# Optimal Power Management in a Stand Alone Hybrid Power System Based on Photovoltaic, Fuel Cell and Battery

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***Abstract***—This paper presents an optimal power management strategy in a stand-alone hybrid power system based on photovoltaic (PV), fuel cell (FC) and Battery sources. PV provides the basic load demand in normal condition and the FC/Battery combination used as a backup source. FC used to complement the intermittent output of the PV source. Because of the slow dynamic response of the FC, in fast step loading, battery storage used to compensate that part of the temporary peak demand, which the PV and FC could not meet that. By sizing the battery to supply the peaking load in surplus of what can be meet by the FC and PV, the fuel cell can be size only for the average load, thus avoiding oversized of fuel cell. At First, the structure of the hybrid power system and then control strategies for optimal power management with considering the output voltage regulation will be discuss. It will be model and simulated using Matlab/Simulink software package.

***Key words***— Hybrid Power System, Stand-alone, Fuel cell, Photovoltaic, Battery, DC/DC converter.

## 1 INTRODUCTION

Since 1992, through Kyoto Treaty, there has been a growing awareness of the society regarding environmental impacts resulting from the widespread utilization of energy sources derived from petroleum [1]. Besides, the shortage of fossil fuels solutions should be environmentally friendly solutions. Among all alternative sources, photovoltaic (PV) energy has the advantage of, being one of the primary sources that produces less pollution. PV is renewable, silent, modular and a short period of installation. Another issue which makes photovoltaic energy more attractive is linked with the fact that this system can locally generate energy, without the need of long transmission lines (which produce losses), also generating a low environmental impact and being easily integrated onto the architecture of any building [1] .

The power generated by PV system is highly dependent on weather conditions. Natural variations in temperature and sunlight causes power fluctuations in PV system [2]. To reduce these problems, we integrate PV source with other alternative power systems, and use them as a hybrid power system, that consists of a combination of two or more energy sources, converters and/or storage devices. Fuel cell is one of the attractive options to integrate with PV system. Low environmental impact, low visual impact, no noise, no emissions, no moving parts and therefore minimal maintenance requirements and small footprint are some of the FC usage advantages. PV provides the base load demand in normal condition and fuel cell is use to complement the intermittent output of the PV source.

Fuel cells have slow transient response and slow output power ramping thus cannot follow loads effectively. To provide good voltage supporting, PV/FC hybrid system should be integrate with a fast responding storage unit. The overall structure of purposed hybrid system is as shown in Fig.1.

The performances of the PV and FC systems integrate with a common DC bus through the necessary power electronic interface. Dynamic model of the fuel cell is considered. To boost low output DC voltage of the FC and PV to high DC voltage, three full-bridge DC-DC converters adopt and their controllers design.

Fig.1 shows the overall structure of purposed hybrid system. The load in the figure1 stands for either a DC load or a voltage source inverter, depending on the application. A low passed filter used for connecting the converters to the DC bus. An overall control strategy will manage the power flow properly by considering the regulation of the DC bus voltage in the accepted range.

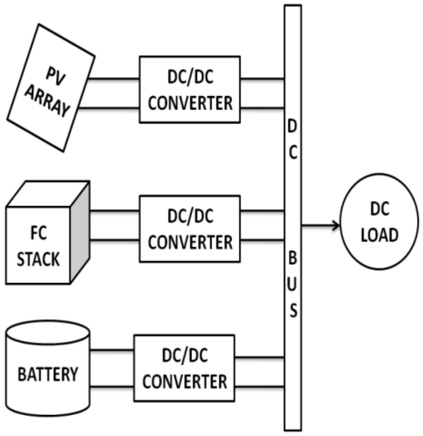


Fig.1 overall structure of purposed hybrid system

## 2 Photovoltaic

Photovoltaic energy conversion is the direct conversion of light energy to electric energy. Radiation of appropriate wavelengths must be absorb by an upper layer of dissimilar semiconducting materials so that some electrons jump to a higher conducting and energy level, thereby creating mobile electron/hole pairs. The electron/hole pairs must then migrate to opposite sides of a built-in voltage barrier between the dissimilar materials, where the charges are collected at low resistance metallic contacts [11]. Direct current (DC) power can be extract if the two oppositely charged contacts connect through an external load circuit. Desired currents and voltages obtain by connecting cells in series and parallel to form modules, and by aggregating modules in series and parallel groupings to form arrays. Though the magnitudes of currents and voltages differ, the electrical characteristics are similar for cells, modules, or arrays.

### 2.1 Photovoltaic Model

The most commonly used model for a PV cell is the Simplified one diode equivalent circuit [3-5] as shown in Fig.2.

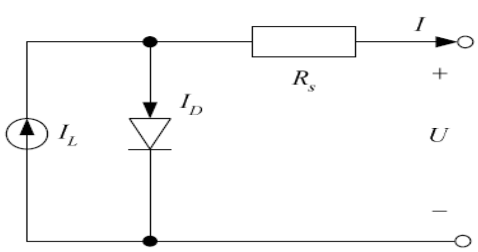


Fig.2 Simplified equivalent circuit model for a PV cell

Relationship between the output voltage (U) and the load current (I) can be express as:

$$I = I_L - I_D = I_L - I_o\left[exp\left(\frac{U + IR_S}{\alpha}\right) - 1\right] \quad (1)$$

$I_L$ : The light current of the PV cell (A)
$I_o$: The saturation current (A)
$R_S$: Series resistance (Ω)
$\alpha$: Thermal voltage timing completion factor of cell (V)

By simulating the PV model based on the parameters that used at el [5], the power-voltage (P-U) characteristic curve of the PV model under different irradiances (Φ) (at 25 °c) is shown in Fig.3.

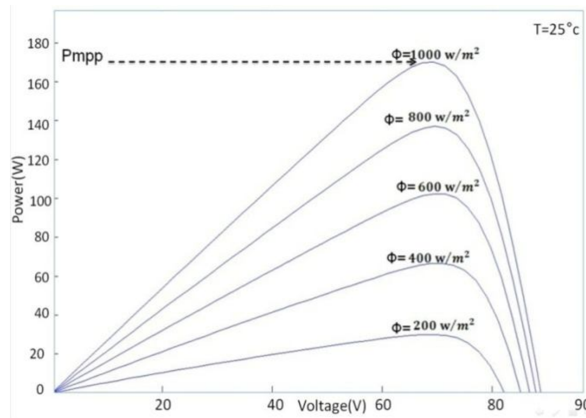


Fig.3 P-U characteristic curves of the PV model under different irradiances

We found from the fig.3 that with increasing the irradiances amount, the PV's power output will been increased. The P-U characteristic curve of the PV model under different temperature (Φ=1000 $w/m^2$) is given in Fig.4.

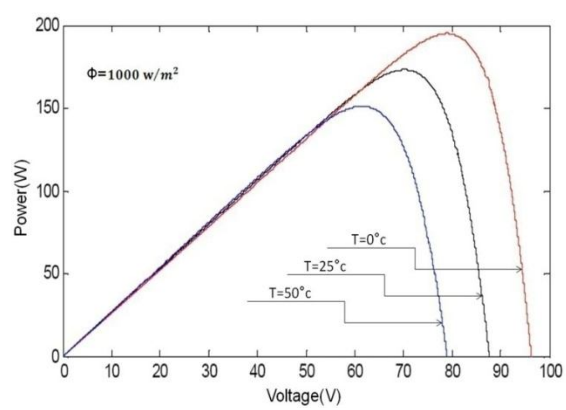


Fig.4 P-U characteristic curves of the PV model under different temperature

Fig.4 shows that, the lower the temperature, the higher is the maximum power.

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# 3 Fuel cell

Fuel cells have attracted great attention in recent years as a promising technology for power generation. Interest in fuel cell systems arises not only because of their essentially zero pollution emission but also because of their high efficiency, which is higher than that of a conventional power plant [7]. We consider The Proton exchange membrane fuel cell (PEMFC), in this study. A PEMFC has faster transient response than other types of fuel cells [6]. It has a solid polymer membrane as an electrolyte. Due to membrane limitations, PEMFCs usually operate at low temperatures (60-100°C), but new developments have produced higher temperature PEMFCs (up to 200°C). The reactions at the anode and cathode that place in the PEMFC are shown in Fig.5 [6].

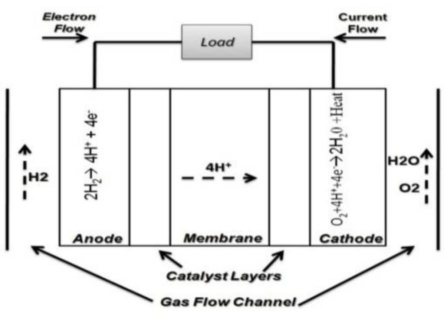


Fig.5 Schematic diagram of a PEMFC

Anode side reaction: $2H_2 \rightarrow 4H^+ + 4e^-$

Cathode side reaction: $O_2 + 4H^+ + 4e^- \rightarrow 2H_20$ +Heat

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Overall reaction: $2H_2 + O_2 \rightarrow 2H_20$ + Heat

The PEMFC model is base on the validated dynamic model for a PEMFC stack reported in [6]. It is an autonomous model operated under constant channel pressure with no control on the input fuel flow, into the FC.

# 4 Battery

Fuel cells are good energy sources to provide reliable power at steady state, but they cannot respond to electrical load transients as fast as desired. This problem is mainly due to their slow internal electrochemical and thermodynamic responses. It is common that use another source for recovering this shortage. In this paper, we use a lead acid battery [8] that has a fast responding in step load changing. A validated simplified electrical circuit model for lead acid battery is as shown in Fig.6.

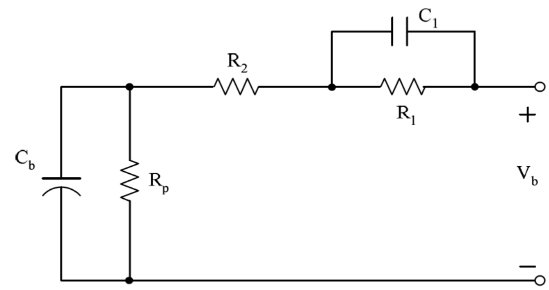


Fig.6 Simplified circuit model for lead-acid batteries

Cb: battery capacitance
Rp: self-discharge resistance, or insulation resistance
R2= internal resistance for charge or discharge
R1= overvoltage resistance for charge or discharge
C1= overvoltage capacitance

# 5 Control strategy

We offered an overall control strategy for power management, among different energy sources in the purposed hybrid power system.

There are two operations mode for the power converters:

1.operation with maximum duty cycle mode
2.operation with considering the dc bus voltage regulation (BVR) mode.

In this paper, we used Predictive Current Control (PCC) technique [13] in BVR mode. In the PCC technique by measuring circuit's current and voltage in the existing state ($i_n$ and $v_n$ ) try to predict the next state duty cycle ($D_{n+1}$) in the discrete time state, to make desirable voltage and current. It is desirable to have a fixed dc bus voltage in 1pu. We used isolated full bridge DC-DC converter for power conditioning unit. We described purposed Predictive Current Control strategy (PCC) in a generic DC-DC converter model (Fig.7).

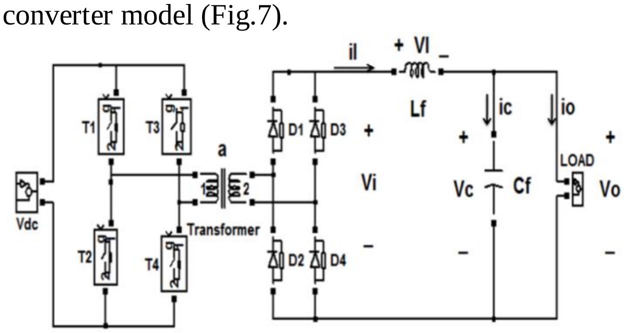


Fig.7 power conditioning unit

By a simple kvl :

$$V_o = V_c = V_i - V_l \tag{3}$$

The internal voltage ($V_i$) in the Isolated Full Bridge DC-DC converter is [10]:

$$V_i = 2.a.D.V_{dc} \qquad D < 0.5 \tag{4}$$

$a$ is the secondary to primary winding turn ratio:

$$a = \frac{n_2}{n_1} \quad (5)$$

D, is the switches ($T_1$ and $T_4$) duty cycle:

$$D = \frac{T_{on_{1,4}}}{T} \quad (6)$$

($T_{on}$) is time that ($T_1, T_4$) are on in the switching period (T). $\Delta$ is the time that, switches are off :

$$\Delta = 0.5 - D \quad (7)$$

$$\Delta + T_{on_{1,4}} = {}^{T}/_{2} \quad (8)$$

Base on switching rule when $T_2$ and $T_3$ are on $T_1$ and $T_4$ should be off and inverse.
In discrete time state, capacitor current ($i_c$) is:

$$i_{C_{n+1}} = \frac{C_f}{T}\left[V_{C_{n+1}} - V_{C_n}\right] \quad (9)$$

$$V_{l_{n+1}} = \frac{L_f}{T}\left(i_{L_{n+1}} - i_{L_n}\right) \quad (10)$$

By considering the equations (3-9), we have:

$$V_{O_{n+1}} = \left[2.a.D_{n+1}.V_{dc_{n+1}}\right] - \left[\frac{L_f}{T}\left(i_{L_{n+1}} - i_{L_n}\right)\right] \quad (11)$$

$$i_{L_{n+1}} = i_{C_{n+1}} - i_{O_{n+1}} \quad (12)$$

$$i_{L_{n+1}} = \frac{C_f}{T}\left[V_{C_{n+1}} - V_{C_n}\right] - i_{O_n+1} \quad (13)$$

By considering the load current and output voltage changes in the resources, we can assume that:

$$i_{O_{n+1}} = i_{O_n}\ , V_{dc_{n+1}} = V_{dc_n} \quad (14)$$

The output voltage should been kept in the desire range also, (1pu =480 volts in this paper):

$$V_{O_{n+1}} = V_{C_{n+1}} = 1\text{pu} \quad (15)$$

$$V_{O_{n+1}} = \left[2.a.D_{n+1}.V_{dc_n}\right] - \frac{L_f}{T}\left[\frac{C_f}{T}\left(480 - V_{C_n}\right) + i_{O_n} - i_{L_n}\right] \quad (16)$$

$$D_{n+1} = \frac{1}{2.a.V_{dc_n}}\left[1 + \frac{L_f}{T}\left[\frac{C_f}{T}\left(480 - V_{C_n}\right) + i_{O_n} - i_{L_n}\right]\right] \quad (17)$$

Equation (17) uses as a general equation for all sources in BVR mode.
Now we study on different operational mode of the purposed system.

Mode1:
As mention before PV source is the primary source and sizing to provide the average load demand in the normal operation.
Firstly: we assume that the PV source can provide the whole load demand individually. So the PV's converter duty cycle calculate in the BVR mode.
When PV works in the BVR mode alone, by considering Fig.8 there is:

$$i_{L_n} = i_{p_n}, V_{dc_n} = V_{p_n}, a = a_1, S_f = S_b = 0 \quad (18)$$

Thus based on the equation [17] the PV's converter duty cycle in the BVR mode is:

$$D_{p_{n+1}} = \frac{1}{2.a_1.V_{p_n}}\left[1 + \frac{L_f}{T}\left[\frac{C_f}{T}\left(480 - V_{C_n}\right) + i_{O_n} - i_{p_n}\right]\right] \quad (19)$$

Thus by using the PCC technique, duty cycle of the switches for regulating the DC bus voltage in the 1pu been predicted.
Mode2:
By increasing the load demand, when the PV system cannot supply the load demand, the FC system starts to prepare excess power. The FC's duty cycle will be determined in the BVR mode and the PV will work with maximum duty cycle:

$$D_{p_n} = D_{p_{max}} \approx 0.5, i_{p_n} = i_{p_{n+1}} = i_{p_{max}}, a = a_2 \quad (20)$$
$$L_f = L_{fc}\ ,\ i_{l_n} = i_{p_{max}} + i_{f_n}\ , V_{dc_n} = V_{f_n}$$

Thus based on the equation [17] the FC's converter duty cycle in the BVR mode is:

$$D_{f_{n+1}} = \frac{1}{2.a_2.V_{f_n}}\left[1 + \frac{L_{fc}}{T}\left[\frac{C_f}{T}\left(1 - V_{C_n}\right) + i_{O_n} - \left(i_{p_{max}} + i_{f_n}\right)\right]\right] \quad (21)$$

Mode3:
When PV and FC could not reach to the power load demand properly, the FC will work with maximum duty cycle and Battery starts to produce excess power ($S_b = 1$).The Battery's duty cycle will be determined in the BVR mode. In this mode by considering Fig.8 there is:

$$V_{dc_n} = V_{b_n}, i_{l_n} = i_{p_{max}} + i_{f_{max}} + i_{b_n}, \quad (22)$$
$$a = a_3,\ L_f = L_b, D_{f_n} = D_{f_{n+1}} \approx 0.5$$

Thus based on the equation [17] the Battery's converter duty cycle in the BVR mode is:

$$D_{b_{n+1}} = \frac{1}{2.a_3.V_{b_n}}\left[1 + \frac{L_b}{T}\left[\frac{C_f}{T}\left(1 - V_{C_n}\right) + i_{O_n} - \left(i_{p_{max}} + i_{f_{max}} + i_{b_n}\right)\right]\right] \quad (23)$$

Battery helps system to provide the step loads demand while the FC could not provide them.

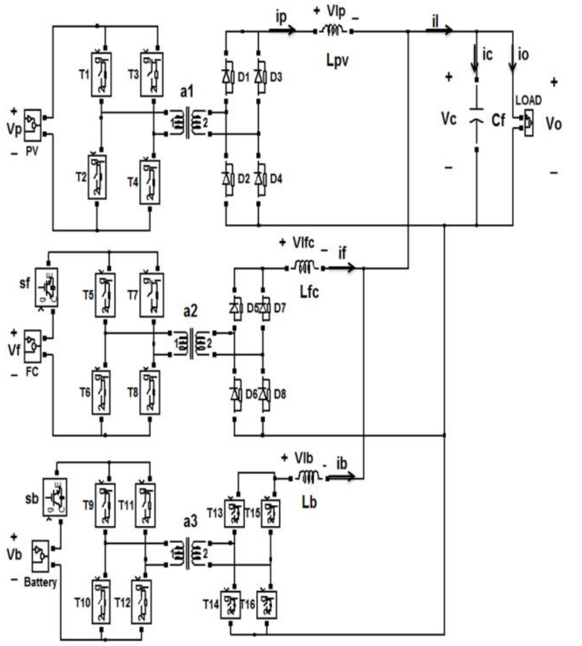

Fig.8 Detailed structure of the hybrid system

## 6 Overall control algorithm

The desired control algorithm with consideration of different modes is shown in Fig.9. In this algorithm, Subscripts (p, f, b) related to photovoltaic, fuel cell and battery. Based on [10], the converter's duty cycle could not be larger than 0.5. In otherwise (when D>0.5) it shows that the system cannot provide the whole load demand alone and the system need another auxiliary source.

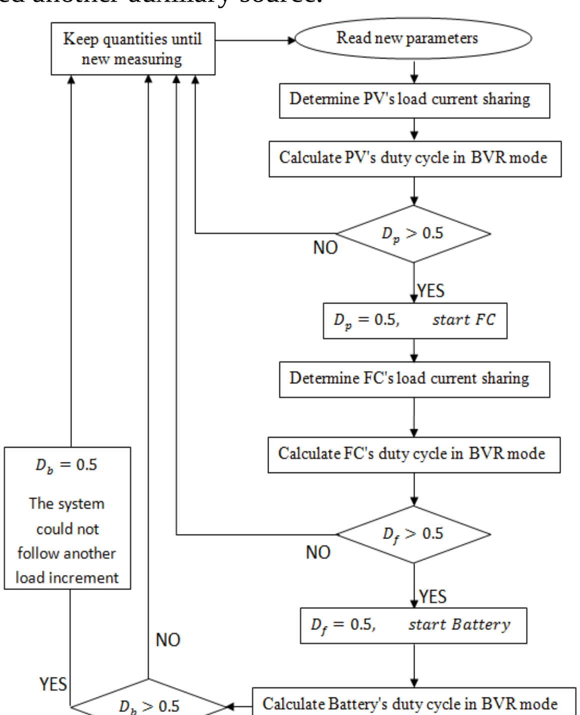

Fig.9 overall control algorithm

## 7 Simulation results

By simulation in the Matlab/Simulink software, it shown that the desired system and purposed control algorithm are working properly. Variable load characteristic is as shown in fig.10.

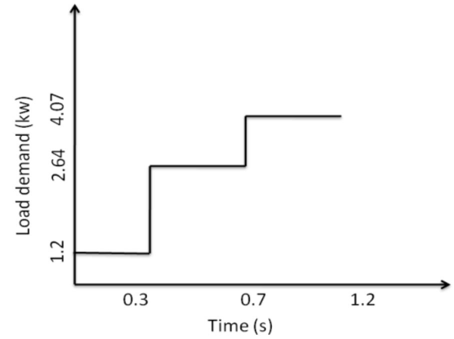

Fig.10. load characteristic

By considering the load changes, we can determine the capacity of resources with a proper unit sizing [6].Table1 shows the capacity of different resources.

| Source | PV | FC | Battery |
|---|---|---|---|
| Capacity(kw) | 2.4kw | 7kw | 5kwh |

Table1 Capacity of different sources

## 7-1 Output power changes

Fig.11 shows the output power changes. In the first step (t=0.3sec) based on the load demand (DC link output power), PV's output reach to the maximum level, and remain in that level in other times. By increasing the load in the second step (t=0.7sec) another backup source should be started, so the FC stack start to increase output level. Because of the slow dynamic response of FC stack, Battery should been started. The battery gives power until that the FC's output level recovered.

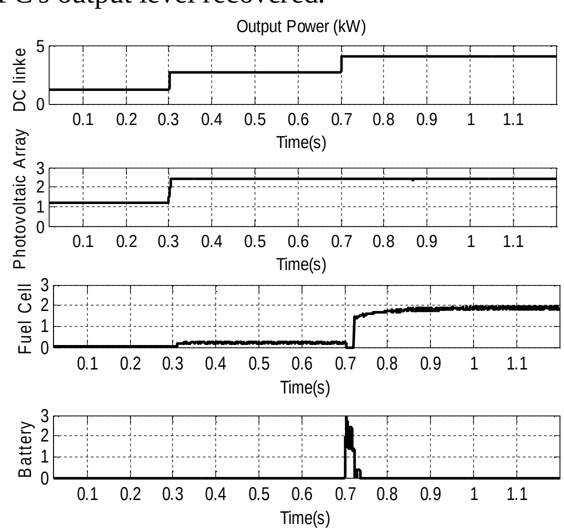

Fig.11 The output power changes

## 7.2 Load feeding contribution

Before the first step (t<0.3sec) PV generated the load's demand and had 100% load feeding contribution. After the first step, because of the FC's power generation the PV's contribution reduced and in the second step FC's contribution increased up to 45%. Battery produced about 50% of the load demand when the FC could not track the step load changing. Fig.12 shows the load feeding contribution of each source.

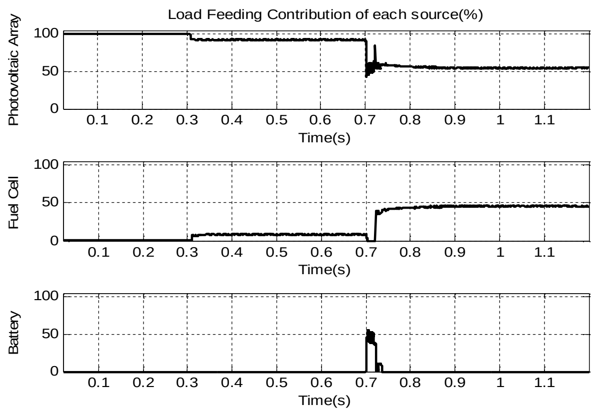


Fig.12 Load feeding contribution

## 7.3 Output current changes

Fig.13 shows output current changes in different sources. Before the first step, PV produces the whole load current requirement alone. After the first step, PV's output current reach to it's maximum level and remain constant after this step. FC's current level increased after the transient time while, battery helps the FC to pass the transient time. The output current of battery shows that in the second load step, when the FC don't follow the load changes, it's good transient response helps the system to pass this stage properly.

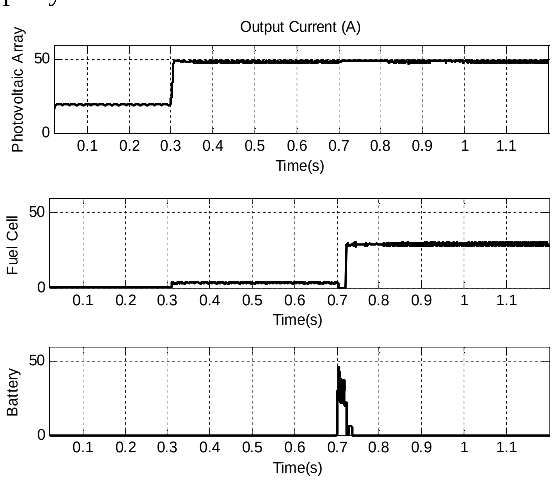


Fig.13 Output current changes

## 7.4 Output voltage changes

Output voltage changes shown in the Fig.14. Based on the PV's output characteristic reported in [10], in the constant irradiance and temperature when the output current increased it's voltage will be decreased, that shown in the first load step change, Because of the slow dynamic response of the FC, in any momentary changes in it's output power, the output voltage will decreased. Battery and the DC link have a constant voltage level.

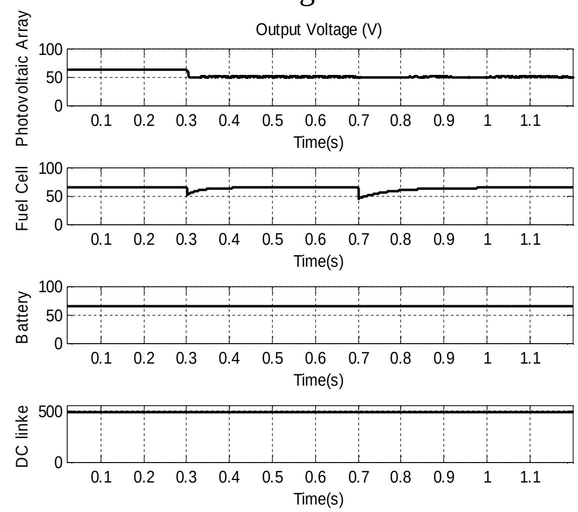


Fig.14 Output voltage changes

The aim of the DC link voltage regulation, obtain truly in the system. Fig.15 shows that in the worst case, it has about 1.5 volts decrement in the DC link voltage. That is less than 3% of the output voltage. Good output voltage regulation is as shown in Fig.15.

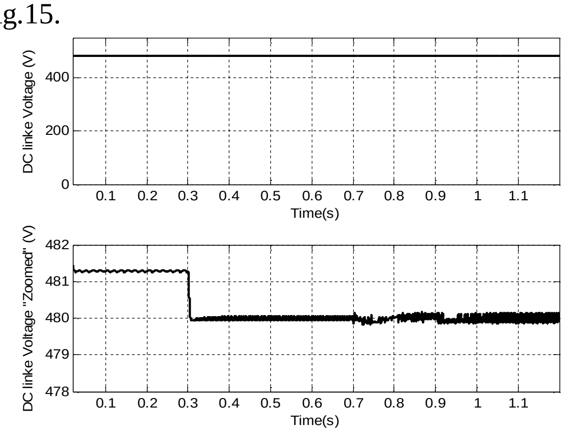


Fig.15 DC link voltage regulation

# 8 Conclusion

In this paper, hybrid distributed generation is presented, that consists of fuel cell stack, photovoltaic array and battery. The available power from photovoltaic array is highly dependent on

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environmental conditions, such as temperature and irradiance. To overcome this deficiency of the photovoltaic system, we integrated it with the FC/Battery system. This hybrid topology exhibits excellent performance under variable load power requirement. The proposed system can be use for non-interconnected remote areas.

For an optimal power management among different sources, a new control strategy based on predictive current control (PCC) is offered. In the control algorithm, the purposes of output power management between different sources and output voltage regulation in the accepted range are considered.

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