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Some Aspects on Design and Performance Evaluation of Integrated Three Phase Solar PV-UPQC

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ABSTRACT: This paper dealt the design and operation of an integrated, unified three-phase solar photovoltaic power quality conditioner (PV-UPQC). Shunt and series voltage compensators are coupled back to back with a shared DC-link to form the PV-UPQC. Besides with adjusting for load current harmonics, the shunt compensator also extracts energy from a PV array. For better performance of the PV-UPQC, a moving average filter-based improved synchronous reference frame control is employed to extract the load active current component.Grid voltage sags and swells are just two examples of the power quality issues that the series compensator corrects. During sag and swell circumstances, the compensator injects voltage that is either in phase or out of phase with the point of common coupling (PCC) voltage. The suggested solution combines the advantages of producing clean energy with bettering electricity quality. By simulating in Matlab-Simulink under a nonlinear load, the steady state and dynamic performance of the system are assessed. A scaled-down laboratory prototype is then used to test the system's performance in the presence of various disturbances, including load unbalance, PCC voltage swings, and irradiation fluctuation.

KEYWORDS:UPQC,power quality, shunt- series compensator, solar-PV, PCC.

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I. INTRODUCTION

There is an emphasis on clean energy generation is increasing day by day and the solar PV generation is such clean energy generation sources available abundantly. The power quality of electric power has become an important issue in electrical power system operation in the last few years. But due to the intermittent nature of the PV energy sources and also the increased penetration of such systems particularly in weak distribution systems leading to voltage quality problems like voltage sags/swells which eventually lead to the grid instability. With the advancement of semiconductor technology there is an increased penetration of power electronic loads Which draws nonlinear currents these currents cause voltage distortion problems at the point of common coupling in the distribution systems. These voltage quality problems lead to frequent false tripping of power electronic systems, malfunctioning and false triggering system components. Power quality issues at both load side and grid side are the major problems faced by modern distribution systems integrated with the three-phase renewable Grid interfaced source.

An unified power quality conditioner (UPQC) has been considered in this work. The solar PV Integrated with UPQC has numerous advantages such as improving power quality of the grid, protecting critical loads from grid side disturbances. UPQC is the combination of both is hunt and series compensators. The is hunt compensators compensates for ithe load power quality problems such as load current harmonics and load reactive power and also extracts power from the PV-array by using Maximum Power Point Tracking (MPPT).The series compensator protects the load from the grid side power quality problems such as voltage sags/swells by injecting appropriate voltage in phase with the grid voltage. The imajor task in the control of UPQC is the generation of reference Signal. The techniques for the reference signal generation are broadly classified in to time-domain and frequency domain techniques. The commonly used techniques are instantaneous reactive power theory(p-q Theory),synchronous ireference iframe itheory i(d-q itheory) iand iinstantaneous symmetrical component theory. The main issue with the use of synchronous reference frame theory is that during load unbalanced condition double harmonic component is present in the d-axis current. This result in poor dynamic performance of UPQC. To mitigate this a moving average filter (MAF) is used to filter the d-axis current to obtain fundamental load active current. The Present Work Concentrated on Analysis of an UPQC integrated with Solar PV using MAF along with MPC to improve the dynamic performance. The Proposed System is analyzed under Dynamic and steady state conditions using Matlab-Simulink software.

In [1] B.Mountain outlines the opportunities and challenges associated with solar pv systems. In [28] B.subuddi given a comparative study on different MPPT techniques. In [2] A.R Malekpur outlined the significant factors associated with the integration of solar PV in smart distribution systems. With the integration of renewable resources imposes new challenges in power quality problems. In [8] B.singh illustrated the problems arising with power quality and its mitigation techniques. Many mitigation techniques that available for controlling power quality are assuring grid adequacy, advanced distributed resources, codes and standards, Enhanced Interface devices, equipment design, harmonic cancellation, dedicated line or transformer, optimal placement and sizing of capacitor bank, de-rating of devices, reducing the number of faults, faster fault clearing, improved network design and operation, harmonics filters, improved end user equipment, FACTS devices and custom power devices. Among them,Unified Power Quality Conditioner (UPQC) is most efficient and effective custom power device used in the power systems to mitigate the power quality issues. The UPQC is a combination of series(DVR) and shunt (DSTATCOM) compensators. The series compensator compensates for the voltage sags and swells where as the shunt compensator compensates the load side disturbances. It is a device that utilizes solid stste power electronic components. The concept of UPQC integrated with solar PV system is demonstrated in [18] by B.Singh in this they proposed the design and analysis of three phase Solar PV-UPQC. In [28,29] B.Subuddi proposed several compensation strategies of dynamic voltage restorer taking in to consideration of compensation for voltage sag and swells. In [11,12,13,23] proposed various control strategies for the d-statcom and dvr with usage of different filters such as active, passive, kalman and moving average filters. Synchronous reference frame d-q theory based control approach has been proposed in[18,25]. The purpose of Integrating the conventional grid with the solar PV through UPQC is to make optimal usage of available solar energy and to reduce the power generation through conventional resources.

II. SOLAR PV SYSTEM MODEL

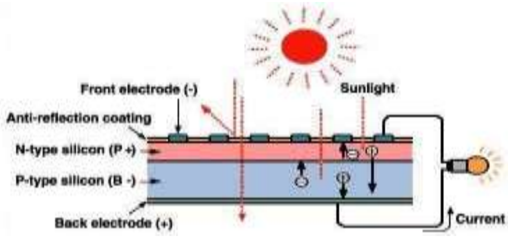

Fig. Schematic Cross-Section of a Typical Solar Cell

Typically a solar cell can be modelled by a current source and an inverted diode connected in parallel to it. It has its own series and parallel resistance. Series resistance is due to hindrance in the path of flow of electrons from n to p junction and parallel resistance is due to the leakage current. When irradiance hits the surface of solar PV cell, an electrical field is generated inside the cell. This process separates positive and negative charge carriers in an absorbing material (joining p-type and n-type). In the presence of an electric field, these charges can produce a current that can be used in an external circuit. This generated current depends on the intensity of the incident radiation. The higher the level of light intensity, the more electrons can be unleashed from the surface, the more current is generated.

The most important component that affects the accuracy of the simulation is the PV cell model. Modeling of PV cell involves the estimation of the I-V and P-V characteristics curves to emulate the real cell under various environmental conditions. An ideal solar cell is modeled by a current source in parallel with a diode. However no solar cell is ideal and thereby shunt and series resistances are added to the model.

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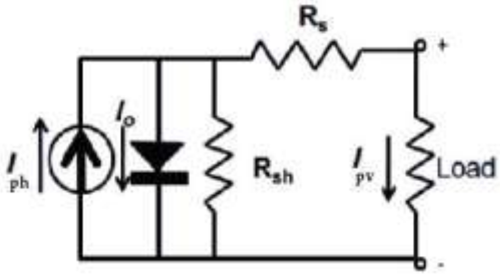

Fig. Equivalent Circuit of PV cell

The voltage–current characteristic equation of a solar cell is provided as: Module photo-current I_{ph}:

$$I_{ph} = [I_{sc} + K_i(T - 298)] \times Ir/1000$$

Here, I_{ph}: photo-current (A); I_{sc}: short circuit current (A) ; K_i: short-circuit current of cell at 25 °C and 1000 W/m^2; T: operating temperature (K); Ir: solar irradiation (W/m^2).

Module reverse saturation current I_{rs}:

$$I_{rs} = I_{sc}/[\exp(qV_{OC}/N_S knT) - 1]$$

Here, q: electron charge, = 1.6 × 10^{-19}C; V_{oc}: open circuit voltage (V); N_s: number of cells connected in series; n: the ideality factor of the diode; k: Boltzmann's constant, = 1.3805 × 10^{-23} J/K.

The module saturation current I_0 varies with the cell temperature, which is given by:

$$I_0 = I_{rs}\left[\frac{T}{T_r}\right]^3 \exp\left[\frac{q \times E_{g0}}{nk}\left(\frac{1}{T} - \frac{1}{T_r}\right)\right]$$

Here, T_r: nominal temperature = 298.15 K; E_{g0}: band gap energy of the semiconductor, = 1.1 eV;

The current output of PV module is:

$$I = N_P \times I_{ph} - N_P \times I_0 \times \left[\exp\left(\frac{V/N_S + I \times R_s/N_P}{n \times V_t}\right) - 1\right] - I_{sh}$$

With

$$V_t = \frac{k \times T}{q}$$

And

$$I_{sh} = \frac{V \times N_P/N_S + I \times R_S}{R_{sh}}$$

Here: N_p: number of PV modules connected in parallel; R_s: series resistance (Ω); R_{sh}: shunt resistance (Ω); V_t: diode thermal voltage (V).The current source Ipv represents the cell photo current, Rsh and Rs are used to represent the intrinsic series and shunt resistance of the cell respectively. Usually the value of Rsh is very large and that of Rs is very small, hence they may be neglected to simplify the analysis.The PV mathematical model used to simplify our PV array is represented by the equations(1)to(4).

III. CONTROL OF SERIES COMPENSATOR (SERIES APF)

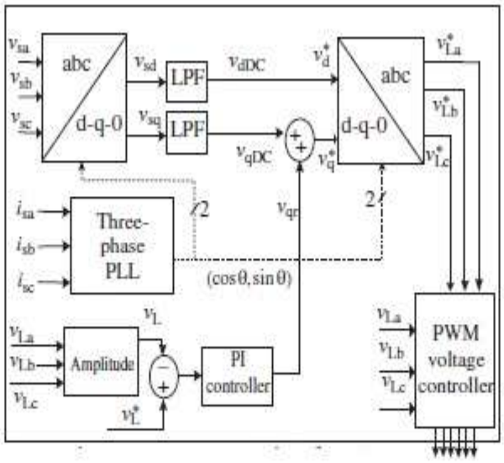

Fig . Control Scheme of Series Compensator

The control block of the DVR of the UPQC is shown in above Figure, in which the synchronous reference frame theory is used for reference signal generation. The PCC voltages (vs), supply currents (is), and load terminal voltages (vL) are sensed for deriving the gate signals of IGBTs. The PCC voltages are converted to the rotating reference frame using the abc–dq0 conversion using the Park's transformation with unit vectors (sin θ, cos θ) derived from the supply currents using a PLL as follows:

$$I_0 = I_{rs}\left[\frac{T}{T_r}\right]^3 \exp\left[\frac{q \times E_{g0}}{nk}\left(\frac{1}{T} - \frac{1}{T_r}\right)\right]$$

Here, Tr: nominal temperature = 298.15 K; Eg0: band gap energy of the semiconductor, = 1.1 eV; The current output of PV module is:

$$\begin{bmatrix} vsq \\ vsd \\ vs0 \end{bmatrix} = 2/3 \begin{bmatrix} \cos\theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ \sin\theta & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \begin{bmatrix} vsa \\ vsb \\ vsc \end{bmatrix}$$

Then, d-axis and q-axis voltages consist of DC (fundamental) and ripple (harmonic) components:

$$vsd = vdDC + vLdAC$$
$$vsq = vqDC = vLqAC$$

The amplitude of AC load terminal voltage (VL) is controlled to its reference voltage (VL*) using a PI controller and the output of the PI controller is considered as the voltage (vqr) to be injected by the

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DVR. The amplitude of AC load terminal voltage (VL) is calculated from the load terminal voltages (vLa, vLb,vLc) as follows:

$$VL = \sqrt{(\frac{2}{3})}\sqrt{(v^2La + v^2Lb + v^2Lc)}$$

Then, a PI controller is used to regulate this voltage to a reference value as follows:
$Vqr(n) = vqr(n-1) + Kpq\{vte(n) - vte n-1 + Kiqvte(n),$

where vte(n)= V*L(n)-VL(n) denotes the error between reference (V*L(n) and sensed (VL(n)) terminal voltage amplitudes at the nth sampling instant, and Kpq and Kiq are the proportional and integral gain constants of the DC bus voltage PI controller, respectively.
The reference quadrature-axis load voltage is

$$V*Lq = Vqdc + Vqr$$

The reference direct-axis load voltage is

$$V*Ld = VdcDC$$

The reference load voltage in the abc frame is obtained by reverse Park's transformation,

$$\begin{bmatrix} v*La \\ v*Lb \\ v*Lc \end{bmatrix} = \begin{bmatrix} cos\theta & sin\theta & 1 \\ cos(\theta - \frac{2\pi}{3}) & sin(\theta - \frac{2\pi}{3}) & 1 \\ cos(\theta + \frac{2\pi}{3}) & sin(\theta + \frac{2\pi}{3}) & 1 \end{bmatrix} \begin{bmatrix} v*Lq \\ v*Ld \\ v*L0 \end{bmatrix}$$

The reference load voltages (v*La) (v*Lb) (v*Lc) and the sensed load voltages (vLa, vLb, vLc) are used in a PWM controller to generate gating pulses to the VSC of the DVR.

IV. CONTROL OF SHUNT COMPENSATOR USING MPC CONTROLLER

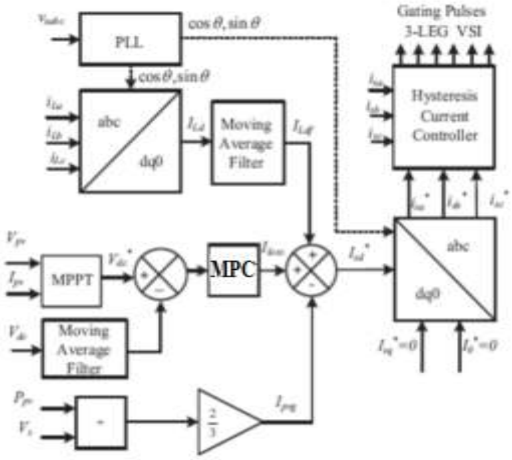

Fig. Control Scheme of shunt compensator using MPC controller

In the UPQC shunt control system, the considered MPC controller was located in the place of the PI controller. The output values are not correct while using the PI controller, during the steady state condition. The MPC controller is used to mitigate the limitations of the PI controller. During steady state output, the MPC controller can get accurate results. This controller produces the reference voltage by differentiating the voltage of the dc connection and the voltage of the reference dc link. By using the MPC controller, the reference current can be analyzed.

V. SYSTEM CONFIGURATION AND DESIGN

In the below figure, the PV-UPQC configuration is seen. A three-stage structure is required to contain the PV-UPQC. The PV-UPQC provides both the shunt and series compensation. On the load side, the shunt compensator is connected where the series compensator is connected on the source side. The PV array powered by the sun is directly fused through an opposite obstructing diode to the DC-association of UPQC. In voltage control mode, the series compensator functions and compensates for the sags/swells of the device voltage. By interconnecting inductors, the shunt and series compensators are connected to the system. A series injection transformer is used to inject the voltage in to the line through series compensator. The load used is a nonlinear load.

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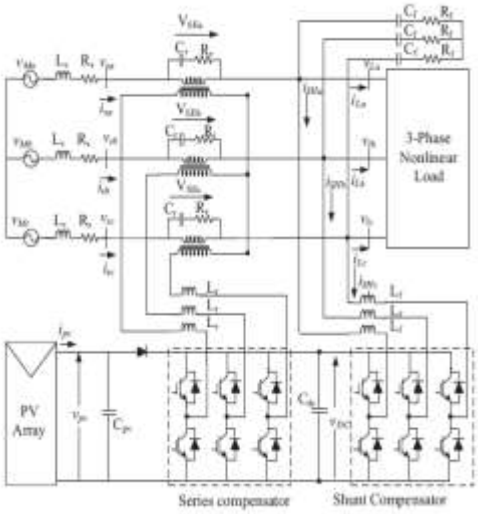

Fig. System Configuration PV-UPQC

A) PV-UPQC Concept

The PV-UPQC arrangement system starts with proper measurement of PV system, DC-link condenser, voltage level of DC-Link, etc. The shunt compensator extracts the PV Array current apart from compensating the load current harmonics. Since the PV Array directly connected to the UPQC DC-Link, the final goal for the PV System is that the voltage of the MPP is equal to the DC link voltage required.

b) Voltage Magnitude of DC-Link:

The value of DC link voltage Vdc depends upon the phase voltage of the system ad the modulation depth.

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

The grid line voltage is used where the modulation depth (m) is as 1 andVLL. The DC-bus Voltage is set to$700\,V(approx)$, which corresponds to the MPPT operating voltage of the PV under STC conditions. The minimum DC Bus voltage is set to$677{,}7\ V$.

c) **Capacitor ratings of DC-Bus:**

The DC-link Condenser sized based on the DC-bus voltage and power requirements. For the DC-bus condenser the energy balance is equation is[8],

$$C_{dc} = \frac{3k_a V_{ph} I_{sh} t}{0.5*(V_{dc}^2 - V_{dc1}^2)} = \frac{3*0.1*1.5*239.6*34.5*0.03}{0.5*(700^2 - 677.79^2)} = 9.3mF \quad (2)$$

Where Vdc is average DC-bus voltage, Vdc1 is the lower value of DC-bus voltage. a is the over-loading factor, Vph phase voltage, t is the minimum time required for the achievement of steady state value. 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 $dynamicenergychange = 10\%, k = 0.1, theassessmentofCdcisgottenas\ 9.3\,mF.$

d) Shunt Compensator Interfacing Inductor:

The shunt compensator interface inductor rating depends on ripple current, frequency of switching, and DC Link voltage. The equation for the interfacing inductor is

$$L_f = \frac{\sqrt{3}mV_{dc}}{12af_{sh}I_{cr,pp}} = \frac{\sqrt{3}*1*700}{12*1.2*10000*6.9} = 800\mu H \approx 1mH \quad (3)$$

where m is modulation depth, a is pu value of maximum over load, 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 of inductance and it is choosen as $1mH$.

e) Arrangement of Injection Transformer:

The PV-UPQC is needed to compensate for a sag/swell of 0.3 pui.e 71.88 V. Accordingly, the required voltage to be injected is just 71.88 V which accomplishes low modulation for the series compensator when the DC-Link voltage is 700V. To work the series compensator with less harmonics, one keeps the modulation to almost unity. As such a strategy the series transformer is utilized with a turns ratio,

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

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

$$S_{SE} = 3V_{SE}I_{SEsag} = 3*72*46 = 10kVA \quad (5)$$

$$L_r = \frac{\sqrt{3}*mV_{dc}K_{SE}}{12af_{se}I_r} = \frac{\sqrt{3}*1*700*3}{12*1.2*10000*7.1} = 3.6mH \quad (6)$$

where m is the modulation depth, a is the pu value of peak over load. fse is the switching frequency, Ir is the inductor current ripple, which is taken to be 20% of system 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.

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Table No-1 System Parameters used for PV-UPQC

PCC line voltage and system frequency	415V,50Hz
DC-link Voltage	700V
Dc-Link capacitor	9.3mF
Shunt and series compensator interfacing inductors	1mH,3.6mH
PWM switching ferequency	10kHz
Ripple filter	10micro F
Dc-Link PI controller gains	Kp=1.5,Ki=0.1
Series VSC PI gains	Kp=8Ki
PV Array open circuit voltage	864V
Short circuit current of PV Array	62.65A
MPP voltage	701V
MPP current	58.94A
PV array power	41.35kW

VI.SIMULATION AND RESULTS

The below figure shows the matlab simulation model of a MPC based PV-UPQC under voltage sag and voltage swell conditions , in which it consists of a three phase non-linear load fed with three phase supply through transmission lines. And due to non linear load the power quality problem like voltage sag and voltage swell problems and current distortion problems may rise, which can be controlled by PV-UPQC is the integration of shunt and series compensator.

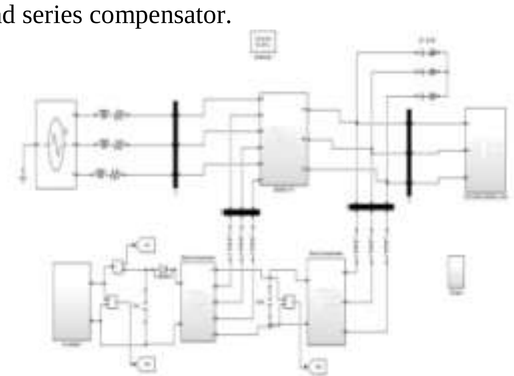
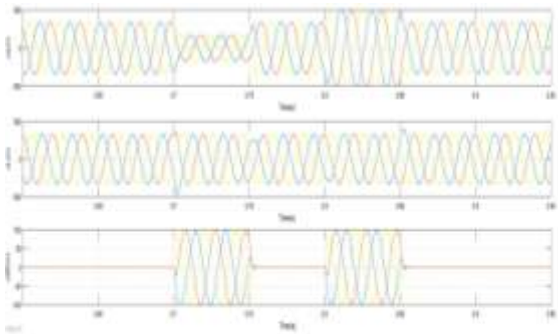
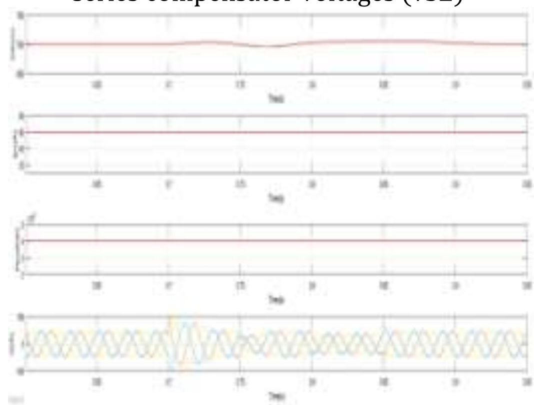


Fig. Simulation Model MPC based PV-UPQC under Voltage Sag and Swell Conditions



$(a) PCC\ voltages\ (vs), load\ voltages\ (vL)$, series compensator voltages (vSE)



b)DC − link voltage (Vdc), solar PV array current (Ipv), solar PV array power (Ppv)Grid Currents(iS)

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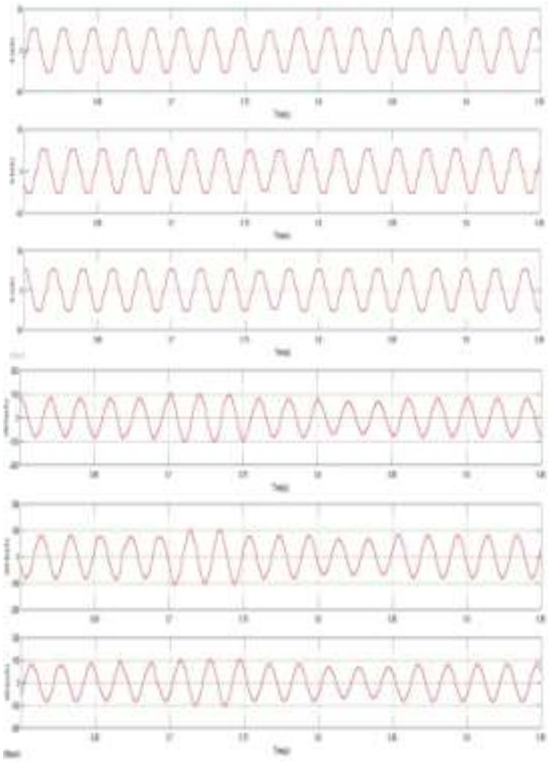


(c) Load currents (iLa, iLb, iLc), (d)shunt compensator currents (iSHa, iSHb, iSHc)
Fig. Performance of MPC PV − UPQC under Voltage Sag and Swell Conditions

A) Performance of PV-UPQC at Load Unbalancing Condition

The dynamic performance of PV-UPQC with MPC regulator under load unbalance condition is appeared At t=0.8s, phase 'b' of the laod is disconnected. The source current being sinusoidal and the DC-Link Voltage is maintained near its regulated value.

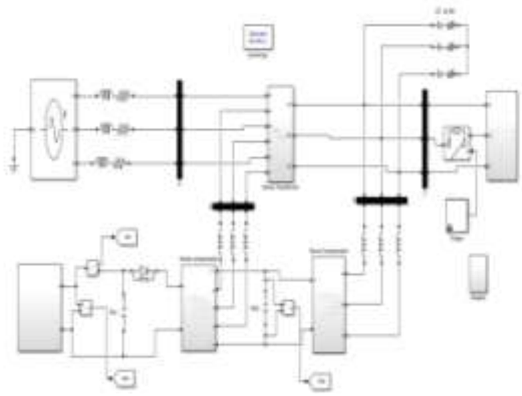
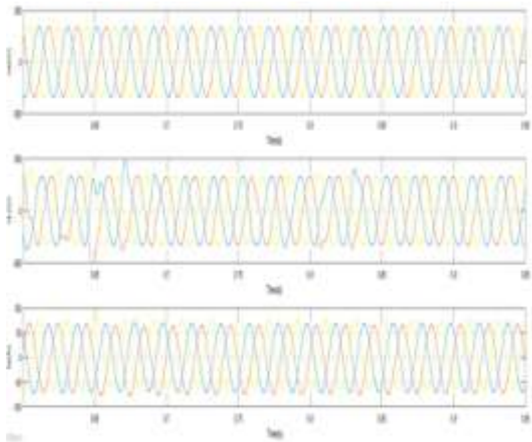
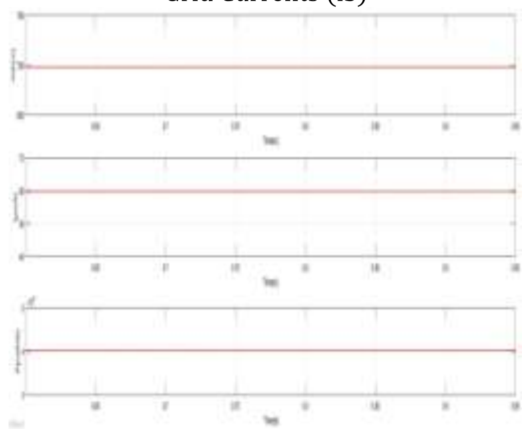


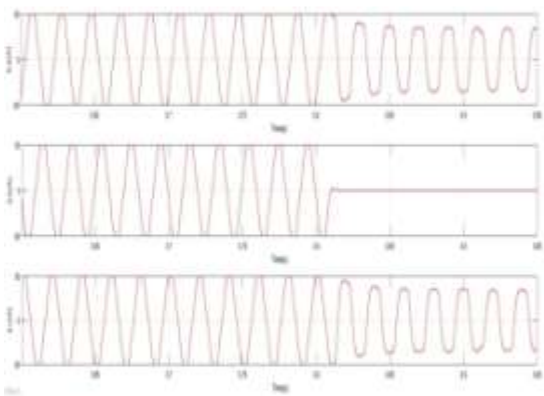
Fig . Simulation model of MPC based PV-UPQC during Load Unbalance Conditions



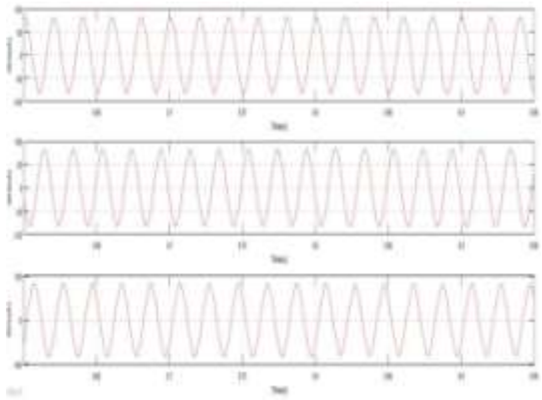
(a)PCC voltages (vs), load voltages (vL), Grid Currents (iS)



(b)DC − link voltage (Vdc), solar PV array current (Ipv), solar PV array power (Ppv)



(c)Load currents (iLa, iLb, iLc),



d)shunt compensator currents (iSHa, iSHb, iSHc)
Fig. Performance MPC based PV – UPQC during Load Unbalance Condition

b) Performance of PV-UPQC under Varying Irradiation

The dynamic showcase of PV-UPQC with MPC controller under varying irradiation is shown in Fig below. The irradiation is changed from 500W/m2 at 0.8s to 1000W/m2 at 0.85s.It is noticed that as the irradiation is increased the PV output is increased. The THD of both the load and grid gridcurrrents is under the Standards of IEEE 519.

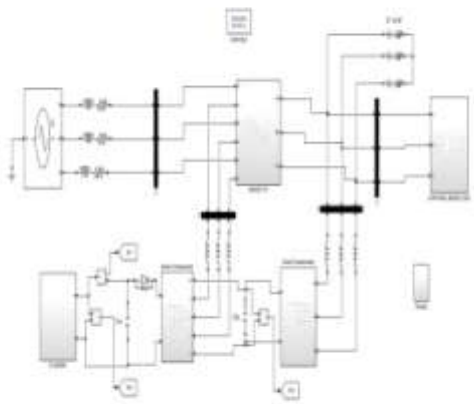
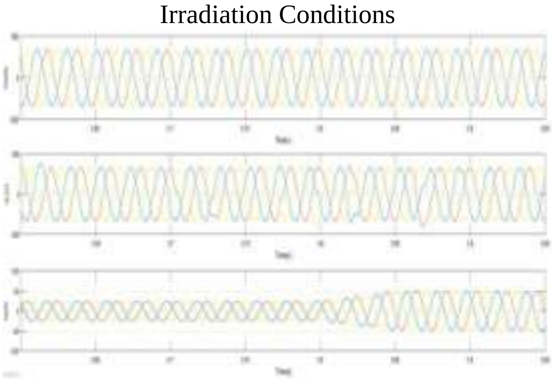
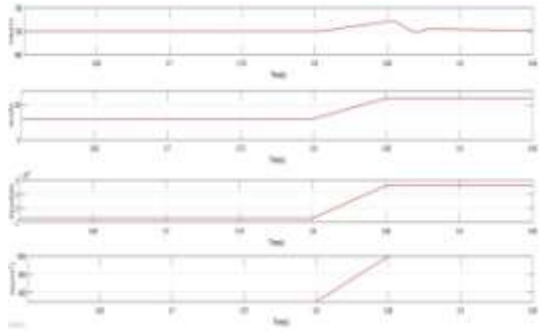


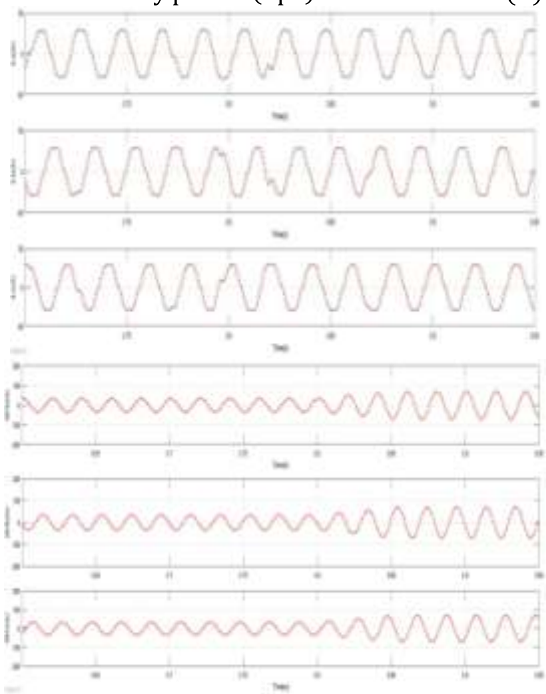
Fig . Simulation model of PV-UPQC at Varying Irradiation Conditions



(a)PCC voltages (vs), load voltages (vL), Grid Currents(iS)



(b)DClink voltage (Vdc), solar PV array current (Ipv),
solar PV array power (Ppv)Solar Irradiation(G)



(c)Grid currents (iS), load currents (iLa, iLb, iLc), shunt compensator currents (iSHa, iSHb, iSHc)
Fig. Performance PV – UPQC at Varying Irradiation Condition

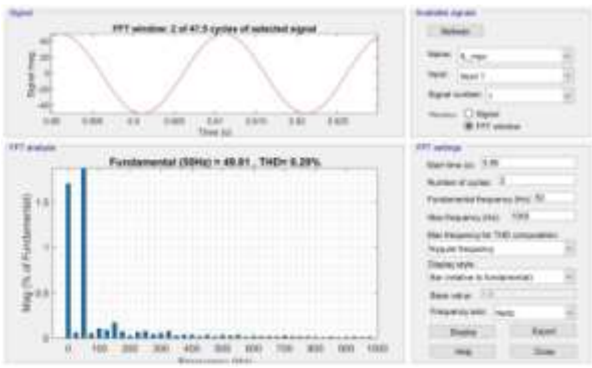


Fig . THD in grid current during change in solar irradiation

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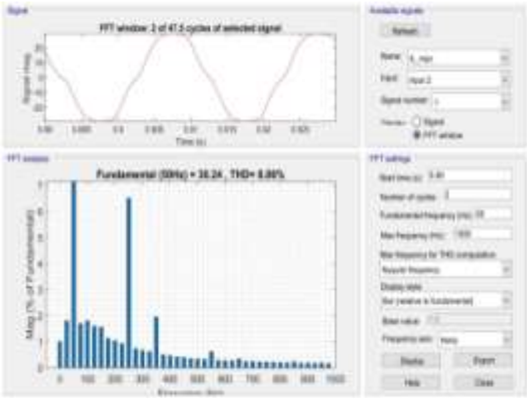

Fig. THD in load current during change in irradiation

Table No:2. Comparison of THD Values

Comparison of Total Harmonic Distortion	
THD(PI Controller)	THD(MPC Controller)
Grid Currents=21.06%	Grid Currents=8.06%
Load Currents=1.49%	Load Currents=0.29%

The THD Value of the both PI and MPC controllers are compared in the above table no.4.It is observed that the Grid Current and Load current THD Value are reduced with MPC when compared with the PI Controller and are maintained under the limitation of IEEE 519-1992 Standards.

VII. CONCLUSION

Unified quality conditioner was studied iand ianalysed in this thesis for power quality enrichement. UPQC is a type of advance hybrid filter which uses series APF for removal of voltage realted problmes like voltage dip/rise, fluctutaion, imbalance and shunt APF for removal of harmonics in current harmonics. What type of problems are there in power quality was studied and discussed. UPQC system is developed and discussed in detail. The simulink models of Shunt APF, Series APF, UPQC are developed. Shunt APF model is developed using "Synchronous reference frame Theory" and control techniques used here is model predictive controller. The simulation is done and current harmonics are eliminated and current drawn from source is completely sinusoidal. The THD of source current is within the limit that is 10%. Series APF model is developed using Park's transformation and controlling techniques used are Model predictive controller. The simulation is done and source voltage dip/rise are mitigated and load voltage is made completely balanced. UPQC integrated with PV System model was developed by joining Shunt APF and series APF back to back using DC capacitor. The controlling techniques used here are model predictive controller. The simuation is done and current harmonics are removed and source current is complerely sinusoidal. And the voltage dip/rise in supply side is mitigated and load voltage is perfectly balanced. The THD of source current is within the limit that is less than 5%.

VIII. FUTURE EXTENSION:

The work in this theory is restricted to Model predictive based(MPC) based PV-UPQC only. This work can be further implemented for the power quality improvement in the integration of other renewable sources with the grid. The power quality can be refined more error-free with the other controllers such as Fuzzy logic controllers, Adaptiveneuro fuzzy deduction controller(ANFIS) etc.

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