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Performance Analysis of Distribution System with Optimal Allocation of Unified Power Quality Conditioner Considering Distribution Network Reconfiguration

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Abstract: The distribution systems act as the primary connecting point between the power utility and the end users of the electricity. It is vital to assess the behaviour of the network when subjected to a variety of various types of loads and any new D-FACTS devices that may be developed in the near future, in order to improve the operation and planning of electrical distribution systems. The authors of this article performed an analysis of the distribution system when unified power quality conditioner (UPQC) was present and acting as a Distribution FACTS device. The main objective of this article is to minimization of total investment cost of UPQC as well as system operating considering distribution network reconfiguration (DNR). For optimal solution, an improved whale optimization algorithm (IWOA) has been introduced. Besides, impact of voltage dependent load models has been studied. In order to evaluate the practicability and usefulness of the suggested strategy, a number of potential outcomes involving the DNR and allocation of UPQC under a voltage dependent load model have been considered. The active and reactive power losses have been reduced by 44.67 % and 37.42 %, respectively, as compared to conventional schemes (such as UPQC allocation solely). In addition, the proposed methodology results in cost reductions of around 33.68 % annually.

Keywords: Unified power quality conditioner, Improved whale optimization algorithm, Distribution network reconfiguration.

1. Introduction

1.1 Motivation

The distribution network is an essential component in the process by which customers are connected to the utility. It is very necessary for the network to have as few losses as possible and a better voltage profile in order to provide improved operations and control of the distribution system [1]. However, as a result of rising consumer demand and the burden of sudden increases in load demand from the residential, industrial and commercial sectors, the voltage profile may begin to deviate from the standards, and regulation may become inadequate [2]. This is due to the fact that consumers are demanding more electricity. An abrupt shift in load demand can cause a divergence in the voltage profile, a reduction in the capability to transmit active power, and an increase in the amount of active power lost. The management of reactive power regulation will be necessary for the distribution network if the aforementioned problems are to be resolved [3]. In today's world, with an ever-increasing number of nonlinear loads, the application of custom power devices (CPD) in the most efficient functioning of distribution systems has garnered a great deal of interest. On the other side, distribution network reconfiguration (DNR) provides various benefits, including as reducing the amount of electricity that is lost, improving voltage, and making distribution systems more reliable [4-7]. In order to accomplish the aforementioned objectives, it is necessary for the operators to perform optimum switching along with UPQC allocation.

1.2 Literature survey

For the management of reactive power, several conventional methods, such as the deployment of series voltage regulators and shunt capacitors, are available [4, 5]. However, these devices [4, 5] have a number of severe limitations, including the incapability to generate changeable reactive power and a slow response time. In comparison to other reactive power compensators, CPDs such as UPQC, provide a number of advantages, including a higher degree of voltage control, reduced harmonic distortion, and decreased power loss [6, 7].

For effective functioning of distribution networks, various authors have published in this field of study in recent years [8-12]. The comprehensive mathematical model of UPQC is described in [8], however optimal placement of UPQC has not been performed. Benefits of implementing UPQC for reactive power correction in the distribution system have been discussed in [9], cost analysis has not been evaluated. Impact of UPQC allocation in presence of voltage dependent load models and load growth has been studied in [10], optimal allocation has not been performed. Significance of coordinated operation of flexible device SOP and DNR in reduction of energy demand and losses was presented in [11] using grey wolf optimization (GWO), cost analysis has not been evaluated. In [12], particle swarm optimization (PSO) and exhaustive search algorithm have been adopted for coordinated operation of DNR operation and UPQC allocation. In this methodology, optimal switching of tie lines has been conducted by PSO, UPQC allocation has been obtained exhaustive search algorithm. However, the methodology proposed in [1-12], not fully explored the effect of distribution reconfiguration and voltage dependent load models in combination of UPQC device. This paper attempted to fill the gap and also reveals the profits of coordinated operation of DNR and UPQC allocation. Further, studies the impact of different voltage sensitives load model on sizing and placing of UPQC.

1.3 Metaheuristic methods

The objective of the metaheuristic method is to locate a solution that is either near optimal, sub-optimal, or acceptable. This is a different approach from the exact method, which guarantees the discovery of the genuine best solution. Few popular metaheuristic methods were published in recent times, such as stochastic komodo algorithm (SKO) was inspired by Komodo foraging and mating [13]. Fixed step average and subtraction-based optimizer (FA-ASBO) used average knowledge to guide the population toward the best option by removing the best and worst [14]. Mixed leader-based optimizer (MLBO) was utilised to create a new algorithmic population leader by merging the best population member with a random member [15]. Three influential members-based optimizers (TIMBO) used three significant population members best, worst, and mean to update the algorithm's population members in the issue search space [16]. To navigate the search space, Random Selected Leader Based Optimizer (RSLBO) algorithm updated population members depending on random leaders [17]. Squirrel search optimizer (SSO) mimics the rapid leaping and gliding motions that squirrels employ while foraging [18]. Puzzle optimization algorithm (POA) was designed around a mathematical simulation of solving a challenge as an evolutionary optimizer [19]. Ring toss game-based optimization (RTGBO) algorithm simulated the ring toss game's rules and player behaviour as they throw rings toward the scoring bar [20]. Whale optimization algorithm (WOA) mimics humpback whale hunting and was inspired by bubble-net hunting [21]. In this paper, authors have employed whale optimization algorithm with some improvements for solving the present complex optimization problem.

1.4 Contribution of paper

The main contributions of the present paper as follow

1) Coordinated allocation of UPQC and DNR operation in distribution network has been performed
2) The dynamic variation of the exploration rate has been proposed for effective communication between the agents responsible for exploration and exploitation in improved whale optimization algorithm (IWOA).
3) Whale position updating has been changed to incorporate data from prior personal best and global best positions.
4) The effects of voltage-dependent load models have been studied.

To the authors' knowledge, coordinated allocation of UPQC and DNR using voltage-dependent load models has not been reported. The application of the WOA technique to UPQC allocation challenges in distribution systems has yet to be explored. This work develops improved WOA (IWOA) for UPQC allocation problems with voltage-dependent load models. The proposed IWOA's effectiveness is validated by using large test cases and comparing the findings to other methodologies reported in the literature.

1.5 Structure of paper

The organization of the present paper is as follows: The mathematical modelling of UPQC is discussed in Section 2, which follows. The formulation of the research problem that is being investigated in this study has been described in section 3. The proposed algorithm for the solution can be found in section 4. The application of the enhanced whale optimization technique that was developed to the UPQC allocation problem is explained in section 5. In section 6, a summary of the outcomes and the discussions has been provided. In the last part, the conclusion was discussed in section 7.

2. Modelling of unified power quality conditioner (UPQC) in distribution system load flow

The section is made up of two buses, each of which has a load ($P_{\text{Lm}} + \text{j}Q_{\text{Lm}}$ and $P_{\text{Lm}} + \text{j}Q_{\text{Ln}}$). The line segment is linked between these buses possesses resistance (R) and reactance (X). Fig. 1 depicts UPQC inserted between bus m and bus n. The voltage on the n^{th} node bus may be compensated to desired voltage value. After the UPQC installation, the voltage at the compensated node will be V_{nnew} and its angle will be $\angle\alpha_{new}$. Both of these values will change. Since the only purpose of the UPQC in this configuration is to compensate for reactive power, the current I_{Series} produced by the series compensator is at 90^0 apart with the voltage produced by the series, and the current produced by the shunt compensator is at 90^0 apart with the voltage produced at the node that is being compensated.

Eq. (1) describes the relationship between the voltage and current produced for the system

$$\text{V}_{0n}\angle\alpha_{new} = \text{V}_m\angle\delta - (R + jX)\text{I}_L \angle\theta - (R + jX)\text{I}_{shunt}\angle\left(\alpha_{new} + \frac{\pi}{2}\right) + \overrightarrow{\text{V}_{series}} \quad (1)$$

Where, $\text{V}_{0n}\angle\alpha_{new}$: Voltage of the compensated node after UPQC allocation.

$\overrightarrow{\text{I}_{Shunt}} = \text{I}_{Shunt}\angle\left(\alpha_{new} + \frac{\pi}{2}\right)$: Injected current by shunt compensator.

$\overrightarrow{\text{I}_L} = \text{I}_L\angle\theta$: Current flow in the line after compensation.

$\overrightarrow{\text{V}_{series}}$: Voltage injected by series compensator of the device.

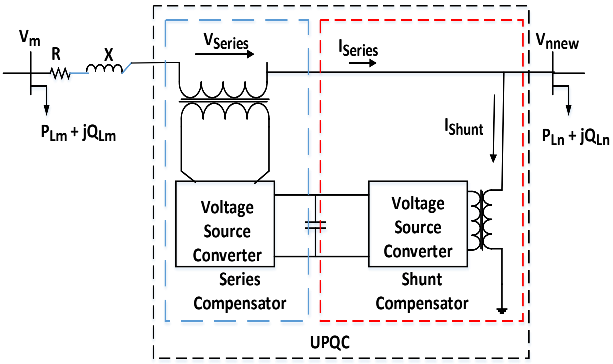

Figure. 1 Distribution system: Single line diagram of UPQC connected between two buses

The current I_{Series} may lag with respect to V_{series}. When it is lagging then the angle of corresponding V_{series} is given by Eq. (2)

$$\angle\text{V}_{series} = \angle\text{I}_{Series} - \frac{\pi}{2}, \ \angle\text{I}_{Series} > 0 \quad (2)$$

The current injected by the series compensator is given by

$$\overrightarrow{\text{I}_{Series}} = \overrightarrow{\text{I}_{Shunt}} + \overrightarrow{\text{I}_L} \quad (3)$$

The equation has three unknown variables I_{shunt}, $\angle\alpha_{new}$ and V_{series} and there are infinite number of solutions for these quantities. Therefore, the reactive power compensated by the shunt compensator is considered as Q_{shunt}, a negative constant load in the load model shown in Fig. 2.

$$V_{series}\angle\rho = V_{jnew}\angle\alpha_{new} + (R + jX)I'_L \angle\theta' - V_m\angle\delta \quad (4)$$

The angle ρ is the angle by which voltage V_{series} injected lags by current I'_L flowing through the line where UPQC is connected.

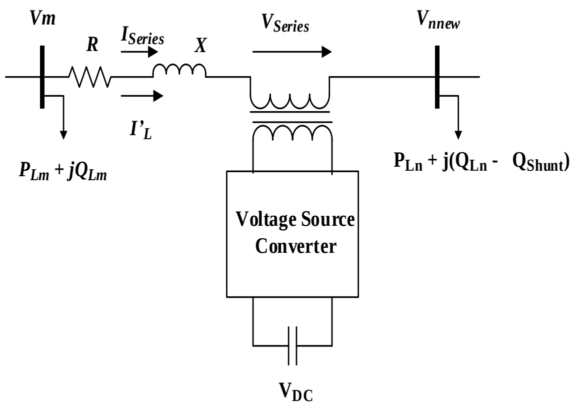

Figure. 2 Distribution system: with UPQC connected between two buses

$$\rho = \frac{\pi}{2} + \theta', \quad \theta' \le 0 \tag{5}$$

$$\rho = -\frac{\pi}{2} + \theta', \quad \theta' > 0 \tag{6}$$

Real and imaginary parts of Eq. (4) have been separated. The following equation can be obtained using Eqs. (7) and (8) respectively.

$$\mathrm{V}_{series} \cos\rho = \mathrm{V}_{nnew} \cos\alpha_{new} + \mathrm{Real}(\mathrm{ZI}'_L \angle\theta') \\ -\mathrm{Real}(\mathrm{V}_m \angle\delta\ ) \tag{7}$$

$$\mathrm{V}_{series} \sin\rho = \mathrm{V}_{nnew} \sin\alpha_{new} + \mathrm{Imag}(\mathrm{ZI}'_L \angle\theta') \\ -\mathrm{Imag}(\mathrm{V}_m\angle\delta)\ ) \tag{8}$$

The Eqs. (7) and (8) can be reformulated as Eqs. (9) and (10) respectively

$$a_1 x_1 = b cos x_2 + c_1 \tag{9}$$

$$a_2 x_2 = b sin x_2 + c_2 \tag{10}$$

Where

$$a_1 = cos\rho \tag{11}$$

$$a_2 = sin\rho \tag{12}$$

$$b = V_{nnew} \tag{13}$$

$$c_1 = Real(ZI'_L \angle\theta') - Real(V_m \angle\delta) \tag{14}$$

$$c_2 = Imag(ZI'_L \angle\theta') - Imag(V_m \angle\delta) \tag{15}$$

$$x_1 = V_{series} \tag{16}$$

Where, b is compensated node voltage magnitude, and $\mathrm{x}_1 \, and \, \mathrm{x}_2$ are the variables and $a_1, a_2, c_1 \, and \, c_2$ are constants. Rearranging the Eqs. (9) and (10), can obtained Eqs. (17) and (18) respectively.

$$cos x_2 = \frac{a_1 x_1 - c_1}{b} \tag{17}$$

And

$$sin x_2 = \frac{a_2 x_1 - c_2}{b} \tag{18}$$

Adding the square formed by the numbers Eqs. (17) and (18)

$$\left(\frac{a_1 x_1 - c a_1}{b}\right)^2 + \left(\frac{a_2 x_1 - c_2}{b}\right)^2 = 1 \tag{19}$$

Then

$$\frac{{a_1}^2 + {a_2}^2}{b^2} {x_1}^2 - 2\frac{a_1 c_1 + a_2 c_2}{b^2} x_1 + \frac{{c_1}^2 + {c_2}^2}{b^2} = 1 \tag{20}$$

Thus

$$x_1 = \frac{-B \pm \sqrt{\Delta}}{2A} \tag{21}$$

here:

$\Delta = \mathrm{B}^2 - 4\mathrm{AC}$

$B = -2\dfrac{a_1 c_1 + a_2 c_2}{b^2}$

$A = \dfrac{{a_1}^2 + {a_2}^2}{b^2}$

$C = \dfrac{{c_1}^2 + {c_2}^2}{b^2} - 1$

The algebraic Eq. (21) results in to two values of $x_1 = V_{Series}$, but out of these values one value is acceptable.

The load flow analysis ensuing boundary conditions to get the ideal value for x_1

"$If, b = V_{nnew} = V_{0n} \; then \; x_1 = V_{Series} = 0$"

The ideal value for x_1 can be determined by testing boundary conditions on the results of the load flow, and it is:

$$x_1 = \frac{-B + \sqrt{\Delta}}{2A} \tag{22}$$

The value of $x_2 = \alpha_{\mathrm{new}}$ can be obtained by using Eqs. (17) and (18)

$$x_2 = cos^{-1}\left(\frac{a_1 x_1 - c_1}{b}\right) \tag{23}$$

Or

$$x_2 = sin^{-1}\left(\frac{a_2 x_1 - a_2}{b}\right) \tag{24}$$

Thus, UPQC series compensator's reactive power injection may be determined as

$$j.Q_{Series} = \vec{V}_{Series}.\vec{I}_L^{\ *} \tag{25}$$

Here, $\vec{V}_{Series} = V_{Series}\angle\left(\theta + \frac{\pi}{2}\right)$

$\vec{I}_L = I_L \angle\theta$

Where the complex variable's conjugate is indicated by the symbol "*."

Finally, the total capacity of reactive compensation of UPQC can be obtained by using

$$Q_{UPQC} = Q_{Series} + Q_{Shunt} \tag{26}$$

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3. Problem formulation

The proposed methodology is to determine the optical allocation of UPQC along with DNR operation for improvement in voltage magnitude as well as reduction of the power losses considering economic constraints.

3.1 Objective function

Mathematical representation of the proposed objective function (OF) has been given in Eq. (27)

$$OF = \left[K_e \sum_{ll=1}^{3}(APL_{ll} \times T_{ll}) + K_{UPQC} \sum_{ll=1}^{3}(UPQC_{ll} \times T_{cll}) + K_{SW} \sum_{ll=1}^{3} \sum_{j=1}^{N_{sw}} \left|sw_{j,ll} - sw_{0,j,ll}\right|\right] \times \left[\prod_{ll=1}^{3}\left|\prod_{mn=1}^{nl} OC_{mn} \times \prod_{m=1}^{nb} OV_n\right|\right] \quad (27)$$

First term of the right-hand side of Eq. (27) represents the cost of total active power losses (APL) under different load levels. Where K_e is the cost coefficient of active power loss. T_{ll} is the time duration under different load levels over a year. The APL at ll^{th} load level, can be determined by using Eq. (28)

$$APL_{ll} = \sum_{mn=1}^{nb} R_{mn} |I_{mn}|^2 \quad (28)$$

In Eq. (28), the second term represents the investment cost of UPQC, K_{UPQC} is the cost associated with UPQC, T_{cll} is the proportion of the ll^{th} load level time duration to the total time duration, which can be determined as

$$T_{cll} = \frac{T_{ll}}{\sum_{ll=1}^{3} T_{ll}} \quad (29)$$

The third term in Eq. (27) represents the switching cost due to DNR operation, K_{SW} is the switching cost, NSW is the switching operations number. $sw_{mn,ll}$ and $sw_{0,mn,ll}$ are the status of switch current and previous configuration respectively. For minimization of deviations in bus voltage and line current, a penalty factor has been multiplied to the cost parameters as given in Eq. (27).

$$OC_{mn} = \begin{cases} 1; & if\ I_{mn} \le I_{max} \\ exp\left(\lambda \left|1 - \frac{I_{mn}}{I_{max}}\right|\right) & if\ I_{mn} > I_{max} \end{cases} \quad (30)$$

$$OV_m = \begin{cases} 1; & if\ V_{\min} \le V_m \le V_{\max} \\ \exp\left(\xi\left|1 - V_m\right|\right); & otherwise \end{cases} \quad (31)$$

Here OC_{mn} is the over current flowing in the branch connecting between bus m and n. I_{mn} is the current flowing in the branch connecting between bus m and n. I_{max} is the maximum capacity of the current flowing in the branch, is the positive constant. Similarly, OV_m is the over voltage at bus m, V_m is voltage magnitude at bus m, is the positive constant V_{min} and V_{max} are the minimum and maximum voltages respectively. Here OC_{mn} and OV_m will acquire the very large value, which acts as penalty factor in the objective function.

3.2 System operation constraints

a) Minimum and maximum voltage magnitude limits

$$V_{min} \le V_m \le V_{max} \quad (32)$$

b) Limit of reactive power rating capacity

$$0 \le Q_{UPQC} \le Q_L^{total} \quad (33)$$

c) Voltage dependent load models: In practically, most of the load are combination of constant impedance, constant power and constant current load model. The active and reactive power ZIP load models have been expressed as given below

$$P_{L,m} = P_{L,m}^{ll}\left[Z_m^p\left(\frac{V_i}{V^n}\right)^2 + I_m^p\left(\frac{V_i}{V^n}\right) + P_m^p\right] \quad (34)$$

$$Q_{L,m} = Q_{L,m}^{ll}\left[Z_m^q\left(\frac{V_i}{V^n}\right)^2 + I_m^q\left(\frac{V_i}{V^n}\right) + P_m^q\right] \quad (35)$$

d) DNR operation: Radial topology constraints

The total number of branches in the system to maintain radial topology as given below

$$N_{br} = N_b - 1 \quad (36)$$

Branch-node incidence (BN) matrix has been employed for determination of radial topology structure.

- if branch m^{th} branch is not incident into n^{th} bus , then BN_{mn}=0.
- if branch m^{th} branch is incident to and oriented toward the n^{th} bus , then BN_{mn} =-1.
- if branch m^{th} branch is incident to and oriented away the n^{th} bus, then BN_{mn} =1.

The dimension of the above matrix is $nbr \times nb$. Here, substation node is selected as reference node, variables of other nodes defined as buses. The branch bus incidence matrix is calculated by removing the reference column of the matrix (BN). Rank of BB matrix must be *nbr*, which indicating that the topology is radial. As well as determinant of BN as given below

$$|\det(BN)| = 1 \tag{37}$$

4. Solution algorithm

In this section, improved whale optimization algorithm (IWOA) has been employed to solve this optimization problem described in section 3.

4.1 Whale optimization algorithm: overview

The Whale Optimization Algorithm (WOA) [21] uses each humpback whale's position as a search agent. The WOA updates the search agent often in an effort to discover the best solution to the global optimization problem. The WOA simulation process may be implemented in the following three stages.

Stage 1: When hunting, humpback whales can locate their prey and circle around it. The WOA method assumes that the best candidate solution at the moment is either the target prey or really close to the optimum because the exact location of the best design in the search region is unknown. The equations that follow serve as representations for these behaviours

$$\vec{D} = \left|\vec{E}.\vec{Y}_p(it) - \vec{Y}(it)\right| \tag{38}$$

$$\vec{Y}(it+1) = \overrightarrow{Y_p}(it) - \vec{R}.\vec{D} \tag{39}$$

Here, *it* indicates the current iteration in this case. The vectors $\vec{Y}$ and $\overrightarrow{Y_p}$, which represents the locations of the whale and its prey respectively. The following formula can be used to calculate the coefficient vectors $\vec{R}$ and $\vec{E}$.

$$\vec{R} = 2\varepsilon.\overrightarrow{r_1} - \varepsilon \tag{40}$$

$$\vec{E} = 2\overrightarrow{r_2} \tag{41}$$

The exploration rate 'ε' decreases during the process from two to zero due to the iterations required in controlling exploitation and exploration. The expression for the factor is $\varepsilon=2-2.it/it^{max}$.

Stage 2: Humpback whales swim around their prey by either swimming in a decreasing circle or a spiral-shaped route. In order to represent this simultaneous behaviour, it is assumed that there is a 50% chance that the spiral model or the shrinking encircling mechanism will be used to update the position of whales during optimization.

$$\vec{Y}(it+1) = \begin{cases} \overrightarrow{Y_p}(it) - \vec{R}.\vec{D}\left|\vec{E}.\vec{Y}_p(it) - \vec{Y}(it)\right| & if\ pr < 0.5 \\ \vec{D} \times e^{hk} \times cos(2\pi k) + \vec{Y}_p(it) & if\ pr \geq 0.5 \end{cases} \tag{42}$$

Where *pr* is probability number

Stage 3: We update a search agent's position based on a randomly chosen search agent during the exploration phase as opposed to the best search agent thus far identified during the exploitation phase. This method and |A| > 1 emphasise exploration and allow for a global search to be conducted using the WOA algorithm.

4.2 Improvements in whale optimization algorithm

a) In a normal WOA, the exploration rate 'ε' changes linearly, however this leads to a lack of communication between the agents in charge of exploration and exploitation regarding the current iteration, which yields the local optimum. in order to include the dynamic fluctuation of 'ε'. The following enhancement can be done as shown below.

$$\varepsilon = \left(1 - \mu.\frac{it}{it^{max}}\right)^{-1}\left(1 - \frac{it}{it^{max}}\right) \tag{43}$$

here, μ represents nonlinear modulation index in the limit (0,3).

b) The individual data from the previous generation of agents have not been utilised by the next generation of agents since WOA is a memory-less algorithm. This is the circumstance as a direct outcome of the technique's apparent transparency. It is more likely that acquired updated locations will become locked in localised optima since there is a lack of diversity among agents. This is due to the fact that localised optimals are frequently more effective. To make use of the information that was provided at the previous personal best and global best positions, the updating of the whale positions has been modified as follows.

$$\vec{v}(it+1) = \begin{Bmatrix} \omega.\vec{v}(it) + c_1.r_2.\left(\overrightarrow{Y_{pbest}}(it) - \vec{Y}(it)\right) \\ +c_2.r_3.\left(\overrightarrow{Y_{gbest}}(it) - \vec{Y}(it)\right) \end{Bmatrix} \tag{44}$$

$$\vec{Y}(it+1) = \vec{Y}(it) + \vec{v}(it+1) \tag{45}$$

Where the communication coefficient is denoted by c2, and the specific coefficient is denoted by c1.

The notation ($\overrightarrow{Y_{gbest}}$) signifies the historically best position on a global scale in the area, whereas ($\overrightarrow{Y_{pbest}}$) denotes the best individual position in the area. The inertia weight is represented by the symbol ω and is present in Eq. (46)

$$\omega(it) = \frac{it^{max}}{it^{max} \times (\omega_{initial} - \omega_{final}) + \omega_{final}} \qquad (46)$$

PSO [22] has an impact on how the IWOA position update method is carried out. The first term of the whale's name describes where the best whales are found in Eq. (44). This provides the essential push that the agents in the search area require. The second term refers to the various ideas that cross each searcher's mind as they approach the best location thus far discovered. The collaborative role that the whale agents played in locating the global optimum is shown in the third term.

5. Implementation of improved whale optimization algorithm on UPQC allocation problem

In the section, IWOA has been employed to solve the UPQC allocation problem along with DNR operation. The decision variables in the present problem are the location of UPQC and status of remotely controlled switches.

The Eq. (47) depicts the solution vector for the present optimization

$$Y_i = [sw_1, sw_2, \ldots . sw_{Nsw}, loc_1, loc_2, \ldots . loc_{NC_b}] \quad (47)$$

In Eq. (47) opened switches in the fundamental loops and locations of UPQC are denoted *sw*, and *loc* respectively. Pseudo code of the proposed IWOA for present optimization problem has been given in Table 1.

6. Outcomes and discussions

The IEEE 33 bus distribution system [23] has been chosen for the validation and its line diagram has been portray in Fig. 3. Polynomial ZIP coefficients have been tabulated in Table 2.

6.1 Cases studied:

Three different cases have been studied as seen depicted in Table 3 to test efficacy of the proposed methodology. Case 1 represents base case, where no DNR operation and without UPQC allocation. Optimal allocation of UPQC considering voltage

Table 1. Pseudo code of the proposed IWOA for UPQC allocation problem

Input: Number of whale agents (n_w), and maximum number of iterations ($iter^{max}$), load the system data of the given distribution system.
Step 1: a) The upper and lower boundaries of each tie line has been initialized corresponding to the fundamental loops
b) The upper and lower boundaries of UPQC installed locations have been initialized.
Step 2: The whale agents population has been initialized as $Y_i = [Y_1^i, \ldots., Y_{d-1}^i, Y_d^i]$ with i=1,2,….n_w randomly
Step 3: determine the values of $\vec{R}$ and $\vec{E}$ using Eq. (40) and Eq. (41) respectively. The value of exploration rate ε as 2,
Check the radial topology structure of distribution network condition using constraint in section 3.2 for each whale agent.
If (whale agent Y_i is satisfying the radial topology configuration) **then**
Evaluate the objective value of agent by using Eq. (27).
Else
objective value is set to infinity value
End if
while (iter ≤ iter^{max}) do
for each Y_i $\mathcal{E}$ pack **do**
current whale's agent has been updated by using Eq. (45).
end for
In each iteration ε has been updated by using Eq. (43)
$\vec{R}$ and $\vec{E}$ has been updated by Eq. (40) and Eq. (41) respectively.
If (whale agent Y_i is satisfying the radial topology configuration) **then**
Evaluate the objective function of whale agent by using Eq. (27)
else
fitness of position=infinity
end if
it=it+1
end while
Output : A cost-effective distribution of UPQC has been made in conjunction with DNR.

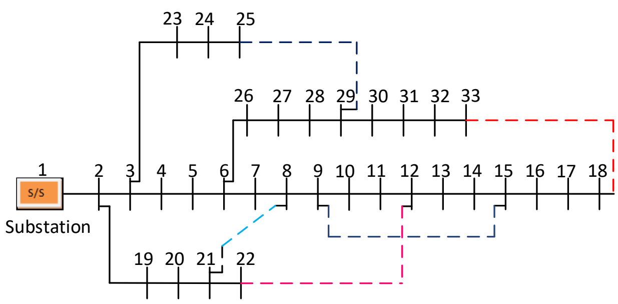

Figure 3. IEEE 33-bus distribution system single line diagram

Table 2. ZIP coefficients under polynomial loads

Customers	ZIP coefficients		33 bus system
Industrial	$[Z_p\ I_p\ P_p]$ =[0 0 1]	$[Z_q\ I_q\ P_q]$ =[0 0 1]	Bus no. 1 to 4
Residential	$[Z_p\ I_p\ P_p]$=[0.85 -1.12 1.27]	$[Z_q\ I_q\ P_q]$ =[10.97 -18.74 8.78]	Bus no. 5 to 18; Bus no. 29 to 33
commercial	$[Z_p\ I_p\ P_p]$ =[0.4 -0.07 0.64]	$[Z_q\ I_q\ P_q]$ =[4.05 -6.66 3.6]	Bus no. 19 to 28

Table 3. List of cases studied

Cases	**ZIP load model**	**UPQC**	**DNR**
Case 1	yes	No	No
Case 2	yes	yes	No
Case 3	yes	yes	yes

Table 4. Different load levels and duration hours over a year

Load level	**light**	**Nominal**	**Heavy**
Multiplication factor	0.5	1	1.6
Duration (hours)	2000	5260	1500

sensitive load models (i.e. ZIP load model in this paper) has been studied in case 2. Finally, both UPQC allocation and DNR along with ZIP (polynomial) load model have been considered in case 3. Further, Table 4 depicts the division of different load levels and corresponding hours over a year.

6.2 Discussions on numerical results:

Table 5 depicts the numerical results of different cases under three different levels namely light load, nominal load and heavy load conditions and their corresponding load value 50%, 100% and 160% respectively.

6.2.1. Case 2 (UPQC allocation only):

With optimal allocation of UPQC with size of 0.45 MVAR, 0.85 MVAR and 1.33 MVAR corresponding to different load levels (i.e 50%, 100% and 160%), at bus no. 30 results in total active power losses (APL) reduced by 22.99%, 21.752% and 21.721% respectively with respect to case 1. Similarly total reactive power losses (RPL) reduced by 22.88%, 21.622% and 21.586% respectively with respect to case 1. Besides, minimum voltage magnitude has been improved from 0.96 pu, 0.9198 pu and 0.8694 pu to 0.9638 pu, 0.9275 and 0.8825 pu respectively. It has been noted that the amount of the

Table 5. Summary of the results in IEEE 33 bus distribution system

Cases	**Parameters**	**Light load (0.5)**	**Nominal load (1.0)**	**Heavy load (1.6)**
Case 1 (Base case)	Active Power loss (kW)	43.250	173.071	455.613
	Reactive Power loss (kVAR)	28.763	115.098	303.198
	Minimum voltage (pu)	0.9600	0.91982	0.8694
	Switches opened	33, 34, 35, 36, 37	33, 34, 35, 36, 37	33, 34, 35, 36, 37
Case 2 (only UPQC allocation)	Active Power loss (kW)	33.307	135.425	356.649
	% APL reduction	22.990	21.752	21.721
	Reactive Power loss (kVAR)	22.182	90.211	237.75
	% RPL reduction	22.880	21.622	21.586
	Minimum voltage (pu)	0.9638	0.9275	0.8825
	Switches opened	33, 34, 35, 36, 37	33, 34, 35, 36, 37	33, 34, 35, 36, 37
	Bus number	30	30	30
	UPQC (MVAR)	0.444	0.85	1.33
Case 3 (UPQC allocation along with DNR)	Active Power loss (kW)	24.112	97.184	252.06
	% APL reduction	44.2497	43.8473	44.6767
	Reactive Power loss (kVAR)	18.151	73.142	189.73
	% RPL reduction	36.8946	36.4524	37.4237
	Minimum voltage (pu)	0.9751	0.9502	0.92
	Switches opened	7, 14, 9, 32, 37	7, 14, 9, 32, 37	7, 14, 9, 32, 37
	Bus number	30	30	30
	UPQC (MVAR)	0.390	0.750	1.16

UPQC rating is dependent on the network's load. Additionally, UPQC allocation has been found to be significant in reducing losses and improving voltage profiles.

6.2.2. Case 3 (with UPQC allocation along with DNR):

With optimal opening the switches {7, 14, 9, 32, 37} for DNR operation along with optimal allocation of UPQC with size of 0.39 MVAR, 0.75 MVAR and 1.16 MVAR corresponding to different load levels (i.e 50%, 100% and 160%), at bus no. 30 results in total active power losses (APL) reduced by 44.25%, 43.847% and 44.676% respectively with respect to case 1. Similarly total reactive power losses (RPL) reduced by 36.894%, 36.452% and 37.423% respectively with respect to case 1. Besides, minimum voltage magnitude has been improved from 0.96 pu, 0.9198 pu and 0.8694 pu to 0.9751 pu, 0.9502 pu and 0.92 pu respectively. Allocation of UPQC together with DNR operation has greatly decreased the size of UPQC and produces better outcomes.

6.3 Cost analysis for different cases

For analysis purpose, the cost parameters such as annual UPQC investment cost, cost of energy losses and switching cost have been taken from [11], [24, 25]. Table 6 depicts the total annual cost analysis for three different cases. From Table 6, it can be observed that optimal allocation of UPQC yields up to $ 16745.2 total cost savings, which results 10.97 % of total cost savings as seen in case 2 with respect to case 1. With optimal allocation of UPQC along with DNR operation yields upto $ 51515.7 total cost savings, which results in of total cost savings as seen in case 3 with respect to case 1.

Table 6. Summary of the results in IEEE 33 bus distribution system over a year

Cases	Case 1	Case 2	Case 3
Annual Energy Loss Cost $ (I)	152646	119380	85083
Annual UPQC Investment cost $ (II)	-----	16521.3	14524.1
Annual Switching cost $ (III)	----	----	1624
Total cost $ (I+II+II)	152646	135901.3	101231.1
Total cost savings ($)	------	16745.2	51415.7
% Total cost savings	------	10.97	33.68

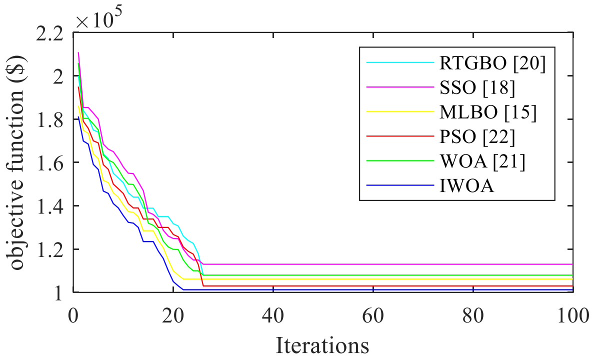

Figure. 4 Convergence pattern of different metaheuristic algorithms

Table 7. Comparative analysis of different algorithms

Algorithm	Best value ($)	Average value ($)	Standard deviation
RTGBO [20]	108001	118068	24337
SSO [18]	113000	122247	24561
MLBO [15]	106231	113580	21243
PSO [22]	103001	113068	20337
WOA [21]	108134	117247	20561
Proposed IWOA	101231	108580	17243

6.4 Performance of proposed IWOA and conventional algorithms

The effectiveness of PSO, WOA, and IWOA has been assessed on case 3 (i.e., UPQC allocation along with DNR operation) due to its complexity. The convergence trend that may be noticed when examining RTGBO, SSO, MLBO, PSO, WOA, and IWOA metaheuristic algorithms is shown in Fig. 4. Table 7 displays the best, average and standard deviation values of aforementioned metaheuristic algorithms. Proposed IWOA approaches its minimum value, which is converged at $ 101231, whereas RTGBO, SSO, MLBO, PSO, and WOA are converged at $108001, $ 113000, $ 106231, $ 103001 and $ 108134, respectively. It is obvious that the IWOA is superior than the reported metaheuristic algorithms. It is feasible to say that adjusting the diversification-intensification balance while keeping track of past bests allows the IWOA algorithm to provide outcomes that are closer to ideal than those produced by the other reported metaheuristic algorithms.

6 Conclusion

In this article, performance analysis of the distribution network with optimal placement of unified power quality conditioner (UPQC) with distribution network reconfiguration (DNR) has been studied. For optimal solution, an improved whale optimization algorithm (IWOA) has been employed. Besides, impact of voltage dependent load models has been studied. The results reveal that size of the UPQC rating depends upon the load of the network. Hence consideration voltage sensitive loads play a significant role in allocation of UPQC. Besides, with DNR operation along with UPQC allocation, the compensated reactive power from UPQC device has been significantly reduced as well as yields superior results. In addition, proposed IWOA generated better outcomes than other metaheuristic techniques. Therefore, proposed methodology can be recommended to distribution system operator for most reliable in terms of reduction of active and reactive power loss as well as voltage profile improvement simultaneously.

Conflicts of Interest

The authors declare no conflict of interest.

Author Contributions

Conceptualization, Priyanka; methodology, Priyanka; software, Priyanka; validation, Priyanka; formal analysis, Priyanka; investigation, Priyanka; resources, Raghuram; data curation, Raghuram; writing—original draft preparation, Priyanka; writing—review and editing, Raghuram; visualization, Raghuram; supervision, Raghuram.

Nomenclature

m,n	Index of buses
nbr,nb	Number of branches, buses
Nsw	Number of switching
Ncb	Number of capacitor banks
R_{mn}	Branch resistance
APL_{ll}	Active power losses at Load level (ll)
Z_i^p, I_i^p, P_i^p	ZIP coefficients of active power
Z_i^q, I_i^q, P_i^q	ZIP coefficients of reactive power
V_{min}, V_{max}	Minimum and maximum voltage
$P_{L,m}$, $Q_{L,m}$	Active and reactive power load at m^{th} bus
$UPQC_{ll}$	Rated capacity of UPQC at load level (ll)
Q_{UPQC}	Rated capacity of UPQC
Q_L^{total}	Total reactive power load of the system

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