Design of Soccer League Optimization Based Hybrid Controller for Solar-Battery Integrated UPQC

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ABSTRACT Nowadays, integration of renewable energy source like solar, wind etc in the grid is encouraged to reduce the losses and meet the demand. However, the integration of these renewable sources, power electronic devices, non-linear and un-balanced loads leads to the power quality issues which motivated power researchers for the development of new controllers and techniques. This paper develops a soccer-league algorithm based optimal tuned hybrid controller for the unified power quality conditioner associated with the solar power and battery-storage systems with the Boost converter and Buck Boost converter. The UPQC simultaneously performs both the functions of Shunt active power filter and series active power filter. The proposed optimally designed controller adapts both the properties of fuzzy logic-controller and SOL algorithm tuned proportional-integral controllers. The $K_p$, $K_i$ values of shunt and series controllers are treated as control variables, which are optimally tuned by SOL to satisfy the objective function. The key contributions of the proposed work are the reduction of total harmonics in current waveforms thereby enhancing the power factor, quick action to maintain the constant DC-Link capacitor voltage during the solar irradiation variations, elimination of voltage sag/swell/large disturbance, and appropriate compensation for the un-balanced networks and loads. The performance investigation of SLOHC was carried out with four test studies for different combinations of unbalanced/balanced loads and supply voltage of 3-phase distribution network. Comparative analysis was carried out with those of standard methods like a genetic algorithm, biogeography-based optimization, and proportional-integral controllers. The proposed method reduces the total harmonic distortion to 2.06%, 2.44%, 2.40%, and 2.32% which are much lower than those of existing methods available in literature. The design has been performed on MATLAB/simulink software.

INDEX TERMS Power quality, soccer league optimization, UPQC, fuzzy logic, PI-C, battery storage system, solar PV system.

NOMENCLATURE

UPQC Unified Power Quality Conditioner.
SLOHC Soccer league optimization based hybrid controller.

SOL Soccer league optimization.
BBO Biogeography-based optimization.
GA Genetic algorithm.
U-PVBS Solar battery integrated UPQC.
SHAPF Shunt active power filter.
PQ Power quality.
I. INTRODUCTION

The Distribution network is prone to huge PQ problems when compared to the Generation/Transmission. The deterioration of PQ refers to the quality of voltage and currents like harmonics, PF, voltage sag/swell/large disturbance, interruptions, flickers, etc., mainly due to the integration of renewable energy sources, ever-growing usage of power electronic devices and unbalanced nonlinear loads.

A. CHALLENGES AND MOTIVATION

The increase in application of large non-linear industrial load has led to increase in harmonic currents thereby reducing PF. Electricity with a bad quality is dangerous and uneconomical at both utility and consumer end. Therefore, maintain of PQ became a challenge to the power engineers. The regulation of capacitor voltage across the DC-Link in addition to minimization of THD in current waveforms, improving PF, and elimination of voltage sag, swell, disturbance, flicker and voltage unbalances to improve the stability and reliability of the grid. To improve the PQ, FACTS device used at the Distribution side of the utility grid is the UPQC.

B. LITERATURE REVIEW

The THD is a significant measure of PQ and it is must to keep it as low as possible. Lower the THD higher the efficiency, PF, and life duration of equipment [1]. The advancement in power electronics has contributed to active power filters involving VSCs for mitigating PQ issues. The UPQC, an important member of the FACTS family employing two back-to-back VSCs, finds more applications in addressing the PQ issues than those of other FACTS devices [2]. The PV associated UPQC was developed with a view to minimize the THD, voltage distortions, and compensating reactive power by extracting the maximum power from the PV panel by adopting MPPT technique [3]. Meanwhile, different artificial-intelligent control techniques like FL-C and ANN [4], [5], [6] for improving PQ in the grid connected distribution network were outlined [4]. The development of intelligent algorithms enables the online control of APF in UPQCs through PI-C, FL-C, SM-C, and ANN [4], [5], [6] for improving PQ for varying nonlinear loads.
Recently, an artificial-neuro fuzzy interface system-based controller was designed for solar integrated UPQC for PQ improvement. The performance analysis was done for various combinations of loads and supply conditions to exhibit the superiority of the proposed technique [7]. In addition, an UPQC associated with a PV system with PI-C was designed with the goal of minimizing the distortions associated with voltages and currents. The PV system was coupled to the DC-link through a BC. The compensation to voltage interruptions and power transfer under islanding were also discussed [8].

The FL-C based controller was developed for the multi-converter UPQC to address the PQ issues effectively [9]. The predator-prey firefly optimization technique was applied in optimally designing shunt active power filters with the objective of minimizing THD and improving power factors [10]. Solar, wind, and fuel cell integrated multi-level UPQC was designed with a view of diminishing the voltage distortions like sag, swell, disturbances, and harmonics in the source currents by injecting suitable voltage and currents [11]. The Predictive phase dispersion modulation technique was implemented on Cascaded H-Bridge Multi-Level UPQC with the motive of compensating the voltage fluctuations, harmonics in current waveform, and maintaining stable DC-Link voltage [12]. Various PQ issues, different design schemes, and THD reduction methods for UPQC were reviewed in detail [13]. THD minimization of induction-furnace load at the steel plant with an UPQC was carried out and to exhibit its superiority the comparative analysis was done with a synchronous compensating device [14]. The development of ANN-based controller for UPQC and its performances were studied by considering issues like sag, swell, harmonics supply voltage, and unbalanced nonlinear loads. The significance of DC-link capacitor voltage on supply currents and THD’s was also discussed [15].

A nonlinear SM-C along with real and reactive power hypothesis was developed for UPQC with a view of effectively compensating voltage and current distortions. The controller provided a complete and fast response for compensating the voltage sags/swells and unbalanced supply voltages [16]. The UPQC employed with solar PV-wind-fuel cell-battery system is proposed to minimize the various power quality issues [17]. An Ant colony algorithm based optimal tuning of PI- was designed for SHAPF to minimize THD for different combinations of loads [18].

A hybrid fuzzy back-propagation control scheme based on 5-level UPQC was proposed to minimize the THD and improve the PF [19]. The SOL based load flow (LF) for both transmission and distribution systems was presented with a objective of minimizing the sum of the squares of the active, and reactive power mismatches at all the busses, while considering the net deviations of bus voltage angles, and magnitudes as unknown variables [20]. An Adaptive full order observer based control algorithm was developed for the UPQC to improve the PQ due to its fast response in fault detection for all positive sequence components, and high accuracy in monitoring under all various loads / grid conditions. In addition, a BBO algorithm was employed for the optimal tuning of Kp and Ki values for PI-C on UPQC with a view of minimizing the DC-Link voltage oscillations [21]. However, the PQ issues for the micro-grid integrated distribution network were addressed using UPQC in order to mitigate voltage imbalances and current harmonics. Adaptive network-based fuzzy inference system was proposed to maximize the utilization and the efficiency of the system [22].

An automated shifting method between the grid and island modes was developed for PV battery integrated UPQC in the view of addressing the PQ issues with low disturbance to the local loads. Further, the system performance was validated with experimental results [23]. Beside, the grid connected network with an adaptive FL-C based on series active power filter was designed to address the PQ problems like voltage fluctuations/interruptions, reduction of current harmonics, and maintain of constant DC-Link voltage [24]. The combination of both Improved Bat Algorithm and Moth Flame Algorithm optimization based hybrid control technique was developed to address the PQ issues in microgrid system with a view of minimizing the error function of power variation. In addition, operation cost of renewable sources was also reduced with optimal tuning of Kp and Ki parameters [25].

An ANN controller based on the hybrid combination of reactive power control with unit vector template generation was designed for UPQC with an objective to mitigate PQ issues effectively. In addition, solar PV connected in order to reduced the ratings of then power converters, and stable the DC-Link capacitor voltage during faulty and load variation conditions [26]. Besides, the novel sequence-component detection method hybridized with unit vector-template generation was proposed for the double stage solar integrated UPQC with a goal of diminishing PQ issues [27]. The review of various topologies, compensation techniques, controllers, and the technological advancements of the recent years for the UPQC were outlined with a motive of eliminating of PQ issues [28].

A SMC based adaptive linear neuron-proportional resonant control method was developed to enhance performance of Vienna rectifier, an AC–DC converter, as a charger for series-linked battery packs of electric vehicles operating under unbalanced and distorted grid conditions. In addition, reference current signals are generated without sequences component separation, coordinate transformation and phase-locked loop to achieve superior dynamic and steady-state performances and eliminate harmonics of source currents and ripples in active power, DC-link voltage and battery current compared to the existing studies [29]. The proposes a coordinated virtual impedance control scheme for a vehicle to grid three phase four leg (V2G 3p4L) inverter was proposed with an objective of objectives consisting of
effective and good harmonic rejection capability, power sharing among V2G 3p4L inverter units with a smaller error, reactive power/voltage support during load power changes and balanced/unbalanced voltage sag conditions. In addition, technique exhibits superior performance for both grid and island modes [30].

A Lyapunov proportional integral with anti-windup (PI with AW) control is proposed to regulate oscillations of the DC-link voltage without increasing DC-link capacitor size, harmonic compensation and charging through three-phase SHAPF as interface EV applications and the electric grid was designed for effective harmonics mitigation under various non-linear loads (NLLs) groups and grid disturbances [31]. A swarm intelligence tuned Kalman filter based PV integrated SHAPF was designed with an objectives of maintaining sinusoidal waveform at the common utility point, unity PF, reduction of harmonics and improvement of overall performance. To show the superior performance of proposed method different case studies with balanced/unbalanced loads and supply voltages with variable irradiations was analyzed [32]. Adaptive generalized maximum Versoria criterion (AGMVC) controller was suggested for PV associated VSC to address PQ issues such as harmonics, redundant reactive power and load unbalancing. To exhibit viability of proposed technique is compared with synchronous reference frame theory (SRFT) and instantaneous reactive power theory (IRPT), least mean square (LMS), least mean mixed norm (LMMN) and normalized kernel least mean fourth-neural network (NKLMF-NN). In addition, performance of AGMVC control technique is verified experimentally using laboratory prototype with dSPACE DS-1202 [33].

An Euclidean direction search (EDS) technique based adaptive control theory was designed for three-phase four-wire distribution static compensator (DSTATCOM) for elimination of several power quality (PQ) issues, namely harmonics, reactive power, load unbalancing, and neutral current. The real-time performance investigation was carried out using dSPACE1104 R&D controller [34]. Although quite a lot of techniques were recommended in the literature review, still there is a possibility for designing new controllers and techniques for efficiently eliminating the PQ problems.

C. KEY CONTRIBUTION
This study is to enhance the PQ in Distribution network. The highlights of this article are emphasized below:

- Design of Hybrid controller involving fuzzy logic and soccer league algorithm optimal tuned PI-C (SLOHC) for Solar PV and BS integrated UPQC (U-PVBS).
- The prime aim of the proposed method is to minimize THD thereby improving PF, eliminate sag/swell/large disturbance in source voltage and maintain constant DC-Link voltage.
- The results are obtained for variation in loads, PV-irradiation, and supply voltage as case studies.

- Future, performance analysis was carried out with standard methods like a GA, BBO, and PI-C. To exhibit the superiority of the proposed technique comparison was done with those of existing methods available in literature review.

However, from the literature survey as shown in Table 1, it is clearly noticed that the majority of research papers focused mainly on THD reduction and or DC-Link voltage regulation with sag/swell elimination as their main objectives with the various controllers. In the proposed work along with the optimal tuning of PI controller \( K_p \) and \( K_i \) values for the THD minimization, the DC-Link voltage balancing for solar irradiation variation, the PF improvement was also considered. However, along with sag/swell the voltage disturbance is also considered as PQ issues for different combination of balanced/ unbalanced non-linear loads and supply voltage with fuzzy based SLOHC for optimal instead of conventional methods.

D. PAPER ORGANIZATION
The proposed paper involves the design of SLOHC for solar battery integrated UPQC to enhance PQ. Section 2 deals with the configuration, components and working of U-PVBS along with the Shunt and series converter controllers, section 3 discusses proposed soccer league optimization, section 4 deals with fuzzy controller and lastly, section 5 gives the conclusion.

II. PROPOSED U-PVBS
Figure1 gives the layout of UPQC with the external support of BS with BBC and solar PV system with BC connected to DC-link. This paper proposes SLOHC for exploiting both the properties of the FL-C and optimally tuned PI-C. \( V_a, V_b, V_c \), are the grid voltages, \( V_{S,a}, V_{S,b}, V_{S,c} \) are source phase voltages, \( R_s, L_S \) are source side resistance and inductances. UPQC is made of the series and shunt converters connected via a DC-Link. The SAPF eliminates the supply voltage related distortions and unbalances by injecting the suitable compensating voltage \( V_{se} \) through an isolating transformers. It consists of series-resistor \( R_{se} \), series-inductor \( L_{se} \) and series-capacitor \( C_{se} \).

The SHAPF consist of a shunt-resistance \( R_{sh} \), shunt-interfacing inductor \( L_{sh} \), shunt-capacitance \( C_{sh} \). It reduces the harmonics in current waveform and regulates the DC-link capacitor voltage \( V_{dc} \) stable during load and irradiation variations by injecting a suitable compensating shunt current \( i_{sh} \). The U-PVBS specifications, ratings of the loads considered were exhibited in Table 2.

A. EXTERNAL SUPPORT OF DC-LINK
The SP and BS acts as external support to the DC-Link via a BC and BBC with a view of maintaining stable DC-Link voltage during load/solar irradiation variations, minimizing PQ issues as figure 2. The power balance equation of U-PVBS at
the DC-Link is as given in Eq. (1).

\[ P_{PV} + P_{BS} - P_{dc\text{-}link} = 0 \]  

where, \( P_{PV} \) and \( P_{BS} \) denote the output power of solar and battery systems.

\( P_{dc\text{-}link} \) denotes the power demand at DC-Link.
TABLE 1. Literature review.

| Controller   | THD | PF | DC-Link balancing | Voltage sag/swell | Voltage disturbance | Supply voltage Imbalance | Non-linear load | Un-balanced non-liner load | Induction Furnace load | Induction Motor Load |
|--------------|-----|----|-------------------|------------------|---------------------|--------------------------|-----------------|--------------------------|----------------------|---------------------|
| ANFIS [7]    | √   |    |                   |                  |                     |                          |                 |                          |                      |                    |
| PI-C [8]     | √   |    |                   |                  |                     |                          |                 |                          |                      |                    |
| FL-C [9]     | √   |    |                   |                  |                     |                          |                 |                          |                      |                    |
| PPF [10]     | √   |    |                   |                  |                     |                          |                 |                          |                      |                    |
| FL-C [11]    | √   |    |                   |                  |                     |                          |                 |                          |                      |                    |
| Predictive   |     |    |                   |                  |                     |                          |                 |                          |                      |                    |
| BBO [12]     |     |    |                   |                  |                     |                          |                 |                          |                      |                    |

TABLE 2. UPQC specifications and Loads.

| Source side | Voltage =415 V; Frequency =50Hz | Resistance =0.1 Ω; Inductance = 0.15 mH | Resistance =1.0 Ω; Inductor=3.60nH; Capacitor= 60.0 μf | Resistor= 0.0010Ω; Inductor= 2.150mH; Capacitor= 1.0 μf; Hysteresis band: 0.010A | DC-Link capacitor= 9400 μf; Voltage at DC-Link =700 V |
|-------------|----------------------------------|-------------------------------------------|-------------------------------------------------|-------------------------------------------------|-----------------------------------------------|
| Series-     |                                  |                                            | 1. Balanced 3 Φ Rectifier load: R=10.0Ω, L=40.0mH |                                  |                                              |
| compensator |                                  |                                            | Loads                                           |                                  |                                              |
| Shunt-      |                                  |                                            | 2. Unbalanced 3 Φ R-L load: R1=10.Ω, L1=9.50mH, R2=3.20 Ω, L2=10.50mH, R3=15.0 Ω, L3=18.50 mH |                                  |                                              |
| compensator |                                  |                                            | 3. Induction Motor Load: LC = 400 mH, 50 μF, RL = 10Ω, 100 mH |                                  |                                              |
| DC-Link     |                                  |                                            | 4. Induction Furnace load: LC = 400.0 mH,50.0 μF, RL = 10.0 Ω,100.0 mH |                                  |                                              |

B. SOLAR PV SYSTEM

Solar energy is the non-conventional energy source, preferred it is freely available, clean, and pollution free. The UPQC can be connected with distributed energy resources like solar, wind, fuel cell, etc. In this paper PV is connected at the DC-link element for the following reasons outlined below:

- It enhances PQ at the utility grid
- It reduces the supply side demand
- It protects the loads from grid disturbances

TABLE 3. BS and solar-PV specifications.

| Device          | Parameters                  | Values          |
|-----------------|-----------------------------|-----------------|
| Li-ion battery  | Rated-capacity             | 350 Ah          |
|                 | Max-capacity               | 450 Ah          |
|                 | Nominal-voltage            | 650 V           |
|                 | Full charge-voltage        | 756 V           |
|                 | Open-circuit voltage       | 48.3 V          |
|                 | Short-circuit current      | 5.8 A           |
| Solar-PV panel  | Voltage/current at max power | 39.80 V/5.40A  |
| (SPR-215-WHT-U) |                             |                 |
|                 | Total parallel cells       | 11              |
|                 | Total series cells         | 18              |

- It reduces the stress and voltage ratings of the converter

In general, the PV panels are arranged in a series and or parallel connection to produce the required DC power. Further, it can be boosted up to the desired level with the help of BC. However, the SP charges the capacitor of DC-Link in addition to the real power exchange during load variations. Hence, MPPT controller is necessary to extract the maximum power from the PV panels. The controller of the SP with MPPT, a BC to boost up the output voltage cell was exhibited in figure 3 while figure 4 provides the basic working model of PV cell. The output power $P_{PV}$ of the SP can be calculated by using the Eq. (2).

$$P_{PV} = V_{PV}.I_{PV}$$ (2)
In this work, one of the most familiar MPPT technique i.e., P&O algorithm was adopted. The ratings of SP, BS are given in Table 3.

### C. BATTERY-STORAGE SYSTEM

The BS consists of a battery, BBC with PI-C, for regulating the stable DC-Link voltage as figure 5. The SOC plays a vital role in improving the performance and overall life of the battery given by Eq. (3).

$$SOC = 100(1 + \int i_{BS} \, dtQ)$$

In general, it works on two modes; charging or discharging which mainly depends on the amount of solar power generated. The SOC limits are given by Eq. (4).

$$SOC_{min} \leq SOC \leq SOC_{max}$$

The reference current $i_{ref}^{dc}$ is approximated by reducing the of DC-Link voltage error $V_{dc, error}$ using a PI-C controller in mathematic terms, the approximation can be explained as given in Eq. (5) and (6). The battery error current reference $i_{BS, error}^{ref}$ is obtained by PI-C of battery error current.

where, $i_{BS, error}$ is the difference between the reference DC-Link current $i_{ref}^{dc}$ and reference battery current $i_{ref}^{BS}$ given in Eq. (7) obtained from LPF is given in Eq. (8), (9).

$$V_{dc, error}(t) = V_{dc}^{ref} - V_{dc}$$

Table 4 gives the power sharing between SPG, BS and DC-Link power demand under different operating conditions of the U-PVBS.

### D. SHUNT CONVERTER

The shunt converter performs the dual function of compensating harmonics in load current waveforms thereby improving PF, and supplying solar power to maintain constant and stable DC-Link voltage during load variations. The shunt-VSC adapts (i) abc-dq0 and dq0-abc domain conversions, (ii) firefly based PI-C with FL-C. The load current is converted into dq0 domain by using the phase/frequency information of the grid voltage using PLL. Both the FL-C and firefly based PI-C compares the DC-link voltage with the reference voltage and converts the error voltage into a required change in current for regulating the DC-link capacitor voltage. The q-th component load current is added with the error current signal derived from FL-C and optimal designed PI-C. The dq0 components are again transformed into abc domain, which are compared with the actual load currents in a hysteresis current-controller to produce appropriate gate pulses for shunt VSC as in figure 6.

### E. SERIES CONVERTER

During under/over loading conditions at the load side, the grid supply voltage may fluctuate. The control signals are produced by comparing the actual load voltage with the reference voltage through a optimally designed PI-C after transformations from abc-to-dq0 domain. Later, it is again transformed into abc domain as in figure 7. The control signals serve...
as gating pulses for performing PWM in a series converter. As abc to dq0 and dq0 to abc domain transformations are available in the literature, the design of firefly optimization-based PI-C and fuzzy control part is explained below chapter.

III. SOCCER LEAGUE OPTIMIZATION

SOL is a population-based sports algorithm that is derived from the competition behaviour of players within the team and with the other teams of the league [20]. The performance of each player can be improved by competing with another player, thus by improving the strength of the team. This paper provides soccer league optimization with a view of improving

| TABLE 5. Chosen parameters. |
|-----------------------------|
| Algorithm | Parameter | Chosen Value |
| SOL       | nap       | 6            |
|           | nsp       | 4            |
|           | m         | 4            |
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the THD thereby PF and elimination of voltage distortions by optimally designing the PI-C.

The proposed algorithm chooses the $K_p$, $K_i$ of the PI-C for shunt and series converters as problem variables, and the formation of the fitness function. The tuning of PI-C can be treated as an optimization problem with a view of minimizing the THD through optimally choosing $K_{p,sh}$, $K_{i,sh}$, $K_{p,se,d}$, $K_{i,se,d}$, $K_{p,se,q}$, $K_{i,se,q}$ parameters. In this approach, each player ($y$) is treated as a selected design parameter represented in vector form given in Eq. (11).

$$y = [K_{p,sh}, K_{i,sh}, K_{p,se,d}, K_{i,se,d}, K_{p,se,q}, K_{i,se,q}]$$

The constraints are represented as

$$y^k_{(min)} \leq y^k \leq y^k_{(max)}; \quad k = 1, 2 \ldots nd$$

where, $nd =$ number of design variables

The total number of players are randomly produced and clustered into the number of teams. Each and every team consists of a set of active-players (APL’s), and substitute-players (SPL’s). In any team each player has his/her own skills which are represented in Eq. (12).

$$[y^1_{kj}, y^2_{kj}, \ldots, y^n_{kj}] = [K_{p,sh}, K_{i,sh}, K_{p,se,d}, K_{i,se,d}, K_{p,se,q}, K_{i,se,q}]$$

The total number of players (population) and their teams (T) are denoted as in Eq. (13).

**Population**

$$T_1 \rightarrow AT_1 = \begin{bmatrix} APL_{1,1} \\ APL_{1,2} \\ \vdots \\ APL_{1,nap} \end{bmatrix}; \quad ST_1 = \begin{bmatrix} SPL_{1,1} \\ SPL_{1,2} \\ \vdots \\ SPL_{1,nap} \end{bmatrix}$$

$$T_2 \rightarrow AT_2 = \begin{bmatrix} APL_{2,1} \\ APL_{2,2} \\ \vdots \\ APL_{2,nap} \end{bmatrix}; \quad ST_2 = \begin{bmatrix} SPL_{2,1} \\ SPL_{2,2} \\ \vdots \\ SPL_{2,nap} \end{bmatrix}$$

$$\vdots$$

$$T_m \rightarrow AT_m = \begin{bmatrix} APL_{m,1} \\ APL_{m,2} \\ \vdots \\ APL_{m,nap} \end{bmatrix}; \quad ST_m = \begin{bmatrix} SPL_{m,1} \\ SPL_{m,2} \\ \vdots \\ SPL_{m,nap} \end{bmatrix}$$

**FIGURE 7.** Soccer league optimization based hybrid controller for Series Converter.
nap and nsp denotes the number of APL’s and SPL’s respectively.

$AT_k$ is the $k^{th}$ active-team with nap.

$ST_k$ is the $k^{th}$ substitute-team with nsp.

$md$ denotes the total number of control variables.

$m$ denotes the number of teams.

In a team the fitness of each player depends on his/her skills and it is calculated by a performance function ($FF_{kj}$), derived from the objective function (THD of source current). The max performance function indicates the lower objective function as given in Eq. (14).

$$MaxFF_{kj} = \frac{1}{1 + THD}$$ \hspace{1cm} (14)

A probability of the team to win the league depends on the strength of the players. The strength of $k^{th}$ team ($ST_k$) can be calculated by Eq. (15).

$$ST_k = \sum_{j=1}^{nap+nsp} \frac{FF_{kj}}{nap + nsp}$$ \hspace{1cm} (15)
The player having the largest fitness value in each (k\textsuperscript{th}) team is considered as team leader (TL\textsubscript{k}), and the best player among all team leaders, is called the super player (SuperPL) of the league. The probability of winning of k\textsuperscript{th} over q\textsuperscript{th} team is given by Eq. (16).

\[
\begin{aligned}
\text{if } \text{rand}(.) < \left( \frac{S_{T_k}}{S_{T_k} + S_{T_q}} \right), \quad & \text{k-th team is winner} \\
\text{else,} \quad & \text{k-th team is loser} \\
\end{aligned}
\]  

(16)

Once the match is completed, the players of winning team and losing team implement certain actions for their performance enhancement. The mathematical representation of these actions in a form of operators is given below:

**Imitation Operator:** The APL’s of the champion team tries to imitate the TL and SuperPL for the performance enhancement given by Eq. (17) and (18).

\[
\begin{align*}
\text{APL}_{kj} &= \mu_1 \text{APL}_{kj} + \tau_1 (\text{SuperPL} - \text{APL}_{kj}) + \tau_2 (\text{TL}_k - \text{APL}_{kj}) \quad (17) \\
\text{APL}_{kj} &= \mu_2 \text{APL}_{kj} + \tau_1 (\text{SuperPL} - \text{APL}_{kj}) + \tau_2 (\text{TL}_k - \text{APL}_{kj}) \quad (18)
\end{align*}
\]

where, \(\mu_2, \mu_1, \tau_1 \) and \(\tau_2 \) are random numbers.

If the performance of APL’s is better than old one, then APL\textsubscript{k,j} carry out large movements by Eq. (17). Or else, the player shifts towards the medium movements by Eq. (18). If there is no improvement from the above actions, the player will be retained in previous position.

**Provocation operator:** The SPL’s tries to perform better than those of APL’s of the winner team. The SPLs move towards the average direction of APL’s using Eq. (19) and (20).

\[
\begin{align*}
\text{SPL}_{kj} &= D(k) + \chi_1 (D(k) - \text{SPL}_{kj}) \quad (19) \\
\text{SPL}_{kj} &= D(k) + \chi_2 (\text{SPL}_{kj} - D(k)) \quad (20)
\end{align*}
\]

where, \(\chi_1, \chi_2\) are random numbers, \(D(k)\) is the mean direction of APL’s in winner’s team. \(\text{SP}_{kj}\) is the j-th substitute of k-th team.

If the performance of APL’s is better than the old one then the SPL\textsubscript{k,j} performs forward move in the average direction of APL’s by using Eq. (19). Or else, the player takes back movement by Eq. (20). If there is no performance improvement from the above movements, he/she is replaced by a vector with a random solution.

**Mutation operator:** The APL’s of the loser team try to explore possible ways for enhancing their performance during this process they randomly change their positions by adopting the mutation operator.

**Substitution Operator:** To escape from the local traps the loser’s team creates a fresh combination of substitutes (j and p) by integrating two of the existing members by Eqs. (21) and (22).

\[
\begin{align*}
\text{SPL}_{kj} &= \alpha \text{SPL}_{kj} + (1 - \alpha) \text{SPL}_{kp} \quad (21) \\
\text{SPL}_{kp} &= \alpha \text{SPL}_{kp} + (1 - \alpha) \text{SPL}_{kj} \quad (22)
\end{align*}
\]

where, \(\alpha\) is a random number.

The main aim of using SOL in this work is its superior performance in solving multi-objective optimization problems with faster convergence, accuracy and cost effective. Compare to conventional algorithms like GA, PSO it has the lowest sensitivity to the problem’s dimensions [23]. It can also be implemented on both linear and non-linear loads. However, it has its own limitation like complexity as the number of control variables increases. In order to satisfy the equality constraints, single objective function was selected.

The player having the largest fitness value in each (k\textsuperscript{th}) team is considered as team leader (TL\textsubscript{k}), and the best player among all team leaders, is called the super player (SuperPL) of the league. The probability of winning of k\textsuperscript{th} over q\textsuperscript{th} team is given by Eq. (16).
and the decision vector structure designed such a way that only the valid manifold is searched so that every random solution automatically has the constraint satisfied.

However, the drawback of conventional PI controller is poor selection of $K_p$, $K_i$ values but by adopting SOL based tuning method the algorithm automatically
tune $K_p$, $K_i$ according to the required objective function within the given range with less execution time and high accuracy.

The flowchart as in figure 8 gives the design method of the proposed SOL for optimal selection of $K_p$, $K_i$ values for series and shunt converters. The star players of the match indicates

| Method          | Case1 | Case2 | Case3 | Case4 |
|-----------------|-------|-------|-------|-------|
| Without U-PVBS  | 27.67 | 15.89 | 33.91 | 7.33  |
| PI-C            | 6.20  | 7.37  | 7.51  | 4.02  |
| GA              | 4.41  | 5.12  | 5.40  | 2.58  |
| BBO             | 4.05  | 4.59  | 3.02  | 2.96  |
| PI-C [16]       | 3.28  | --    | --    | --    |
| SM-C [16]       | 2.44  | --    | --    | --    |
| BBO [21]        | 4.13  | --    | --    | --    |
| PI-C [22]       | 14.74 | --    | --    | --    |
| FL-C [22]       | 6.13  | --    | --    | --    |
| ANFIS [22]      | 2.43  | --    | --    | --    |
| PI-C [24]       | 3.65  | --    | --    | --    |
| FL-C [24]       | 2.52  | --    | --    | --    |
| Conv. PI-C [17] | 3.88  | --    | --    | --    |
| ACO-PI-C [17]   | 3.72  | --    | --    | --    |
| BF-PI-C [17]    | 3.71  | --    | --    | --    |
| PSO [10]        | 2.109 | --    | --    | --    |
| HSO [10]        | 2.231 | --    | --    | --    |
| ZN [10]         | 7.57  | --    | --    | --    |
| ICM [10]        | 4.2   | --    | --    | --    |
| SLOHC           | 2.06  | 2.44  | 2.40  | 2.32  |

FIGURE 14. Waveforms of the proposed system for case-1.
the solution vector i.e $K_p$, $K_i$ where, the objective (THD) is minimum.

**IV. FUZZY CONTROLLER FOR DC-LINK**

The FL-C takes the E and CE, and generates an output representing the required change in current, which is then added with the output of PI-C. The fuzzy variables are denoted by triangular membership functions for error, change in error and the output duty cycle involving PSH, medium positive (PSM), PSL, ZE, NEH, medium negative (NEM) and NEL as in figures [9], [10], [11], and the developed fuzzy IF-THEN rules are given in Table 6.

The rules attempt to maintain the present control setting $i_{dc} = 0$, when both E and CE are zero, and also when E is not zero but approaching the reference value at a satisfactory rate. When E is increasing, these rules appropriately change the control signal ($i_{dc}$) depending on the magnitude and the sign of E and CE with a view of forcing E towards zero. Here, the matrix rules are created according to the complexity of the control system. In this control application, the control system involved is two input single output type. Rules are formed according to the system requirements. The fuzzy inference system performs an evaluation of the rules, and then, it combines all of the results to form a final output, which is a fuzzy value. The accurateness can be increased by increasing the number of rules at a cost of increased data size and complexity, and a larger execution time of the control system [7].

**V. SIMULATION AND RESULTS**

The performance of proposed U-PVBS was studied on a grid connected 3-$\varphi$ AC distribution system. The simulink model
for the U-PVBS with different loads has developed in Matlab-2016a as exhibited in figure 12. The approach has been carried out 20times and the best one has been presented as an optimal solution. Four test cases with the different combinations of nonlinear/unbalanced loads, sag/swell/disturbance, and variation in irradiation are exhibited in Table 7, were considered for analyzing the performance of the U-PVBS. The supply voltage was considered to be balanced for cases 1-3 and unbalanced for case 4. In addition, source voltage sag was considered in case 1, voltage swells in case 2, and large voltage disturbances in case 3 respectively. The results are compared with existing methods PI-C, GA, BBO. The lower/upper bounds for the control variables are in range of [0.0001 100], and the chosen parameters for the SOL along with are given in Table 5. The obtained optimal control parameters by the proposed SLOHC along with existing methods are exhibited in Table 9. The PF is calculated by Eq. (23) for all test cases and comparisons with PI-C, GA, and BBO are given in figure13.

\[
\text{Powerfactor} = \cos \theta \ast \frac{1}{\sqrt{1 + \text{THD}^2}}
\]

where, \( \theta \) is the angle between voltage, current while it represent the displacement factor. The voltage sag or swell with SLOHC is calculated by Eq. (24)

\[
V_{\text{sag/swell}} = \frac{V_l - V_S}{V_l} = \frac{V_{se}}{V_l}
\]

The voltage injected by the series compensator to compensate voltage sag/swell and disturbance of U-PVBS is given by Eq. (25) [7].

\[
V_{se} = V_l - V_S
\]
The current injected by the shunt compensator is given by Eq. (26) [7].

\[ i_{sh} = i_i - i_S \] (26)

Figure 13 exhibits that the PF of proposed method is much higher than that of standard methods and the waveforms of the proposed U-PVBS for the test cases 1-4 are illustrated in Fig. 14-17.

In Table 8, the THD of the proposed method for all case studies was compared with those of the existing real and practical methods as cases that are available in the literature with citations. The reason behind choosing GA and BBO for comparison is GA is one of the standard genetic inspired algorithms while BBO is the study on natural biogeography. BBO has features in common with other biology-based optimization methods, such as GAs and particle swarm optimization (PSO) to show the superiority of the proposed method these two optimizations was chosen.

However, according to the results and comparative analysis it clearly exhibits the superior performance of the proposed method in reducing THD. Figure 13 exhibits that the PF of proposed method is much higher than that of standard methods. Selection of the suitable algorithm plays a vital role which mainly depends on the objective function of the optimization problem. Generally, classical techniques give more accurate results but they are time consuming and having some limitations. For faster processing you can select the meta-heuristic algorithms.

In case-1, the source voltage was sagged by 30% during the interval of 0.25-0.35s; the proposed U-PVBS injects
a suitable amount of required voltage to improve the load voltage as shown in figure 14(a). Moreover, the load current was observed to be balanced but non-sinusoidal with the THD of 27.67%, and PF of 0.783 due to the non-linear rectifier load as shown in figure 14(b). It can be seen clearly from figure 14 that the proposed U-PVBS was able to eliminate sag effectively by injecting suitable compensating voltage and improves sinusoidal source current. However, such improvement in current waveforms reflects to the THD and PF values. Therefore, the THD of the load current was reduced from 27.67% to 2.06% and the PF rose from 0.783 to 0.989 by injecting appropriate shunt currents. The Kp, Ki values of shunt and series controllers $K_{p_{sh}}, K_{i_{sh}}, K_{p_{se_d}}, K_{i_{se_d}}, K_{p_{se_q}}, K_{i_{se_q}}$ are optimal tuned to 1.0112, 18.0323, 1.0057, 1.01200, 14.0025, 0.0011 respectively while satisfying the limits.

In case-2, the voltage swell was introduced from interval 0.4 to 0.5s; the proposed system effectively eliminates it by injecting suitable compensating voltage as shown in figure 15(a). However, always a negligible amount of voltage exits across the series converter during steady state. Here, the load current was observed to be non-sinusoidal but balanced with a THD of 15.89% and a PF of 0.623 due to the non-linear rectifier and motor load connected simultaneously as presented in figure 15(b). It can be seen that the U-PVBS was able to suppress swell successfully and reduce THD from 15.89% to 2.44% thereby boosting up the PF value from 0.623 to 0.985 by injecting suitable shunt currents. The Kp,
Ki values of shunt and series controllers are optimally tuned to 6.0121, 13.08, 15.3612, 4.08, 2.1087, 5.6604 respectively.

In case 3 the large voltage disturbance was introduced in the source voltage. Here, the load current was unbalanced and non-sinusoidal with a THD of 33.91% and a PF of 0.668 due to nonlinear and unbalanced loads. It can be seen that the U-PVBS was able to eliminate voltage disturbances very effectively by the suitable compensating voltage and reduce THD from 33.91% to 2.40% thereby raising the PF value from 0.668 to 0.989 in addition to the improving the shape of sinusoidal waveform shown in figure 16(a)-16(b) respectively. The Kp, Ki values of shunt and series controllers are optimally tuned to 3.023, 1.32, 2.2002, 79.012, 1.0245, 54.785 to attain objective function.

### TABLE 9. Comparison of design parameters.

| Case | Method  | $K_{p_{sh}}$ | $K_{i_{sh}}$ | $K_{p_{se,d}}$ | $K_{i_{se,d}}$ | $K_{p_{se,q}}$ | $K_{i_{se,q}}$ |
|------|---------|-------------|-------------|----------------|----------------|----------------|----------------|
| 1    | PI-C    | 0.712       | 18.4525     | 1.2532         | 15.3123        | 2.1271         | 37.1452        |
|      | GA      | 0.00415     | 0.0171      | 12.137         | 1.2581         | 15.3254        | 41.3254        |
|      | BBO     | 0.00829     | 0.0088      | 0.008          | 0.1321         | 0.0141         | 0.035          |
|      | Conv. PI-C [18] | 0.507 | 10.3 | -- | -- | -- | -- |
|      | ACO-PI-C [18] | 0.912 | 247.93 | -- | -- | -- | -- |
|      | BF-PI-C [18] | 0.843 | 288.5 | -- | -- | -- | -- |
|      | PSO [10] | 2.1345 | 10.2581 | -- | -- | -- | -- |
|      | HSO [10] | 3.7151 | 45.4126 | -- | -- | -- | -- |
|      | ZN [10] | 0.019 | 0.0004 | -- | -- | -- | -- |
|      | ICM [10] | 0.0455 | 0.064 | -- | -- | -- | -- |
|      | ABC [25] | 8.2270 | 0.0020 | -- | -- | -- | -- |
|      | GSA [25] | 9.6325 | 2.3020 | -- | -- | -- | -- |
|      | FA [25] | 9.2545 | 1.6580 | -- | -- | -- | -- |
|      | MFOA [25] | 8.8554 | 1.8569 | -- | -- | -- | -- |
|      | SLOHC   | 1.0112 | 18.0323 | 1.0057 | 1.0120 | 14.0025 | 0.0011 |
| 2    | PI-C    | 6.5201     | 19.2101     | 0.3508         | 13.5721        | 1.325          | 10.3214        |
|      | GA      | 2.2112     | 8.4011      | 1.2131         | 58.2464        | 1.8245         | 56.378         |
|      | BBO     | 3.0804     | 5.03        | 3.2475         | 9.1308         | 16.3245        | 62.289         |
|      | SLOHC   | 6.0121     | 13.08       | 15.3612        | 4.08           | 2.1087         | 5.6604         |
| 3    | PI-C    | 4.2635     | 3.6231      | 44.249         | 32.6387        | 2.3651         | 64.378         |
|      | GA      | 2.241      | 7.45        | 16.1332        | 51.32          | 12.3657        | 71.3241        |
|      | BBO     | 12.4965    | 9.7512      | 8.32           | 3.58           | 3.254          | 15.378         |
|      | SLOHC   | 3.023      | 1.32        | 2.2002         | 79.012         | 1.0245         | 54.785         |
| 4    | PI-C    | 5.0207     | 0.001       | 66.9137        | 94.4397        | 4.3247         | 0.1257         |
|      | GA      | 26.6918    | 19.42       | 50.7312        | 0.0132         | 5.3974         | 22.478         |
|      | BBO     | 4.1387     | 0.1001      | 0.1891         | 10.1736        | 3.578          | 1.3478         |
|      | SLOHC   | 15.1998    | 0.001       | 6.1940         | 10.001         | 1.3078         | 0.2147         |
In case 4 the unbalanced supply voltage was considered, but proposed U-PVBS effectively provides balanced load voltage as shown in figure 17(a). Here, the load current was seems to be sinusoidal and unbalanced with a THD of 7.33% and a PF of 0.775 figure 17(b). The SLOHC was able to reduce THD from 7.33% to 2.32% and improve PF from 0.775 to 0.999. The performance of the proposed method was tested with solar irradiation variation from 1000 W/m² to 800 W/m² and from 800 W/m² to 1000 W/m² under the constant 25°C temperature. The Kp, Ki values of shunt and series controllers are optimally tuned to 15.1198, 0.001, 6.194, 10.001, 1.3078, 0.2147 while satisfying the upper and lower limits.

However, from the figure 18 it is clearly understood that the proposed system exhibits its superior performance in maintaining the constant DC-Link voltage during irradiation variation. In addition, to it the output power of PV panel, voltages and duty cycle was also given. The load and source voltages...
in d-q frame are shown in figure 19-20. Figure 21 gives the THD spectrum for all four test cases. Figure 22 shows the convergence characteristics of the proposed controller with GA and BBO where it can clearly seen that proposed method converge to an optimal point in a less number of iterations when compared to other methods.

VI. CONCLUSION
A hybrid controller involving FL-C and optimal tuned PI-C was designed for U-PVBS. The controllers of BS and SP were explained in-addition to developing of SOL based PI-C for shunt and series converters and FL-C for DC-Link to regulate and maintain stable DC-link capacitor voltage, eliminating of sags/swells/disturbances in supply voltage, diminishing the THD in load voltage and source current, and boosting the PF. The investigation was carried on four test cases with different combinations of loads, balanced/ unbalanced network voltages, voltage sag/swells/disturbances, and variation on irradiation was exhibited.

The proposed method optimally tunes the $K_{i_{sh}}, K_{p_{sh}}, K_{i_{se,d}}, K_{p_{se,d}}, K_{i_{se,q}}, K_{p_{se,q}}$ values to 18.0323, 1.0112, 1.0120, 1.0057, 0.0011, 14.0025 in case-1 in order to satisfy the objective function. Analyzing the THD and PF of the system without U-PVBS the THD value was 27.67% for case1, 15.89% for case2, 33.91%, 7.33% for case3 & 4 and value of PF was 0.783, 0.623, 0.688, and 0.775 for case 1-4 test cases. By implementation of U-PVBS with SLOHC the THD reduces to 2.06%, 2.44%, 2.40%, and 2.32% respectively. It clearly exhibits that the proposed SLOHC was able to lower the THDs within acceptable levels and power factors to almost unity. Moreover, these performances were much better than those of the existing controllers like conventional PI-C, GA, BBO, and controllers that are available in literature. The SLOHC took a smaller time to reach the steady-state dc-link voltage than those of existing methods. This paper presents with an objective of total harmonic distortion for two-level UPQC with simulation results. However, the selective harmonic elimination technique (SHE) can be implemented, and optimal design of two and multi-level UPQC for the microgrid with hard ware can be designed as the future study.

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