

Power management of a hybrid PEMFC-PV and Ultracapacitor for stand-alone and grid connected applications

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Abstract— This paper presents the integration of photovoltaic (PV), fuel cell (FC) and energy storage systems for reliable power generation. In this system FC is used as main power source and power from PV whenever available is harvested completely with storage system compensating for power fluctuations. This topology has high efficiency, modularity and fuel flexibility. The sources in this hybrid system complement each other very well against environmental variations and load variations. Of the many storage systems the use of ultracapacitor gives advantage of absorbing and contributing to power transients quickly and efficiently. The aim of this study is to design an effective power management system for PV/FC/storage hybrid system thus to give high quality reliable power. MPPT for PV system is used for maximum power extraction. Finally the structure of hybrid system with control strategies for power management is discussed. The proposed hybrid system is modeled, simulated and verified by MATLAB/Simulink simulations for standalone and grid connected systems.

Keywords- PV system; PEM Fuel Cell; MPPT; power management; hybrid system.

I. INTRODUCTION

As the conventional energy sources are getting diminished the need for alternate power sources is increasing drastically. Of the renewable sources, PV systems have many advantages as they are portable in nature, give clean power and suitable for different areas of applications from communication systems to solar cars. Though the fabrication cost is bit high at present it will gradually reduce with research and large scale use.

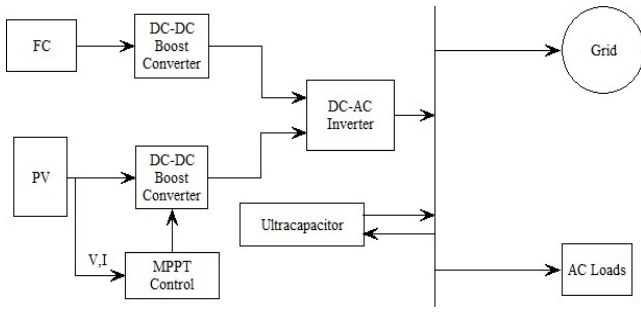
PV systems experience large variations of power fluctuations due to variable weather conditions thus the need to integrate with other power sources is imperative; for example battery energy storage, diesel generators and fuel cells[1]. Diesel generators can give back up for limited periods and battery storage cannot meet all the load fluctuations. PV system being an insolation dependent source it has high degree

of output power fluctuations. A controlled source is required which can match deficient power of PV and supply additional power to give rated power. So fuel cells present with an attractive option for integration with PV systems. Fuel cells also have added advantages of higher efficiency, modularity and fuel flexibility. Their only short coming is in the slow dynamics of fuel supply system, any sudden variations in the load will have direct effect on the terminal voltage of the fuel cells which can cause shutdown of the system. So to maintain the system in healthy state of operation PV, fuel cell and secondary storage have to be integrated with suitable power conditioning methods [2][3]. Ultracapacitors are very effective in the use as storage devices as they provide high power density along with high energy density of fuel cells. They can quickly absorb or contribute power at a DC bus, giving a constant voltage without any fluctuations.

Fuel cells can be integrated with PV in either as independent power source or as a part of long term energy storage with dedicated electrolyzer [4][5]. Here the independent operation is considered in which power from both sources is actively controlled to meet the load demands. The objective of the study is to design an effective power management system of PV/fuel cell/ultracapacitor. The structure and control strategies for the proposed system are discussed and then verified the results by numerical simulation.

II. SYSTEM REPRESENTATION

The hybrid power system in Fig. 1, consists of two main sources PV and fuel cells with ultracapacitor managing the transient power from the main sources. PV system will provide as much power as available according to the environmental conditions and remaining average power will be supplied by the fuel cells which PV cannot meet. Suitable power converters are used to connect the power sources to a common DC-bus. The currents and voltages are monitored continually and through proper power management subsystem power flow is monitored.



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III. PV SYSTEM MODEL, MPPT

In PV system many cells are connected in series and parallel to provide the desired output terminal voltage and current. This PV system exhibits a nonlinear I-V characteristic and is modeled as a current source across a diode [6]-[8]. The parameters used in the mathematical modeling of the PV system and the governing equations are expressed as below.

$$I = I_{PV} - I_o \left[\exp \left(\frac{V + R_s I}{V_t a} \right) - 1 \right] - \frac{V + R_s I}{R_p} \quad (1)$$

where,

- I_{PV} is current due to incident light
- I_o is reverse saturation current
- V_t thermal voltage of array
- a ideality factor
- R_s series resistance
- R_p parallel resistance

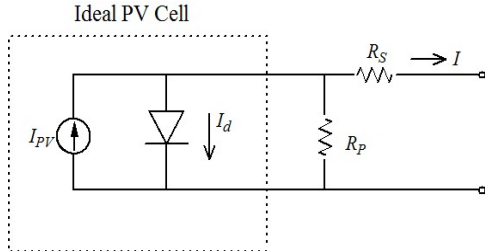


Fig.(2). Photovoltaic Model

Since the solar insolation varies with time and other environmental factors the operating point of the PV should be adjusted to track maximum power. Perturb and Observe method of MPPT algorithm [9][10], is used for adjustment of duty cycle of the boost converter in this paper and the algorithm used is given below in Fig.3.

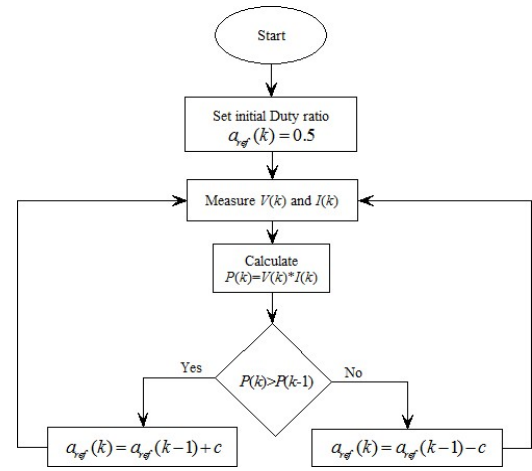


Fig. (3). Flow chart of Perturb and Observe MPPT method

IV. DYNAMIC MODELING OF A PEMFC

The PEMFC source [4][11], is modeled in MATLAB/Simulink with the following parameters as,

- E Nernst instantaneous voltage [V];
- E_o standard no load voltage [V];
- F Faraday's constant [C/kmol];
- I'_{FC} FC feedback current [A];
- K_{H_2} hydrogen valve molar constant [kmol/(atm·s)];
- K_{H_2O} water valve molar constant [kmol/(atm·s)];
- K_{O_2} oxygen valve molar constant [kmol/(atm·s)];
- M_{H_2} molar mass of hydrogen [kg·kmol⁻¹];
- N_o number of series fuel cells in stack;
- p_{H_2} hydrogen partial pressure [atm];
- p_{H_2O} water partial pressure [atm];
- p_{O_2} oxygen partial pressure [atm];
- q_{H_2} molar flow of hydrogen [kmol/s];
- q_{O_2} molar flow of oxygen [kmol/s];
- $q_{H_2}^{in}$ hydrogen input flow [kmol/s];
- $q_{H_2}^{out}$ hydrogen output flow [kmol/s];
- R universal gas constant [(1 atm)/(kmol·K)];
- R_{int} FC internal resistance [Ohm];
- T absolute temperature [K];
- τ_{H_2} hydrogen time constant [s];
- τ_{H_2O} water time constant [s];
- τ_{O_2} oxygen time constant [s];

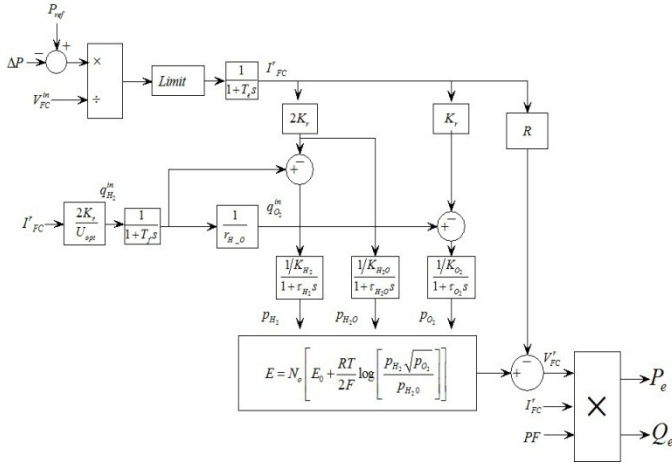


Fig.(4). Dynamic modeling of PEMFC

The relationship between the molar flow of any gas (hydrogen) through the valve and its partial pressure inside the channel can be expressed as,

$$\frac{q_{H_2}}{p_{H_2}} = \frac{K_{an}}{\sqrt{M_{H_2}}} = K_{H_2} \quad (2)$$

Then, the net hydrogen flow can be written as sum of hydrogen input flow, hydrogen output flow and hydrogen flow during the reaction as,

$$\frac{d}{dx} p_{H_2} = \frac{RT}{V_{an}} (q_{H_2}^{in} - q_{H_2}^{out} - q_{H_2}^r) \quad (3)$$

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

$$q_{H_2}^r = \frac{N_0 I'_{FC}}{2F} = 2K_r I'_{FC} \quad (4)$$

Using (2) and (4), and applying Laplace transform, the hydrogen partial pressure can be obtained as,

$$p_{H_2} = \frac{1/K_{H_2}}{1 + \tau_{H_2} s} (q_{H_2}^{in} - 2K_r I'_{FC}) \quad (5)$$

Same can be obtained for water and oxygen partial pressures. The FC output voltage is the sum of Nernst instantaneous voltage and the ohmic voltage drop,

$$V_{cell} = E + \eta_{ohmic} \quad (6)$$

Where,

$$E = N_o \left[E_0 + \frac{RT}{2F} \log \left[\frac{p_{H_2} \sqrt{p_{O_2}}}{p_{H_2,0}} \right] \right] \quad (7)$$

V. ULTRACAPACITOR MODELING

The classical equivalent circuit of a UC unit[11][12], consists of a capacitance (C), an equivalent series resistance (ESR, R) which represents the charging and discharging resistance and an equivalent parallel resistance (EPR, R) which models self discharging losses. The electrical equivalent diagram is given in Fig. 5.

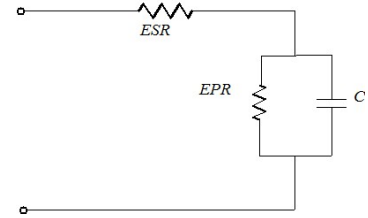


Fig.(5). Electrical equivalent of Ultracapacitor

VI. INVERTER CONTROL STRATEGY

Voltage source inverters (VSI) are generally used for transfer of energy from DC to AC side [13]. The structures for the stand-alone and grid connected operation are given in Fig.6,

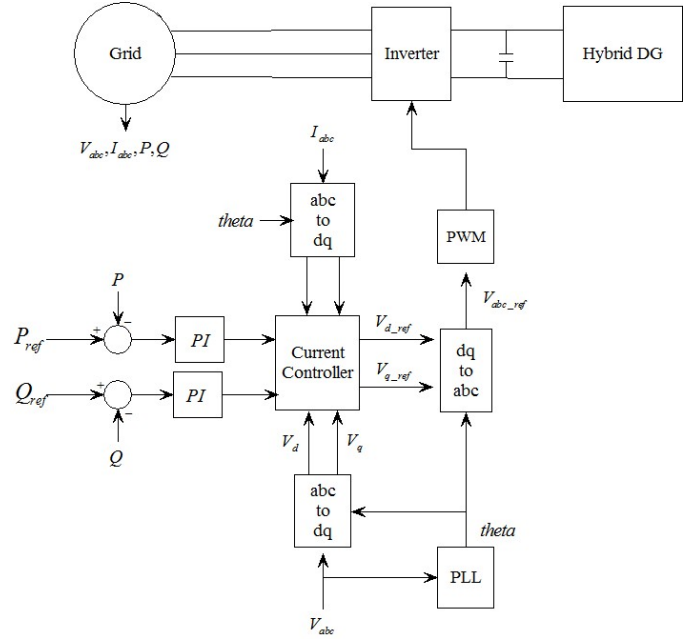


Fig.(6). Control scheme for P-Q mode of operation

The P-Q mode of control in Fig. 6, is used in grid-connected mode of operation. P_{ref} and Q_{ref} are the set limits of active and reactive power to be generated by the hybrid system thus making a fixed allocated generation. Any variations in load will be met by the grid power. The current controller is used for adjusting the power flow to the grid by decoupling the active and reactive power demands in d-q frame of reference as i_{dref} and i_{qref} . The phase angle required for the Park's transformation is obtained by a PLL which has grid voltage as its reference. Finally PWM control strategy is used for switching the inverter for DC to AC conversion.

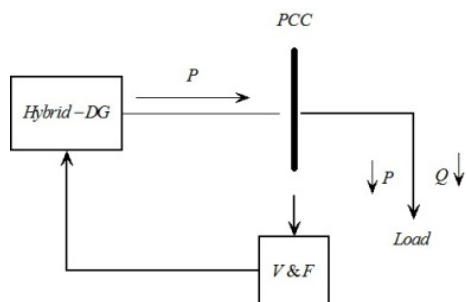


Fig.(7). Control scheme for P-V mode of operation

The control strategy for islanding mode of operation is P-V control as shown in Fig.7. Unlike grid connected mode of operation the reference for voltage and frequency are predetermined here at desired values. The voltage at reference node and frequency profile for all of the system is to be maintained here using two set of controllers. $V_{d.ref}$ and $V_{q.ref}$ are the set values of active and reactive components of power used respectively for voltage amplitude and frequency control. The frequency control scheme helps in maintaining active power demand and voltage regulation scheme helps in maintaining reactive power demand.

VII. RESULTS AND DISCUSSIONS

To investigate the performance of proposed PV-PEMFC hybrid system the studies were carried out in MATLAB. The temperature is taken to be 25°C . The power rating of stand-alone mode of operation is 50 kW and for grid-connected mode of operation 100 kW system is considered, which helps in realizing the modularity of proposed model. For stand-alone mode of operation, variations due to change in insolation and load have been considered. Fig.8, gives contribution of all source currents and Fig.9, gives active and reactive power delivered to load by DG. Initially power is delivered by FC and UC with zero power from PV. The slow response of FC is compensated by UC power. At time 5s, insolation to PV system is raised to 500 W/m^2 , reducing the power contribution from FC and UC will absorb the transient power from FC. At time 8s, PV insolation is 1000 W/m^2 . This much power is enough to supply the load and to charge the UC and no power is taken from the FC system. At time 12s, PV insolation is reduced to 500 W/m^2 . UC will supply the load immediately and FC will deliver its power with slow response. At time 15s, there is increase in load by 50%, which is contributed by FC with UC supplying the dynamic power.

For grid connected mode of operation only active power sharing is considered. Here the DG acts as a source of 100 kW scheduled power supply. The excess power after meeting the local loads is given to grid. Initially FC and UC will share the power. At time 2s, PV insolation is increased to 500 W/m^2 and FC power is reduced correspondingly with UC absorbing the transient power. At time 4s, local load is increased by 30%, thus reducing the power to grid by 20 kW. PV insolation is increased to 1000 W/m^2 then, reduced to 500 W/m^2 and to zero at 12s and 16s respectively. FC will supply the average load which PV can not meet. UC being online always will absorb

or supply power instantaneously. At time 15s, all the local loads are removed, so DG will supply its rated power to grid completely.

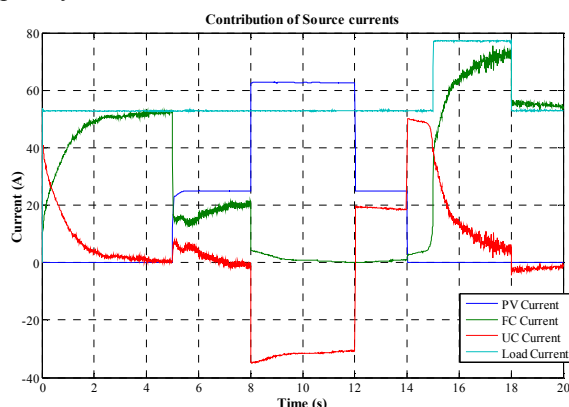


Fig.(8). Gives contribution of source currents at different load and environmental conditions.

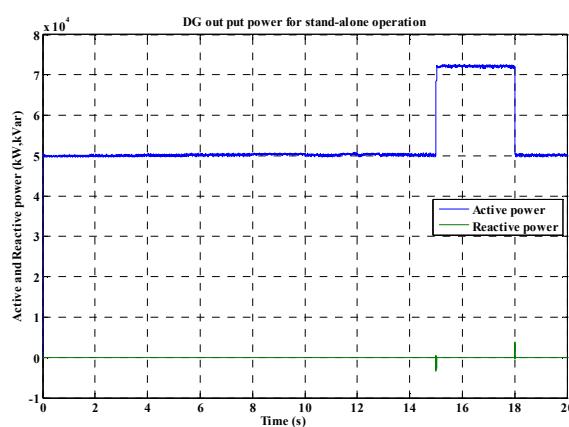


Fig.(9). Power from hybrid-DG source to load for stand alone mode of operation.

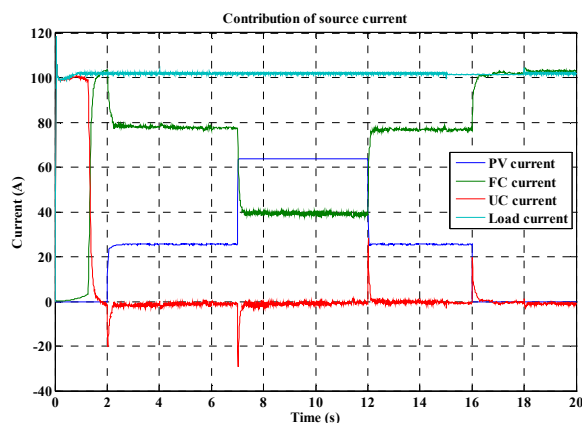


Fig.(10). contribution of source currents at different load and environmental conditions for grid-connected operation.

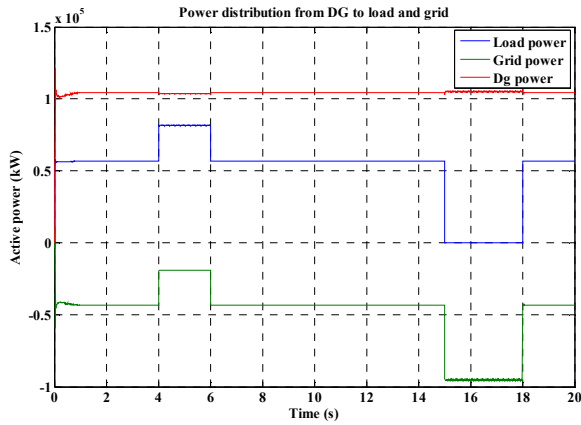


Fig.(11). Active power from hybrid-DG source to load for grid-connected mode of operation.

VIII. CONCLUSIONS

In this paper an effective power management system of PEMFC-PV and Ultracapacitor is presented which can be used as a reliable power source. PV system voltage is controlled by a MPPT boost converter for extracting all the power available while FC system is voltage regulated by a closed loop boost converter and Ultracapacitor is connected through a bidirectional converter to the DC bus so that transients are minimised. The power controllers are realised for grid connected operation of the hybrid system. By proper system sizing, the model is analysed for power sharing between PV and FC sources. Simulation studies for grid connected and stand alone mode of operation demonstrate that power management system controls the power of each source properly and hybrid power system works reliably. Simulation results also show the power sharing by hybrid system for changes in load and environmental conditions.

TABLE 1: PAMETERS USED IN SIMULATTION STUDIES

Parameter	Value
The No. of series cells per string N_{ss}	36
The No. of parallel cells per string N_{pp}	586
Power rating of PV kW	50
Ideality factor(a)	1.9
PV cell temperature [$^{\circ}C$]	25
PEMFC Power rating (standalone, Grid connected) [kW]	50,100
FC electrical response time [s]	2.5
Hydrogen time constant [s]	3.37
Oxygen time constant [s]	6.74
Water time constant [s]	18.418
No of series FC cells (50kW,100kW)	880,1760
UC capacitance [F]	500
UC voltage [V]	450

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