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Integration of Utility Grid with Hybrid Generation for Power Quality Conditioning Using Dynamic Voltage Restorer

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Abstract- The intermittent nature of renewable energy sources is influencing the system parameters while being integrated with the power system. The switching of the load also influences the system and may causes the power quality issues such as voltage sag, swell, voltage interruption and voltage spikes. Getting the smoothening power and meeting the peak demand is the greatest challenge in the current scenario. The necessary and sufficient power is provided with the use of integration of renewable sources and power conditioning unit. In this work, the grid integration of solar photovoltaic, fuel cell with heavy duty gas turbine generator is made. The voltage interruption is avoided using hybrid generation with dynamic voltage restorer. The solar photovoltaic is integrated with DC link through the boost converter and the maximum power is extracted using fuzzy based maximum power point tracking technique. The fuel cell and the heavy-duty gas turbine are integrated with DC link for providing continues power and this integration can avoid the effect of intermittent nature of solar power. The DC link power is integrated with the grid through the voltage source converter. The voltage source converter and the dynamic voltage restorer are operated through a power conditioning unit. The performances of the hybrid generation with dynamic voltage restorer are simulated under dynamic source and load variations. The total harmonic distortion of the hybrid generation with dynamic voltage restorer performance is maintained within the limit as per IEEE-519 standard.

Keywords Dynamic Voltage Restorer (DVR), Fuel cell, Fuzzy logic controller, Heavy duty gas turbine generator, Solar photovoltaic (SPV), Voltage Source Converter.

1. Introduction

The effective utilization of the intermittent nature of renewable energy sources is a key role in the present power system and it became a biggest challenge in the current prime research**.** The stochastic nature of renewable energy sources is influencing the system parameters and diminishes the sensitive load. The effective utilization of renewable energy source can be achieved using the integration of solar, wind, tidal etc. [1, 2]. The integration of solar photovoltaic (SPV) with the distribution system is more flexible among the other renewable energy sources. The different kind of MPPT (Maximum Power Point Tracking) technique [3-5] is used for extracting the maximum power from SPV systems such as perturb and observation, incremental conductance (INC) method etc. The extracted solar power is influencing the sensitive load due to dependency of solar dynamic irradiance and temperature. This issue is avoided with integration of solar and wind.

The integration of solar, wind energy sources are used for effective utilization of renewable sources and it is defined as a hybrid system. But the solar, wind integrations of two sources are dependable nature and may fail to supply the power continuous for the whole day. This can be achieved with the storage system and its response is very quick [6-9]. The storage for high power requires large size and space required is more. The storage system is used for limitedly based on the availability of power and state of the charge. It may not support for longer time.

The one way of providing continues power supply without storage system is the integration of the SPV, Fuel cell and heavy-duty gas turbine-based generator. The integration of these three sources with a grid playing vital role in meeting the peak demand and providing continues power supply. The fuel cell is supported as a secondary source and the base power supply are used for heavy-duty gas turbine based generation. The heavy-duty gas turbine is response is very quick under dynamic condition of the load.

The heavy duty gas turbine generator is free from greenhouse gases. The integration of these sources is providing flexible power for meeting the necessary peak demand for longer time**.** The hybrid generation is integrated with the grid through the power converter and it is providing continues power supply to the load.

The integration of SPV sources are influencing the system voltage due to dynamic in nature and the switching of load may lead to cause the power quality problem such as voltage spikes, sag, and swell [10]. The voltage related problems may overcome with the customer power devices. The sensitive loads are protected by the customer power devices and these are used in the distribution system such as dynamic voltage restorer (DVR), distribution static compensator (DSTATCOM), and unified power quality conditioner (UPQC). The DVR is most favourable among the customer power device and cost-effective solution to solve voltage related issues. A DVR is a voltage restoring device which is integrated in series with the line through the series connected transformer. The dynamic voltage restorer topology categorized two types based on the integration and location. The first integration is source side connected DVR and the second one is load side connected DVR as shown in the Fig.1. The based on the input of the DVR at the DC link support is categorized as storage system, self-supported charging capacitor and without storage DVR.

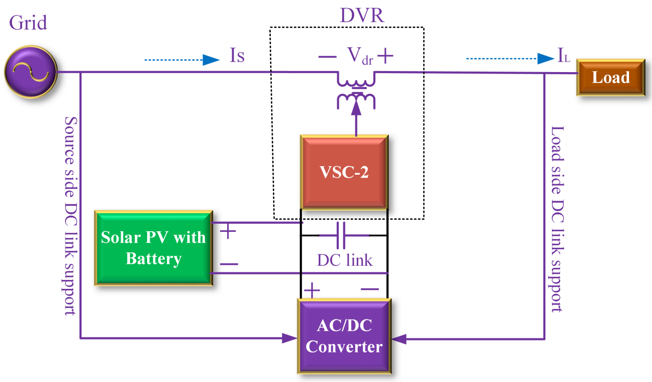

Fig. 1. Dynamic Voltage Restorer Layout

In the Self charging DVR is protecting the sensitive load within the short period of time and its contribution is based on the source intensity. The author in [11, 12] has been explained the self-supported DVR with a novel synchronous reference theory control algorithm using a reference with positive sequence voltage of two unbalanced voltages. In the steady state, the need of active power is not required in capacitor-based DVR due to injected voltage in orthogonal with line current. This configuration is the most cost effective, but it depends on the source side or load side integrated power supply. The self-supported is DVR will not support long time for higher rating of loads and it required a large size capacitor. This can be avoided by maintaining the separate source or storage. The DC power supply or external batteries supported DVR is inject the unbalanced voltage efficiently, but the cost is high.

To protect sensitive load, DVR requires the necessary DC link power, and this can be provided through the voltage source converter instead of using separate supply. The voltage source converter-based source and load side connected DVR and the DC link of DVR again depends on the line supply voltage [13-16]. It may not reliably for compensating the line voltage. In abnormal conditions DVR may not protect the sensitive load. The line interference in the DC link can be avoided using the renewable energy integration with an energy storage system [17-18]. The solar power with battery is employed only for providing necessary DC link power only, but it will not provide the continuous power to the load. The advantages compare to conventional DVR and it can provide power supply during the daytime, but the intermittent nature of solar power can't provide quality power. It works in the day time only. The continuous peak power and sensitive load protection can be achieved by the proposed hybrid system.

In the utility system, the major issue is continuous load interruption and unavailability of necessary power. The load interruption and switching on the instant load continuously leads to create the low voltage issues. The necessary power supply and low voltage issue together can be overcome by the invention of hybrid generation with dynamic voltage restorer. The continuous peak power and sensitive load protection can be achieved by the proposed hybrid system. In this work, the utility grid integrated hybrid generation with DVR is integrated with DC link system. The DC link system is common bus for the hybrid generation and DVR. The hybrid generation excessive power is integrated with the utility grid and DVR is protecting the sensitive load based on the DC link power available.

In this paper, the proposed hybrid system maintains constant DC link voltage and it stabilizes the load under dynamic condition of solar power. The next section deals with modules of the hybrid generation with dynamic voltage restore and its layout. The third section dealing with control strategy of the proposed system and the final section deals with the MATLAB-SIMULINK results of proposed hybrid system.

2. Proposed Hybrid System

The proposed hybrid generation with dynamic voltage restorer is shown in Fig.2. The module of the proposed hybrid system contains SPV with boost converter, Fuel cell, DC-DC Converter, Heavy duty gas turbine-based generator, DC/AC voltage source converter, AC loads. The utility grid is fed to the load through the DVR and point of common coupling (PCC). The DC link is interfaced with various sources through the DC-DC converter such as SPV, Fuel cell and the heavy-duty gas turbine-based generator. The SPV and fuel cell are integrated through the boost converter. The heavy-duty gas turbine (HVDGT) generators are integrated through the uncontrolled rectifier. The load is connected through the DVR.

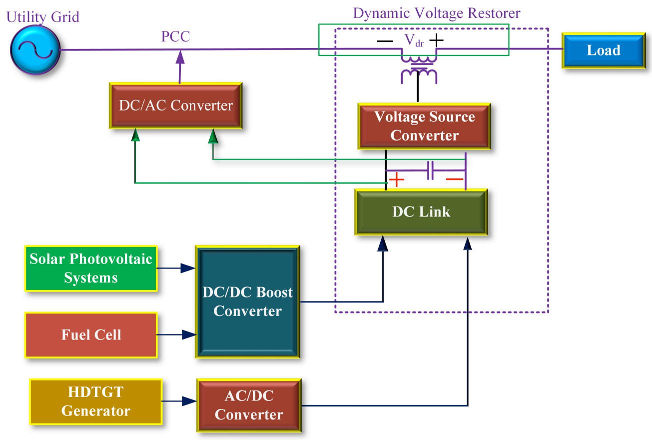

Fig. 2. Dynamic Voltage Restorers with Hybrid System

The voltage at DC link is stabilized with the hybrid system and the loads are protected with DVR. The power transfer capability is increased in the distribution line. During the intermittent nature of the SPV, the fuel cell is stabilizing the power. The heavy-duty gas turbine power generation will support the base load and peak demand. It will stabilize the DC link voltage. When the peak power demanded in the day time, the integration of the SPV system with fuel cell and HVDGT generator can support and the DC link maintains constant. The proposed system each module function is described in the following section in detail.

2.1. Solar photovoltaic with DC-DC

The SPV system is playing an important role in providing green power and it is abundant. According to the principles of the photoelectric effect, SPV system converts solar power into electrical power. The SPV is integrated with the DC link through the boost converter as shown in the Fig.3. The maximum power from the solar power is extracted using a fuzzy logic controller (FLC) based MPPT technique. The switching pulse of the DC-DC boost converter is analysed with the FLC based MPPT.

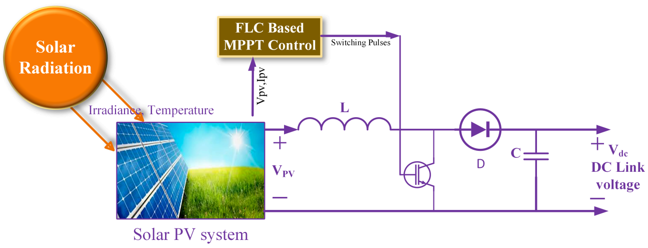

Fig. 3. Solar photovoltaic with Boost Converter [19]

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

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

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

Where, V_{pv}, ipv, – PV voltage (V) and current (A), isc – 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), Rs, Rsh-series and shunt resistance (Ω).

2.2. Proton Exchange Membrane Fuel Cell (PEMFC)

The PEMFC is having fast response, high efficiency and the lifetime is more. PEMFC stack is fed with the hydrogen and air (oxygen) and its layout is shown in the Fig.4.

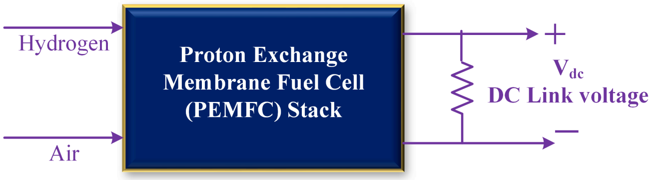

Fig. 4 Layout of PEMFC

PEMFC One of the most electrochemical devices, which turn chemical power expressing into an electrical power with the by-product of water. It contains three major parts such as fuel, oxidant electrode and an electrolyte squeezing between them. The PEMFC can be modelled using the Eq.3 and Eq.4 [20].

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

$$V_{cell} = E_{cell} - \eta_{act} - \eta_{ohm} - \eta_{mt} \quad (4)$$

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. The PEMFC fuel cell simplified model is integrated with the DC link for stabilizing the DC link voltage. The PEMFC fuel cell voltage synchronized with the DC link and it is consider as a secondary source for the proposed hybrid system.

2.3. Heavy Duty Gas Turbine (HVDGT) Generator with AC-DC Converter

The HVDGT with uncontrolled AC-DC converter is integrated with the DC link as shown in the Fig.5. The HVDGT generator is having two sections. One is the heavy-duty gas turbine modelling and the other section is regulating the AC to DC converter output. The immediate response of mechanical power is fed with synchronous generator. The heavy-duty gas turbine-based generator is used to stabilize the DC link with quick response. It will support the maximum demand and provides continuing supply [21].

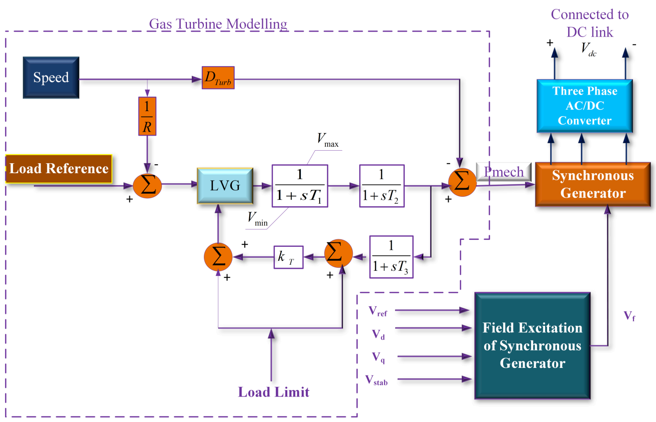

Fig. 5. Schematic diagram of Heavy-duty gas turbine based synchronous generator

In the Fig.5, LVG stands for the low value gate, V_{max} & V_{min} are the Maximum and minimum valve position, V_{ref} desired voltage of stator terminal, V_{stab} stabilized voltage of power system V_d, V_q are the terminal voltage. V_f is the field voltage of synchronous machine block. T_1 = 10 sec, T_2 = 0.1 sec and T_3 = 3 sec are time constant of valve, fuel system and combustor delay, K_t =1 and K_r = 0.04 are the gain of the turbine and fuel system respectively, D_{turb} = 0.03 is turbine constant Pmech is the turbine output power [22].

2.4. Three Phase Dynamic Voltage Restorer (DVR)

The DVR is injecting the voltage in quadrant with the line and is placed in series in the distribution line through the series connected transformer as shown in the Fig.6. The three-phase DVR is directly integrated with the DC link of the proposed systems and it doesn't require any storage device or large size capacitor.

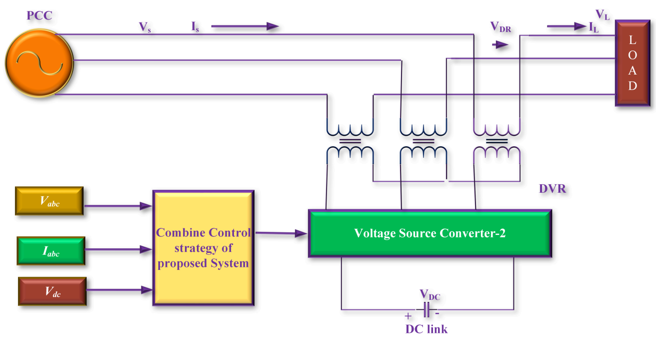

Fig. 6. Layout of three phase Dynamic Voltage restorers

The combine control switching strategy is generating the switching pulses to DVR by taking the reference of line voltage and DC link voltage. The stabilized load voltage is given by Eq.5.

$$V_L = V_{DVR} + V_{PCC} \tag{5}$$

Where, VL is voltage at the load point, VDVR is DVR injected voltage and VPCC is the point of common coupling voltage.

3. Control Strategies

The control strategies of the proposed hybrid system are categorized into two modules. One is Fuzzy logic controller (FLC) based maximum power tracking technique (MPPT) and another one is a grid synchronization unit. The FLC based MPPT is extracts the maximum power from the SPV system. The grid synchronization units contain the combine control strategy of DVR and voltage source converter. The control section is described in the following section.

3.1. Fuzzy logic Controller(FLC) based MPPT Method

The FLC based MPPT is used for tracking the maximum power and efficient utilization solar power. The FLC based MPPT generate the switching pulses to boost converter as shown in the Fig.7. In the FLC based MPPT, the ratio of change in power to change in voltage (called as a fuzzy factor) as an error signal (Eo) and it 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 Eq.6 and Eq.7.

$$E(i) = \frac{P_{pv}(i) - P_{pv}(i-1)}{V_{pv}(i) - V_{pv}(i-1)} \tag{6}$$

$$\Delta E(i) = E(i) - E(i-1) \tag{7}$$

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).

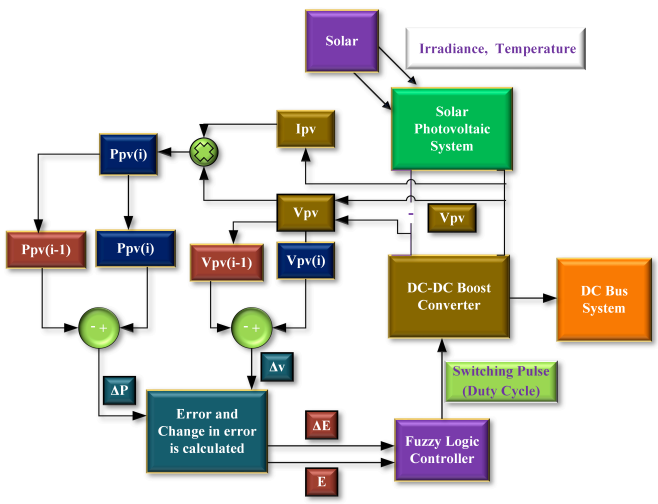

Fig. 7. Fuzzy based MPPT tracking [21]

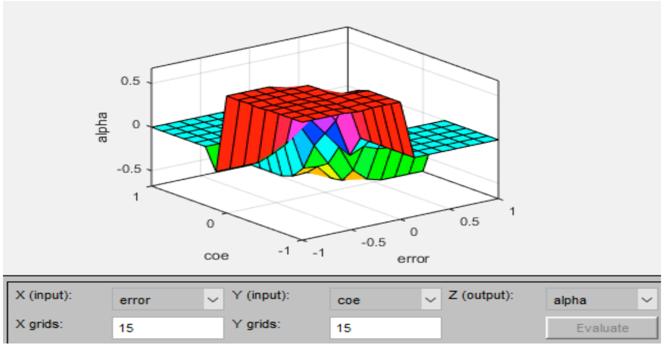

Fig. 8. Fuzzy logic controller surface viewer

The boost converter duty cycle is regulated using the fuzzy factor in obtaining the maximum power from the SPV system. The maximum power from the solar is obtained using a fuzzy rule viewer. The membership functions of fuzzy logic controller are modulated, and the output as shown in Fig.8. The switching function of the boost converter is regulated using the FLC based MPPT method. This control switching function helps in achieving DC link voltage.

3.2. Grid Synchronization Control Unit

The grid synchronization unit is regulating the switching pulses of voltage source converter and DVR as shown in the Fig.9. Grid synchronization unit synchronizes the DC link-based hybrid generation with the grid voltage through the three phase three level voltage source converter. The Grid control unit contains the current regulator, phase locked loop (PLL) and measurement, voltage regulator and voltage reference generator. The PCC voltage, currents are monitored through the voltage, current sensor respectively. The measured voltage (V_{abc}) and currents (I_{abc}) are regulated by the reference quantity with the help of PLL and current regulator.

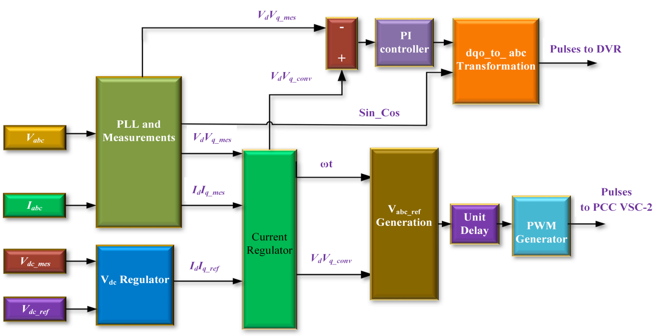

Fig. 9. Grid synchronization units

The PLL is used to calculate the magnitude and phase separately without taking input and it will help in the synchronization process. The voltage regulator regulates the voltage at DC link based on the reference DC link voltage. The current regulator with feed forward path monitore the active and reactive power of grid. It regulate the swiching pulses of the grid conncted inverter through the pulse width modulation generator.

The behavior of three phase voltage calculated using park's transformation in the following way

$$\begin{bmatrix} V_d \\ V_q \\ V_o \end{bmatrix} = \sqrt{\frac{2}{3}} \times \begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta - \frac{4\pi}{3}) \\ -\sin(\theta) & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta - \frac{4\pi}{3}) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \times \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (8)$$

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) & 1 \\ \cos(\theta - \frac{2\pi}{3}) & -\sin(\theta - \frac{2\pi}{3}) & 1 \\ \cos(\theta + \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) & 1 \end{bmatrix} \times \begin{bmatrix} V_d \\ V_q \\ V_o \end{bmatrix} \quad (9)$$

Where Va, Vb, Vc are the PCC voltages. Vabc reference generator generates the switching pulses for the voltage source converter connected at PCC through the pulse width modulation generator. These switching pulses are regulating the voltage source converter output and are synchronized with the grid voltage. The dynamic voltage restorer control unit contains PLL unit, PI controller and three-phase to two phase transformation vice-versa. The control unit stabilizes the load voltage through the PI controller. The three-phase voltage is analyzed with inverse park transformation using Eq.9. Similarly, the three phase's current is measured with current sensor and is analyzed with parks transformation. The switching pulses of DVR are regulated through the PI controller and these pulses are given to three phase voltage source converters of the DVR. The grid synchronization unit monitor the grid connected voltage source converter and DVR.

4. Simulink Results

The hybrid generation of SPV source is the primary source for supplying the power during the day. The SPV with boost converter specification is mentioned in the Tab.1. The dynamic irradiance, temperature is considered for the simulation of SPV system.

Table 1. Solar PV array with boost converter Specification

Si.No.	Name of the Parameter	Rating
1.	Solar Parallel strings	02
2.	Solar Series 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

The solar irradiance varies from 1000W/m^2 to 250 W/m^2 at t=0.05sec and then at t=0.2sec irradiance varies 250 W/m^2 to 1000 W/m^2 as shown in the Fig.10. The temperature also varied from 25^{o}c to 50^{o}c at t=0.25sec. Due to dynamic variation in the temperature and irradiance, the SPV power is becoming intermittent. The solar power is stabilized with integration of battery, fuel cell and HVDT. This hybrid generation maintains the constant voltage at DC link, which is represented in the Fig.11.

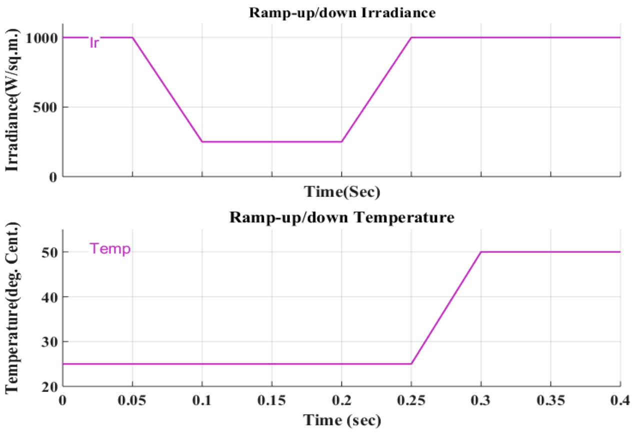

Fig. 10. Dynamic Irradiances and Temperature

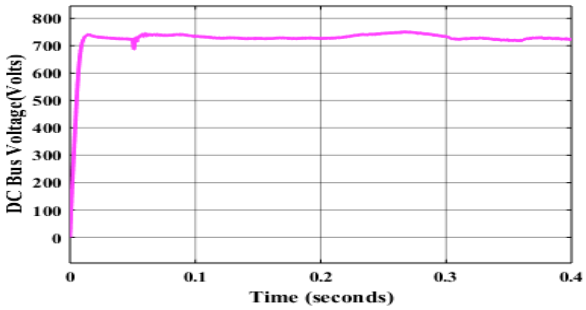

Fig. 11. DC link voltage

The voltage at the DC link maintained constant even under dynamic variation in of the integrated sources. The battery and fuel cell are designed with the rating of DC link voltage. The HVDT gas turbine generator is integrated at the DC link with the help of AC-DC converter and it used as a base load power supply. The performance of HVDT gas turbine is shown in the Fig.12. It will maintain the stabilized active and reactive power within the short time. From the characteristic of the HVDT gas turbine is observed that the response is very quick and maintain the balanced current. The corresponding load angle of HVDT gas generator is also shown and its DC link support for maintaining the constant voltage.

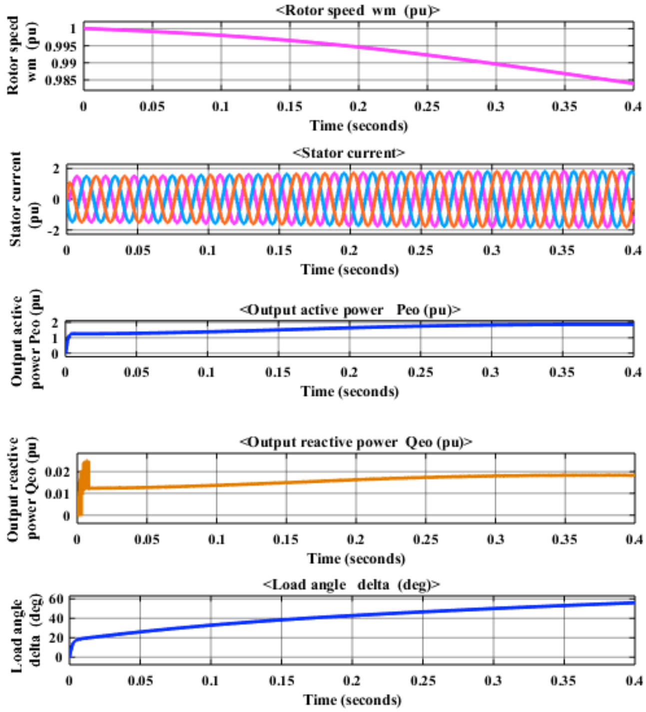

Fig. 12. Heavy duty gas turbine-based generator speed, current, active power, reactive power and load angle

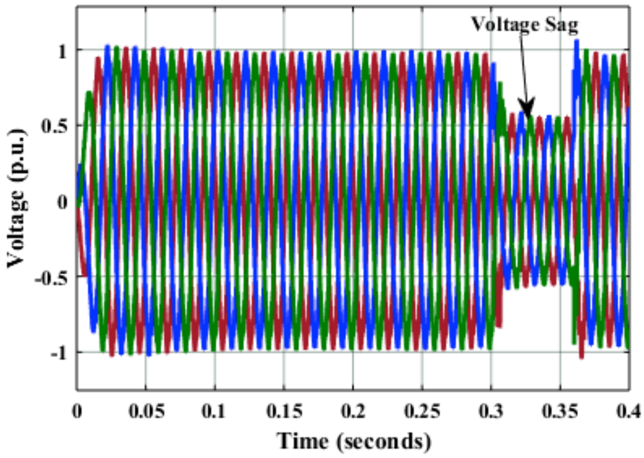

Fig. 13. Voltage under the dynamic condition of load

The hybrid generation-based DC link power is integrated with the grid through the point of common coupling (PCC) using the DC to AC converter. The PCC is fed to the load through the DVR. The voltage sag is created during the interval t=0.3sec to 0.37sec is represented in the Fig.13. The voltage sag under fault condition is shown in the Fig.14. The Fig.15 shows the DVR injected voltage.

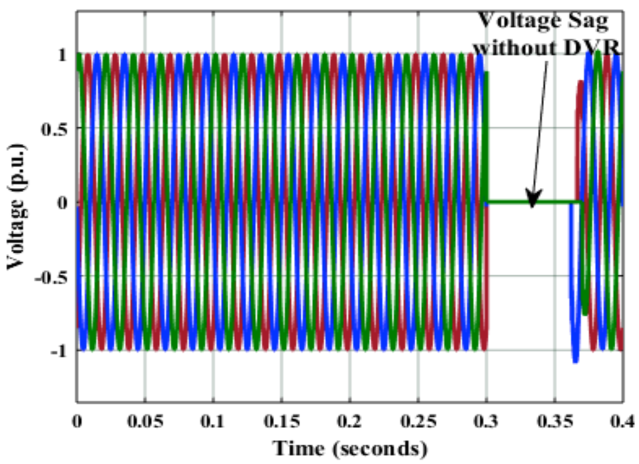

Fig. 14. The load voltage under fault condition

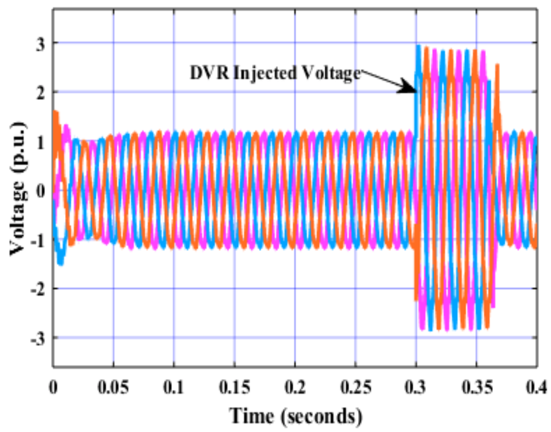

Fig. 15. DVR compensated voltage

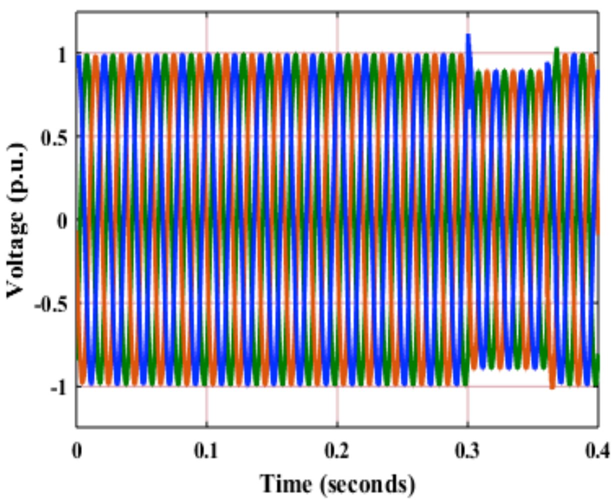

Fig. 16. Load voltages with DVR

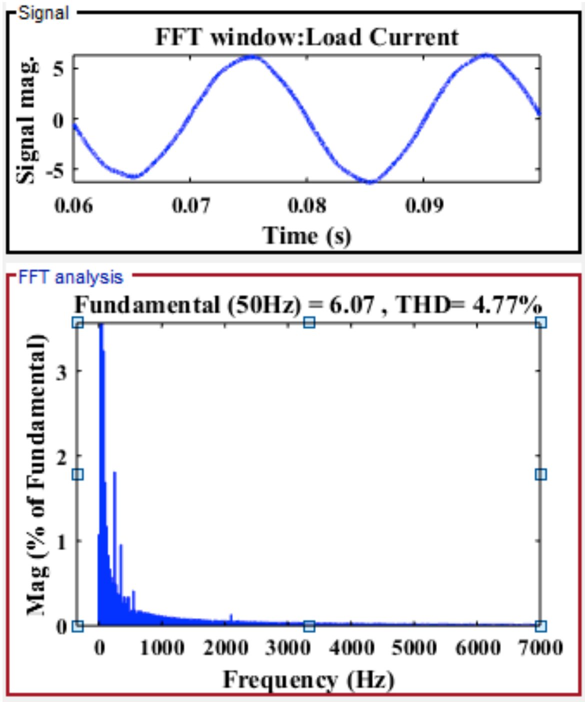

Fig. 17. Load Current

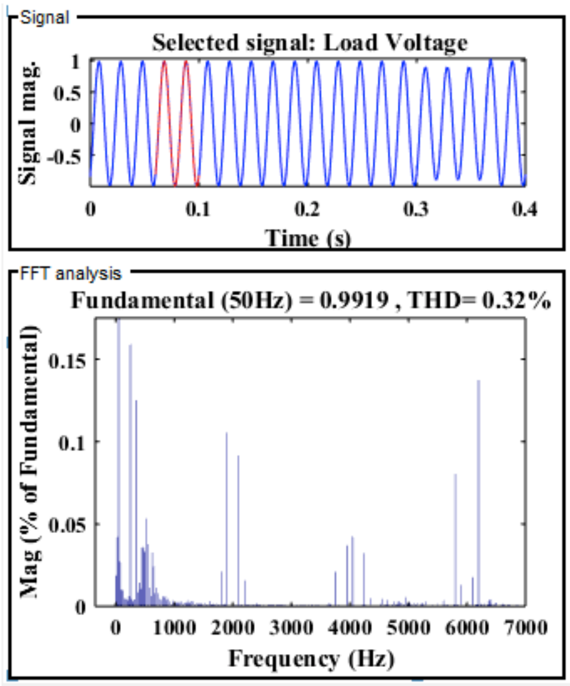

Fig. 18. THD of Load Voltage

The DVR is protecting the sensitive load by maintaining the balanced voltage at the load point is shown in the Fig.16. The voltage is stabilized during sags in the interval t=0.3sec to 0.36 sec. The voltage is maintaining balance during the source and load variation. The proposed system is providing continues power. The total harmonic distortion of the load current and voltage are within the limit as per IEEE-519 standard as shown in the Fig.17 and Fig.18.

5. Conclusion

The grid integration of SPV, fuel cell with heavy duty gas turbine stabilizes with the DC link voltage under dynamic condition of source and load. The solar power is extracted using fuzzy based maximum power point tracking method under dynamic irradiance and temperature. The heavy-duty gas turbine output is regulated with field excitation system and is integrated with the DC link through the AC-DC converter. The fuel cells maintained the constant DC link voltage through the DC-DC converter. The grid integration of hybrid generation with dynamic voltage restorer is stabilizing the source and load. The combine control strategies of the proposed hybrid system performance are satisfactory and it maintained the total harmonic distortion within the limit as per IEEE-519 standard. The load is protected with DVR by maintaining the balanced voltages at the load point.

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