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AN EFFICIENT IMPLEMENTATION OF THREE-PHASE SOLAR PV INTEGRATED UPQC

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Abstract: Today it is very important to provide clean, reliable and continue power to the consumer from supply authority. Due to the increasing customers and use of modern power electronic devices, there is no. of disturbances in quality of power such as voltage sag , swell ,harmonics . Hence In order to maintain quality of power, different power electronic devices has been used. The PV-UPQC consists of a shunt and series connected voltage compensators connected back to back with common DC-link .The shunt compensator performs the dual function of extracting power from PV array apart from compensating for load current harmonics. An improved synchronous reference frame control based on moving average filter is used for extraction of load active current component for improved performance of the PVUPQC. The series compensator compensates for the grid side power quality problems such as grid voltage sags/swells. The compensator or injects voltage in-phase/out of phase with point of common coupling (PCC) voltage during sag and swell conditions respectively. The proposed system combines both the benefits of clean energy generation along with improving power quality. The steady state and dynamic performance of the system are evaluated by simulating in MATLAB-SIMULINK under a nonlinear load. The system performance is then verified using a scaled down laboratory prototype under a number of disturbances such as load unbalancing, PCC voltage sags/swells and irradiation variation.

Index Terms—Power Quality, shunt compensator, series compensator, UPQC, Solar PV, MPPT.

I. INTRODUCTION

With the advancement in semiconductor technology, there is an increased penetration of power electronic loads. These loads such as computer power supplies, adjustable speed drives, switched mode power supplies etc. have very good efficiency, however, they draw nonlinear currents. These nonlinear currents cause voltage distortion at point of common coupling particularly in distribution systems. There is also increasing emphasis on clean energy generation through installation of rooftop PV systems in small apartments as well as in commercial buildings [1], [2]. However, due to the intermittent nature of the PV energy sources, an increased penetration of such systems, particularly in weak distribution systems leads to voltage quality problems like voltage sags and swells, which eventually instability in the grid [3]–[7]. These voltage quality problems also lead to frequent false tripping of power electronic systems, malfunctioning and false triggering of electronic systems and increased heating of capacitor banks etc [8]–[10]. Power quality issues at both load side and grid side are major problems faced by modern distribution systems

Due to the demand for clean energy as well as stringent power quality requirement of sophisticated electronic loads, there is need for multifunctional systems which can integrate clean energy generation along with power quality improvement. A three phase multi-functional solar energy conversion system, which compensates for load side power quality issues has been proposed in [11], [12]. A single phase solar PV inverter along with active power filtering capability has been proposed in [13], [14]. Major research work has been done in integrating clean energy generation along with shunt active filtering. Though shunt active filtering has capability for both load voltage regulation, it comes at the cause of injecting reactive power. Thus shunt active filtering cannot regulate PCC voltage as well as maintain grid current unity power factor at same time. Recently, due to the stringent voltage quality requirements for sophisticated electronics loads, the use of series active filters has been proposed for use in small apartments and commercial buildings [15], [16]. A solar photovoltaic system integrated along with dynamic voltage restorer has been proposed in [17]. Compared to shunt and series active power filters, a unified power quality conditioner (UPQC), which has both series and shunt compensators can perform both load voltage regulation and maintain grid current sinusoidal at unity power factor at same time. Integrating PV array along with UPQC, gives the dual benefits of clean energy generation along with universal active. The integration of PV array with UPQC has been reported in [18]–[20]. Compared to conventional grid connected inverters, the solar PV integrated UPQC has numerous benefits such as improving power quality of the grid, protecting critical loads from grid side disturbances apart from increasing the fault ride through capability of converter during transients. With the increased emphasis on distributed generation and micro grids, there is a renewed interest in UPQC systems [21], [22].

In this paper, the design and performance analysis of a three-phase PV-UPQC are presented. An MAF based d-q theory based control is used to improve the dynamic performance during load active current extraction. The main advantages of the proposed system are as follows

• Integration of clean energy generation and power quality improvement.
• Simultaneous voltage and current quality improvement.
• Improved load current compensation due to use of MAF in d-q control of PV-UPQC.
• Stable under various dynamic conditions of voltage sags/swells, load unbalance and irradiation variation.

The performance of the proposed system is analyzed extensively under both dynamic and steady state conditions using MATLAB-SIMULINK software. The performance is then experimentally verified using a scaled down laboratory prototype under various conditions experienced in the distribution system such as voltage sags/swells, load unbalance and irradiation variation.

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II. SYSTEM CONFIGURATION

UPQC is the combination of series and shunt converter .Basic structure of UPQC is as shown in Fig1.The role of series inverter inject compensated voltage in series with load voltage when source voltage become unbalanced and non sinusoidal .Series compensator inject or absorb voltage at the required magnitude and phase angle which can solve the problem of voltage sag ,swell and flicker .series inverter absorb or inject real power in addition to reactive power .The shunt converter has the ability to regulate the dc link voltage and compensate the current related PQ issues such as harmonics ,inter harmonics and reactive power requirement. The structure of the PV-UPQC is shown in Fig2. The PV-UPQC is designed for a three-phase system. The PV-UPQC consists of shunt and series compensator connected with a common DC-bus. At load side, shunt compensator is connected. The solar PV array is directly integrated to the DC-link of UPQC through a reverse blocking diode. The series compensator used to compensate the voltage which can reduce the voltage sag and swell. The shunt and series compensators are connected to the grid through interfacing inductors. A series compensator injects the voltage into the grid by using series injection transformer. Harmonics are generated by converters are eliminated by using filters. The load used is a nonlinear load consisting of a bridge rectifier with a voltage-fed load.

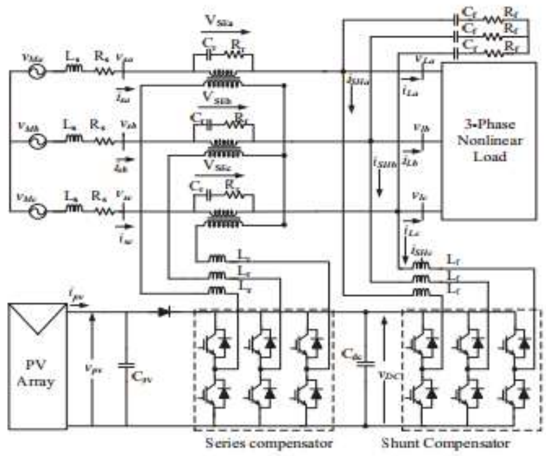

Fig. 1. System Configuration PV-UPQC

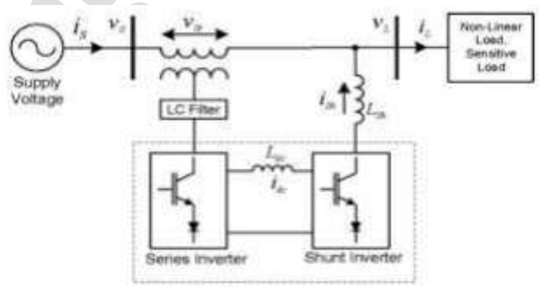

Fig 2.Basic structure of UPQC

A .Design of PV-UPQ

The design procedure for PV-UPQC begins with the proper sizing of PV array, DC-link capacitor, DC-Link voltage level etc. The shunt compensator is sized such that it handles the peak power output from PV array apart from compensating for the load current reactive power and current harmonics. As the PV array is directly integrated to the DC-link of UPQC, the PV array is sized such that the MPP voltage is same as desired DC link voltage. The rating is such that, under nominal conditions, the PV array supplies the load active power and also feeds power into the grid. The detailed PV array specifications are given in Appendix A. The other designed components are the interfacing inductors of series and shunt compensators and series injection transformer of the series compensator. The design of PV-UPQC is elaborated as follows.

1)Voltage Magnitude of DC-Link: The magnitude of DC link voltage Vdc depends on the depth of modulation used and per-phase voltage of the system. The DC-link voltage magnitude should more than double the peak of per-phase voltage of the three phase system [8] and is given as,

$$V_{dc} = \frac{2\sqrt{2}V_{LL}}{\sqrt{3}m} \qquad (1)$$

where depth of modulation (m) is taken as 1 and VLL is the grid line voltage. For a line voltage of 415 V, the required minimum value DC-bus voltage is 677.7 V. The DC-bus voltage is set at 700 V(approx), which is same as the MPPT operating voltage of PV array at STC conditions.

2) DC-Bus Capacitor Rating: The DC-link capacitor is sized based upon power requirement as well as DC-bus voltage level. The energy balance equation for the DC-bus capacitor is given as follows [8],

$$\begin{aligned} C_{dc} &= \frac{3kaV_{ph}I_{sh}t}{0.5 \times (V_{dc}^2 - V_{dc1}^2)} \\ &= \frac{3 \times 0.1 \times 1.5 \times 239.6 \times 34.5 \times 0.03}{0.5 \times (700^2 - 677.79^2)} \\ &= 9.3mF \qquad (2) \end{aligned}$$

where Vdc is the average DC-bus voltage, Vdc1 is the lowest required value of DC-bus voltage,a is the overloading factor, Vph is per-phase voltage, t is the minimum time required for attaining steady value after a disturbance, Ish is per-phase current of shunt compensator, k factor considers variation in energy during dynamics.

The minimum required DC-link voltage is Vdc1 = 677.69 V as obtained from (2), Vdc = 700 V, Vph= 239.60 V,Ish=57.5 A, t= 30 ms, a = 1.2, and for dynamic energy change = 10%, k= 0.1, the value of Cdc is obtained as 9.3 mF.

3) Interfacing Inductor for Shunt Compensator: The interfacing inductor rating of the shunt compensator depends upon the ripple current, the switching frequency and DC-link voltage. The expression for the interfacing inductor is as,

$$\begin{aligned} L_f = \frac{\sqrt{3}mV_{dc}}{12af_{sh}I_{cr,pp}} &= \frac{\sqrt{3} \times 1 \times 700}{12 \times 1.2 \times 10000 \times 6.9} \\ &= 800\mu H \approx 1mH \qquad (3) \end{aligned}$$

where m is depth of modulation, a is pu value of maximum overload, fsh is the switching frequency , Icr ,pp is the inductor ripple current which is taken as 20% of rms phase current of shunt compensator. Here, m=1, a=1.2, fsh=10kHz, Vdc=700V, one gets 800 µH as value. The value chosen is approximated to 1mH.

4) Series Injection Transformer: The PV-UPQC is designed to compensate for a sag/swell of 0.3 pu i.e 71.88 V. Hence, the required voltage to be injection is only 71.88 V which results in low modulation index for the series compensator when the DC-link voltage is 700V. In order to operate the series compensator with minimum harmonics, one keeps modulation index of the series compensator near to unity. Hence a series transformer is used with a turns ratio,

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

The value obtained for KSE is 3.33. The value selected is 3. The rating of series injection transformer is given as

$$S_{SE} = 3V_{SE}I_{SE_{sag}} = 3 \times 72 \times 46 = 10kVA \qquad (5)$$

The current through series VSC is same as grid current. The supply current under sag condition of 0.3 pu is 46 A and hence the VA rating of injection transformer achieved is 10 kVA.

5) Interfacing Inductor of Series Compensator: The rating of interfacing inductor of the series compensator depends on ripple current at swell condition, switching frequency and DClink voltage. Its value is expressed as,

$$\begin{aligned} L_r = \frac{\sqrt{3} \times mV_{dc}K_{SE}}{12af_{se}I_r} &= \frac{\sqrt{3} \times 1 \times 700 \times 3}{12 \times 1.2 \times 10000 \times 7.1} \\ &= 3.6mH \qquad (6) \end{aligned}$$

where m is the depth of modulation, a is the pu value of maximum overload, fse is the switching frequency, Ir is the inductor current ripple, which is taken to be 20% of grid current. Here, m=1, a=1.5, fse=10 kHz, Vdc=700 V and 20% ripple current, one gets 3.6 mH as selected value.

III. CONTROL STRATEGY

A .Control Strategy for shunt converter

The measured load current is transformed into the synchronous dqo reference frame. By this transform, the fundamental positive- sequence component, which is transformed into dc quantities in the d and q axes, can be easily extracted by low-pass filters (LPFs). Also, all harmonic components are transformed into ac quantities with a fundamental frequency shift.

The shunt compensator extracts the maximum power from the solar PV array by operating at its maximum power point .The maximum power point tracking(MPPT) algorithm generates the reference voltage for the DC link of UPQC. Current from dc link is converted to the reference grid currents. The reference grid currents are compared with the sensed grid currents is given to hysteresis controller. Hysteresis controller generate the gating pulses for shunt converter

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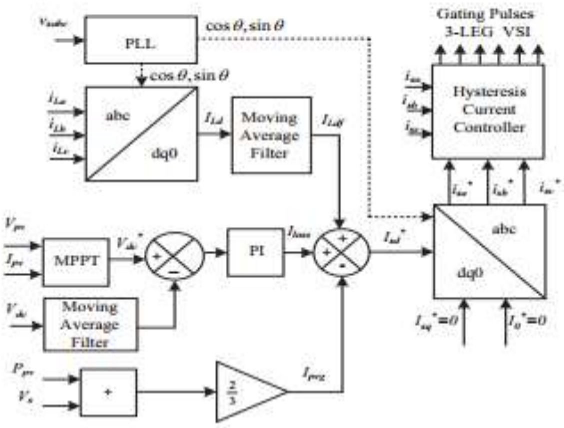
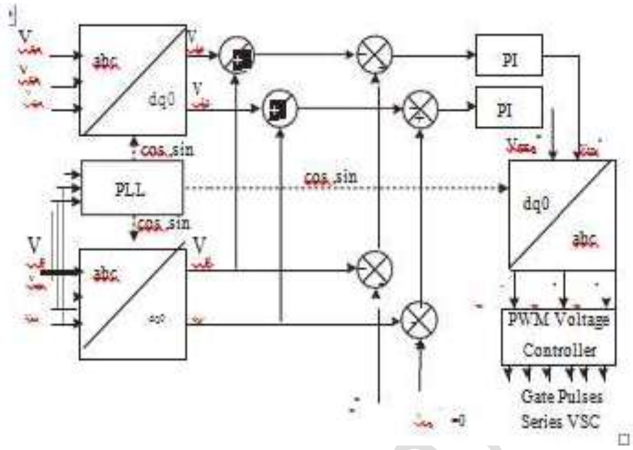


Control Structure of Shunt Compensator



Control Structure of Series Compensator

B. Control of Series Compensator

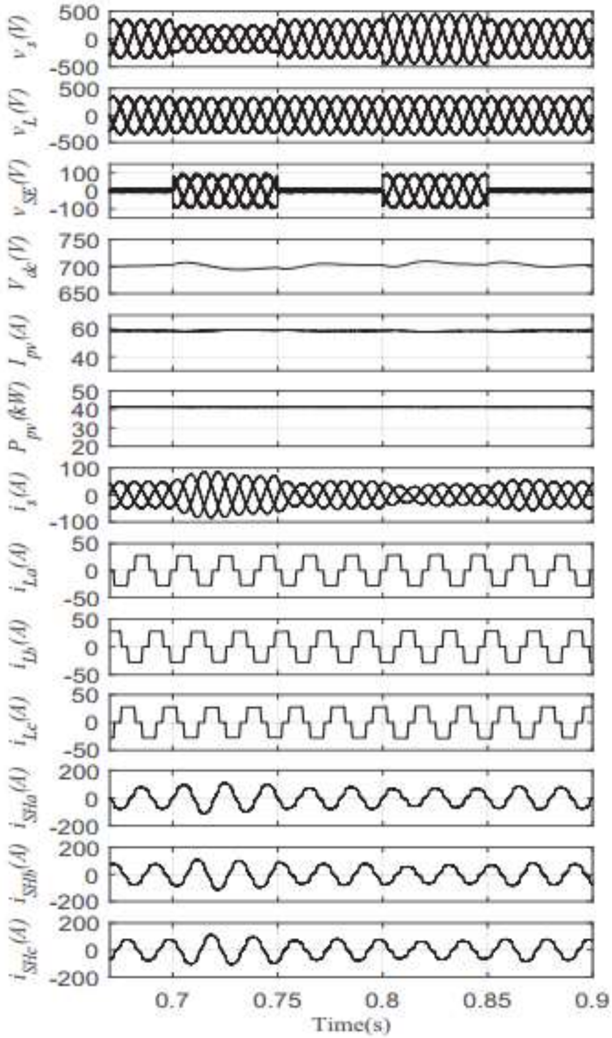
The bus voltage is detected and then transformed into the synchronous dq0 reference frame The control strategy for the series compensator are pre-sag compensation, in phase compensation and energy optimal compensation. In this work, the series compensator injects voltage in same phase as that of grid voltage, which results in minimum injection voltage by the series compensator. The control structure of the series compensator is shown in Fig.5. The fundamental component of PCC voltage is extracted using a PLL which is used for generating the reference axis in dq-0 domain. The reference load voltage is generated using the phase and frequency information of PCC voltage obtained using PLL. The PCC voltages and load voltages are converted into d-q-0 domain. As the reference load voltage is to be in phase with the PCC voltage, the peak load reference voltage is the d-axis component value of load reference voltage. The q-axis component is kept at zero. The difference between the load reference voltage and PCC voltage gives the reference voltage for the series compensator. The difference between load voltage and PCC voltage gives the actual series compensator voltages. The difference between reference and actual series compensator voltages is passed to PI controllers to generate appropriate reference signals. These signals are converted to abc domain and passed through pulse width modulation (PWM) voltage controller to generate appropriate gating signals for the series compensator.

IV. SIMULATION STUDIES

The steady state and dynamic performances of PV-UPQC are analyzed by simulating the system in MATLAB-SIMULATION software. The load used is a nonlinear load consisting of three phase diode bridge rectifier with R-L load. The solver step size used for the simulation is 1e-6s. The system is subjected to various dynamic conditions such as sag and swell in PCC voltage and PV irradiation variation. The detailed system parameters are given in Appendix.

A .Performance of PV-UPQC at PCC Voltage Fluctuations

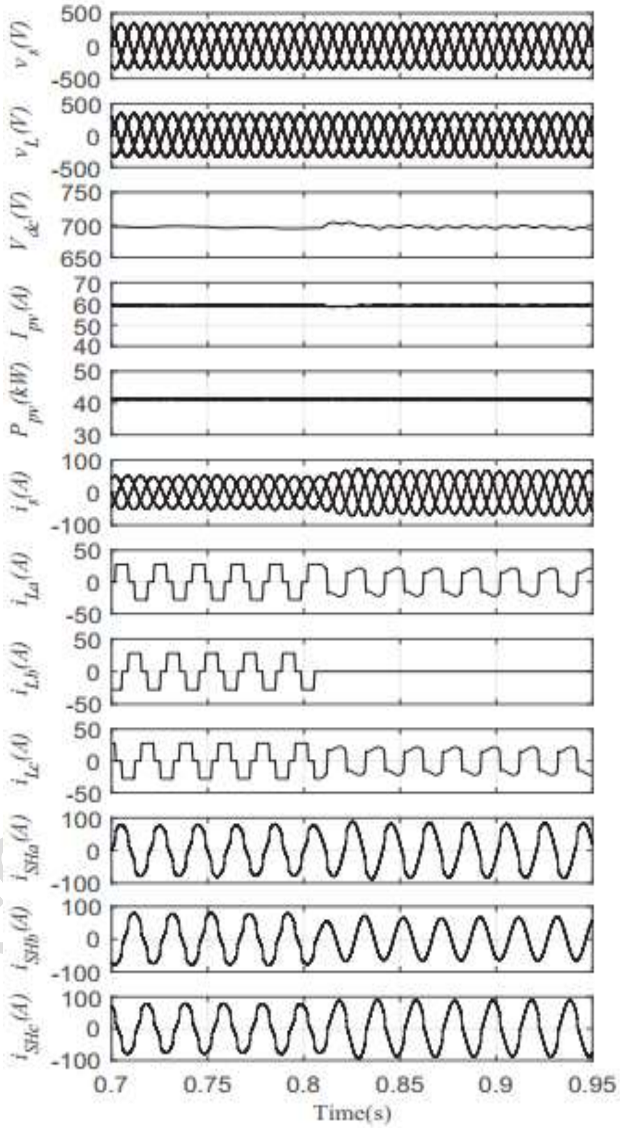
The dynamic performance of PV-UPQC under conditions of PCC voltage sags/swells is shown in Fig.4. The irradiation (G) is kept at 1000W/m2. The various sensed signals are PCC voltages (vs), load voltages(vL), series compensator voltages (vSE), DC-link voltage (Vdc), solar PV array current (Ipv), solar PV array power (Ppv), grid currents (iS), load currents (iLa, iLb, iLc), shunt compensator currents (iSHa, iSHb, iSHc). Between 0.7s and 0.75s, there is voltage sag of 0.3pu and from 0.8s to 0.85s there is voltage swell of 0.3pu. The series compensator compensates for the grid voltage under these conditions by injecting a suitable voltage Vse in opposite phase with the grid voltage disturbance to maintain the load voltage at rated voltage condition.



Performance of PV-UPQC under Voltage Sag and Swell Conditions

B. Performance of PV-UPQC at Load Unbalancing Condition

The dynamic performance of PV-UPQC under load unbalance condition is shown in Fig.5. At t=0.8s, phase ’b’ of the load is disconnected. It can be observed that the grid current is sinusoidal and at unity power factor. The current fed into the grid rises leading due to the reduction in the total effective load. The DC-link voltage is also stable and it is maintained near its desired regulated value of 700V.



Performance PV-UPQC during Load Unbalance Condition

C.Performance of PV-UPQC under Varying Irradiation

The dynamic performance of PV-UPQC under varying solar irradiation is shown in Fig.6. The solar irradiation is varied from 500W/m2 at 0.8s to 1000W/m2 at 0.85s. It is observed that as irradiation increases, the PV array output increases and hence grid current rises as the PV array is feeding power into the grid. The shunt compensator tracks MPPT along with compensating for the harmonics due to load current. The harmonic spectra and THD load current and grid current are shown in Fig. 7 and Fig.8. It is observed that the load current THD is 26.31% and the grid current THD is 2.00% thus meeting the requirement of IEEE-519 standard [31].

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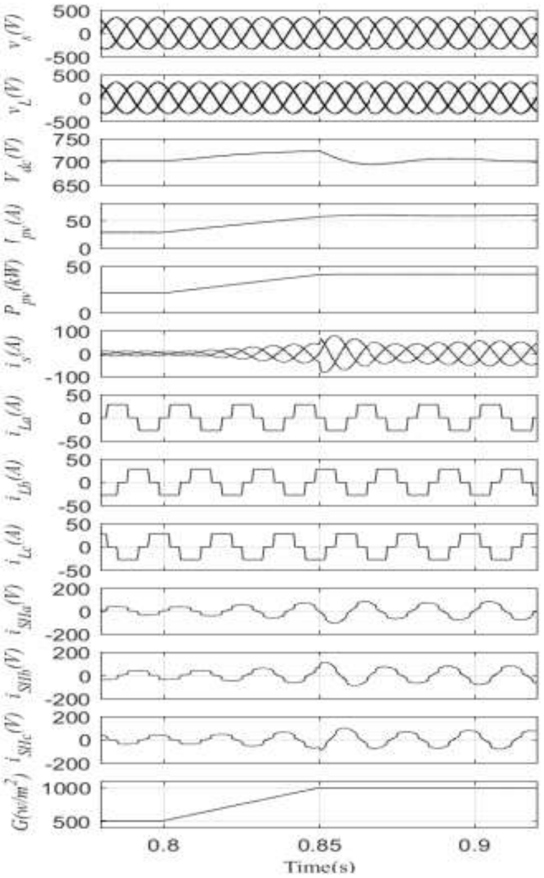
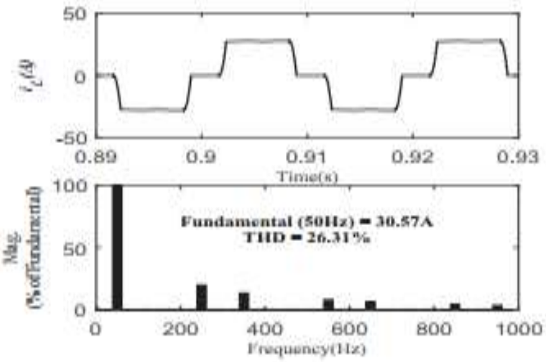
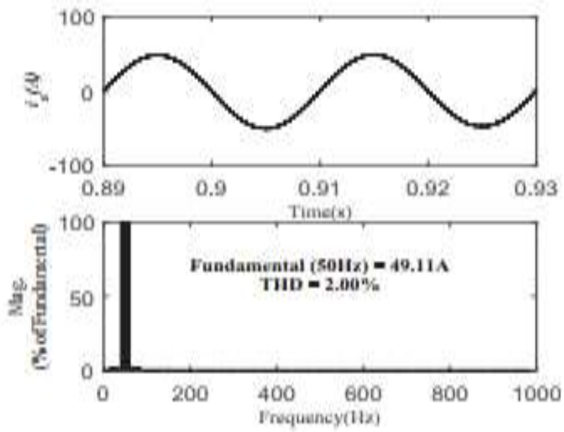


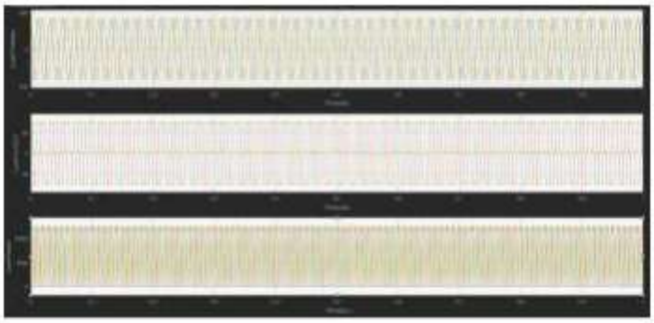
Performance PV-UPQC at Varying Irradiation Condition



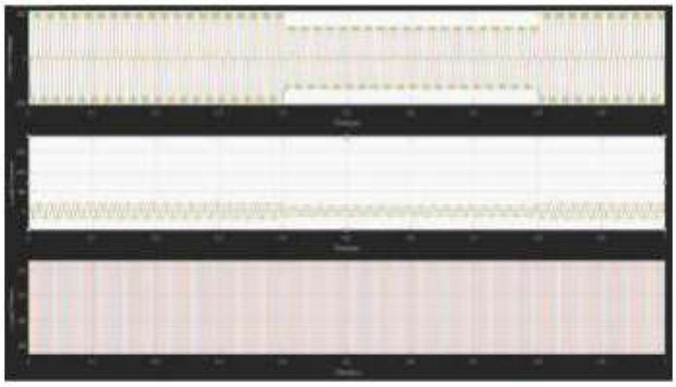
Load Current Harmonic Spectrum and THD



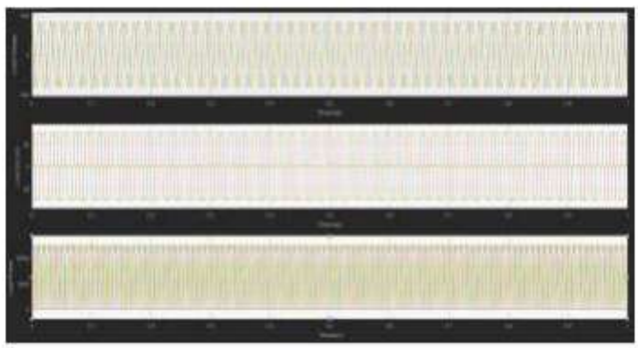
Grid Current Harmonic Spectrum and THD



Load voltage, current and power with load with UPQC



Load voltage, current and power with load without UPQC(generation of sag)



Load voltage, current and power with load with UPQC

V. CONCLUSION

In this work modeling and simulation of UPQC with necessary control strategy is implemented. The simulation results showed clearly the performance of the UPQC in mitigating the voltage sag and swell. The UPQC is modeled in conjunction with solar photovoltaic for multi control function. The source voltage and source current harmonic re eliminated by shunt controller and Voltage sag and swell are eliminated by series controller. The use of

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solar photovoltaic gives dual function as it gives clean energy with improvement of power quality. In this paper. The nonlinear load is connected to the system and result of voltage, current and power is observed with and without UPQC.

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