Implementation and Performance Evaluation of Three Phase Solar PV-UPQC for Power Quality Enhancement

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ABSTRACT
This paper deals with the modeling, simulation and performance analysis of the three-phase solar PV (photovoltaic) integrated UPQC (PV-UPQC). This proposed system combines both the functionality of distributed generation and active power filtering. The PV-UPQC is the combination of shunt compensator and series compensator with solar PV array integrated to the DC-link of UPQC. The shunt compensator of the PV-UPQC counteracts for the load current harmonics and provides active power injection. The shunt compensator is also deriving the maximum power from PV array by controlling it at its maximum power point (MPP). The series compensator counteracts for the power quality problems related to grid such as grid voltage sags/swells, voltage disturbances by injecting voltage opposite in phase with the grid voltage. The dynamic performance of the proposed PV-UPQC system is simulated at conditions of varying irradiation and grid voltage disturbances using Matlab-Simulink under a nonlinear load consisting of a bridge rectifier with load.

Keywords— Power Quality, DSTATCOM, DVR, UPQC, Solar PV, MPPT,PCC.PV-UPQC

I. INTRODUCTION
In the modern electrical world with the increase in integration of renewable energy systems such as solar PV energy and wind energy into modern electrical distribution systems owing to its benefits of being eco-friendly. However, these energy sources are discontinuous in nature. With the proliferation of the power semi conductor devices such as power diodes, thyristors, IGBTs, GTOs etc. over the last quarter a century. They increases controllability of the equipment but at the same time power quality and efficiency decreases. They provides the polluted load current and voltage waveforms. With the increase in installation of renewable energy sources and nonlinear loads results in various power quality problems both at load side and grid side.

Since renewable energy sources like solar PV energy and wind energy are intermittent, their increased used in distribution systems leads to power quality problems like voltage sags/swells, interruption, flicker and eventually instability in the grid [1]. These power quality problems can also lead to frequent malfunctioning of power electronic systems and false triggering of electronic systems and increased capacitor banks heating etc [2]–[4]. Current quality issues are usually caused by the nonlinear loads connected in the power distribution systems. These nonlinear loads inject harmonics into distribution system. These current harmonics distorts the point of coupling (PCC) voltage especially in weak grids apart from causing distribution cables losses and transformers.

Custom power devices such as distribution static compensator (DSTATCOM), dynamic voltage restorer (DVR) and unified power quality conditioner (UPQC) are used to mitigate power quality problems caused at the load side as well as at grid side. DSTATCOM [5] is a shunt connected power electronic device which compensates for the power quality issues caused by loads such as reactive current, harmonics in the system. DVR is a series connected power electronic device which counteracts for the grid voltage sag/swells [6]–[10]. UPQC is the combination of shunt and series compensator which combines functionality of both DSTATCOM and DVR for the power quality enhancement[7].

Recently the concept of integration of distributed generation sources with active power filters [8]–[10] have been reported in the literature. The integration of PV array with UPQC [11]–[12] has numerous advantages such as grid power quality enhancement, load side power quality improvement, active power injection.

In this paper, the design and performance analysis of a three-phase PV-UPQC is presented. The dynamic performance of PV-UPQC is analyzed under conditions of grid voltage disturbances and irradiation variations. The load used is a nonlinear load consisting of an uncontrolled bridge rectifier alongwith.

II. SYSTEM CONFIGURATION AND DESIGN
The structure of the PV-UPQC is shown in Fig.1. The PV-UPQC is designed for a three-phase system. The shunt compensator is connected at the load side to handle the current quality issues. The solar PV array is directly
The control strategy considers that the supply current consists of three strings each containing 23 SPV modules. The SPV module and SPV array specification is given in Table 1.1 and Table 1.2 respectively.

### Table 1.1 Solar PV Module Specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Power(P)</td>
<td>254.97W</td>
</tr>
<tr>
<td>Open Circuit Voltage(V_{oc})</td>
<td>37.87V</td>
</tr>
<tr>
<td>Short Circuit Current(I_{sc})</td>
<td>8.82A</td>
</tr>
<tr>
<td>Voltage at Maximum Power Point(V_{max})</td>
<td>30.39V</td>
</tr>
<tr>
<td>Current at Maximum Power Point(I_{max})</td>
<td>8.39A</td>
</tr>
</tbody>
</table>

### Table 1.2 Solar PV Array Specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Power(P)</td>
<td>18 kW</td>
</tr>
</tbody>
</table>

III. SYSTEM MODELING AND DESCRIPTION CONTROL ALGORITHM

The UPQC system consists of a three phase supply and three-phase non linear loads. A shunt connected VSC is interfaced to the supply system via interfacing inductor. The DSTATCOM is modeled using the MATLAB/ Simulink environment. The control objective for the shunt portion of the UPQC is described below. The control algorithm for the DSTATCOM portion of the UPQC[4]. The objective of the DSTATCOM is to enhance the power quality of the supply current as well as to support the common DC bus of the DSTATCOM and DVR by absorbing active power and to estimate the reference supply currents and the gating pulses for the IGBTs of the VSC of the DSTATCOM. The reference supply currents are derived from the sensed PCC voltages (V_{sa},V_{sb},V_{sc}), load currents (i_{l_a},i_{l_b},i_{l_c}), and the common DC bus voltage (V_{dc})[4]. The load currents from the abc frame are first converted to the dq0 frame as follows:

\[
\begin{bmatrix}
    i_{ld} \\
    i_{ld}
\end{bmatrix} = \begin{bmatrix}
    \cos \theta & \cos(\theta - 2\pi/3) & \cos(\theta + 2\pi/3) \\
    \sin \theta & \sin(\theta - 2\pi/3) & \sin(\theta + 2\pi/3)
\end{bmatrix} \begin{bmatrix}
    i_{la} \\
    i_{lb} \\
    i_{lc}
\end{bmatrix}
\]

(1.1)

Where \(\cos \theta\) and \(\sin \theta\) are obtained using a three phase PLL over PCC voltages. A PLL signal is obtained from PCC terminal voltages for generating fundamental unit vectors for conversion of sensed currents to the dq0 reference frame. The SRF controller extracts DC quantities by low pass filter (LPFs) and hence the non-DC quantities (ripple) are separated from the reference signal[4].The d-axis and q-axis currents consist of DC and ripple (negative sequence and harmonics) components:

\[
i_{ld} = i_{ldc} + i_{ldc}
\]

(1.2)

\[
i_{lp} = i_{lpdc} + i_{lpdc}
\]

(1.3)

The control strategy considers that the supply must deliver the mean value of the direct-axis component of the load current along with the active power component current for maintaining the DC bus and the meeting losses (i_{bus}) in the UPQC. The output of the PI controller at the

![Fig. 1. System Configuration PV-UPQC](image-url)
DC bus voltage of the UPQC is considered as the current (i\text{loss}) for meeting its losses[4].

\[i_{\text{loss}}(n)=i_{\text{loss}}(n-1)+k_{pd} \{v_{sd}(n)-v_{dc}(n-1)\}+k_{pd}v_{dc}(n)\]

(1.4)

where \(v_{sd}(n)=v_{*_{dc}}-v_{dc}(n)\) is the error between the reference \((v^{*}_{dc})\) and sensed \((v_{dc})\) DC voltage at the nth sampling instant. And the \(K_{pd}\) and \(K_{pd}\) are the proportional and integral gain constants of the DC bus voltage PI controller[4].

Therefore, the amplitude of reference supply current is

\[i^{*}_{sc}=i_{dsc}+i_{loss}\]

(1.5)

The reference supply current must be in phase with voltage at PCC but with no zero-sequence component. It is therefore obtained by the reverse park’s transformation with \(i^{*}_{dq}\) and \(i^{*}_{0}\) as zero[4]. The resultant \(dq0\) currents are again converted into the reference supply currents using the reverse park’s transformation. A PWM current controller is used over the reference and sensed supply current to generate the gating signals for the IGBTs of the VSC of the DSTATCOM[4].

\[
\begin{bmatrix}
i^{*}_{sa} \\
i^{*}_{sb} \\
i^{*}_{sc}
\end{bmatrix} =
\begin{bmatrix}
\cos \theta & \sin \theta & 1 \\
\cos(\theta-2\pi/3) & \sin(\theta-2\pi/3) & 1 \\
\cos(\theta+2\pi/3) & \sin(\theta+2\pi/3) & 1
\end{bmatrix}
\begin{bmatrix}
i^{*}_{d} \\
i^{*}_{q} \\
i^{*}_{0}
\end{bmatrix}
\]

(1.6)

The Reference supply neutral current \((i^{*}_{sc})\) is set to zero for neutral current compensation.

![Figure 2 Control Algorithm of shunt controller(2)](image)

The available model (in MATLAB) of IGBTs with an antiparallel diode is used to realize the VSC of the DVR. The series RLC components of SPS block set is used to realize the filter inductor and ripple filter of the DVR. The linear transformers, which include losses, are used for modeling the series injection transformers of the DVR[4]. The control algorithm is implemented using Simulink blocks. The control algorithm for the DVR of the UPQC in which the synchronous reference frame theory is used for reference signal generation. The PCV voltages \((v_{ls})\), supply currents \((i_{ls})\), the load terminal voltage \((v_{l})\), are sensed for deriving the IGBT gate signals[4]. The PCV voltages are converted to the rotating reference frame using the abc – dq0 conversion using the park’s transformation with unit vectors \((\sin \theta, \cos \theta)\) derived from the supply currents using a PLL.

\[
\begin{bmatrix}
v_{s}\n\end{bmatrix} =
\begin{bmatrix}
\cos \theta & \cos(\theta-2\pi/3) & \cos(\theta+2\pi/3) \\
\sin \theta & \sin(\theta-2\pi/3) & \sin(\theta+2\pi/3)
\end{bmatrix}
\begin{bmatrix}
v_{d}\n\end{bmatrix}
\]

(1.7)

The SRF controller extracts DC quantities by LPFs and hence the non DC quantities (ripples) are separated from the reference signal [4]. The control strategy considers that the reference load voltage consists of a DC component of d-axis PCC voltage the DC component of q-axis PCC voltage along with the quadrature component estimated by the PI controller over the load terminal voltage[4].

\[
v_{sd}=v_{dc}+v_{LQAC}
\]

(1.8)

\[
v_{sq}=v_{dc}+v_{LQAC}
\]

(1.9)

The amplitude of AC load terminal voltage \((v_{L})\) is the controlled to its reference voltage \((v^{*}_{L})\) using a PI controller and the output of the PI controller is considered as voltage \((v_{pq})\) to be injected by DVR[4].

The amplitude of AC load terminal \((v_{L})\) is calculated from the load terminal voltages \((v_{L_{La}}, v_{L_{Lb}}, v_{L_{Lc}})\) [4]. Thus, a PI controller is used to regulate this voltage to a reference value as follows:

\[
v_{L}(n)=v_{L}(n-1)+k_{pL}\{v_{L}(n)-v_{L}(n-1)\}+k_{iL}v_{L}(n)
\]

(1.10)

Where \(v_{L}(n)=v_{L_{La}}(n)-v_{L_{Lc}}(n)\) denotes the error between reference \((v^{*}_{L})\) and sensed \((v_{L})\) terminal voltage amplitudes at the nth sampling instant, and the \(K_{pL}\) and \(K_{iL}\) are the proportional and integral gain constants of the DC bus voltage PI controller[4].

The reference quadrature axis load voltage is

\[
v_{LQ}=v_{dc}+v_{q}
\]

(1.11)

The reference direct axis load voltage is

\[
v_{Ld}=v_{dc}
\]

(1.12)

The reference load voltage in the abc frame is obtained by reverse park’s transformation.

\[
\begin{bmatrix}
v^{*}_{Ld} \\
v^{*}_{Lq}
\end{bmatrix} =
\begin{bmatrix}
\cos \theta & \sin \theta & 1 \\
\cos(\theta-2\pi/3) & \sin(\theta-2\pi/3) & 1 \\
\cos(\theta+2\pi/3) & \sin(\theta+2\pi/3) & 1
\end{bmatrix}
\begin{bmatrix}
v^{*}_{L}
\end{bmatrix}
\]

(1.13)

The reference load voltage \((v^{*}_{Ld}, v^{*}_{Lq})\) and the sensed load voltages \((v_{Ld}, v_{Lq})\) are used in PWM voltage controller unit to generate gating pulses to the VSC of DVR. The PMW voltage controller is operated with a switching frequency of 10kHz[4].
IV. MATLAB/SIMULINK MODEL OF PROPOSED PV-UPQC

The PV-UPQC is designed for a three-phase system. The shunt compensator is connected at the load side. The solar PV array is directly integrated to the DC-link of UPQC through a reverse blocking diode. The series compensator operates in voltage control mode and compensates for the grid voltage sags/swells. The shunt and series compensators are integrated to the grid through interfacing inductors. A series injection transformer is used to inject voltage generated by the series compensator into the grid. Ripple filters are used to filter harmonics generated due to switching action of converters. The load used is a nonlinear load consisting of a bridge rectifier with a voltage-fed load[2].

V. SIMULATION RESULT AND PERFORMANCE EVALUATION

The steady state and dynamic performance of PV-UPQC is analyzed by simulating the PV-UPQC system in Matlab-Simulink. The load used is a non-linear load of $R=5\, \Omega$ and $L=20\, mH$ consisting of three phase diode bridge rectifier. The grid is modeled with a source impedance of $2\, mH$. The PV module is modeled based on Panasonic Solar Module PE255PBBB.

A. STEADY STATE OPERATION OF PV-UPQC
The steady state operation of PV-UPQC is shown in Fig. 5 and 6. The sensed signals are point of common coupling (PCC) voltages, load voltages, DC-link voltage, solar PV array current, solar PV array power, grid currents, phase a,b,c load current, phase a,b,c shunt compensator current, and irradiation. All three phases is shown in case of load current and shunt compensator currents and they are symmetrically 120 degree apart. The DC-link voltage is maintained at 700V which is the MPPT point of the solar PV array. The load current harmonics are compensated by the shunt compensator thus maintaining the grid currents sinusoidal.

It is observed that the load current THD is 21.4% and the grid current THD is 1.44%. The load current harmonics are compensated by the shunt compensator thus maintaining the grid currents sinusoidal and at unity power factor. The PCC voltage THD and load voltage THD are also limited to below 5%, thus meeting the requirements of IEEE-519 standard[13].
B. PERFORMANCE OF PV-UPQC UNDER VARYING IRRADIATION

The dynamic performance of PV-UPQC under varying solar irradiation is shown in Fig.11. The sensed signals are PCC voltages, load voltages, DC-link voltage, solar PV array current, solar PV array power, grid line current, load currents, shunt compensator currents and irradiation. The solar irradiation is varied from 1000 W/m² to 700 W/m² between 0.4 to 0.68s. It is observed that as irradiation decreases, the PV array output reduces and hence the load draws more active current from the grid and the shunt compensator mainly compensates for load harmonics and reactive power apart from maintaining the DC-link within at desired voltage of 700V.

The simulation results shows that under the varying irradiation between 0.4 to 0.68, the constant power is maintained at the load side by PV-UPQC.

C. Performance of PV-UPQC under Grid Voltage Disturbances

The simulation results shows that under the varying irradiation between 0.4 to 0.68, the constant power is maintained at the load side by PV-UPQC.
The dynamic performance of PV-UPQC under conditions of grid sags/swells is shown in Fig.14. The irradiation (Irr) is at 1000 W/m². The various sensed signals are grid voltages, load voltages, series compensator voltages, DC-link voltage, solar PV array current, solar PV array power, grid line currents, load line currents, shunt compensator currents. Between 0.3 to 0.5 there is a voltage interruptions, but the load voltage is maintained a constant value by the shunt inverter. During the voltage interruptions shunt inverter only powers to the load side. The voltage of DC bus maintains a constant value by the support of PV array during interruptions. Between 0.5 to 0.7 there is a voltage swell but the load voltage is maintained a constant value by the series inverter. Between 0.7s and 0.8s, there is voltage sag of 0.2 pu and the series compensator compensates for the grid voltage under these conditions by injecting a suitable voltage in opposite phase with the grid voltage disturbance to maintain the load voltage at rated voltage condition. Hence, a constant load voltage is achieved using PV-UPQC.

![Figure 16 Under Grid Voltage Disturbance](image)

Figure 16 Under Grid Voltage Disturbance (a) Source Voltage (b) Load Voltage (c) Active Power

Between 0.3 to 0.5 there is a voltage interruptions, but the load voltage is maintained a constant value by the shunt inverter. During the voltage interruptions shunt inverter only provides power to the load side. The voltage of DC bus maintains a constant value by the support of PV array during interruptions. Between 0.5 to 0.7 there is a voltage swell but the load voltage is maintained a constant value by the series inverter. Between 0.7s and 0.8s, there is voltage sag of 0.2 pu, still the constant power is provided by the PV-UPQC. Hence, it is a good solution under grid voltage disturbances.

VI. CONCLUSION

The dynamic performance of three-phase PV-UPQC has been analyzed under conditions of variable irradiation and grid voltage disturbances. It is observed that PV-UPQC mitigates the harmonics caused by nonlinear and maintains the THD of grid voltage, load voltage and grid current under limits of IEEE-519 standard[13]. The system is found to be stable under variation of irradiation from 1000 W/m² to 6000W/m². It is also providing the active power injection during the voltage interruptions. It can be seen that PV-UPQC is a good solution for modern distribution system by integrating distributed generation with power quality improvement.

VII. FUTURE SCOPE

In high power applications, the filtering task cannot be performed for the whole spectrum of harmonics by using a single converter due to the limitations on switching frequency and power rating of the semiconductor devices. Therefore, compensating the reactive harmonic components to improve the power quality of the DG integrated system as well as to avoid the large capacity centralized APF, parallel operation of multiple low power APF units are increasing. It can be used with two feeder have a single PV-UPQC linking feeders. Parallel operation of UPQC integrated with the PV array.

APPENDIX

System Parameters: AC line voltage: 415V, 50Hz; Line impedance:2mH,0.02Ω; Load:Rectifier with R-L 5Ω,20mH; DC-link Voltage:700V; DC-link Capacitor:10mF; Shunt compensator interfacing inductor:3mH; Ripple Filter:1mF,0.1Ω; Series compensator interfacing inductor:3mH; VA Rating of shunt compensator=45kVA; Rating of series compensator=20kVA. DC-link PI controller gains:Kp=1.5, Ki=0.1; Series VSC PI gains for d and q axis: Kd=1, Kq=0; Shunt VSC hysteresis controller band: 0.01A, Series VSC voltage hysteresis controller band: 0.1V.

REFERENCES

Arrays", IEEE Transactions, 978-1-4799-1797-6/15 $31.00 © 2015 IEEE.