Optimal dual design based on capacitor placement and reconfiguration techniques for loss reduction and voltage enhancement

H F Kadom¹, A N Hussain² and W K S Al-Jubori³

¹, ²Department of Electrical Engineering, Electrical Engineering Technical College, Middle Technical University, Baghdad, Iraq.
³Department of Electrical Engineering, AL-Furat AL-Awsat Technical University, Babil, Iraq.

Abstract. Distribution System Reconfiguration (DSR) and Optimal Capacitor Placement (OCP) are the most economical and beneficial techniques that have been used in the Radial Distribution Systems (RDSs) to increase the reduction of losses and to perform a better voltage improvement. The DSR technique is a search process to find the shortest path length between the substation and the loads to achieve a maximum reduction in real losses. The OCP technique is used to compensate the reactive power that is required for the inductive loads, which reduces the active and reactive losses and enhances the voltage for the system buses. The approach of combining these techniques provides more improvement than using them individually. In this paper, four cases are implemented that employs either a single or double approach to identify the design with the best performance. The single approach is either DSR or OCP technique as individual technique, while the double approach is either OCP technique for the reconfigured RDS or reconfiguration for the RDS after the application of OCP technique. The optimal selection of tie switches, size and location of capacitors in the individual and dual approaches are achieved by using Qualified Binary Particle Swarm Optimization (QBPSO) and Modified Grey Wolf Optimization (MGWO) algorithms. The four cases are tested for standard IEEE system 33-bus RDS under different loading conditions. The results show the superior performance of the optimal proposed approaches compared to the literature works. Furthermore, the optimal dual techniques have show more effectiveness for loss reduction and voltage enhancement over their individual techniques.

1. Introduction

The distribution systems are designed to be as a radial structure in order to guarantee lower fault currents and effective arrangement of protective systems. The radial constraint is achieved using the Normally Closed (NC) and Normally Opened (NO) switches that are used to reconfigure the Distribution System (DS) to enhance the overall performance. The Radial Distribution System (RDS) suffer from several problems such as higher real losses, bus voltage deviations, overloading and unbalanced loads and these problems can be solved using several techniques [1].

The techniques that are proposed for solving the aforementioned RDS problems are Distribution System Reconfiguration (DSR), Optimal Capacitor Placement (OCP), Distributed Generation (DG),
Voltage Regulator (VR) and Replacement of Conductors (RC) techniques [2, 3]. The proposed techniques such as DG and RC are expensive to be purchased and installed, while the gain saving do not recover these costs and make it used only for special requirements [4]. The most economical approaches are the DSR and OCP techniques. The DSR technique does not require any cost, while the investment cost of the capacitor in the OCP technique is recovered through the saving gain resulted from this technique.

DSR technique is a process of finding the shortest path from the substation feeder to the loads using the NO and NC switches. It is used with various objective functions such as real losses reduction, enhancements of system voltage and the reliability indices while keeping the required constraints for RDS. DSR technique is implemented by using different optimization algorithms such as; Evolutionary Algorithm (EA) [5], Binary Particle Swarm Optimization Gravity Search Algorithm (BPSOGSA) [6], Harmony Search Algorithm (HSA) [7], hybrid of PSO and Ant Colony Optimization algorithms (PSO-ACO) [8], Genetic Algorithm (GA) [9] and Selective PSO (SPSO) [10]. The drawback of these approaches is their dependent on the other techniques such as DG and PV to satisfy the RDS requirements. In addition, the voltage constraints are broken in order to attain the objective functions. These works did not guaranteed the economic benefit when using DSR technique as a multi objective functions that combine both the real losses reduction and the voltage enhancements.

The OCP technique is an optimization process that determines the optimal location, size, type and number of capacitors based on the considered objective functions. The OCP technique has been applied for different objective functions such as real loss reduction, increase the saving cost, power factor correction and voltage improvement etc. [11]. The location of the capacitors is identified based on different indices such as Loss Sensitivity index (LSI), Voltage Sensitivity (VSI), randomly based and normalized voltage ($V_n$) indices that provide the potential buses for reactive power compensation. Furthermore, the capacitor locations that are based on LSI and VSI are proved less than satisfactory and therefore the locations specified using these indices not always the appropriate locations [12]. The optimal size of the capacitors for the candidate locations are specified using the optimization algorithms and the type of capacitors used either fixed, switched or a combination of these types [13]. The number of capacitors is determined based on experience and literature works that consider the economic factors while achieving better improvements in the proposed objective functions.

The double approach has different kinds that either OCP technique for the reconfigured RDS (DSR-OCP) or a reconfiguration for the RDS after the application of OCP technique (OCP-DSR) [14-16]. The previous work suffer from several drawbacks such as the economic benefits not considered as an important goal in the objective functions and also the installation and operation cost of the capacitors are not specified with the total investment cost of the capacitors. In addition, the voltage and total reactive power compensation constraints have not confirmed and the purchase cost of the capacitors were considered as a fixed cost per kVAR unit and these resulting further costs are more than the typical costs.

In this paper, four cases are used as individual and double approaches. These cases are applied for standard 33-bus RDS under different loading conditions based on MGWO and QBPSO optimization algorithms. Therefore, these optimization algorithms are used for selecting the optimal configuration, location and size of the capacitors. A multi-objective function is used comprising, real loss minimization, increasing of saving cost and voltage enhancement of system buses. The Direct Backward Forward Sweep Method (DBFSM) is used to calculate the voltage, losses and other load flow calculations. Comparing the results with the available literature work has been carried out to demonstrate the superiority of the proposed techniques and algorithms and the RDS constraints are confirmed. Furthermore, the double techniques have provided better improvement over the individual techniques in terms of losses, saving and voltage profile. Finally, the typical purchase cost is considered for different sizes of capacitors to provide further reduction to the capacitor investment cost compared to the fixed cost approach.
2. Methodology
The proposed load flow method, the principles of DSR and OCP techniques, the proposed optimization algorithms and the proposed multi objective functions are presented in this section as follows:

2.1 Direct approach load flow method
The importance of load flow methods have been increased recently due to its ability to perform the calculations that are related to the power system such as current of the branches, voltage of the buses, real losses and the total cost. Different types of load flow methods were used for power systems such as, Newton Raphson (NR), Gauss Seidal (GS), Fast Decoupled (FD) and direct approach methods. The conventional methods did not achieve fast convergent for the distribution systems because of the radial nature and the high ratio of the resistance to reactance and the unbalanced nature of loads. These characteristics have enabled the direct approach that is called Direct Backward Forward Sweep (DBFS) method that provides superiority and stability over other methods. The steps of the DBFS load flow have been demonstrated in [17].

2.2 DSR Technique
It is a process performed by altering the status of NO and NC switches under different operating conditions. It is a combinatorial optimization technique that confirms the proposed objective functions by finding the best status of switches to provide the lower impedance path between the feeder and load centers. This optimization process is frequently limited by several constraints like the voltage drop limits, branch current limits and other operational constraints [6].

2.3 OCP Technique
It is a process of injecting the reactive power into the DS using shunt capacitors such that the reactive part of the branch current decreases and this compensation enhances the bus voltage and reduces the reactive and active power losses. This optimization problem considers the optimal selection of size, type, number and location for capacitors as decision variables to achieve the specified objective functions and constraints [11]. The type of capacitors either fixed, switched or a combination of both types while sizes and cost per size are available in [18]. In this paper, the optimization algorithms are used for selecting the optimal location of the capacitors and the number of capacitors is specified based on the economic saving.

2.4 Optimization algorithms
A modified and enhanced version of the conventional BPSO and GWO algorithms is used in this study to solve the proposed DSR and OCP techniques with four different cases. These modified algorithms are explained below and compared with other algorithms to prove their superiority.

2.4.1 MGWO algorithm. The Grey Wolf Optimization (GWO) algorithm is a nature-inspired meta-heuristic optimization algorithm that is first found by Mirjalili in 2014, which imitate the leading hierarchy and hunting process of grey wolves packs [19]. It has been employed in the economic dispatch problems for the power system operations successfully. The basic GWO algorithm suffers from the drawback of the unbalancing between the two searching components (exploration and exploitation) to get fast convergent for the optimal or near optimal solutions. This problem can be solved by using a modified form that is called Modified Grey Wolf Optimization (MGWO) algorithm and the mimic model of this algorithm can be divided into encircling phase, hunting phase and attacking phase. This algorithm can be represented using the following steps [20]:

1. Initialize each search agent by initializing the position \( (X_\alpha, X_\beta, X_\delta) \) for wolves \( \alpha, \beta \) and \( \delta \) respectively. In addition to the initial value of vector \( \vec{a} \) and the coefficient vectors \( \vec{A} \) and \( \vec{C} \). The number of grey wolves \( N_{GW} \) and maximum number of iterations \( iter_{max} \) for the proposed RDS under different loading conditions are given in Table 1.
Table 1. Optimal values of MGWO algorithm parameters.

| Parameter | Value                  |
|-----------|------------------------|
| $N_{GW}$  | 10 for constant load, 9 for light load, 10 for heavy load |
| $\text{iter}_{\text{max}}$ | 50                  |

2. Calculate the fitness function for each agent of the three dominant wolves alpha ($\alpha$), beta ($\beta$) and gamma ($\gamma$) and grade them for the specified cases.

3. Encircling phase: During this phase, the wolves encircle the prey prior to the hunting phase that can be explained using the following equations:

$$\vec{a} = 2 \times (1 - \frac{k^2}{(\text{iter}_{\text{max}})^2})$$  \hspace{1cm} (1)

$$\vec{A} = 2 \times \vec{a} \times \vec{rn} \vec{d}_1 - \vec{a}$$  \hspace{1cm} (2)

$$\vec{C} = 2 \times \vec{rn} \vec{d}_2$$  \hspace{1cm} (3)

$$\vec{D} = |\vec{C} \times \vec{X}_{\text{prey}}(k) - \vec{X}_{\text{wolf}}(k)|$$  \hspace{1cm} (4)

$$\vec{X}_{\text{wolf}}(k + 1) = \vec{X}_{\text{prey}}(k) - \vec{A} \times \vec{D}$$  \hspace{1cm} (5)

where, $\vec{a}$ is a vector that has a value decreases exponentially from 2 to 0 with the iterations instead of being linearly decreased as in the conventional GWO algorithm. $\vec{A}$ and $\vec{C}$ are the coefficients of the vectors, $\vec{X}_{\text{prey}}(k)$ is prey position for the $k$th iteration, $\vec{X}_{\text{wolf}}(k)$ is the wolf position for $k$th iteration, $\vec{rn} \vec{d}_1$ and $\vec{rn} \vec{d}_2$ are random numbers between 0 and 1, and $\vec{D}$ is the distance vector between the three dominant and follower wolves.

4. Hunting phase: During this phase, the three dominant wolves (i.e. $\alpha$, $\beta$, $\gamma$) represent the best solutions for the suggested fitness function. These three wolves represent the leader for the remaining wolves that called the agents of followers ($w$). The follower positions are updated to the corresponding positions of leaders by using the following equations:

$$\vec{D}_\alpha = |\vec{C}_1 \times \vec{X}_\alpha(k) - \vec{X}(k)|$$  \hspace{1cm} (6)

$$\vec{D}_\beta = |\vec{C}_2 \times \vec{X}_\beta(k) - \vec{X}(k)|$$  \hspace{1cm} (7)

$$\vec{D}_\gamma = |\vec{C}_3 \times \vec{X}_\gamma(k) - \vec{X}(k)|$$  \hspace{1cm} (8)

$$\vec{X}_1(k) = \vec{X}_\alpha(k) - \vec{a}_1 \times \vec{D}_\alpha$$  \hspace{1cm} (9)

$$\vec{X}_2(k) = \vec{X}_\beta(k) - \vec{a}_2 \times \vec{D}_\beta$$  \hspace{1cm} (10)

$$\vec{X}_3(k) = \vec{X}_\gamma(k) - \vec{a}_3 \times \vec{D}_\gamma$$  \hspace{1cm} (11)

$$\vec{X}_w(k + 1) = \frac{\vec{X}_1(k) + \vec{X}_2(k) + \vec{X}_3(k)}{3}$$  \hspace{1cm} (12)

where, $\vec{X}(k)$ and $\vec{X}_w$ are search agent vectors for locations of leader and followers, respectively.

5. Attacking phase: During this phase, the update are carried out for the ($\vec{a}$) value and the corresponding coefficient vectors $\vec{a}$ and $\vec{C}$ for ($k + 1$) iteration using equations (1-3), respectively, following that, a check for the value of vector $\vec{A}$ within the range limit between −1 and 1 is performed. The $\vec{A}$ value forces the wolves to attack the prey if this value is lower than 1.

6. Repeat steps (2-5) for a new iteration ($k + 1$) and continue until reaching $\text{iter}_{\text{max}}$.

7. End.
The flowchart of MGWO algorithm for the proposed four cases is shown in Figure 1.

![Flow chart of MGWO algorithm for the proposed techniques](image)

**Figure 1.** Flow chart of MGWO algorithm for the proposed techniques.

2.4.2 QBPSO algorithm. The Particle Swarm Optimization (PSO) is a meta-heuristic algorithm that is inspired by a collective intelligence for flocks of birds which is found by Kennedy and Eberhart in 1995. This algorithm has several drawbacks such as easy slip in local optimum solution and not robust for discrete optimization problems. These problems are solved using the Qualified Binary Particle Swarm Optimization (QBPSO) algorithm that is resulted from combining the Modified PSO (MPSO) and Enhanced Binary PSO (EBPSO) algorithms [21-22]. This algorithm used to limit the values of velocity and position for each particle between 0 and 1 using the following steps:

1. Generate initial population by defining the acceleration constants ($A_1$ and $A_2$), weighting factor limits ($W^{min}$ and $W^{max}$), the number of particles ($N_p$) and $iter_{max}$, as in Table 2. In addition, set the best position ($p^p_b$) and the global position ($p^p_g$) values of particle $p$ that represent the minimum losses solution and better bus voltage with more saving.

2. Evaluate the fitness of each particle in the searching space of dimension ($dim$) for the specified cases as follows:

   1. Update the inertia weight $W^k$ for $k$ iteration using:
   
   $$W^k = \frac{w^{max} - w^{min}}{iter_{max}} \times k$$
   
   2. Update the velocity ($V_{dim}^{p(k+1)}$) and position ($P_{dim}^{p(k+1)}$) for ($k + 1$) iteration based on previous iteration values for $V_{dim}^{p(k)}$, $P_{dim}^{p(k)}$, $p^p_b$ and $p^p_g$ as follows:
   
   $$V_{dim}^{p(k+1)} = W^k \times V_{dim}^{p(k)} + A_1 \times \text{rand}_1 \times (p^p_b - P_{dim}^{p(k)}) + A_2 \times \text{rand}_2 \times (p^p_g - P_{dim}^{p(k)})$$
   
   $$P_{dim}^{p(k+1)} = P_{dim}^{p(k)} + V_{dim}^{p(k+1)}$$

   where $\text{rand}_1$ and $\text{rand}_2$ are random numbers between 0 & 1.
3. Generate a new solutions for velocity and position based on the transfer function 
\( T. f(V_{dim}^{p(k+1)}) \) as follows [30]:
\[
T. f(V_{dim}^{p(k+1)}) = \frac{1}{1 + e^{-p_{dim}^{p(k+1)}}}
\]
\[
p_{dim}^{p(k+1)} = \begin{cases} 
1 & \text{if } \text{rnd} \geq T. f(V_{dim}^{p(k+1)}) \\
0 & \text{else}
\end{cases}
\]

4. Update the values of \( P_b^P \) and \( P_g^P \).
5. Increase the iteration number.
6. Repeat steps (2-5) until it reach \( \text{iter}_{max} \).
7. End.

Table 2. Optimal values of QBPSO algorithm parameters.

| Parameter | Value |
|-----------|-------|
| \( N^P \) | 25 for all load types |
| \( W_{max} \) | 0.9 |
| \( W_{min} \) | 0.4 |
| \( A_1 \) and \( A_2 \) | 2.0 |
| \( \text{iter}_{max} \) | 50 |

The flowchart of QBPSO algorithm for the proposed four cases is shown in Figure 2.

2.5 The Multi-objective functions
Three specified objective functions are used in this work and explained as follows:
1. Minimize the active power losses. This objective can be describe by the following equations:
\[
P_{lossbr} = I_{br}^2 \times R_{br} \text{ kW}
\]
\[ P_{loss} = \sum_{br=1}^{N_{br}} P_{loss_{br}} \text{ kW} \]  

(19)

\[ Obj. f.1 = \min(P_{loss}) \]  

(20)

where, \( N_{br}, P_{loss}, P_{loss_{br}} \text{ and } R_{br} \) represent the number of branches, the total power losses, the loss per branch, current and resistance of branch \( br \), respectively.

2. Improve the voltage profile. This objective can be achieved using the voltage violation constraint \( \lambda_{c}^j \) and corresponding penalty factor \( P_{v}^j \) for all the buses (\( N_{bus} \)) by the following equation,

\[ Obj. f.2 = \sum_{j=1}^{N_{bus}} \lambda_{c}^j \times P_{v}^j \]  

(21)

where \( \lambda_{c}^j \) is used to check the violation of bus voltage limits while the \( P_{v}^j \) value equals zero if voltage limits are achieved and a higher value if these limits violated (specified equals 1000).

3. Increase the saving cost (\( C_{saving} \)). The cost function contains the cost of active power losses, capacitor purchasing cost (\( C_{p} \)), capacitor installation and operation costs (\( C_{I_c}^j \) and \( C_{O_c}^j \)), respectively. The saving cost is obtained by minimizing the total cost that is caused from power loss costs and reactive power compensation costs under specific operating constraints. It is equal to the difference between the cost before the compensation \( C_{B} \) (i.e. base loss cost) and the cost after the compensation \( C_{com} \).[11] The cost after the compensation equals to the cost of active power losses after compensation plus total capacitor cost \( C_{T_c} \) for specified number of capacitors (\( N_{c} \)) as demonstrated in the following equations:

\[ C_{p} = \sum_{c=1}^{N_{c}} Q_{c}^j \times C_{c}^j \quad j \in N_{bus} \]  

(22)

\[ C_{T_c} = C_{p} + \sum_{c=1}^{N_{c}} (C_{I_c}^j + C_{O_c}^j) \]  

(23)

\[ C_{B} = C_{Energy} \times Time \times P_{lossB} \]  

(24)

\[ C_{Com} = (C_{Energy} \times Time \times P_{loss(Com)} + C_{T_c}) \]  

(25)

\[ Obj. f.3 = C_{saving} = C_{B} - C_{Com} \]  

(26)

where, \( Q_{c}^j, C_{c}^j, C_{Energy}, P_{lossB} \) and \( P_{loss(Com)} \) are a specified capacitor size, cost per capacitor size, cost of energy losses in kilo Watt hour (kWh), total real power losses before and after applying the techniques, respectively.

The cost coefficients and specified time are given in Table 3 while the specified sizes and corresponding purchasing costs for the selected capacitors are given in [23].

The percentage loss reduction (\% Red.) that is obtained by the proposed techniques and the optimization algorithms are calculated using the following equation:

\[ % \text{Red.} = \frac{P_{lossB} - P_{loss(Com)}}{P_{lossB}} \times 100\% \]  

(27)

| Table 3. The values of cost coefficients and specified time. |
|-------------------------------------------------------------|
| Parameter | Value |
|-----------|-------|
| \( C_{I_c} \) ($/Loc.) | 1600 |
| \( C_{O_c} \) ($/Loc./year) | 300 |
| \( C_{Energy} \) ($/kWh) | 0.06 |
| Time (h) | 8760 |

The final objective function is a combination of the above three objective functions using their weighting factors as follows:

\[ Obj. f.1_{final} = W_1 \times Obj. f.1 + W_2 \times Obj. f.2 + W_3 \times Obj. f.3 \]  

(28)

\[ W_1 + W_2 + W_3 = 1 \]  

(29)
where $W_1$, $W_2$, $W_3$ are the weighting factors of the active power losses, voltage profile and saving cost for the objective functions, respectively.

2.6 Operating constraints of the RDS

These constraints are classified into equality and inequality as follows:

2.6.1 Equality constraints

1. Radially constraint. This constraint is achieved using the bus incidence matrix $[M]$ that explained the system is radial and not isolate for any load if the matrix determinant not equals zero [22].

2. Power balance constraint. This constraint explain that the power supplied from main feeder ($P_{feeder}$) must supply the demand load power $P_{load}$ and power losses $P_{loss}$ [6]:

$$P_{feeder} = P_{load} + P_{loss}$$ (30)

2.6.2 Inequality constraints

1. Voltage constraint. The bus voltage value must be within the acceptable limit [24]:

$$|V_{j_{min}}| \leq |V_j| \leq |V_{j_{max}}|, \; j \in N_{bus}$$ (31)

where the standard minimum ($V_{j_{min}}$) and maximum ($V_{j_{max}}$) limits are 0.95 p. u. and 1.05 p. u. respectively.

2. Branch current. The branch current $I_{br}$ must not exceed its maximum limited value $I_{br_{max}}$ as [25]:

$$|I_{br}| \leq |I_{br_{max}}|, \; br \in N_{br}$$ (32)

3. Capacitor type, number and total size constraints. The switched capacitors are used and only one capacitor allowed per bus. In the study, the number of capacitors is specified 3 based on experience and economical factor. Also, the total reactive power compensation $Q_{ct}$ that installed to the system must be not exceed over the reactive load power ($Q_{load}$) [25]:

$$Q_{ct} \leq Q_{load}$$ (33)

3. Results and discussions

In order to validate the effectiveness and robustness of the proposed algorithms, it have been tested for a standard IEEE-33 bus RDS under different loading conditions and compared to the available literature works such as, Modified Flower Pollination (MFP) [24], Locust Search (LS) [23], Grey Wolf Optimization (GWO) [26], Analytical [25] and Improved Binary Particle Swarm Optimization (IBPSO) algorithms [27]. Four cases are considered in this paper:

Case 1: DSR only.

Case 2: OCP only.

Case 3: DSR first after that OCP applied for the reconfigured RDS.

Case 4: OCP first after that DSR applied for the compensated RDS.

3.1 33-bus-RDS

The standard system 12.66 kV in the base case contains one feeder with three literals, 33 bus and 37 branches (32 NC switches, and 5 NO switches). This RDS Load is 3715 kW and 2300 kVAr at constant loading and the branch and bus data are given in [28]. The single line diagram of this system in base case is shown in Figure 3. The $P_{loss}$, $V_{min}$, $V_{max}$, open switches, % Red. and other parameters are listed in Tables 4-7 for the four cases respectively. Also, these tables contain the comparison with the available literature works for the same objective functions and constraints.
Figure 3. The single line scheme for IEEE 33-bus RDS.

Table 4. Results and comparisons of individual DSR case for 33-bus RDS at constant load.

| Parameter | Without DSR | Literature algorithms | Proposed algorithms |
|-----------|-------------|-----------------------|---------------------|
|           | MFP[24]     | IBPSO[27]             | QBPSO               | MGWO                |
| Open switches | [33-37]   | [7, 14, 9, 32,37]     | [14, 7, 11, 36, 28] | [11,14, 25,37,33]  |
| $P_{loss}$ (kW) | 202.6771 | 139.54              | 139.55             | 133.6786            | 129.9043            |
| $V_{min}$ (p. u.) | 0.9131  | 0.938               | 0.938              | 0.95                | 0.95                |
| $V_{max}$ (p. u.) | 1       | NK                  | 1                  | 1                   | 1                   |
| $C_{com}$ ($) | 106527   | 73342               | 73347              | 70261               | 68278               |
| $C_{saving}$ ($) | -       | 33185              | 33180              | 36266               | 38249               |
| % Red. | -         | 31.15               | 31.146             | 34.0436             | 35.9058             |
| Obj. No. | -         | 3* # $             | 2* #              | 3* # $             | 3* # $             |

where (NK): Not Known and (*, #, $): losses reduction, voltage improvement and saving cost increment, respectively.

Table 5. Results and comparisons of individual OCP case for 33-bus RDS at constant load.

| Parameter | Without OCP | Literature algorithms | Proposed algorithms |
|-----------|-------------|-----------------------|---------------------|
|           | LS [23]     | MFP [24]             | Analytical [25]     | GWO [26]            | IBPSO [27]         | QBPSO               | MGWO                |
| $P_{loss}$ (kW) | 202.6771 | 139.23              | 139.54             | 138.77              | 134.0725            | 134.2               | 124.492             | 121.976             |
| $V_{min}$ (p. u.) | 0.9131  | 0.9291             | 0.9302             | 0.9428              | 0.9400              | 0.9389              | 0.95                | 0.95                |
| $V_{max}$ (p. u.) | 1       | NK                  | 1                  | NK                  | 1                   | 1                   | 1                   | 1                   |
| $C_{com}$ ($) | 106527   | 79280               | 79496              | 78977               | 76552               | 84684               | 71580               | 70245               |
| $C_{saving}$ ($) | -       | 27247              | 27031              | 27550               | 29975               | 21843               | 34947               | 36282               |
| % Red. | -         | 31.304             | 31.136             | 31.5314             | 33.8492             | 33.7863             | 38.5761             | 39.8174             |
| Obj. No. | -         | 3* # $             | 2* #              | 3* # $             | 3* # $             | 3* # $             | 3* # $             | 3* # $             |

$Q_c$ (kVar)  

$Q_{CT}$ (kVar)  

Obj. No.  

9
Table 6. Results and comparisons for dual DSR-OCP case for 33-bus RDS at constant load.

| Parameter          | Without DSR-OCP | Literature algorithms | Proposed algorithms |
|--------------------|-----------------|-----------------------|---------------------|
| Open switches      | [33-37]         | [7, 14, 9, 32, 37]    | [14, 7, 11, 36, 28] |
| $P_{\text{loss}}$(kW) | 202.6771       | 94.26                 | 112.68              |
| $V_{\text{min}}$(p. u.) | 0.9131         | 0.9612                | 0.95801             |
| $V_{\text{max}}$(p. u.) | 1              | 1                     | 1                   |
| $C_{\text{Com}}$($\$) | 106527         | 60057                 | 65371               |
| $C_{\text{saving}}$(\$) | -              | 46470                 | 41156               |
| % Red.             | -               | 53.4925               | 44.4042             |
| $Q_c$(kVAR)        | 1200, 900, 1800, 1200, 300 | [750, 150, 900] | [150, 150, 150] |
| $Q_{CT}$(kVAR)     | 5400            | 1800                  | 450                 |
| Obj. No.           | 2* #           | 3** $                | 3** $              |

Table 7. Results and comparisons of dual OCP-DSR case for 33-bus RDS at constant load.

| Parameter          | Without OCP-DSR | Literature algorithms | Proposed algorithms |
|--------------------|-----------------|-----------------------|---------------------|
| Open switches      | [33-37]         | [7, 10, 34, 36, 37]   | [7, 36, 37, 14, 21] |
| $P_{\text{loss}}$(kW) | 202.6771       | 95.91                 | 99.5959             |
| $V_{\text{min}}$(p. u.) | 0.9131         | 0.9658                | 0.95077             |
| $V_{\text{max}}$(p. u.) | 1              | 1                     | 1                   |
| $C_{\text{Com}}$($\$) | 106527         | 64559                 | 58494               |
| $C_{\text{saving}}$(\$) | -              | 41968                 | 48033               |
| % Red.             | -               | 52.678                | 50.8598             |
| $Q_c$(kVAR)        | 900, 300, 300, 300, 300, 600, 600 | [600, 150, 1050] | [750, 450, 450] |
| $Q_{CT}$(kVAR)     | 3300            | 1800                  | 1650                |
| Obj. No.           | 2* #           | 3** $                | 3** $              |

Some of these literature works have two objective functions as identified in the tables with row of (Obj. No.). The marks *, # and $ denote the real losses reduction, voltage profile improvement and annual saving cost increment, respectively. It is observed from these tables the better results are obtained by using MGWO algorithm compared to the QBPSO and other proposed algorithms of recently published work.

The voltage profile of the base and four cases are shown in Figures 4-7 respectively while the graphs of real loss for these cases are shown in Figures 8-11 respectively at constant loading condition. These tables and figures demonstrate the significant enhancements in the voltage and losses that obtained from using the proposed algorithms and efficiency of these algorithms for solving the complex problems such as DSR and OCP techniques. The dual approach provides further improvements in losses reduction and bus voltage over their individual techniques. The comparison with the literature work demonstrates that the range limit of the voltage and the total compensation size have been broken in the previous work. These works have applied a larger numbers and sizes of capacitors to gain the lower losses than the proposed algorithms. This causes increasing total operation cost and decreasing the saving cost that is required for recovering the operation and installation costs of the capacitors.
Figure 4. Voltage for individual DSR of 33-bus RDS at constant load.

Figure 5. Voltage for individual OCP of 33-bus RDS at constant load.

Figure 6. Voltage for dual DSR-OCP of 33-bus RDS at constant load.

Figure 7. Voltage for dual OCP-DSR of 33-bus RDS at constant load.

Figure 8. Real losses for individual DSR of 33-bus RDS at constant load.

Figure 9. Real losses for individual OCP of 33-bus RDS at constant load.
These algorithms and techniques can be tested using variable load conditions such as light and heavy loading. For light load operating condition, the RDS Load is 2786.25 kW and 1725 kVAr that is obtained using a factor of 0.75 multiplied with constant power load therefore the total compensation size constraint is changed to 1725 kVAr. The results of applying the four cases are listed in Tables 8-11, respectively. Because of the literature works are not available for the same system, load type and objective functions, the comparison are made only among the proposed algorithms for both individual and dual techniques.

Table 8. Results and comparisons of individual DSR case for 33-bus RDS at light load.

| Parameter | Without DSR | Proposed algorithms | QBPSO | MGWO |
|-----------|-------------|---------------------|-------|-------|
| Open switches | [33-37] | [37, 14, 7, 10, 36] | [11, 14, 37, 7, 36] | |
| $P_{loss}$ (kW) | 109.7536 | 103.2044 | 100.9352 | |
| $V_{min}$ (p. u.) | 0.93614 | 0.95 | 0.95 | |
| $V_{max}$ (p. u.) | 1 | 1 | 1 | |
| $C_{com}$ ($) | 57687 | 54244 | 53052 | |
| $C_{saving}$ ($) | - | 3443 | 4635 | |
| % Red. | - | 5.9684 | 8.0347 | |

Table 9. Results and comparisons of individual OCP case for 33-bus RDS at light load.

| Parameter | Without OCP | Proposed algorithms | QBPSO | MGWO |
|-----------|-------------|---------------------|-------|-------|
| $P_{loss}$ (kW) | 109.7536 | 74.5576 | 72.7054 | |
| $V_{min}$ (p. u.) | 0.93614 | 0.95066 | 0.95364 | |
| $V_{max}$ (p. u.) | 1 | 1 | 1 | |
| $C_{com}$ ($) | 57687 | 45199 | 44331 | |
| $C_{saving}$ ($) | - | 12488 | 13356 | |
| % Red. | - | 32.0682 | 33.7558 | |
| $Q_c$ (kVAr) | - | [600, 150, 300] | [300, 300, 750] | |
| $Loc.$ | - | [30, 33, 11] | [13, 25, 30] | |
| $Q_{CTR}$ (kVAr) | - | 1050 | 1350 | |

Figure 10. Real losses for dual DSR-OCP of 33-bus RDS at constant load.

Figure 11. Real losses for dual OCP-DSR of 33-bus RDS at constant load.
Table 10. Results and comparisons for dual DSR-OCP case for 33-bus RDS at light load.

| Parameter          | Without DSR-OCP | Proposed algorithms |
|--------------------|-----------------|---------------------|
|                    |                 | QBPSO               |
|                    |                 | MGWO                |
| Open switches      | [33-37]         | [37, 14, 7, 10, 36]| [11, 14, 37, 7, 36] |
| $P_{loss}$ (kW)    | 109.7536        | 67.5862             | 65.8956             |
| $V_{min}$ (p. u.)  | 0.93614         | 0.95693             | 0.95924             |
| $V_{max}$ (p. u.)  | 1               | 1                   | 1                   |
| $C_{Com}$ ($)      | 57687           | 41505               | 40677               |
| $C_{saving}$ ($)   | -               | 16182               | 17010               |
| % Red.             | -               | 38.4201             | 39.9605             |
| $Q_c$ (kVAr)       | -               | [150, 600, 150]     | [300, 600, 300]     |
| Loc.               | -               | [22, 30, 3]         | [9, 30, 7]          |
| $Q_{CT}$ (kVAr)    | -               | 900                 | 1200                |

Table 11. Results and comparisons of dual OCP-DSR case for 33-bus RDS at light load.

| Parameter          | Without OCP-DSR | Proposed algorithms |
|--------------------|-----------------|---------------------|
|                    |                 | QBPSO               |
|                    |                 | MGWO                |
| Open switches      | [33-37]         | [6, 8, 14, 31, 37]  | [32, 12, 37, 7, 8]  |
| $P_{loss}$ (kW)    | 109.7536        | 60.8205             | 58.0959             |
| $V_{min}$ (p. u.)  | 0.93614         | 0.97625             | 0.96333             |
| $V_{max}$ (p. u.)  | 1               | 1                   | 1                   |
| $C_{Com}$ ($)      | 57687           | 37979               | 36652               |
| $C_{saving}$ ($)   | -               | 19708               | 21035               |
| % Red.             | -               | 44.5845             | 47.067              |
| $Q_c$ (kVAr)       | -               | [600, 150, 300]     | [300, 300, 750]     |
| Loc.               | -               | [30, 33, 11]        | [13, 25, 30]        |
| $Q_{CT}$ (kVAr)    | -               | 1050                | 1350                |

The graphs of real losses for four cases at light load are show in Figures 12-15 respectively while voltage profile of a base and four cases are shown in Figures 16-19 respectively.

Figure 12. Real losses for individual DSR of 33-bus RDS at light load.

Figure 13. Real losses for individual OCP of 33-bus RDS at light load.

Figure 14. Real losses for dual DSR-OCP of 33-bus RDS at light load.

Figure 15. Real losses for dual OCP-DSR of 33-bus RDS at light load.
Figure 16. Voltage for individual DSR of 33-bus RDS at light load.

Figure 17. Voltage for individual OCP of 33-bus RDS at light load.

For heavy loading condition, the RDS Load is 4643.75 kW and 2875 kVAR that is obtained using a factor of 1.25 and is multiplied with a constant power load, therefore the total compensation size constraint has been altered to 2875 kVAR and bus voltage constraints unchanged. The results are listed in Tables 12-15 for the application of the four aforementioned cases respectively. Because of the literature works are not available for the same system, load type and objective functions, the comparisons are made only among the proposed algorithms for both individual and dual techniques.

Table 12. Results and comparisons of individual DSR case for 33-bus RDS at heavy load.

| Parameter     | Without DSR | Proposed algorithms | QBPSO | MGWO |
|---------------|-------------|---------------------|-------|------|
| Open switches | [33-37]     | [14, 33, 37, 26, 9] | [36, 7, 28, 8, 12] |
| $P_{\text{loss}}$ (kW) | 329.855     | 183.0095            | 162.5394  |
| $V_{\text{min}}$ (p. u.) | 0.88885     | 0.95                | 0.95     |
| $V_{\text{max}}$ (p. u.) | 1           | 1                   | 1        |
| $C_{\text{Com}}$ ($) | 173372      | 96190               | 85431    |
| $C_{\text{saving}}$ ($) | -           | 77182               | 87941    |
| % Red. | -           | 44.5182             | 50.724   |

Table 13. Results and comparisons of individual OCP case for 33-bus RDS at heavy load.

| Parameter     | Without OCP | Proposed algorithms | QBPSO | MGWO |
|---------------|-------------|---------------------|-------|------|
| $P_{\text{loss}}$ (kW) | 329.855     | 170.9366            | 145.5483 |
| $V_{\text{min}}$ (p. u.) | 0.88885     | 0.95                | 0.95    |
| $V_{\text{max}}$ (p. u.) | 1           | 1                   | 1       |
| $C_{\text{Com}}$ ($) | 173372      | 96013               | 82614   |
| $C_{\text{saving}}$ ($) | -           | 77359               | 90758   |
| % Red. | -           | 48.2958             | 55.8751  |
| $Q_c$ (kVAR) | -           | [300, 300, 1200]    | [300, 300, 1200] |
| $L_{\text{oc}}$ | -           | [5, 23, 33]         | [3, 25, 5]  |
| $Q_{\text{CT}}$ (kVAR) | -           | 1950                | 1800    |
Table 14. Results and comparisons for dual DSR-OCP case for 33-bus RDS at heavy load.

| Parameter          | Without DSR-OCP | Proposed algorithms | QBPSO | MGWO |
|--------------------|-----------------|---------------------|-------|------|
|                    | [33-37]         | Open switches       | [14, 33, 37, 26, 9] |       |
| $P_{loss}$ (kW)    | 329.855         | 153.2842            | 131.4251 |     |
| $V_{min}$ (p. u.)  | 0.88885         | 0.95                | 0.95   |     |
| $V_{max}$ (p. u.)  | 1.00            | 1.00                | 1.00   |     |
| $C_{Com}$ ($)      | 173372          | 86599               | 75259  |     |
| $C_{saving}$ ($)   | 86773           | 98113               |        |     |
| % Red.             | -               | 53.5298             | 60.1567 |     |
| $Q_{e}$ (kVAr)     | [450, 300, 450] | [300, 150, 1500]    |       |     |
| $Loc.$             | [24, 14, 19]    | [6, 22, 3]          |       |     |
| $Q_{CT}$ (kVAr)    | 1200            | 1950                |        |     |

Table 15. Results and comparisons of dual OCP-DSR case for 33-bus RDS at heavy load.

| Parameter          | Without OCP-DSR | Proposed algorithms | QBPSO | MGWO |
|--------------------|-----------------|---------------------|-------|------|
|                    | [33-37]         | Open switches       | [31, 6, 13, 8, 28] |     |
| $P_{loss}$ (kW)    | 329.855         | 134.1586            | 107.0819 |     |
| $V_{min}$ (p. u.)  | 0.88885         | 0.95                | 0.95   |     |
| $V_{max}$ (p. u.)  | 1.00            | 1.00                | 1.00   |     |
| $C_{Com}$ ($)      | 173372          | 76682               | 62396  |     |
| $C_{saving}$ ($)   | 96690           | 110976              |        |     |
| % Red.             | -               | 59.328              | 67.5367 |     |
| $Q_{e}$ (kVAr)     | [1350, 450, 150] | [300, 300, 1200]    |       |     |
| $Loc.$             | [5, 23, 33]     | [3, 25, 5]          |       |     |
| $Q_{CT}$ (kVAr)    | 1950            | 1800                |        |     |

The graphs of real loss for four cases at heavy load are show in Figures 20-23 respectively while voltage profile of a base and four cases are shown in Figures 24-27 respectively.
It is quite clear from these tables the better results that obtained by using MGWO algorithm comparing to the QBPSO algorithm under both light and heavy loading conditions. The dual approach provides further improvements in losses reduction, bus voltage and annual saving cost over their individual techniques.

4. Conclusions
DSR and OCP are the most effective and affordable techniques that have superior performance in regarding to the RDS. Three principle objective functions (active losses, voltage deviation and annual saving cost) are required to be used together to achieve better performance in the RDS. These multi-objective functions are complex with nonlinear problem, and a limited work has accomplished due to the nature of these objectives that require efficient and stable algorithms. Therefore, two algorithms are applied QBPSO and MGWO algorithms and proved its superiority in the solving of the optimization problems. These algorithms are tested for the standard 33-bus RDS under different loading conditions, which have been used to find the optimal structure for the RDS, the optimal size and location of the capacitors. The results indicated the MGWO algorithm is the best economical tool in comparison with QBPSO algorithm and literature works, which achieved a minimum real losses and improved voltage profile. Both algorithms and the four cases have confirmed the required constraints of the RDS and as expected the double cases are better than the individual cases. The double cases achieve significant improvements in losses, voltages and saving.
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