CONTROL AND POWER MANAGEMENT OF STAND-ALONE PV-FC-UC HYBRID SYSTEM

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Abstract: *The photovoltaic energy is naturally intermittent with stochastic fluctuations, hybridization of PV system with other sources is necessary so as to ensure continuous supply of electricity. This paper presents the power management of PV-fuel cell hybrid system with ultracapacitor bank for stand-alone applications. The transient power is absorbed or supplied by ultracapacitors during unpredictable solar or load power variations. The DC-DC bidirectional converter with controller is used to connect ultracapacitor bank to DC bus. The PV power system is controlled to extract maximum power. The hybrid system aims to provide a single phase power supply to consumers with constant voltage and frequency which is achieved through inverter controller. Dynamic modeling and simulation study are accomplished in MATLAB/Simulink environment.*

Keywords: *Photovoltaic system; PEM fuel cell; MPPT controller; Controller of Ultracapacitor bank; voltage and frequency controller*

1. Introduction

With the rapid depletion of conventional energy sources, and due to increasing pollutions, the demand for effective renewable energy sources is growing. The main sources of green energy are solar, wind and hydro etc., and the most predominant of which is solar energy. The photovoltaic (PV) cells are p-n junction devices which convert the energy from sun directly into DC power. Operation of photovoltaic modules in noiseless and their maintenance cost is negligibly small. As the solar PV power output is intermittent, hybridization of PV system with other sources is essential to supply continuous power to the consumers. Fuel cell (FC) system gives DC power by utilizing hydrogen as fuel. Power output of fuel cell can be controlled either by managing the flow of fuel into the FC system or by incorporating appropriate power electronic converters with controllers.

Many literature works describe the modeling of a PV array [1-3]. Researchers have done comparative study on the maximum power point tracking (MPPT) techniques for photovoltaic modules and have concluded that the incremental conductance algorithm is accurate as compared to perturb and observe algorithm [4-6]. The modeling of fuel cell system is reported in [7]. The comparison of different types of fuel cells shows that the proton exchange membrane fuel cell (PEMFC) is a good option and is considered in this paper. A dynamic model for PEMFC with reformer is described in [8] and the hybrid system is developed without DC-DC converters. The ultracapacitor bank is able to compensate effectively for load variations [8]. In [9], the model of PEMFC with voltage and power control strategies was developed for stand-alone operation without considering other sources. In [10], PV modules and FC stacks were hybridized along with ultracapacitors to provide continuous power supply. In [11], a complex control method for the same hybrid system is proposed with dump load where additional power was stored in ultracapacitors and electrolyzer.

To obtain pure sinusoidal voltage output from the inverter, filters are essential. Different types of filters are described in [12-14]. In a stand-alone system when the load demand changes suddenly, the voltage and frequency will be disturbed. In [15, 16], a control strategy is implemented to control voltage and frequency to ensure the quality of power supplied to consumers. The different techniques to balance the powers in a hybrid power system by using power converters are reported in [17, 18]. The design and details of bi-directional DC-DC converters to manage ultracapacitors power are described in [19, 20]. This paper focuses on simple control strategies for voltage, frequency and power control of the PV-FC-UC hybrid power system. The PV array is controlled to extract maximum power from it. The ultracapacitor bank is used to supply or absorb power during transient changes in the load.

The paper is organized as follows: Section 2 provides the detailed description of the stand-alone hybrid system. Section 3 details complete modeling of the hybrid system and control methods. In section 4 the simulation results are discussed and analyzed. Finally the conclusions are briefed in section 5.

2. Hybrid System Configuration

The schematic diagram of the PV-FC-UC hybrid power system for supplying stand-alone load is shown in Fig. 1. In this hybrid configuration, the PV array and fuel cell system are taken as main power sources. These power sources are interfaced with the DC bus through DC-DC boost converters. The PV system consists of boost converter with MPPT controller. The ultracapacitor bank is connected to the DC link with a bidirectional DC-DC converter so as to supply or absorb power during transient changes in the demand. The produced DC power is converted to AC by a single phase H-bridge inverter. The AC output is filtered by using LCL filter. The inverter controller regulates the voltage and frequency of the across the load connected to the hybrid system. The power controller of the hybrid system balances power output of fuel cell system and power of UC bank.

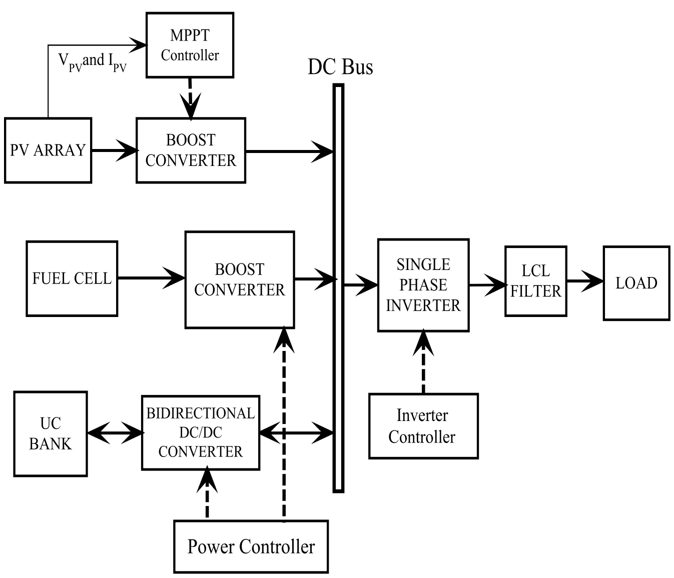

Fig. 1. Schematic diagram of the PV-Fuel cell-UC hybrid system

3. Modeling and Control Strategies

In this work, a dynamic model of PV power system and proton exchange membrane fuel cell and are implemented. The control systems of the hybrid system involve MPPT controller, voltage and frequency controller for inverter and power controller.

A. PV modeling and MPPT Controller

The light generated current (photocurrent) I_{pv} of the PV cell is given by [6]

$$I_{pv} = [K \times (T_C - T_r) + I_{sc}] \times G \quad (1)$$

The reverse saturation current of the solar cell I_r is also dependent on cell temperature by the relation

$$I_r = I_{rs} \times \left[\frac{T_c}{T_r}\right]^3 \times \exp\left[\frac{q.v_g \times (\frac{1}{T_c} - \frac{1}{T_r})}{n.k}\right] \quad (2)$$

Where I_{rs} is the reverse saturation current at standard temperature. The output current of the solar array is given by

$$I_o = N_p \times I_{pv} - N_p \times I_r \times \exp\left[\frac{q \times (N_p V_o + N_s I_o R_s}{N_s N_p k T_c n} - 1\right] \quad (3)$$

Where q = the charge of an electron k = Boltzmann's constant, n = Cell idealizing factor, T_r = reference temperature (K), K = temperature coefficient, G = solar irradiation (W/m^2), I_r = reverse saturation current of the cell (A), N_p and, N_s = Number of cells in parallel and series respectively and $R_{p,}$ and R_s = Shunt and series resistance of solar cell respectively (Ω), T_c = absolute temperature of solar cell (K).

The PV array uses MPPT controller to extract the maximum power under varied insolation and temperature conditions. MPPT control algorithm is based on incremental conductance method. At maximum power point (MPP), the error between the incremental conductance and negative of conductance (dl/dV + I/V) is zero. The controller varies the duty cycle of MPPT boost converter so as to extract power from MPP.

B. Modeling PEMFC System

In this paper, the PEM fuel cell is used. In this type of fuel cell system, hydrogen is used to generate electricity from the fuel cell system. The power generated is expressed as a function of partial pressure (p) and molar flow rate (q) of gases and water [8, 9]. The partial pressure and molar flow of any gas is related by equation

$$\frac{q_{H_2}}{p_{H_2}} = \frac{K_{an}}{\sqrt{M_{H_2}}} = K_{H_2} \quad (4)$$

Where K_{H_2} is the hydrogen valve constant and M_{H_2} is molar mass of hydrogen (kg/kmol).

The relationship between flow rate of hydrogen that has reacted and the fuel cell system current (I_{fc}) is given by the electrochemical equation

$$q_{H_2}^{r} = \frac{N_o \times I_{fc}}{2.F} = 2K_r I_{fc} \quad (5)$$

Also, the partial pressure of hydrogen gas is given by the equation

$$p_{H_2} = \frac{K_{H_2}}{1 + T_{H_2} s} \times (q_{H_2}^{in} - 2K_r I_{fc}) \quad (6)$$

Where activation over voltage (η_{act}) and ohmic over voltage (η_{ohmic}), time constant of hydrogen, $T_{H_2} = \frac{V_{an}}{K_{H_2} RT}$ R=universal gas constant (kmol/s.atm), T=Absolute temperature (K). Similarly the partial pressure of water and oxygen can be written. The output voltage of fuel cell system is expressed as the sum of Nernst voltage (E)

$$V_{cell} = E + \eta_{act} + \eta_{ohmic} \quad (7)$$

$$\eta_{act} = -B \times \ln(C \times I_{fc}) \quad (8)$$

$$\eta_{ohmic} = -R_{\text{int}} \times I_{fc} \quad (9)$$

$$E_o = N_o \times \left[E_o + \frac{RT}{NF} \times \log\left(\frac{p_{H_2} \times \sqrt{p_{O_2}}}{p_{H_2O}} \right) \right] \quad (10)$$

Where B and C are constants, E_o = No load voltage (V), N_o = Number of series cells and F = Faraday's constant (C/kmol).

C. Voltage and Frequency Controller

Whenever the load on the power system changes, the voltage and frequency will also changes. For proper operation of the stand-alone power system, voltage and frequency across the load is maintained constant. Fig. 2 shows the schematic of voltage and frequency control system used in this work. The root mean square (RMS) value of fundamental component of the voltage across load is taken and is compared with the reference voltage (230 V). The error is fed to the PI controller [15]. The value of modulation index is updated after every time delay. This modulation index is multiplied with a unit magnitude sine wave which is compared with a repeating sequence to generate PWM pulses for inverter switches. This control strategy helps to maintain both voltage and frequency [16].

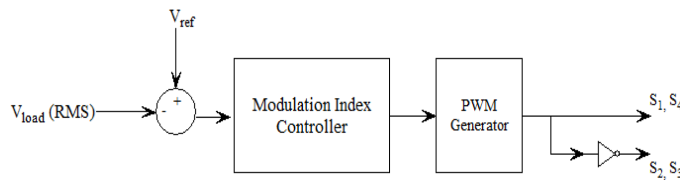

Fig. 2. Voltage and frequency control strategy

D. Power balancing controller

The photovoltaic energy being intermittent in nature, cannot meet the load alone and additional power has to be supplied by the fuel cell system. The load current is taken as the reference and the total current generated from PV and fuel cell system is compared with the reference. The PI controller functions as current controller generating the duty cycle for boost converter of fuel cell system based on power mismatch in demand and generation.

The sudden variations of load are common in stand-alone systems. During transients in the demand, the system becomes unstable and may damage the system. Hence in this hybrid system, an ultracapacitor bank is used to supply or absorb the sudden changes in the load power. Ultracapacitor is a device with high power density, small time constants and can absorb or supply high power within a short interval of time. Here ultracapacitor bank is connected to the DC bus through a bidirectional DC-DC converter which consists of two switches and capable of performing both boost and buck operations. When the transients in the load appear, the control system decides whether ultracapacitor bank has to supply or absorb the power according to the current reference generated by the controller. When the power generated by PV array exceeds the load demand, the ultracapacitor bank absorbs the additional power generated. During transient changes in load, UC bank supplies this difference of power due to slow response of fuel cell system. Fig. 3 depicts the power balancing control method used for the DC-DC converters of ultracapacitor bank and fuel cell system.

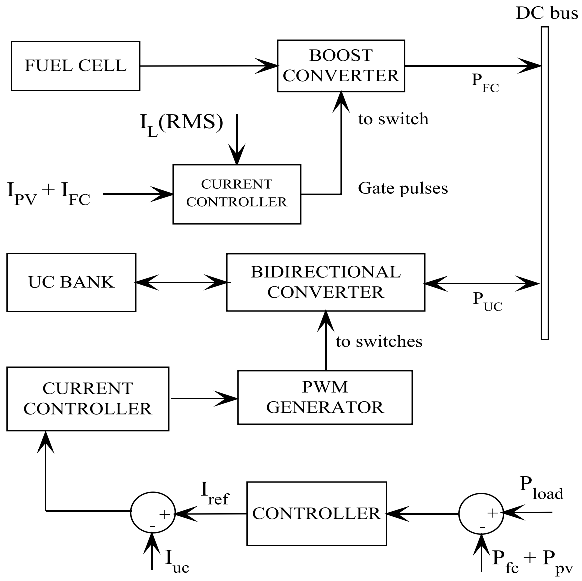

Fig. 3. Control strategy for balancing power

4. Results and Discussions

In this section, the simulated results of the proposed hybrid system using MATLAB/Simulink under different operating conditions are presented. Two different cases are considered for the simulation study and analysis of the hybrid power system. The simulation parameters of the system are given below.

PV System: k=1.38e-23, q = 1.6e-19, n=1.2, V_g = 1.12 V, open circuit voltage (V_{oc}) of the module = 21.924 V, short circuit current of the module (I_{sc}) = 8.21 A, number of series cells in a module = 36, standard irradiance = 1000W/m^2, standard temperature = 25^o C. K = 0.0032, R_p = 415.405 Ω, R_s = 0.221 Ω, N_s = 9 and N_p = 5. P_{output}= 5.7 kW;

FC System: F = 96484600 C/kmol, K_{H_2} = 4.22×10^{-5} kmol/s.atm, K_r = 2.2802×10^{-7} kmol/s.A, V_o = 0.6 V, N_o = 250, Fuel cell internal resistance (R_{int}) = 0.00303 Ω, T = 343 K, B = 0.0136 V, C = 0.04777 A^{-1}, R = 8314.47 J/kmol.K, T_{H_2} = 3.37 s, Voltage output = 150 V;

Ultracapacitors: voltage rating of individual ultracapacitor = 2.7 V, Number of series UCs = 150, Capacitance = 3 F;

LCL Filter Parameters: L_1 = 1 mH, L_2 = 0.6 mH, C = 20µF, r = 1.44Ω;

Case A: Constant Irradiation with Varying Load

In this case, the irradiation is kept constant at 500 W/m^2 and load demand of the hybrid system is varied. Fig. 4 shows the variation of load demand connected to the system. Fig. 5 depicts the power output of PV array, fuel cell system and ultracapacitor bank. From Fig. 5 it is observed that the power is shared among different sources to meet the load demand. If the load is more than the generation from PV system, the fuel cell system gives the additional power required to meet the demand. The sudden load changes are compensated by ultracapacitor bank. If the power generation exceeds the load demand, the surplus power is stored in ultracapacitor. Fig. 6 shows the voltage across ultracapacitor bank. The voltage reduces when it discharges and rises when it charges.

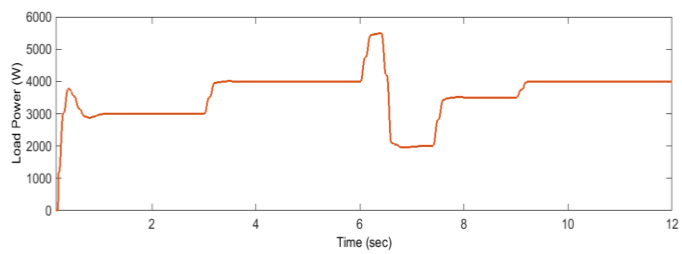

Fig. 4. Load power variations

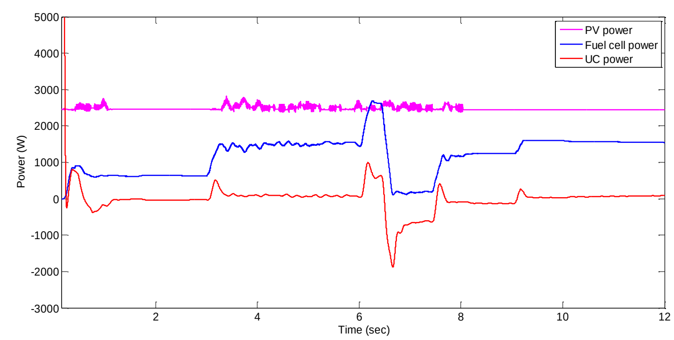

Fig. 5. Power sharing among different sources

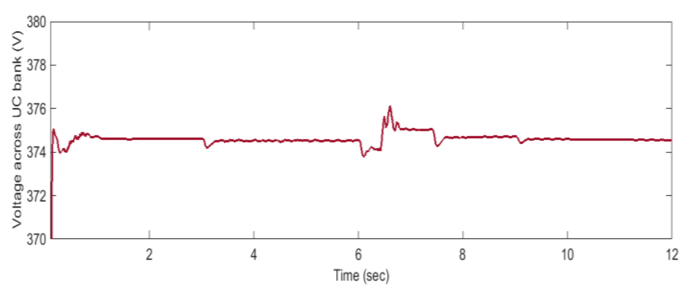

Fig. 6. Voltage across ultracapacitor bank

The load variations will disturb the voltage and frequency of the system. The inverter control strategy regulates the voltage and frequency of the system constant. Fig. 7 shows the AC voltage across the load which is a sine wave with minimum distortions. Fig. 8 shows the frequency of the voltage which is maintained within the acceptable limits. Fig. 9 shows the total harmonic distortion and is found to be very less (2.09%).

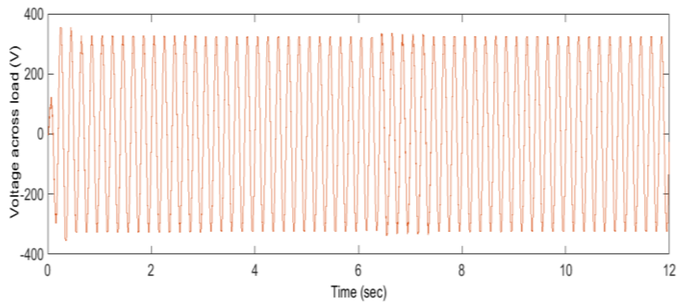

Fig. 7. Voltage across the load

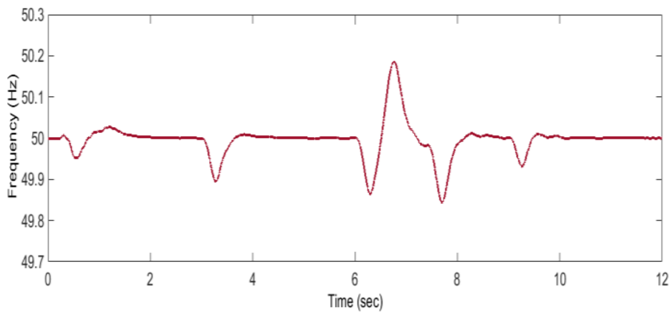

Fig. 8. Frequency of load voltage

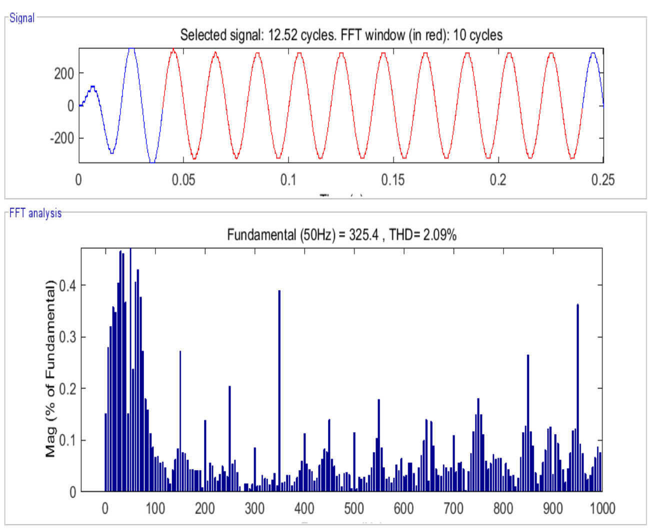

Fig. 9. Harmonic spectrum of load voltage

B. Variable irradiation with constant load

In this case, a constant load of 3.5 kW is considered for analysis and the irradiance input to the PV array is varied. Fig. 10 shows the irradiance input to the PV array. To describe the hybrid system behavior the step variations for irradiation are considered. Fig. 11 shows the power output of PV array, fuel cell system and ultracapacitor bank with the load power. When the power output of PV system exceeds the load demand, ultracapacitor bank absorbs the surplus power and when load demand is higher than the power generation, fuel cell system gives the additional power. Fig. 12 shows the voltage across ultracapacitor bank during its charging and discharging operation.

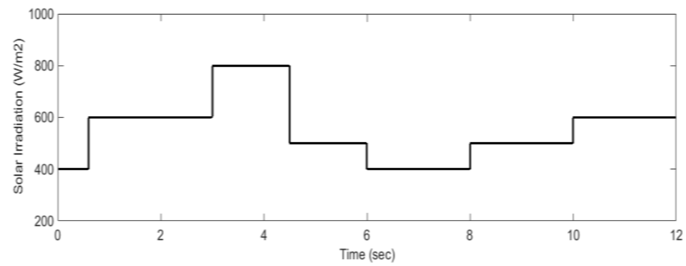

Fig. 10. Irradiance input to PV array

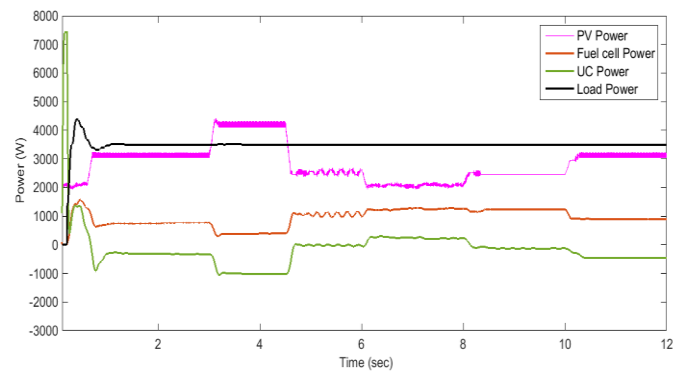

Fig. 11. Load demand and power output of different sources

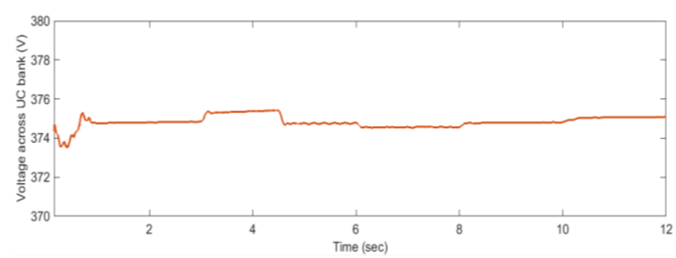

Fig. 12. Voltage across supercapacitor bank.

5. Conclusion

The dynamic model of PV and fuel cell system is implemented in MATLAB/Simulink platform. The hybrid power system consists of PV array, fuel cell system and ultracapacitor bank as sources for supplying isolated loads. The control strategies are developed and the sources share their power effectively to meet the load demand. The ultracapacitor bank keeps the system stable during sudden load changes. The system is capable of managing power effectively for variations in both source and load. From the simulation results reported, it can be seen that irrespective of intermittency in PV power generation and load variations the inverter control strategy is able to maintain the voltage and frequency within the acceptable limits. The consumer gets a quality supply with constant voltage and frequency.

Reference

[1] Natsheh E. M. and Albarbar A: *Photovoltaic Model with MPP Tracker for Standalone/Grid Connected Applications*, IET Conference on Renewable Power Generation (RPG), 2011.

[2] Suthar M., Singh G.K., Saini R.P: *Comparison of Mathematical Models of Photo-Voltaic (PV) Module and effect of various Parameters on its Performance*, International Conference on Energy Efficient Technologies for Sustainability (ICEETS), 2013.

[3] Krishan R, Sood Y.R. and Uday Kumar B: *The Simulation and Design for Analysis of Photovoltaic System Based on MATLAB*, International Conference on Energy Efficient Technologies for Sustainability (ICEETS), 2013.

[4] William Christopher I and Dr Ramesh R: *Comparative Study of P&O and InC MPPT Algorithms*, American Journal of Engineering Research (AJER), Vol. 02, No. 12, pp. 402-408.

[5] Pratik U.M. and Moharil R.M.: *Comparative Analysis of the Perturb-and-Observe and Incremental Conductance MPPT Methods*, International Journal of Research in Engineering and Applied Sciences (IJREAS), Vol. 02, No. 02, July 2014.

[6] Jayalakshmi, N. S. and Gaonkar, D. N.: *Modeling and Performance Analysis of Grid Integrated Hybrid Wind and PV Based DG System with MPPT Controllers*, International Journal of Distributed Energy Resources and Smart Grids, Technology and Science Publishers, Germany, 10(2), pp. 115-131.

[7] M. Hashem Nehrir and Caisheng Wang: *Modeling and Control of Fuel Cells: Distributed Generation Applications*, IEEE Press, A. John Wiley & Sons, INC., publication.

[8] Uzunoglu M and Alam M. S.: *Dynamic modeling, design and simulation of a combined PEM fuel cell and ultracapacitor system for stand-alone residential Applications*, IEEE Transactions on Energy Conversion 2006; 21(3), pp. 767–75.

[9] El-Sharkh M.Y., Rahman A, Alam M.S., Byrne P. C., Sakla A.A. and Thomas T: *A dynamic model for a stand-alone PEM fuel cell power plant for residential applications*, Journal of Power Sources 138 (2004), pp. 199–204.

[10] Mangipudi Sreedevi, Carmel Tensy Pereira and Jyothi Bojjamma K.: *Simulation Model of a Hybrid Photo Voltaic/Fuel Cell/ Ultra-Capacitor System for Stand Alone Applications*, International Journal of Engineering Research & Technology, Vol. 4, No. 06, June-2015.

[11] Uzunoglu M, Onar O.C. and Alam M.S.: *Modeling, control and simulation of a PV/FC/UC based hybrid power generation system for stand-alone applications*, Renewable Energy 34 (2009), pp. 509–520.

[12] Hanju Cha and Trung-Kien Vu: *Comparative Analysis of Low-pass Output Filter for Single phase Grid-connected Photovoltaic Inverter*, Applied Power Electronics Conference and Exposition, IEEE (APEC), 2010.

[13] Xu Renzhong, Xia Lie, Zhang Junjun, and Ding Jie: *Design and Research on the LCL Filter in Three-Phase PV Grid-Connected Inverters*, International Journal of Computer and Electrical Engineering, Vol. 5, No. 3, pp. 322-325 June 2013.

[14] Kahlane A.E.W.H., Hassaine L and Kherchi M: *LCL Filter Design for Photovoltaic Grid Connected Systems*, the Journal of Renewable Energies, pp. 227-232.

[15] Tiang Tow Leong and Dahaman Ishak: *Deadbeat-based PI Controller for Stand-Alone Single-Phase Voltage Source Inverter using Battery Cell as Primary Sources*, IEEE First Conference on Clean Energy and Technology (CET), 2011.

[16] Tow Leong Tiang and Dahaman Ishak: *Modeling and simulation of deadbeat-based PI controller in a single-phase H-bridge inverter for stand-alone applications*, Turkish Journal of Electrical Engineering & Computer Sciences, 2014, vol. 22, pp. 43-56.

[17] Guiting Xue, Yan Zhang and Dakang Zhu: *Synthetically Control of a Hybrid PV/FC/SC Power System for Stand-Alone Applications*, Research Journal of Applied Sciences, Engineering and Technology, vol. 5, No. 5, pp. 1796-1803.

[18] Anant Naik, Udaykumar R.Y and Vinayak Kole: *Power Management of a Hybrid PEMFC-PV and Ultracapacitor for Stand-alone and Grid Connected Applications*, IEEE International Conference on Power Electronics, Drives and Energy Systems 2012.

[19] Jan Leuchter, Pavol Bauer, Petr Bojda and Vladimir Rerucha: *Bi-directional DC-DC Converters for Supercapacitor based Energy Buffer for Electrical Gen-Sets*, European Conference on Power Electronics and Applications, 2007.

[20] Kumar A.S, Gaonkar D.N, and Nayak S.K.: *Performance Study of Grid Connected Fuel Cell Based Distribute Generation System with Ultracapacitor*, IEEE PES Conference on Innovative Smart Grid Technologies, 2011.