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Multi-Objective Grey Wolf Optimization for Optimal Allocation of Distributed Generators in Distribution Networks

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Abstract*: The power loss in the radial distribution network is appreciable as compared to transmission network. To reduce the power loss in distribution network which is radial in nature, the solution methodology adopted in this paper is optimal placement of distributed generators (DG). The optimization incorporated is Multi-objective Grey Wolf Optimization (MOGWO). The optimization is accomplished for three different cases. In each case two objective functions are simultaneously optimized to obtain non-dominated solutions using Multi-objective Grey Wolf Optimization. Case (1): To minimize the real power loss and maximize the savings obtained due to DG installation. Case (2): To minimize real power loss and maximum voltage deviation in the network. Case (3): To minimize real power loss and rating of DG installed. MOGWO method maintains an archive which contains pareto-optimal solutions. The archive mimics the behaviour of grey wolves. MOGWO method is verified on radial distribution networks. The effectiveness of the optimization method is proven by comparing the results with other optimization methods available in the literature.

Keywords*: Distributed Generators, Multi-objective Grey Wolf Optimization, Real Power Loss, Savings, Voltage deviation.

I. INTRODUCTION

Now-a-days, the problems in each and every field are solved by Optimization methods. These are an important tool to obtain the best probable solutions for a given problem. Modern heuristic based optimization methods outperform traditional optimization methods. The traditional optimization methods are classified as direct method and gradient method. Modern optimization methods include evolutionary methods and swarm intelligence based methods. Evolutionary based optimization methods include genetic algorithm, differential evolutionary algorithm, and so on. Swarm intelligence based methods include Particle Swarm Optimization, Ant Lion Optimization, Moth flame Optimization and so on. Real life problems are complex. Hence optimization of single objective function is not sufficient. In order to solve real life problems, the multiple objective functions must be considered. Hence multiobjective optimization methods have evolved. Some of the multiobjective optimization based approaches are weighted sum approach and pareto-optimal approach. Weighted sum approach has its own disadvantage. In this approach, weights play a significant role to decide the optimal solution. Hence selection of weights must be done appropriately. The other approach is Pareto optimal approach. This approach is widely used approach in which there is a tradeoff between the objective functions to be optimized. Depending upon the priority of the objective functions, the solutions are selected. The problem of distributed generator placement has been tackled using various optimization methods for single and multiobjective functions. Distributed Generators are deployed to meet the power requirements of the customers connected to distribution system or customers having their own generation systems. DG technologies produce electricity from conventional as well as nonconventional sources of energy. These sources of energy include diesel and gas turbines, fuel cell technology, solar energy, biomass, geothermal, wind energy, etc. The incorporation of DGs in distribution systems have social, economic, environmental and technical benefits. Social benefits include the health benefits attained due to production of electricity from pollution less sources. DGs installed at the customer side by reducing the costs of transportation of electricity add to economic benefits. Also the reduction in the investment of transmission and distribution systems and their upgradation can be avoided due to onsite power generation. Since DGs employ renewable sources to generate electricity, the problem of carbon emissions is reduced. Technical benefits include enhancement in voltage, decrease in power losses, reliable power, frequency stabilization and so on. To reduce the power losses, appropriate location of DG and rating of DG has to be selected. DG location affects the required load demand to be provided, reducing the network losses, enhancing the network voltage profile. The rating of DG is important to reduce the losses. Too less value cannot meet the requisite load demand and too high value can lead to increased losses. Hence, it is essential to adopt apt location of DG and rating of DG for including in the power systems to meet the goal. In the literature, researchers have addressed the problem of distribution and systems using DGs.

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Wai Lip Theo et al. has given an elaborate review on DG planning in power systems [1]. A.M. El - Zonkoly has applied PSO for the positioning of several DGs in the distribution network [2]. F. S. Abu-Mouti et al. has explained the difficulties of DG placement using artificial bee colony method [3]. V. Ramalingaiah and M.

Damodar Reddy have adopted fuzzy to ascertain the best position of DG units and genetic algorithm for revealing the optimal sizes of DG units[4]. D.Q. Hung and N. Mithulananthan have proposed a method based on the improvement in analytical technique known as IA method in combination with the Loss Sensitivity Factor (LSF) to address the difficulties of DG placement [5]. B. Mohanty and S. Tripathy have solved DG placement problem using modified Teaching learning based optimization [6]. K. Nekooei et al. [7] has identified Harmony Search algorithm as the potential solution to DG placement problem in power system. P.S. Georgilakis et al. has presented a summary of the different DG models available and the techniques applied to DG placement problem [8]. D. Rama Prabha and T. Jayabarathi in has identified the location of DG by LSF and rating by invasive weed method [9]. S. Kansal et al. has solved DG placement problem using hybrid method [10]. S.Ganguly and D. Samajpati Sanjib has adopted genetic algorithm to implement DG in practical distribution system [11]. S. Kansal et al. has given an optimization method to obtain the profit of DG as well as capacitor placement in the distribution system [12].

From literature survey it is evident, the issues of DG placement has been dealt with the intention of either power loss minimization or maximization of DG savings or minimization of maximum nodal voltage deviation or DG rating minimization. All the objective functions contradict each other. If power loss minimization is taken into account, then the savings obtained due to DG installation decreases. The objective of power loss minimization and DG rating minimization contradict each other. Hence, to consider the effect of DG placement in distribution network on network power loss voltage deviation, profits obtained through DG placement and rating of DG, a pareto-optimal approach based optimization known as multiobjective Grey Wolf Optimization (GWO) is proposed. From the literature it is seen that the problem of DG placement has not been considered by multiobjective Grey Wolf Optimization. Hence in this paper multiobjective Grey Wolf Optimization is adopted to consider the technical and economic benefits of DG placement. The optimization is accomplished for three different cases. In each case two objective functions are simultaneously optimized to obtain non-dominated solutions using Multiobjective Grey Wolf Optimization.

Case (1): To minimize real power loss and maximize the savings obtained due to DG installation.

Case (2): To minimize real power loss and maximum voltage deviation.

Case (3): To minimize real power loss and rating of DG installed.

The aim of this work is (1) To decide the best location and rating of distributed generator. (2) To minimize the power loss, improve voltage profile and maximize the savings of distributed generator employment in the network and minimize the rating of DG installed. (3) To test the effectiveness of multiobjective Grey Wolf Optimization in standard distribution networks. MOGWO method is verified with 15-bus system. 33-bus and 69-bus radial networks are also taken into consideration and the comparison of results is given for all the bus systems.

The remaining paper is structured as given. Section 2 details the problem description, Section 3 elaborates the algorithm employed, Section 4 furnishes the details of result analysis and Section 5 gives conclusions of the work.

II. PROBLEM FORMULATION

The optimization is introduced to obtain the performance of DG placement in radial distribution systems. The objective functions considered are (1) Real power loss minimization (2) Minimization of maximum voltage deviation and (3) Maximization of the savings on DG placement in radial distribution networks. (4) Minimization of DG rating. These are mathematically stated as follows:

(1) Minimization of $P_{Total} = \sum_{i=1}^{nb} P_{loss}(i)$ (1)

$$P_{loss}(i) = (I_b(i))^2.R(i) \quad (2)$$

Where P_{Total} is the network real power loss.
$P_{loss}(i)$ indicates i^{th} branch real power loss.
nb represents the total branches in the network.
The branch real power loss relies on resistance and current in that particular branch.

The equality constraints related to the objective function are as follows:
The total power in the network must be balanced.

$$P_i = P_L + P_{loss} \quad (3)$$

$$Q_i = Q_L + Q_{loss} \quad (4)$$

Where P_i, P_L and P_{Loss} represents the real power input, demand and losses. Q_i, Q_L and Q_{Loss} represents the reactive power input, demand and losses.

(2) Minimization of maximum voltage deviation

$$V_{deviation} = \max(V_{substation} - V_L(m)) \quad (5)$$

$\forall$ m =1, 2 ….N

Here $V_{substation}$ is the voltage at the substation, V_m is the voltage at the m^{th} bus.

(3) Maximization of the savings of DG placement

Savings=Max(Benefits-Investment) (6)

Benefits=benefits due to real power demand reduction (BA) + benefits due to real power loss reduction (BL). (7)

Benefits of reduced real power demand are obtained due to the addition of DGs in the network. The present worth of these benefits obtained for a time span of 10 years are calculated as given in eq. (8).

$$BA = \sum_{m=1}^{nDG} K_{DG,m}.EP_G.\Delta T.\beta^t \quad (8)$$

$K_{DG,m}$: rating of DG in MW
EP_G :electricity purchasing price from the grid in rupees/kW.
ΔT: DG operating hours is a year

β^t: Present worth factor given as

$$\beta^t = \sum_{t=1}^{n}\left(\frac{1+Inf}{1+Int}\right)^t \quad (9)$$

Where Inf : inflation rate

Int : Interest rate

n : total number of years of planning

Benefits due to power loss reduction are obtained due to the reduction of real power losses in radial distribution network. The present worth of these benefits are calculated as given in eq. (10).

$$BL = \sum_{m}^{nDG} \Delta P_{Loss}.EP_G.\Delta T.\beta^t \quad (10)$$

Where ΔP_{Loss} : Real power loss reduction due to DG.

The investment cost of DG is the summation of purchase cost, operating and maintenance cost of DG.

Investment cost of DG = $C_1+C_2+C_3$ (11)

Where C_1 is the purchasing cost of DG in rupees

C_2 is the operating cost of DG in rupees.

C_3 is the maintenance cost of DG in rupees.

$$C_1 = \sum_{m=1}^{nDG} K_{DG,m}.IC_m \quad (12)$$

Where IC_m: installation cost of m^{th} DG

$$C_2 = \sum_{m=1}^{nDG} (K_{DG,m}.OC_m).\Delta T.\beta^t \quad (13)$$

where OC_m : operating cost of m^{th} DG

$$C_3 = \sum_{m=1}^{nDG} K_{DG,m}.IC_m.MC_{DG,m}.\beta^t \quad (14)$$

where $MC_{DG,m}$: maintenance cost of m^{th} DG

(4) Minimization of DG rating

$$0 \le \sum_{m=1}^{nbb} P_{DG} \le \sum_{m=1}^{nbb} P_L \quad (15)$$

Where nbb = number of DG units.

The inequality limits applicable are given as:

1. The bus voltage magnitude should be within ± 5% of the nominal voltage value. That is.

$$V_{\min} \le V(m) \le V_{\max} \quad (16)$$

2. The inequality constraint coupled with real power injected by DG is

$$P_{DG,m} \le P_L \quad (17)$$

3. DG location can be at any bus except the substation bus.

$$2 \le m \le nbb \quad (18)$$

nbb represents the maximum number of buses in the network. The losses are obtained by Forward Sweep and Backward Sweep Load Flow technique illustrated in [10].

Backward sweep: Let P_L and Q_L be the real and reactive power demand at bus m, voltage at the load bus as $\bar{V}_L$ The load current $\bar{I}_L$ at bus m is estimated as:

$$I_L(m) = \left(\frac{P_L(m)+jQ_L(m)}{V_L(m)}\right)^* \quad (19)$$

Here m=1, 2, 3 ….N

N indicates the number of buses

The branch current is calculated as

$$I_B(j) = I_L(recv(j)) + \sum loadcurrentsbeyondbranch(j) \quad (20)$$

Here j = 1, 2, 3 ….nb

nb symbolizes the total branches.

Forward sweep: The voltage at the network bus is obtaine as given in the equation (21)

$$V_L(recv(j)) = V_L(send(j)) - I_B(j).Z_B(j) \quad (21)$$

Here $Z_B(j)$ is the impedance of the j^{th} branch.

Assumptions:

(1) The network is assumed as balanced.

(2) In radial distribution network, DG is not connected at the substation.

(3) All the loads are presumed as constant power loads.

(4) All the branches are characterized as short branches and half line charging susceptance of is insignificant for the reason of low level voltages.

III. MULTI-OBJECTIVE GREY WOLF OPTIMIZATION

Grey Wolf optimization is a new Swarm Intelligence technique revealed by Mirjalili. The algorithm is detailed in [13] and [14]. MOGWO is described in [15].The encouragement of this algorithm is grey wolves behavior during hunting. The behavior of the grey wolves is characterized into two phases namely social hierarchy and hunting.

In traditional society, hierarchical administration was prevalent. Similar behavior is observed in the social hierarchy phase of GWO in which the strongest wolf monitors the other wolves. The strongest among the wolves are alpha, beta and delta wolves. Hunting behavior is characterized by locating and encircling the prey.

The main features of this optimization apart from social hierarchy and hunting behaviour are:

The inclusion of non-dominated solutions in external archive.

The enhancement of non-dominated solutions with the integration of grid.

The updation of solutions included in the archive for the selection of the leader.

The external archive and grid helps to store the non-dominated solutions. Leader selection strategy helps to decide alpha, beta and delta solutions. These solutions are taken as the leaders from the archive.

The mechanism to select non-dominated solutions in the archive is as follows: If the newly obtained solution dictates the solutions in the archive, then the archive is replaced with the new solution. If the new solutions and the archive solutions do not dictate each other, then the new solution enters the archive. In case the archive is fully occupied by the solutions, then the grid mechanism searches for the most crowded space. Some of the archive solutions in this crowded space are deleted to provide room for the new solutions.

Grey wolf optimization contributes exploitation and exploration. These are explained in [12].

An exploitation stage involves encircling and attacking the prey.

In this stage, the neighbourhood solutions are explored. Exploration stage involves search for prey in the search space. In this stage, the grey wolves investigate for the food in a global search space.

The exploitation phase is given by equations (22) and (23).

$$D = | C.X_p(t) - X(t) | \quad (22)$$

$$X(t+1) = X_p(t) - A.D \quad (23)$$

Here t indicates the present iteration, A and C are random numbers generated over the course of iterations defined by equations (24) and (25), X_p is the target solution i.e. prey, X is the solution.

$$C = 2r \quad (24)$$

$$A = 2ar - a \quad (25)$$

Here *a* decreases from 2 to 0 in each iteration and *r* lies in the range [0, 1]. The coefficient vectors *A* and *C* are adjusted to achieve the best search agent in different places.

A lies in the range [-2a 2a], *C* lies in the range [0 2].

The hunting phase of GWO involves selection of first three best solutions as alpha, beta and delta. In the iterations, all these solutions are stored and modified to adjust the position of omega. Mathematically, this stage is formulated as

$$\left.\begin{aligned} D_\alpha &= C_1.X_\alpha - X \\ D_\beta &= C_1.X_\beta - X \\ D_\delta &= C_1.X_\delta - X \end{aligned}\right\} \quad (26)$$

D_α, D_β and D_δ are the modified distance vectors between the alpha, beta, and delta positions to the other wolves.

X_α, X_β and X_δ are the alpha, beta and delta solutions. Here C_1, C_2 and C_3 are the coefficient vectors which helps to adjust distance vector, X_1, X_2 and X_3 are the solutions (omega wolves).

$$\begin{aligned} X_1 &= X_\alpha - A_1.D_\alpha \\ X_2 &= X_\beta - A_2.D_\beta \\ X_3 &= X_\delta - A_3.D_\delta \end{aligned} \quad (27)$$

$$X(t+1) = (X_1 + X_2 + X_3)/3 \quad (28)$$

X(t+1) is the new solution obtained by taking the average sum of the solutions denoted by X_1, X_2 and X_3 are obtained using alpha, beta and delta wolves.

IV. ALGORITHM INCORPORATING DG IN RADIAL DISTRIBUTION NETWORK USING MULTIOBJECTIVE GREY WOLF OPTIMIZATION

Step (1): Obtain the bus data and line data of the test system.

Step (2): Read the number of DG's to be installed and the maximum rating of DG.

Step (3): Generate the random population of grey wolves. Evaluate the objective function given by eq. (1), eq. (5) and eq. (6).

Step (4): Find the best three solutions from the archive

Step (5): Identify the non-dominated solutions. Store these solutions in the repository or archive.

Step (6): Revise the position of the search agent using eq. (28). Calculate the objective function. Find the non-dominated solutions. Revise the archive with the newly obtained non-dominated solutions.

Step (7): Check the archive size. If the archive size is full, run the grid to discard the archive solutions. Include the new solutions in the archive. If any of the recent solutions are exterior to the hypercube, revise the grid to add the newly obtained solutions. Retain the alpha and beta solutions to the archive.

Step (8): Repeat the steps from 5 to 6 until convergence criterion is fulfilled or maximum iterations have reached.

V. RESULTS AND DISCUSSIONS

The effect of type 1 DG placement on power loss minimization is evaluated with Grey Wolf Optimization method. The efficacy of the optimization method to decide the optimal location and rating of DG is tested using two distribution networks, 33-bus network and 69-bus network. 33-bus network is a 12.66 kV network with the real and reactive load of the network as 3715 kW and 2300 kVAr respectively. The data of the network is obtained from [16]. 69-bus network is a 12.66 kV real reactive load of the network as 3802.19 kW and 2694.6 kVAr respectively. The data of the network is obtained from [17]. The base case results of the load flow for the test systems without the integration of DG are given in [18]. Case (1) indicates the results of MOGWO to reduce the real power loss and increase the savings obtained due to DG installation in the test systems. Case (2) indicates minimization of real power loss and minimization of maximum voltage deviation in the network. Case (3) indicates minimization of real power loss and rating of DG installed.

Case (1) results of MOGWO to minimize real power loss and maximize the savings obtained due to DG installation in 15-bus, 33-bus and 69-bus are given in the tables 1, 2 and 3 respectively.

Table 1: Case (1): 15-bus network

No of DG	DG location	DG rating (MW)	Real power loss (kW)	Savings (rupees)
Base case	-		61.794	-
One DG	3	1.0329	37.8646	$\times 10^7$ 11.03
Two DG	4 6	0.7227 0.4589	33.3267	$\times 10^7$ 12.65

As observed in Table 1, when one DG is placed at bus 3 in the 15-bus radial distribution network, the real power loss is acquired as 37.87kW and the savings acquired are 11.03 crores and the rating of DG obtained is 1.03 MW. After placement of two DGs in the distribution network at buses 4 and 6, the real power loss is obtained as 33.33 kW and the savings obtained are 12.65 crores with DG rating of 1.182 kW.

As shown in Table 2, one DG placed at bus 6 in the 33-bus radial distribution network yields the power loss of 127.53 kW and savings of 39.45 crores with the DG rating of 3.70 MW. After the placement of two DGs in the distribution network at buses 6 and 24, the real power loss is obtained as 101.35 kW and the savings obtained are 39.99 crores. With the addition of three DGs at buses 24, 13 and 30, the power loss is reduced to 75.22 kW but the savings are also reduced to 38.55 crores in comparison to the savings obtained with two DGs placement.

Table 3: Case (1): 69-bus network

No of DG	DG Location	DG rating (MW)	Real power loss (kW)	Savings (rupees)
Base case	-		225.0044	-
One DG	61	2.2714	88.6314	27.05 $\times 10^7$
Two DG	61 9	1.726 1.953	81.7584	41.22 $\times 10^7$
Three DG	49 61 17	1.0344 1.7869 0.5383	70.3099	38.45 $\times 10^7$

From Table 3, when one DG is placed at bus 61 in the 69-bus radial distribution network, the real power loss is obtained as 88.6314 kW and the savings obtained are 27.05 crores and the rating of DG obtained is 2.27 MW. Two DGs placed at buses 61 and 9 gives the real power loss of 81.758 kW and the corresponding savings as 41.22 crores. If three DGs are placed in the distribution network, 70.310 kW real power loss is obtained and the savings are obtained as 38.45 crores. Case (2) results for the minimization of real power loss and the minimization of maximum voltage deviation are presented in the Tables 4, 5 and 6 for 15-bus, 33-bus and 69-bus distribution networks respectively.

Table 4: Case (2): 15-bus network

No of DG	DG Location	DG rating (MW)	Real power loss (kW)	Voltage deviation (p.u.)
Base case	-		61.7944	-
One DG	3	1.0316	37.8642	0.03258

From Table 4, for 15-bus network, One DG when placed at bus 3 the real power loss is acquired as 37.86kW and the voltage deviation is obtained as 0.0325 p.u. The corresponding rating of DG is 1.032 MW.

Table 5: Case (2): 33-bus network

No. of DG	Location of DG	DG rating (MW)	Real power loss (kW)	Voltage deviation (p.u.)
Base case	-		210.99	-
One DG	8	3.6755	203.3295	0.03226
Two DG	30 13	1.2045 0.8738	87.295	0.0296
Three DG	31 13 25	1.4591 1.316 0.924	102.3094	0.0095

As observed from Table 5, when one DG is placed at bus 8 in the 33-bus network, the real power loss is acquired as 203.3295 kW and the voltage deviation is obtained as 0.03226 p.u. The corresponding rating of DG is 3.68 MW. After placement of two DGs in the distribution network at buses 30 and 13, the real power loss is acquired as 87.29 kW and the voltage deviation is obtained as 0.029692 p.u With the addition of three DGs at buses 31, 13 and 25, the real power loss is increased to 102.31 kW and the corresponding voltage deviation obtained is 0.009575 p.u.

Table 6: Case (2): 69-bus network

No of DG	Location of DG	DG rating (MW)	Real power loss (kW)	Voltage deviation (p.u.)
Base case	-		225.004	-
One DG	61	1.9417	83.392	0.0313
Two DG	17 61	0.5546 1.959	72.8407	0.01485
Three DG	21 61 66	0.3989 2.035 0.681	74.4864	0.0092

As seen in Table 6, one DG placed at bus 61 in the 69-bus network yields the power loss of 83.392 kW and the voltage deviation as 0.0313 p.u and the DG rating as 1.942 MW. With two DGs placed at the buses 17 and 61, the real power loss is achieved as 72.841 kW and the voltage deviation is achieved as 0.0149 p.u. Addition of one more DG gives the real power loss of 74.486 kW and the voltage deviation as 0.009 p.u.

For 33-bus and 69-bus networks, with the addition of three DGs, the real power loss increases, but the voltage deviation reduces. Hence, if minimization of voltage deviation is the priority, then three DGs must be included in the distribution network, else two DGs are more than enough from the view point of loss minimization.

Case (3) results for minimization of real power loss and rating of DG installed are specified in the table 7, 8 and 9 for 15-bus, 33-bus and 69-bus systems respectively.

Table 7: Case (3): 15-bus network

No. of DG	DG Location	DG rating (MW)	Real power loss (kW)
Base case	-		61.794
One DG	4	0.504	42.723

Two DG	4 6	0.54 0.306	34.902

In Table 7, the results of DG assignment for 15-bus network are detailed. When one DG is employed at bus 4, the power loss acquired is 42.72 kW and the DG rating obtained is 0.5039 MW. After placement of two DGs in the distribution network at buses 4 and 6, the real power loss is acquired as 42.72 kW and the DG rating is obtained as 0.846 MW.

Table 8: Case (3): 33-bus network

No. of DG	Location of DG	DG rating (MW)	Real power loss (kW)
Base case	-	-	210.99
One DG	14	0.3342	168.5671
Two DG	31 15	0.3207 0.3978	132.5300
Three DG	25 31 14	0.5382 0.8777 0.6135	80.8636

From Table 8, when one DG is positioned at bus 14 in the 33-bus network, the power loss is acquired as 168.567 kW and the DG rating is obtained as 0.33 MW. After placement of two DGs in the distribution network at buses 31 and 15, the real power loss is acquired as 132.53 kW and the DG rating is obtained as 0.719 MW. With the addition of three DGs at buses 25, 31 and 14, the power loss is declined to 80.86 kW and DG rating is obtained as 2.03 MW.

Table 9: Case (3): 69-bus network

No. of DG	DG Location	DG rating (MW)	Real power loss (kW)
Base case	-		225.0044
One DG	61	0.2085	193.1844
Two DG	10 62	0.0117 0.1541	200.4912
Three DG	61 8 15	0.3518 0.0189 0.0573	169.903

From Table 9, when one DG is placed at bus 61 in the 69-bus radial distribution network, the real power loss is acquired as 193.1844kW and the rating of DG obtained is 0.209 MW. DGs placed at the buses 10 and 62, 200.491 kW is the real power loss obtained and DG rating obtained is 0.165 MW. DGs placed at the buses 61, 8 and 15, 169.903 kW is the real power loss obtained and DG rating obtained is 0.428 MW. For case (3), real power loss decreases at the cost of increased rating of DG placed in the network.

VI. CONCLUSION

From the results it is obvious that the cost of DG placement is reduced significantly and the decrease in real power loss is appreciable. In addition to this, there is significant improvement in voltage profile. The multiobjective Grey Wolf Optimization based on pareto-optimal approach is effective for obtaining the best solutions.

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