

# Technical Indices Evaluation of Radial Distribution Network with Optimally Allocated DGs and Capacitors using Golden Jackal Optimization Algorithm

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## ABSTRACT

Electric power distribution system planning is a key area of concentration for developing more efficient, trustworthy, and environmentally friendly energy sources in the future. While distributed generations (DGs) are excellent at reducing system actual power losses, shunt capacitors can supplement their effectiveness when utilized in tandem. It is feasible to achieve even higher reductions in power losses and enhanced system efficiency by combining DGs with shunt capacitors. The Loss Sensitivity Factor (LSF) measures how sensitive real power loss in a network is to changes in power injection (active or reactive power) at a single bus. The methodology analyses LSFs to assess the ideal sites for placing DGs and capacitors in radial distribution networks (RDNs). The Golden Jackal Optimization (GJO) strategy is adopted to discover the ideal sizing and allocation of DGs and capacitors. The strategy is tested using two RDNs, one with 33 buses and the other with 69 buses. In addition, five major technical indices are explored and examined, used as an evaluation criterion to distinguish between the optimal and baseline performances. These are the voltage deviation index (VDI), power loss index (PLI), fast voltage stability index (FVSI), line stability factor (LQP), and novel line stability index (NLSI). Voltage deviation, power loss, and voltage stability analysis-related indices are among the technical characteristics addressed.

**Keywords:** Radial Distribution Network, Distributed Generations, Sensitivity Factor, Optimization Algorithm

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## 1. INTRODUCTION

### 1.1 Introduction and Motivation

Electric power distribution system is responsible for delivering electricity from the transmission system to end-users, and its efficient design and operation are critical for minimizing power losses, ensuring reliability, and meeting consumer demand. Effective planning of electric power distribution systems involves various factors, such as load forecasting, optimal sizing and sitting of distribution equipment, selection of appropriate distribution system configuration, and control strategies. Utilities can save capital expenditure, minimize distribution power losses, and improve the power quality delivered to customers by optimizing these aspects [1-2]. However, adopting alternative power generation sources, such as distributed generations (DGs), electric power distribution systems can become more efficient and sustainable. These alternative sources can help reduce transmission and distribution losses, improve system reliability, and provide a cleaner source of energy. As a result, research on distribution network planning incorporating DGs becoming more and more popular [3-5].

DGs refer to the use of technologies to generate power in small-scale that are situated close to the point of consumption. These technologies may be traditional and alternative sources of energy, such as solar photovoltaic, wind turbines, fuel cells and microturbines. DG can assist reduce transmission and radial distribution network (RDN) losses and increase system dependability by generating power closer to the point of use. Planning for DG installations requires careful consideration of technical, economic, and regulatory factors. The place of installation, size, and type of DG technologies needs to be carefully chosen to ensure that they are compatible with the existing distribution system and can be integrated seamlessly into the grid. The cost-effectiveness of DG projects must also be evaluated, taking into account factors such as capital costs, fuel costs, and the value of any renewable energy credits or incentives. To avoid power quality difficulties such as voltage swings, harmonic distortion, and flicker, DGs must be connected and integrated correctly into distribution networks [4-5]. Shunt capacitor banks, in addition to DGs, can be used

to boost the power factor, voltage profile, and feeder capacity in RDNs [6-7]. These capacitor banks need to be placed in an ideal location and of the right size to optimize the benefits. Features like the feeder capacity, line voltage drop, and network topology should all be considered while placing capacitors.

Furthermore, while DGs are excellent at reducing system actual power losses, shunt capacitors can supplement their effectiveness when utilized in tandem. It is feasible to achieve even higher drops in power losses and enhanced system efficiency by combining DGs with shunt capacitors. Overall, the proper place and size of shunt capacitors and DGs in RDNs necessitate careful consideration of technical and economic variables to provide the best system performance and efficiency.

### 1.2 Literature Survey on Capacitor Placement

Previously, different statistical, soft-computing, meta-heuristic, and mathematical techniques are employed to identify the suitable location of the shunt capacitor in RDN were presented and demonstrated. These techniques are based on mixed integer programming [7], neural network [8], fuzzy logic [9], Particle Swarm Optimization (PSO) algorithm [10], Teaching-learning Based Optimization (TLBO) algorithm [11], and Gravitational Search Algorithm (GSA) [12]. However, these techniques are silent on sensitivity analysis and computation of loss sensitivity factor (LSF). Thus, various methods have been proposed further, incorporating the LSFs. These are Plant Growth Simulation Algorithm (PGSA) [13], Flower Pollination Optimization Algorithm (FPOA) [14-16], Mine Blast Algorithm (MBA) [17], Grey Wolf Optimization (GWO) [18], Dragon Fly Optimization (DFO) [16], Moth-Flame Optimization (MFO) [18] and Golden Jackal Optimization (GJO) algorithm [19].

### 1.3 Literature Survey on DG Placement

An analytical method on examining the best installation site and capacity of DGs to reduce power losses is given in [20]. The recommended analytical method used exact loss computation to select the appropriate placement and DG size. The analytical method offered use of an LSF to select the optimum DG size and position [21]. The DG allocation and scaling through a power stability index is evaluated in [22]. In [23], a mathematical conventional method ((MINLP)) is addressed to forecast the suitable position of DGs in RDN, as well as the reduction in generating expenditures and power losses.

Apart from that numerous heuristic approaches have been introduced to choose the appropriate location and capacity of DG. These approaches are Genetic Algorithm (GA) [24]. [25], GA integrated PSO [26], Simulated Annealing (SA) [27], and BFO technique [28]. A range of heuristic methods have recently been created and effectively used to deal the RDN planning issues employing DGs to improve the efficacy of optimization tactics or work around other constraints [29-37]. These

methodologies include the Backtracking Search Optimization Algorithm (BSOA) [29], Intelligent Water Drop (IWD) Optimization [30], Stud Krill herd Optimization Algorithm (SKHA) [29], Cuckoo Search Optimization Algorithm (CSA) [32], Hybrid Grey Wolf Optimization (HGWO) [33] etc. DGs with a high penetration level, such as solar PV modules and wind power generating units, are incorporated into the RDN using GA-PSO algorithms [34]. In contrast to most studies that employ fixed loads and dispatchable sources, a technique is developed to reduce annual energy losses and RDN's voltage variations by taking into emphasis on seasonal uncertainty in generation and utilization. A voltage stability index based approach to solve this issue is addressed in [35]. The LSF considered different methods such as Whale Optimization Algorithm (WOA) [36], Golden Jackal Optimization (GJO) algorithms [37] have been proposed in this context.

### 1.4 Literature Survey on DG and Capacitor Placement Simultaneously

Further, various studies have considered both the objectives like DG and capacitor placement simultaneously [38]. Numerous heuristic techniques have been proposed in recent years to address this multi-objective problem, including Intersect Mutation Differential Evolution (IMDE) [39], Multi Objective Evolutionary Algorithm with Decomposition (MOEA/D) [40], Salp-swarm Algorithm (SSA) [41], hybrid WIPSO-GSA algorithm [42], enhanced GA (EGA) [43] and improved African vultures optimizer (IAVO) [44]. Ref. [45] shows techno-economic parameters for the reliable and secure operation of DGs integrating battery energy storage into RDN.

### 1.5 Contribution and Organization of the Paper

The main contributions of this study are summarized as follows:

- An effective optimization approach is devised to solve the issue of the appropriate installation sites and sizes of DGs and capacitors in an RDN in order to reduce power losses and voltage deviation. The proposed algorithm chooses the best capacitor sizes from among the commercially available options.
- In order to shorten search times, improve convergence properties, and ultimately improve overall solution quality, a novel optimization procedure is employed.
- The proposed technique has been implemented on two RDNs (33-bus and 69-bus), distribution networks, with varying numbers of DGs and capacitors.
- The simulation outcomes are contrasted with recently proposed techniques.
- The success of the proposed RDN technique is evaluated using a variety of technical criteria.

The problem formulation along with the power flow and sensitivity studies is described in Section II. Section III illustrates the details of GJO. Section IV and V present the implementation and results, respectively. Finally, Section VI concludes this article.

## 2. METHODOLOGY

### 2.1 Distribution System Load Flow (DSLFL)

The direct technique is used here to address power flow issues in distribution systems. [46]. The Distribution System Load Flow (DSLFL) matrix is built upon the bus-injection to branch-current (BIBC) and the branch-current to bus voltage (BCBV) matrices. This provides a precise and effective way for resolving power flow problems in RDNs.

The apparent power  $S_m$  flowing from the bus  $m$  is,

$$S_m = P_m + jQ_m. \quad (1)$$

At each bus  $m$ , the injected current is measured by,

$$I_m = \left( \frac{P_m + jQ_m}{V_m} \right)^*, \quad (2)$$

$V_m$  is the bus voltage.

The line currents are calculated as,

$$[J] = [BIBC][I] \quad (3)$$

where, the branch current matrix is denoted by the letters  $I$ . It is possible to express the bus voltages as,

$$[\Delta V] = [BCBV][BIBC][I] = [DSLFL][I] \quad (4)$$

The results for load flow are to be achieved iteratively at the  $k - th$  iteration.

$$[\Delta V^{k+1}] = [DSLFL][I^k] \quad (5)$$

$$[V^{k+1}] = [V^0] + [\Delta V^{k+1}] \quad (6)$$

The power flow is computed as follows,

$$P_n = P_m - P_{L,n} - R_{m,n} \left( \frac{P_m^2 + Q_m^2}{|V_m|^2} \right) \quad (7)$$

$$Q_n = Q_m - Q_{L,n} - X_{m,n} \left( \frac{P_m^2 + Q_m^2}{|V_m|^2} \right) \quad (8)$$

$P_{L,n} + jQ_{L,n}$  is the apparent electrical load power connected at bus  $n$ . In the line sections between buses  $m$  and  $n$ , the active and reactive power losses are calculated as,

$$P_{Loss}(m, n) = R_{m,n} \left( \frac{P_m^2 + Q_m^2}{|V_m|^2} \right), \quad (9)$$

$$= BIBC * P_{RLPM}$$

$$Q_{Loss}(m, n) = X_{m,n} \left( \frac{P_m^2 + Q_m^2}{|V_m|^2} \right), \quad (10)$$

$$= BIBC * Q_{REPM}$$

where,  $P_{RLPM}$  and  $Q_{REPM}$  represents the matrix of active and reactive power.

The overall network power losses can now be expressed as Equations (11) and (12),

$$P_{TLoss} = \sum_{l=1}^{NB-1} P_{Loss}(l) \quad (11)$$

$$Q_{TLoss} = \sum_{l=1}^{NB-1} Q_{Loss}(l), \quad (12)$$

where,  $NB$  is the total number of buses in the network. The total number of branches in the network is  $NB - 1$  and  $l = 1, 2, 3, \dots, NB - 1$  is the branch number.

### 2.2 Loss Sensitivity Factor (LSF)

The active and reactive power loss sensitivity factors at the branch between  $m$  and  $n$  buses can be computed as follows.

$$PLSF(m, n) = \frac{\partial P_{lineLoss}}{\partial P_{n,eff}} = \frac{2P_{n,eff}R_{m,n}}{|V_n|^2} \quad (13)$$

$$QLSF(m, n) = \frac{\partial P_{lineLoss}}{\partial Q_{n,eff}} = \frac{2Q_{n,eff}R_{m,n}}{|V_n|^2} \quad (14)$$

The PLSF and QLSF values are derived from load flows in the base case using Equations (13) and (14). The values are then arranged in descending order for each line segment of the test system. Using a vector bus position named  $vbpos[i]$ , the respective "end" buses of the lines are kept in decreasing order of the LSF values. The descending order of the vector's LSF will determine the order of buses to be considered for compensation. The voltage sensitivity factor ( $VSF[m]$ ) is used to derive the standardized voltage magnitudes at these buses of the  $vbpos[i]$  vector. The formula below has been used to calculate  $VSF[m]$ :

$$VSF[m] = \frac{|V_m|}{0.95} \quad (15)$$

The  $VSF[m]$  determines whether real/reactive power correction is required for the buses. A sequence list bus that has a healthy voltage ( $VSF[m] > 1.01$ ) is not compensated for and is discarded from priority lists. The nodes with the higher LSF values and VSF values less than 1.01 are considered when selecting candidate buses for DG and capacitor allocations. The nodes that exhibit the highest real power loss sensitivity to real power injection are those that may be used for the deployment of DG units, and the same nodes that exhibit the highest real power loss sensitivity to reactive power injection may be used for the installation of shunt capacitors. The candidate buses for installing capacitors and DGs based on LSFs are included as control variables in the optimization procedures. The search area for the optimization programme is compressed using the LSF, which cuts down on the amount of time needed to do the computations necessary to identify the best solution.

### 2.3 Problem Formulation

The DGs and capacitors placement/sizing challenge is presented with the following objective function,

$$\text{Minimize } F = \min P_{TLoss} \quad (16)$$

Subject to the constraints,

$$|V_m|^{\min} \leq |V_m| \leq |V_m|^{\max} \quad (17)$$

$$|I_l| \leq |I_l|^{\max} \quad (18)$$

The total actual power supplied by the DGs must be less than the entire real power demand plus the total real power loss in the lines.

$$\sum_{m=1}^{ndg} P_{DG,m} \leq \sum_{m=2}^{NB} P_{L(m)} + \sum_{m=1}^{NB-1} P_{Loss}(m, n) \quad (19)$$

Similarly, to avoid overcompensation, the total reactive power that the capacitors contribute must be less than the total reactive power required.

$$\sum_{m=1}^{nc} Q_{c,m} \leq \sum_{m=2}^{NB} Q_{L(m)} \quad (20)$$

$$Q_{c,m} \leq NQ_c, \quad N = 1, 2, \dots, nc \quad (21)$$

where,  $P_{DG,m}$  and  $Q_{c,m}$  are the DG capacity and capacitor size respectively at bus  $m$ .  $N$  is an integer number and  $Q_c$  is the smallest capacitor size taken into account for the installation. Consequently,  $NQ_c$  sizes are commercially available capacitors for installation in specific positions for each location [13].

## 2.4 Technical indices evaluation

In order to compare the results of the optimized and basic scenario, certain significant technical indicators are investigated and examined in this work [45]. Among the technical parameters taken into account are indicators linked to voltage variation, power loss, and voltage stability study. The competence of power systems to maintain a voltage range that is appropriate at every bus under every power system operating condition is commonly known as voltage stability. The incapacity to supply reactive power support at local load locations makes many power systems susceptible to voltage instability; this is a regular occurrence at the distribution end of many power networks in developing countries. The integration of DGs and capacitors at the distribution level requires a sound design technique and has the potential to enhance the voltage stability condition of the power system. Otherwise, the additional power injection from DGs/capacitors integration could have a severe effect on the power system's safety. Voltage stability issues are inherently dynamic, however static analysis using a few established voltage stability indices has been demonstrated to be sufficient for quickly and simply forecasting the voltage stability issue.

### (i) Total voltage deviation index (TVDI)

Each component of the distribution network is impacted by voltage variations, and the network enters the zone of power outages when there is a significant

deviation from the recommended range. The voltage variations from a fixed value, which is often expressed as 1 per unit, is estimated using the voltage deviation index (VDI). The expression for TVDI is given by;

$$TVDI = \sum_{m=1}^{NB} |V_{rated} - V_m| \quad (22)$$

$$TVDI_{p.u.} = \frac{TVDI_{Optimized}}{TVDI_{base}} \quad (23)$$

### (ii) Total power loss index (TPLI)

In power system research, less real power loss is required to prevent extra costs and give better power delivery. As a result, as illustrated below, the TPLI is defined.

$$TPLI = \sum_{l=1}^{NB-1} R_l \times I_l^2 \quad (24)$$

$$TPLI_{p.u.} = \frac{TPLI_{Optimized}}{TPLI_{base}} \quad (25)$$

### (iii) Total fast voltage stability index (TFVSI)

On a two-bus system, the fast voltage stability index (FVSI) was constructed from the voltage quadratic equation at the receiving bus. The index is given by;

$$FVSI = \frac{4z_{m,n}^2 Q_n}{V_m^2 x_{m,n}} \quad (26)$$

$$TFVSI_{p.u.} = \sum_{m=1}^{NB} \sum_{l=1}^{NB-1} \frac{FVSI_{Optimized}}{FVSI_{base}} \quad (27)$$

Any line in the system that displays FVSI close to unity is reaching the limit of its stability. Consequently, to maintain a stable system, FVSI must be kept below unity.

### (iv) Total line stability factor (TLQP)

Since it reveals the line voltage stability with relation to variations in reactive power, the line stability factor (LQP) is used for comparison. The formula for LQP is provided by;

$$LQP = \frac{(x_{m,n} P_m)^2}{0.25 V_m^4} + \frac{x_{m,n} Q_n}{0.25 V_m^2} \quad (28)$$

$$TLQP_{p.u.} = \sum_{m=1}^{NB} \sum_{l=1}^{NB-1} \frac{TLQP_{Optimized}}{TLQP_{base}} \quad (29)$$

LQP must be maintained less unity to achieve system stability.

### (v) Total novel line stability index (TNLSI)

Also, the line stability index is another index which indicates voltage stability. The following is an expression for the novel line stability index (NLSI),

$$NLSI = \frac{R_{m,n} P_n + X_{m,n} Q_n}{0.25 (V_m)^2} \quad (30)$$

$$TNLSI_{p.u.} = \sum_{m=1}^{NB} \sum_{l=1}^{NB-1} \frac{NLSI_{Optimized}}{NLSI_{base}} \quad (31)$$

The line is approaching its stability margin and may potentially violate the system if any branch in the system has a NLSI that is near to unity. Consequently, to maintain a stable system, NLSI must be kept below unity.

### 3. GOLDEN JACKEL OPTIMIZATION ALGORITHM

The community hunting habits of golden jackals serve as the inspiration for the Golden Jackal Optimization (GJO) programme. Probing the prey, encircling, and attacking are the three fundamental GJO stages. The steps of GJO algorithm are listed below [47].

#### 3.1 Search Area Design

The GJO is a population-specific technique in which the beginning points are distributed at random over the search region as:

$$X_{initial} = X_{minimum} + R_n (X_{maximum} - X_{minimum}) \quad (32)$$

where,  $X_{initial}$  refers the position of the initial golden jackals, " $R_n$ " is a random value from 0 to 1,  $X_{minimum}$  and  $X_{maximum}$  are the lower and upper bound of the solution.

The two fittest are selected as the jackal pair after this stage generates the initial *Prey* matrix, which is provided in Equation (33).

$$Prey = \begin{bmatrix} X_{1,1} & X_{1,2} & \dots & X_{1,q} \\ X_{2,1} & X_{2,2} & \dots & X_{2,q} \\ \vdots & \vdots & \ddots & \vdots \\ X_{p,1} & X_{p,2} & \dots & X_{p,q} \end{bmatrix} \quad (33)$$

There is " $p$ " no. of preys with " $q$ " variables. The placement of the prey indicates a certain resolution. An objective function is used in the optimization process to calculate each prey's fitness. Every prey's (*FPrey*) fitness is established by,

$$FPrey = \begin{bmatrix} f(X_{1,1}; X_{1,2}; \dots; X_{1,q}) \\ f(X_{2,1}; X_{2,2}; \dots; X_{2,q}) \\ \vdots \\ f(X_{p,1}; X_{p,2}; \dots; X_{p,q}) \end{bmatrix} \quad (34)$$

where, " $f$ " is the objective function. Male and female jackals are the two ultimate fittest.

#### 3.2 Exploration Phase

Jackals are skilled at seeing and tracking prey, however occasionally the prey escapes because they are not caught. Then, jackals stop and look for new prey later. The male jackal leads the hunt, with the female jackal following.

$$X_1(t) = X_M(t) - E_n \cdot |X_M(t) - r_s \cdot Prey(t)| \quad (35)$$

$$X_2(t) = X_{FM}(t) - E_n \cdot |X_{FM}(t) - r_s \cdot Prey(t)| \quad (36)$$

$Prey(t)$  is the location of the prey in  $t$  iterations, and  $X_M(t)$  and  $X_{FM}(t)$  signify the positions of jackal pair,  $X_1(t)$  and  $X_2(t)$  are new positions of the jackal pair, respectively.

$E_n$  is fleeing prey energy discovered as:

$$E_n = E_{n1} \cdot E_{n0} \quad (37)$$

$E_{n0}$  and  $E_{n1}$  stand for the prey's initial and falling energy, respectively.  $E_{n0}$  is varied from  $-1$  to  $1$  and found as:

$$E_{n0} = 2 \cdot r - 1 \quad (38)$$

where, " $r$ " is a random parameter in  $[0, 1]$ .  $E_{n1}$  is found as:

$$E_{n1} = c_1 \cdot (1 - (t/T)) \quad (39)$$

where,  $T$  expresses the maximum iteration,  $c_1$  is a constant equals to  $1.5$ ,  $E_{n1}$  gradually declined from  $1.5$  to  $0$  during the process of iterations.

The value of  $|X_M(t) - r_s \cdot Prey(t)|$  and  $|X_{FM}(t) - r_s \cdot Prey(t)|$  represents the distance that the golden jackal has to go to reach its prey in Equations (35) and (36) and is added or subtracted from the jackal's current location depending on  $E_n$ . " $r_s$ " is evaluated based on Levy Flight (*LF*) distribution.

$$r_s = 0.05 \cdot LF(x) \quad (40)$$

The *LF* expresses the levy flight's fitness function, which is calculated as follows:

$$LF(x) = 0.01 \times (\mu \times \sigma) / (|v^{(1/\beta)}|) \quad (41)$$

and,

$$\sigma = \left( \frac{\Gamma(1 + \beta) \times \sin(\pi\beta/2)}{\Gamma\left(\frac{1+\beta}{2}\right) \times \beta \times \left(2^{\frac{\beta-1}{2}}\right)} \right)$$

where,  $\mu$  and  $v$  are random value in  $[0, 1]$ ,  $\beta$  is a constant and its value is  $1.5$ . The places of the jackals are rearranged as:

$$X(t+1) = \frac{X_1(t) + X_2(t)}{2} \quad (42)$$

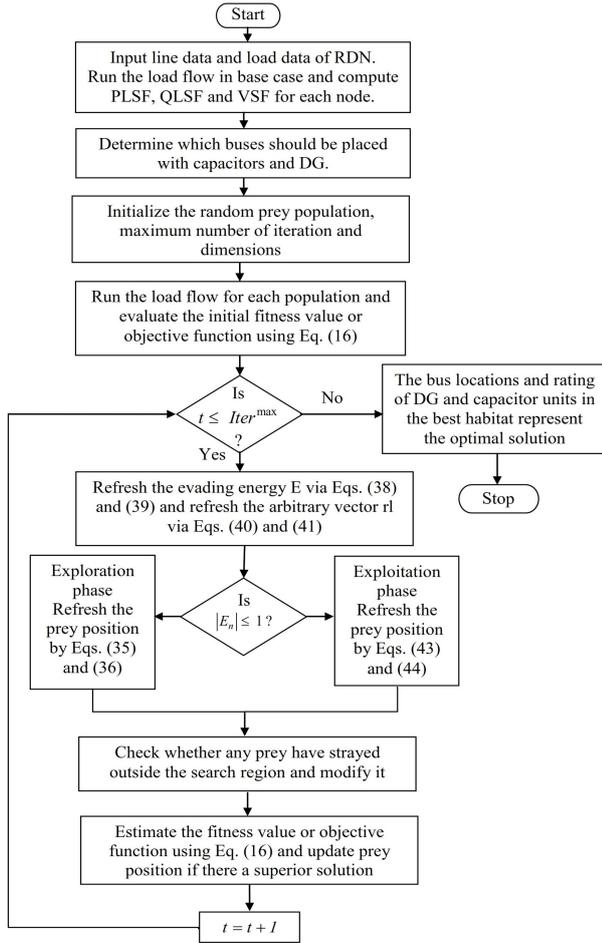
#### 3.3 Exploitation Phase

When jackals tackle their prey, the prey's energy levels drop, and the jackals then surround the prey they had earlier spotted. They then leap onto their target and devour it. This jackal's methodical pursuit is articulated as:

$$X_1(t) = X_M(t) - E_n \cdot |r_s \cdot X_M(t) - Prey(t)| \quad (43)$$

$$X_2(t) = X_{FM}(t) - E_n \cdot |r_s \cdot X_{FM}(t) - Prey(t)| \quad (44)$$

In Equations (43) and (44) " $r_s$ " serves as a random action generator to aid in exploration and local optima evasion during the exploitation phase.



**Fig. 1:** Flowchart of the optimal DG and capacitor placement methodology using GJO algorithm.

### 3.4 Transition from Exploration to Exploitation

E value is utilized in the GJO technique to go from exploration to exploitation. As the prey engages in evasive behavior, its energy level significantly decreases. When it decreases from 0 to -1, the prey actually becomes weaker, and when it increases from 0 to 1, the prey becomes stronger. If  $|E_n| > 1$ , jackal couple explores various areas for potential prey, and if  $|E_n| < 1$ , jackals attack the potential prey before engaging in exploitation.

## 4. IMPLEMENTATION OF GJO ALGORITHM FOR OPTIMAL DGS AND CAPACITORS PLACEMENT PROBLEM

The steps followed for application of the proposed methodology, which is shown in Fig. 1, is as follows:

Step 1: Set up input information such load power and line impedance.

Step 2: Run the DSLF at the base case of the system. Calculate the total power loss and each node voltage.

Step 3: Compute PLSF, QLSF and VSF for each node. Determine which buses are candidates for DG and capacitor placement.

Step 4: Create a sample of prey with random place-

ments and set the iteration number to  $t=1$ . The prey positions indicate the possible results, which are the locations and sizes of the capacitor and DG units.

Step 5: Check whether the requirements are met by running the DSLF on each particle, and if they are, determine the target function specified in Equation (16). Otherwise, it would not be possible to be in that prey position. It is necessary to compare the objective value for every prey position. Store the objective value and record the location of the matched prey if it is less than the previously obtained result.

Step 6: The jackal pair estimate the prey's location through iterations. Each contender revises their distance from the jackal pair estimate. The  $E_{n1}$  value has been changed from 1.5 to 0 to emphasize exploration and exploitation. A duet of hunting jackals flees from their victim when energy  $E_n > 1$  is present, and they assemble near the prey when energy  $E_n < 1$  is present.

Step 7: Once the fitness rating of each prey has been determined, select the top target to finish the loop.

Step 8: Each prey's position should be updated. If  $t < \max t$ ,  $set t = 1 + t$  and go to step 4. If not, proceed to step 9.

Step 9: Record the data that, in terms of the DG and capacitor units placements and sizes, most accurately captures the corresponding objective values.

## 5. RESULTS AND DISCUSSIONS

The test systems that are subjected to the recommended technique are the RDNs for 33 and 69 buses, which are shown in Figs. 2 and 6, respectively. The DSLF simulation work was finished using MATLAB R2021a 9.10 on a personal computer, and the outcomes are discussed. DG and capacitor sensitivity study has been done to determine the best placements. Sensitivity analysis is used to evaluate the PLSFs, QLSFs, and VSFs for all nodes in the nominal case load flow. The buses' suitability for DG allocation and reactive power correction was determined by the VSF. The GJO method is then used to find the best locations and sizes of DGs and/or capacitors. The search area for the optimization algorithm is compressed using the LSF, which cuts down on the amount of time needed to do the computations necessary to identify the best solution. The optimization objective with the combination of DGs and reactive power compensation devices is to reduce the RDN's overall real power loss. Discrete value capacitors are present in the commercially available capacitors [13]. Therefore, it should be thought of as an integer-programming issue to arrange capacitors in the best location possible. This study takes discrete capacitors into account. The GJO method has been used to choose the best capacitor sizes from the range of sizes that are commercially available. Additionally, 30 iterations of the algorithm have been run for each scenario. Other methods found in the literature are compared to the results.

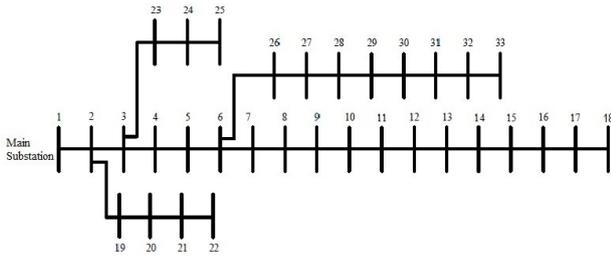


Fig. 2: Single line diagram of standard 33-bus RDN.

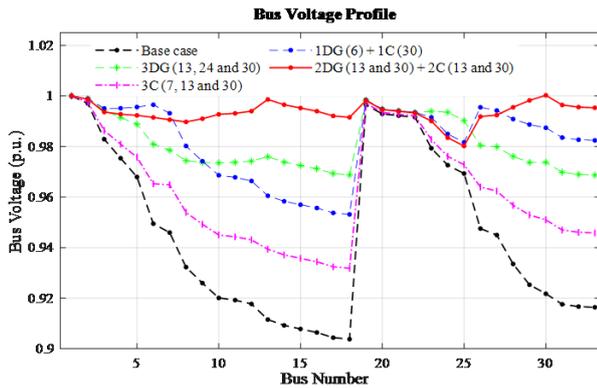


Fig. 3: Bus voltage profile of 33-bus RDN with different test cases.

### 5.1 A 33 Bus Test System

Figure 3 depicts a 12.66 kV, 33-bus RDN under consideration. 32 branches and 33 buses make up the network. The network information comes from [48]. At buses, a total actual and reactive power loads connected are of 3715 kW and 2300 kVAR, respectively. Real power loss in the basic case at rated load is calculated to be 210.9884 kW after DSLF [46]. Following 30 separate trials, the simulation findings are tabulated in Table 1 using various test cases. With the combination of DGs and capacitors, it has been seen that overall real power losses have greatly decreased and the voltage profile has improved. About 72.29% loss reduction is obtained with single DG and single capacitor placement, simultaneously. About 86.48% loss reduction is possible with two DGs and two capacitors placement, simultaneously. Voltage profile with different placement scenarios is shown in Fig.3. Fig.4 depicts the branch current profile of 33-bus RDN with different test cases. Reduction in branch current due to DGs integration and reactive power compensation delay the need for investment in conductor size up-gradation and supply system line extension.

The proposed method is tested with comparing the simulation results with other techniques published previously and listed in Table 2. The results show better performance as the proposed approach find optimal sizes of DGs and capacitors with minimum total real power loss in the RDN in the given scenarios. Figure 5 illustrates how rapidly the suggested GJO algorithm converges in comparison to PSO and GWO algorithms. The optimal parameters and the simulation results of these three

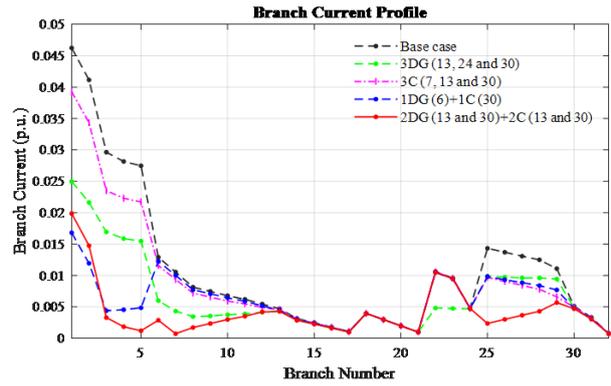


Fig. 4: Branch current profile of 33-bus RDN with various test cases.

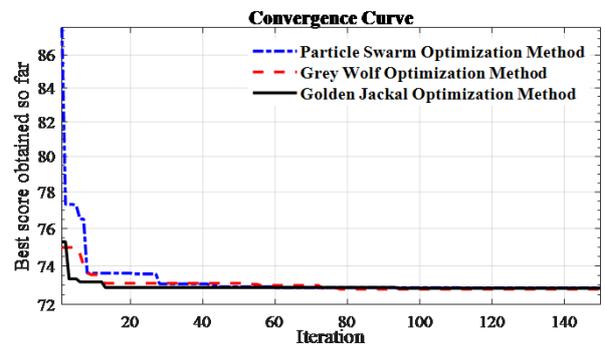


Fig. 5: Variation in the goal value for the 3DGs' size in the RDN with each iteration.

algorithms (PSO, GWO, and GJO) are depicted in Table 3. The results confirms the superior performance of GJO over PSO and GWO, as the total real power loss of the 33 bus RDN is minimum with given combination of 3DGs.

### 5.2 A 69 Bus Test System

As seen in Fig. 6 [9], the suggested methodology is extended to a fictitious 12.66 kV, 69-bus RDN to confirm the suitability of the executed approach. The 68 sections of the test system are subjected to a total connected actual and reactive power demand of 3801.39 kW and 2693.6 kVAR, respectively. The system's overall real power loss in the base case is calculated to be 224.9827 kW. The outcomes of the simulation are tabulated in Table 4 utilizing different test cases after 30 independent tests. With the combination of DGs and capacitors, it has been seen that overall real power losses have greatly decreased and the voltage profile has become better. About 89.71% loss reduction is accomplished with single DG and single capacitor placement, simultaneously. About 96.79% loss reduction is come out with two DGs and two capacitors placement, simultaneously. Voltage profile with different placement scenarios is appeared in Fig.7. The branch current profile of 69-bus RDN is depicted in Fig.8 with different test cases. Reduction in branch current due to DGs integration and reactive power compensation delay the need for investment in conductor size up-gradation

**Table 1:** Comparison of the simulation outcomes for the 33-bus RDN.

Test cases	DG Size in kW (#DG location)	Capacitor Size in kVAR (#Capacitor location)	$P_{T Loss}$ (kW)	% loss reduction	Vmin in p.u. (#Bus number)
TBase case	–	–	210.9884	–	0.9038 (#18)
Single DG	2590.2 (6)	–	111.0194	47.38	0.9423 (#18)
Two DGs	852.4 (13) 1157.9 (30)	–	87.1662	58.69	0.9685 (#33)
Three DGs	801.8 (13) 1091.2 (24) 1053.6 (30)	–	72.7859	65.5	0.9687 (#33)
Single Capacitor	–	1250 (30)	151.3676	28.26	0.9164 (#18)
Two Capacitors	–	400 (13) 1100 (30)	141.9211	32.74	0.9316 (#18)
Three Capacitors	–	450 (7) 300 (13) 900 (30)	139.8136	33.73	0.9318 (#18)
Single DG+Single Capacitor	2510 (6)	1250 (30)	58.4509	72.29	0.9532 (#18)
Two DGs+Two Capacitors	845 (13) 1138 (30)	400 (13) 1050 (30)	28.5098	86.48	0.9802 (#25)

**Table 2:** Comparison of the performance of different techniques with various combinations of DGs and Capacitors for the 33-bus RDN.

Algorithm (Particulars)	DG Size in kW (#DG location)	Capacitor Size in kVAR (#Capacitor location)	$P_{T Loss}$ (kW)	% loss reduction	Vmin in p.u. (#Bus number)
Base case	–	–	210.9884	–	0.9038 (#18)
GA (1DG+1C) [43]	1905.74 (7)	1248.4 (30)	62.9852	70.15	0.9471 (#18)
EGA (1DG+1C) [43]	2499.9 (6)	1253.2 (30)	58.4574	72.29	0.9532 (#18)
PSO (1DG+1C) [43]	2511 (6)	1457 (30)	59.7151	–	0.9551 (#18)
GJO (1DG+1C)	2510 (6)	1250 (30)	58.4509	72.29	0.9532 (#18)
GA (2DG+2C) [43]	930.83 (30) 1007.9 (12)	947.95 (30) 578.18 (26)	32.6462	84.52	0.9783 (#18)
Analytical (2DG+2C) [38]	447 (18) 559 (17)	400 (33) 500 (32)	96.989	54.03	0.9585 (#30)
IMDE (2DG+2C) [39]	1080 (10) 896.4 (31)	254.8 (16) 932.3 (30)	32.4363	84.63	0.9797 (#25)
EGA (2DG+2C)[43]	835.66 (13) 1161.7 (30)	438.57 (13) 1047.4 (30)	28.593	86.45	0.9804 (#25)
GJO (2DG+2C)	845 (13) 1138 (30)	400 (13) 1050 (30)	28.5098	86.48	0.9802 (#25)

\* The values are recalculated using the same proposed DG and capacitor ratings.

**Table 3:** Comparison of the performance of different algorithms with combinations of three DGs for the 33-bus RDN.

Algorithms	Optimum controlling parameters of the algorithms	DG Size in kW (#DG location)	$P_{T Loss}$ (kW)	Number of iterations for final results
PSO	Itermax, $T_{max} = 200$ , Number of particles, NP = 30 $r1$ and $r2$ are arbitrary values in (0,1) $\omega_{max} = 0.9$ is the maximum inertia weight, $\omega_{min} = 0.2$ is the minimum inertia weight $\omega = \omega_{max} - \frac{\omega_{max} - \omega_{min}}{T_{max}} t$ $T_{max}$ is the maximum iteration number and $t$ is current iteration number $C1 = C2 = 2$ and Fitness threshold $\epsilon = 0.001$	800 (13) 1095 (24) 1050 (30)	72.7867	60
GWO	SearchAgents_no = 30, Itermax = 200 $r1$ and $r2$ are arbitrary values in (0,1) $c1$ , $c2$ , and $c3$ are arbitrary values in (0,1)	805 (13) 1093 (24) 1052.5 (30)	72.7865	72
GJO	SearchAgents_no = 30, Itermax = 200 $R_a$ is an arbitrary values in (0,1), $r$ is an arbitrary values in (0,1) $c1 = 0.5$ , $\beta = 1.5$ , $\mu$ and $v$ are arbitrary values in (0,1)	801.8 (13) 1091.2 (24) 1053.6 (30)	72.7859	14

and supply system line extension. By contrasting the simulation results with those from other methodologies published previously and listed in Table 5, the superiority of the suggested method is examined and proven.

### 5.3 Technical Indices Evaluation and Analysis

Five technical indices such as VDI, PLI, FVSI, TLQP and TNLSI are determined for the test cases with different

**Table 4:** Comparison of the simulation outcomes for the 69-bus RDN.

Test cases	DG Size in kW (#DG location)	Capacitor Size in kVAR (#Capacitor location)	$P_{T Loss}$ (kW)	% loss reduction	Vmin in p.u. (#Bus number)
Base case	–	–	224.9539	–	0.9092 (#65)
Single DG	1872 (61)	–	83.1962	63.02	0.9683 (#27)
Two DGs	531 (17) 1781 (61)	–	71.6609	68.15	0.9789 (#65)
Three DGs	671 (11) 332 (17) 1697 (61)	–	69.5822	69.07	0.9788 (#65)
Single Capacitor	–	1350 (61)	152.0473	32.42	0.9313 (#65)
Two Capacitors	–	400 (16) 1250 (61)	146.5104	34.91	0.9308 (#65)
Three Capacitors	–	300 (16) 1200 (61) 300 (66)	145.4586	35.38	0.9318 (#65)
Single DG+Single Capacitor	1828 (61)	1300 (61)	23.1502	89.71	0.9725 (#27)
Two DGs+Two Capacitors	516.95 (17) 1735.45 (61)	350 (17) 1240 (61)	7.2	96.79	0.9943 (#50)

**Table 5:** Comparison of the performance of different techniques with various combinations of DGs and Capacitors for the 69-bus RDN.

Algorithm (Particulars)	DG Size in kW (#DG location)	Capacitor Size in kVAR (#Capacitor location)	$P_{T Loss}$ (kW)	% loss reduction	Vmin in p.u. (#Bus number)
Base case	–	–	224.9827	–	0.9092 (#65)
GA (1DG+1C) [43]	1694.51 (61)	1268.8 (61)	23.7917	89.42	0.9716 (#27)
EGA (1DG+1C) [43]	1838.71 (61)	1306.26 (61)	23.1547	89.71	0.9726 (#27)
PSO (1DG+1C) [43]	1566 (61)	1401.3 (61)	25.8781	88.49	0.9713 (#27)
MOEA/D (1DG+1C) [40]	1829 (61)	1301 (61)	23.1502	89.71	0.9725 (#27)
GJO (1DG+1C)	1828 (61)	1300 (61)	23.1502	89.71	0.9725 (#27)
GA (2DG+2C) [43]	532.37 (18) 1507.24 (61)	437.28 (15) 1116.21 (61)	9.5913	95.74	0.9877 (#65)
MOEA/D (2DG+2C) [40]	520 (17) 1731 (61)	353 (17) 1239 (61)	7.204	96.79	0.9942 (#69)
IMDE (2DG+2C) [39]	479 (24) 1738 (62)	1192 (61) 109 (63)	14.2086	93.68	0.9914 (#69)
EGA (2DG+2C) [43]	522.85 (18) 1734.1 (61)	355.08 (17) 1243.66 (61)	7.2052	96.79	0.9943 (#50)
GJO (2DG+2C)	516.95 (17) 1735.45 (61)	350 (17) 1240 (61)	7.2	96.79	0.9943 (#50)

\* The values are recalculated using the same proposed DG and capacitor ratings.

**Table 6:** Comparison of the simulation outcomes for the 33 bus RDN.

Test cases	TVDI Actual/pu	TPLI Actual/pu	FVSI Actual/pu	TLQP Actual/pu	TNLSI Actual/pu
Base case	1.8048/1	210.9884/1	0.5816/1	0.2017/1	0.6143/1
Single DG	0.9238/0.5118	111.0194/0.5262	0.5529/0.9506	0.1887/0.9355	0.4364/0.7104
Two DGs	0.6764/0.3748	87.1662/0.4131	0.5515/0.9482	0.1868/0.9261	0.2408/0.3919
Three DGs	0.6167/0.3417	72.7859/0.345	0.549/0.9439	0.1858/0.9211	0.21/0.3418
Single Capacitor	1.4214/0.7876	151.3676/0.7174	0.1989/0.3419	0.0768/0.3807	0.4797/0.7809
Two Capacitors	1.2599/0.6981	141.9211/0.6726	0.04/0.0688	0.0232/0.115	0.4225/0.6878
Three Capacitors	1.2501/0.6927	139.8136/0.6627	0.0839/0.1442	0.0350/	0.4338/0.7062
Single DG+Single Capacitor	0.5829/0.3227	58.4509/0.277	0.1906/0.3277	0.0724/0.3589	0.3185/0.5184
Two DGs+Two Capacitors	0.1916/0.1062	28.5098/0.1351	0.0557/0.0957	0.0265/0.1314	0.0852/0.1386

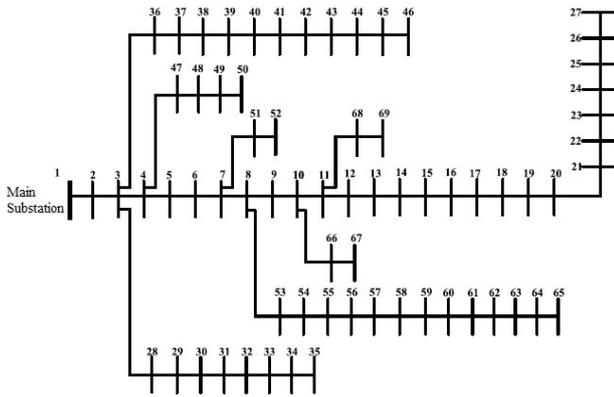
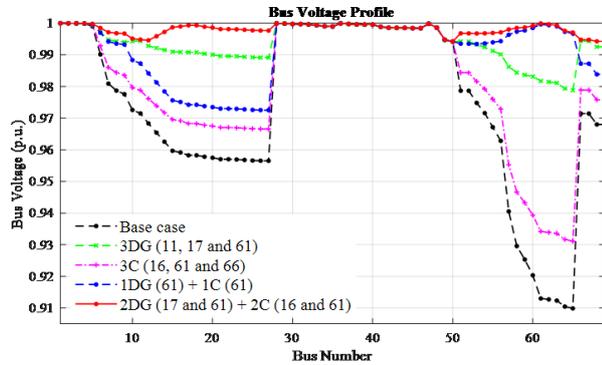
operating scenarios. The VDI referred to the degree of voltage variation from the preset voltage which is commonly specified as 1pu. Reduction of TVDI in the Table 6 and 7 with integration of DGs and capacitors indicate improvement of voltage profiles of the 33-bus RDN and 69-bus RDN. Similarly, the total power loss index (TPLI) reduction shows the reduction of RDNs

power loss.

For voltage stability analysis FVSI, TLQP and TNLSI are determined after simulation and listed in Tables 6 and 7 for the 33-bus RDN and the 69-bus RDN, respectively, with different test cases. The decreasing values of FVSI, TLQP and TNLSI with integration of DGs and capacitors indicate improvement of voltage stability margin. In

**Table 7:** Comparison of the simulation outcomes for the 69-bus RDN.

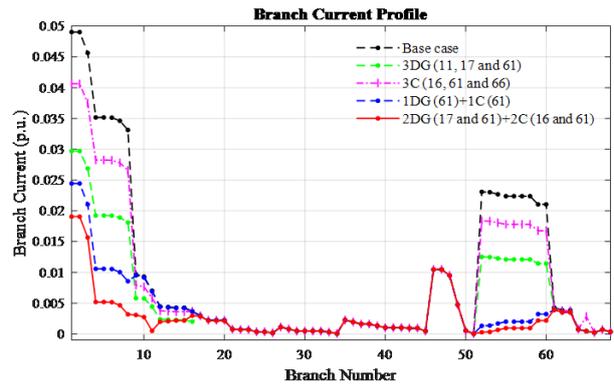
Test cases	TVDI Actual/pu	TPLI Actual/pu	FVSI Actual/pu	TLQP Actual/pu	TNLSI Actual/pu
Base case	1.8367/1	224.9827/1	0.7692/1	0.1206/1	0.4914/1
Single DG	0.8725/0.475	83.1962/0.3698	0.7299/0.9489	0.1138/0.9436	0.2003/0.4076
Two DGs	0.5001/0.2723	71.6609/0.3185	0.7253/0.9429	0.1132/0.9386	0.125/0.2543
Three DGs	0.4434/0.2414	69.5822/0.3093	0.7232/0.9402	0.113/0.9369	0.1358/0.2763
Single Capacitor	1.5013/0.8174	152.0473/0.6758	0.173/0.2249	0.0366/0.3035	0.3992/0.8123
Two Capacitors	1.402/0.7633	146.5104/0.6512	0.0147/0.0191	0.02/0.1658	0.3819/0.7771
Three Capacitors	1.3904/0.757	145.4586/0.6465	0.0369/.0479	0.0219/0.1816	0.3835/0.7804
Single DG+Single Capacitor	0.5869/0.3195	23.1502/0.1029	0.1918/0.2493	0.0389/0.3225	0.131/0.2665
Two DGs+Two Capacitors	0.1328/0.0723	7.2413/0.0322	0.0394/0.0512	0.0223/0.1849	0.0422/0.0858

**Fig. 6:** Single line diagram of 69-bus test system.**Fig. 7:** Bus voltage profile of 69-bus RDN with different test cases.

three capacitors case these indices increased, which indicates the case of over reactive power compensation. The minimum values of FVSI, TLQP and TNLSI are obtained in combined placement scenarios of DGs and capacitors, which indicate the best option to improve voltage stability margin.

## 6. CONCLUSIONS

This article computes the various sensitivity factors such as PLSF and QLSF from the base case DSLF. To compute these factors identification of the suitable buses for placement of DGs and capacitors are desired and accomplished by GJO algorithm. This approach to

**Fig. 8:** Branch current profile of 69-bus RDN with various test cases.

compute LSF leads to reduction of search space which results lower computational burden. The proposed method is tested for two RDNs having 33 and 69 buses, respectively. Results obtained using proposed logic are compared with alternative methods which demonstrates the suggested algorithm's dependability, yielding promising results and having a good solution quality. A range of technical criteria are employed to assess the efficacy of the suggested methodology for RDNs. The technical indices of the test cases with different operating scenarios demonstrate the improved voltage stability conditions and power loss reductions in RDNs with integration of DGs and capacitors.

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