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Performance of Distribution Grid Connected Solar Photovoltaic Array with Unified Power Quality Conditioner

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Abstract: ***The control of distribution grid connected Solar Photovoltaic Array with Unified Power Quality Conditioner (SPV-UPQC) is presented. The SPV-UPQC comprises of a solar photovoltaic array, a shunt active power filter (APF) and series APF. In UPQC, the series and shunt Active Power Filters (APFs are connected in back to back with a common DC-bus capacitor. The shunt active compensator is used to extracts the power from solar PV array as well as compensates load current harmonics. The Synchronous Reference Frame (SRF) based control theory is used in shunt active compensator for extracting fundamental load active current component. The Unit Vector Template (UVT) technique is used in series active compensator. The series active compensator mitigates grid voltage sags and swells conditions by injecting voltage in phase or out of phase at the Point of Common Coupling (PCC) respectively. The proposed system performs both the transfer of active power and power quality enhancement simultaneously. The performance of the test system are examined under steady-state condition, grid voltage fluctuations and varying solar irradiation conditions by detailed simulation in MATLAB/Simulink software.***

Keywords: MPPT, SPV-UPQC, Solar PV Array, Unified Power Quality Conditioner.

I. INTRODUCTION

Now a days solar Photovoltaic systems is an important source of distributed generation by installation on the rooftop on residential and commercial buildings. The penetration of distributed energy sources causes grid voltage fluctuations due to their intermittent characteristics in nature [1]. Furthermore, the proliferation of power electronics loads like switched mode power supplies, adjustable speed drives etc. cause voltage distortion at PCC as they draw nonlinear currents. The voltage quality problems causes malfunctioning, false triggering, increased heating of power factor correction capacitor etc. Hence, both load side and grid side power quality problems is to be mitigated in the modern distribution systems [2]. Under this circumstances, active power filters (APFs) such as series APF, shunt APF and Unified Power Quality Conditioner (UPQC) has been focused as solutions to integrate distributed generation capability with power quality enhancement in modern distribution system [3]. The grid tied solar PV system with shunt active filter (SPV-DSTATCOM) is proposed in [4]. The shunt active filter effectively compensate current related power quality problems. But it demands reactive power to regulate the grid/PCC voltage. Hence, it cannot regulate simultaneously both grid voltage and grid current with unity power factor. The grid integration of solar PV array with Dynamic Voltage Restorer (SPV-DVR) using six-port converter topology has been presented [5].The series active compensator can effectively compensate voltage fluctuations at PCC such as grid sag/swells for protecting sensitive loads. Many researchers have focused the grid tied solar PV array with UPQC (SPV-UPQC) to achieve both load voltage regulation and maintain balanced grid current at unity power factor in distribution system [6]. Reference voltage and current signal computation plays a major role in the function of PV-UPQC. Time-domain techniques require less computation over frequency-domain for implementation. Instantaneous Reactive Power (IRP) theory, Synchronous Reference Frame (SRF) theory and Instantaneous Symmetrical Component (ISC) theory are commonly used time domain techniques [2-3]. The SRF theory gives poor performance under unbalanced load condition. To remove second order harmonics component in direct-axis, low pass filter is used. In addition, low pass filter is employed to enhance performance of DC bus controller [3]. This paper presents the steady state and dynamic performance of a SPV-UPQC under grid voltage fluctuations and solar irradiation variations. The paper is planned with five sections as follows. The circuit configuration of the SPV-UPQC system is detailed in section II. The control algorithm of SPV-UPQC is provided in section III. The performance analysis of test system is discussed on section IV. Finally section V concludes the paper.

II. CIRCUIT CONFIGURATION OF SPV-UPQC

The circuit configuration of the grid tied solar PV with UPQC system is illustrated in Fig. 1. The PV-UPQC made up of back to back connected shunt and series Voltage Source Inverters (VSIs) with a DC bus capacitor. The PV-UPQC system is a one stage system where the solar PV array is directly interfaced to the DC capacitor of UPQC through a reverse blocking diode. The

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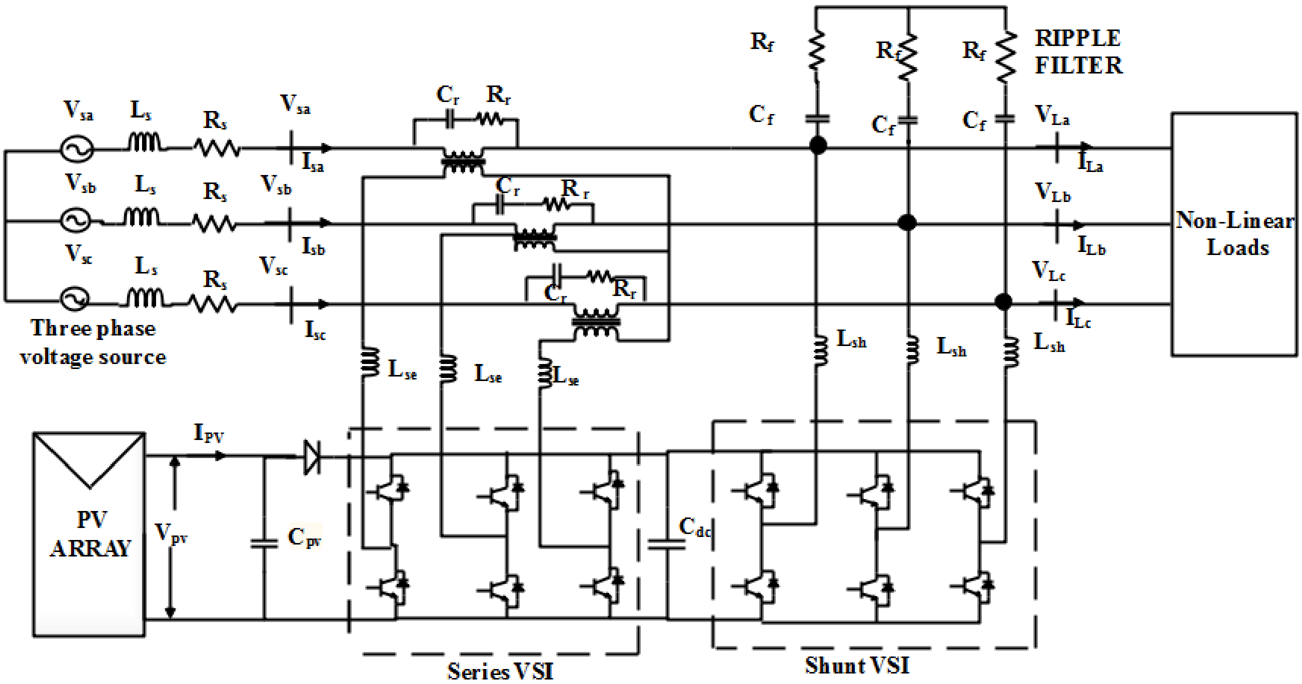

Fig. 1. Circuit configuration of the SPV-UPQC system.

function of the reverse blocking diode is to protect the PV array from any reverse power flow. The shunt and series VSIs are integrated to the grid through interfacing inductor and series injection transformer respectively. The shunt VSI is connected at the load side. It operates in current control mode to compensate reactive power and current harmonics. A series VSI is connected in series between PCC and the load. It operates in voltage control mode that compensates the grid voltage related power quality problems. Ripple filters are used to filter out high-frequency harmonics due to switching action of VSIs. The three-phase diode bridge rectifier with RL load is considered as a non-linear load.

III. CONTROL PHILOSOPHY OF SPV-UPQC

The major part in the control of the SPV-UPQC is computation of reference grid currents and load voltages for the series and shunt APFs respectively. The control aspects of shunt APF and series APF are detailed as follows.

A. Perturb & Observe MPPT method for solar PV array

The output voltage of solar PV cells is influenced by ambient temperature and the radiation intensity. Perturb & Observe method is used for realizing MPPT control in solar PV array [7]. The algorithmic steps are as follows.

- Measure solar PV module voltage *(V_{PV})* and current *(I_{PV})* values at k^{th} and $(k\text{-}1)^{th}$ instant.
- Calculate solar PV panel power *(P_{PV})* values at k^{th} and $(k\text{-}1)^{th}$ instant.
- Check the conditions $P_{PV}(k) > P_{PV}(k\text{-}1)$
- If the condition is reached, then increase operating voltage, otherwise decrease the operating voltage.

The system operating point oscillates around the maximum power point of solar cell. The process of increase or decrease of solar PV power *(P_{PV})* is repeated until it converged to the maximum power point. The flowchart of P&O based MPPT algorithm is explained in Fig. 2. The MPPT algorithm produces the desired voltage for the DC bus capacitor of SPV-UPQC.

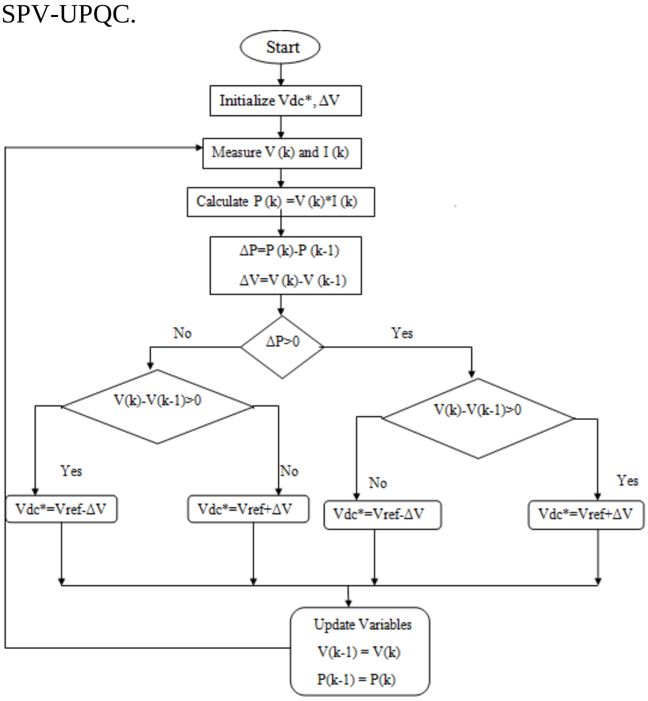

Fig. 2. The flowchart of Perturb & Observe MPPT method

The reference DC bus capacitor voltage is compared with the measured one to compute error voltage and it is processed by Proportional-Integral (PI) controller to regulate DC bus voltage of the SPV-UPQC. The LPF is used to eliminate ripples in the measured DC bus capacitor voltage. The active load current component required to regulate DC bus capacitor by PI controller is represented by I_{DC}.

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B. Shunt APF of SPV-UPQC

The main function of shunt APF control is generation of reference grid currents using indirect control technique. The current harmonics and reactive power burden are compensated by shunt APF. In the SPV-UPQC, the shunt APF performs an additional function of supplying active power from the solar PV array. The control scheme of shunt APF of SPV-UPQC is depicted in Fig.3. It includes three sub-blocks namely DC bus voltage controller, fundamental active load current estimation and solar PV feed forward current estimation.

The SRF theory is used to estimate fundamental active load current component. The grid/PCC voltages is given to Phase Locked Loop (PLL) to compute transformation angle (wt). The load currents in *a-b-c* coordinates are converted to *d-q-0* coordinates using Parks transformation (T). The DC quantity of *direct*-axis of the load current component (I_{Ldf}) is extracted using the Butterworth LPF.

$$\begin{bmatrix} i_{Ld} \\ i_{Lq} \\ i_{L0} \end{bmatrix} = T \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \quad (1)$$

$$T = \sqrt{\frac{2}{3}} \begin{bmatrix} \sin(wt) & \sin(wt - \frac{2\pi}{3}) & \sin(wt + \frac{2\pi}{3}) \\ \cos(wt) & \cos(wt - \frac{2\pi}{3}) & \cos(wt + \frac{2\pi}{3}) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \quad (2)$$

$$i_{Ld} = I_{Ld,dc} + I_{Ld,ac} \quad (3)$$

The I_{Ldf} represents the fundamental active load current component in reference *a-b-c* coordinates. The active load current required to regulate DC-link capacitor by PI controller is represented by loss component (I_{loss}). The feed-forward current component (I_{PVg}) of injected solar PV array power is calculated as,

$$I_{pvg} = \frac{2}{3} \cdot \frac{P_{pv}}{V_S} \quad (4)$$

The peak amplitude of the grid/PCC voltage is calculated as,

$$V_S = \sqrt{\frac{2}{3}(V_{sa}^2 + V_{sb}^2 + V_{sc}^2)} \quad (5)$$

The reference grid current in direct-axis (I_{sd}^*) is comprised three active load current components and is evaluated as,

$$I_{sd}^* = I_{Ld,dc} + I_{DC} - I_{pvg} \quad (6)$$

The reference grid currents in *q*-axis and *0*-axis are set to zero to compensate load harmonics and unbalanced currents. Then reference grid currents in *d-q-0* frame are converted back to *a-b-c* frame. The instantaneous reference grid currents are compared with the measured grid currents. The error signal is processed by hysteresis PWM current controller to generate the switching pulses for the shunt APF.

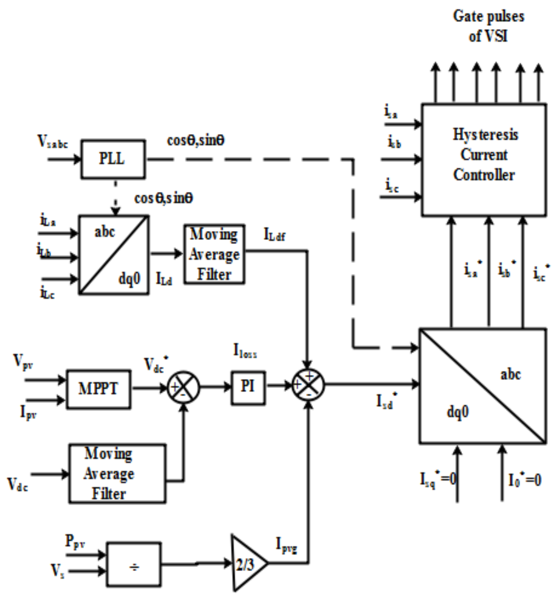


Fig. 3. Control scheme of shunt APF of SPV-UPQC

C. Series APF of SPV-UPQC

The series compensator injects voltage with an equal magnitude and opposite phase as that of grid voltage to obtain rated sinusoidal balanced load voltage.

The control scheme of series APF of SPV-UPQC is based on Unit Vector Template technique to generated reference load signals and its block diagram is shown in Fig. 4.

The three-phase grid voltages is given to PLL which produces transformation angle ($\theta = \omega t$). This transformation angle is used to generate three-phase balanced unit vectors using equation (7).

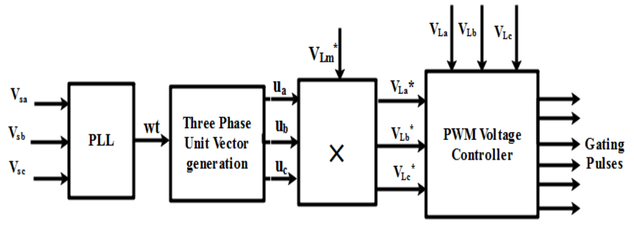


Fig. 4. Control scheme of Series APF of SPV-UPQC

The desired peak magnitude of load voltage (V^*_{Lm}) multiplied with three phase balanced unit vectors to generate instantaneous reference load voltages and is given by (8). The error between instantaneous reference load

$$\begin{bmatrix} U_a \\ U_b \\ U_c \end{bmatrix} = \begin{bmatrix} sin(wt) \\ \sin(wt - 2\pi/3) \\ \sin(wt - 2\pi/3) \end{bmatrix} \quad (7)$$

$$\begin{bmatrix} v_{La}^* \\ v_{Lb}^* \\ v_{Lc}^* \end{bmatrix} = V_{Lm}^* \begin{bmatrix} U_a \\ U_b \\ U_c \end{bmatrix} \quad (8)$$

voltage measured load voltage is processed by hysteresis PWM voltage controller to generate required switching pulses for the series APF.

IV. TEST RESULTS AND DISCUSSION

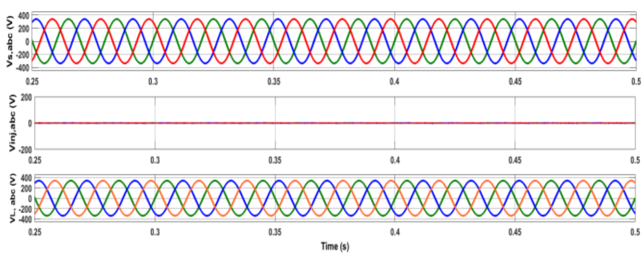
The steady-state and dynamic performance of the proposed SPV-UPQC system are evaluated using SimPowersystems toolbox under MATLAB/Simulink environment. The description of test system and solar PV module parameters are given in Appendix. The distribution grid is considered with a impedance of 0.01Ω and 0.1mH. The three phase diode bridge rectifier fed R-L load is taken as non-linear loads. The performance of the proposed test system has been validated by three test conditions namely steady state condition, grid voltage variations, and varying solar irradiation levels. The simulation results displays the wave shapes of PCC/grid voltages *(V_{sabc})*, series compensator voltages *(V_{injabc})*, load voltages (V_{Labc}) , grid currents (i_{sabc}), shunt compensator currents *(i_{shabc})*, load currents *(i_{Labc})* , DC capacitor voltage *(V_{dc})*, SPV array current (I_{PV}), SPV array power *(P_{PV})* and solar irradiance *(G)*.The performance results obtained are detailed below.

A. Response under steady state operation

The response of SPV-UPQC under steady state operating condition is presented in Fig.5. The solar irradiance is kept at 990 W/m^2.The DC bus capacitor voltage is regulated around desired value of 690V. It confirms that the desired DC bus voltage is equal with maximum power point of the SPV array. The shunt APF eliminates unbalanced and harmonics present in the nonlinear load current. Thus grid currents becomes balanced sinusoidal with UPF operation. The series APF injects zero voltage under steady state operating condition.

B. Response under grid voltage fluctuations

The dynamic response of SPV-UPQC under grid voltage fluctuations is presented in Fig.6.The solar irradiance is not changed and is kept at 990 W/m^2. The three-phase voltage sag of 0.20 p.u. is created between at 0.30s to 0.35s and the three-phase voltage swell of 0.20 p.u. is created between 0.40s to 0.45s. It is seen that the series APF injects a suitable voltage to the grid in order to maintain the rated load voltage of 415V. The grid currents is free from harmonics and DC bus capacitor voltage is regulated to the reference value. Also, the grid current increases under voltage sag condition voltage swell in order to regulate constant load power.



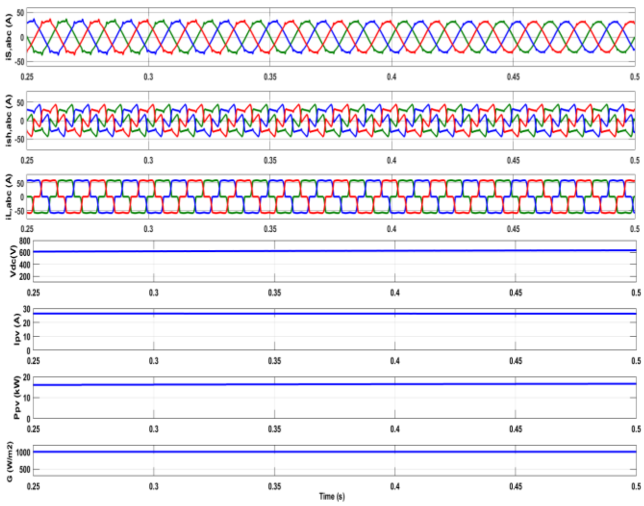


Fig. 5. Steady state response of SPV-UPQC

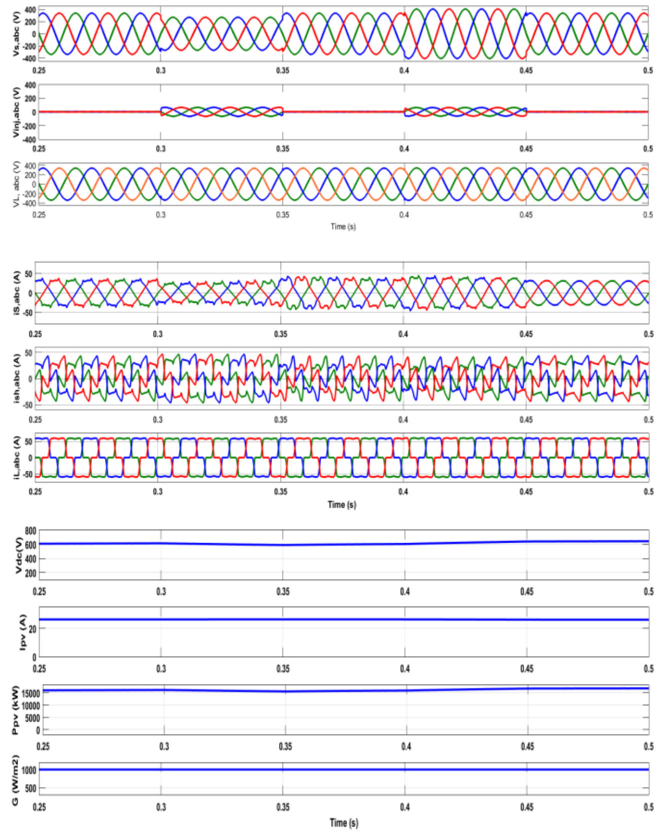


Fig. 6. Dynamic response of SPV-UPQC under grid voltage fluctuations

C. Dynamic response of SPV-UPQC under varying solar irradiation condition

The dynamic response of SPV-UPQC system under varying solar irradiance levels is displayed in Fig.7. The test system is subjected to the ramp change in solar irradiance level. From 0.3s to 0.4s, it is decreased from 990 W/m^2 to 500 W/m^2 . It is seen that the irradiation level decreases, the solar PV output power decreases. Now, shunt APF injected current to the grid decreases thereby load draws more active current from the grid.

From the grid current signals, it is noticed that shunt APF compensates load current harmonics and reactive power burden. The DC bus capacitor voltage is stable under change in irradiation levels.

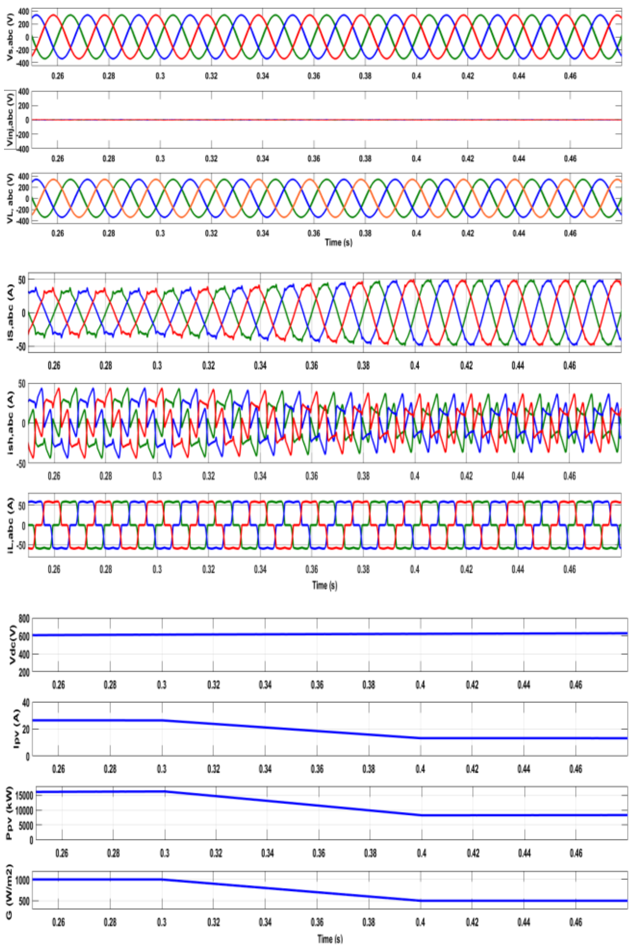


Fig. 7. Dynamic response of SPV-UPQC under varying solar irradiance

V. CONCLUSION

The control performance of distribution grid connected SPV-UPQC using SRF theory and UVT technique has been studied under steady state operation, grid voltage fluctuations and varying solar irradiation. It is found that shunt APF eliminates the harmonics of nonlinear loads and also transfer of active power from solar PV array in to the distribution grid. Further, series APF compensates grid voltage fluctuations. The test results confirms that SPV-UPQC gives dual benefits by grid integration of distributed generation and enhancement of power quality for modern distribution system.

APPENDIX

Test System specifications: AC line voltage 415 V, 50 Hz; Load: three-phase diode bridge rectifier fed RL load 15kW, shunt ripple filter: 10Ω, 10μF; shunt interfacing inductor (L_f): 4mH; series compensator interfacing inductor (L_s): 0.5mH; DC voltage controller: proportional gain: 1.6; integral gain : 0.10; DC bus capacitor: 9.3mF; DC bus reference voltage: 690V; Series ripple filter: 5Ω, 200μF.

Solar PV array specifications: Open circuit output voltage (V_{oc}): 865V, short circuit current (I_{sc}): 27A, voltage at maximum power point (V_{mpp}): 700V, maximum power (P_{pv}):17.6 kW; current at maximum power point (I_{mpp}):25 A.

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