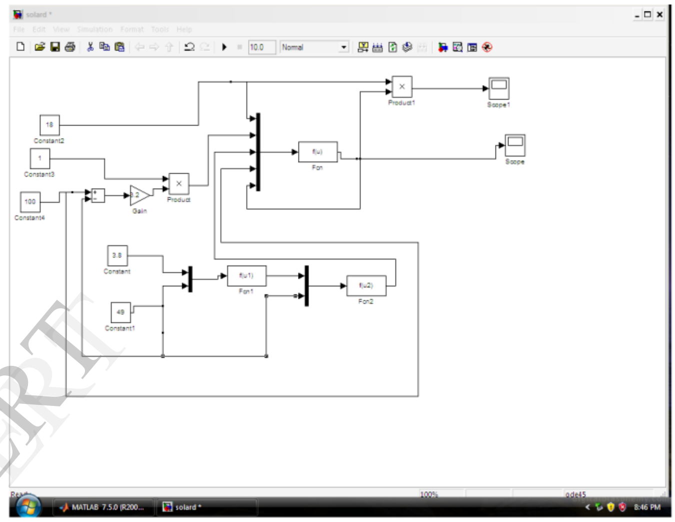

Figure 3 "Model of Solar Cell"

In general, the PV efficiency is insensitive to variation in R_{SH} and the shunt-leakage resistance can be assumed to approach infinity without leakage current to ground. On the other hand, a small variation in R_S will significantly affect the PV output power.

$$I = I_{PH} - I_S [\exp \ (q (V + I_{RS})/k \, T_C A) - 1] \qquad \text{Equation 4}$$

For an ideal PV cell, there is no series loss and no leakage to ground, i.e., R_S = 0 and R_{SH} = ∞. The above equivalent circuit of PV solar cell can be simplified.

$$I = I_{PH} - I_S [\exp \ (q \, V / kT_C A) - 1] \qquad \text{Equation 5}$$

- **Determination of Model Parameters**

All of the model parameters can be determined by examining the manufacturer's specifications of PV products. The most important parameters widely used for describing the cell electrical performance is the open-circuit voltage V_{OC} and the short circuit current I_{SC}. The aforementioned equations are implicit and nonlinear; therefore, it is difficult to arrive at an analytical solution for a set of model parameters at a specific temperature and irradiance [3]. Since normally $I_{PH} >> I_S$ and ignoring the small diode and ground-leakage currents under zero-terminal voltage, the short-circuit current I_{SC} is approximately equal to the photocurrent I_{PH} I_{PH} [1], i.e.

$$I_{PH} = I_S \quad \text{Equation 6}$$

On the other hand, the V_{OC} parameter is obtained by assuming the output current is zero. Given the PV open-circuit voltage V_{OC} at reference temperature and ignoring the shunt-leakage current, the reverse saturation current at reference temperature can be approximately obtained as [1],

$$I_{RS} = I_{SC} / [\exp\ (q\, V_{OC} / N_S kAT_C) - 1] \quad \text{Equation 7}$$

In addition, the maximum power can be expressed as

$$P_{\max} = V_{\max} I_{\max} = \gamma V_{OC} I_{SC} \quad \text{Equation 8}$$

Where $V_{\max}$ and $I_{\max}$ are terminal voltage and output current of PV module at maximum power point (MPP), and γ is the cell fill factor which is a measure of cell quality. The specifications of variables used in the model of PV cell are listed below:

Table 1 specifications of variables used in the model of PV cell

Characteristics	SPEC
Typical peak power(P_p)	60W
Voltage at peak power(V_{VV})	17.1V
Current at peak power(I_{PP})	3.5A
Short circuit current(I_{SC})	3.8A
Open circuit voltage(V_{OC})	21.1V
Temperature coefficient of open circuit voltage	-73mV/ °C
Temperature coefficient of short circuit current(K_I)	3mA /°C
Approximate effect of temperature on power	-0.38W/°C
Nominal operating cell temperature	49°C

B. Modeling of PEM Fuel Cell

The FC model used in this thesis is realized in MATLAB and Simulink. Then, this model is embedded into the SimPower Systems of MATLAB as a controlled voltage source. The relationship between the molar flow of any gas (hydrogen) through the valve and its partial pressure inside the channel can be expressed as [3]

$$q_{H2} / p_{H2} = K_{an} / \sqrt{M_{H2}} \quad \text{Equation 9}$$

For hydrogen molar flow, there are three significant factors: hydrogen input flow, hydrogen output flow and hydrogen flow during the reaction [4]. The relationship among these factors can be expressed as [3],

$$d/dt(PH_2) = RT / V_{an}(q_{H2}^{in} - q_{H2}^{out} - q^r{}_{H2}) \quad \text{Equation 10}$$

According to the basic electrochemical relationship between the hydrogen flow and the FC system current, the flow rate of reacted hydrogen is given by [6]

$$q^r{}_{H2} = N_o I_{FC} / 2F = 2KrI_{FC} \quad \text{Equation 11}$$

Using Equation (10) and (11) and applying Laplace's transform, the hydrogen partial pressure can be obtained in the s domain as [3]

$$P_{H2} = 1/ K_{H2} / 1 + \tau_{H2} S(q^{in}{}_{H2} - 2KrI_{FC}) \quad \text{Equation 12}$$

Where,

$$\tau_{H2} = V_{an} / K_{H2} RT \quad \text{Equation 13}$$

Similarly, the water partial pressure and oxygen partial pressure can be obtained. The polarization curve for the PEMFC is obtained from the sum of Nernst's voltage, the activation over voltage and the ohmic over voltage. Assuming constant temperature and oxygen concentration, the FC output voltage may be expressed as [3]

$$V_{cell} = E + \eta_{act} + \eta_{ohmic} \quad \text{Equation 14}$$

$$\eta_{act} = -B \ln(CI_{FC}) \quad \text{Equation 15}$$

And,

$$\eta_{ohmic} = -R_{\text{int}} I_{FC} \quad \text{Equation 16}$$

Now, the Nernst's instantaneous voltage may be expressed as [16],

$$E = N_o [E_o + RT / 2F \log\left[P_{H2} \sqrt{P_{o2}} / P_{H2o}\right] \quad \text{Equation 17}$$

The fuel cell system consumes hydrogen according to the power demand. The hydrogen is obtained from a high pressure hydrogen tank for the stack operation. During operational conditions, to control the hydrogen flow rate according to the FC power output, a feedback control strategy is utilized. To achieve this feedback control, the FC current from the output is taken back to the input while converting the hydrogen into molar form [4]. The amount of hydrogen available from the hydrogen tank is given by,

$$q^{req}_{H2} = N_o I_{FC} / 2FU \qquad \text{Equation 18}$$

Depending on the FC system configuration and the flow of hydrogen and oxygen, the FC system produces the dc output voltage [4]. The hydrogen–oxygen flow ratio $r_{H\text{-}O}$ in the FC system determines the oxygen flow rate. Different time constants can be defined for fuel increase and fuel decrease. The MATLAB and Simulink based FC system model developed in this paper with its block parameters are shown below.

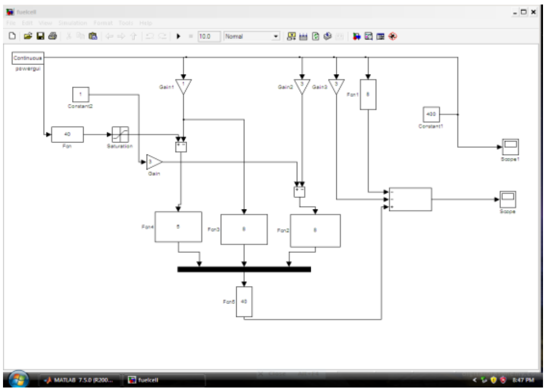

Figure 4 “Model of fuel cell”

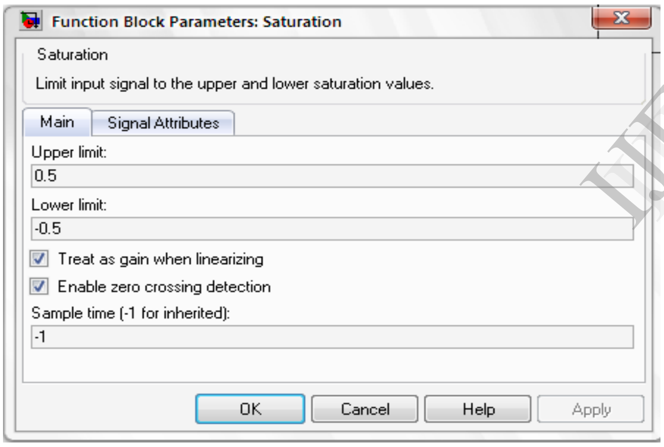

Figure 5 “Function Block parameter; Saturation of FC Model”

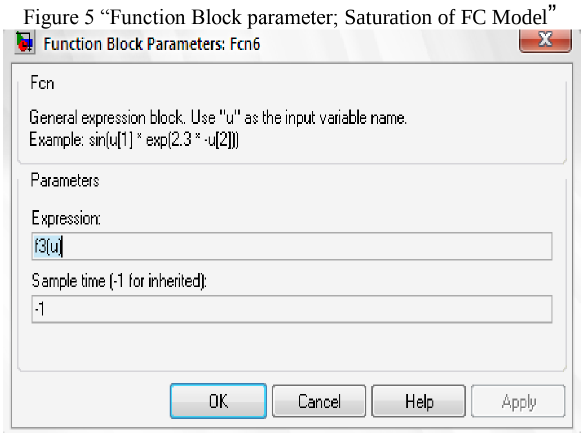

Figure 6 “Function Block parameter; Fcn_6 of FC Model”

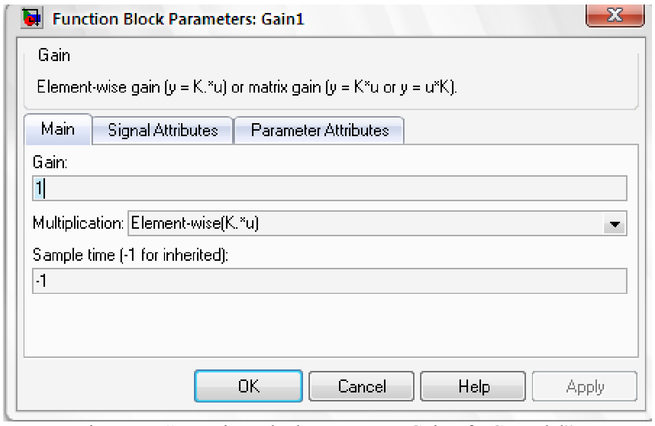

Figure 7. “Function Block parameter; Gain of FC Model”

The values of various variables used in the modelling of the model are described in the following table.

Table 2 Specification of variables used in fuel cell model

Parameters	SEPF
Activation voltage constant(B)	0.04777 [A-1]
Activation voltage constant(C)	0.0136 [V]
Faraday’s constant(F)	96484600 [C kmol(s atm)-1]
Hydrogen time constant(τ_{H2})	3.37[s]
Hydrogen valve constantK_{H2})	4.22*10-5[kmol(s atm)-1]
Kr constant(=N_O/4F)	8.3951*10-7 [kmol (s A)-1]
Hydrogen oxygen flow ratio (r_{H_O})	1.168
No load voltage(E_O)	0.6 [V]
Number of cells(NO)	332
Oxygen time constant(T_{O2})	6.74 [s]
Oxygen valve constant(k_{O2})	2.1*10-5 [kmol(s atm)-1]
FC absolute temp.[T]	343 [K]
Universal gas factor[R]	8314.47 [J(kmol K)-1]
Water time constant(τ_{H2O})	18.418 [s]
Water valve constant(K_{H2O})	7.716*10-6 [kmol(s atm)-1]
Utilization factor(U)	0.8
PI gain constants(k_1,k_2)	10

C. Modelling of DC – DC Converter

Under steady-state conditions, the voltage and current waveforms of a dc-dc converter can be found by use of two basic circuit analysis principles. The principle of inductor volt-second balance states that the average value, or dc component, of voltage applied across an ideal inductor winding must be zero. This principle also applies to each winding of a transformer or other multiple winding magnetic devices. Its dual, the principle of capacitor amp-second or charge balance, states that the average current that flows through an ideal capacitor must be zero. Hence, to determine the voltages and currents of dc-dc converters operating in periodic steady state, one averages the inductor current and capacitor voltage waveforms over one switching period, and equates the results to zero. The equations are greatly simplified by use of a third artifice, the small ripple approximation. The inductor currents and capacitor voltages contain dc components, plus switching ripple at the switching frequency and its harmonics. In most well designed converters, the switching ripple is small in magnitude compared to the dc components. For inductor currents, a typical value of switching ripple at maximum load is 10% to 20% of the dc component of current. For an output capacitor voltage, the switching ripple is typically required to be much less than 1% of the dc output voltage. In both cases, the ripple magnitude is small compared with the dc component, and can be ignored. A resistor RL is included in series with the inductor, to model the resistance of the inductor winding. It is desired to determine simple expressions for the output voltage V, inductor current I_L, and efficiency. With the switch in position1, the inductor voltage is equal to $V_L(t) = V_g - I_L(t)R_L$. By use of the small ripple approximation, we can replace $I_L(t)$ with its dc component I_L, and hence obtain $V_L(t) = V_g - I_L(t)R_L$. Likewise, the capacitor current is equal to $I_C(t) = -V(t)/R$, which can be approximated as $I_C(t) = -V/R$ [7].

The model of DC-DC Converter with its block parameters are shown in the below figures and specifications of various model parameters are listed in table 3.

Table 3 Specification of variables used in DC-DC Converter model

Parameters	Specifications
Converter inductance	66 [mH]
Converter capacitance	2200[μF]
Semiconductor type	MOSFET
Rated switching frequency	1000[Hz]
Proportional gain of PI voltage control system	0.0001
Integral gain of PI voltage control system	0.01
Reference voltage	400[V]

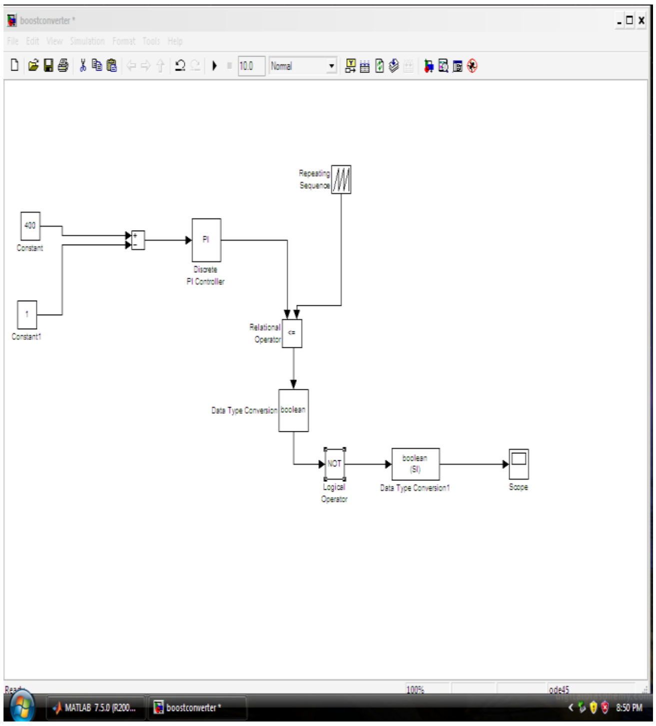

Figure 8 "Model of DC-DC Converter"

When the switch is in position 2, the inductor is connected between the input and output voltages. The inductor voltage can now be written. $V_L(t) = V_g - I_L(t)R_L - V(t) \approx V_g - I_L R_L - V$.

The capacitor current can be expressed as I_C (t) = I_L (t) – v (t)/R~I_L-V/R.

When the converter operates in steady state, the average value, or dc component, of the inductor voltage waveform V_L (t) must be equal to zero.

Upon equating the average value of the $V_L(t)$ to zero, we obtain [8],

$$0 = D(V_g - I_L R_L) + (1-D)(V_g - I_L R_L - V)$$

Equation 19

Likewise, application of the principle of capacitor charge balance to the capacitor current leads to,

$$0 = D(-V/R) + (1-D)(I - V/R) \quad \text{Equation 20}$$

From equation 17 and 18,

$$V/V_g = 1/(1-D).1/1 + R_L/(1-D)^2 R$$

Equation 21

And,

$$I_L = V_g/(1-D)^2 R.1/(1 + R_L/(1-D)^2 R$$

Equation 22

In the ideal case when $R_L = 0$, the voltage conversion ratio M (D) is equal to one at D = 0, and tends to infinity as *D* approaches one. In the practical case where some small inductor resistance R_L is present, the output voltage tends to zero at D = 1. In addition, it can be seen that the inductor winding resistance R_L (and other loss elements as well) limits the maximum output voltage that the converter can produce. Obtaining a given large value of V/Vg requires that the winding resistance R_L be sufficiently small. The converter efficiency can also be calculated. For this boost converter the efficiency is equal to [8],

$$\eta = \frac{P_{out}}{P_{in}} = \frac{\left(V^2/R\right)}{\left(V_g I_L\right)} \qquad \text{Equation 23}$$

From equation 6, 7 and 8 the efficiency becomes.

$$\eta = 1\big/\left(1 + R_L/(1+D)^2 R\right) \qquad \text{Equation 24}$$

It can be seen that, to obtain high efficiency, the inductor winding resistance R_L should be much smaller than $(1 - D)^2$ *R*. This is much easier to accomplish at low duty cycles, where (1 – D) is close to unity, that at high duty cycles where (1 – D) approaches zero. The output simulation result of DC-DC converter is shown in figure 9.

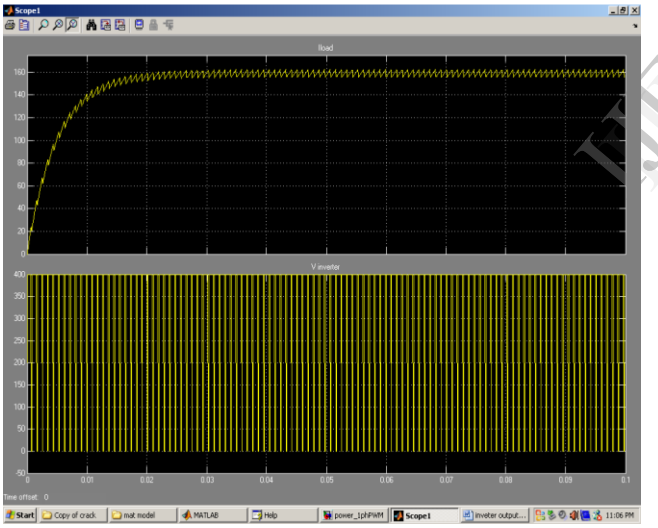

Figure.9 "Output of DC-DC Converter"

The figure 9 shows the output of the DC-DC Converter. Consequently, the efficiency is high at low duty cycles, but decreases rapidly to zero near D = 1. This behavior is typical of converters having boost or buck-boost characteristics.

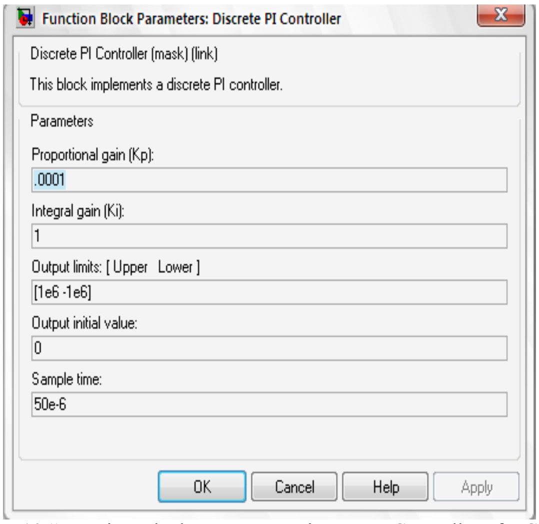

Figure 10 "Function Block parameter; Discrete PI Controller of DC-DC Converter Model"

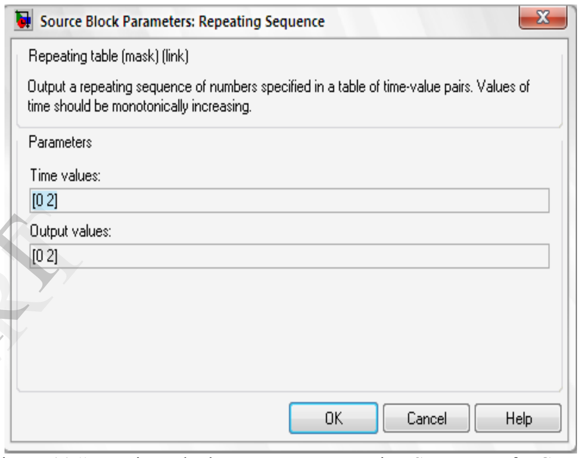

Figure 11 "Function Block parameter; Repeating Sequence of DC-DC Converter Model"

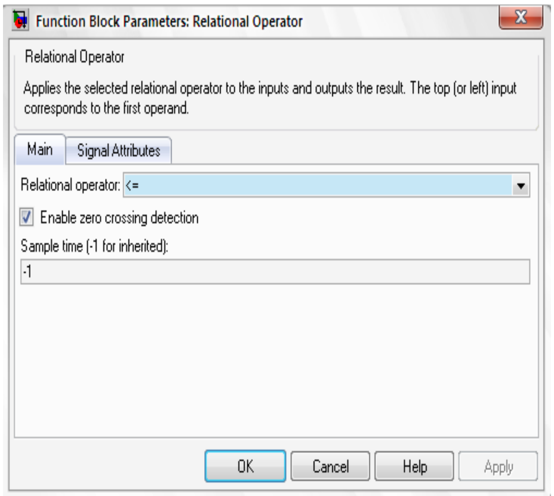

Figure 12 "Function Block parameter; Relational Operator of DC-DC Converter Model"

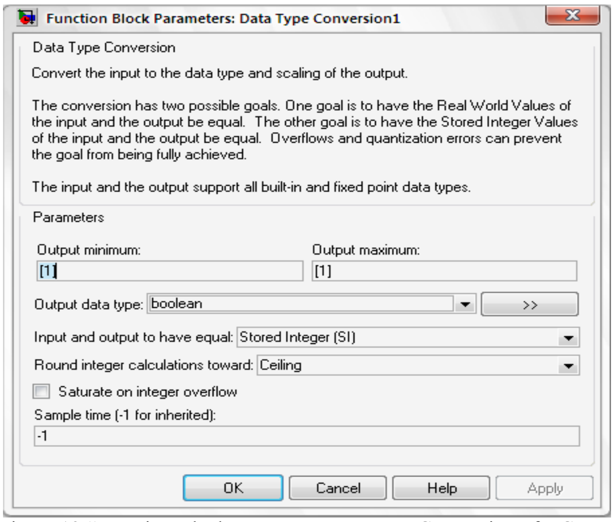

Figure 13 "Function Block parameter; Data type Conversion of DC-DC Converter Model"

D. Modelling of the Inverter

The main circuit is the part where the DC electric power is converted to AC. This is virtually implemented with the one that is shown at the Figure 14, in this circuit we use a 3 leg inverter for 3-phase conversion which is composed of 6 IGBTs and the control unit. The last generates control pulses to drive the IGBTs. The pulse generator gives a digital signal to the IGBTs. When the signal from the pulse generator is not zero then it reacts as a switch and opens. This consists the basic operation in order to convert the DC to AC, with the technique of the Pulse Width Modulation (PWM).The frequency of the IGBTs we use is 1 KHz. For the time interval the IGBTs are open, we get a pulse at power circuit, which has the same amplitude of source. The RMS time integral give us the output values. The on-off is determined by a control unit which is analyzed below. The modulation factor ma can be used as a parameter for the dynamic control of the system. When m_a is changing we can control the voltage output and correct the voltage fluctuations due to the PV array and MPPT. The losses will be analogue to the change over the ma. A useful reference for cascaded multilevel converters which discuses the control circuit of new topology [7]. A three phase inverter has the basic advantage that generates power in 3-phase and is working without a hitch.

At one node of the circuit, supposing we have an input voltage $V_{oi}(t)$ an LC filter ,L inductance and C capacitance and the r_L resistant Load ,if we apply the Kirchhoff's laws and if we consider that the IGBTs at an open state, we get:

$$r_L i_L + L\frac{di_L}{dt} + V_C = V_{oi}(t)$$ Equation 25

$$i_L - C(\frac{dV_C}{dt}) - \frac{V_C}{R}$$ Equation 26

The above problem is depending on the output of the PV array and in order to have a simple solution we consider only the switching part of the circuit that is in figure 14 one obtain the solution [9] which is:

$$V_{SN} = \sum_{\infty} n = 1{,}5{,}7{,}11 \frac{4\text{V}}{3\text{n}\pi}(\cos\frac{\text{n}\pi}{3} + 1)\,\text{sinn}\,(\omega t - 120^0)$$

Equation 27

$$V_{TN} = \sum_{\infty} n = 1{,}5{,}7{,}11 \frac{4\text{V}}{3\text{n}\pi}(\cos\frac{\text{n}\pi}{3} + 1)\,\text{sinn}\,(\omega t - 240^0)$$

Equation 28

$$V_{SN} = \sum_{\infty} n = 1{,}5{,}7{,}11 \frac{4\text{V}}{3\text{n}\pi}(\cos\frac{\text{n}\pi}{3} + 1)\,\text{sinn}\,\omega t$$

Equation 29

Each one of the 3-phases to neutral voltage, the 1, 5, 7, 11 are the harmonics appearing and $\omega = 2\pi f$ the basic frequency at 50Hz.The Matlab Lab/Simulink using the numerical methods is solving the problem, taking into account not only this part of the system, but the total circuit as it can be seen at figure 14 [10].

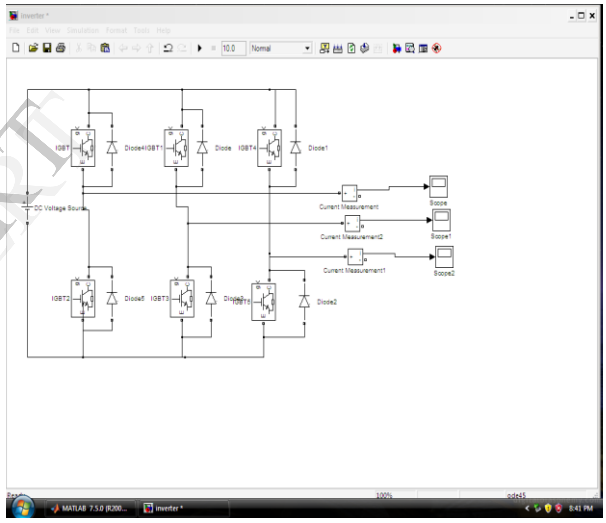

Figure14 "Model of Inverter"

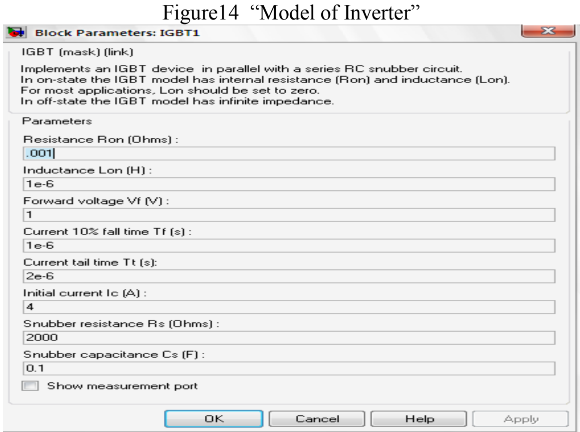

Figure 15 "Function Block parameter; IGBT1 of Inverter Model"

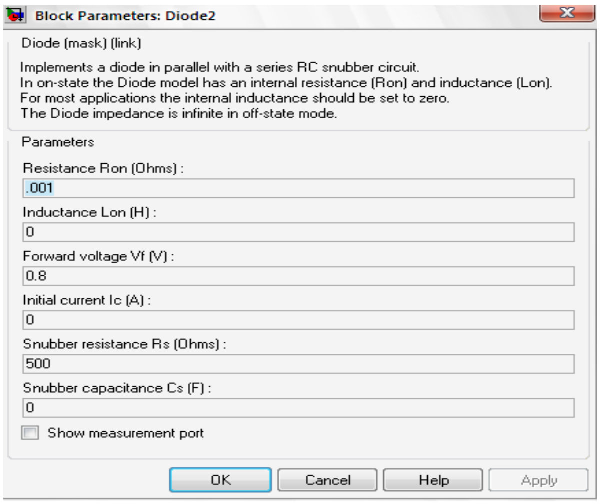

Figure 16 "Function Block parameter; Diode of Inverter Model"

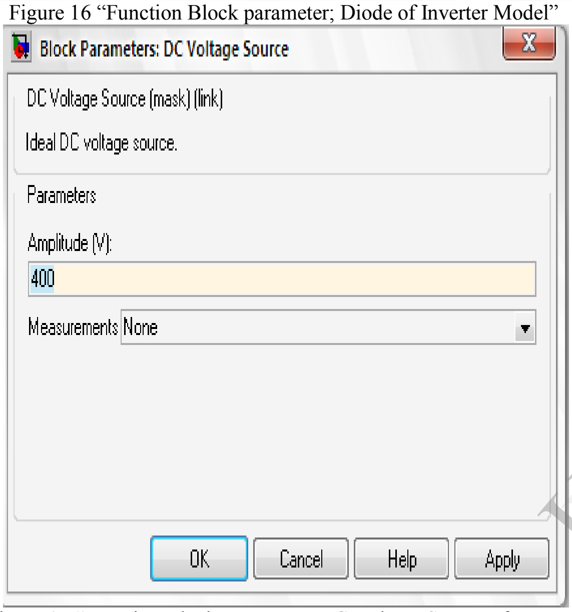

Figure 17 "Function Block parameter; DC Voltage Source of Inverter Model"

IV. SIMULATION RESULTS

A. Simulation Result of PV Cell

The simulation results of PV cell model with its block parameters are shown below. The following results show the output of the solar cell.

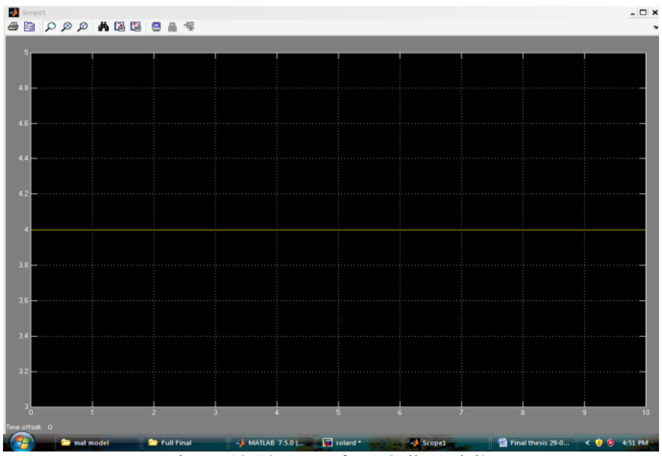

Figure 18 "Output of PV Cell Model'

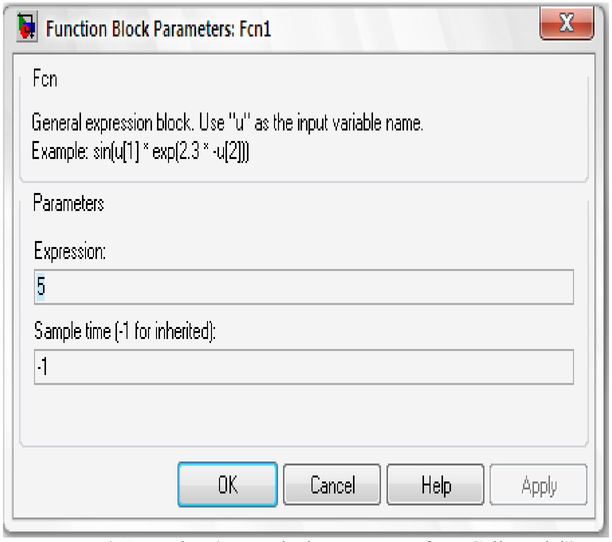

Figure 19 "Function (Fcn_1) Block parameter of PV Cell Model"

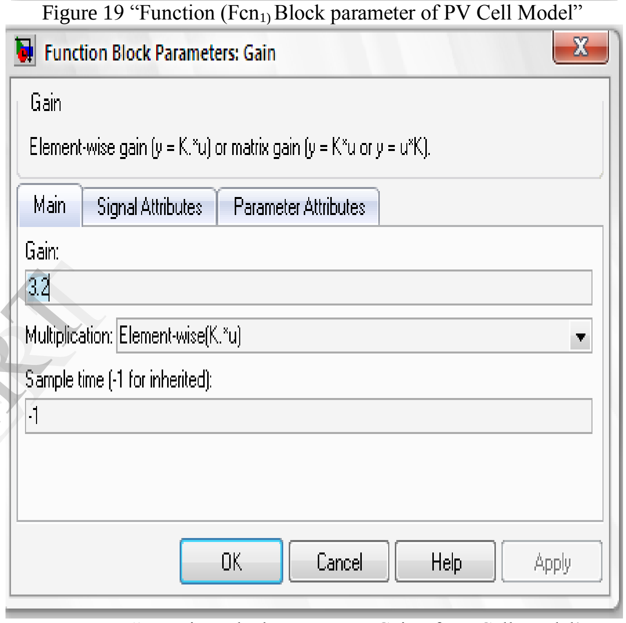

Figure 20 "Function Block Parameter; Gain of PV Cell Model'

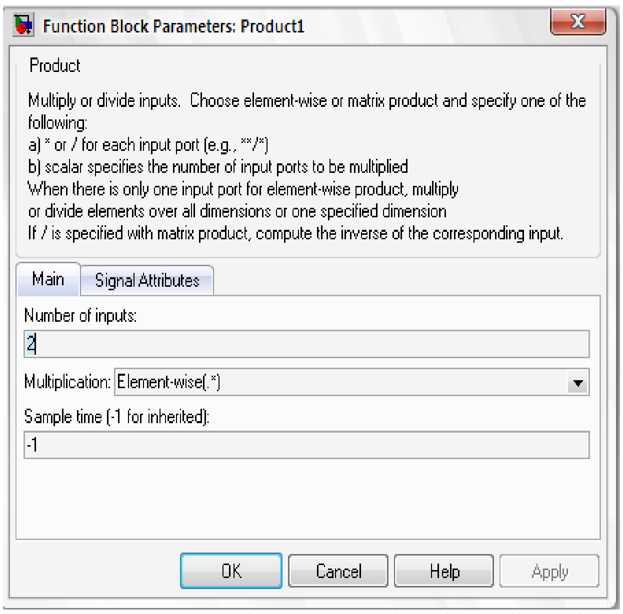

Figure 21 "Function Block parameter; Product of PV Cell Model"

B. Simulation Result of PEM Fuel Cell

The simulation results of fuel cell are shown as follows:

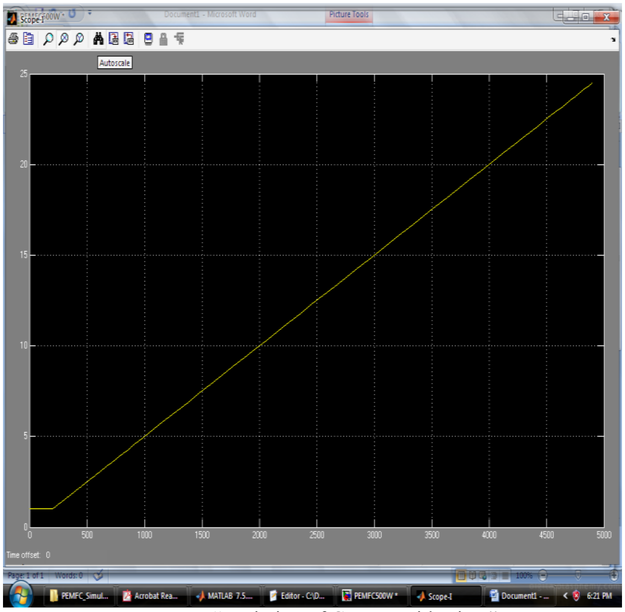

Figure 22 "Variation of Current with Time"

The experimental results show that very different local dynamic respect through the response of the average current shows very little dynamic.

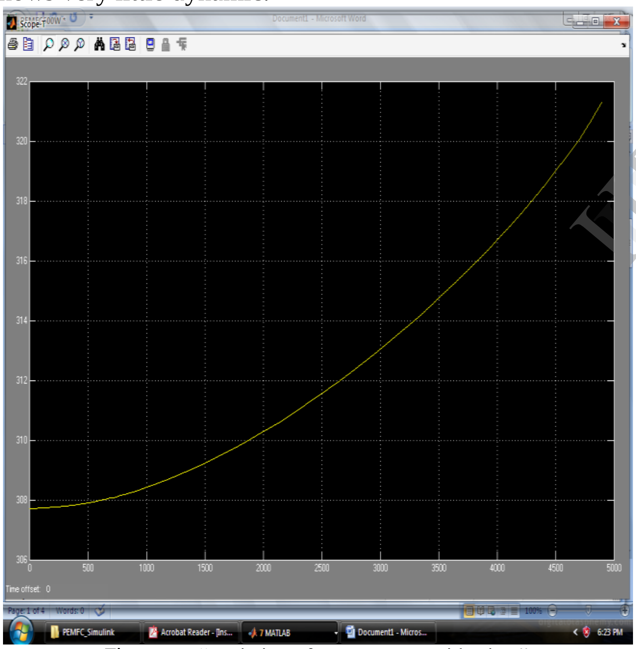

Figure 23 "Variation of Temperature with Time"

Fuel cell temperature has an important role on performance of PEM fuel cells, when fuel cell temperature is lower than or equal to humidification temperature, local current decreases along the channel.

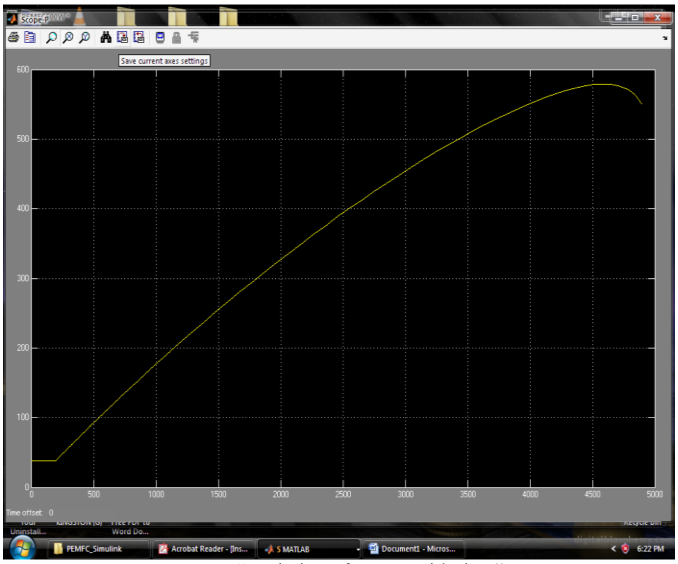

Figure 24 "Variation of Power with time"

Photovoltaic and Fuel cells are ideal candidates for use in hybrid system due to their high energy density and the power requirements of these can be satisfied by the transient response of system. These have high power density and provide good transient characteristics. The behavior of the two in tandem is studied through simulations.

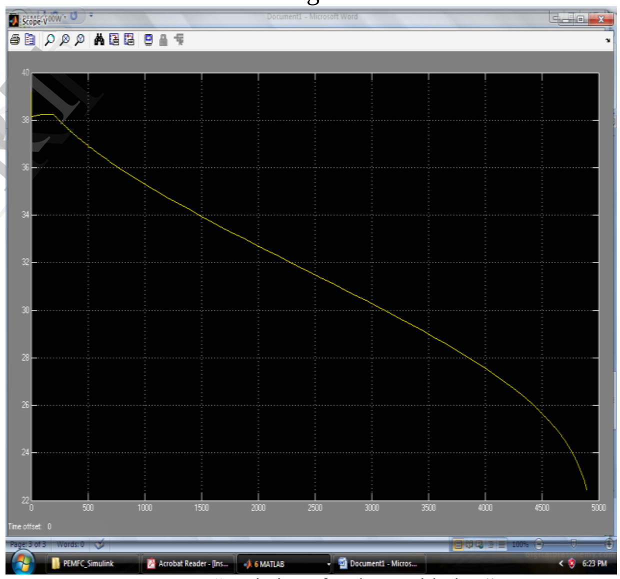

Figure 25 "Variation of Voltage with time"

C. Simulation of Inverter Module

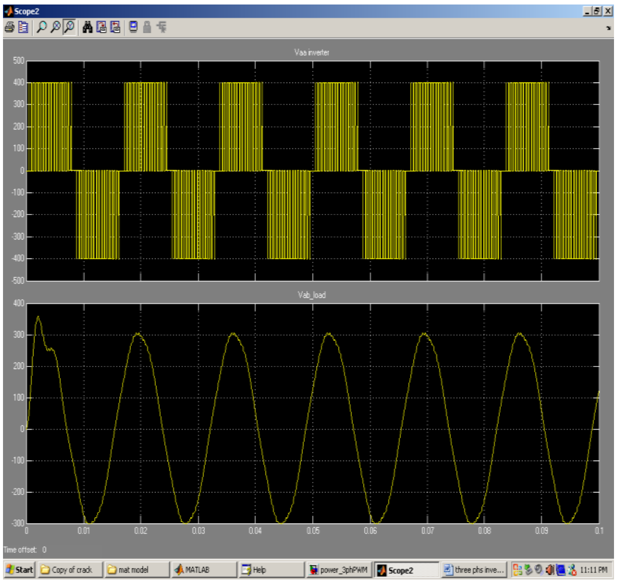

Figure 26 "Simulation Result of Inverter Model"

Table 4. Specification of variables used in Inverter model

Parameters	Specifications
Semiconductor type	IGBT-DIODE
Snubber resistance	2[Kω]
Snubber capacitance	0.1[μF]
Internal resistance	1[mΩ]
Carrier frequency	5[kHz]
Modulation index	0.98
Frequency of output voltage	60[Hz]

V. CONCLUSION

The overall goal of this thesis is to model and simulate the different models of a PVFC hybrid system. In this work, different models of a PVFC hybrid system has been implemented in computer codes and utilized to predict its operational performance through numerical simulation. Detailed descriptions of the individual component models required to simulate a PVFC hybrid system are presented. These models are mainly based one electrical and electrochemical relation. However, a number of empirical relationships for some models are also used. The models of PV generator, PEM fuel cell and power conditioning units are discussed in details.

The modeling, identification and validation of the component models show that the agreement between simulated and measured data is very good. Several short-term simulations are performed, such that the I-U characteristics, hydrogen production and consumption rates, and other physical processes of the individual component models are properly evaluated. The main conclusions that could be drawn from the evaluation of the individual component models of the hydrogen PVFC hybrid system are given in the following subsections. The main conclusions about the overall operation of the hydrogen PVFC hybrid system at two sites with different topologies that it can also stabilize the fuel cell operation within the set limits especially when sudden load variations occur. This is better than to oversize the power sources, which is an expensive solution. However, coupling PV generator and fuel cell directly to the DC bus-bar may be a good alternative for small systems. The energy losses in this system associated with the power conditioning units are minimized. For long-term operation, the results of the simulation have been used for a detailed energy analysis, in which the energy conversion steps and losses for each individual component are analyzed and quantified, and their influence on the system overall efficiency is investigated.

The results of the energy analysis have shown that the operational performance of the system does not depend only on component efficiencies but also on system design and consumption behavior. This fact points out that the search for performance improvement of PVFC hybrid system should be concentrated on development of subsystem components, especially the fuel cell. The results obtained from the analysis have shown that the performance of PVFC hybrid system can be optimized in different ways: by understanding the system behavior better, by improving component's efficiency, by utilizing new systems concepts, and by helping people to use their systems as efficiently as possible. This ensures that the system as a whole can be operated in such a way as to supply a definite amount of power all the time irrespective of the available solar insulation and other environmental factors. This thesis deals with a hybrid system containing PV array and FC stack operating in tandem. In due course of the project, various options available for hybrid system and the interfaces have been studied and a new hybrid system has been proposed whose simulation is done to show its validity. The two-stage inverter provides both active power and reactive power independently of each other giving the .edibility of operating in accordance with the system requirements. The dc/dc boost converter gives the added advantage of being able to extract maximum power available from the PV array ensuring maximum utilization of the source. Thus, the PCU provides active power and reactive power whose value is decided by the grid requirement. The PCU which is intended for interfacing the Fuel Cell stack to the grid can in actual practice be used in many applications with different voltage levels. Its operation makes it possible to alter the switching control to switch from one configuration to the other while the inverter is in operation. The ability of the inverter that it can be operated in any of the three configurations, make it a universal configuration with its applications in interfacing different sources. Hence, the hybrid system as a whole, is self-sufficient in the sense that it can provide required amount of power at a given instant. This is done by operating the PV array at its MPP taking full advantage of the PV source. From the simulations, it can be seen that the system is operated in grid connected mode only.

A photovoltaic fuel cell system hybrid power system is designed and modeled for a grid-independent user with appropriate power flow controllers. The available power from the renewable energy sources is highly dependent on environmental conditions such as intensity of solar radiation. To overcome this deficiency of the solar system, we integrated photovoltaic generator with the fuel cell system using a novel topology. The purpose of this thesis is the modeling and simulation of a stand-alone hybrid power system, referred to as "Photovoltaic-Fuel Cell (PVFC) hybrid system". This hybrid topology exhibits excellent Performance under variable solar radiation and load power requirements. The proposed system can be used for non-interconnected remote areas.

VI. FUTURE WORK

To enhance the performance of PVFC hybrid systems, the following recommendations for future work are proposed. The choice of the suitable concept should be based on the type of application, adding other renewable sources such as a wind turbine to the system. A wind energy conversion would reduce the required PV generator area, and reduce the hydrogen storage volume. A trade-off between PV generator area and wind generator size is an interesting challenge for systems located at sites with high average wind speeds. A practical limitation on the system design is the voltage operating range of the available power conditioning units, which are designed mainly for lead-acid batteries rather than fuel cells or super capacitors. Thus, designing a new power conditioning units that can match the characteristics of these components is recommended. In hydrogen PVFC hybrid system without battery energy storage, such as in this work, the annual numbers of the on and off switching of the electrochemical components and also the annual operating times of these components are large. This would probably affect in the overall simulation results, if the hydrogen losses are not included in the simulation. These losses must be calculated to make the simulation more accurate. The H_2/O_2 PEM fuel cell has a better performance than the Air/H_2 PEM fuel cell which is used in this work, but requires a storage tank for oxygen and a purification system. Thus, it is recommended to study using H_2/O_2 PEM fuel cell with the PVFC hybrid system and evaluate the system according to the cost point of view. Designing of a high pressure electrolyser could eliminate the need for a compressor to compress hydrogen into high pressure and, thus the volume of the gas storage tank is decreased. Other concept is to store the hydrogen in metal hydride (MH) storage, i.e., replacing the compressed hydrogen gas storage with low pressure ambient temperature metal hydride storage. The greatest advantage of the MH-storage is that it can be coupled directly to a low pressure electrolyser, thus eliminating the need for a compressor. The choice of the suitable concept should be based on the type of application.

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