International Journal on Emerging Technologies **1**(2): 60-67(2010) **ISSN : 0975-8364**

Modeling & Simulation of different components of a stand-alone Photovoltaic and PEM Fuel Cell Hybrid System

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ABSTRACT : In a Hybrid power system a number of electrical power generators and electrical power storage components are combined together to meet the electrical power demand of remote as well as rural area or even a whole community. 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 technically feasible and also not a cost effective option. Therefore, hybrid systems are well suited for such areas. The purpose of this Paper is to model and simulate the different components of a PVFC hybrid system which may fulfill the electric demands for remote and rural areas. This hybrid system consists of a photovoltaic generator and a proton exchange membrane fuel cell (PKMFC) coupled together to form a hybrid system which is connected to the load or grid as per the user demand.

I. INTRODUCTION

In a Hybrid power system a number of electrical power generators and electrical power storage components are combined together to meet the electrical power demand of remote as well as rural area or even a whole community. In addition to PV generators, small hydro plants, fuel cells, wind generators and others sources of electrical energy can be added as needed to meet the electrical power demand in a way other specifies. A hybrid system, also used as a stand alone power system, is an autonomous system that supplies electricity to the user load without being connected to the electrical power grid. Such 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 technically feasible and also not a cost effective option, therefore hybrid systems are well suited for such area. The purpose of this Paper is the modeling and simulation of a stand alone PVFC hybrid power system. It couples a photovoltaic generator & proton exchange membrane fuel cell (PEMFC) and power conditioning unit to give different system topologies. This system is intended to be an environmentally friendly solution since it tries to maximize the use of a renewable energy source. Photovoltaic generators which directly convert solar radiation into electricity have a lot of significant advantage such as being inexhaustible and pollution free, silent with no rotating part and with size independent electric conversion efficiency [1, 2]. From an operation point of view a PV power generation experiences large variations in its output power due to intermittent weather conditions. One method to overcome this problem is to integrate the photovoltaic system with other power source such as fuel cell, wind power, battery back up and the diesel back up generator so, as to ensure a continuous 24 hour supply. Hybrid system topologies available in literature are discussed briefly.

II. PHOTOVOLTAIC-DIESEL HYBRID SYSTEM

The PV hybrid system may be an economical alternative to a large stand-alone PV system, because the PV generator doesn't have to be sized large enough for worst case weather conditions. A diesel generator combined with a battery charger can supply power to the user load when the PV generator fails. If the PV generator is sized for average user load, then during periods of higher user loads, the diesel generator supplies the difference. When batteries are low, the diesel generator supplies the loads as well as the battery charger to recharge the batteries. If the PV generator is sized smaller than needed for normal load, the diesel generator can supply peak loads, such as water pumping, and simultaneously the battery charger to charge battery system. Diesel generator and battery bank sizes must be chosen carefully for reliable system operation [10]

III. PHOTOVOLTAIC-WIND HYBRID SYSTEM

A Wind generator combined with a battery charger can supply power to the user load when the PV generator fails. If the PV generator is sized for average user load, then during periods of higher user loads, the Wind generator supplies the difference. When batteries are low, the Wind generator supplies the loads as well as the battery charger to recharge the batteries. If the PV generator is sized smaller than needed for normal load, the Wind generator can supply peak loads. [1]

IV. PHOTOVOLTAIC -FUEL CELL HYBRID

System The Wind & Diesel generator in this system is replaced by a fuel cell system. The fuel cell system is used as a back-up generator, when the batteries reach the minimum allowable charging level and the load exceeds the power produced by the PV generator. The advantages of this system are in general the same as for a Photovoltaic-Battery-Wind & Diesel hybrid system with regard to the PV generator size and batteries availability. Some principle differences exist between a Wind & Diesel generator and a fuel cell which affect the design, sizing and the operating strategy of such a hybrid system. For example, a Wind & Diesel generator will provide the rated power to the load in a few seconds after start up, but a fuel cell system needs more time to provide the rated power and the output should only be increased slowly after start up. The increasing operating temperature which occurs during operation does improve the efficiency of a fuel cell significantly According to the load profile, the feasible fuel cell capacity can be determined, whereas a diesel generator should be operating at the rated power as much as possible. [10, 11]

V. PROPOSED SYSTEM

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 paper 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 Power Conditioning 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. 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 (he system performance. The system design and performance analysis could thus be achieved through computer modeling and simulation prior to practical realization. This paper aim to an accurate simulation system model to predict the real performance of the PVFC hybrid system, and then to undertake detailed analysis of the effect of changes in the system configurations, power conditioning unit, and sites to choose an optimal system design. The object of the study is to reach a design that optimizes the operation of a PVFC hybrid system. 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.

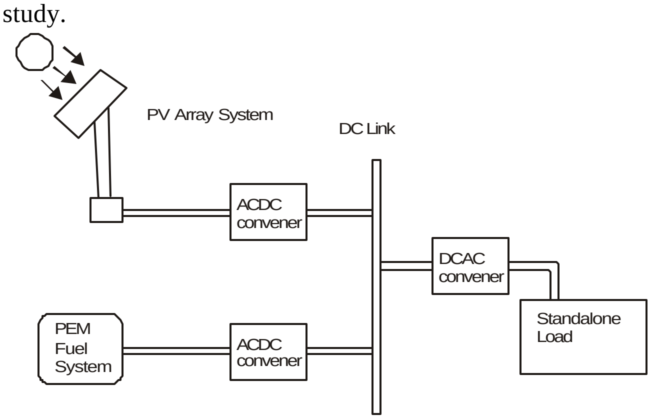

Fig.1 Block Diagram of Photovoltaic-Fuel Cell Hybrid System

VI. MODELING AND SIMULATION OF PV CELL

A general mathematical description of I-V output characteristics for a PV cell has been studied for over the past four decades [13]. Such an equivalent circuit-based model is mainly used for the Maximum Power Point Tracker (MPPT) technologies. The equivalent circuit of the general model which consists of a photo current, a diode, a parallel resistor expressing leakage current, and a series resistor describing an internal resistance to the current flow, is shown in Figure 2

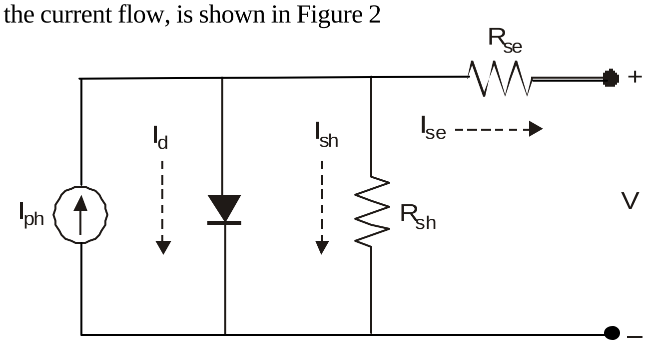

Fig. 2 Electrical model of PV cell

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

$$I = I_{Ph} - I_{Se}\exp q(V + I_{rs})/kT_C A - 1 - (V + I_{rs})/R_{sh} \quad \text{...(i)}$$

Where,

I_{Ph} = Light-generated current or photocurrent,

I_{Se} = Cell saturation of dark current,

$q = 1.6 \times 10^{-19}$C,

k = Boltzmann's constant 1.38×10^{-23}J/K,

T_c = Cell's working temperature,

A = Ideal factor,

R_{sh} = Shunt resistance,

R_{Se} = Series resistance.

The photocurrent mainly depends on the solar insulation and cell's working temperature, which is described as

$$I_{Ph} = [I_{sc} + K_1 (T_C - T_{ref})]\lambda \quad \text{... (ii)}$$

Where,

I_{sc} = Cell's short-circuit current at a 25°C and lkw/m^2

K_{I} = Cell's short-circuit current temperature coefficient,

T_{ref} = Cell's reference temperature,

λ = is the solar insulation in kw/m^2.

On the other hand, the cell's saturation current varies with the cell temperature, which is described as

$$I s = I_{rs} (T_c/T_{ref})^3 \exp [q\ E_G (1/T_{ref} 1/T_C)/kA] \quad \text{.....(iii)}$$

Where,

I_{ref} = Cell's reverse saturation current at a reference temperature and a solar radiation

E_G = 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 behavior 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 I-V 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. The shunt resistance R_{sh} is inversely related with shunt leakage current to the ground 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.

Equation can be rewritten to be.

$$I = I_{ph} - I_s [\exp (q (V + I_{rs})/k T_C A) - 1] \quad \text{.... (iv)}$$

For an ideal PV cell, there is no series loss and no leakage to ground, i.e., $R_S = 0$ and $R_{sh} = \infty$. The above equivalent circuit of PV solar cell can be simplified thus; the can be rewritten to be,

$$I = I_{ph} - I_s [\exp(q V/kT_c A) - l] \quad \text{....(v)}$$

The MATLAB and Simulink based of PV Cell System Model developed using the above equation is shown in figure 3.

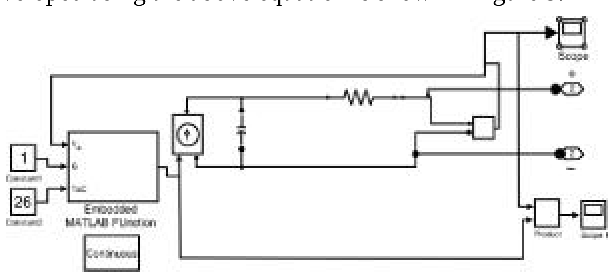

Fig-3 Simulink Model of PV Cell

Table 1. Electrical Characteristics of Solar Cells

Characteristics	SPEC
Typical peak power(P_p)	150W
Voltage at peak power(V_v\/)	34.5V
Current at peak power(I_{PP})	4.35A
Short circuit current(I_{sc})	4.75A
Open circuit voltage(V_Oc)	43.5V
Temperature coefficient of open circuit voltage	- (160 ± 20)mV/°C
Temperature coefficient of short circuit current(Ki)	(0.065±0.015)%/
Approximate effect of temperature on power	-(0.5±0.05)%/°C
Nominal operating cell temperature	49°C

VII. MODELING AND SIMULATION OF PEM FUEL CELL

A fuel cell is an electrochemical cell that converts a source fuel into an electrical current. It generates electricity inside a cell through reactions between a fuel and an oxidant, triggered in the presence of an electrolyte. The reactants flow into the cell, and the reaction products flow out of it, while the electrolyte remains within it. Fuel cells can operate continuously as long as the necessary reactant and oxidant flows are maintained. Fuel cell has higher energy storage capability, thus enhancing the range of operation for automotive applications and is a cleaner source of energy. Fuel cell also has the further advantage of using hydrogen as fuel that could reduce world's dependence on nonrenewable hydrocarbon sources. In recent years different types of technologies have been developed , such as the: Alkaline Fuel Cell (AFC); Proton Exchange Membrane (PEM) Fuel Cell; Phosphoric Acid Fuel Cell (PAFC); Molten Carbonate Fuel Cell (MCFC); Solid Oxide Fuel Cell (SOFC) and Direct Methanol Fuel Cell(DMFC). One of the most diffused, the PEM fuel cell, has a high proton conductivity membrane as electrolyte. The PEM uses a thin layer of solid organic polymer (the most commonly used is Nafion) as electrolyte. This ion-conductive membrane is coated on both sides with highly dispersed metal alloy particles (mostly platinum) that constitute the active catalyst. The PEM fuel cell basically requires hydrogen and oxygen as reactants, though the oxidant may also be ambient air, and these gasses must be humidified to prevent membrane dehydration. Each single cell produces about 0.6 V and can be combined in a fuel cell stack to obtain the required electrical voltage and power. The operating temperature is in the range of 70-100°C. One of the main weak points of fuel cell is its slow dynamics. In fact, the fuel cell dynamic is limited by different phenomena, as the resistance variation of the membrane due to the temperature, or the hydrogen delivery system itself, which can introduce delays due to the pumps, the valves and in some cases to the reforming process.

The Fuel Cell model used in this Paper 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 (qn2) through the valve and its partial pressure inside the channel phi can be expressed as [5]

$$q_{H2}/P_{H2} = K_{an}/\sqrt{}M_{H2} \quad \text{...(vi)}$$

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

$$d/dt\,(p_{H2}) = RT/Van\,(q^{in}\,H2 - q^{out}\,H2 - q^{r}\,H2) \quad \text{...(vii)}$$

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

$$q^{r}_{H2} = N_0 I_{FC}/2F = 2Kr\, I_{FC} \quad \text{...(vii)}$$

Using and applying Laplace transform, the hydrogen partial pressure can be obtained in the s domain as

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

Where, $\tau_{H2} = Van/K_{H2}RT$ ....(x)

Similarly, the water partial pressure and oxygen partial pressure can be obtained [13]. The polarization curve for the PEMFC is obtained from the sum of nearest voltage, the activation over voltage and the ohmic over voltage. Assuming constant temperature and oxygen concentration, the FC output voltage may be expressed as

$$V_{cell} = E + \eta_{act} + \eta\ \eta_{act} = -BIn(CI_{FC}) \quad ....(xi)$$

And,

$$\eta_{ohmic=-R^{int}\ I_{FC}}$$

Now, the nearest instantaneous voltage may be expressed as

$$= N_O\ [E_O + RT/2F \log [\ P_{H2}\sqrt{\ } P_{O2}/P_{H2O}]] \quad ...(xii)$$

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. The amount of hydrogen available from the hydrogen tank is given by,

$$q^{req}{}_{H2} = N_O I_{FC} /2FU \quad ....(xiii)$$

Depending on the FC system configuration and the flow of hydrogen and oxygen, the FC system produces the dc output voltage. The hydrogen-oxygen flow ratio in the FC system determines the oxygen flow rate. Different time constants can be defined for fuel increase and fuel decrease. Using above equation is developed, MATLAB and Simulink Model shown in figure 4.

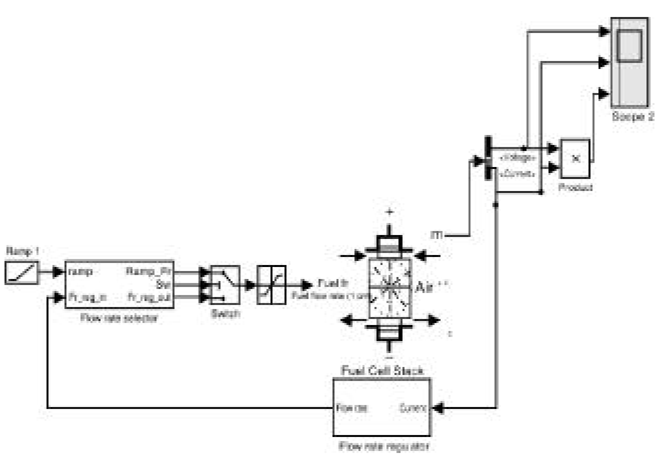

Fig. 4 Simulink Model of PEM Fuel Cell

VIII. MODELING & SIMULATION OF PCU

The Power Conditioning unit is used to convert DC output Voltage to AC. the power conditioning Unit include a DC/DC converter to raise DC output voltage to DC bus voltage to AC. Photovoltaic or fuel cell power systems, which generate power as a direct current (DC), require power conversion units to convert the power from DC to AC. This power could be connected to the transmission and distribution network of a utility grid. There are other applications, where it isnecessary to be able to control power flow in both directions between the AC and DC sides. For all these cases power conditioning units are used. Power conditioning unit are defined generally as electronic units that transform DC power to AC power, AC power to DC power, both bi-directional power electronic converters, or convert DC power at one voltage level to DC power at another voltage level.

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[4]. The principle of inductor volt-second balance slates 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 R_L 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 position 1, the inductor voltage is equal to V_L (t) = Vg – I_L (t) R_L. By use of the small ripple approximation, we can replace il (t) with its dc component il, and hence obtain V_L (t) = Vg – $I_L R_L$. Likewise, the capacitor current is equal to I_C (t) = – V (t)/R, which can be approximated as I_C (t) = – V/R [13]. 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) ~ Vg $- I_L R_L -$ 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

$$0 = D (V_g - I_L R_L) + (1 - D) (Vg - 1, R_L - v) \quad ...(xiv)$$

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

$$0 = D(-V/R) + (1-D)(I-V/R) \quad ....(xv)$$

From equation

$$V/V_g = I/(1\text{-}D).\ 1/1+R_L/(1\text{-}D)^2R) \quad ....(xvi)$$

$$\text{And, } I_L = V_g/(l\text{-}D)^2\ R.I/\ (1+ R_L/\ (1-D)^2R) \quad ....(xvii)$$

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 rl be sufficiently small. The converter efficiency can also be calculated. For this boost converter the efficiency is equal to

$$\eta = P_{out}/P_{in} = (V^2/R)/V_g l_L) \quad ....(xviii)$$

$$\eta = l/(l + R_L/(l + D)^2R \quad ....(xix)$$

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 MATLAB and Simulink based of a dc-dc converter (PCU) Model developed in this paper using the above equation in shown in figure 5.

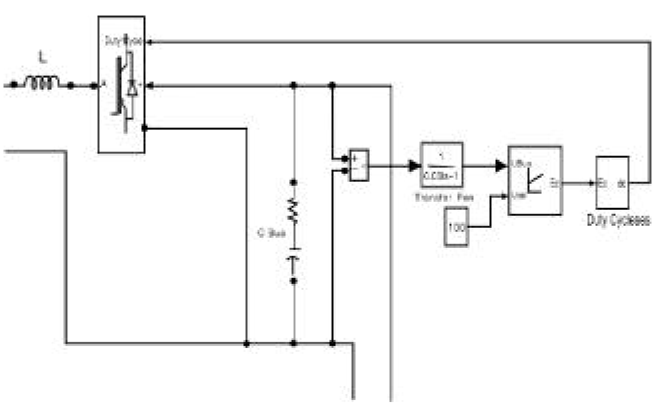

Fig-5 Simulink Model of DC-DC Converter

B. DC-AC Converter

The main circuit is/the part where the DC electric power is converted to AC [6]. This is virtually implemented with the one that is shown at the Figure. 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 generation to 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 m_a 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 m_a. A useful reference for cascaded multilevel converters which discuses the control circuit of new topology. 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 it and if we consider that trie IGBTs at an open state, we get:

$$r_L i_L + L di_L/dt + V_c = V_{oi}(t) \quad ....(xx)$$

$$i_L - C(dV_c/dt) - V_c/R \quad .....(xxi)$$

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, can obtain the solution which is:

$$V_{SN} = \Sigma^{\infty}_{n = 1,5,7,11} 4V/3n\pi\ (\cos n\pi/3+1\ )\text{Sin } n\ (\omega t\ 120) \quad ...(xxii)$$

$$V_{TN} = \Sigma^{\infty}_{n = 1,\ 5,\ 7,\ 11} 4V/3n\pi(\cos n\pi/3+l)\text{Sin } n(\omega t 240°) \quad ...(xxiii)$$

$$V_{RN} = \Sigma^{\infty}_{n = 1,5,7,11}\ 4V/3n\pi(\cos n\pi/3+l)\text{Sin} n(\omega t) \quad ...(xxiv)$$

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 and Simulink based of a dc-ac converter (PCU) Model with connected standalone system developed in this paper using the above equation in shown in figure 6.

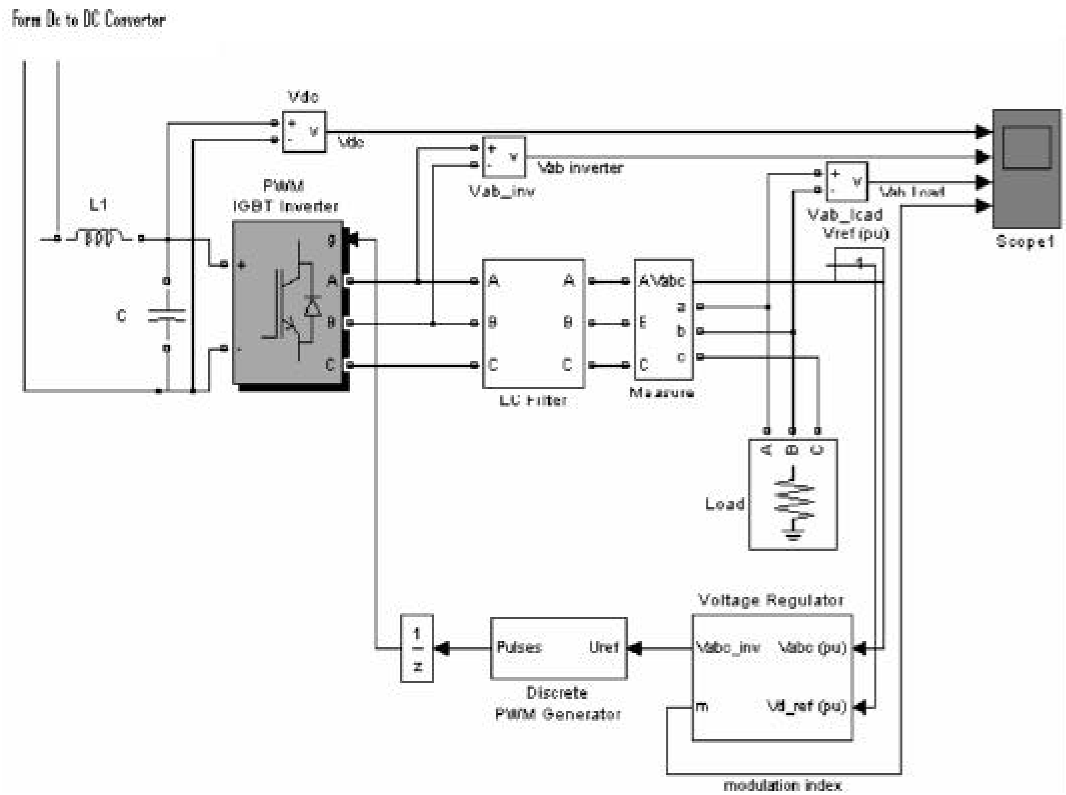

Fig. 6. Simulink Model of the DC-AC Converter

IX. SIMULATION RESULTS

The topology used in this study for the different components of the hybrid system; PV Array and PEM based Fuel Cell, PCU and Standalone System. Simulation results are obtained by developing a detailed MATLAB, Simulink based software package using the mathematical and electrical models of the system described earlier.

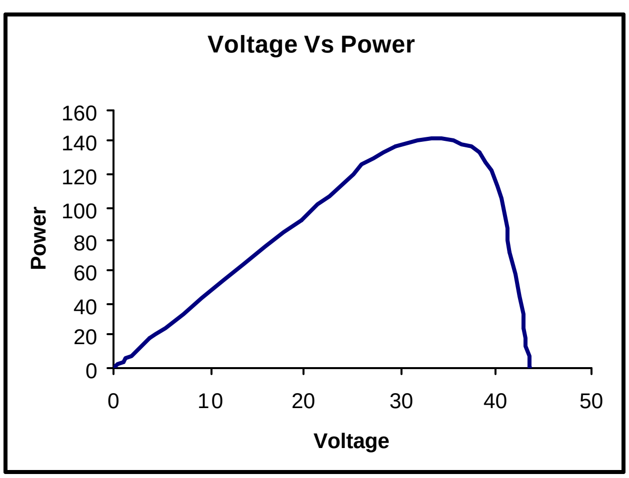

Fig. 7. P-V Curve of the PV model under temperature (25°C)

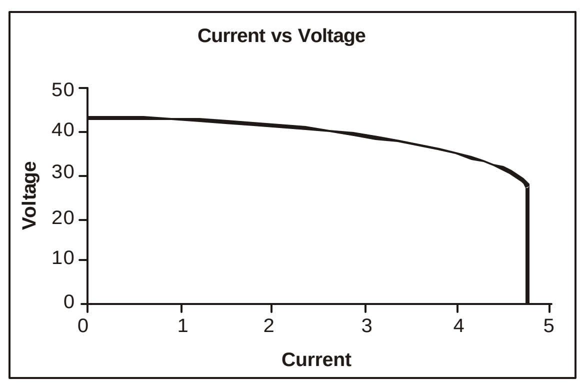

Fig. 8. I-V Curve of the PV model under temperature (25°C)

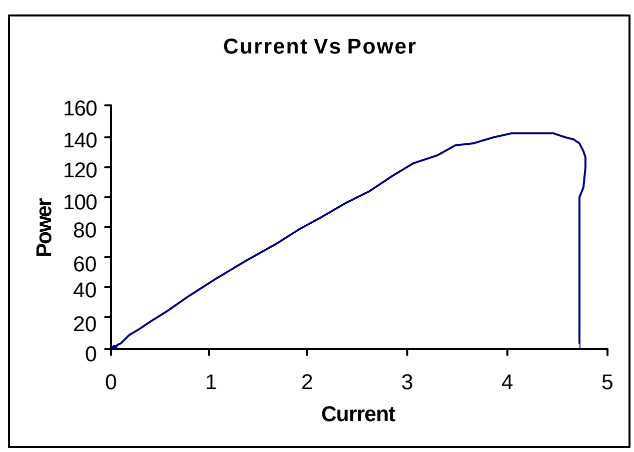

Fig. 9. P-I Curve of the PV model under temperature (25°C)

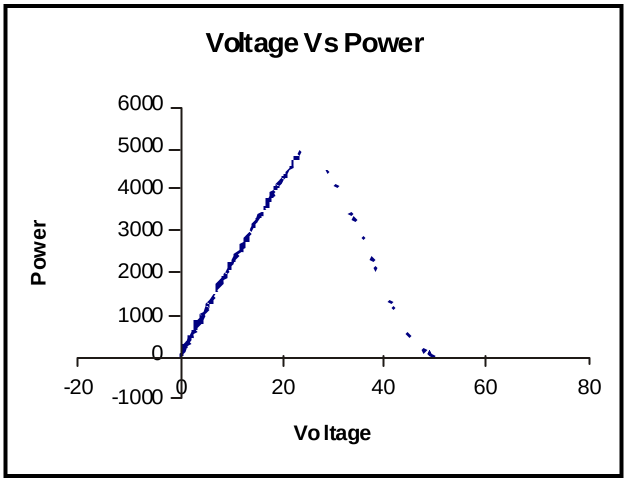

Fig. 10. P-V Curve of the PEM Fuel Cell model

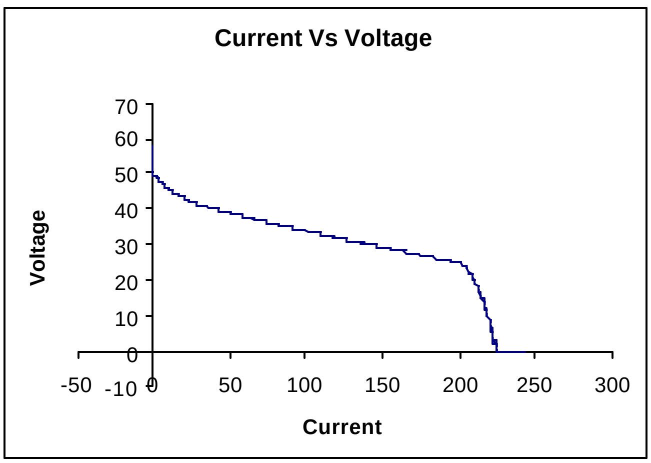

Fig. 11. V-I Curve of the PEM Fuel Cell model

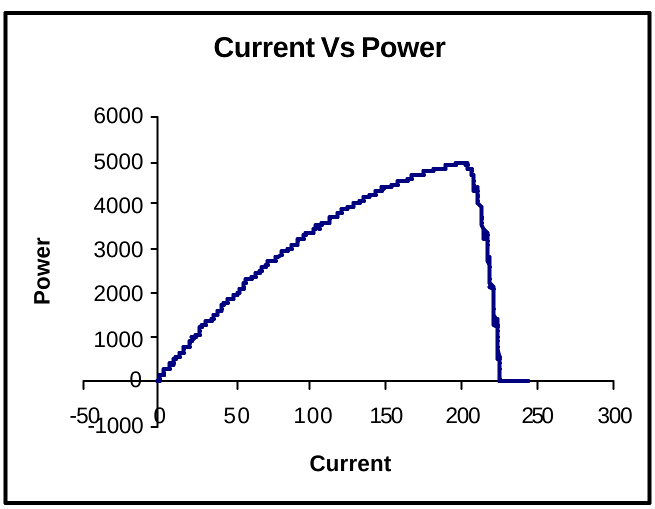

Fig. 12. P-I Curve of the PEM Fuel Cell model

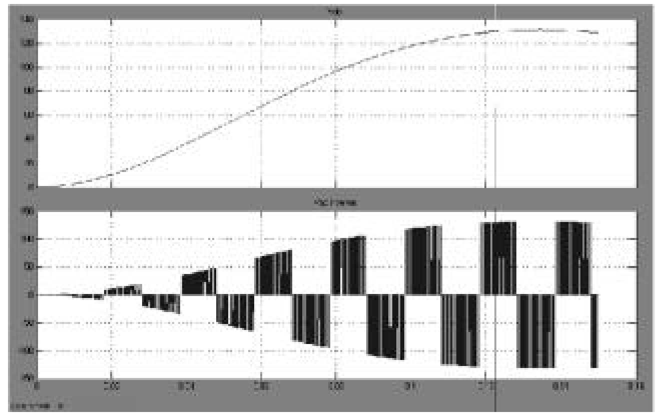

Fig. 13. Chopper Voltage & Inverter Voltage for PCU

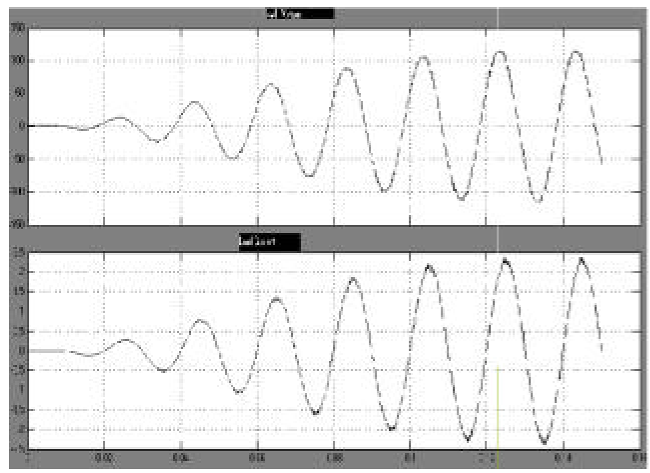

Fig. 14. Load Voltage & Load Current for Standalone System

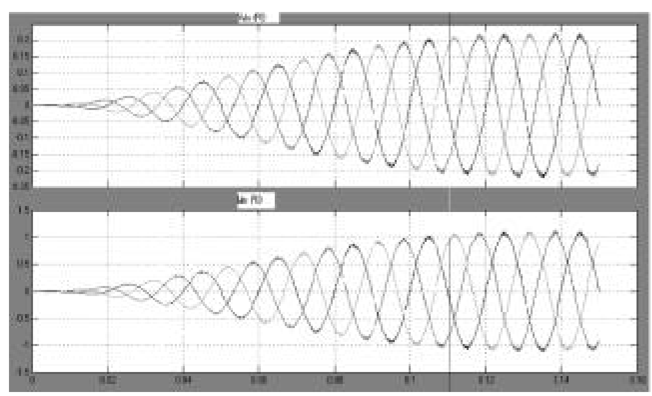

Fig. 15. V_{abc} & L_{abc} 3 F Voltage & Current in (PU) For Standalone System

X. CONCLUSION

Several conclusions can be drawn from this work: PV, fuel cells, and energy efficiency may all be an economically attractive part of a Hybrid System, fuel cells (operated in a cogeneration mode) and PV complement each other in terms of electricity supply because fuel cell electricity production peaks in the winter while PV electricity production peaks in the summer. Hybrid System may represent a new market for PV, fuel cells, and energy efficiency. PVFC electric systems offer many advantages. Standalone systems can eliminate the need to build expensive new power lines to remote locations. For rural and remote applications, PVFC electricity can cost less than any other means of producing electricity. PVFC electric systems can also connect to existing power lines to boost electricity output during times of high demand such as on hot, sunny days when air conditioners are on. PVFC electric systems are flexible. PVFC electric modules can stand on the ground or be mounted on rooftops. They can also be built into glass skylights and walls. They can be made to look like roof shingles and can even come equipped with devices to turn their DC output into the same AC utilities deliver to wall sockets. These advances mean individual homeowners and businesses can relieve pressure on local utilities struggling to meet the increasing demand for electricity.PVFC power systems require minimal maintenance. They run quietly and efficiently without polluting. They are easy to combine with other types of electric generators such as wind, hydro, or natural gas turbines. They can charge batteries to make PVFC electricity continuously available. For utilities large can help meet demand for new power generation, especially in distributed applications. A solar electric power plant is created from multiple arrays that are interconnected electronically. Solar electric plants are easier to site and are quicker to build than conventional power plants. They are also easy to expand incrementally by adding more mode less power demand increases. PVFC electric power systems are good for the environment. When PVFC electric technologies displace fossil fuels for pumping water, lighting homes, or running appliances, they reduce the greenhouse gases and pollutants emitted into the atmosphere. The use of PVFC electric systems is particularly important in developing nations because it can help avert the expected increases in emissions of greenhouse gases caused by the growing demand for electricity in those countries.

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