Fuzzy Controller Based Solar Photovoltaic System, Fuel Cell Integration for Conditioning the Electrical Power

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Received 25 September 2018; Accepted 27 September 2018;
Publication 19 October 2018

Abstract

In the present world, the solar photovoltaic system plays an essential role in the modern power systems due to inertialess, abundant and freely available in nature. But the intermittent nature of the solar photovoltaic system is unable to provide continuous power supply. The proposed system should be highly reliable, secured with sufficient quantity and quality. Providing continuous supply is a great challenge in the present power system. One such solution is to bring the reliable and flexible power by introducing the solar photovoltaic, battery storage and fuel cell system. In this work, the integration of Solar Photovoltaic, battery with a fuel cell system is considered to provide the seamless power continuously. The solar power is extracted using fuzzy control based maximum power point tracking method which can be fed with DC bus using the boost converter. The battery storage system is connected to the DC bus using the bi-directional converter. The switching pulses for the bi-directional converter are generated using a PI controller based on the battery state of the charge. The Proton Exchange Membrane (PEM) fuel cell is used as a secondary source to maintain the flexible power at the DC bus system. The DC bus power can be fed to the load and the excessive power can be integrated with the grid through the synchronization process. The proposed structure stabilizes the DC link voltage and the grid voltages even under dynamic conditions of intermittent solar power and load variations

Journal of Green Engineering, Vol. 8_3, 301–318. *River Publishers*
doi: 10.13052/jge1904-4720.835

respectively. This can be accomplished utilizing the battery storage with a bi-directional converter and PEM fuel cell. The load sharing from the grid and the grid connected hybrid generation through the voltage source converter operation is performed and the load is stabilized. The simultaneous change of both the performance of grid synchronization and DC link stabilization of planned hybrid system is simulated using MATLAB/Simulink.

Keywords: Solar photovoltaic (PV), fuel cell, battery storage system, bi-directional DC-DC converter, power conditioning unit, Voltage Source Converter (VSC).

1 Introduction

The demand for electricity has been increased enormously due to the invention of technology, industries, population growth. This high power can be provided with the help of integration of non-conventional energy sources like solar, wind, etc. and a lot of research is taking place on the integration of renewable energy sources. In the present trend solar photovoltaic is one of the most favourable non-conventional energy source and use many applications such as grid connected, stand alone, electric vehicles, household applications, etc. [1]. Solar power can be obtained using various maximum power tracking techniques [2–3] such as perturb and observation, incremental conductance method, modified maximum power point tracking methods, soft computing based maximum power point tracking method etc.

In the grid based solar photovoltaic system, the solar DC power is integrated with grid through the inverter and a boost converter to supply the peak power. But the intermittent nature of the solar photovoltaic system influences the variation in the DC power and also effect the common point integration of the grid. This dynamic variation leads to effect the variation in grid frequency and voltage [4] which also lead to changes in the real power flow variation and effect the change in reactive power. The author in [5] has explained the common point variation of solar photovoltaic with grid connected three phase system. The maximum power is extracted using a fuzzy logic controller which was implemented, but due to intermittent nature of the solar photovoltaic system, it may fail to stabilize the DC bus voltage and will finally lose the synchronization at the common point interface. The variations in DC link voltage causes severe problems in the integration of grid connected systems. There is a necessity to maintain the DC link voltage constant and to utilize the solar power efficiently. This can be accomplished with the battery storage system. The battery storage with solar photovoltaic systems will avoid the voltage interference. But the battery storage is based on the battery state of charge and it is supported for a limited period only. It may fail to support the DC link voltage for a long time, especially during peak demand. To support the DC link voltage for longer time, it requires large size of battery storage systems and is more expensive.

The continuous charging and discharging of the battery may reduce the life of battery. This can be avoided using external source for supporting the DC link voltage. A secondary source is needed to prevent the failure of battery and supporting the DC link voltage. One such solution is integrating the solar photovoltaic, battery storage with fuel cells. The fuel cell stabilizes the DC link voltage for longer time and it will support during the intermittent nature of the solar power. The fuel cell increases the life of the battery and it will avoid the battery charging, discharging continuously. The size of the battery required for backup can be reduced and the cost requirement is also less. The integration of fuzzy based solar photovoltaic, battery with fuel cell can provide the smoothening dc link voltage with secured power supply. This DC link power is integrated with the grid through the voltage source inverter for providing a continuous power supply to the load. But the dynamics of load influence the grid connected system and finally comes out of the synchronization process. This can be achieved using grid synchronization unit.

In this paper, the performance of proposed solar photovoltaic, fuel cell, battery storage with the grid connected system is studied under dynamic condition of the load and source. The second section deals with each module of the proposed system. The third section presents the control strategy followed by the simulation results of the proposed system.

2 Modules of Proposed System

The integration of a solar photovoltaic, battery storage with the fuel cell hybrid system connected to DC load, grid and AC load, is shown in the Figure 1. The main modules of the hybrid system consist of solar photovoltaic with boost converter, battery storage, bi-directional converters, fuel cell, voltage source converter, grids and the AC loads.

The solar photovoltaic can be used as a primary source and the fuel cell used as a secondary source. The solar photovoltaic with boost converter is used to step-up the solar voltage using fuzzy based maximum power point tracking method. The output of the boost voltage is fed to the DC bus system. The battery and fuel cell are integrated with DC bus through the DC-DC boost

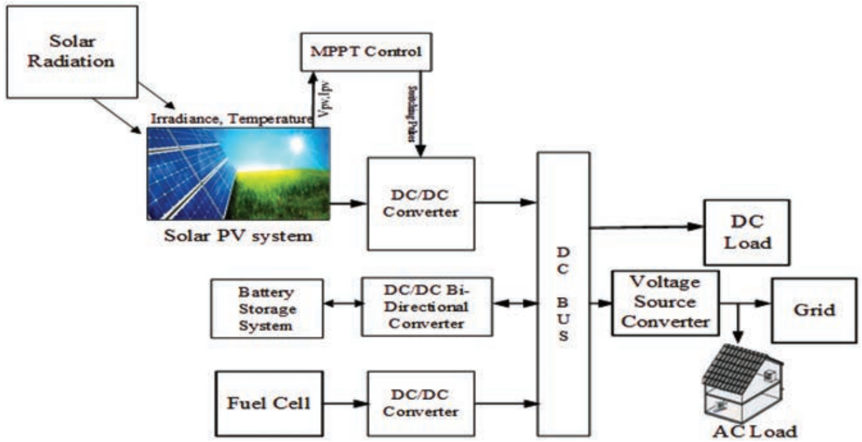

Figure 1 Integration of Solar photovoltaic, Battery storage, Fuel cell.

converter. The DC bus voltage is maintained constant with the help of battery storage and a fuel cell. The DC bus power can be fed to the DC load, and the excessive power of the DC bus system is fed to the grid as well as AC loads through the voltage source inverter. Each module of the proposed system and their control strategies are described in the following sections.

2.1 Solar Photovoltaic (PV) System

The solar photovoltaic system converts solar power into electrical power due to the process of photoelectric effect. Presently mono-crystalline panels are efficiently used because of the aesthetics of mono-crystalline solar cells are in a black hue and high efficiency. In this solar PV array, solar cells are framed in a series and parallel form. The 4 kW mono crystalline module (1STH-250-WH) specifications are mentioned in the Table 2. The basic solar PV equivalent circuit is shown in Figure 2 [4].

The solar photovoltaic current-voltage and power-voltage characteristic is simulated under different temperatures as shown in Figure 3. The solar characteristic shows the variation in the temperature and irradiance which will impact the variations in the electrical power. The maximum operating point of the solar photovoltaic panel is obtained using fuzzy controller based Maximum Power Point Tracking (MPPT). The solar PV array is modelled using the following Equations 1 and 2.

$$V_{PV} == \frac{nKT}{q} \ln\left(\frac{I_{sc}}{I_{pv}} + 1\right) \quad (1)$$

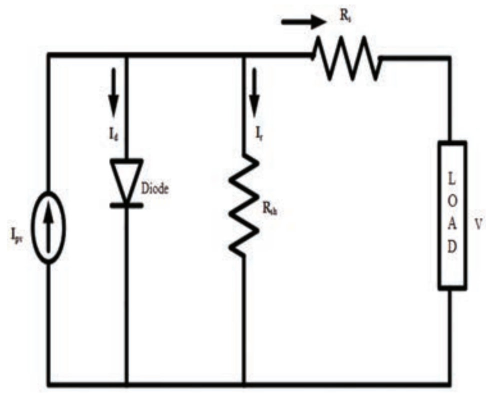

Figure 2 Solar photovoltaic equivalent circuit [4].

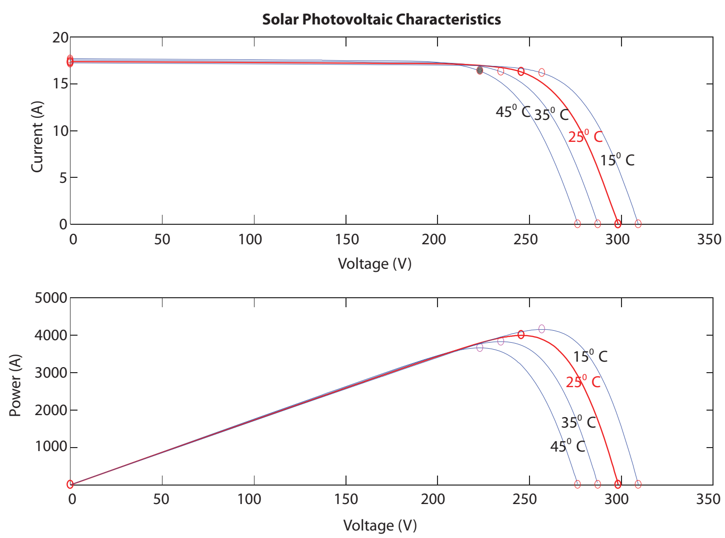

Figure 3 Mono crystalline solar panel characteristics.

$$I_{pv} = I_{sc} - I_{pvo}\left[\exp\left(\frac{q(V_{pv} + I_{pv}R_s)}{N_s K T n}\right) - 1\right] - \frac{V_{pv} + R_s I_{sc}}{R_{sh}} \qquad (2)$$

where, I_{pv}, V_{pv}-current (A) & voltage (V) of solar PV, T-cell temperature, I_{sc}-short circuit current (A), K-Boltzmann constant, n-ideality factor of diode, q-electronic charge (coulombs), N_s-number of series cells, I_{pvo}-saturation current (A) of diode, R_s, R_{sh}-series and shunt resistance (Ω).

Power from a solar Photovoltaic system (P_{PV}) is calculated using Equation 3.

$$P_{PV} = V_{pv} \times I_{pv} \tag{3}$$

Where, I_{pv}-Photovoltaic current (A),V_{pv}-Photovoltaic voltage (V).

2.2 Boost Converter

The boost converter is connected between solar PV source and DC link to synchronize solar voltage with the dc link voltage. It is used to step-up the solar PV source voltage into at desired DC link voltage. The boost converter is modelled using the following Equations 4 and 5 [6].

$$\Delta V_c = \frac{I_o * D}{C * F} \tag{4}$$

$$\Delta I = \frac{V_s * D}{L * F} \tag{5}$$

L (mH) and $C(\mu\mathrm{F})$ is inductance and capacitance of the boost converter calculated based on the voltage and current ratings. I_o- is the boost converter output current (A), F-Temperature in^0C, ΔV_c and ΔI are tolerable voltage (V) and current (A) limits, V_s- Input voltage of the boost converter (V). The boost converter design specifications are mentioned in the Table 2.

2.3 Voltage Source Converter

The DC link and the AC grid are connected through the single-phase AC Voltage Source Converter (VSC). The AC load is connected between the VSC and grid. The inverter and the Single phase VSC function are similar. It converts the DC power into AC power at a specified voltage, frequency and can be synchronized with the grid voltage. Through the voltage source inverter and grid synchronization control unit the grid synchronization process is achieved.

The output of the single phase AC voltage source inverter depends on the DC link voltage and the switching pulses generated from the grid synchronization unit. The inverter dc link voltage is regulated with the help of integration of solar photovoltaic, battery storage and fuel cell. The DC link voltage is stabilized with a rating of 750 V. The necessary supply for the grid and load is balanced with the voltage source inverter and this can be maintained using grid synchronization unit. The grid synchronization control technique is explained in Section 3.3.

2.4 Fuel Cell

The fuel cell generates the electricity due to the electrochemical process and is filled with air and hydrogen [5]. The different kinds of fuel cell technology based on the efficiency and storage capacity are developed such as phosphoric acid fuel cell, Proton Exchange Membrane Fuel Cell (PEMFC), solid oxide fuel cell, carbon Melton fuel cell and direct methanol fuel cell. In order to get instant response and durability, the PEMFC is used instead of all other fuel cells. [6–8] The PEM fuel cell can be used as a secondary source for providing continuous power supply. The PEMFC model is implemented using Equations 6, 7 and 8.

$$E_{nerst} = 1.129 - 0.85 \times 0.001(T_{cell} - 298.15) + 4.3085 \times 10^{-5} \times T \times \ln(p_{H_2}\sqrt{p_{O_2}}) \tag{6}$$

$$E_{nerst} = 1.129 - 0.85 \times 0.001(T_{cell} - 298.15) + 4.3085 \times 10^{-5} \times T \times \ln(p_{H_2}\sqrt{p_{O_2}}) \tag{7}$$

$$V_{cell} = E_{nernst} - \eta_{act} - \eta_{ohm} - \eta_{mt} \tag{8}$$

Where V_{cell} is the single cell terminal voltage of fuel cell (V), E_{nernst}-Nernst voltage is the voltage across each cell and is given by thermodynamic principle (V), p_{H2}, p_{O2} are the hydrogen and oxygen partial pressures, T_{cell}-the temperature of fuel cell (K), η_{act}-activation loss, η_{ohm}-Ohmic loss, η_{mt}-mass transfer loss. PEMFC is stabilizing the DC link voltage under dynamic condition of the solar photovoltaic power and battery storage system. The 50 kW PEMFC with the boost converter is used to support the DC link and it maintain constant voltage on the DC bus at 750 V.

3 Control Strategies

3.1 Fuzzy Logic based Maximum Power Point Tracking (FLC MPPT)

The fuzzy logic controller is preferred to solve the complex problem where the conventional algorithm fails to attain decision making for the desired response. The fuzzy controller is utilized to get the flexible output for taking the smooth decision which is adapted for a range of control system applications. The fuzzy logic controller framed with four processes such as fuzzifier, fuzzy interface, rule base, defuzzification as shown in the Figure 4.

The fuzzy logic controller based MPPT is preferred to track the maximum power from the solar photovoltaic system which will generate the switching

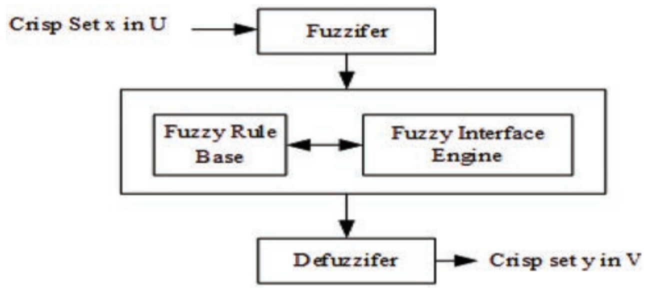

Figure 4 Fuzzy logic control circuits [9].

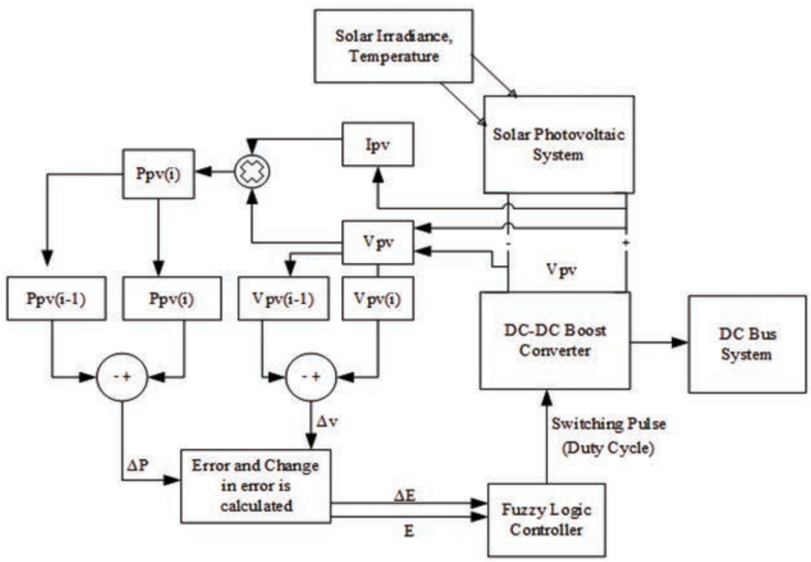

Figure 5 Fuzzy based MPPT control of solar PV.

pulses to boost converter as revealed in the Figure 5. In the fuzzy logic controller based MPPT, the error signal is defined as the ratio of change in power to change in voltage ($\frac{\Delta P}{\Delta V}$ called as a fuzzy factor). The error signal, E_o is zero at the maximum power point. For desired response, the fuzzy inputs are considered as the error and the change in error signals are obtained using following equations.

$$E(i) = \frac{P_{PV}(i) - P_{PV}(i-1)}{V_{PV}(i) - V_{PV}(i-1)} \tag{9}$$

$$\Delta E(i) = E(i) - E(i-1) \tag{10}$$

where E(i) is the error, ΔE-Change in the ratio error, ΔP-Change in power(W), ΔV-Change in voltage(V), E(i-1) is error in the previous state, P_{PV}(i)-Instant power(W), P_{PV}(i-1)-Previous state instantaneous power(W), V_{PV}(i)-Instant Voltage(V), V_{PV}(i-1)-Previous instant voltage(V). The boost converter duty cycle is regulated using the fuzzy factor in obtaining the maximum power from the solar photovoltaic system. The membership functions of fuzzy logic controller are modulated and the output as shown in Figure 8. The Figures 6 and 7 indicate the membership function of error input and change in error input respectively.

The input and output variable of the fuzzy rule is segmented into seven logistic variables. These variables are Positive Big (PB), Positive Average (PA), Positive Low (PL), Zero (Z), Negative Low (NL), Negative Average (NA), Negative Big (NB), and is presented in Table 1. If the E and ΔE are NB then the duty cycle is positive large. The output of the boost converter is synchronized with the DC bus voltage based on the possible variations in duty cycle.

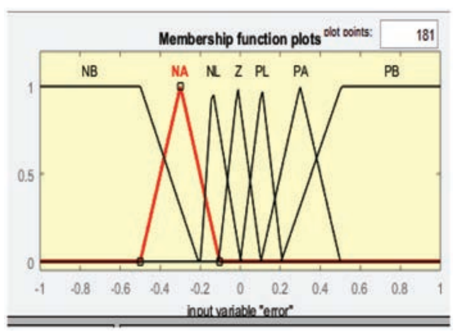

Figure 6 Error input.

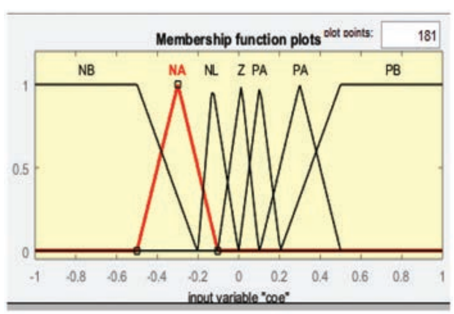

Figure 7 Change in error input.

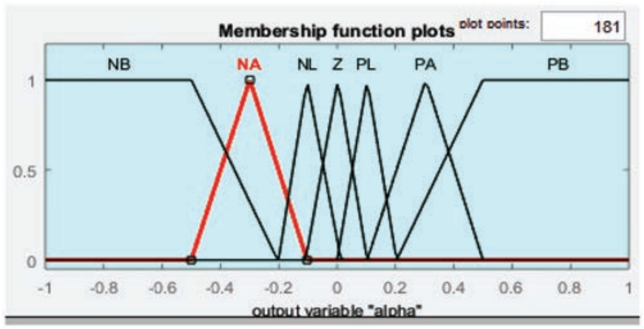

Figure 8 Fuzzy output variable.

Table 1 Rule based fuzzy information table [5]

E/ΔE	**NB**	**NA**	**NL**	**Z**	**PL**	**PA**	**PB**
NB	PB	PB	PB	PB	NA	Z	PB
NA	PB	PB	PA	PB	PL	Z	Z
NL	PB	PA	PL	PL	PL	Z	Z
Z	PB	PA	PL	Z	NL	NA	NB
PL	Z	Z	NA	NL	NL	NA	NB
PA	Z	Z	NL	NA	NB	NB	NB
PB	Z	Z	NA	NB	NB	NB	NB

3.2 Battery Charge Controller

The battery storage system is integrated with DC bus through the bi-directional converter [10, 11] to provide energy back-up. The controller of DC-DC bidirectional converter is shown in Figure 9.

The bi-directional controllers are implemented with PI (Proportional and Integral) controller. The PI controller is included in two sections, one is to regulate the measured DC voltage (V_{DC_meas}) with reference DC (V_{DC})

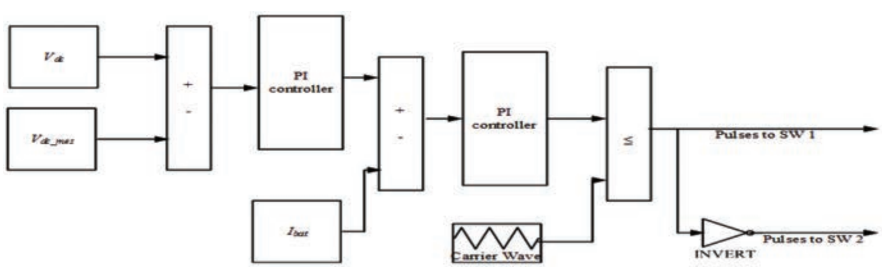

Figure 9 Bi-directional controller.

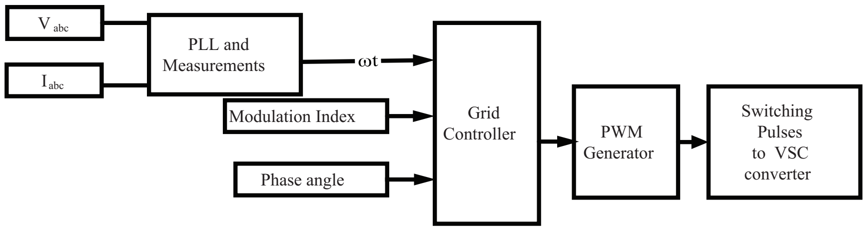

Figure 10 Power conditioning unit [11].

voltage and generates switching pulses to converter for maintaining the constant DC link voltage. The other one is to maintain the battery state of the charge based on the battery charging current (I_{bat}). The switching pulses (sw1, sw2) to the bi-directional converter are operated based on the state of the charge.

3.3 Control Technique for synchronization of Voltage Source Converter

The voltage source converter output voltage and frequency is synchronized with the grid voltage and frequency respectively, using a grid power conditioning unit as shown in the Figure 10. The grid voltage (V_{abc}) and frequency are traced with the help of Phase Locked Loop (PLL) system. The PLL system is preferred in the synchronization process and scales the signal based on the grid voltage (V_{abc}), grid currents (I_{abc}) respectively. The grid controller generates the reference signal to pulse width modulation generator by regulating the angular frequency (ωt), modulation index and phase angle.

The synchronization switching pulses are regulated with the help of modulation index and phase shift using Sinusoidal Pulse Width Modulation (SPWM) technique. SPWM is the most prominent method and it reduces the harmonics in the output of the voltage source converter. The harmonic effects on the sensitive load are prevented. It also maintains the rated voltage at the output of the voltage source converter.

4 Simulink Results

The integration of solar photovoltaic, battery and fuel cell with grid connection is simulated in MATLAB-Simulink under two dynamic conditions. The first case is a dynamic variation in the source and the second case is a dynamic variation in the load. The specification of the proposed hybrid system is shown in Table 2.

Table 2 Specifications of proposed system

S. No.	Name of the Parameter	Rating
1.	Solar parallel strings	02
2.	Solar series connected module per string	06
3.	Solar PV array open circuit voltage	36.3V
4.	Solar PV short circuit current	7.84A
5.	Maximum power point voltage (V_{mp})	29V
6.	Current at maximum power point (I_{mp})	7.35A
7.	Capacitor at solar PV	300µF
8.	Boost converter switching frequency	5kHz
9.	Boost inductor	2.5mH
10.	Boost capacitor	2000µF
11.	Inverter DC link voltage	750V
12.	AC load	5kW, 230V
13.	DC load resistor	64Ω
14.	Fuel cell	50kW

In the first case, the solar irradiance fluctuate from 600 kW/m^2 to 1000 kW/m^2 and the temperature variation are varied from 25°C to 40°C vice-versa as shown in Figure 11. The solar irradiance and temperature are considered as dynamic at 600 kW/m^2 during time interval 0sec to 0.016 sec when connected to the boost converter, battery and fuel cells. At t = 0.016 sec,

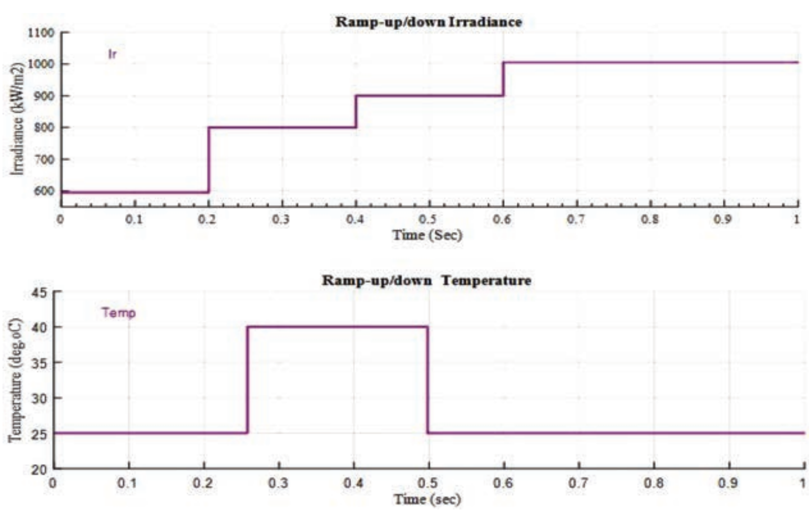

Figure 11 Solar irradiances and temperature.

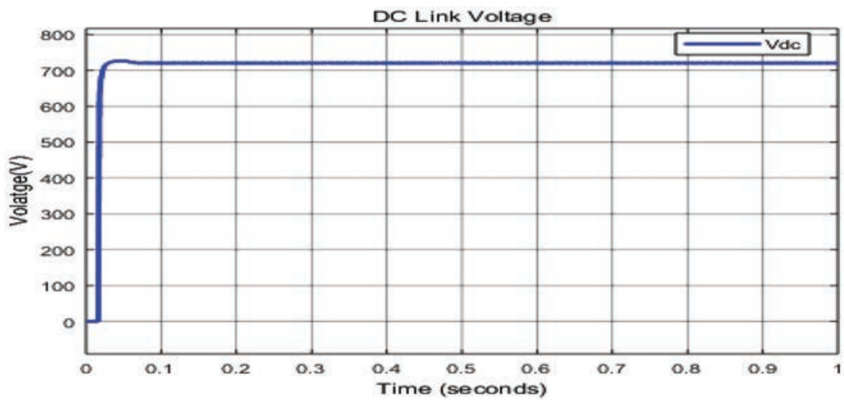

Figure 12 DC link voltage.

the integration of solar, battery and fuel cell are maintaining constant voltage of DC link at 750 V as shown in the Figure 12.

The irradiance varies from 600 kW/m^2 to 1000 kW/m^2 during the interval 0.2 sec to 0.6 sec and the temperature varies from 25°C to 40°C during the interval 0.25 sec to 0.5 sec. In this duration, the solar power is fluctuating but the constant DC link voltage is maintained with the support of battery and fuel cell as shown in the Figure 12. At 0.1 sec the voltage source inverter is integrated with the grid and the voltage source converter switching pulses are generated at 3 kHz switching frequency. The synchronized grid voltage and reference phase shift are shown in Figure 13. The integrated hybrid system

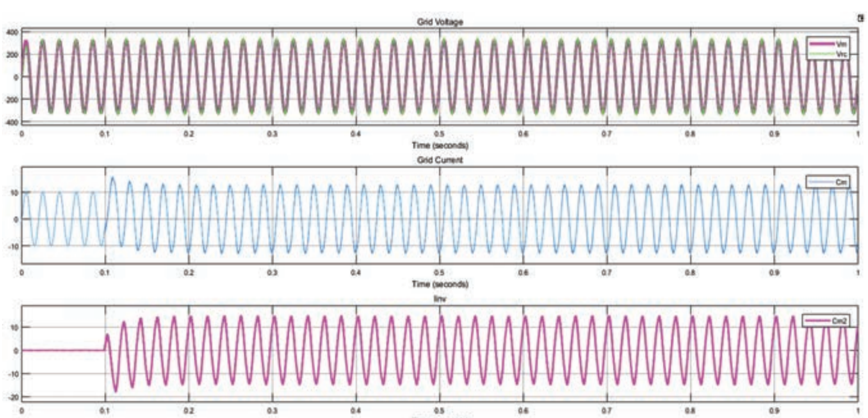

Figure 13 Grid voltages, VSC voltage, grid current and inverter current under dynamic variation in solar source.

starts sharing the power to loads at 0.1 sec. The grid and inverter are connected to the two parallel connected 2.2 kW, 10 A AC loads and the loads are operated continuously. The loads are protected with the grid connected hybrid system when the temperature and irradiance are variable during the interval 0.2 sec to 0.6 sec. The loads draw the current continuously without any fluctuation when connected to the hybrid system as shown in the Figure 14. The load-1 is constant load and the load-2 is variable and is switched on at time of 0.16 sec. After switching ON, the loads draw continuously a constant current of 10 A each.

In the second case, the dynamic variation in the solar photovoltaic and load will not effect on the grid synchronized voltage which is represented in Figure 15. The inverter is synchronized at 0.1 sec by regulating the modulation index and phase shift of VSC. The DC link supports the grid through the inverter for continuous power flow. The load-1 is constant throughout as shown in the Figure 16 and load-2 is operated under dynamic condition.

The load-2 is connected during the time interval 0.06 sec to 0.02 sec, and during the time 0.49 sec to 0.6 sec. The load-2 is operating in two different intervals to observe the dynamics in the load as shown in the Figure 17. The grid voltages and single phase AC voltage are balanced during different loading conditions. The dynamic variations of load are sharing both the power supply which is shown in Figure 15. The dynamic variation in the sources and load are balanced by the proposed system due to the integration of solar photovoltaic system with fuel cell and battery storage system. The peak demand of load-1 and load-2 are supplied continuously.

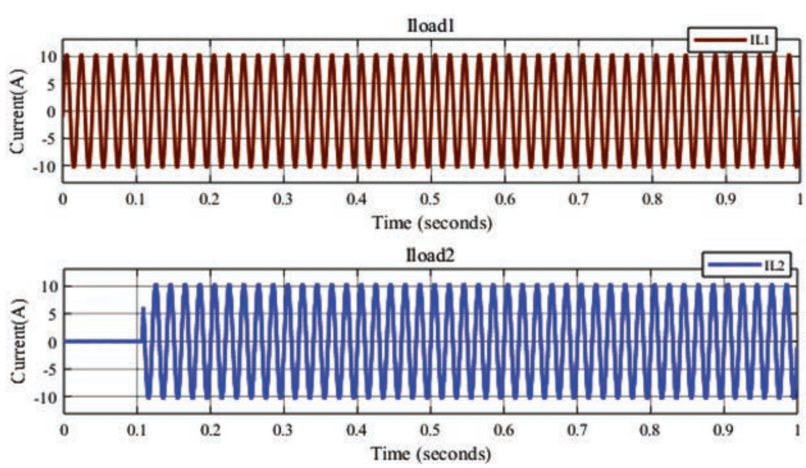

Figure 14 Load currents under dynamic source condition.

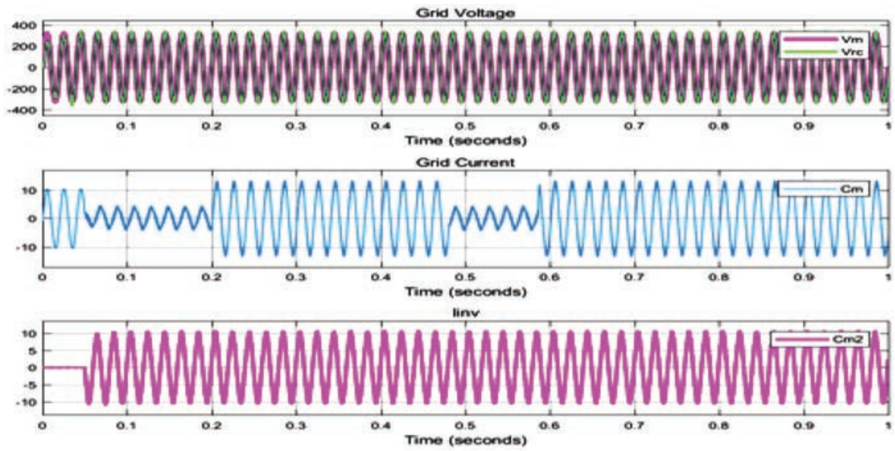

Figure 15 Grid synchronized voltages, grid current, and inverter current under dynamic load condition.

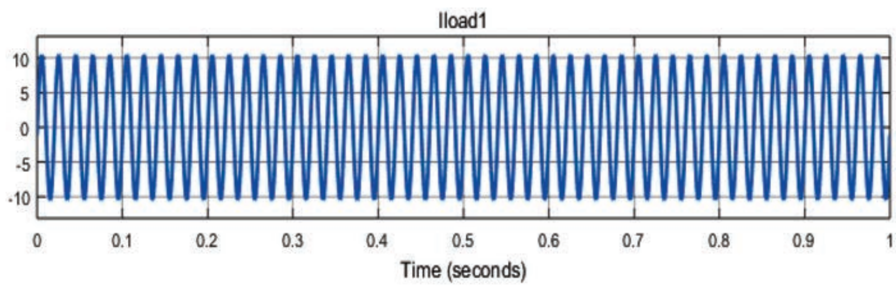

Figure 16 Load-1 current under dynamic load condition.

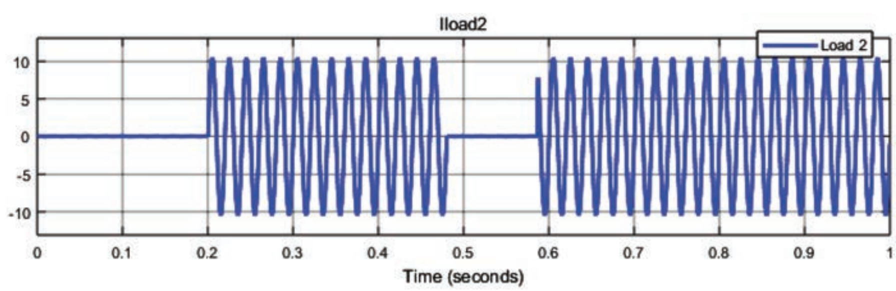

Figure 17 Load-2 current under dynamic load condition.

5 Conclusion

The integration of solar photovoltaic, battery storage and fuel cell with grid connected system performance is simulated satisfactory in two different cases. In the first case, the grid synchronization is achieved by regulating the modulation index and phase angle of the voltage source converter. The DC link voltage is maintained constant at 750 V using PI controller, even though the solar power affected by the intermittent nature. This can be achieved using fast response of PEMFC and battery storage system. The intermittent solar maximum power is extracted instantaneously using fuzzy controller. In the second case, performance of the grid synchronization voltage is stabilized even under the dynamic variations in load. The solar PV, batteries, fuel cell maintain the necessary grid voltage and continuously supplies the power without any fluctuation. The proposed system performance is stabilized even simultaneous variations are caused in the DC link voltage, grid and load.

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Biographies

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