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Enhancing Power Quality of Grid Using Solar PV Integrated UPQC

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Abstract: **It is critical now for supply authorities to provide consumers with clean, reliable, and continuous power. There are no. interruptions in power quality such as voltage sag, swell, or harmonics due to the growing number of consumers and use of advanced power electronic devices. Hence Different power electronic devices have been utilized to maintain power quality. Also Because of a scarcity of nonrenewable energy sources, the world is shifting toward renewable energy sources. However, using nonrenewable energy sources has its own set of benefits and drawbacks. To maintain acceptable power quality in this project, we deployed a unified power quality conditioner in conjunction with a solar PV array. The UPQC is a series and shunt compensator that performs multiple tasks to improve power quality. The grid side power quality concerns, such as voltage sag and swell, are compensated by the series converter, which also keeps the load voltage constant. It also controls the voltage of the PCC. The current harmonics caused by a nonlinear load are compensated by a shunt compensator. It gets its energy from a photovoltaic array. A Synchronous Reference Frame (SRF) control based on a moving average filter is used to generate the reference signal. The system proposed in this paper provides benefits in clean power generation and also improves the power quality of the distribution system. The performance of the system under various conditions was tested by simulation in MATLAB simulation software using a non-linear load. In this document, the system was tested for different conditions such as voltage fluctuations, sags, and swells.**

Index Terms **- Keywords: Power Quality, Photovoltaic System, Unified Power Flow Controller, and Voltage Fluctuation**

I. INTRODUCTION

Recently, a new trend in power electronics equipment has evolved, with significant growth in the use of various power electronics drives and controllers. These are devices like SMPS, electrical furnaces, frequency-based speed drives, power electronic converters, and others that may have high efficiency but generate nonlinear current in the system. Because of the use of these power electronic components, harmonics are generated by nonlinear current passing through the instrument [1], [2]. The utility must offer the highest quality and range of power feasible. The utility should be able to provide continuous and dependable service. As a result, a multifunctional device is needed to maintain a constant voltage on both the grid and the load side. Integrating clean energy generation with shunt active filtering has been the subject of extensive research. Although shunt active filtering is capable of both load voltage management and reactive power injection, it does so at the cost of injecting reactive power. As a result, shunt active filtering is unable to simultaneously manage PCC voltage and preserve grid current unity power factor. Series active filters have recently been recommended for usage in small residences and commercial buildings due to the stringent voltage quality requirements for advanced electronics loads. [3], [4]. As a result, the emphasis of this research is on the use of solar-powered UPQC devices. [5], [6] Using UPQC in conjunction with solar power to maintain sinusoidal grid current at a unity power factor is a winning combination. Photovoltaic technology offers two benefits: it produces clean energy and is environmentally beneficial. [7], [8] The fundamental disadvantage of using the synchronous reference frame theory-based method is that the d-axis current contains a double harmonic component when the load is imbalanced. Low pass filters with a very low cut-off frequency are employed to filter out the double harmonic component as a result. The d-axis current is filtered using a moving average filter (MAF) to produce a fundamental load active current [9]

The following are the primary benefits of the suggested system:

• Integration of renewable energy generation and improved power quality.
• Improved voltage and current quality at the same time.
• Improved load current compensation due to the usage of MAF in PV-UPQC's d-q control.
• Stable under a wide range of dynamic situations, including voltage sags/swells, load unbalance, and irradiation variation.

Using MATLAB-Simulink software, the suggested system's performance is thoroughly examined under both dynamic and steady-state situations.

II. UNIFIED POWER QUALITY CONDITIONER STRUCTURE

The block diagram of the Unified Power Quality Conditioner (UPQC) is shown in Figure 1. The topology was created with a 3ph system in consideration. The system configuration included series and shunt converters connected in a back-to-back configuration with a DC-bus in the middle. Shunt converters are generally linked at the load end to compensate for load-side power quality problems. The series converter is generally set to manage voltage and will compensate for grid voltage sags and swells. A shunt converter and a series converter are connected to a network or an electrical grid via interface inductors. So, in other words, we can say that UPQC is a combination of DSTATCOM and DVR.

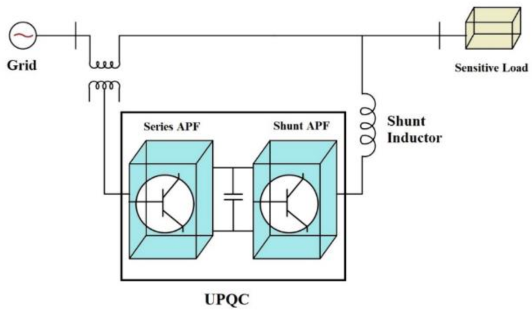

Figure 1:Block Diagram of UPQC

The UPQC can be categorized into three types based on the control strategy.

i. UPQC-P: The grid current is in phase with the series compensator's voltage injection. The series compensator tends to use more active power in this instance.
ii. UPQC-Q: The grid current is in quadrature with the series compensator's injected voltage. Only reactive power is consumed by the series compensator.
iii. UPQC-S- The grid current is at the desired angle, which is determined by the specifications. The series compensator consumes both active and reactive power [10].

The series compensation is only performed for a brief time in UPQC-P and UPQC-Q. The most prominent control technique is UPQC-P, which ensures that the source current is constantly in phase with the source voltage. The UPQC-P system can be used in conjunction with renewable energy sources such as solar energy The 3 Phase PV integrated UPQC system's circuit diagram is shown in Figure 2 below. The solar photovoltaic array is directly connected to the UPQC's common DC-link capacitor through a diode with reverse blocking capabilities, to prevent the reverse flow of current. The series compensator will protect the load from grid side power quality problems like voltage sag and swells by injecting compensating voltage. A series transformer is also used in the UPQC system to inject the compensated voltage into the grid. The shunt compensator will compensate for load side power quality issues and in addition, it will extract maximum power from the PV array with the help of the proposed MPPT algorithm. To connect the shunt and series compensator with the grid interfacing inductors are connected. The ripple filters are connected to filter out the harmonics generated due to the switching of thyristors. For analysis, the 3 phase RL load is taken into account.

III. PV SYSTEM DESIGN

Photovoltaic panels use solar energy to generate electricity. Integrating solar energy with the UPQC can improve its utilization and functionality. MATLAB Simulink is used to mathematically model the solar system. The PV panel's output voltage is DC. The PV panel's output is enhanced and sent into a DC link capacitor. 23 modules per string are connected in series and 18 parallel strings are connected. To track the maximum power from the solar panels, the P&O MPPT algorithm is used. The DC link voltage is kept at 700 volts. The Solar PV Array specifications are as follows.

Table 1: Solar PV Array Specification

Parameters	Specifications
Maximum Power	213.15 W
Open Circuit Voltage V_{OC}	36.3 V
Short Circuit Current I_{sc}	7.84 A
Maximum Peak Voltage V_{mpp}	29 A
Maximum Peak Current I_{mpp}	7.35 A

Mathematical aspects to design a PV array are described in [11] PV panels can be connected to generate the necessary amount of energy. By connecting the panels in series, the voltage level of the panels can be increased, and by connecting the panels in parallel, the current level of the panels may be increased. PV modules can be linked together to create a PV array. To maintain the DC link voltage at desired value PI Controller is used.

I. DESIGN ASPECTS OF PV-UPQC SYSTEM

To design Photo Voltaic Integrated UPQC mathematical aspects are calculated as follows.

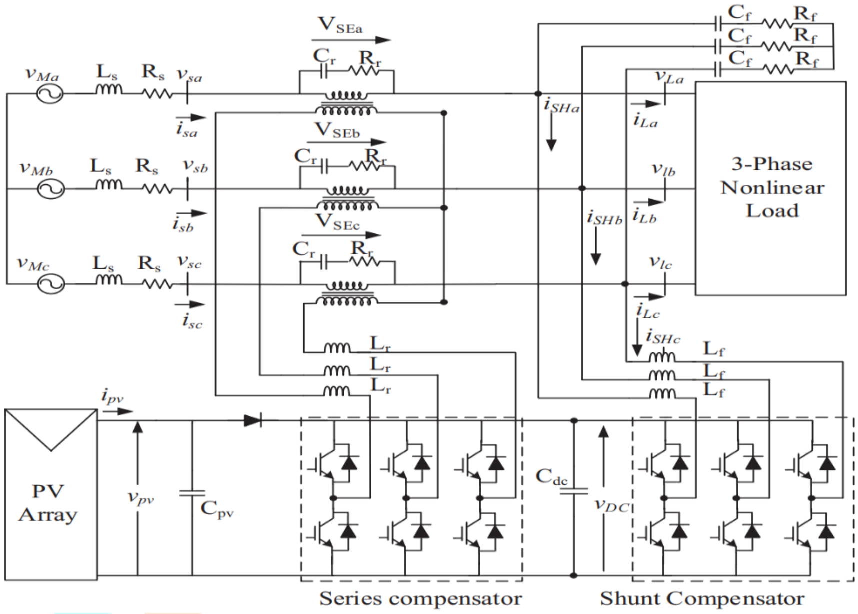

Fig. 2: 3 Phase Solar PV Integrated UPQC

1. DC-Link Voltage:

The magnitude of the DC link voltage Vdc is determined by the modulation depth and per phase voltage of the system. The magnitude of a common DC-voltage link must be larger than twice the per-phase peak value of the three-phase system voltage [12], which is calculated as,

$$Vdc=\frac{2\sqrt{2}\,VLL}{\sqrt{3}\,m} \qquad (1)$$

VLL denotes a grid line voltage, whereas the modulation depth (m) can be considered as 1. If the line voltage is assumed to be 400 volts, the DC-bus voltage must be at least 677.7 volts. As a result, the estimated value of a DC link bus voltage should be set at 700 Volts, which is exactly equivalent to the magnitude of the solar photovoltaic system's MPPT voltage under standard test conditions.

2. DC Bus Capacitor Rating:

DC bus capacitor rating is mainly based on power requirement at the DC link and DC bus voltage level. An energy balance equation for a DC-bus system coupling capacitor can be written as follows [12], Vdc is the average DC-bus voltage; Vdc1 is the minimum DC-bus voltage necessary and is also known as the system's overload factor.

$$Cdc = \frac{3\ K\ a\ Vph\ Ish\ t}{0.5 \times (Vdc^2 - Vdc1^2)} \qquad (2)$$

$$= \frac{3 \times 0.1 \times 230.94 \times 76.3 \times 0.03}{0.5 \times (725^2 - 653.19^2)}$$

$$= 6.668\ mF$$

Vdc and Vdc1 are average DC bus voltage and the lowest required value of DC bus respectively, Vph is per phase voltage and Ish is shunt compensator per phase current, a is the overloading factor and is taken as 0.1, t is the

minimum time required to attain steady-state value after disturbance, Ish per phase current of shunt compensator and K is variation factor during energy dynamics.

The minimum required DC-Link voltage is 653.19 V, Vdc is set at 725 V, 6.3 A, and t is 30 msec hence the value obtained for Cdc is 6.668 mF.

3. Interfacing Inductor for Shunt Compensator:

The rating of interfacing inductor of shunt compensator is dependent upon ripple current which is 20% of RMS phase current of shunt compensator, the switching frequency fs which is 10 kHz & depend upon DC-Link voltage which is set at 725 V. The expression for interfacing inductor is given as

$$Lf = \frac{\sqrt{3}\,m\ Vdc}{12\ a\ fsh\ Icr,pp} = \frac{\sqrt{3} \times 1 \times 725}{12 \times 1.5 \times 10000 \times 6.23}$$

$$= 1.39\ e\text{-}3\ H \qquad (3)$$

Here m is taken as 1 & a is per unit value of maximum overload & is taken as 1.5. Icr, pp is the ripple current of the shunt compensator & is coming out to be 6.23 A. The value of the interfacing inductor obtained is $1.39\ e-3$ H.

4. Series Injection Transformer:

The design of PV integrated UPQC is made such that it will compensate for a sag/swell of 0.2 pu i.e., 46 V. As a result, the injection voltage required is just 46 V, resulting in a low modulation index for the series compensator with a 725 V DC-link voltage. The modulation index of the series compensator should be kept close to unity to operate it with the fewest harmonics. As a result, a series transformer with a turns ratio of 3 is employed. The turns ratio for the series transformer is given as

$$K_{SE} = \frac{V_{VSC}}{V_{SE}} = 3.33 \approx 3 \qquad (4)$$

The rating of the series transformer is given as,

$$S_{SE} = 3\ V_{SE}\ I_{SEsag} = 3 \times 46 \times 30 = 4.1\ KVA \qquad (5)$$

The current flowing through VSC will be the same as the current flowing in a grid. Hence the current obtained at 0.2 pu sag condition is 30 A. The VA rating of the transformer obtained is 4.1 KVA.

5. Interfacing Inductor of Series Compensator:

The rating of series interfacing inductor is depending upon ripple current at swell condition, switching frequency & DC- link voltage. The expression for interfacing inductor is given as follows,

$$L_f = \frac{\sqrt{3} m\ V_{dc}\ K_{SE}}{12\ a\ f_{sh}\ I_r} = \frac{\sqrt{3} \times 1 \times 700 \times 3}{12 \times 1 \times 10000 \times 28.24} = 1.06\ e\text{-}3\ H \qquad (6)$$

Where m is the depth of modulation, a is the pu value of maximum overload, Ir is series inductor ripple current which is 20% of grid current, fsh is switching frequency which is taken as 10 kHz, m is taken as 1, Vdc is 700 V hence the value obtained after the substitution of all the values is 1.06 e-3 H.

II. Control of PV-UPQC

The shunt compensator and the series compensator are the two primary subsystems of PV-UPQC. The shunt compensator corrects difficulties with load power quality, such as load current harmonics and reactive power. In PV-UPQC, the shunt compensator also serves as a power source for the solar PV array. The maximum power point tracking (MPPT) technique is used by the shunt compensator to harvest power from the PV array. By injecting suitable voltage in phase with grid voltage, the series compensator protects the load against grid side power quality concerns such as sags/swells.

A. Control of Shunt Compensator

By running the solar PV array at its maximum power point, the shunt compensator pulls the maximum power from it. The reference for PV-DC-link UPQCs is generated via the maximum power point tracking technique. The Perturb and Observe (P&0) technique and the incremental conductance algorithm (INC) are two commonly used MPPT algorithms [13]. The P&O algorithm is employed to implement MPPT in this study. A PI-controller is used to keep the DC-link voltage at the generated reference. The shunt compensator takes the active fundamental component of the load current to perform load current compensation. Instantaneous reactive power theory (IRP), synchronous reference frame (SRF) theory instantaneous symmetrical component theory, and other signal extraction approaches have been widely documented in [14]. The shunt compensator is adjusted in this study by employing the SRF approach to derive the fundamental active component of load current. Figure 2 depicts the shunt compensator's control structure. The phase and frequency information collected from the PLL is used to convert the load current to the d-q-0 domain. The grid voltage is the PLL input. A low pass filter is used to isolate the DC component from the d-component of the load current, which represents the basic component in the ABC frame of reference. This component is combined with the DC-link PI controller's output and then translated to the ABC domain, yielding the reference grid currents. To create the gating pulses for the shunt converter, the reference grid currents are compared to the measured grid currents in a hysteresis current controller.

A MAF has been used to remove a direct current component without affecting the system's dynamics. MAF can be represented using a transfer function,

$$MAF(s) = \frac{1 - e^{-T_{ws}}}{T_{ws}}$$

Where Tw is the length of the MAF window. To the window length, the MAF will have 1 DC gain and 0 gain integer multiplex. A PV system with similar current parameters has been approximated by,

$$I_{pvg} = \frac{2}{3}\frac{P_{pv}}{V_s}$$

Where Ppv is the power delivered by the PV system and Vs is the voltage at the PCC. The grid's reference current in the d-axis can be represented as *Isd First, reference grid currents are converted into ABC form. These source grid currents must be compared to obtained grid currents using a hysteresis controller to generate pulse signals for the shunt converter.

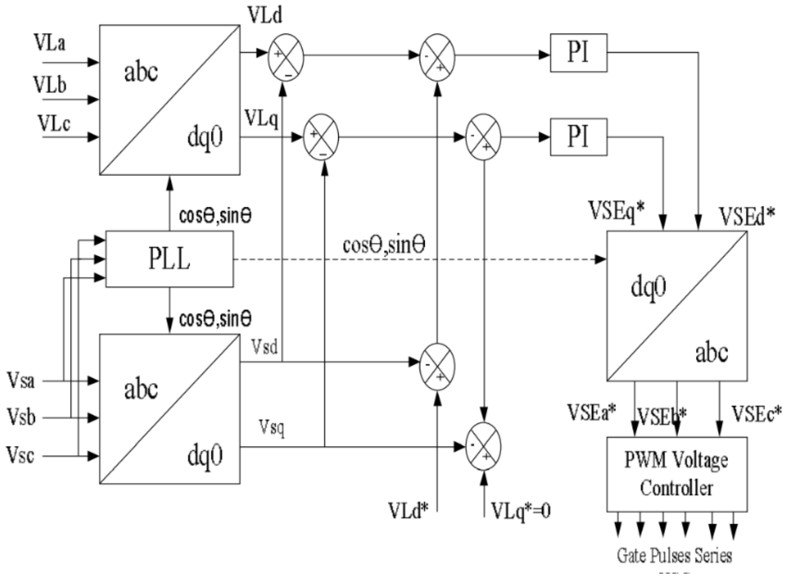

Fig. 3:Control of Shunt Compensator

B. Control of Series Compensator

A series-connected converter's controlling methodology includes precise compensation, phase compensation, and excellent power compensation. [15] and [16] provide descriptive knowledge of various compensating techniques used to control series converters. In the proposed system, a series converter injects voltage signals into similar phases as the system grid voltage signals, resulting in a small vale of the injection voltage signal from the series converter.

Figure 3 depicts the control of a series-connected converter. The basic parameters of the PCC voltage are extracted by the PLL, which generates reference signals in the d-q-0 axis domain. The voltage reference signal at the load side is generated by utilizing the phase and frequency information at the PCC voltage, which is measured using a PLL. The PCC voltages and system voltages at the load end will be converted to the d-q-0 frame. It must be ensured that the reference voltage signals are exactly in phase with the voltage at the PCC. The q-axis parameter is kept at zero. The comparison of the load side reference signal and the PCC signal yields the value of the reference voltage to be supplied to the series converter.

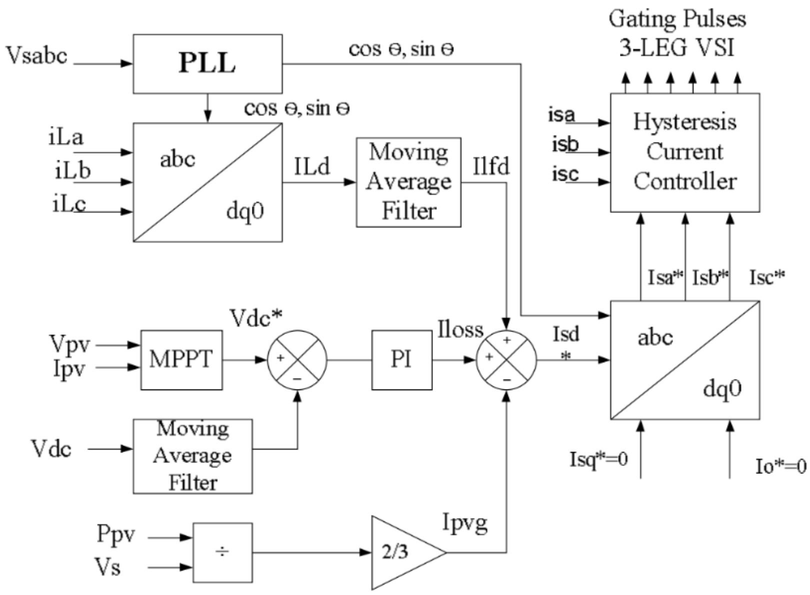

Fig. 4: Control of series compensator

The voltage difference between the load site and the voltage at the PCC end represents the actual series converter voltages. The difference signal between the reference and actual series converter voltages will now be supplied to the PI controllers to generate the required reference signals. The signals are then converted to the ABC domain and fed into the series converter via a PWM-based voltage signal controller to generate the required gate pulse.

III. Simulation Studies

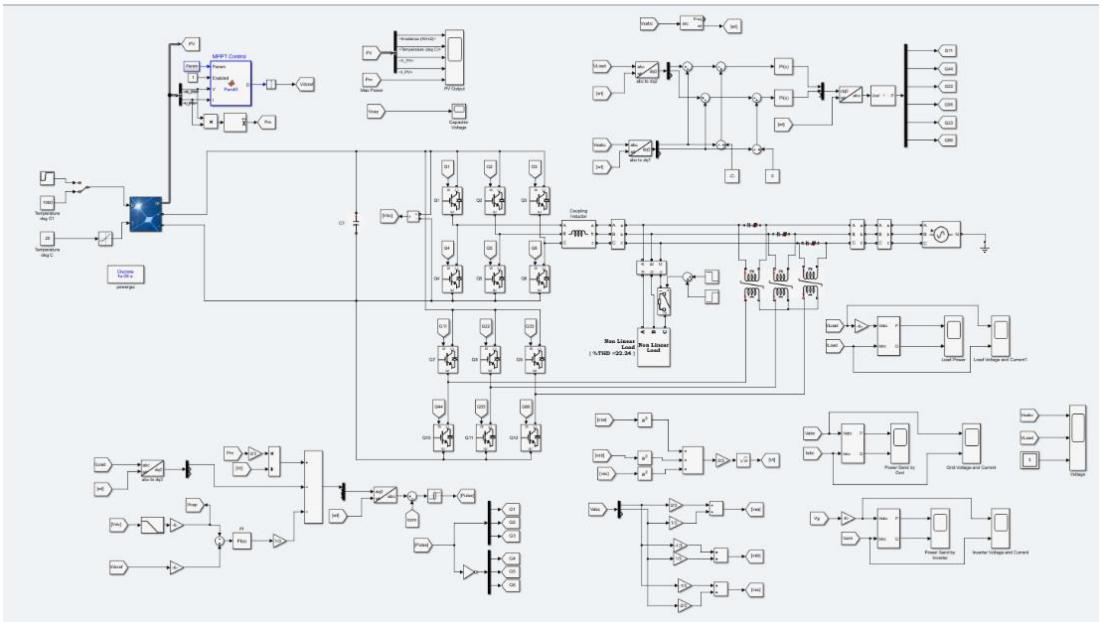

Fig. 5: Simulation Model of PV integrated UPQC

The PV Integrated UPQC system's MATLAB model is shown in Figure 5. A steady-state and dynamic system behavior of Solar PV-UPQC can be investigated using a simulation study in MATLAB software A 3 ph diode-connected RL load is used as a nonlinear load. The simulation study employs a solver stepping size of 1e-6s. The system is tested through different conditions such as voltage sag, voltage swell, and unbalanced load conditions. The results are discussed below.

A. Performance analysis of PV integrated UPQC system under influence of Fluctuations at PCC Voltage:

Figure 6 depicts the dynamics of the behavior of a PV integrated UPQC in the presence of PCC end voltage sags/swells. The solar irradiation (Rad) has been calculated to be 1000W/m2. PCC voltages (Vs), solar PV array current (Ipv), series compensator voltages (Vse), load voltages (VL), DC-link voltage (Vdc), solar PV array power (Ppv), grid currents (IS), and shunt converter currents and load currents are all to be sensed. Figure 6 (a) shows the parameters Source voltage (Vs), Load voltage (VL), and DVR voltage (Vse) on the Y-axis, and time in seconds on the X-axis. It is assumed that between the times of 0.5sec and 0.6sec, there will be a 0.2 per unit sag in voltage, and between the times of 0.7seconds and 0.8 seconds, there will be a 0.2 per unit swell in voltage. During this time, a series converter injects the required voltage (Vse) in phase with the system network voltage variations to keep the system load voltage (VL) at the required voltage.

Similarly, Figure 6 (b) depicts the effect of voltage sag and swell on source current (Is) and load current (I_{Labc}). Even if the source voltage varies, the current on the load side will remain constant, and the current of the shunt converter (DSTATCOM Current) Ish will be as shown in fig.6 (b). Figure 6 (c) depicts the Radiation (rad), PV array voltage (Vpv), Solar PV current (Ipv), and Solar power (Ppv).

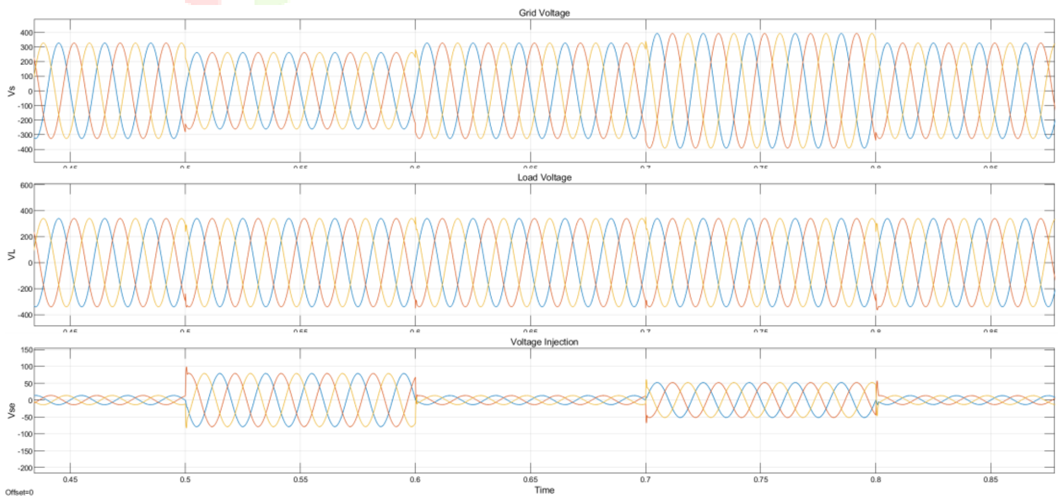

Fig. 6:(a) Source Voltage (Vs), Load Voltage (VL), Voltage Injection (Vse)

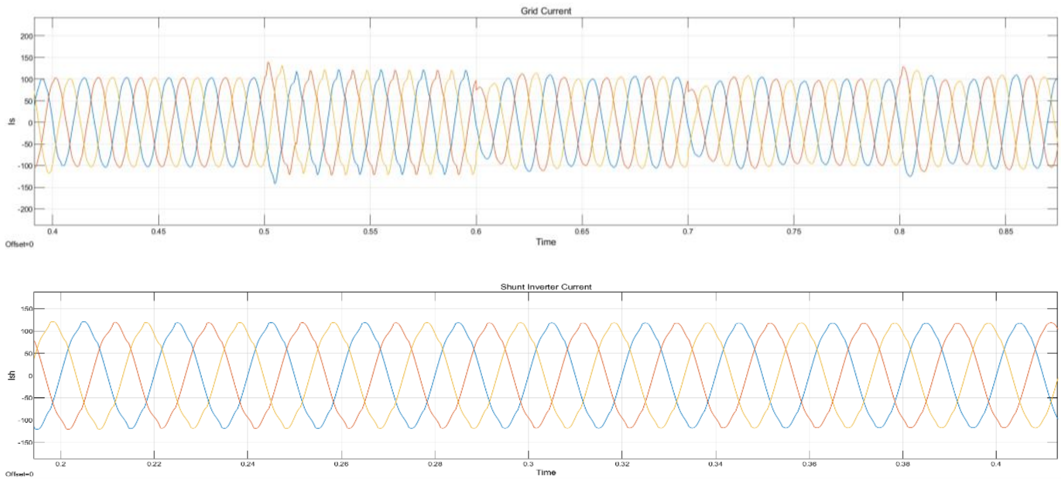

Figure 6 (b): Source Current (Is), Shunt Inverter Current (Ish)

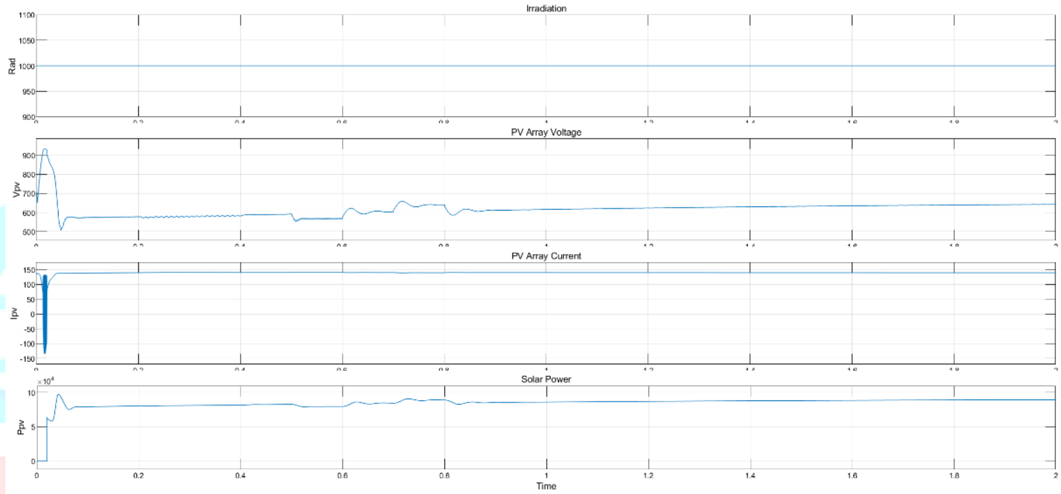

Figure 6 (c): Radiation (rad), PV array voltage (Vpv), Solar PV current (Ipv), and Solar power (Ppv).

B. Performance analysis of PV-UPQC during Load Unbalancing Condition:

Fig 7 is showing the dynamics of the PV integrated UPQC under the influence of load unbalancing. Fig 7(a) Source voltage (Vs), Load voltage (VL), and DC-Link voltage (Vdc) is taken on the Y-axis and the X-axis represents the time in seconds.

The signal connected to the load at phase 'b' was disconnected at time t=0.2s. In Fig 7(a), The load current waveform is shown, one of the phases is disconnected at 0.2 s. The grid current will increase significantly as a result of the sudden reduction in load which can be seen in fig 7 (c). The voltage at a common dc link is kept constant and at its regulated value of 700V. The PV panel voltage and current is shown in the fig. 7(d)

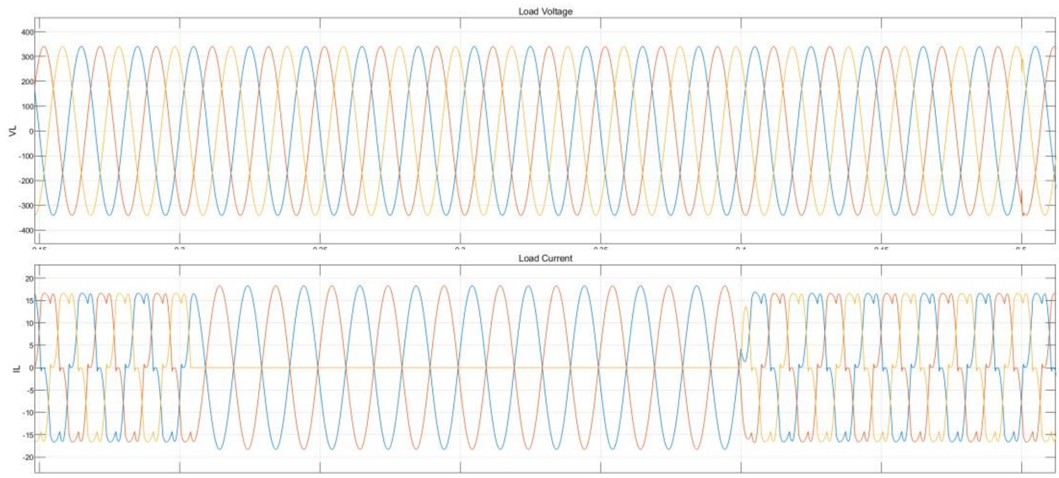

Fig.7 (a): Load Voltage (VL), Load Current (IL)

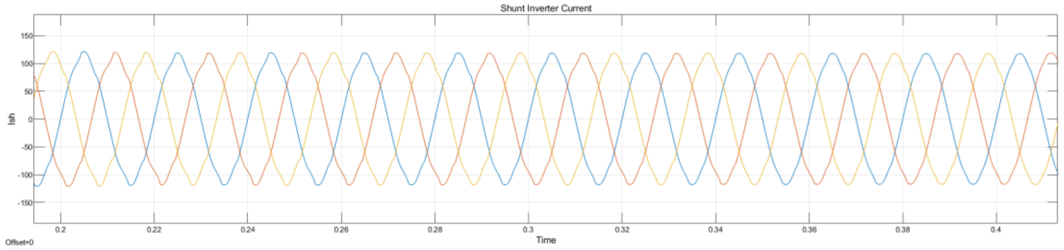

Figure 7 (b): Shunt Inverter Current

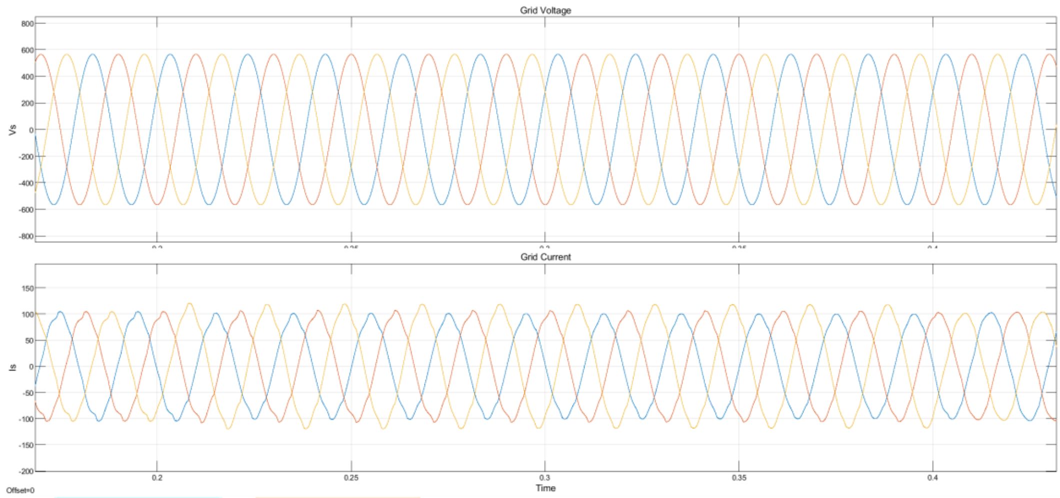

Figure 7 (c): Grid Voltage (Vs), Grid Current (Is)

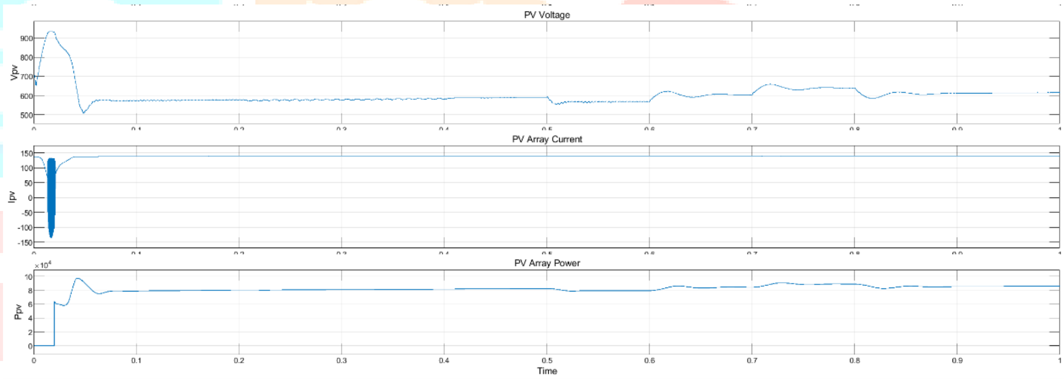

Figure 7 (d): PV Voltage (Vpv), PV Current (Ipv), PV power (Ppv)

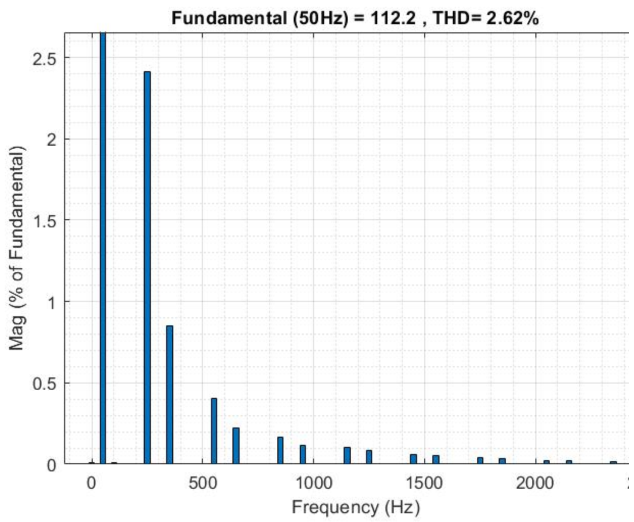

Figure 8: THD of Grid Current

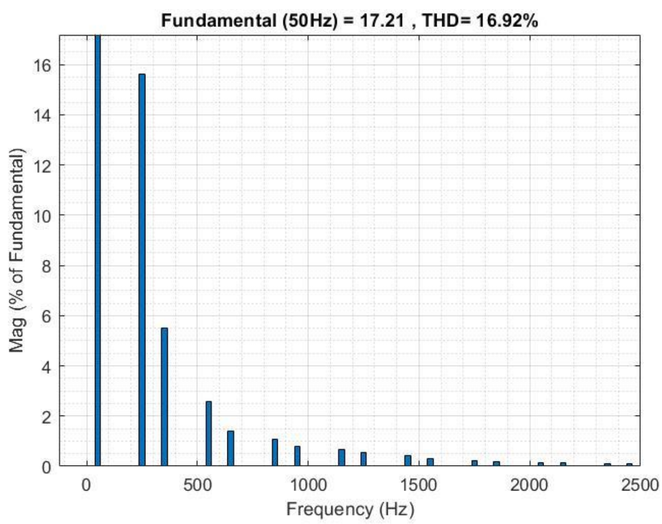

Figure 9: THD of Load Current

IV. CONCLUSION

The performance of a Solar PV integrated UPQC has been evaluated under various power quality variations such as voltage sag and swell and load unbalance conditions. The series compensator (DVR) is used to inject the required voltage value, which must be in phase with the system grid voltage magnitude, requiring the lowest value injection voltage. The dynamics of a solar PV system integrated with a UPQC is tested under load unbalancing condition. It has been seen that the system remains stable at the time of numerous disturbances. The Solar PV-UPQC arrangement provides reactive power mitigation as well as active power delivery. The system has a THD of load current is 16.92% and a THD of grid current is 2.62% which meets the requirement of the IEEE-519 standard. The method is most sensitive to changes and imbalances in voltages at the PCC. The analysis of a d-q methodology has been recovered by the use of an active average filtering scheme in this load unbalancing circumstance. It has been observed and analyzed that PV integrated UPQC is superior in terms of current power generation with improved power quality.

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