

Power Quality Improvement Utilizing PV Fed Unified Power Quality Conditioner Based on UV-PI and PR-R Controller

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Abstract—This paper presents control and configuration of photovoltaic fed unified power quality conditioner for the purpose of power quality enhancement. Literature studies convey that fixed PI gains used in the control schemes of Unified Power Quality Conditioners (UPQC) and PV-UPQC cannot easily adapt to various dynamic conditions. In this paper a novel online tunings method for PI control gains is adopted in the controllers of series and shunt converters of PV-UPQC. Unlike the previously implemented JAYA algorithm which has a single objective function utilized in the controller of DSTATCOM for improvement of only current quality, the new adaptive JAYA algorithm has two separate objective function, employed in shunt and series inverter control of PV-UPQC system for improvement of both current and voltage quality under various operational scenarios for power quality issues. The experimental results verify that implementation of JAYA based auto tuning PI controller increases the adaptivity of PV-UPQC system towards various dynamic conditions. Results obtained are compared with conventional optimization algorithms with fixed PI gains pertaining to a distribution system for validating its efficacy.

Index Terms—Adaptive JAYA Optimization, current harmonics, power quality, PV-UPQC, voltage sags/swells.

I. INTRODUCTION

THE sudden increase in application of non-linear loads in distribution system has induced power quality issues related to voltage and current which has become a serious concern among researchers. The advanced semiconductor technology based systems are the primary cause of current perturbations in the distributed system. Moreover, these nonlinear loads behave abnormally in presence of voltage disturbances. Thereby power quality enhancement devices or power conditioners have received much concentration towards power quality enhancement applications [1], [2]. Among various power types of conditioners unified power quality conditioner (UPQC) has earned enormous interest due to high performance capability for mitigation of voltage and current perturbations in the distribution system [2], [3]. Moreover, increased proliferation of renewable energy systems like solar and wind to the distribution systems have become major concern due to their intermittent nature. Various

topologies for grid connected PV systems are reported along with active filtering solution to maintain the current quality in the supply system [4]. PV grid integration adds advantage to the conventional system but due to the presence of nonlinear loads, voltage perturbations which appear at the point of common coupling (PCC). Therefore the demand of the future energy systems to acquire improved power quality can be achieved through suitable grid integration topology with satisfactory cost effective solutions. The utilization of UPQC for grid integration of PV systems has increased the functionality of conventional UPQC which provide desired solution for issues related to power quality and protection of critical loads from voltage fluctuations [5], [6].

Power control of inverters of UPQC has been traditionally implemented with SRF, modified SRF theory [7], resonant controllers (PR-R and V-PI) [9], and UVTG controller [8], [10] for the generation of reference signals. Despite of good performance of advanced controllers for UPQC, conventional PI controllers fail to operate satisfactorily in dynamic conditions of voltage and current, due to its non zero steady state error. The utilization of PI controller for conventional control algorithm for PV interfaced UPQC system may not provide satisfactory performance during dynamic conditions. As the PV interfaced UPQC system is responsible for simultaneous elimination of various voltage and current power quality issues. Therefore the need to design an advanced controller and perfect PI controller gains in concern with adaptivity towards severe conditions of grid cannot be ignored.

The drawback of the utilized optimization schemes for PV-DSTATCOM lies in the selection of appropriate parameter to reach the optimum solution [11], [12]. On the contrary, finding the optimum solution by selection of proper system parameters becomes difficult, for complex system like PV-UPQC. In this regard, a rigorous literature survey have been done, which clearly reveals that many attempts have adopted for the performance enhancement of UPQC but there are very few literatures reported for PV-UPQC systems for performance and efficiency enhancement through the utilization of optimization schemes which is specifically free from algorithmic parameters. The conventional optimization schemes may be inactive during the dynamic conditions and there is much chance to converge at local minima due to inappropriate selection of the control parameters. Utilizing advanced optimization algorithms for PV-DSTATCOM in [11], solution for only current quality issues with fixed PI controller gains have been presented. Therefore an initiative

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has been taken by the authors to enhance the performance of PV-UPQC system.

Traditional evolutionary optimization algorithms have common controlling parameters like population size, number of generations and they also require algorithm specific parameters like PSO uses inertia weight, cognitive parameters; Ant colony bee uses number of onlooker bees, employed bees [11]. Considering all these facts, JAYA optimization algorithm has an advanced solution, which doesn't use the algorithm specific parameters, but it only depends on the common controlling parameters. The JAYA algorithm also has major advantage over Teaching Learning Based Optimization (TLBO) such as economical in computation, provides easy platform for discrete optimization and suitable for fewer design variables [11]. The proposed JAYA optimization scheme converges comparatively faster than TLBO to reach the global optimum solution.

To cope with the severe dynamic conditions of voltage and current, PV interfaced UPQC system requires an online and automatic tuning approach. Therefore authors have proposed a novel JAYA optimization scheme with a feature of auto tuning capability of PI controller gain values for PV interfaced UPQC system. Inspired from the auto tuning JAYA optimization scheme in [13] for efficient MPPT tracking and the critic based self tuning PI structure for voltage source converters in [14], the research work has been developed for the PV-UPQC system. The implementation of JAYA algorithm in online manner for PV interfaced UPQC systems have not been reported so far for performance and power quality improvement. The previously proposed JAYA algorithm for DSTATCOM has utilized single cost function useful for improvement of current quality [11]; however the authors have presented a new JAYA optimization algorithm, which has separate objective function for shunt and series inverter control useful for simultaneous current and voltage quality improvement in the PV interfaced UPQC system. The present novel JAYA optimization methodology is introduced in this research work to reach the optimum values for PI gains in accordance with the aforementioned grid disturbances by increasing the adaptivity of the system. Adaptive JAYA optimization based Proportional Resonant and Resonant (PR-R) controller for series converter and Unit Vector PI controller (UV-PI) for shunt converter of PV-UPQC have been implemented, which are presented in Section III. New JAYA adaptive optimization technique explained in Section IV is useful for determination of suitable PI gain values on occurrence of severe grid conditions. Furthermore, PV interfaced UPQC (PV-UPQC) system presented in Section II is integrated with grid by utilizing a LCL filter at the output of shunt converter of PV-UPQC to minimize harmonics in PWM switching. The experimental prototype development, discussion on obtained experimental results by the implementation of proposed algorithm is clearly presented in Section V. The conclusion of the research work presented in the paper is included in Section VI.

II. SYSTEM CONFIGURATION

Photovoltaic interfaced UPQC topology as proposed by the author in the paper is shown in Fig. 1. The grid is connected to

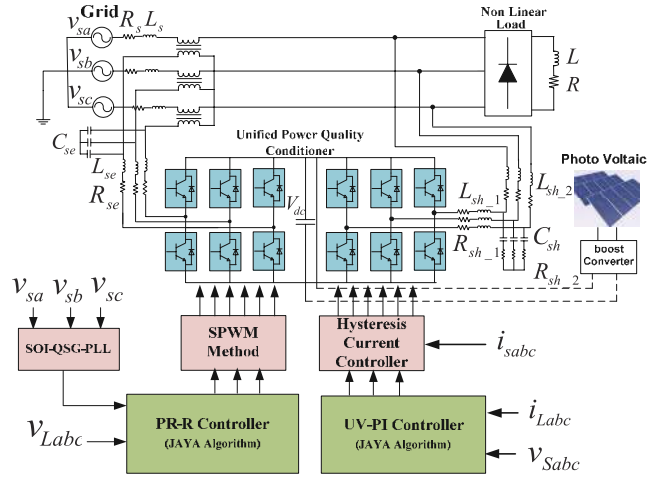


Fig.1. Block diagram of proposed photovoltaic fed-UPQC.

a linear as well as a nonlinear load. UPQC system is installed in the distribution line where shunt inverter is placed at load side and the series inverter is present close to source side through series transformers. The series and shunt inverter of the UPQC share a common dc-link. The PV system containing a boost converter is interfaced to the grid through the dc-link of the UPQC. The grid voltage and the voltage required by the load can be represented here as v_s and v_L . The current consumed by the load is given as i_L and the grid current is presented as i_s .

III. PROPOSED CONTROL SCHEME OF PV-UPQC

The complexity arises in the UPQC when photovoltaic system is fed to the grid through UPQC. As PV-UPQC system is new therefore, most of the conventional control scheme applied to the UPQC system may be applied to the present configuration. However the present complex system becomes more complex with the conventional algorithm and may not perform satisfactorily. The control configuration of the PV-UPQC includes shunt inverter control, series inverter control and maximum power point tracking controller. The system utilizes UV-PI controller for shunt inverter based on novel JAYA optimization to determine the best values for PI gains. The controller of PV-UPQC utilizes P&O (Perturb and Observer) MPPT method for maximum power extraction from the PV [13] for the regulation of dc link voltage.

A. MPPT Controller for the Boost Converter

The MPPT algorithms are utilized for boost converter of the PV System to extract maximum power. In the present paper authors have adopted P&O scheme of MPPT [13] to extract maximum power from PV array. The utilization of MPP controller is associated with shunt inverter controller is shown in Fig. 2(a).

B. UV-PI Controller Along With JAYA Optimization for Shunt Inverter

In the present paper authors have proposed UV-PI controller based on JAYA optimization for the control of shunt inverter of

UPQC as shown in Fig. 2. The measured amplitude of the three phase voltage (v_{sa}, v_{sb}, v_{sc}) is given as

$$v_t = \sqrt{\frac{2}{3}(v_{sa}^2 + v_{sb}^2 + v_{sc}^2)} \quad (1)$$

Evaluation of unit templates for instantaneous phase voltage is given as (v_{ap}, v_{bp}, v_{cp})

$$v_{ap} = \frac{v_{sa}}{v_t}, \quad v_{bp} = \frac{v_{sb}}{v_t}, \quad v_{cp} = \frac{v_{sc}}{v_t} \quad (2)$$

Another set of unit templates are formed with a phase shift of 90° is given as (v_{aq}, v_{bq}, v_{cq})

$$v_{aq} = -\frac{v_{bp}}{\sqrt{3}} + \frac{v_{cp}}{\sqrt{3}}, \quad v_{bq} = \frac{(3v_{ap} + v_{bp} - v_{cp})}{2\sqrt{3}} \quad (3)$$

$$v_{cq} = (-3v_{ap} + v_{bp} - v_{cp})/2\sqrt{3}$$

Optimization of the perfect PI gain is required for the performance enhancement of present system. Thereby JAYA optimization is employed with the controller to find perfect PI gains. The evaluated error between terminal voltage (v_t) and the reference of terminal voltage is the input to the discussed JAYA optimization based PI controller block. The active power component of grid current is determined by comparison of measured actual dc link voltage and reference dc bus voltage. The regulation of dc voltage is highly essential which is maintained through PI controller (I_{cdp}). In Fig. 2(b) amplitude of active power component of reference source current is given. The amplitude of the active power is generated by subtraction of feed forward component of PV (I_{Fpv}) from the summation of active power component of self generated dc bus of PV-UPQC and average magnitude of active power component of load current (I_{Lap}). In presence of voltage sag and voltage swell in the grid voltage, adjustment in the grid currents are necessary to maintain the power balance in the system. Thereby feed forward signal of PV is essential for the control algorithm for fast dynamic response and to suppress oscillations in the grid currents. The feed forward signal of PV (I_{Fpv}) is evaluated from amplitude of terminal voltage (v_t) and power extracted from PV array, which is represented as (P_{pv}/v_t).

$$I_{dp}^* = I_{cdp} + I_{Lap} - I_{Fpv} \quad (4)$$

Comparison of output obtained from dc bus voltage of PI controller and average load reactive power component results in amplitude of reactive power component of reference source current.

$$I_{dq}^* = I_{cdq} - I_{Laq} \quad (5)$$

Where reactive power component of load current average is presented as I_{Laq} is the output obtained from the output of low pass filter. The evaluated terminal voltage is compared with a

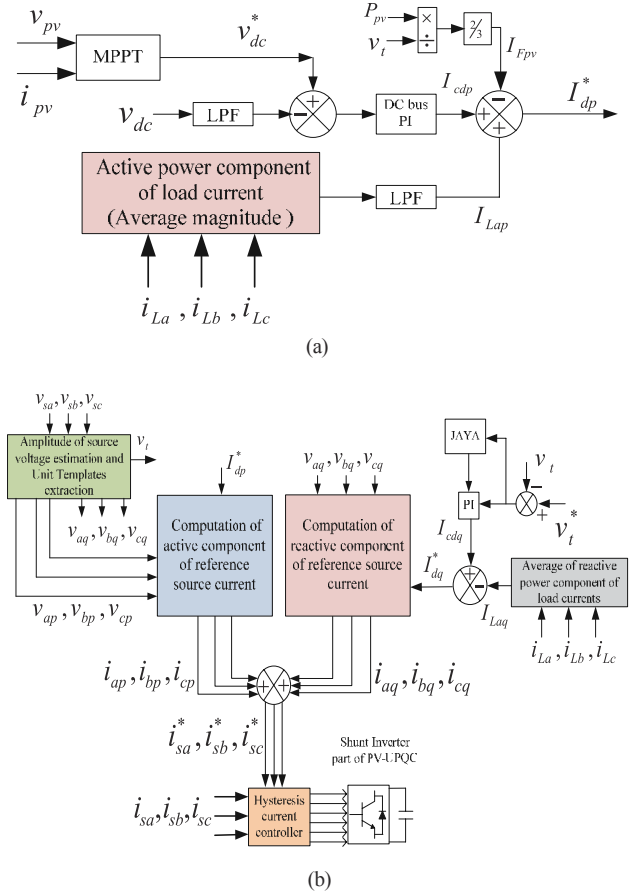


Fig. 2. Approximate diagram of shunt inverter controller (a) block diagram of DC link controller, (b) proposed controller for shunt inverter.

reference terminal voltage (v_t^*) to generate errors corresponding to grid voltage conditions (voltage sags and voltage swells). The generated error is given to PI controller supported by proposed JAYA algorithm to provide suitable output. As the proposed JAYA optimization is implemented, PI controller is tuned according to the sensed voltage distortions. The output of JAYA based PI controller (I_{cdq}) is compared with average reactive power component of load current (I_{Laq}) to provide the reactive power component of the reference source current (I_{dq}^*) as given in (9).

So the present shunt controller computation method provides error free evaluation of reactive power component of the reference source current (I_{dq}^*). The active current component and reactive current component per phase is evaluated as

$$i_{ap} = I_{dp}^* v_{ap}, i_{bp} = I_{dp}^* v_{bp}, i_{cp} = I_{dp}^* v_{cp} \quad (6)$$

$$i_{aq} = I_{dq}^* v_{aq}, i_{bq} = I_{dq}^* v_{bq}, i_{cq} = I_{dq}^* v_{cq} \quad (7)$$

The total reference source currents can be evaluated for PV-UPQC are represented as

$$i_{sa}^* = i_{ap} + i_{aq}, \quad i_{sb}^* = i_{bp} + i_{bq}, \quad i_{sc}^* = i_{cp} + i_{cq} \quad (8)$$

The considered PV-UPQC system has the responsibility to supply active component as well as reactive component, both the components are added. The generated reference currents are passed through hysteresis current controller, which is employed to provide desired gate pulses for the shunt inverter of PV-UPQC. The tuning of PI controller gains is desired to improve the PV-UPQC performance which affects the controller efficiency and improvement of power quality. Therefore the proposed optimization is utilized to obtain the gain of PI controller.

C. Controller Based on JAYA Optimization for Series Inverter

Presence of voltage sags and voltage swells in the distribution line make the load voltage distorted. Therefore series inverter of PV-UPQC plays significant role in elimination of voltage distortions from the load voltages for steady state behaviour of loads. In the present scenario, control of series inverter is much necessary for better elimination of voltage distortions. Thereby the authors have proposed a new PR-R controller utilizing an adaptive JAYA optimization as given in Fig. 3 and is implemented for PV-UPQC. The present controller has the ability for regulation of positive sequence components. Even in highly distorted grid conditions, it is desired that series inverter of PV-UPQC has to provide suitable injecting voltage signal to regulate the load voltage magnitude.

$$v_L = v_s + v_i \quad (9)$$

Where v_L is sensed load voltage, v_i is the injected voltage and v_s is the source voltage. It is assumed that during steady state condition, measured grid voltage remains sinusoidal with phase angle of θ_s . The supply voltage is reduced from V_s' to V_s'' with voltage sag condition without having phase jump. On the contrary, the condition of voltage sag with a phase jump of δ , the series inverter controller of PV-UPQC injecting voltage signal with phase angle of $(\theta_s + \delta)$. The voltage controller of PV-UPQC in d-q reference frame has been implemented. In the present controller an advanced PLL has been utilized to obtain the phase angle of supply voltage for the desired transformation. The SOI-QSG-PLL is discussed in the following section. The switching signals for the series inverter are provided by the voltage reference signal generated by the proposed series inverter controller of PV-UPQC as given in Fig. 3.

The transfer function to explain the PR-R controller [9] is given as

$$G_{PR-R} = K_p + \frac{K_{r1}\omega_c s}{s^2 + 2\omega_c s + (\omega_s)^2} \quad (10)$$

Where K_{r1} denotes the resonant gain, proportional gain is presented as K_p , ω_s is selected resonant frequency, cut-off frequency is represented as ω_c . The configuration and development of a nonlinear controller is seems to be difficult. Therefore PR-R controller is developed to enlarge the bandwidth and quick action against voltage disturbances. The present series inverter controller shows its performance to achieve unity gain and zero phases at the respective resonant frequency.

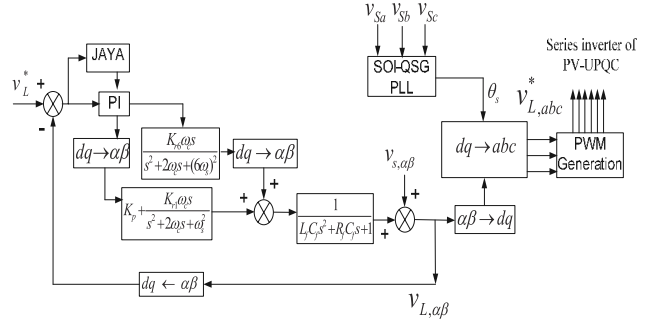


Fig. 3. Approximate block diagram of JAYA based voltage controller for series inverter.

The series inverter controller of the system utilizes new adaptive JAYA optimization as shown in Fig. 3. The PI controller gains are important for the operation of PR-R voltage controller for the generation of the reference voltages useful for switching signal generation for series inverter. To find suitable of PI controller gains, proposed JAYA optimization has been employed. The presence of LC filter in PV-UPQC at the output of series inverter is represented by the transfer function G_{LC} . The disturbances in the grid voltages are measured to evaluate the error for the updating the parameter values.

To determine the suitable values of proportional gain and integral gain, implementation of proposed new JAYA algorithm in the PV-UPQC controller has been achieved. The selected parameters for the PR-R series inverter controller are given here as $K_p = 2$, $K_{r1} = 2000$, $\omega_c = 10$ rad/sec, which are selected before optimization [9]. The suitable optimization parameters obtained from computation of JAYA optimization is given in TABLE II. The developed transfer function can be represented as

$$G_c = \frac{G_{PR-R}(s)G_{LC}(s)}{1 + G_{PR-R}(s)G_{LC}(s)}, \quad (11) \quad \text{where} \quad G_{LC}(s) = \frac{1}{L_f C_f s^2 + R_f C_f s + 1}$$

The present research work proposes a new and adaptive JAYA optimization algorithm to reach the best optimal values for the enhancement of efficiency of the present system.

D. SOI-QSG Based PLL

Grid synchronization of PV-UPQC is important in the present complex system; therefore double second order integral-quadrature signal generator based phase locked loop SOI-QSG-PLL block is implemented in the present system. The advanced PLL technique of SOI-QSG-PLL is employed in the present series inverter controller. The SOI-QSG-PLL is utilized for filtering function to determine signals with 90° phase shift which act as input to the positive sequence calculator. The effective utilization of synchronous reference frame based PLL provides adaptive characteristic to system for any frequency change condition. A detailed explanation of SOI-QSG is given in [15].

IV. JAYA OPTIMIZATION ALGORITHM AND FORMULATION

Celebration at defeating an opponent by neglecting the failure

at any condition to become victorious is termed as victory. Following this culture, an optimization method is named as JAYA (means victory) optimization tool. The speciality of this algorithm is to have the control parameters which propel its result more nearer to the best solution by eliminating the worst one. Due to its less implementation complexity, faster convergence and little computation time over other optimization schemes, the authors have considered JAYA optimization for the present system. Combining the features of JAYA algorithm and online tuning process of the PI controller, inspired from literatures [11], [13] and [14], the JAYA based auto tuning PI controller is proposed. The system feedback, evaluated by the actual and reference signals is considered as the objective function of the system. As the shunt converter is responsible for current quality in the grid, thereby objective function is defined as presented in (14). Similarly for the series converter the objective function is defined which depends on the actual load voltage and reference load voltage signals as presented in (15). The computation at iterations or steps of implementation of JAYA optimization is shown in the flow chart of Fig. 4.

A. JAYA Based Algorithm

In the JAYA based methodology, considered objective function is required to be minimized or maximized. Before the computation of the algorithm, population size is needed to be addressed clearly which is denoted as $(y=1, 2, 3\dots n)$. It is assumed in the algorithm that at any of the iteration “ i ”, the determination of the design variables can be given as $(d=1, 2, 3\dots k)$. At the initialization point the termination criteria is also required to be defined. After initialization of the population size and determination of design variables, a random population is generated. Determination of the best candidate solution from the selected range of the candidate solution for the objective function of $f(x)$ is the priority of the algorithm. Finding the worst solution from the range of candidate solution is required for the computation. After considering minimizing function, lowest value of $f(x)$ is selected as the solution which is best among the range. The random variable selected for the algorithm are r_1 and r_2 of the range $[0,1]$. It is assumed that $D_{d,y,i}$ value of d^{th} variable, y^{th} candidate and i^{th} iteration, which can be presented as

$$D_{d,y,i}^i = D_{d,y,i} + r_{1,d,i} (D_{d,best,i} - |D_{d,y,i}|) - r_{2,d,i} (D_{d,worst,i} - |D_{d,y,i}|) \quad (12)$$

where $D_{d,y,i}$ denoted as the value of d^{th} variable for y^{th} candidate at i^{th} iteration. $D_{d,best,i}$ is represented as the best candidate obtained and $D_{d,worst,i}$ is considered as the worst candidate. The important characteristic of proposed JAYA algorithm has shown its tendency to move towards the best solution by dominating over the worst solution. The concept utilized for the present algorithm is represented by (12). The positive term present in (12) clearly denotes that the candidate moves towards the best solution. Similarly the negative part of (12) reveals the truth that the candidate solution is away from the worst. After evaluation of all the particles present in the solution, it is required that the convergence criteria should be met. According to the change

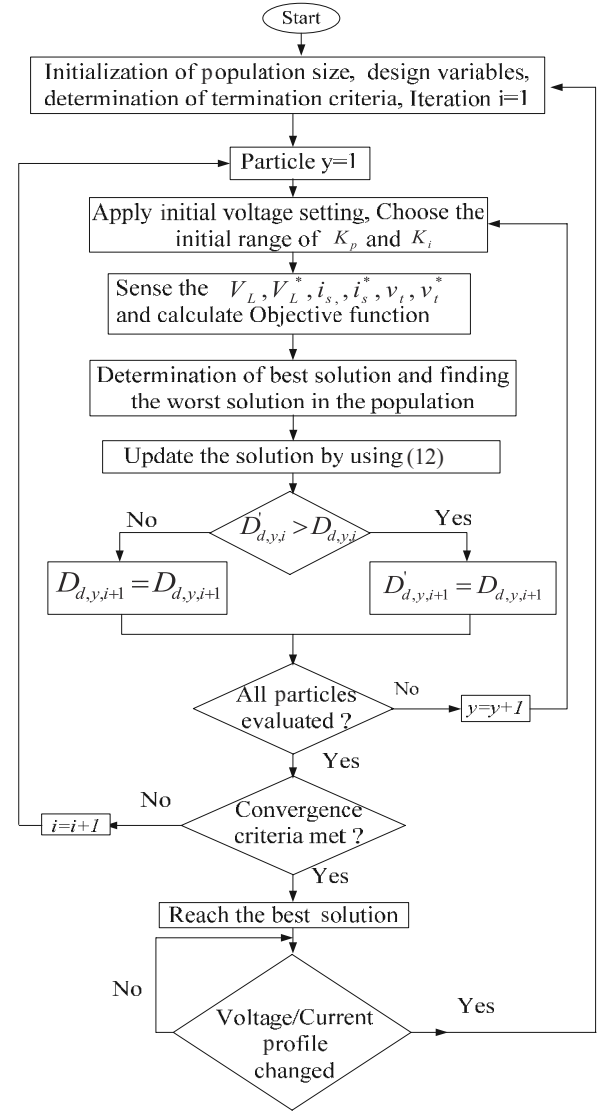


Fig. 4. Proposed flow chart for JAYA optimization based auto tuned PI controller.

in grid disturbances, the algorithm again looks for the new best solution by generating a fresh initialization command. Again upon finding the new values of design variables, objective function is evaluated which is compared with previously obtained value.

B. Implementation of JAYA Based Algorithm for PI Controller

As the PV-UPQC system is open to voltage and current disturbances, so novel JAYA optimization scheme is employed to determine the PI controller gains (K_p and K_i) in the present paper. Therefore the algorithm should have adaptive nature to sense the type of disturbances; thereby it can define the objective function. The tuning of the PI controller gains and evaluation in this study relies on the grid disturbances according to grid situations. The reduction on the updates of negative solution and thereby auto tuning of PI gains lead to enhancement of

the controller performance. The updated solution will be considered as the best solution if it satisfies the convergence criteria. Otherwise, the considered solution is discarded and new updated solution of the algorithm will be generated. The flow chart of the proposed JAYA methodology for PV-UPQC is presented in Fig. 4.

Step 1 Initialization and parameter setting: The population size as n has been considered for the proposed JAYA algorithm. The initial values of the K_p and K_i is set within the range of [1.2, 3.8] and [0.6, 2.4].

Step 2 Objective function evaluation: Two different objective functions are selected for the PV-UPQC for shunt converter and series converter as both are employed for different function with separate controller.

Problem defined in the present paper signifies the formulation of a minimizing function. Therefore a candidate solution providing the lowest value of $f(x)$ has been selected as the required best solution. The evaluated mean square error (MSE) is considered as the objective function is given as

$$J = MSE = \sum_{i=1}^{iter} e_r^2 \quad (13)$$

Where e_r is different for both shunt and series inverter of PV-UPQC as they have different control algorithms. Therefore e_r for shunt and series inverter can be presented as

$$e_{r_shunt} = \frac{|i_{sa}^* - i_{sa}| + |i_{sb}^* - i_{sb}| + |i_{sc}^* - i_{sc}| + |v_t^* - v_t|}{iter} \quad (14)$$

$$e_{r_series} = \frac{|v_{La}^* - v_{La}| + |v_{Lb}^* - v_{Lb}| + |v_{Lc}^* - v_{Lc}|}{iter} \quad (15)$$

Step 3 Fitness solution evaluation: The implementation of JAYA optimization in PV-UPQC system controller is to determine minimum constraints values. The application of JAYA algorithm has a randomly generated initial condition which is evaluated according to predefined cost function. At the time of initialization command for JAYA algorithm, require selection of initial population size or candidate solution, is defined as ($y=1,2,3...n$). Considering the candidate solution controller gains are determined through i^{th} iteration and d^{th} variable for choosing the best and worst solutions. Therefore $D_{d,y,i}$ is directly related to the proposed inverter controllers of PV-UPQC. This method is selected to find controller gains to increase the performance and efficiency to achieve power quality standards.

Step 4 Convergence criterion: The proposed JAYA algorithm will conclude with the best solution if the error between the best candidate solution and the worst candidate solution is less than the threshold ε .

Step 5 Re-initialization of JAYA algorithm: The proposed JAYA algorithm will be initialized again, when a different grid perturbations occurs. The occurrence of current harmonics, voltage sags, voltage swells, and voltage unbalance will activate the proposed JAYA algorithm.

Determination of optimized PI controller gains values are achieved through the aforementioned method. (12) plays major role in this process, where $D'_{d,y,i}$ is the value of optimized parameter. Previously obtained value of PI controller gain is considered as $D_{d,y,i}$ for this algorithm. In accordance with new JAYA optimization methodology, the worst performing gain values are eliminated which is related to the negative term of (12) presented as “ $-r_{2,d,i}(D_{d,worst,i} - |D_{d,y,i}|)$ ”.

The best performing gain values are accepted by the optimization algorithm presented as the positive term of (12) “ $D_{d,y,i} + r_{1,d,i}(D_{d,best,i} - |D_{d,y,i}|)$ ”.

In accordance with various grid distortions, the controller of PV-UPQC requires specific value of PI controller gains to provide satisfactory performance. By utilization of conventional PI gain tuning method, certain values of PI gains have been obtained for particular type of grid distortion.

These values of PI gains have been considered to provide a valid range for proposed JAYA based optimization algorithm, useful for accurate gain tuning on the appearance of different distortion levels. The initialization of JAYA optimization for the computation to find the PI controller gains has been done with selection of the range of PI controller gains is presented as $k_p(1.2 \rightarrow 3.8)$ and $k_i(0.6 \rightarrow 2.4)$.

V. RESULTS AND DISCUSSION

The proposed JAYA based auto tuned PI controller is applied to the controller of PV-UPQC system for the performance improvement. Simulation models are developed for the proposed system and methodology in MATLAB/Simulink environment to verify the efficiency and performance of the proposed controller. The superiority of the JAYA based auto tuned PI controller is claimed by comparing the results from the proposed controller with the conventional PSO and TLBO based fixed PI gain optimization method. The comparative evaluations of the methodologies considered are quantitatively evaluated in TABLE I. Various cases are considered for different grid conditions, represented as the mean and standard deviation of PI gain error values are presented the TABLE I.

A detail discussion on prototype development and results are presented in this section. Prototype developed for PV-UPQC is shown in Fig. 5. The PV system is interfaced to the UPQC at the dc link. SEMIKRON inverters are implemented for UPQC, which share a common dc-link. The grid voltages, PV voltage and grid currents are sensed by the calibrated Hall effect transducer. The measured signals are utilized by dSPACE 1103 processor for implementation of the control algorithm for the generation of the switching signals. Proposed JAYA optimization scheme has shown its capability to update the PI controller parameters according to the sensed disturbance, the variations in measured PI controller gains are listed in TABLE II. Variation in sampling time can directly affect the controller performance to achieve desired results. Sampling time considered for the proposed algorithm is 31.4 μs which is selected in accordance with the complexity of the overall algorithm to achieve satisfactory performance. It has been analysed with the proposed controller that upon increasing or decreasing the sampling time, the sys-

TABLE I
EXPERIMENTAL SIMULATION RESULTS, CONVERGENCE TIME (MEAN, STANDARD DEVIATION) FOR VARIOUS CASES

Case	Performance of PV-UPQC Under Various Conditions	With PSO		With TLBO		With Proposed JAYA	
		mean	SD	mean	SD	mean	SD
A	Linear and Nonlinear Load	5.88	1.90	4.02	1.65	1.32	0.36
B	Unbalanced Linear Load	6.52	1.65	3.87	0.92	1.27	0.19
C	Voltage Sag	5.96	1.86	3.43	0.99	1.58	0.21
D	Voltage Swell	6.74	1.72	3.77	1.05	1.31	0.14
E	Unbalance Voltage Sag	5.91	1.7	3.32	1.83	1.69	0.34
F	Irradiance Variation	5.81	1.92	4.04	1.61	1.34	0.38

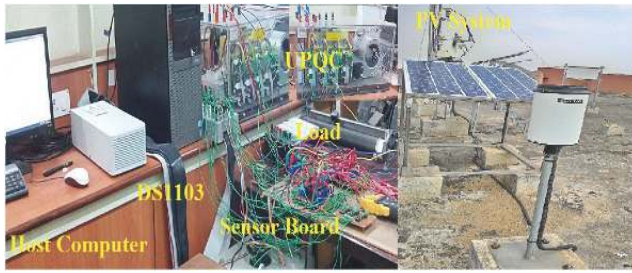


Fig.5. Hardware Prototype developed for PV-UPQC.

TABLE II
VARIATION OF PI CONTROLLER GAINS WITH PROPOSED JAYA ALGORITHM

Type of Disturbances	K _p	K _i
Voltage swell	2.3	0.85
Voltage sag	1.8	2.1
Current harmonics	2	1.3
Linear and nonlinear	3.7	1.2
Unbalanced linear load	1.5	0.8

tem has performed in an average manner and results obtained are worst than with selected sampling time.

A. Performance of PV-UPQC Under Linear and Nonlinear Load Conditions

In the PV connected mode to the grid through UPQC under linear and nonlinear load conditions, controllers are implemented for developed prototype and experimental results are analyzed in this section. The measured nonlinear load currents rich in harmonics are presented in Fig. 6(a). For the elimination of the harmonics, PV-UPQC is employed and current waveforms at the PCC side based on implemented controllers are depicted in Fig. 6(b) to Fig. 6(e). Despite of controllers implemented, performance of the system varies with PI gains. Fig. 6(b) shows the PCC side currents with UV-PI controller with fixed value of PI gains without any optimization (Scenario I). PCC side currents with PSO algorithm (Scenario II), TLBO algorithm (Scenario III) after compensation of harmonics are shown in Fig. 6(c) and Fig. 6(d) respectively. The PV-UPQC with proposed JAYA based auto tuning PI controller (Scenario IV) elim-

TABLE III
EXPERIMENTAL PARAMETERS FOR PROTOTYPE DEVELOPMENT

Selected Parameters	Value
Grid voltage	110 V
Fundamental frequency	50 Hz
Source inductance	0.4 mH
DC bus capacitor, dc bus voltage	3.5 mF, 200 V
Series inverter coupling inductance	0.5 mH
Ripple filter at series inverter	20 μ F, 10 Ω
Shunt inverter coupling inductance	3.5 mH
Non linear load	100 Ω /40 mH
Unbalanced load	50 Ω /30 mH, 100 Ω /40 mH, 80 Ω /50 mH
Switching frequency	10 kHz
Sampling time	31.4 μ s
Parameters of PV array	
Maximum power of PV(P _{pv})	600 W
Open-circuit voltage (V _{oc})	250 V
Short circuit current (I _{sc})	4.5 A
Voltage at maximum power (V _{mpp})	150 V
Current at Maximum power (I _{mpp})	4.1 A

TABLE IV
PERFORMANCE ANALYSIS OF PSO, TLBO, PROPOSED JAYA FOR PV-UPQC

Parameters	With PSO	With TLBO	With Proposed JAYA
Dependency on algorithm specific parameters	Highly dependent	Independent	Independent
Algorithmic phases	>2	2	1
THD in %	4.2	3.1	1.4
Settling time after switch on	1	0.5	0.5
Switching harmonics	Very High	High	Low
Reference tracking under load unbalance condition	Average	Good	Exact
Reference tracking under voltage sag	Average	Good	Exact
Reference tracking under voltage swell	Average	Good	Exact
Dynamic response	Poor	Average	Better
Convergence time	Mean	Comparatively high	Reduced
	Standard Deviation	Comparatively high	Reduced
		Average	Reduced

inates the harmonics and maintains nearly sinusoidal current at PCC is shown in Fig. 6(e). The total harmonic distortion of load and PCC currents of the present case is presented in TABLE IV.

B. Performance of PV-UPQC Under Unbalanced Linear Load Conditions

Fig. 7(a) presents experimental results of load side currents under unbalanced load conditions. The unbalanced load parameters are given in the TABLE III. As UPQC is installed in the grid with proposed controller, sensed currents at the PCC side are balanced and sinusoidal. The source currents after compensation without optimization are presented in Fig. 7(b). Experimental results of source currents with PSO algorithm, TLBO algorithm and JAYA based auto tuning PI controller are given in Fig. 7(c), Fig. 7(d), and Fig. 7(e) respectively.

C. Performance of PV-UPQC Under Voltage Sag Condition

Fig. 8(a) shows the PCC side voltage during voltage sag condition and Fig. 8(b) present the load side voltage after compensation of voltage sag by PV-UPQC for phase a. During the

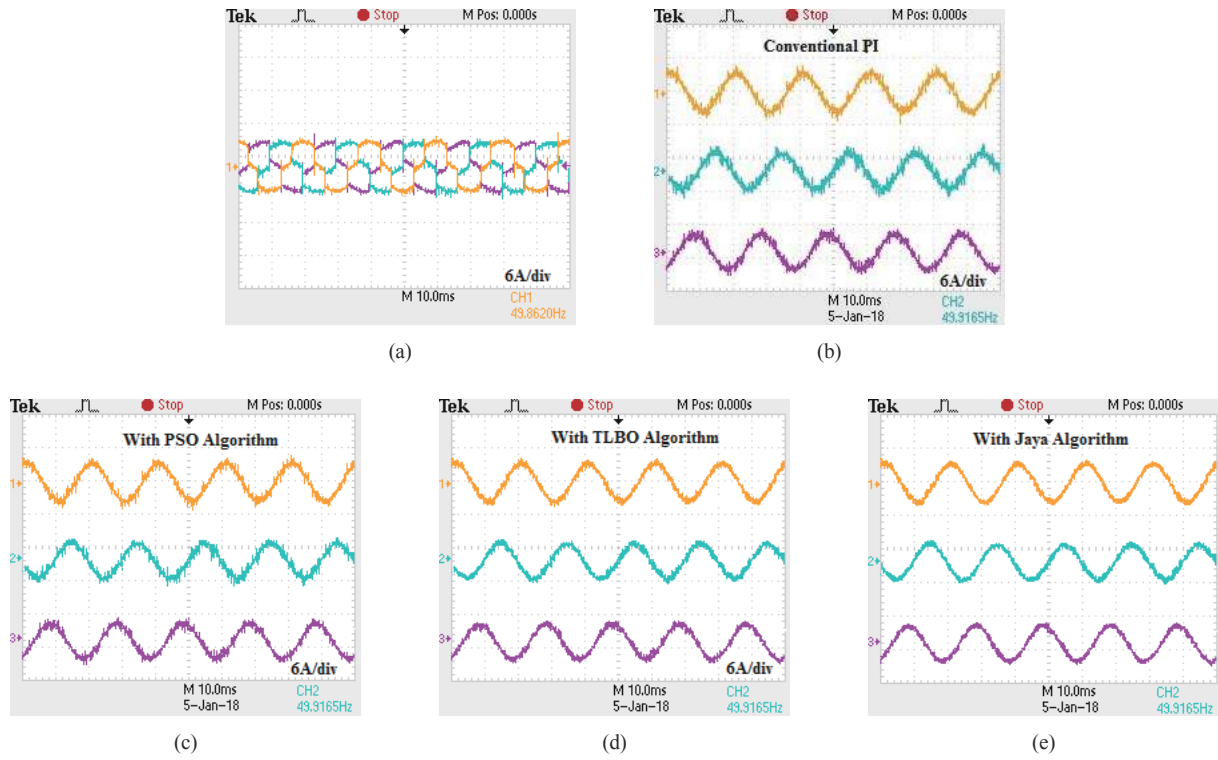


Fig. 6. Performance of PV-UPQC under linear and nonlinear load condition: (a) Load side current, PCC side current after compensation; (b) with conventional PI controller (without optimization); (c) with PSO algorithm; (d)with TLBO algorithm; (e) with JAYA based auto tuning PI controller.

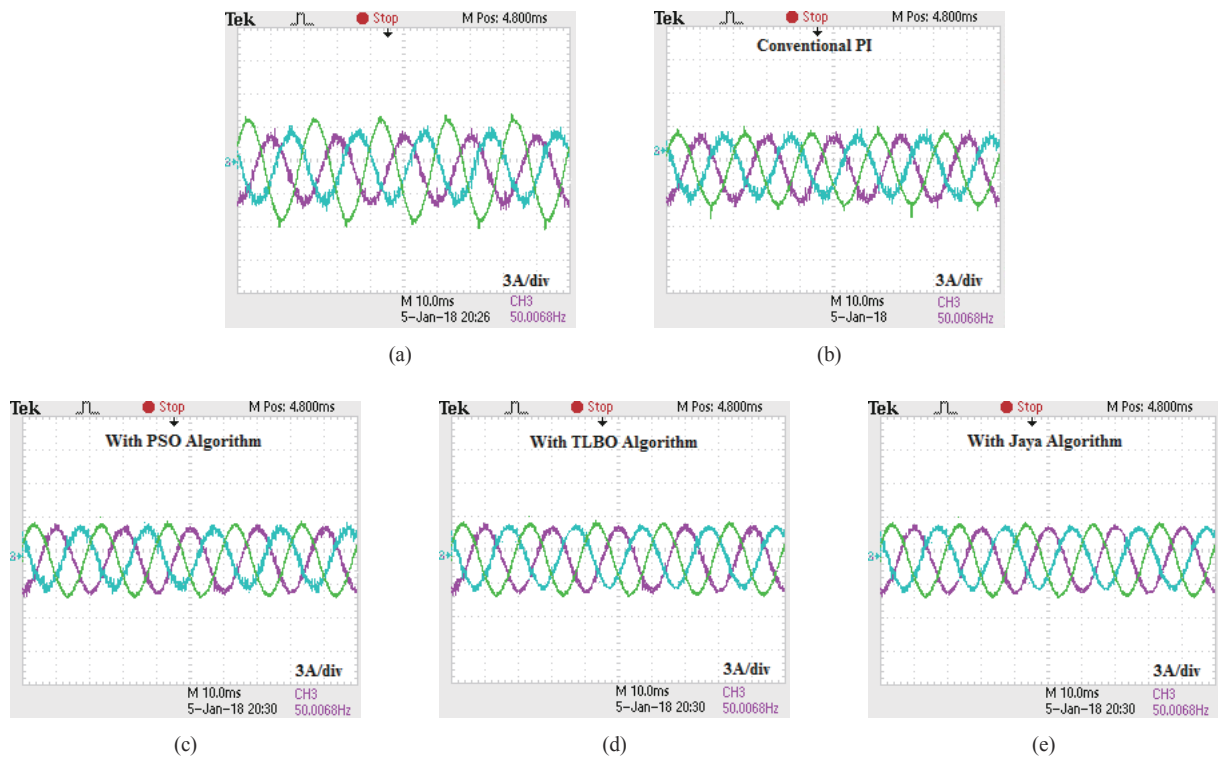


Fig. 7. Performance of PV-UPQC under unbalanced linear load condition: (a) Load side current, PCC side current after compensation; (b) with conventional PI controller (without optimization); (c) with PSO algorithm; (d) with TLBO algorithm; (e) with JAYA based auto tuning PI controller.

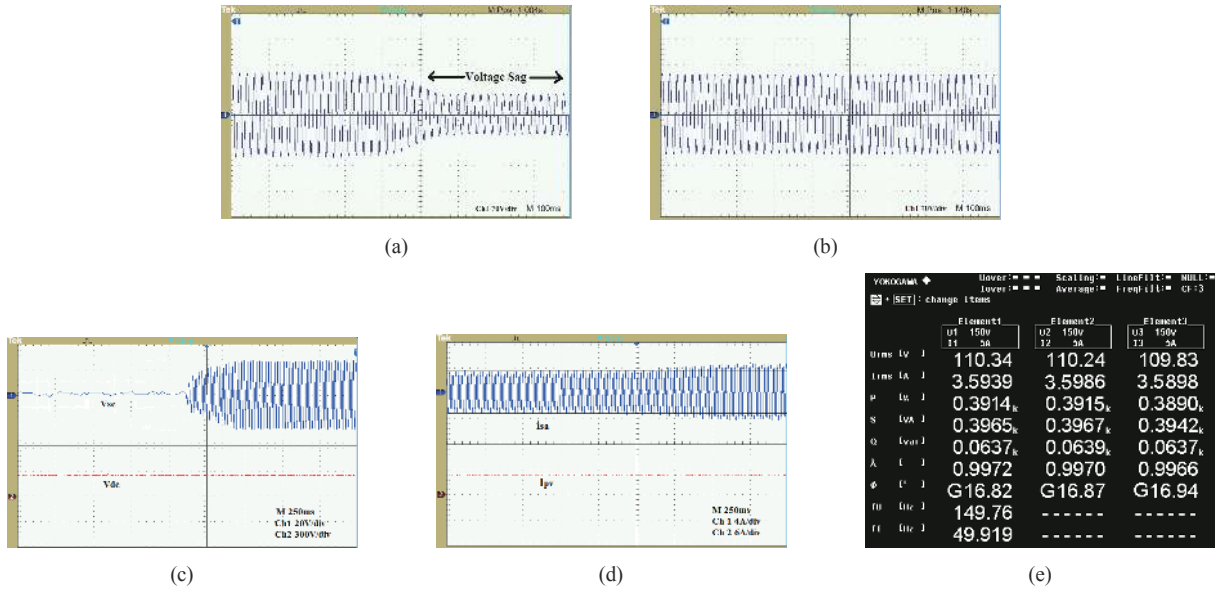


Fig. 8. Performance of PV-UPQC under voltage sag condition: (a) PCC side voltage with sag; (b) Load side voltage after sag compensation with JAYA based auto tuning PI controller; (c) Injecting voltage from series APF and dc-link voltage; (d) PCC current during voltage sag and PV current at constant irradiation; (e) Load side power analyzer three phase voltage and current.

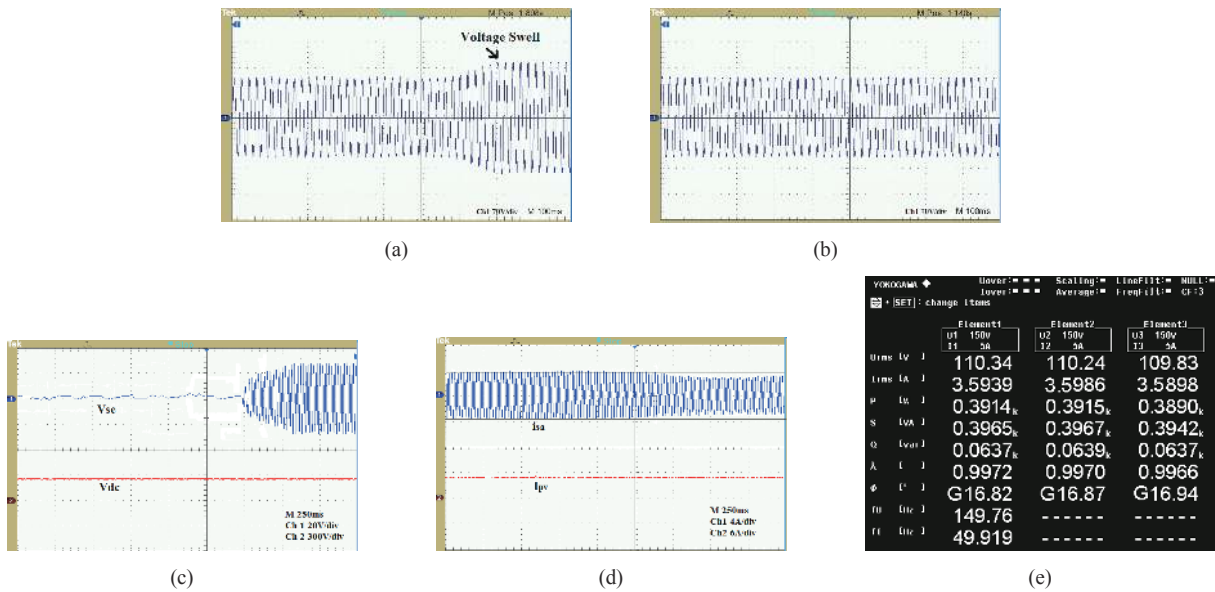


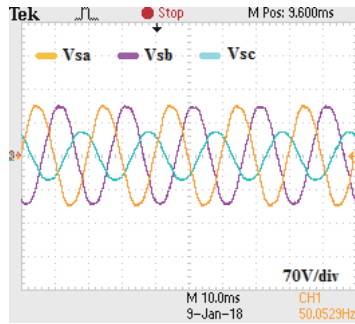
Fig. 9. Performance of PV-UPQC under voltage swell condition: (a) PCC side voltage with swell; (b) Load side voltage after swell compensation with JAYA based auto tuning PI controller; (c) Injecting voltage from series APF and dc-link voltage; (d) PCC current during voltage swell and PV current at constant irradiation; (e) Load side power analyzer three phase voltage and current.

voltage sag, the series inverter voltage injected and the regulated DC-Link voltage is presented in Fig. 8(c). To maintain the power balance at the load, there is increase in grid current as presented in Fig. 8(d). The load side voltages are measured by three phase power analyzer (YOKOGAWA WT500) as shown in Fig. 8(e). From the power analyzer, measured signals are analyzed and it is seen that λ is at near to unity power factor.

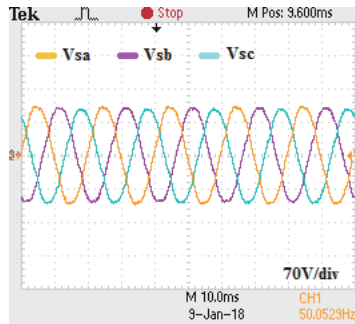
D. Performance of PV-UPQC Under Voltage Swell Condition

Voltage swells occurs due to PCC voltage rises to 130 V as shown in Fig. 9(a). The series converter of PV-UPQC injects

compensating signal to PCC to regulate the load voltage at 110 V as presented in Fig. 9(b) with the proposed JAYA based controller. The series inverter injecting voltage for load voltage regulation is given in Fig. 9(c), which also shows the constant DC-link voltage. During voltage swell condition, there is decrease in grid current to maintain power balance in the system as shown in Fig. 9(d). The results obtained from the experimentation prove the efficiency of proposed JAYA based auto tuned PI controller for the controller of PV-UPQC. Fig. 9(e) shows the power analyzer signals for regulation of the load voltages.



(a)



(b)

Fig. 10. Performance of PV-UPQC under unbalanced voltage sag condition: (a) PCC side voltage with unbalanced phase C; (b) Load side voltage after swell compensation with JAYA based auto tuning PI controller.

E. Performance of PV-UPQC Under Unbalance Voltage Sag Condition

Unbalance voltage sag is a practical scenario taken into consideration in this section to analyze the results of PV-UPQC performance. There is a voltage dip in V_{sc} (Phase C) which is presented in Fig. 10(a). The load voltage is maintained by PV-UPQC based on JAYA based auto tuning PI controller as shown in Fig. 10(b). PV-UPQC with proposed method has shown its performance by maintaining the load voltage at desired level.

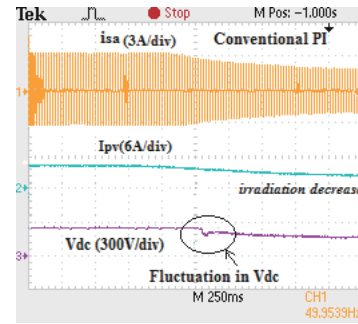
F. Behaviour of PV-UPQC Under Irradiation Variation

From the Fig. 11(a), it is clearly revealed that decrease in irradiation condition from 1000 W/m^2 to 500 W/m^2 helps in decrease in the grid current. By the utilization of conventional PI in Fig. 11(a) under decrease in irradiation condition, fluctuation in DC-Link voltage appears. However, the dc-bus voltage is maintained at the desired level, proves the effectiveness of the proposed controller and performance of the PV-UPQC system as presented in Fig. 11(b).

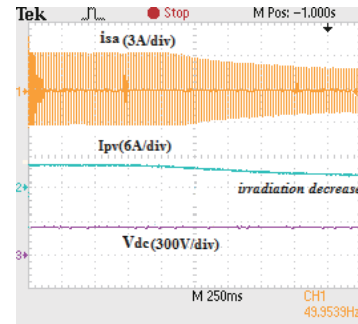
The analytical comparison of adopted optimization methodologies PSO, TLBO and proposed JAYA based algorithm for PV-UPQC topology is presented in nutshell in TABLE IV.

VI. CONCLUSION

The dynamic performance of proposed JAYA based auto tuned PI controller for PV-UPQC system has been analyzed



(a)



(b)

Fig. 11. PV-UPQC performance under irradiation variations: (a) Irradiation decrease from at 1000 W/m^2 to 500 W/m^2 (conventional PI method); (b) Irradiation decrease from 1000 W/m^2 to 500 W/m^2 (proposed JAYA based PI tuning method).

in detail in this present study. An online JAYA optimization methodology is implemented for PV-UPQC to determine the best value of PI controller gains. UV-PI and PR-R controllers of shunt and series converters, based on JAYA optimization technique have enhanced the PV-UPQC performance. The performance and efficiency of the considered method is studied in multiple operational scenarios of the grid and the responses are compared with PSO, TLBO optimization methods. In the verge of increasing efficiency of the system PV-UPQV, an LCL filter is employed at the output of shunt converter to handle the undesired harmonics of PWM switching of converter. The experimental results verify the effectiveness of the proposed novel control method and prove that JAYA based auto tuned PI controller has significantly raised the PV-UPQC performance by reducing the convergence time, settling time, switching harmonics, complexity and effective dynamic response.

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