Intelligent Controller based Solar Photovoltaic with Battery Storage, Fuel Cell Integration for Power Conditioning

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Abstract- Providing clean power and meeting the power demand is the biggest issues in the current power scenario. These issues can be alleviated with the integration of renewable energy sources (RES) such as solar, wind etc. The solar photovoltaic source (SPV) became more prominent in the utility system. The SPV stochastic nature can be overcome with the integration of sustainable sources in the utility system. The day availability and stochastic nature of solar photovoltaic can be used efficiently with the integration of DC link systems. In this work, the hybrid generation with DC link integration is divided into two parts. In the first part the DC link is integrated with the SPV, Fuel cell and battery storage system. These hybrid sources are used to maintain constant DC link voltage. The stochastic nature of the SPV source power is extracted using adaptive Neuro fuzzy information system (ANFIS) based maximum power point tracking technique (MPPT). The battery storage system is used through the bi-directional converter and it's operated based on the battery state of the charge. The battery state of the charge is monitored with the bi-directional controller. In the second part, the DC link integration is made with the utility grid and load through the single phase voltage source Inverter. The grid synchronization can achieve with the grid synchronization unit even under dynamics in the load and sources. The power conditioning of proposed system maintains the DC ink voltage and grid synchronization voltage through the DC link medium. This can be achieved with the use of hybrid sources by maintaining constant voltage at the DC link of voltage source inverter. The dynamic variation in the load and the utility grid connected hybrid system performance are simulated under different source conditions using MATLAB/Simulink software.

Keywords Battery storage system, DC-DC converter, Fuel cell; Maximum power point tracking (MPPT), Power conditioning; Solar photovoltaic (PV), Voltage Source Converter.

1. Introduction

The necessity of power has been increasing due to fast development in technology, population growth, as well as development in industries. Providing clean power and met the load demand are the big issues in the current scenario [1]. Still India is suffering a shortage of 929MW to meet the peak demand. This can be alleviated with the invention of renewable sources such as solar, wind and tidal, etc. These renewable sources are intermittent nature and its drawback can be overcome with the integration of two or more sources in the utility system. The integration of these sources is providing flexible power and satisfies the necessary peak demand for longer time. The integration of two or more energy source is defined as hybrid generation. This hybrid generation imparts the major role in the distribution system to meet the load demand [2]. The solar, wind sources are playing important role in isolated and grid connected systems. Among this, the SPV integration is playing a vital role in the distribution system. The SPV became popular in the utility grid connected system among the other renewable sources. The intermittent solar power is extracted using different kind of MPPT technique [3, 4] such as perturb and observation, incremental conductance (INC) method, etc. The predictive mode control based MPPT is used to track the maximum power from solar PV and stability of the system

[5]. The conventional MPPT is tracking the maximum power from the SPV and these techniques are efficient but slow in convergence speed, continuously oscillating the power. These drawbacks are avoided using an intelligent controller for tracking the maximum power from the SPV.

The intelligent techniques are well monitored and it is used for solving in nonlinearity, nature of the time varying problem. The SPV modelling, solar irradiance and temperature are highly nonlinear and dynamic in nature. The fuzzy logic controllers (FLC), particle swarm optimization (PSO) based MPPT techniques are used for extracting the smoothening power [6-7]. These artificial techniques are used to extract the power based on the rules and the formulation of the problem dependent. These intelligent techniques are reducing the oscillation present in the MPP (maximum power point) under steady state. However none of these techniques are completely reduce the oscillation presence. Researchers are working for getting the smoothening power efficiently. The adaptive Neuro-fuzzy information system (ANFIS) based MPPT technique also used to track the maximum power form SPV. The ANFIS intelligent controller is simple to develop the model and tracking the maximum power from the SPV based on the training the data. The tracking efficiency also improves. The oscillation presence is greatly reduced [8-9]. In this paper, the ANFIS based MPPT is used to track the smoothening power from the SPV using boost converter.

The day availability and intermittent nature of SPV can be utilized efficiently with the integration of the DC link system through the boost converter. But the PV power is not providing a continuous power supply due to its intermittent nature. The inconsistent solar power leads to affect the sensitive load as well as impact on the grid when it is integrated with the grid. The dynamic variation of solar power is utilized efficiently using battery storage system. The effect of the inherent nature of SPV is avoided using battery storage system. The effective utilization made with battery storage system.

The authors have addressed the voltage sag and swell with the integration of SPV with battery storage system [10-11]. The Table.1 shows research objective and major contribution of the proposed work. The SPV with battery is considered for micro grid and isolated mode for single phase distribution system [12-14]. The author has addressed for voltage improvement, active power control strategy and robust controller for micro grid system. The experimental study made for the simulation of SPV with battery storage system [15]. The power balance between the generation and load are considered for SPV, wind with battery storage but wind is again intermittent in nature [16-18]. The SPV with battery storage coordinate the load for addressing the voltage and power. But the dynamic variation in the source and load is not taken into account. It may fail to supply continuously due to day availability and with limited battery state of the charge.

This can be avoided using the secondary source and it should provide clean power without harming the environment. In this work, Fuel cell consider as a secondary source for providing continues power to load. The proton exchange membrane fuel cell (PEMFC) is used and integrated with the DC link through the DC-DC converter. The PEMFC is used due to its high efficiency, immediate response, quick start-up time, more life time and less operating temperatures compare to other fuel cell such as alkaline fuel cell, phosphoric acid fuel cell; solid oxide fuel cell, molten carbonate fuel cell; direct methanol fuel cell [19-20]. The proposed SPV with battery storage, Fuel cell integration addresses the DC link voltage, grid voltage and dynamic condition of the source and load for single phase distribution system. It stabilizes the DC link voltage and grid voltage under stochastic nature of the SPV system. Grid synchronization can be achieved with the help of power conditioning unit under dynamic condition of the load.

Table 1 Survey on integration of hybrid system

Si.No.	Objective	Research gap
1.	Coordinating the SPV with Battery for addressing the voltage sag and swell.	Considered a load profile but actual dynamic source and load variations are not taken [10].
2.	Active power conditioning and voltage regulation of Single phase distribution generation system.	Transient performance of single phase output voltage and they didn't highlight the DC link voltage and load dynamics [12].
3.	Coordination control of hybrid on grid and off grid using automatic centralized micro grid controller.	Different voltage level of DC grid only and the grid performance has been presented with low voltage micro grid network [13].
4.	Role of robust controller has been proposed and compared with the PI controller in micro grid modelling.	Presented with the grid side voltage performance and didn't consider for dynamic source and load conditions [14].
5.	The uncertainty with SPV and the battery storage is invistigated.	SPV with storage is investigated and didn't consider for the grid synchronization [15].
6.	Power control of SPV-Wind-Battery	Explained the power flow control of hybrid system but didn't focus on grid synchronization and for maintaining the DC link voltage [16]

In this paper, the grid integration of SPV, Battery storage and fuel cell is presented under dynamic condition of source and load. The first section deals with the modules of the proposed system in detail, operation and its layout. The next section is discusses on control strategy used. The final section deals with the MATLAB-Simulink results of the proposed hybrid system.

2. Modules of Proposed Hybrid Systems

The proposed hybrid generation integration with utility grid is shown in Fig.1. The main module of the hybrid system contains SPV with boost converter, fuel cell, DC-DC converter, DC-AC voltage source converter, and battery storage system with bi-directional converter, AC loads and the utility grid. The utility grid is fed to the load through the voltage source inverter at the point of common coupling. These two are connected with DC link through the voltage source converter.

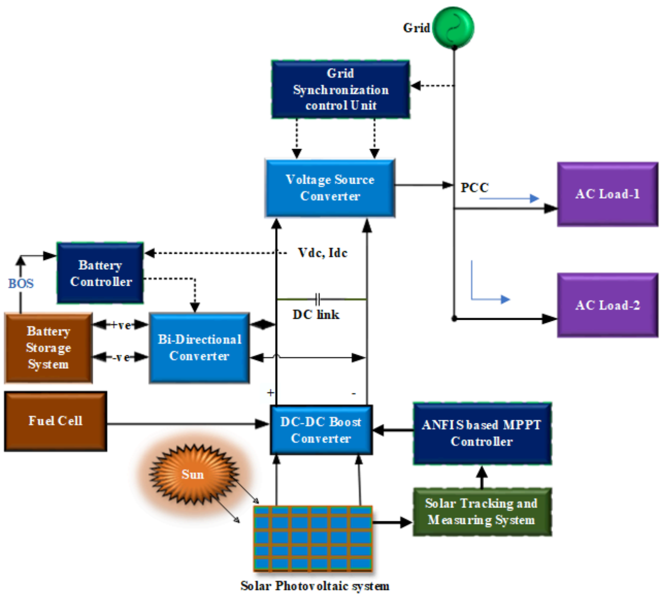

Fig.1. Proposed hybrid system

The DC link is interfaced with various sources through the DC-DC converter such as solar photovoltaic, fuel cell and battery storage system. Stabilized and the power transfer capability is increased in the distribution line. During the intermittent nature of the SPV, the battery storage system and fuel cell stabilize the power. The Fuel cell can supply during the peak demand and it will stabilize the DC link voltage. When the peak power is demanded in the day time, the SPV with fuel cell and battery storage supports the DC link and maintain required voltage. The function of each module is described in the following section in detail.

2.1. Solar Photovoltaic(SPV) with DC-DC converter

The SPV converts solar power into electrical power at room temperature, standard irradiance and its working on the principle of the photoelectric effect. The SPV is integrated with the DC link system using a boost converter for obtaining continues supply at the DC link as shown in the Fig.2. The boost converter switching action is analysed with the rating of DC link using adaptive Neuro fuzzy information system (ANFIS) based MPPT. The switching pulse of the DC-DC boost converter is analysed with the FLC based MPPT.

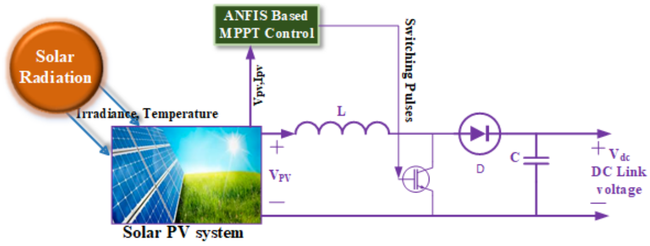

Fig. 2. SPV with Boost Converter.

The solar PV array model based on the using Eq.1 and Eq.2 [21]

$$V_{pv} = \frac{n*K*T}{q*\ln(\frac{i_{sc}}{i_{pv}}+1)} \tag{1}$$

$$i_{pv} = i_{pv} - i_{pvo}*[\exp(\frac{q*(V_{pv}+i_{pv}*R_s)}{N_s*K*T_n}-1] - \frac{(V_{pv}+i_{SC}*R_s)}{R_s} \tag{2}$$

Where , V_{pv} , i_{pv}, – PV voltage (V) and current (A), i_{sc} – Short circuit current (A), K- Boltzmann constant, ipvo-diode saturation current (A), T- cell reference temperature, n- is ideality factor of diode, Ns- number of series cell, q- Electronic charge (coulombs), P- Power calculated from solar PV (Watt), R_s, R_{sh}-series and shunt resistance (Ω). SPV voltage is step-up the at the DC link voltage level using DC-DC boost converter and the SPV power is tracked through the ANFIS based MPPT controller.

2.2. Proton Exchange Membrane Fuel Cell (PEMFC)

PEMFC is filled with the hydrogen and air (oxygen) as shown in the Fig.3. PEMFC is an electrochemical stack, which converts chemical power into electrical power with the by-products of water. Mainly PEMFC consist of three parts such as fuel, oxidant electrode and an electrolyte squeezing between them.

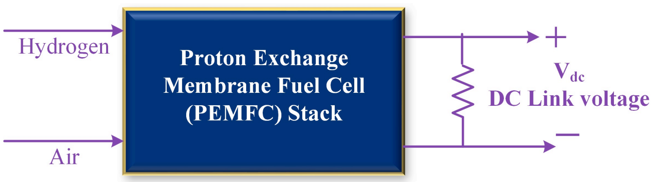

Fig. 3. Layout of PEMFC

The PEMFC can be modelled using the Eq.3 and Eq.4 [22].

$$E_{nerst} = 1.129 - 0.85*0.001*(T_{cell} - 298.15) + 4.3085*10^{-5}*T*\ln(P_{H_2}*\sqrt{P_{O_2}}) \tag{3}$$

$$V_{cell} = E_{cell} - \eta_{act} - \eta_{ohm} - \eta_{mt} \tag{4}$$

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.

2.3. Battery storage System

The battery storage is a backup power supply. It stores the charge during the excessive power generated form the source and can supply back through the bi-directional converter during the load demand. The layout of battery storage and controller is shown in Fig.4. The battery storage is integrated with the DC link through the bi-directional converter for stabilizing the DC link voltages at 720V. The bi-directional controller maintains the DC link voltage based on the state of the charge. The switching pulses of the bi-directional converter operate through the bi-directional controller. The battery state of the charge in the range of 30% to 80% is considered to perform the battery state of the charge.

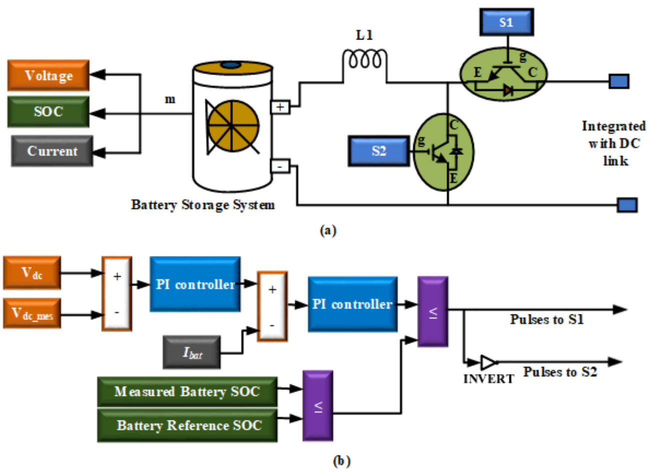

Fig.4. Battery storage systems (a) Battery with bi-directional converter, (b) Bi-directional controller

Proportional Integral (P and I) controllers are added for regulating the voltage at DC link by computing the measured DC voltage ($V_{dcmeans}$) with the reference DC voltage (V_{dc}). Similarly, it will regulate the battery charging current and battery state of the charge. It generates the switching pulses to bi-directional converter based on the reference battery state of the charge (SoC).

3. Single Phase Voltage Source Converter (VSC)

The single phase voltage source converter is placed in between the DC link and point of common coupling (PCC). It converts DC link power into AC power. It will support the load as well as grid during the load demand as shown in the Fig.5. The switching pulses of the VSC and its performance depending on the grid synchronization unit.

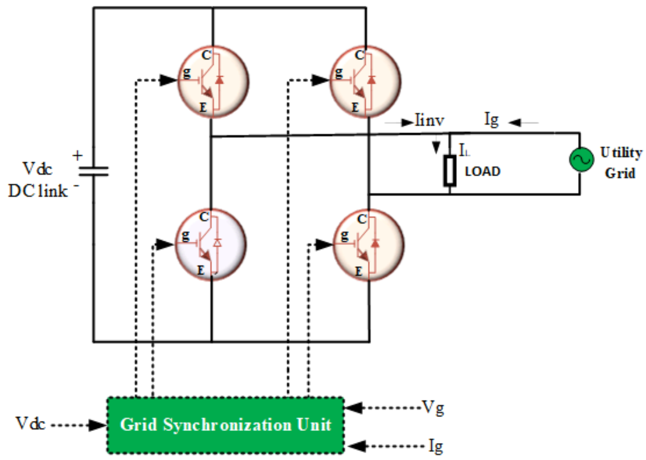

Fig.5. Grid Connected VSC

The VSC voltage and the grid voltages are synchronized through the synchronization process by regulating the modulation index and phase angle of the VSC voltage. The synchronization units perform based on the DC link voltage (V_{dc}) and grid voltage (V_g). The DC link voltage of the VSC is maintained with the SPV, fuel cell and battery storage system.

4. Control Strategies

The main control strategy of solar photovoltaic system and the grid synchronization unit are described in the following section in detail. The first section deals with the solar power extraction using ANFIS based maximum power point tracking technique. The next section is about the grid synchronization unit of the proposed hybrid system.

4.1. ANFIS controller based MPPT

The SPV power is extracted using ANFIS based MPPT. The ANFIS controller is employed to solve the complex problem where the conventional algorithm fails to attain decision making for the desired response. The ANFIS controller is utilized for obtaining the flexible output with the smooth decision which is adapted for a range of control system applications. The ANFIS based MPPT is employed for generating the switching pulses to boost converter to step up the SPV voltage. For the best response, the ANFIS targeted output power is obtained based on the training of the input variable such as solar irradiance and temperature.

The training data, neural network (NN) structure, neuro-fuzzy designer, fuzzy information system (FIS) and the process of switching pulse generation is shown in the Fig.6. Based on the target output ANFIS based MPPT gives the better response. Minimal checking root mean square error is 0.44855.The surface view of fuzzy information system is shown in the Fig.7. The boost converter duty cycle is regulated using ANFIS controller for obtaining the maximum power from the SPV.

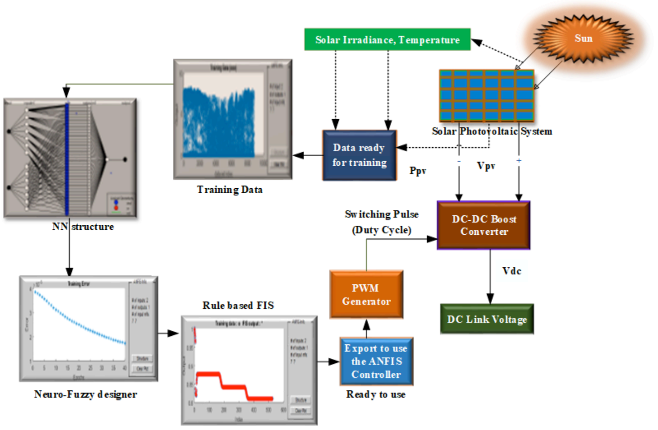

Fig. 6. ANFIS controller based MPPT

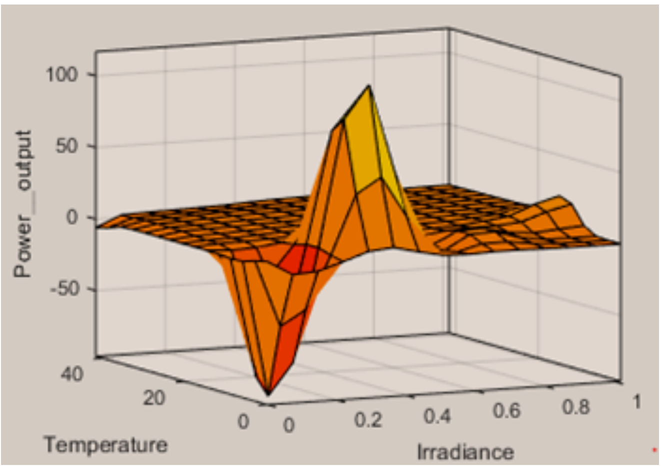

Fig. 7. Surface view of fuzzy logic controller

The input and output variable of the fuzzy rule is segmented into seven logistic variables. These variables are Positive Small (PS), Positive Medium (PM), Positive High (PH), Zero (Z), Negative Small (NS), Negative Medium (NM), Negative High. The targeted output is regulated and weights are updated automatically using ANFIS controller. The output of the boost converter is synchronized with the DC bus voltage based on the possible variations in the duty cycle. This control switching function helps in achieving DC link voltage.

4.2. Grid Control Unit of Hybrid system

The control unit of the hybrid system is shown in Fig.8. The grid control unit contains a phase locked loop (PLL) and measurement unit, voltage reference pulse width modulation (PWM) generator.

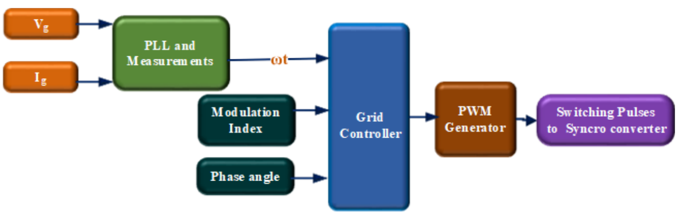

Fig.8 Control Unit of hybrid system

The PCC voltage, currents are monitored through the voltage sensor, current sensor respectively. The measured voltage (V_g) and currents (I_g) are regulated by the reference quantity with the help of PLL measurement. The PLL is used to calculate the magnitude and phase separately without taking input and it will help in the synchronization process. The synchronization of DC link based hybrid generation with the grid voltage is achieved through the single phase two level voltage source converter. The single phase voltage and phase angle are analysed trough the phase locked loop (PLL) and grid monitoring parameter. The synchronization can be achieved using Eq.5.

$$V_{ref} = x * \sin(\omega * t + \phi * \pi / 180) \tag{5}$$

Where, x-modulation index, ω-angular displacement, is the phase shift of the reference voltage. Where, V_g is the reference generator to generate the switching pulses for the voltage source converter connected to PCC through the pulse width modulation generator. These switching pulses regulate the voltage source converter output and are synchronized with the grid voltage. The control unit stabilizes the load voltage through the proportional and integral (PI) controller. The unit of voltage source converter performance is studied in the following section using MATLAB/Simulink software.

5. Simulink Results

The hybrid generation of SPV source is the primary source for supplying the power during the day. The dynamic variations in the solar irradiance, temperature is considered for the simulation of SPV system. The SPV with boost converter specification is mentioned in the Tab.2. The dynamic of solar irradiance varies from 1000W/m^2 to 250W/m^2 at t=0.05sec and then at t=0.2sec irradiance varies 250W/m^2 to 1000W/m^2 as shown in the Fig.9.

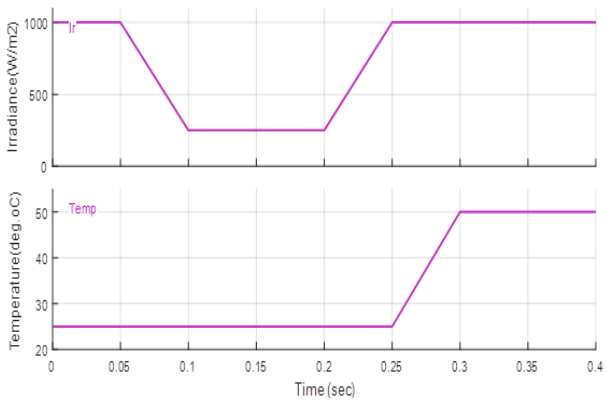

Fig.9. Dynamic Irradiance and Temperature

The temperature also varied from 25°c to 50°c at t=0.25sec. Due to dynamic variation in the temperature and irradiance, the SPV power is becoming intermittent. The SPV voltage becomes intermittent due to change in irradiance and temperature. The SPV power is stabilized with integration of battery, fuel cell. This hybrid generation maintains the constant voltage at the DC link, which is represented in the Fig.10.

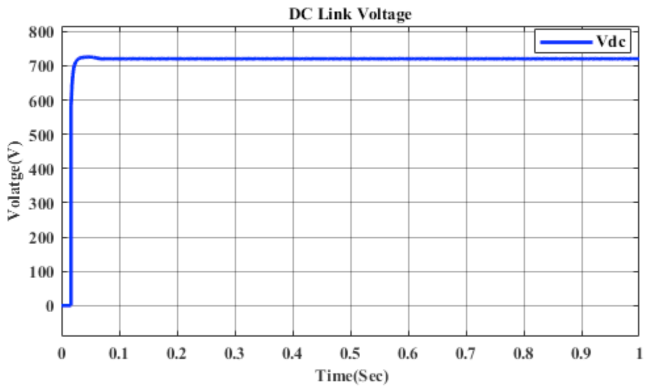

Fig. 10 DC link voltage of proposed system

Table 2 Solar PV array with boost converter Specification

Si.No.	Name of the Parameter	Rating
1.	Solar Parallel strings	02
2.	Solar Series connected module per string	08
3.	Solar PV Array Open Circuit Voltage	37.3V
4.	Solar PV current at Short circuit	8.66A
5.	Voltage at MPP	30.7V
6.	Current at MPP	8.15A
7.	Capacitor at solar PV	212.33µF
8.	Boost converter switching frequency	5kHz
9.	Boost Inductor	2mH
10.	Boost Capacitor	35.211µF
11.	Inverter DC link Voltage	720V
12.	AC Load	5kW, 230V
13.	DC Load Resistor	78Ω

The voltage at the DC link maintained constant even under dynamic variations in the integrated sources. The battery and fuel cell are designed with the rating of a DC link voltage. The hybrid generation based DC link is integrated with the grid through the point of common coupling (PCC) using the DC to AC converter. The inverter output voltage and grid voltage is synchronized with the help of grid synchronization unit as shown in the Fig.11. The dynamics in the load created during the interval t=0.82s to 0.86s and is shown in Fig.12. The hybrid system balances the base load and provides the continuous supply to the load. The constant base load current is represented in the (Iload-1 current waveform) in the Fig.12. The corresponding secondary load current is also shown (Iload-2 current waveform) and the dynamic load interval created between at 0.82s to 0.86s.

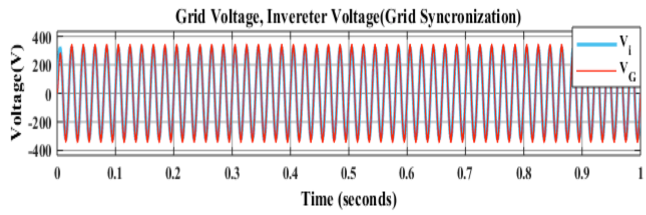

Fig. 11. Grid and Inverter voltages (Grid synchronization)

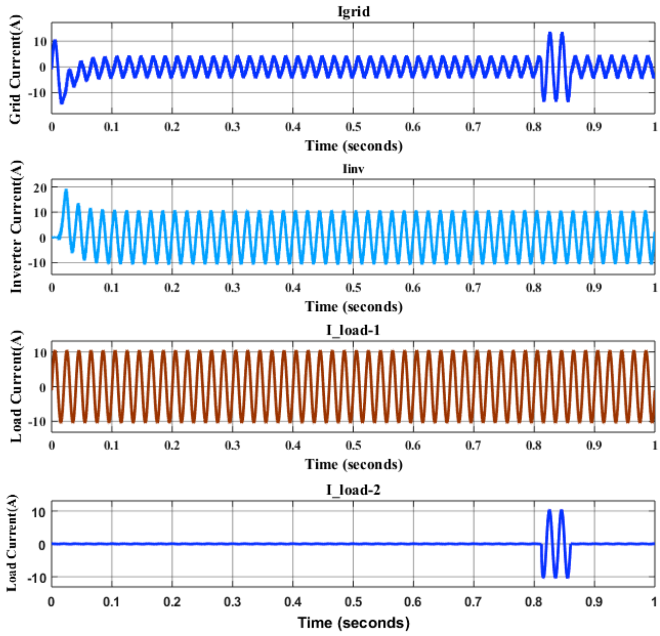

Fig.12. Grid and Inverter current, Load current

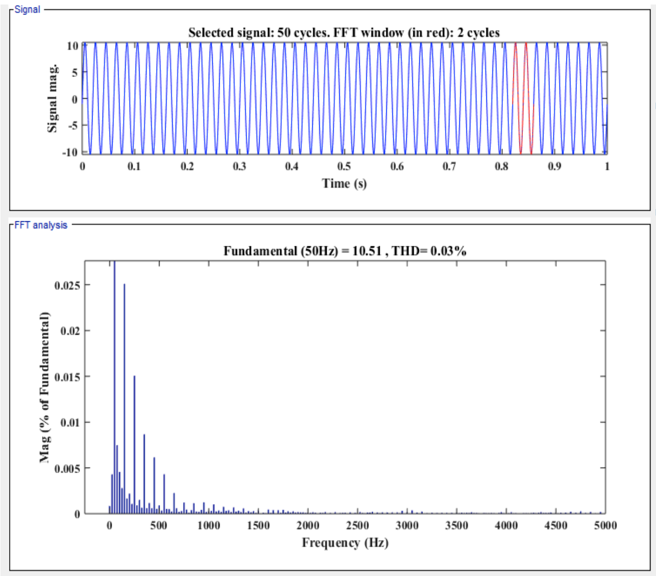

Fig.13. THD of load current-1

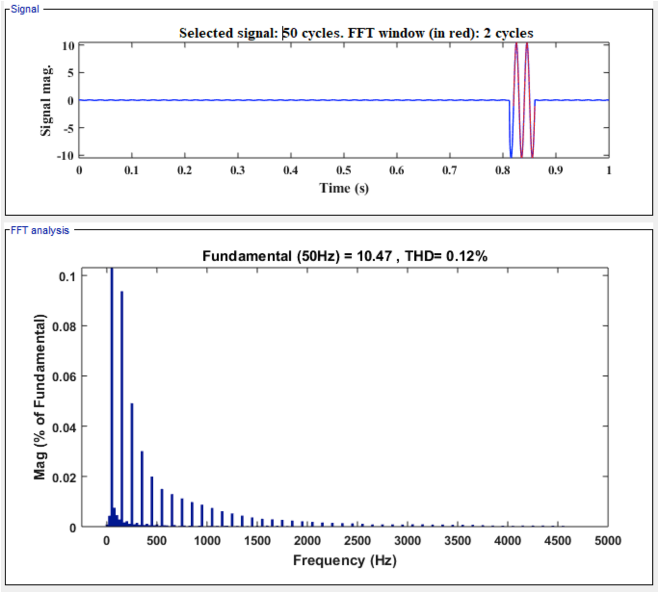

Fig. 14. THD of load current-2

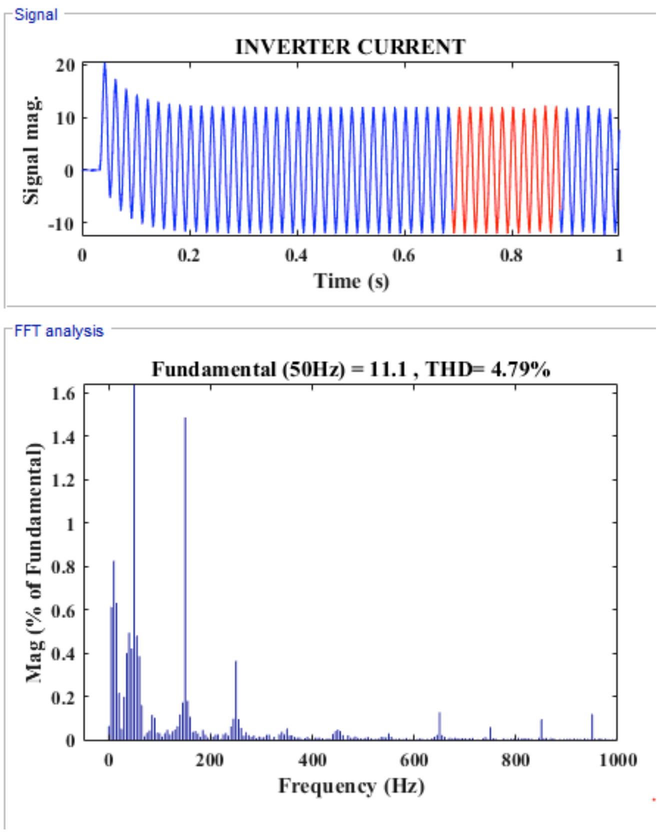

Fig.15. THD of Inverter current

The voltage is maintained constant during in this interval even as the source and load varies. Fig.13 and Fig.14 shows the THD of the load current during the dynamic interval. Fig.15 shows the THD of inverter current is obtain 4.79%. The total harmonic distortion (THD) maintain within the limit as per IEEE-519 standard. The proposed system provides continuous power during the whole intervals. The load current-1 shows the continuous flow of load current even under interruption of solar source and load-2 interruption occurs in two different intervals. Even the load varies between the intervals of 0.82s to 0.86s, the base load maintains stable power.

6. Conclusion

The proposed hybrid system is simulated and results are obtained under dynamic source and load condition. The solar smoothening power is obtain using ANFIS controller based MPPT method under dynamic variations of irradiance and temperature. The battery storage system is regulated and maintains continuous support for the DC link voltage with the help of bi-directional controller through a bi-directional DC-DC converter. The limited state of the battery storage is avoided with the use of sustainable source as a fuel cell. The integration of the SPV, battery storage system and fuel cell maintains a constant voltage at DC link. The proposed hybrid system stabilizes the load. The sensitive load is protected with fuel cell by maintaining the balanced voltages at the DC link. The DC links, grid are balanced and the sensitive loads are protected simultaneously. The continuous and balanced power can be achieved with the integration of the proposed hybrid system.

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