VA Loading Optimization of a Converter Using the Rao Algorithm for Maximum Utilization of the Unified Power Quality Conditioner

Swati Gade[1†] and **Rahul Agrawal**[2], Non-members

ABSTRACT

In a modern power system, the unified power quality conditioner (UPQC) is considered to be the most effective device for mitigating power quality problems. The use of the dynamic voltage restorer (DVR) for active-reactive power-sharing reduces the loading on the UPQC in all operating conditions, leading to better system efficiency and reliability. The VA loading of the DVC can be controlled by maintaining a proper angle between load and source voltage. In this paper, Rao algorithms are proposed to determine the optimal VA loading of the UPQC using the variable phase angle control method. The primary objective of this study is to determine the optimum angle at which the VA loading of the UPQC is minimum without negotiating the compensation capabilities. To illustrate the effectiveness of the proposed methodology, the results are compared to those for JAYA optimization. This research work will help in the development of an efficient, instantaneous VA loading-based control approach for the UPQC.

Keywords: JAYA Optimization, Power Electronic Converter, Rao Algorithms, Steady State, Unified Power Quality Conditioner, Voltage Sag

LIST OF SYMBOLS

V_S	Rated source voltage during normal conditions
I_S	Rated source current during normal conditions
I'_S	Source current during sag/swell conditions
$I_{DSTATCOM}$	Per phase current injected by DSTATCOM
K	Ratio between actual and rated source voltages
V_L	Rated load voltage
I_L	Rated load current
δ	Power angle
ϕ	Rated load power factor angle
γ	Displacement angle between the source and series-injected voltages

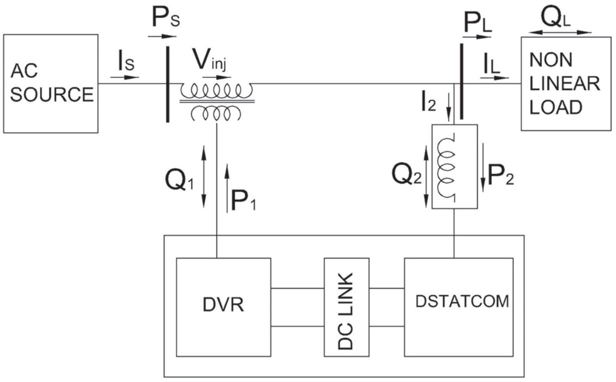


Fig. 1: *Block diagram of UPQC.*

1. INTRODUCTION

Non-linear loads and the integration of renewable energy sources with the main grid using power electronic converters (PEC) are the major sources of power quality (PQ) issues in modern power systems. Unbalanced voltages, voltage sag/swell, compensation of reactive power, and harmonic currents are typical PQ issues. These PQ problems interrupt critical loads, resulting in significant financial losses and a low system power factor (PF). Maintaining supply quality within specified standards has become important for improving power system performance [1]. An active power filter could be a good option for alleviating these PQ issues. However, a custom power device known as the unified power quality compensator (UPQC), introduced by Fujita and Akagi in 1998, is considered an optimal mitigation device for critical and sensitive loads [2]. This device is used in the distribution system for the simultaneous compensation of voltage and current-related PQ problems.

As illustrated in Fig. 1, the UPQC comprises two PECs linked end-to-end to a mutual DC-Link. PQ problems related to voltage are compensated by a series-connected PEC called a dynamic voltage restorer (DVR), whereas the distributed STATCOM (DSTATCOM) compensates the reactive power requirement along with current-related PQ problems [3]. The effective and efficient

---

Manuscript received on April 7, 2022; revised on May 26, 2022; accepted on June 15, 2022. This paper was recommended by Associate Editor Kaan Kerdchuen.

[1] The author is with the Sandip Institute of Technology and Research Center, Nashik, India.

[2] The author is with the Guru Gobind Sing College of Engineering and Research Center, Nashik, India.

[†] Corresponding author: swatiagade@gmail.com

©2023 Author(s). This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivs 4.0 License. To view a copy of this license visit: https://creativecommons.org/licenses/by-nc-nd/4.0/.

Digital Object Identifier: 10.37936/ecti-eec.2023211.248573

control algorithm used for controlling UPQC improves the performance of the UPQC. According to the recent literature, the UPQC has been used effectively and efficiently for the mitigation of PQ problems with different compensation methods under active and reactive power [4].

In the case of active power control (UPQC-P), the compensating voltage is added in phase with the supply current; hence for compensation, only active power is required by the DVR. On the other hand, in reactive power control (UPQC-Q), the compensating voltage is added in quadrature with the supply current, and therefore, only reactive power is absorbed by the DVR for compensation. Although the VA loading on the DVR is minimum in UPQC-Q compared to UPQC-P, due to quadrature voltage injected by the DVR leading the supply current, it cannot be used for the compensation of voltage swell [5].

In the UPQC-S [6] and UPQC-VA$_{\text{min}}$ [7], the series voltage is injected at a certain angle to the supply current; thus, the DVR needs both active and reactive powers for compensation. In this method of compensation, the DVR is not only used for mitigating voltage sag/swell but also to simultaneously compensate the load reactive power with DSTATCOM. This enhances UPQC utilization, resulting in an overall system cost savings and economically appealing. PAC-based control offers benefits such as load reactive power-sharing between converters and greater loss reduction compared to conventional control [8].

To find a suitable angle for the DVR to inject voltage, online/offline optimization techniques can be used. An optimum angle is selected to control the DVR from a pre-calculated 2-D lookup table in the case of offline optimization methods [7]. To address the optimization problem, many system parameters, such as load PF, load current, and voltage sag, are considered, along with the impact of total harmonic distortion in the supply current and load voltage [9]. The particle swarm optimization (PSO) technique is used to estimate the optimum power angle δ between the load and supply voltage. Based on the phase angle control (PAC) approach, Ambati *et al.* suggested an algorithm to maximize the utilization of the UPQC [10]. The optimum power angle δ is calculated to achieve the lowest VA rating of the UPQC to identify the worst sag and swell conditions.

The optimal design based on a variable PAC using a two-stage control algorithm is proposed by [11]. The VA loading of the series transformer is determined by the amount of injected voltage. On the other hand, the transformer and PEC ratings will have an impact on each other [12]. Based on the hierarchical optimization concept, an optimal operation technique for the UPQC under VA rating constraints is proposed in [13]. Based on the priority of objectives, this multi-objective optimization problem is converted into several single-objective optimization problems.

Based on the literature, it can be determined that angle δ is controlled for minimization of the VA loading in the UPQC. It should also be noted that the optimization of the VA loading of the UPQC has received less attention thus far. In [14], the optimal utilization of the UPQC in different operating conditions is presented using Teaching-learning-based optimization (TLBO). Performance analysis on the optimal utilization of the UPQC using the JAYA algorithm is presented in [15, 16].

Table 1: Algorithms and their specific parameters.

Algorithm	Algorithm-specific parameters
Simulated annealing (SA)	Initial annealing temperature and cooling schedule
Genetic algorithm (GA)	Crossover and mutation probabilities, and selection operator
Particle swarm optimization (PSO)	Inertia weight, social and cognitive parameters
Differential evolution (DE)	Crossover probability and differential weight
Artificial bee colony (ABC)	Number of bees such as scouts, onlookers, and employed and the limit
Non-dominated sorting GA (NSGA-II)	Crossover probability, mutation probability, and distribution index

The major challenge in the field of engineering optimization is to solve complex optimization problems in the shortest possible time. Researchers have used numerous innovative optimization methods that emphasize the population size and the number of generations as common control parameters [17]. In addition, regulating the performance of most optimization algorithms requires algorithm-specific control parameters along with common controlling parameters [18]. Various algorithm-specific parameters are listed in Table 1.

Improper tuning of algorithm-specific parameters leads to an increase in greater computational effort and poor performance of the algorithm. This problem of algorithm tuning is overcome by introducing algorithm-specific parameter-less techniques like the JAYA [18] and Rao algorithms [19]. The best and worst solutions obtained during the optimization process, as well as random interactions among the candidate solutions, are used to execute these techniques. The primary contributions of this research paper are as follows:

- Appraising the VA loading of the UPQC under various operating conditions such as voltage sag and steady state using the Rao algorithms.
- Analyzing the optimization techniques using JAYA and Rao algorithms to determine the optimal value of angles δ and K.
- Implementing optimization techniques using JAYA and Rao algorithms for maximum utilization of the UPQC by optimal VA loading of the PEC.
- Assessing the comparative results of the proposed algorithm using the Rao and JAYA algorithms and without optimization approaches.

So far, no work has been published on the implementation of Rao algorithms for optimum utilization of the

UPQC. The authors of this paper find the optimal VA loading of the UPQC using the optimum value of angles δ and K. This study aims to find the optimum angle δ for different operating conditions under which the loading of both PECs is optimal, and thus, UPQC utilization is maximized. The Rao algorithms are used for the same reason. The main objectives of this present study are as follows:

- To implement Rao algorithms to find the optimal angle δ for the corresponding value of K.
- To investigate the performance of the DVR and DSTATCOM and hence the overall UPQC system under different operating conditions without negotiating any of its compensation proficiency.
- To investigate the performance of the various optimization methods using JAYA and Rao algorithms for the optimal utilization of the UPQC based on VA loadings.

The remainder of the paper is presented as follows: Section 2 reports the problem formulation. Section 3 reveals the optimization methods used, such as the use of JAYA and Rao algorithms. The workings of the JAYA algorithm are explained in brief, along with the step-by-step procedure and the pseudo code of Rao algorithms. In Section 4, the implementation of the Rao algorithms is explained for maximum utilization of the UPQC. Section 5 presents the results and discussion while Section 6 contains the concluding comments and recommendations for future assessment.

2. PROBLEM FORMULATION

A phasor diagram explaining the workings of the UPQC-VA$_{\text{min}}$ is presented in Fig. 2. The DVR injects the series voltage V_{inj} at angle γ to maintain the proper angle δ between the resultant load voltage V_S' and V_L'. Similarly, during operation, a phase difference will occur between I_L and load current I_L' of angle δ resulting in a constant magnitude of the load current and PF angle ϕ. To find the optimal loading for the UPQC, the mathematical model is applied from [10].

3. MATHEMATICAL MODELING OF THE UPQC-VA$_{\text{MIN}}$

The primary objective of the UPQC is to maintain a constant load voltage, and to achieve this V_{inj} is added with an instantaneous V_S at angle γ. Another function of the UPQC is to maintain PF unity at the source side, and for that DSTATCOM provides load reactive power. During compensation, DSTATCOM supplies the load reactive power as well as the active power required by the DVR. The magnitude of voltage injected by the DVR,

$$V_{inj}(\delta, K) = \sqrt{(V_L \cos\delta - KV_S)^2 + (V_L \sin\delta)^2} \quad (1)$$

where V_L and V_S are the load and source voltage, respectively.

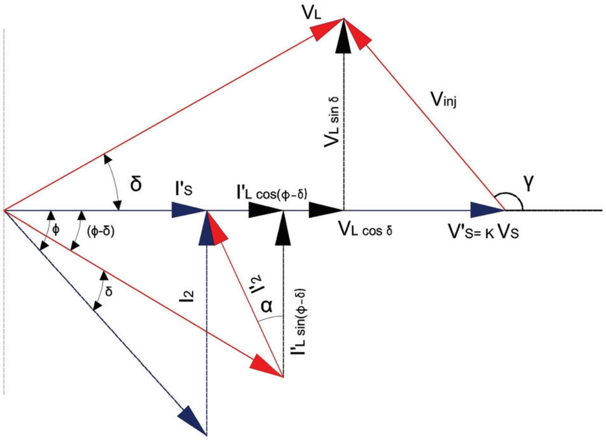


Fig. 2: *Phasor diagram of the UPQC-VA$_{min}$.*

VA loading of the DVR,

$$S_1(\delta, K) = \sqrt{\left(P_1(\delta, K)\right)^2 + \left(Q_1(\delta, K)\right)^2} \quad (2)$$

where S_1 is the VA loading in kVA, P_1 is the active power in kW and Q_1 is the reactive power in kVAR delivered by the DVR.

The loading of the series transformer,

$$S_{dvr\ trans}(\delta, K) = \text{max of } \left[V_{inj}\right]_{K=K_{\text{min}}}^{K=K_{\text{max}}} \times \frac{I_S}{K} \quad (3)$$

where $S_{dvr\ trans}$ is the VA loading of the series transformer in kVA, K_{min} is the worst voltage sag and K_{max} is the worst voltage swell condition. I_S is the source current in A.

The VA loading of the DSTATCOM is given by

$$S_2(\delta, K) = \sqrt{\left(P_2(\delta, K)\right)^2 + \left(Q_2(\delta, K)\right)^2} \quad (4)$$

where S_2 is the VA loading in kVA of the DSTATCOM, P_2 and Q_2 are the active power (kW) and reactive power (kVAR) delivered by DSTATCOM, respectively.

In any operating condition, the VA loading of the UPQC, as a function of δ is given by

$$S_{UPQC}(\delta, K) = S_1(\delta, K) + S_2(\delta, K) \quad (5)$$

where S_{UPQC} is the VA loading (kVA) of the UPQC.

3.1 Objective Function and Constraints

The main objective of this research is to find the optimal value of δ for the corresponding operating condition for which the VA loading of the UPQC will be minimum. The objective function is formulated as follows,

$$Min.\ S_{UPQC}(\delta, K) = S_1(\delta, K) + S_2(\delta, K) \quad (6)$$

Subjected to inequality constraints,

$$S_1(\delta, K) \leq \text{kVA rating of DVR}, \tag{7}$$

$$S_2(\delta, K) \leq \text{kVA rating of DSTATCOM}, \tag{8}$$

$$V_{inj}(\delta, K) \leq V_{inj\ Max} \tag{9}$$

The $V_{inj\ Max}$ is calculated by putting $K = K_{\max}$ and $\delta = 45°$ in Eq. (1).

This optimization problem is subject to the following design variable constraints,

$$0 \leq \delta \leq 45° \tag{10}$$

$$0.6 \leq K \leq 1.1 \tag{11}$$

4. OPTIMIZATION METHODS

In 2016, R. Venkata Rao invented the JAYA algorithm, a swarm intelligence-based heuristic method for addressing constrained and unconstrained optimization problems [18]. He proposed three similar algorithms to the JAYA in 2020, known as Rao algorithms [19]. They are known as the Rao-1 algorithm, Rao-2 algorithm, and Rao-3 algorithm.

4.1 JAYA Algorithm

The JAYA algorithm improves the objective function of each solution to achieve the optimal solution by updating the values of the design variables. For the next generation, only updated solutions with a better objective function value are evaluated. With each iteration of the JAYA algorithm, a solution becomes closer to the optimal and moves away from the worst solution. As a result, the search process is effectively accelerated and diversified. In the JAYA algorithm, the initial population x is randomly generated in the search space bounded by the lower and upper limits of the design variables. Each design variable of every solution is then stochastically modified as follows:

$$x^{i+1}_{j\,k} = x^i_{j\,k} + r^i_{1j}\{x^i_{j\,best} - \mid x^i_j \mid\} - r^i_{2j}\{x^i_{j\,worst} - \mid x^i_j \mid\} \tag{12}$$

where i, j, and k are the indices of the iteration, variable, and candidate solution. r^i_{1j} and r^i_{2j} are random numbers in the range of [0, 1] operating as scaling factors and ensuring good diversification. $x^i_{j\,best}$ and $x^i_{j\,worst}$ are the best and worst solutions among the current population.

4.2 Rao Algorithms

In similarity to the JAYA algorithm, the Rao algorithms track the entire population in search of the optimal solution, determined by the best and worst case. Although the flow of the three Rao algorithms is similar, each movement equation is distinct. Fig. 3 shows the pseudocode for the Rao algorithms. The step-by-step procedure is given as follows.

Step 1: Define the algorithm parameters, such as population size (n); number of design variables (m) and their lower (LB), and upper (UB) limits; and termination criterion.

Step 2: Begin with the random population x in the design space, defined by the candidate solution and design variable.

$$x^i_{j\,k} = x^{min}_j + (x^{max}_j - x^{min}_j) \times rand(k, j) \tag{13}$$

where x^{min}_j and x^{max}_j are the minimum and maximum values of the population.

Step 3: Calculate the objective function $f^i_{j\,k}$ corresponding to $x^i_{j\,k}$.

Step 4: Determine the $x^i_{j\,best}$ as best and $x^i_{j\,worst}$ as worst solution in the initial candidate population.

Step 5: Update the initial population of the j^{th} variable according to the algorithm used as follows:

For Rao-1 algorithm

$$x^{i+1}_{j\,k} = x^i_{j\,k} + r^i_j\left(x^i_{j\,best} - x^i_{j\,worst}\right) \tag{14}$$

where r^i_j is a uniformly distributed random number in the range [0, 1].

For Rao-2 algorithm

$$\begin{aligned} x^{i+1}_{j\,k} = {} & x^i_{j\,k} + r^i_{1j}\left(x^i_{j\,best} - x^i_{j\,worst}\right) \\ & - r^i_{2j}\left(\mid x^i_{j\,k} \text{ or } x^i_{j\,l} \mid - \mid x^i_{j\,l} \text{ or } x^i_{j\,k} \mid\right) \end{aligned} \tag{15}$$

For Rao-3 algorithm

$$\begin{aligned} x^{i+1}_{j\,k} = {} & x^i_{j\,k} + r^i_{1j}\left(x^i_{j\,best} - \mid x^i_{j\,worst} \mid\right) \\ & - r^i_{2j}\left(\mid x^i_{j\,k} \text{ or } x^i_{j\,l} \mid - x^i_{j\,l} \text{ or } x^i_{j\,k}\right) \end{aligned} \tag{16}$$

where r^i_{1j} and r^i_{2j} are uniformly distributed random numbers in the range [0, 1].

The third term in the equation for the Rao-2 and Rao-3 algorithms shows that the candidate solution k can be compared to any randomly chosen candidate solution l, with the exchange of information depending on their fitness values. The value of a k^{th} or l^{th} candidate is determined by their fitness value.

Step 6: Check the boundary limits and calculate the updated objective function $f^{i+1}_{j\,k}$ corresponding to $x^{i+1}_{j\,k}$.

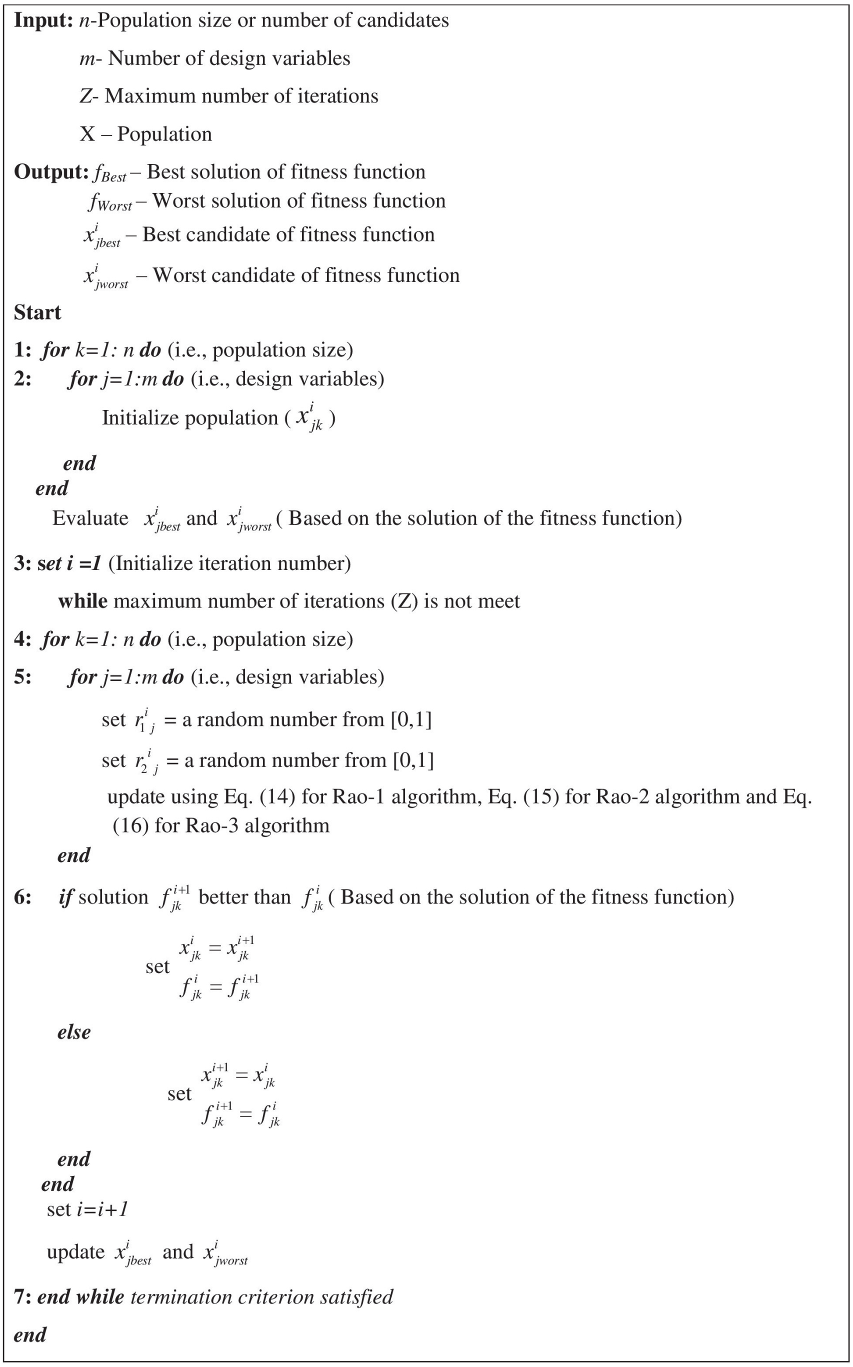
Step 7: Update the best solution in each subpopulation group using the following equation:

$$\text{if } f^{i+1}_{j\,k} \leq f^i_{j\,k}, \text{ then } x^i_{j\,k} = x^{i+1}_{j\,k} \text{ and } f^i_{j\,k} = f^{i+1}_{j\,k} \tag{17}$$

Step 8: Report the best optimum solution and terminate the algorithm according to the termination criteria. Otherwise, go to step 3.

5. IMPLEMENTATION OF RAO ALGORITHMS

For optimum VA loading of converters, the system of the balanced harmonic free inductive load of 10 kW +



```
Input: n-Population size or number of candidates
        m- Number of design variables
        Z- Maximum number of iterations
        X – Population
Output: $f_{Best}$ – Best solution of fitness function
        $f_{Worst}$ – Worst solution of fitness function
        $x^{i}_{jbest}$ – Best candidate of fitness function
        $x^{i}_{jworst}$ – Worst candidate of fitness function
Start
1: for k=1: n do (i.e., population size)
2:     for j=1:m do (i.e., design variables)
           Initialize population ( $x^{i}_{jk}$ )
       end
   end
   Evaluate $x^{i}_{jbest}$ and $x^{i}_{jworst}$ ( Based on the solution of the fitness function)
3: set i =1 (Initialize iteration number)
   while maximum number of iterations (Z) is not meet
4: for k=1: n do (i.e., population size)
5:     for j=1:m do (i.e., design variables)
           set $r^{i}_{1j}$ = a random number from [0,1]
           set $r^{i}_{2j}$ = a random number from [0,1]
           update using Eq. (14) for Rao-1 algorithm, Eq. (15) for Rao-2 algorithm and Eq. (16) for Rao-3 algorithm
       end
6:     if solution $f^{i+1}_{jk}$ better than $f^{i}_{jk}$ ( Based on the solution of the fitness function)
           set $x^{i}_{jk} = x^{i+1}_{jk}$
               $f^{i}_{jk} = f^{i+1}_{jk}$
       else
           set $x^{i+1}_{jk} = x^{i}_{jk}$
               $f^{i+1}_{jk} = f^{i}_{jk}$
       end
   end
   set i=i+1
   update $x^{i}_{jbest}$ and $x^{i}_{jworst}$
7: end while termination criterion satisfied
end
```

Fig. 3: Pseudocode for the Rao algorithm.

$j10$ kVAR supplied by a three-phase 400 V, 50 Hz supply is considered (Table 2).

The UPQC is used in the system to maintain PF unity at the source side and compensate for voltage sag/swell of 40% magnitude. The step-by-step procedure for implementing Rao algorithms and determining the optimum VA loading is given below. Fig. 4 shows the flow chart for the same conditions.

Step 1: Enter the system data as per Table 2.

Step 2: Initialize the JAYA and Rao algorithms as per Table 3.

Step 3: Initialize the design variable power angle δ and the ratio between the actual source and rated source voltages K.

Step 4: Evaluate the UPQC parameters from Eqs. (1) to (5).

Step 5: Implement the Rao algorithms as per the step-by-step procedure given in Section 3 to find optimal values of the design variables.

Step 6: Compare the results of all optimization algorithms and complete the process.

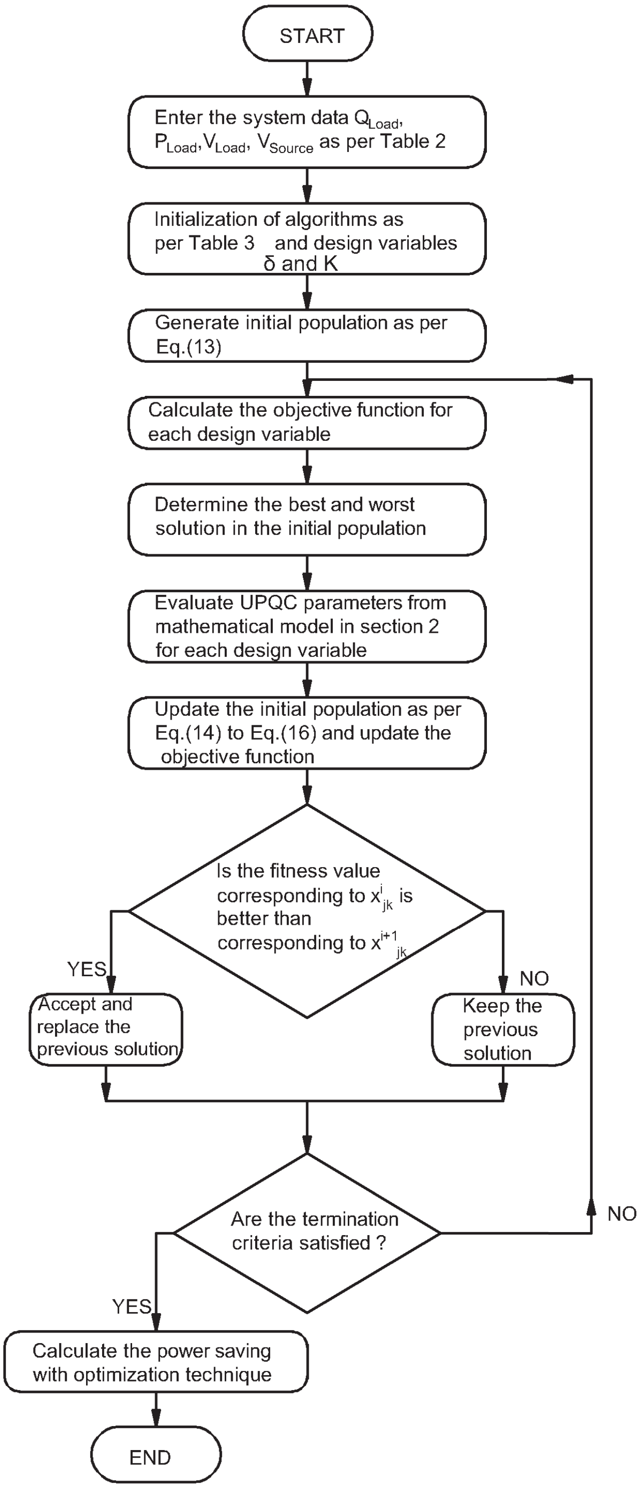


Fig. 4: Flow chart depicting the implementation procedure for the Rao algorithm for maximum utilization of the UPQC by optimal VA loading of the PECs.

6. RESULTS AND DISCUSSION

The proposed optimization algorithms are written in the MATLAB environment. Tables 2 and 3 list the system and algorithm controlling parameters used for simulation, respectively.

6.1 VA Loading of the UPQC without Optimization

Table 4 shows the VA loading of the UPQC without optimization. In the UPQC-P approach, the burden on DSTATCOM is found to be more than the DVR, irrespective of the operating condition causing the VA

***Table 2**: System parameters.*

System Parameter	Quantity
Load	$10\,\text{kW} + j10\,\text{kVAR}$
Load and source Voltage	400 V
Voltage sag condition (K)	0.6–0.9 pu
Steady state condition (K)	0.9–1.1 pu
VA rating of the DVR [10]	2490 VA
VA rating of DSTATCOM [10]	2907 VA

***Table 3**: Optimization algorithm parameters.*

Parameter	Notation	Value
Number of design variables	m	2
Population size	n	50
Maximum number of iterations	Z	50
Random for JAYA, Rao-2 and Rao-3 algorithm	r_1, r_2	[0, 1]
Random for Rao-1 algorithm	r	[0, 1]

***Table 4**: VA loading of converters without optimization.*

	K	Angle	V_{inj}	VA Loading/Phase (VA)		
	(pu)	(δ)	(V)	DVR	DSTATCOM	UPQC
UPQC-P	0.6	0	93	2223	4007	6230
	1	0	0	0	3334	3334
UPQC-VA$_{\text{min}}$	0.6	38°	148	3577	1048	4625
	1	0	0	0	3334	3334

***Table 5**: VA loading of converters with optimization.*

	K	Angle	V_{inj}	VA Loading/Phase (VA)			
	(pu)	(δ)	(V)	DVR	Transformer	DSTATCOM	UPQC
Voltage Sag							
JAYA	0.900	27.500	106.680	1710.850	2013.620	1623.860	3334.720
Rao-1	0.900	25.800	100.500	1612.000	1958.800	1721.400	3333.334
Rao-2	0.900	25.100	98.000	1571.240	1936.280	1762.340	3333.580
Rao-3	0.925	21.680	85.280	1330.750	1783.000	2002.720	3333.485
Steady State							
JAYA	0.941	23.370	91.760	1407.500	1546.000	1930.000	3337.500
Rao-1	0.963	15.700	62.500	936.660	1050.340	2396.680	3333.340
Rao-2	0.964	15.310	61.000	913.000	1026.200	2420.220	3333.220
Rao-3	0.961	15.980	63.600	955.000	1070.000	2378.140	3333.140

loading of the UPQC system to increase. The VA loading of the UPQC is minimum at different angles δ in the UPQC-VA$_{\text{min}}$ approach. During the steady state condition, the DVR remains ideal ($\delta = 0°$) for both approaches, and the load reactive power is shared by DSTATCOM (3334 VA).

6.2 VA Loading of the UPQC with Optimization

The per phase VA loading of UPQC with various optimization algorithms such as JAYA and Rao algorithms during voltage sag and steady state are given in Table 5. According to the output findings, the optimal angle δ differs according to the values of K for each run of the algorithm. After multiple runs of the algorithm, it can be observed that inequality constraints maintain the VA loading of DVR and DSTATCOM and thus the UPQC within their VA rating.

In the optimization approaches, the VA loading of both PECs and series transformer is found to reduce considerably. From Tables 4 and 5, it can be concluded that during voltage sag, the DVR burden is reduced considerably compared to the UPQC-P and UPQC-VA$_{\text{min}}$ due to optimization.

The following subsections provide a detailed analysis of the VA loading for the UPQC using optimization techniques. The robustness and efficacy of the proposed optimization algorithms are investigated for statistical analysis indices such as best (Best), worst (Worst), minimum (F_{min}), mean (F_{mean}) values, standard deviation (SD), and computation time. The output results from the statistical analysis of JAYA and Rao algorithms are presented in Tables 6 and 7.

6.3 Voltage Sag (0.6–0.9 pu)

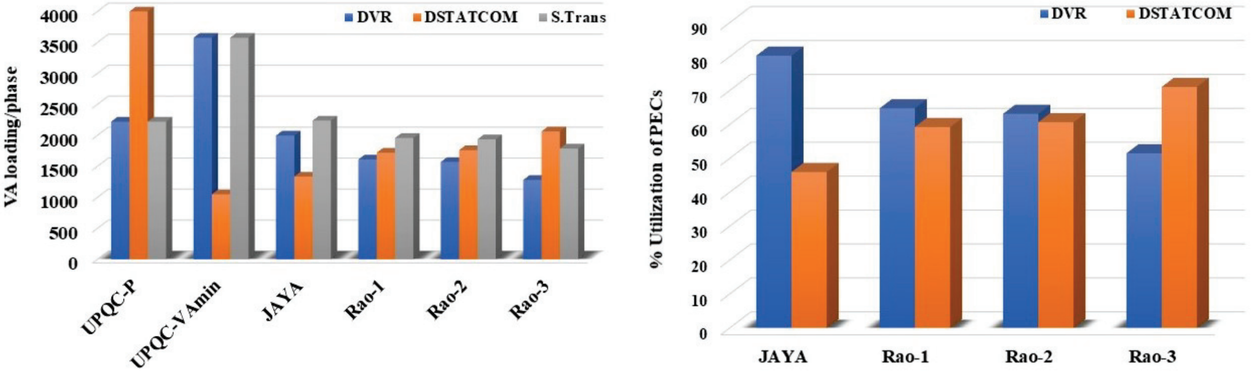
From the output results presented in Table 5, it can be observed that the VA loading of the UPQC is minimum for the Rao-1 (3333.334 VA) algorithm compared to the other algorithms. However, the optimal angle δ (21.68°) for the Rao-3 algorithm is small, and hence less voltage (85.28 V) is required to compensate for voltage sag,

***Table 6**: Statistical parameters of different algorithms during steady state.*

	F_{min}	F_{mean}	Best	Worst
Voltage Sag				
JAYA	3333.549	3334.168	3333.549	4023.568
Rao-1	3333.334	3334.838	3333.334	3335.879
Rao-2	3333.580	3334.038	3333.580	3334.780
Rao-3	3333.333	3333.374	3333.333	3334.282
Steady State				
JAYA	3333.530	3417.000	3333.530	3498.000
Rao-1	3333.333	3333.335	3333.333	3333.363
Rao-2	3333.333	3333.337	3333.333	3333.395
Rao-3	3333.333	3333.339	3333.333	3333.354

***Table 7**: Standard deviation and computation time of different algorithms.*

	JAYA	Rao-1	Rao-2	Rao-3
Voltage Sag				
SD	0.111372	0.107517	1.634500	0.003259
Comp. time (s)	13.476536	4.497252	5.787640	3.272131
Steady State				
SD	18.533300	0.001083	0.001167	0.000783
Comp. time (s)	13.241192	6.001867	6.662119	5.093281



(a) VA loading of the PECs and series transformer

(b) Percentage utilization of the PECs

***Fig. 5**: Voltage sag condition.*

resulting in a reduction in the VA loading of the series transformer (1783 VA). In optimization approaches, reactive power is utilized for compensation, and therefore, the series transformer receives a higher load than the DVR (see Fig. 5(a)). Although the loading of the series transformer is minimum in the Rao-3 algorithm, it is around 33% higher than the DVR, which in turn is higher than the Rao-1 and Rao-2 algorithms.

From Fig. 5(b), it can be clearly observed that in the case of the JAYA algorithm, the DVR is loaded at around 78% and DSTATCOM near to 40% of their rated capacity. However, in the Rao-3 approach, the DVR is loaded near to 53.45% and DSTATCOM to 68.88% of their rated capacity. Whereas, in the Rao-2, both PECs are loaded near to 60% of their rated capacity.

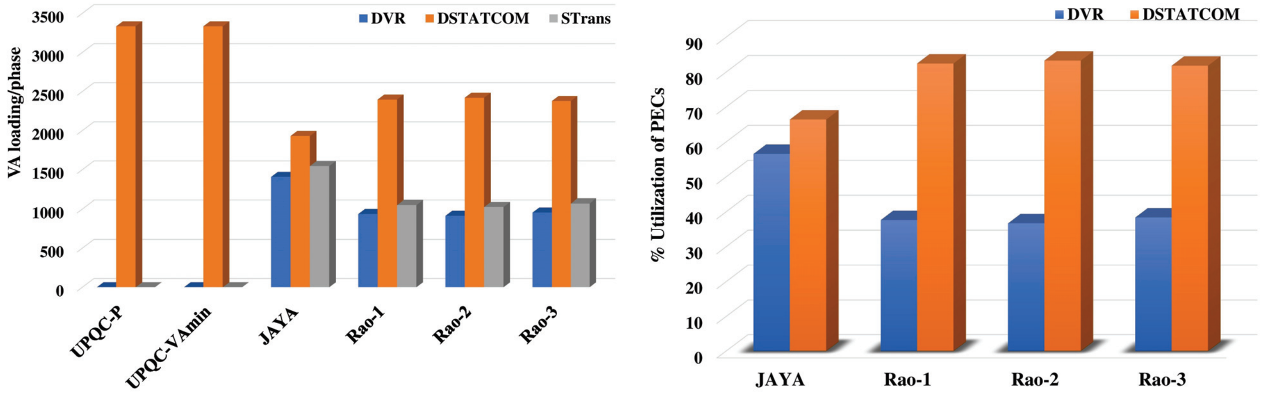
According to the statistical analyses presented in Tables 6 and 7, it can be concluded that the best, worst, minimum, and average values for the Rao-3 are quite near to each other, resulting in small SD values (0.003259). Furthermore, very little computation time is required for the Rao-3 compared to other algorithms. The value of SD confirms the robustness of the Rao-3 algorithm and its ability to find the best solution in every run.

6.4 Steady State Condition (0.9–1.1 pu)

The optimal values of the UPQC parameters are presented in Table 5. According to the output results, the VA loading of the UPQC is minimum (3333.14 VA) for the Rao-3 approach in comparison to others.

From Fig. 6(a), it can be clearly observed that with optimization, some part of the load reactive power is shared by the DVR, thereby reducing the burden on DSTATCOM considerably. It can be observed that in the JAYA algorithm (1407.5 VA), the DVR shares more power compared to the Rao-3 algorithm (955 VA). Although the optimal angle δ (15.31°) and series-injected voltage (61 V) are the smallest for the Rao-2 algorithm, in the Rao-3 algorithm, the VA loading of the series transformer is minimum (12% more than the VA loading of DVR).

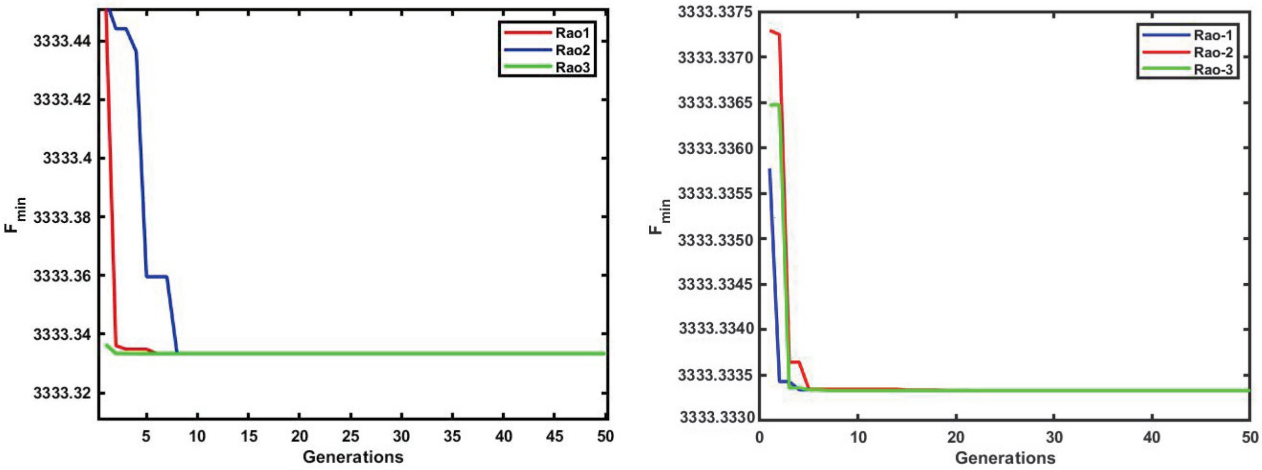
Fig. 6(b) shows that in the case of Rao algorithms, DSTATCOM is loaded at near to 80% of the rated capacity and the DVR near to 40%. The best, worst, minimum, and average values for the Rao-3 are almost the same, resulting in small SD values (0.000783) and minimum computation time (3.272131 s) (Tables 6 and 7). The robustness of the Rao algorithm and its ability to discover the optimum solution in every run is confirmed by the SD value and computation time.



(a) VA loading of the PECs and series transformer

(b) Percentage utilization of the PECs

Fig. 6: *Steady state condition.*



(a) Voltage sag

(b) Steady state

Fig. 7: *Convergence characteristics of Rao algorithms.*

It is well known that the efficiency of the PEC is highest and almost constant for loads ranging from 30–75% of the rated capacity. From Figs. 5(b) and 6(b), it can be observed that with the optimization approach, both PECs are loaded within their higher efficiency region. Although all static devices, such as PECs and series transformers, are included in the UPQC system, the high switching frequency of the PECs causes more losses than a series transformer. As a result, the power losses occurring in both PECs determine the efficiency of the UPQC system. With optimization, since both PECs are loaded with the optimum value, the efficiency of the UPQC system increases.

The convergence graphs (Fig. 7) show the outstanding convergence property of the Rao-3 compared to other algorithms for solving the optimal VA loading of the UPQC problem. According to the output results, the Rao algorithm outperforms the JAYA algorithm because it moves the population in the search space based on the mutual interaction between the population and the worst, best, and randomly picked solutions. These algorithms have various features when it comes to exploring and exploiting the search process. Furthermore, since Rao algorithms take less time to perform, they are found to be computationally economical. They can be used to solve small as well as large-scale optimization problems.

7. CONCLUSION

In this paper, a novel algorithm based on the Rao algorithms is presented to find the best angle δ and K values for maximum utilization of the UPQC. The results for the proposed algorithm are compared to those of the JAYA algorithm to demonstrate its effectiveness.

Based on the output results, the Rao-3 algorithm performs better than the others. If both PECs are used to their full potential power loss, manufacturing costs will be reduced. This makes the UPQC system attractive from the financial perspective, as well as providing an effective solution for PQ problem mitigation and DG grid integration in clean and green energy. As an outcome of this work, researchers will be able to create a control strategy for the UPQC based on optimum instantaneous VA loading to enhance efficiency.

REFERENCES

[1] B. Singh, A. Chandra, and K. Al-Haddad, *Power Quality: Problems and Mitigation Techniques*. Hoboken, New Jersey, USA: John Wiley & Sons, Inc., 2015.

[2] H. Fujita and H. Akagi, "The unified power quality conditioner: the integration of series- and shunt-active filters," *IEEE Transactions on Power Electronics*, vol. 13, no. 2, pp. 315–322, Mar. 1998.

[3] V. Khadkikar, "Enhancing electric power quality using UPQC: A comprehensive overview," *IEEE Transactions on Power Electronics*, vol. 27, no. 5, pp. 2284–2297, May 2012.

[4] S. Gade, R. Agrawal, and R. Munje, "Recent trends in power quality improvement: Review of the unified power quality conditioner," *ECTI Transactions on Electrical Engineering, Electronics, and Communications*, vol. 19, no. 3, pp. 268–288, Oct. 2021.

[5] W. C. Lee, D. M. Lee, and T. K. Lee, "New control scheme for a unified power-quality compensator-q with minimum active power injection," *IEEE Transactions on Power Delivery*, vol. 25, no. 2, pp. 1068–1076, Apr. 2010.

[6] V. Khadkikar and A. Chandra, "UPQC-S: A novel concept of simultaneous voltage sag/swell and load reactive power compensations utilizing series inverter of UPQC," *IEEE Transactions on Power Electronics*, vol. 26, no. 9, pp. 2414–2425, Sep. 2011.

[7] Y. Y. Kolhatkar and S. P. Das, "Experimental investigation of a single-phase UPQC with minimum VA loading," *IEEE Transactions on Power Delivery*, vol. 22, no. 1, pp. 373–380, Jan. 2007.

[8] S. Fagundes, F. Cardoso, E. Stangler, F. Neves, and M. Mezaroba, "A detailed power flow analysis of the dual unified power quality conditioner (iUPQC) using power angle control (PAC)," *Electric Power Systems Research*, vol. 192, Mar. 2021, Art. no. 106933.

[9] G. S. Kumar, B. K. Kumar, and M. M. Kumar, "Optimal VA loading of UPQC during mitigation of unbalanced voltage sags with phase jumps in three-phase four-wire distribution system," in *2010 International Conference on Power System Technology*, Zhejiang, China, 2010.

[10] B. B. Ambati and V. Khadkikar, "Optimal sizing of UPQC considering VA loading and maximum utilization of power-electronic converters," *IEEE Transactions on Power Delivery*, vol. 29, no. 3, pp. 1490–1498, Jun. 2014.

[11] J. Ye, H. B. Gooi, and F. Wu, "Optimal design and control implementation of UPQC based on variable phase angle control method," *IEEE Transactions on Industrial Informatics*, vol. 14, no. 7, pp. 3109–3123, Jul. 2018.

[12] J. Ye, H. B. Gooi, X. Zhang, B. Wang, and U. Manandhar, "Two-level algorithm for UPQC considering power electronic converters and transformers," in *2019 IEEE Applied Power Electronics Conference and Exposition (APEC)*, Anaheim, California, USA, 2019, pp. 3461–3467.

[13] J. Han, X. Li, Y. Sun, D. Luo, and S. Huang, "Optimal operation of UPQC under VA capacity constraints based on hierarchical optimization," *International Journal of Electrical Power & Energy Systems*, vol. 122, Nov. 2020, Art. no. 106168.

[14] S. Gade, R. Agrawal, D. Patil, and S. Antonov, "Optimal utilization of UPQC at different operating condition using TLBO," in *56th International Scientific Conference on Information, Communication and Energy Systems and Technologies (ICEST)*, Sozopol, Bulgaria, 2021, pp. 197–200.

[15] S. Gade and R. Agrawal, "Optimal utilization of unified power quality conditioner using the JAYA optimization algorithm," *Engineering Optimization*, vol. 55, no. 1, pp. 1–18, 2023.

[16] S. A. Gade and R. Agrawal, "Optimal utilization of UPQC during steady state using evolutionary optimization techniques," in *2021 International Conference on Intelligent Technologies (CONIT)*, Hubli, India, 2021.

[17] A. Gotmare, S. S. Bhattacharjee, R. Patidar, and N. V. George, "Swarm and evolutionary computing algorithms for system identification and filter design: A comprehensive review," *Swarm and Evolutionary Computation*, vol. 32, pp. 68–84, Feb. 2017.

[18] R. V. Rao, "Jaya: A simple and new optimization algorithm for solving constrained and unconstrained optimization problems," *International Journal of Industrial Engineering Computations*, vol. 7, no. 1, pp. 19–34, 2016.

[19] R. V. Rao, "Rao algorithms: Three metaphor-less simple algorithms for solving optimization problems," *International Journal of Industrial Engineering Computations*, vol. 11, no. 1, pp. 107–130, 2020.

Swati Gade received her B.E. and M.E. degrees in Electrical Engineering from the Pune University, India in 2003 and 2007, respectively, and Ph.D. degree from Sandip University, Nashik, India in 2022. Currently, she is an associate professor in the Department of Electrical Engineering at Sandip Institute of Technology and Research Center, Nashik, India. She has published about 7 national and international journal and conference papers. Her research interest covers power systems, application of optimization techniques in power system, and power quality. She is a life member of ISTE, IE(i), and IAENGE (H.K.).

Rahul Agrawal received his B.E. Degree in Electrical Engineering from JIT Khargone, India in 2001, and M.E. in Power Electronics from SGSITS Indore, India in 2008, and Ph.D. from Maulana Azad National Institute of Technology Bhopal, India in 2017. Presently, he is a Professor with the Department of Electrical Engineering, Guru Gobind Sing College of Engineering and Research Centre, Nashik, India. He has 20 years of teaching experience. He has published 40 papers in national and international conferences and journals. His current research interests are in the areas of application of optimization technique in power system, power electronics, and FACTS devices. He is a life member of ISTE, India.