

Power Control of PV/Fuel Cell/Supercapacitor Hybrid System for Stand-Alone Applications

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Abstract- This paper presents modeling and control of photovoltaic/fuel cell/supercapacitor hybrid power system for stand-alone applications. The hybrid power system uses solar photovoltaic array and fuel cell as the main sources. These sources share their power effectively to meet the load demand. The supercapacitor bank is used to supply or absorb the power during load transients. The main control system comprises of controller for maximum power tracking from photovoltaic system, a DC-DC boost converter with controller for fuel cell system for power management and inverter controller to regulate voltage and frequency. The stand-alone hybrid system aims to provide quality power supply to the consumers with a constant voltage and frequency along with proper power management using simple control techniques. The modeling and control strategies of the hybrid system are realized in MATLAB/Simulink.

Keywords – Photovoltaic system, proton exchange membrane fuel cell; maximum power extraction, inverter controller.

1. Introduction

At present the power demand is mainly met by the energy from conventional fossil fuels which will be depleted after few years. There is a necessity to conserve the fossil fuel resources for further uses because of increasing energy demand. Due to increased greenhouse gas emissions from the power plants and industries that make use of fossil fuels, the climatic conditions are worsened. This necessitates the use of renewable or alternate energy sources to meet the increasing power demand which are known to cause less pollution. Photovoltaic (PV) cells are semiconductor p-n junction devices produce DC power directly using energy from sunlight. The PV power system operates without noise and requires no maintenance as compared to other renewable energy sources. Since the solar irradiation on earth is intermittent, hybridizing PV system with other source is necessary to provide continuous and reliable supply of electricity. Fuel cells (FC) supply constant DC power by

converting chemical energy to electrical energy. Wind energy has complementary profiles with solar energy but it can be effectively extracted only in the regions where enough wind is available and its installation cost is high. Battery as a storage device is less reliable if used with solar energy systems. Hence the fuel cell is the alternative source for backup when the standalone residential loads are considered. As long as the fuel (hydrogen and oxygen) is available, fuel cell keeps generating DC electricity with an efficiency of about 60%.

The detailed modeling of fuel cell is described in [1]. A model of Proton Exchange Membrane (PEM) fuel cell is described in [2, 3]. Many papers describe the modeling of a PV array [6-8]. A standalone system consisting of fuel cell as the major energy source and supercapacitor as the storage device is reported in [2]. The DC-DC converters are not used at the source side in this proposed system. The voltage and phase angle control strategy is used to control the inverter

operation. The supercapacitor bank can successfully compensate for load and source side variations and transients as it has a high power density. The load tracking was done using sensors and fuel rate control within the fuel cell model. In [4, 5], photovoltaic array and fuel cell system were hybridized along with supercapacitor to provide continuous power supply. The comparison made between the different types of fuel cells in [1] shows that the proton exchange membrane fuel cell (PEMFC) is appropriate for standalone applications and power levels considered. In [5], a complex control structure for the same hybrid system is proposed in which additional power was stored in ultracapacitor and hydrogen electrolyzer and excess power is given to variable dump load.

Many researchers have compared the maximum power point tracking (MPPT) techniques for photovoltaic systems and found that incremental conductance algorithm is accurate and efficient [9, 10]. The inverter output voltage consists of harmonics. The filters are necessary to achieve a sinusoidal output voltage. Different types of filters are described in [12-14]. In a standalone system when the load power suddenly changes, the voltage at the source falls and frequency will be disturbed. Hence a control strategy has to be developed to regulate voltage and frequency of the system so as to maintain the system stable and safe [2, 15-17]. The different techniques are reported in [18-20] to manage the power in a hybrid system. In this work, the hybrid system uses PV array and fuel cell along with supercapacitor bank to supply or absorb load transients. In this isolated hybrid system, the supercapacitor bank is directly connected to the DC bus [2]. This work aims to develop simpler control strategies for power management as compared to the existing literatures. The control system comprises of MPPT controller for PV system, controller for fuel cell system for power management and inverter controller to regulate voltage and frequency.

2. Configuration of Hybrid System and Modeling

Fig. 1 represents the schematic diagram of PV/Fuel cell/SC hybrid system. The system mainly consists of a solar energy source with MPPT controller, fuel cell system with DC-DC converter, single phase inverter with controller and loads. Both PV and fuel cell system are connected to the common DC link. Also the supercapacitor bank is connected to the DC bus so as to supply or absorb load transients. The ratings of PV and fuel cell system are 5.7 kW and 5 kW respectively. The DC link voltage is 370 V. The voltage rating of supercapacitor bank chosen is 400 V. The supercapacitor bank of 3 F capacity is selected (with 150 capacitors of 2.7 V each) and is charged to 92.5% of its capacity. A single phase H-bridge inverter is used to convert produced DC power into AC. The AC output is filtered using LCL filter. The main control system regulates the operation

of the hybrid power system. It consists of current control method to balance power on DC side and voltage and frequency controller on the AC side of the system.

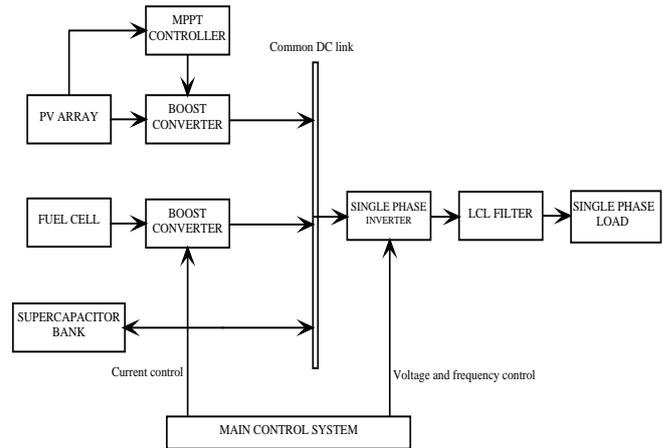


Fig. 1. The PV/FC/SC hybrid system representation

2.1. Modeling of PV Array

A solar PV cell is a semiconductor P-N junction device which generates electric current when photons of energy higher than the band gap energy of semiconductor material fall on it. These cells are arranged in series and parallel combination to form a PV module. Several mathematical models were proposed in the literature for PV generation system and single diode model is used in this paper. Fig. 2 represents the equivalent circuit of single diode model of a solar cell.

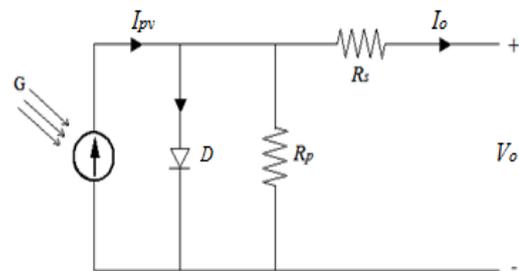


Fig. 2. Equivalent circuit of PV cell

From Fig. 2, output current of the PV cell is given by equation (1) [7]

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

Where q = Charge of an electron (1.6 x 10⁻¹⁹ C), T_c = Absolute temperature of solar cell (K). V_o= output voltage and I_o= output current of PV cell. The light generated current (photocurrent) I_{pv} is dependent on solar irradiation G (W/m²) and cell temperature according to equation (2)

$$I_{pv} = [K \times (T_c - T_r) + I_{sc}] \times G \tag{2}$$

Reverse saturation current of the solar cell (I_r) is also dependent on cell temperature according to equation 3(a)

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

At standard temperature, the reverse saturation current is given by

$$I_{rs} = \frac{I_{sc}}{e \frac{q V_{oc}}{K F \cdot T_r}} \quad (3b)$$

The cell idealizing factor (n) is dependent on the cell material. The output current of the solar array is given by equation (4). The PV system is modeled using MATLAB/Simulink environment.

$$I_o = N_p \times I_{pv} - N_p \times I_r \times \exp \left[\frac{q \times (N_p V_o + N_s I_o R_s)}{N_s N_p k T_c n} - 1 \right] \quad (4)$$

2.2. Modeling of PEM Fuel Cell System

In this paper, PEM fuel cell is used. In this fuel cell system Hydrogen is used as a fuel to generate electricity. Fig. 3 shows PEM fuel cell system. The dynamic model is realized in MATLAB/Simulink.

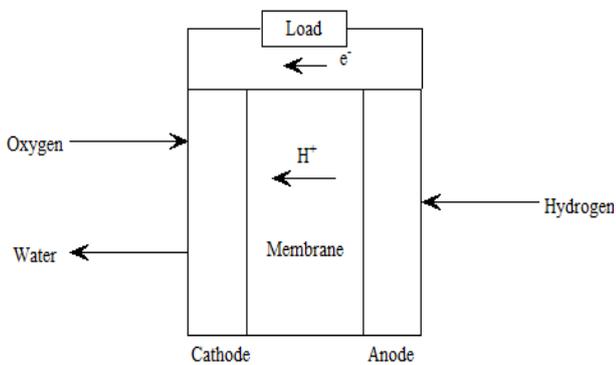


Fig. 3. Proton Exchange Membrane FC system

The generated electricity from the fuel cell is expressed as a function of partial pressure (p) and molar flow rate (q) of gases and water [2], [3]. The partial pressure and molar flow of any gas is related as

$$\frac{q_{H_2}}{p_{H_2}} = \frac{K_{an}}{\sqrt{M_{H_2}}} = K_{H_2} \quad (5)$$

Where K_{H_2} is hydrogen valve constant and M_{H_2} is molar mass of hydrogen (kg/kmol). The input flow of hydrogen, output flow and flow at the time of reaction are related as

$$\frac{d(p_{H_2})}{dt} = \frac{RT}{V_{an}} \left(q_{H_2}^{in} - q_{H_2}^{out} - q_{H_2}^r \right) \quad (6)$$

Where R = Universal gas constant (kmol/s.atm), T = Absolute temperature (K), V_{an} = Volume of Anode (m^3).

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

$$q_{H_2}^r = \frac{N_o \times I_{fc}}{2 \cdot F} = 2 K_r I_{fc} \quad (7)$$

Combining equations (5) and (7) and by applying Laplace transform, the partial pressure of hydrogen gas is obtained as

$$p_{H_2} = \frac{K_{H_2}}{1 + T_{H_2} s} \times (q_{H_2}^{in} - 2 K_r I_{fc}) \quad (8)$$

Where time constant of hydrogen, $T_{H_2} = \frac{V_{an}}{K_{H_2} RT}$ and

similarly the partial pressure of water and oxygen can be obtained. The output voltage of fuel cell system is expressed as the sum of Nernst voltage (E), activation over voltage (η_{act}) and ohmic over voltage (η_{ohmic}).

$$V_{cell} = E + \eta_{act} + \eta_{ohmic} \quad (9)$$

$$\eta_{act} = -B \times \ln(C \times I_{fc}) \quad (10)$$

$$\eta_{ohmic} = -R_{int} \times I_{fc} \quad (11)$$

$$E_o = N_o \times \left[E_o + \frac{RT}{2F} \times \log \left(\frac{p_{H_2} \times \sqrt{p_{O_2}}}{p_{H_2O}} \right) \right] \quad (12)$$

Where B = Activation voltage constant (A^{-1}), C = Activation voltage constant (V), E_o = No load voltage (V), N_o = Number of series cells and F = Faraday's constant (C/kmol).

3. Control strategies for power electronic converters

3.1. Photovoltaic MPPT Control

PV power system makes use of MPPT controller to deliver the maximum power produced to the load all the time under varied insolation and temperature conditions. PV modules have relatively low conversion efficiency; hence MPPT controller is necessary for the solar PV systems. MPPT control is accomplished using DC-DC boost converter.

Among the MPPT techniques proposed in the literatures, the most widely used ones are incremental conductance algorithm (IC) and perturb and observe algorithm (P&O). Many researchers have implemented and compared both the algorithms and have found that implementation of P&O algorithm is simple. But, the output oscillates about the MPP and hence less efficient as compared to the incremental conductance algorithm [9, 10]. According to IC algorithm, $dI/dV = -I/V$ at MPP as shown in Fig. 4. Also compared to than P&O method, this algorithm can track power rapidly for changing irradiance conditions with accuracy [10, 11]. The flow chart of IC method is shown in Fig. 5. This method considers the fact that the ratio of change in output conductance is equal to the negative of the output conductance at MPP. Fig. 6 shows the block diagram implementation of IC algorithm in MATLAB/Simulink.

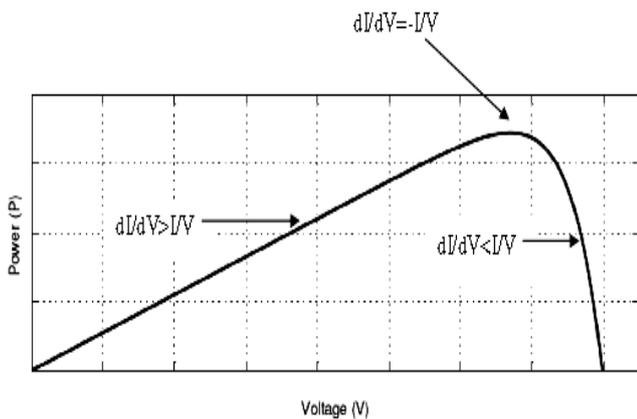


Fig. 4. P-V curve of a PV cell

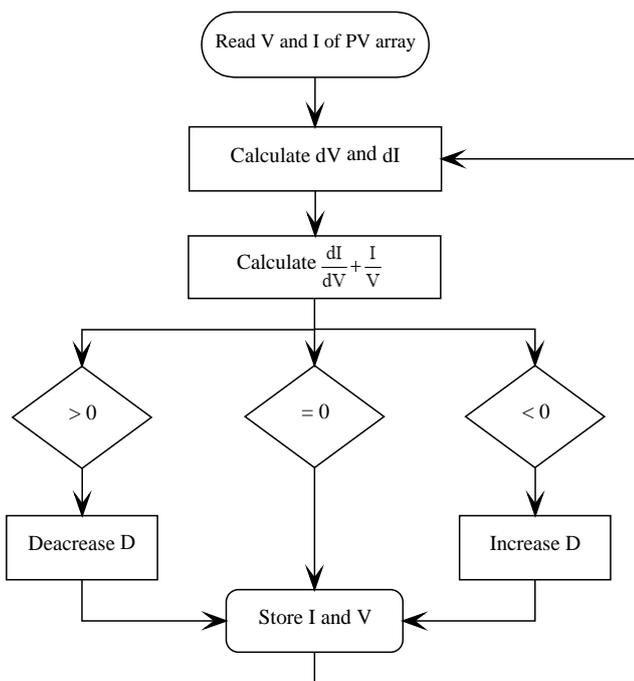


Fig. 5. Flow chart of IC method

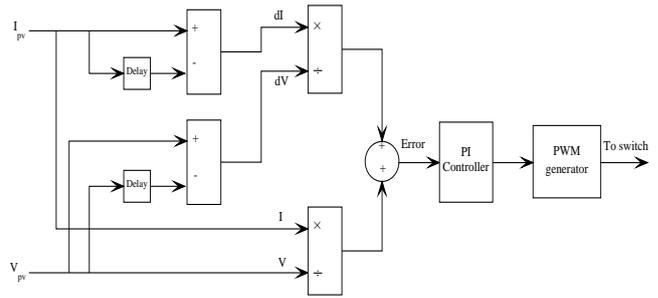


Fig. 6. Block diagram of IC algorithm in MATLAB/Simulink

3.2. Inverter controller

The voltage and frequency changes when there is change in load demand. Loads require constant voltage and frequency for their satisfactory operation [16]. So it is necessary to maintain the voltage and frequency on the AC side of the system. Fig. 7 shows the voltage and frequency controller used in this work. The root mean square value of fundamental component of the load voltage is taken and compared with the reference voltage (230 V). The error is fed to the PI controller. The unit delay updates the value of modulation index for every period. The output of this controller is modulation index (its value ranges from 0 to 1). This modulation index is multiplied with a unit magnitude sine wave which is compared with a triangular wave. The generated pulses are given to four switches of the inverter as shown in Fig. 7. The variations in voltage across load are controlled by adjusting modulation index which also controls the frequency of voltage.

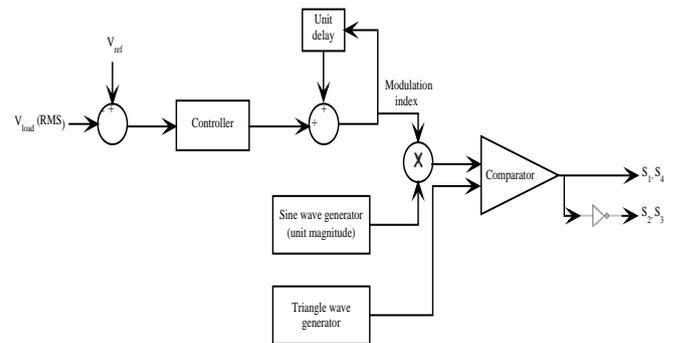


Fig. 7. Voltage and frequency control strategy

3.3. Current Control Strategy for Power Balance

Solar energy being intermittent in nature, cannot meet the load demand alone. So when it is not able to supply the entire load demand, the additional power has to be supplied by the fuel cell system. The control strategy using current control technique for boost converter of fuel cell is shown in Fig. 8. The load current (RMS value) is taken as the reference and the total current generated from fuel cell and PV source is compared with the reference. The PI controller functions as

current controller generating the duty cycle to compensate the mismatch in demand and generation. The PWM generator produces gate pulses depending on the duty cycle and the output power of fuel cell is controlled.

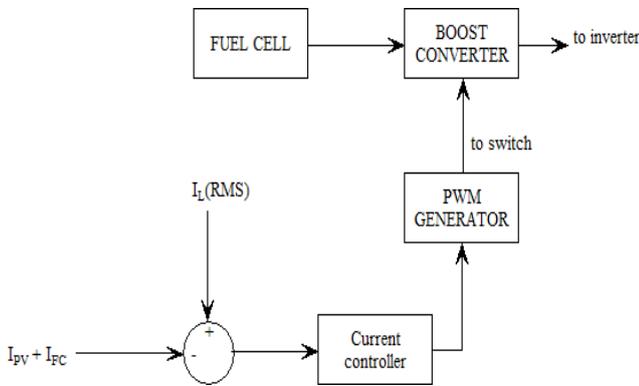


Fig. 8. Current control strategy for power balance

The sudden variations of load are common in stand-alone systems. In this paper, supercapacitor is used to supply or absorb transient power due to load variations. Supercapacitor is a device with high power density, small time constants and can absorb or supply high power within a short interval of time. Here supercapacitor bank is connected to the DC bus directly, as it can respond to transients without converter [2]. When the transients in the load appear, the supercapacitor supplies the power to match the load and to keep the system safe. When the PV power exceeds the load demand; supercapacitor absorbs the additional power from the PV system.

4. Results and Discussions

In this section, the simulation results of the PV/FC/SC hybrid system for different source and load conditions in MATLAB/Simulink environment are presented. A simulation period of 2 sec has been considered for the study. The simulation parameters of PV cell are given in Table 1 [11]. The details of the parameters used for the fuel cell model are considered from [2].

Table 1. Simulation parameters of PV system

| Parameters | Values |
|---------------------------------------|----------------------------|
| k=Boltzmann’s constant | 1.38×10^{-23} J/K |
| V _{oc} of the module | 21.924 V |
| I _{sc} of the module | 8.21 A |
| Number of cells in series in a module | 36 |

| | |
|--|-----------|
| Standard/reference temperature (T _r) | 25 °C |
| Temperature coefficient (K) | 0.0032 |
| Shunt resistance of the module (R _p) | 415.405 Ω |
| Series Resistance of the module (R _s) | 0.221 Ω |
| Number of modules in series (N _s) and parallel (N _p) | 9 and 5 |

Fig. 9 shows the I-V and P-V curves of the designed solar PV array. The PV system generates 5.7 kW for irradiation of 1000 W/m². The current generated by a PV array, is a direct function of irradiance. The output power of PV array reduces with the reduction in irradiance. The irradiance profile of PV array is shown in Fig. 10. The irradiance data is collected from the sun rise to sun set in the interval of 30 minutes in a sunny day and is scaled down to 2 sec. The corresponding output power variation of PV system is shown in Fig. 11.

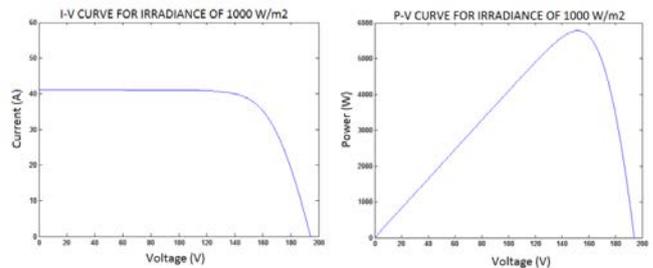


Fig. 9. I-V and P-V curves of solar PV array

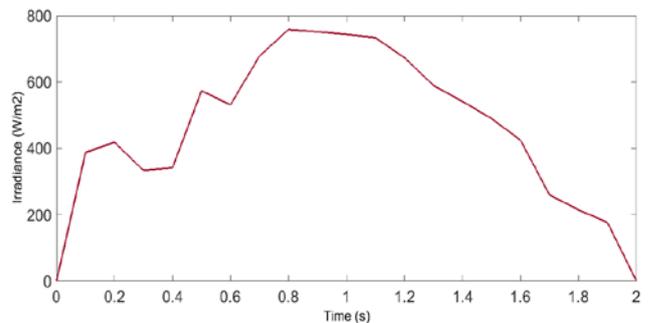


Fig. 10. Irradiation profile (Source: www.imd.gov.in)

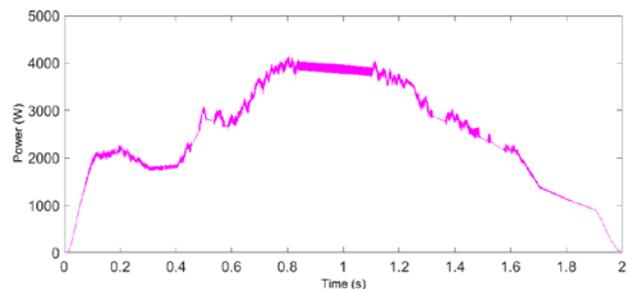


Fig. 11. Power output of PV system

Fig. 12 shows the variations in the load demand considered for the simulation. So as to show the effect of supercapacitor, the sudden load changes are considered at time instants 0.4sec and 1.2sec. Fig. 13 depicts the output power of fuel cell system. It follows the load demand of the system. But whenever PV generation is sufficient to meet the demand, its output power is zero. Fig. 14 illustrates variations of load power and supercapacitor power. Whenever sudden load change occurs, supercapacitor bank responds immediately to the transients. In the time interval from 0.6 to 1.2 sec, the supercapacitor output power is negative. In this interval generation from PV system is higher than the demand and supercapacitor bank is charged.

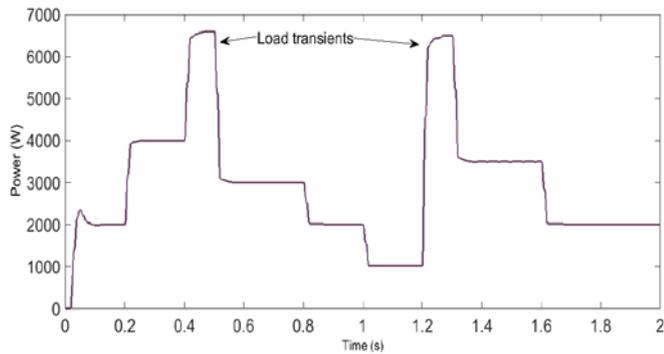


Fig. 12. Load power

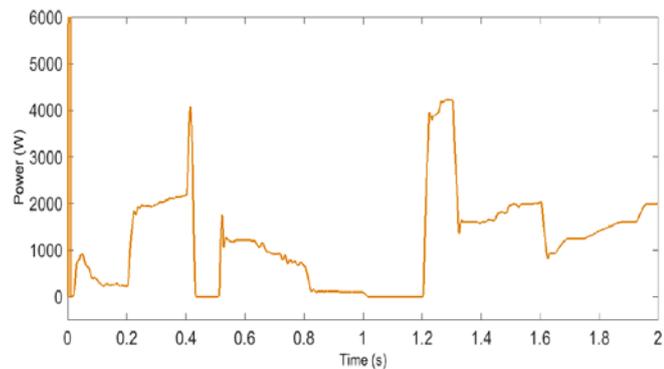


Fig. 13. Fuel cell system output power

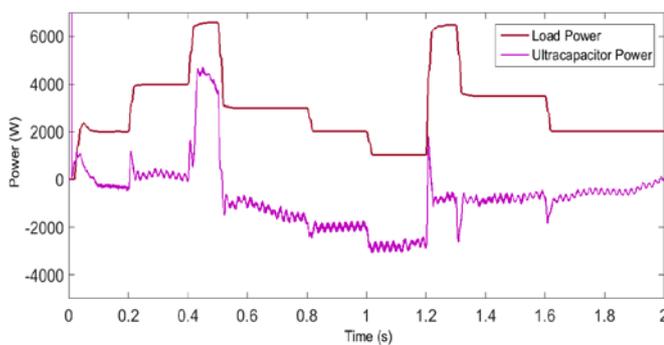


Fig. 14. Load power and supercapacitor power

The power responses of different sources and load demand of the hybrid system is shown in Fig. 15. Fig. 16 shows the total

generated power and load power and it is seen that the total generation meets the load demand of the hybrid system. Fig. 17 shows the RMS voltage across the load (230V). Even during load transients, the voltage variations are found to be within acceptable limits (less $\pm 5\%$ of the rated value as per the standards). Fig. 18 illustrates how the modulation index of the inverter gets adjusted to regulate the voltage during load changes as per voltage and frequency controller used. Fig. 19 shows the frequency of load voltage (50 Hz) controlled within the limits as specified in the standards. Fig. 20 depicts the harmonic spectrum of the load voltage. For the system considered the total harmonic distortion (THD) is 2.66%. As per the IEEE standards, the percentage of harmonics has to be less than 5%.

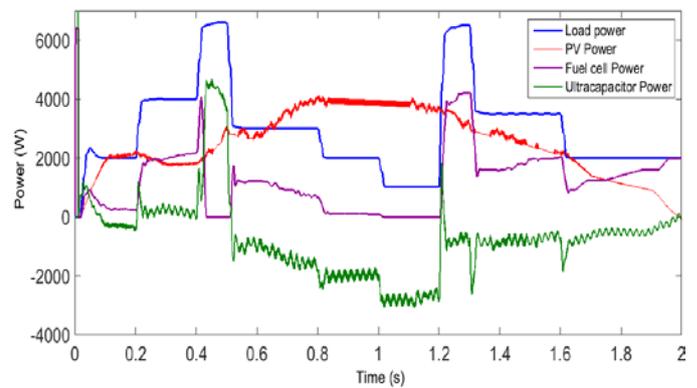


Fig. 15. Power responses of hybrid system

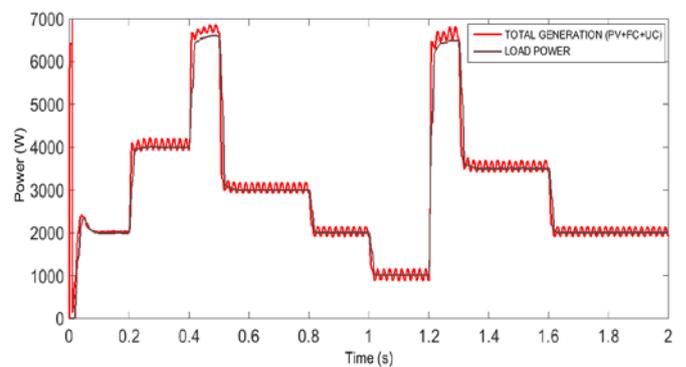


Fig. 16. Total power generated and load demand

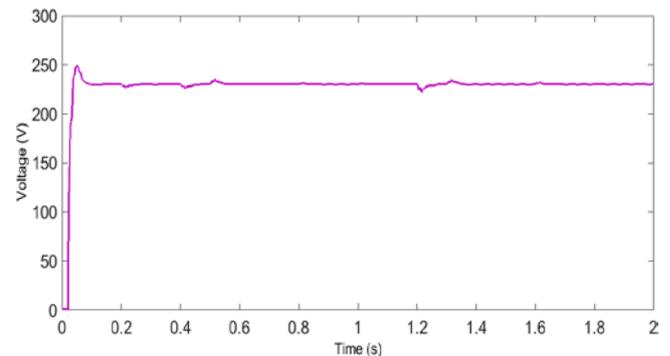


Fig. 17. Voltage across load

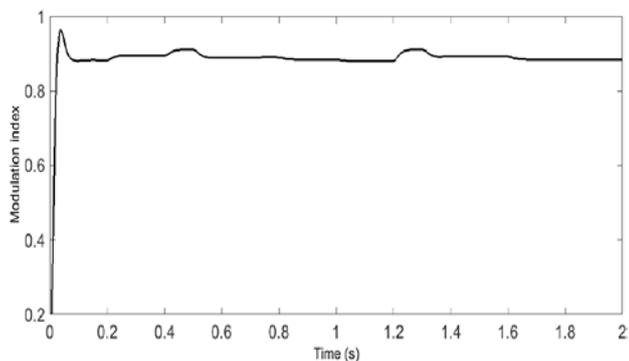


Fig. 18. Modulation index of inverter

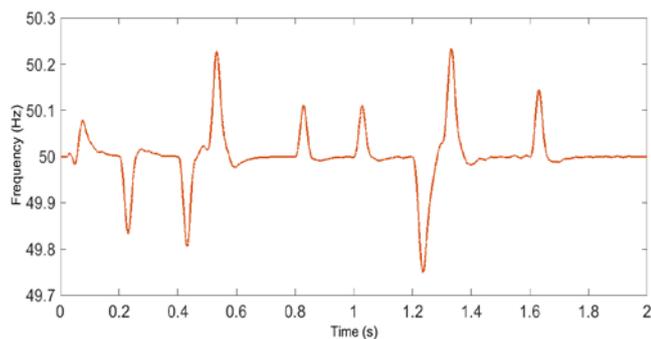


Fig. 19. Frequency of load voltage

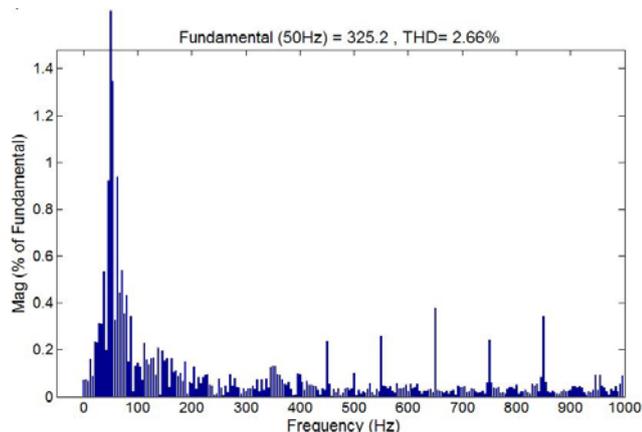


Fig. 20. Harmonic spectrum of load voltage

5. Conclusion

A detailed dynamic model of PV/fuel cell based hybrid system with supercapacitor bank and the control strategies are implemented in the MATLAB /Simulink platform for stand-alone applications. The hybrid power system considered in this work uses PV array and fuel cell system as the main sources. These sources share their power effectively to meet the load demand and supercapacitor bank keeps the system stable and safe even under transient load changes. From the simulation results reported, it can be seen that the control strategy is capable of regulating the voltage and frequency within the acceptable limits irrespective of uncertainty in PV power generation and load variations. The consumer gets a quality supply with constant voltage and frequency with minimum distortions.

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