Power Transfer Analysis Using UPQC-PV System Under Sag and Interruption With Variable Irradiance

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***Abstract*— This paper presents an analysis of the Unified Power Quality Conditioner-Photovoltaic (UPQC-PV) system under sag and interruption voltage with variable irradiance. The PV is connected to a three-phase three-wire (3P3W) distribution system with 380 volts (L-L) and a frequency of 50 hertz, through UPQC-DC link. This system is used to maintain and supply sensitive loads. This paper shows that in the sag voltage and irradiance levels of 200 W/m^2 to 1200 W/m^2, the 3P3W system uses UPQC-PV with proportional-integral (PI) still able to maintain the active load power above 3714 W. However, in the interruption voltage and same irradiance level, the load active power drops to between 2560 W and 2805 W. This research also shows that in the sag voltage and same irradiance levels, the 3P3W system uses UPQC-PV with PI still able to generate PV power between 500 W to 920 W. In the interruption voltage and same irradiance levels, the power that can be generated by PV increases between 1300 W to 1635 W. Otherwise, at 25^0 C and 1000 W/m^2, the increase in PV power on interruption voltage has not been able to meet the load active power consumption, so it finally drops to 2650 W. This paper is simulated using Matlab/Simulink.**

Keywords—UPQC, Photovoltaic, Sag, Interruption, Irradiance

I. INTRODUCTION

The decreasing of fossil energy sources and increasing concerns about environmental impacts have caused renewable energy (RE) sources i.e., photovoltaic (PV) and wind, to develop into alternative energy on power generation. Solar or PV generator is one of the most potential RE technologies because it only converts sunlight to generate electricity, where the resources are available in abundant and they are free and relatively clean. Indonesia has a huge energy potential from the sun because it is located in the equator. Almost all regions of Indonesia receive around 10 to 12 hours of sunshine per day, with an average irradiation intensity of 4.5 kWh/m^2 or equivalent to 112.000 GW.

Even though, PV can generate power, this device also has a disadvantage: it results in several voltage and current disturbances, as well as harmonics due to the presence of several types of PV devices and power converters and increasing the number of non-linear loads connected to the source, causing a decrease in power quality (PQ). To overcome this problem and to improve PQ due to the presence of non-linear load and integration of PV into the grid, UPQC is proposed. This device has been a function to compensate for problems of voltage source quality i.e. sag, swell, unbalance, flicker, harmonics, and load current quality problems i.e. harmonics, imbalance, reactive current, and neutral current. UPQC is part of an active power filter consisting of a shunt active filter and series active filter connected in parallel and serving as a superior controller to solve several PQ problems simultaneously [1]. UPQC series component is responsible for reducing the number of disturbances on source side i.e. sag/swell voltage, flicker, unbalanced voltage, and source voltage harmonics. This equipment has served to inject a certain amount of voltage to keep load voltage at desired level so that it returns to balance and distortion-free. UPQC shunt component is responsible for overcoming current quality problems i.e. low power factor, load current harmonics, and unbalanced currents. This equipment has been a function of injection current into the AC system so that the current source becomes a balanced sinusoidal and in phase with source voltage [2]. The design and dynamic performance of integrated PV with UPQC (PV-UPQC) under variable irradiance condition and voltage sag/swell, and load unbalance has been investigated [3]. The proposed system was able to combine both the benefits of distributed generators (DGs) and active power filters. The PV-UPQC combination was also able to reduce harmonics due to nonlinear loads and was able to maintain total harmonics distortion (THD) of grid voltage, load voltage and grid current below the IEEE-519. The system was found to be stable under radiation variations, voltage sag/swell, and load unbalances conditions.

The dynamic performance-based auto-tuned PI for UPQC-PV system has been analyzed [4]. This online optimization methodology is implemented for PV-UPQC to determine the best value of PI gain. The Vector-Proportional Integral (UV-PI) and Proportional Resonant-Response (PR-R) controllers in shunt and series converters significantly increase PV-UPQC performance by reducing convergence time, settling time, switching harmonics, complexity, and dynamic response so that they become more effective. PV-UPQC performance using a control algorithm based on Synchronous Reference Frame (SRF) with the Phase Lock Loop (PLL) mechanism has been presented [5]. Unbalanced load voltage containing harmonics and pure unbalanced pure load voltage has been compensated and balanced so that the load voltage is maintained constant. UPQC was supplied by 64 PV panels using boost converters, PI controllers, maximum power point tracking (MPPT) with Perturb and Observer (P and O), and having a momentary reactive power theory (p-q theory) which has been proposed [6]. The system has successfully carried out reactive power compensation and reduced source current and load voltage harmonics. However, this study did not address the mitigation of sag voltage and other disturbances caused by PV penetration.

PV supported by UPQC using Space Vector Pulse Width Modulation (SVPWM) compared to hysteresis control in a three-phase distribution system has been proposed [7]. The system was used to improve PQ and to reduce the burden of 3 phase AC network by supplying power obtained from PV. The UPQC system can supply reactive power needed to increase power factor, reduce voltage and current distortion, and PV helps active injection power into the load. A conceptual study of UPQC on three-phase four-wire (3P4W) system connected to linear and non-linear loads simultaneously has been carried out [8]. The sinusoidal current control strategy drives UPQC in such a way that the supply system has drawn a constant sinusoidal current under steady-state conditions. Besides, the shunt converter also produced reactive power as required by load so that it can improve power factor and reduce THD of source current.

Artificial neural networks based on SRF theory as a control to compensate for PQ problems of 3P3W system through UPQC for various balanced/unbalanced/distorted conditions at load and source have been proposed [9]. The proposed model has successfully mitigated harmonic/reactive currents, unbalanced source and load, and unbalanced current/voltage. Investigation on enhancements PQ including sag and source voltage harmonics on the grid using UPQC provided by PV array connected to DC links using PI compared to FLC has been conducted [10]. The simulation shows that FLC on UPQC and PV could increase THD voltage source better than PI. The improvement of PQ using UPQC on microgrid supplied by PV and wind turbine have been implemented using PI and FLC. Both methods can improve PQ and to reduce distortion in output power [11]. Research on the use of Battery Energy Storage (BES) in UPQC supplied by PV to improve PQ in 3P3W system using FLC validated PI on various disturbances in source and load side has been investigated [12]. The research showed that FLC on the UPQC-Battery Energy Storage (BES) system supplied by PV was able to significantly reduce load current harmonics and source voltage harmonics in the number of disturbances, especially in interruption voltage that occurs on the source bus.

This research presents an analysis of the UPQC-PV system model under sag and interruption voltage with variable irradiance. The PV is connected to a 3P3W system with 380 volts (L-L) and a frequency of 50 hertz, through UPQC-DC link. This system is used to maintain load voltage and load active power constant, as well as to supply sensitive loads. This paper is presented as follows. Section 2 explains the proposed method, UPQC-PV model, parameter simulation, PV model, active filter series and shunt filter control, application of PI, as well as UPQC model efficiency. Section 3 shows results and discussion of load voltage, load current, source active power, load active power, series active power, shunt active power, PV power using PI. In this section, six disturbance scenarios are presented and the results are verified with Matlab/Simulink. Finally, this paper is concluded in Section 4.

II. RESEARCH METHOD

A. Proposed Method

Fig. 1 shows the proposed model in this paper. The PV is connected to a 3P3W distribution system with 380 volts (L-L) and a frequency of 50 hertz, through UPQC-DC link circuit. This system is known as the UPQC-PV system and it is used to maintain and supply sensitive loads. The PV array generates DC power at a constant temperature, variable solar irradiance, and it is connected to DC-link via a DC-DC boost converter. The MPPT method with the P and O algorithm helps PV to generate maximum power, result in an output voltage, which then becomes an input voltage for the DC-DC boost converter. This device has a function to adjust duty cycle value with PV output voltage as an input voltage to produce output voltage according to the DC-link voltage of UPQC. The PV has been a function as an alternative source by injecting power to keep load voltage constant, in the case of an interruption voltage that occurs on the source or points common coupling (PCC) bus.

The analysis of the proposed model is carried out by determining sag and interruption voltage scenarios on the source bus in 3P3W using the UPQC-PV system. The measurement parameters are carried out at fixed temperature (T = 25^0 C) and variable irradiance i.e. 200 W/m^2, 400 W/m^2, 600 W/m^2, 800 W/m^2, 1000 W/m^2 and 1200 W/m^2. Each disturbance scenario at variable irradiance level amounts to 6 disturbance, so the total number of scenarios is 12 disturbances. The UPQC-PV system uses PI to maintain voltage in a series active filter and current in an active shunt filter to keep the voltage at sensitive loads remains constant. The parameters investigated i.e. voltage and current on source bus, voltage and current on load bus, active source power, series active power, shunt active power, load active power, and PV power. The next step is to determine the efficiency value of the UPQC-PV system on sag and interruption voltage scenario in variable irradiance to show the contribution of PV in the mitigation of both voltage disturbances on source bus. Fig. 2 shows power transfer using the UPQC-PV system. Then, the simulation parameters for the proposed model are shown in Appendix Section.

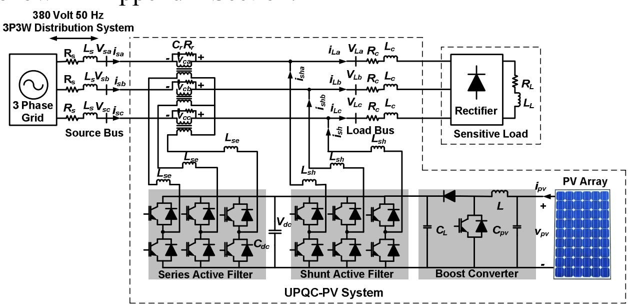

Fig. 1. Proposed model of as UPQC-PV system

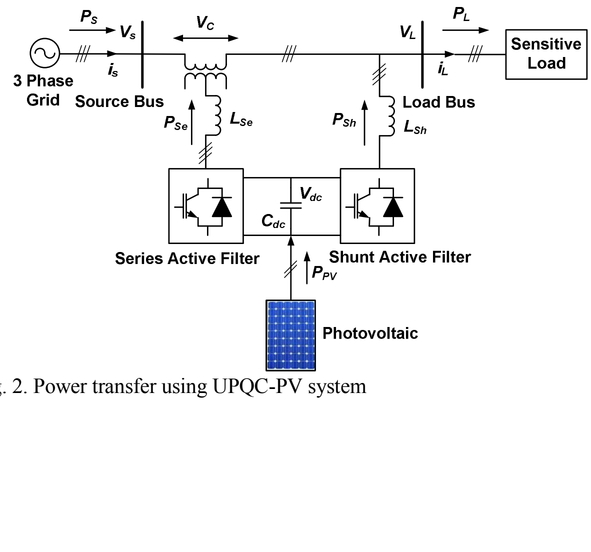

Fig. 2. Power transfer using UPQC-PV system

B. Modeling of PV Array

Fig. 3 shows the equivalent circuit and V-I characteristics of a solar panel. It consists of several PV cells that have external connections in series, parallel, or both combination [13].

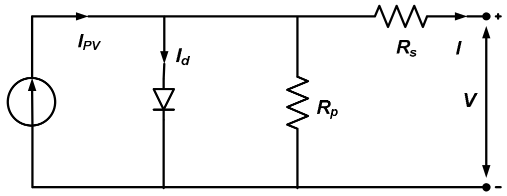

Fig. 3. Equivalent circuit of solar panel

The characteristic of V-I is shown in Eq. (1):

$$I = I_{PV} - I_o \left[exp\left(\frac{V+R_S I}{a\, V_t}\right) - 1 \right] - \frac{V+R_S I}{R_P} \quad (1)$$

Where I_{PV} is PV current, I_o is saturated reverse current, $'a'$ is the ideal diode constant, $Vt = N_S K T q^{-1}$ is the thermal voltage, N_S is the number of series cells, q is electron charge, K is Boltzmann constant. T is temperature p-n junction. R_S and R_P are series and parallel resistance of the solar panels. I_{PV} has a linear relationship with the light intensity and also varies with temperature variations. I_o is dependent value on the temperature variations. The value of I_{PV} and I_o are determined using Eq (2) and Eq. (3):

$$I_{PV} = \left(I_{PV,n} + K_I \Delta T\right) \frac{G}{G_n} \quad (2)$$

$$I_o = \frac{I_{SC,n} + K_I \Delta T}{\exp(V_{OC,n} + K_V \Delta T)/a V_t - 1} \quad (3)$$

Where $I_{PV,n}$, $I_{SC,n}$, and $V_{OC,n}$ are PV current, short-circuit current, and open-circuit voltage under standard conditions ($T_n = 25^0 C$ and $G_n = 1000\ W/m^2$), respectively. The K_I value is a coefficient of short circuit current to temperature, $\Delta T = T - T_n$ is temperature deviation from standard temperature, G is light intensity and K_V is a coefficient of open-circuit voltage ratio to temperature. Open-circuit voltage, short-circuit current, and voltage-current related to maximum power are three important values of I-V characteristics of a solar panel. These points are changed by variation in atmospheric conditions. By using Eq. (4) and Eq. (5) derived from PV model, short-circuit current, and open-circuit voltage can be calculated under different atmospheric conditions.

$$I_{SC} = (I_{SC} + K_I \Delta T) \frac{G}{G_n} \quad (4)$$

$$V_{OC} = (V_{OC} + K_V \Delta T) \quad (5)$$

C. Control of Series Active Filter

The main function of a series active filter is to protect the sensitive load from several voltage disturbances at the PCC bus. The algorithm of a source voltage and a load voltage control strategy in a series active filter circuit is shown in Fig. 4. This control strategy generates the unit vector template from a distorted input source. Then, the template is expected to be an ideal sinusoidal signal with a unity amplitude. Then, the distorted source voltage is measured and divided by peak the amplitude of base input voltage V_m as stated in Eq. (6) [6].

$$V_m = \sqrt{\frac{2}{3}\left(V_{sa}^2 + V_{sb}^2 + V_{sc}^2\right)} \quad (6)$$

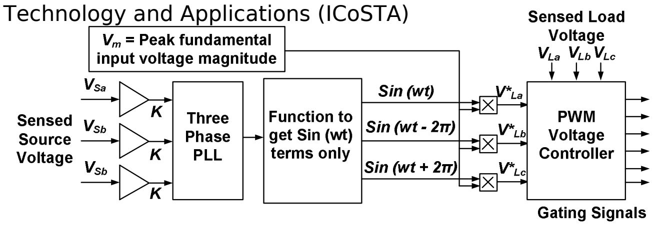

Fig. 4 Series active filter control

A three-phase PLL is used to produce sinusoidal unit vector templates with phase lagging through the use of sine function. The load voltage of the reference signal is determined by multiplying unit vector templates by the peak value of base input voltage amplitude V_m. The load reference voltage $(V_{La}^*, V_{Lb}^*, V_{Lc}^*)$ is then compared with sensed load voltage(V_{La}, V_{Lb}, V_{Lc}) with a PWM controller which is used to generate the desired trigger signal in a series active filter. Fig. 4 shows the control of a series active filter.

D. Control of Shunt Active Filter

The main function of an active shunt filter is to mitigate PQ problems on the load side. The control methodology of a shunt active filter is that the absorbed current from the PCC bus is a balanced positive sequence current including an unbalanced sag voltage on the PCC bus, an unbalanced, or a non-linear load. To obtain satisfactory compensation caused by interference due to non-linear load, many algorithms have been used in some references. This research uses the method of instantaneous reactive power theory or "p-q" theory. The voltages and currents in Cartesian coordinates can be transformed into Cartesian coordinates αβ as stated in Eq. (7) and Eq. (8) [6].

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (7)$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (8)$$

Calculation of real power (p) and imaginary power (q) is shown in Eq. (9). Real and imaginary power are measured power instantaneously and expressed in matrix form. The presence of mean and fluctuating components in an instantaneous component is shown in Eq. (10) [14].

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (9)$$

$$p = \bar{p} + \tilde{p} \quad ; \quad q = \bar{q} + \tilde{q} \quad (10)$$

Where $\bar{p}$ = the average component of real power, $\tilde{p}$ = the fluctuating component of real power, $\bar{q}$ = the average component of imaginary power, $\tilde{q}$ = the fluctuating component of imaginary power. The total of imaginary power (q) and fluctuating components of real power $(\tilde{p})$ is selected as power references and current references and is utilized through the use of Eq. (10) to compensate for harmonics and reactive power [15]. Fig. 5 shows a shunt active filter control [15].

$$\begin{bmatrix} i_{c\alpha}^* \\ i_{c\beta}^* \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} -\tilde{p} + \bar{p}_{loss} \\ -q \end{bmatrix} \quad (11)$$

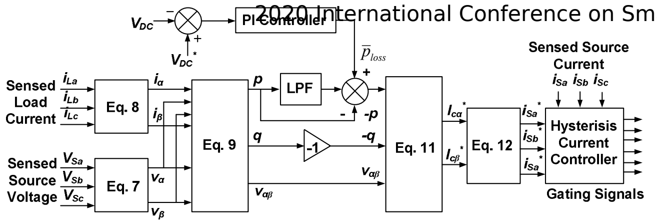

Fig. 5. Shunt active filter control

The $\bar{p}_{loss}$ signal is obtained from the voltage regulator and is used as average real power. It can also be expressed as instantaneous active power associated with resistive losses and switching losses from UPQC. The error is obtained by comparing the actual value of DC-link capacitor voltage with the reference value processed using a PI controller, driven by a closed voltage control to minimize steady-state errors from voltage through DC-link circuit to zero. The compensation current $(i_{c\alpha}^*, i_{c\beta}^*)$ is needed to meet load power demand as shown in Eq. (12). The current is expressed in coordinates $\alpha - \beta$. The compensation current is used to obtain the source phase current by using Eq. (13) for compensation. The source phase current $(i_{sa}^*, i_{sa}^*, i_{sa}^*)$ is expressed in the abc axis obtained from the compensation current in $\alpha - \beta$ coordinates and is presented in Eq. 12 [15] .

$$\begin{bmatrix} i_{sa}^* \\ i_{sb}^* \\ i_{sc}^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_{c\alpha}^* \\ i_{c\beta}^* \end{bmatrix} \quad (12)$$

To operate properly, The UPQC-PV must have a minimum DC-link voltage (V_{dc}) . The general DC-link voltage value depends on the instantaneous energy that can be generated by UPQC which is defined in Eq.13 [16]:

$$V_{dc} = \frac{2\sqrt{2V_{LL}}}{\sqrt{3}m} \quad (13)$$

Where m is the modulation index and V_{LL} is the voltage of UPQC. Considering the modulation index of 1 and the grid voltage between line-line $(V_{LL} = 380\,V)$, V_{dc} is obtained 620.54 V and chosen as 650 V.

The input of active shunt filter shown in Fig. 6 is DC voltage (V_{dc}) dan DC voltage reference (V_{dc}^*), while the output is P_{loss} using the PI controller. Furthermore, P_{loss} of the input variables produce a reference source current $(i_{sa}^*, i_{sa}^*, i_{sa}^*)$. Then, the reference source current output is compared with the current source $(i_{sa},\ i_{sb},\ i_{sc})$ by hysteresis current controller to generate a trigger signal in the IGBT circuit of shunt active filter. In this paper, the PI controller as a DC voltage control algorithm on an active shunt filter, is proposed.

D. Efficiency of UPQC-PV

The research on the use of 3-Phase 4-Leg Unified Series-Parallel Active Filter Systems using Ultra Capacitor Energy Storage (UCES) to mitigate sag and unbalance voltage has been investigated [17]. In this paper, it is found that the implementation of UCES can help the system reduce source current compensation when sag voltage on source bus to keep load voltage constant and balanced. During disturbance, UCES generates extra power flow to load through a series active filter via dc-link and a series active filter to load. Although providing an advantage of sag voltage compensation, the use of UCES in this proposed system is also able to generate losses and to reduce the efficiency of the system. Using the same procedure, the authors propose Eq. (14) for efficiency of UPQC-PV in the formula below.

$$Eff\ (\%) = \frac{P_{Source}+P_{Series}+P_{Shunt}+P_{PV}+P_{BES}}{P_{Load}} \quad (14)$$

III. Result and Discussion

The proposed model analysis is UPQC connected 3P3W (on-grid) system through a DC link supplied by PV known as UPQC-PV system. The system then supplies sensitive voltage devices on the load bus. There are two disturbances scenario i.e. sag voltage (Sag) and interruption voltage (Inter). In the sag voltage scenario, the system is connected to a sensitive load and the source has a 50% sag voltage disturbance for 0.3 s between t = 0.2 s to t = 0.5 s. In the interruption voltage scenario, the system is connected to a sensitive load and the source experiences a 100% source voltage interruption for 0.3 s between t = 0.2 s to t = 0.5 s. The UPQC-PV system uses a PI controller with constant K_P and K_I are 0.2 and 1.5, respectively. PI controller is used as a DC voltage controller on an active filter series and current controller on active shunt filter to keep load voltage constant in case of disturbance voltage happens on the source bus.

The proposed model analysis is carried out by determining sag voltage and interruption voltage on the source bus in 3P3W of the UPQC-PV system. The measurement parameters are carried out at fixed temperature conditions (T = 250 C) and the different radiation i.e. 200 W/m^2, 400 W/m^2, 600 W/ m^2, 800 W/m^2, 1000 W/m^2 and 1200 W/m^2. The disturbance scenarios at the variable irradiance level amounts to 6 disturbances so that the total number of scenarios is 12 interruptions. The UPQC-PV system uses controls mounted on the 3P3W System to keep the voltage at sensitive loads remains constant. Then, using Matlab/Simulink, the model is run following with the scenario that was previously desired to obtain the source voltage curve (V_S), load voltage (V_L), compensation voltage (V_C), source current (I_S), load current (I_L), and DC-Link voltage (V_{DC}). Based on this curve, the average values of source voltage, load voltage, source current and load current are obtained from value of each phase of voltage and current parameters previously obtained. The next research is determining the value of power transfer of active source power, active series power, active shunt power, active load power, PV power contribution, and system efficiency. The measurement of the value of phase voltage, phase current, power transfer, and PV power is determined in one cycle, starting at t = 0.35 s. The results of the average source voltage, source current, load voltage, and load current in the UPQC-PV system model are presented in Table 1.

TABLE I. VOLTAGE AND CURRENT USING UPQC-PV SYSTEM UNDER SAG AND INTERRUPTION WITH VARIABLE IRRADIANCE LEVEL

Irr (W/m^2)	Source Voltage V_S (Volt)				Load Voltage V_L (Volt)				Source Current I_S (Ampere)				Load Current I_L (Ampere)			
	Ph A	Ph B	Ph C	Avg	Ph A	Ph B	Ph C	Avg	Ph A	Ph B	Ph C	Avg	Ph A	Ph B	Ph C	Avg
Sag Voltage and T = 25^0 C																
200	153.9	153.9	153.9	**153.9**	310.1	310.1	310.1	**310.1**	11.77	11.79	11.35	**11.63**	8.590	8.589	8.587	**8.589**
400	154.1	154.1	154.1	**154.1**	310.1	310.1	310.1	**310.1**	10.91	10.98	10.94	**10.94**	8.589	8.590	8.588	**8.589**
600	154.1	154.1	154.1	**154.1**	310.1	310.1	310.1	**310.1**	10.92	10.88	10.98	**10.93**	8.589	8.588	8.589	**8.589**
800	154.0	154.0	154.0	**154.0**	310.1	310.1	310.1	**310.1**	11.45	10.38	11.49	**11.11**	8.588	8.589	8.589	**8.589**
1000	153.8	153.8	153.8	**153.8**	310.1	310.1	310.1	**310.1**	13.39	13.33	13.41	**13.38**	8.589	8.589	8.588	**8.589**
1200	153.8	153.8	153.8	**154.8**	310.1	310.1	310.1	**310.1**	13.69	13.58	13.69	**13.65**	8.589	8.589	8.588	**8.589**
Interuption Voltage and T = 25^0 C																
200	1.229	1.350	1.274	**1.284**	232.8	253.2	247.2	**244.4**	11.65	12.65	12.23	**12.18**	6.561	6.798	6.974	**6.778**
400	1.322	1.416	1.367	**1.368**	245.7	264.2	261.1	**257.0**	12.22	12.66	12.87	**12.51**	6.946	7.051	7.396	**7.131**
600	1.333	1.414	1.363	**1.370**	246.6	263.9	261.8	**257.4**	12.25	12.57	12.85	**12.56**	6.964	7.033	7.406	**7.134**
800	1.304	1.385	1.344	**1.341**	240.1	258.5	255.8	**251.5**	12.13	12.37	12.71	**12.40**	6.788	6.885	7.234	**6.969**
1000	1.190	1.316	1.237	**1.247**	229.2	249.1	242.8	**240.4**	11.31	11.86	11.91	**11.69**	6.443	6.698	6.289	**6.477**
1200	1.227	1.319	1.269	**1.272**	227.5	246.8	243.7	**239.2**	11.50	11.80	12.06	**11.78**	6.433	6.557	6.882	**6.624**

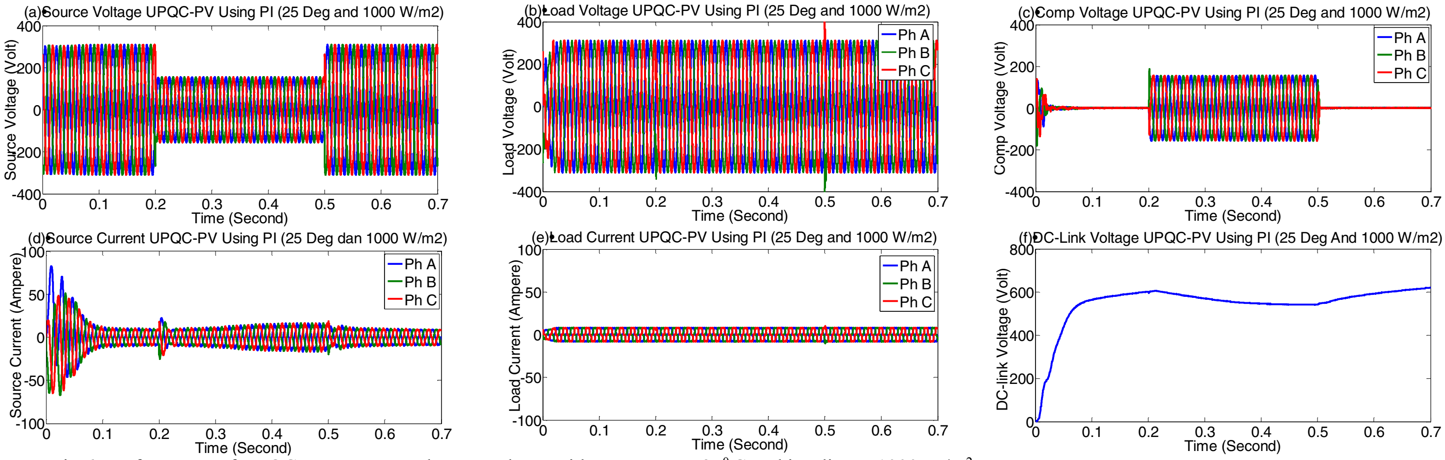

Fig 6. Performance of UPQC-PV system under sag voltage with temperature 25^0C and irradiance 1000 W/m^2

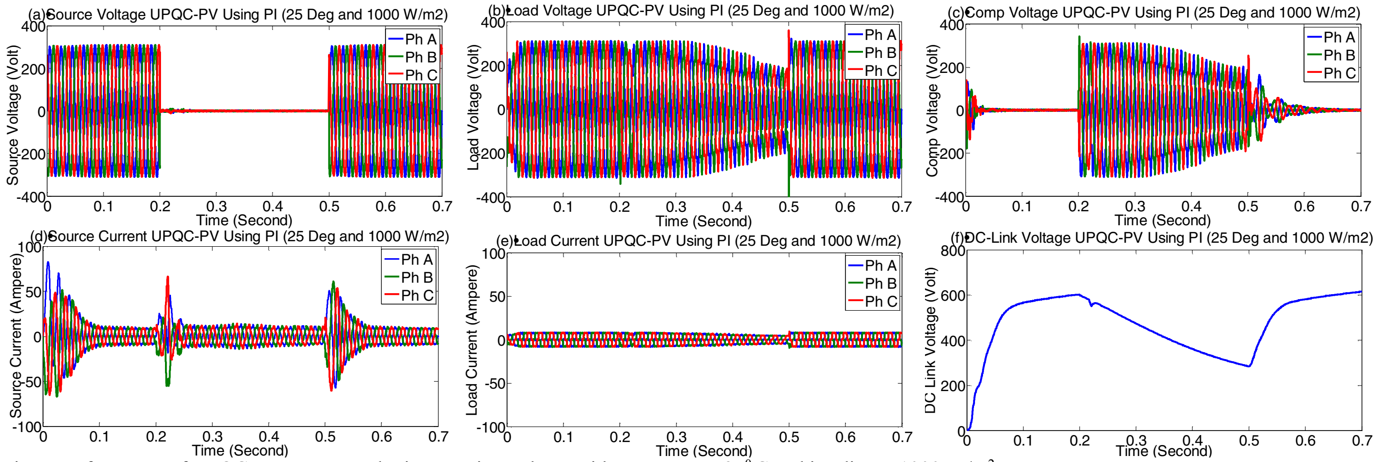

Fig 7. Performance of UPQC-PV system under interruption voltage with temperature 25^0C and irradiance 1000 W/m^2

Fig. 6 shows that in sag voltage, the UPQC-PV system at t = 0.2 s to t = 0.5 s, irradiance = 1000 W/m^2 and temperature = 25^0 using PI control, the average source voltage (V_S) (Fig. 6.a) decreased by 50% from 310.1 V to 153.8 V (Fig. 6.b). During this duration, the average source current (I_S) increases slightly to 13.38 A (Fig. 6.d) because the PV contributes power to the load through a DC-link series active filter by injecting a compensation voltage (V_C) of 156.3 V (Fig. 6.c) through the injection transformer in the active series filter so that an average load voltage (V_L) remains stable at 310.1 V (Fig. 6.b). At the same time, the PI controller on shunt active filter works to keep DC voltage (V_{DC}) stable and the average current source (I_S) increases close to 13.38 A (Fig. 6.d) to keep the average (I_L) stable at 8,589 A (Figure 6.e).

Fig. 7 shows that in the interruption voltage scenario, the UPQC-PV system at t = 0.2 s to t = 0.5 s, irradiation = 1000 W/m2 and temperature = 25^0 using PI controller, the average V_S drops by 100 % to 1.247 V (Fig. 7.a). Under these conditions, the UPQC-PV system is unable to produce maximum power to UPQC DC-link circuit and injects the average V_C (Fig. 7.c) through injection transformer in the active series filter. So at t = 0.2 s to t = 0.5, the average V_L (Fig. 7.b) decreases to 240.4 V. During the interruption period, the application of a PI controller to the active shunt filter is unable to maintain the average V_{DC} (Fig.7.f) and V_C to remain constant, so an average I_L also decreases to 6,447 A (Fig. 7.e).

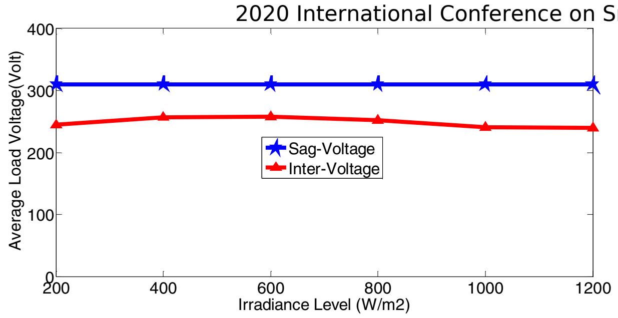

Fig. 8. Average load voltage of UPQC-PV system

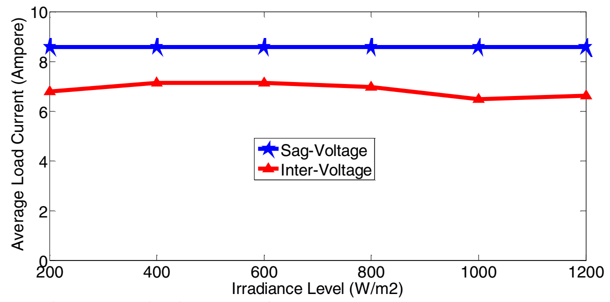

Fig. 9. The average load current of UPQC-PV system

Table 1 and Fig. 8 show that in sag voltage and irradiance level of 200W/m² to 1200 W/m², the 3P3W system using UPQC-PV with PI controller still can maintain the average load voltage $(V_L)$of 310.1 V. However, in the interruption voltage and the irradiance levels, are equally sequential, the average load voltage (V_L)drops to between 239.2 V and 257 V. Table 1 and Fig. 9 also show that in the sag voltage and the irradiance levels of 200 W/m² to 1200 W/m², the 3P3W system uses UPQC-PV with PI controller is still able to maintain the average load current (I_L) of 8.589 A. However, in the scenario of the interruption voltage and same irradiance levels, the average load current (I_L) drops to between 6.624 A and 7.134 A. Thus, the UPQC-PV system can maintain the load voltage (V_L), if there is the sag voltage happens at the source bus. Otherwise, in the interruption voltage scenario, the UPQC-PV system can not maintain load voltage (V_L), and the load current (I_L) remains constant.

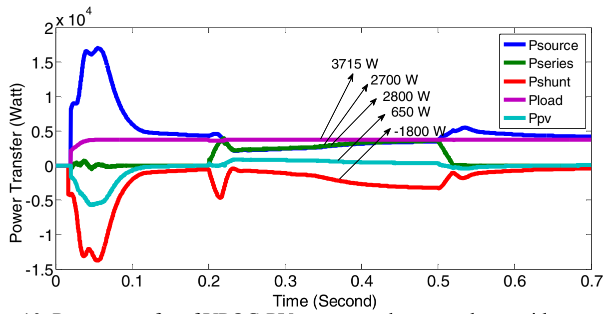

Fig. 10. Power transfer of UPQC-PV system under sag voltage with temperature = 25⁰ C and irradiance = 1000 W/m²

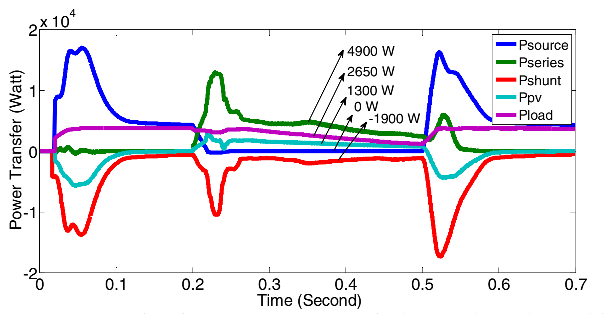

Fig. 11. Power transfer of UPQC-PV system under interruption voltage with temperature = 25⁰ C and irradiance = 1000 W/m²

Fig. 10 shows that in sag voltage, the UPQC-PV system at t = 0.2 s to t = 0.5 s, irradiance = 1000 W/m² and temperature = 25⁰ C using PI controller, source power value (P_S) decreases to 2700 W. Series power (P_{Se}) increased by 2800 W and shunt power (P_{Sh}) decreased by -1800 W, PV power by 650 W, so that load power (P_L) value is equal to 3715 W. Fig. 11 shows that in interruption voltage, UPQC-PV system at t = 0.2 s to t = 0.5 s, irradiance = 1000 W/m² and temperature = 25⁰ C, the value of the source power (P_S) drops to 0 W. The series power (P_{Se}) increases by 4900 W and shunt power (P_{Sh}) decreases by -1900 W, and PV power (P_{PV}) increases by 1300 W, so that the load power (P_L) dropped to 2650 W.

Table 2 and Fig. 12 show that in sag voltage and irradiance levels of 200 W/m² to 1200 W/m², the 3P3W system uses UPQC-PV with PI still able to maintain active power above 3714 W. However, in the interruption voltage and same irradiance level, active load power (P_L) drops to between 2560 W and 2805 W. Table 2 and Fig. 13 also show that in sag voltage and irradiance levels of 200 W/m² to 1200 W/m², the 3P3W system uses UPQC-PV with PI still able to generate PV power (P_{PV}) between 500 W to 920 W. In the scenario of interruption voltage and irradiance levels with the same condition, the PV power increases (P_{PV}) between 1300 W to 1635 W. However, the increase on PV power (P_{PV}) in interruption, voltage has not been able to meet power on load side so that load power (P_L) Finally it drops to 2650 W.

TABLE II. POWER TRANSFER IN UPQC-PV SYSTEM

Irr (W/m²)	Power Transfer (Watt)					Eff (%)
	Source Power	Series Power	Shunt Power	Load Power	PV Power	
Sag Voltage and T= 25⁰ C						
200	2700	2800	-1720	3715	680	83.30
400	2455	2550	-1200	3714	920	78.60
600	2455	2550	-1200	3714	920	78.52
800	2534	2620	-1332	3714	810	80.18
1000	2700	2800	-1800	3715	650	85.40
1200	2960	3080	-2250	3715	500	86.59
Interruption Voltage and T= 25⁰ C						
200	0	4950	-2000	2675	1440	60.93
400	0	4600	-1500	2805	1620	59.43
600	0	4650	-1515	2800	1635	58.70
800	0	4895	-1850	2754	1544	60.01
1000	0	4900	-1900	2650	1300	61.63
1200	0	4850	-1930	2560	1300	59.79

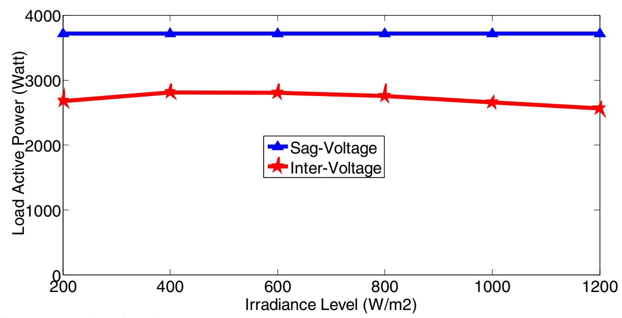

Fig. 12. Active load power on UPQC-PV system

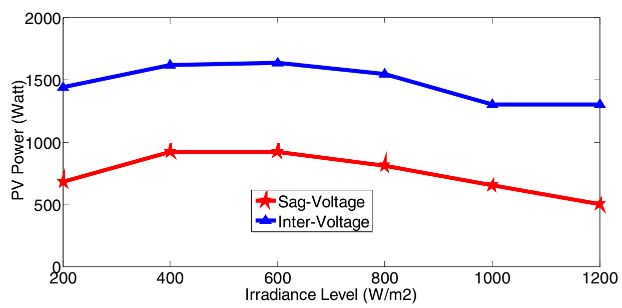

Fig. 13. PV power on UPQC-PV system

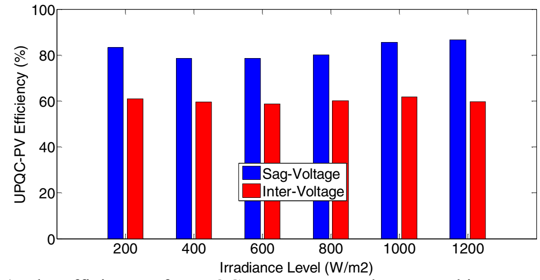

Fig. 14. The efficiency of UPQC-PV system under sag and interruption

Fig. 14 shows that in sag voltage and irradiance level of 200 W/m^2 to 1200 W/m^2, the 3P3W system using UPQC-PV with PI controller can produce a system efficiency of 78.60% to 86.59%. Otherwise, in the interruption voltage and irradiance increases, the efficiency of UPQC-PV decreases between 58.70% to 61.63%.

IV. Conclusion

The analysis of the UPQC-PV system model has been presented in this paper. The PV is connected to a 3P3W distribution system with 380 volts (L-L) and a frequency of 50 hertz, through UPQC-DC link circuit. This system is used to maintain and supply sensitive loads. This research shows that in the sag voltage and irradiance levels of 200 W/m^2 to 1200 W/m^2, the 3P3W system using UPQC-PV with PI can maintain the active load power above 3714 W. However, in the interruption voltage and same irradiance level, the active load power drops to between 2560 W and 2805 W. This paper also shows that in the sag voltage and same irradiance level, the 3P3W system using UPQC-PV with PI can generate PV power between 500 W to 920 W. In the scenario of the interruption voltage and same irradiance levels, the power that can be generated by PV increases between 1300 W to 1635 W. However, at 25^0 C and 1000 W/m^2, the increase in PV power on interruption voltage has not been able to meet the load power so it finally drops to 2650 W. The increase in PV power close to load power is proposed to overcome this problem.

Appendix

Three-phase grid: RMS voltage 380 volt (L-L), 50 Hz, line impedance: R_S = 0.1 Ohm L_S = 15 mH; series and shunt active filter: series inductance L_{Se} = 0.015 mH; shunt inductance L_{Sh} = 15 mH; injection transformers: rating 10 kVA, 50 Hz, turn ratio (N_1/N_2) = 1:1; sensitive load: resistance R_L = 60 ohm, inductance L_L = 0.15 mH, load impedance R_C = 0.4 ohm and L_C = 15 mH; unbalance load: resistance R_1 = 24 ohm, R_2= 12 ohm, and R_3 = 6 ohm, capacitance C_1, C_2, C_3 = 2.2 µF; DC-link: voltage V_{dc} = 650 volt and capacitance C_{dc} = 3000 µF; photovoltaic: active power P_{PV} = 0.6 kW temperature = 25^0 C, irradiance = 1000 W/m^2; PI controller: K_P = 0.2, K_I= 1.5; input: $V_{dc-error}$ and $\Delta V_{dc-error}$; output: instantaneous of power losses ($\bar{p}_{loss}$).

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