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Optimal Allocation of Capacitors in Radial Distribution Network Using the Grey Wolf Optimizer Algorithm

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Abstract

In the modern power system, the most important bond between the consumers and power utility is the Distribution System (DS). The capacitors are being utilized for reactive power compensation for minimizing power losses and thereby improving voltage profile in modern DSs. Subsequently, the Optimal Capacitor Placement (OCP) technique is playing a vital role in minimizing total annual cost in Radial Distribution Systems (RDSs). Thus, the process of optimal allocation of capacitors is of utmost importance in modern distribution systems. The key objective of the proposed research is to identify the optimal location along with the size of capacitors to minimize the total annual cost and thereby reducing Active Power (AP) losses while maintaining a better voltage profile into RDSs. While doing so, the proposed research adopts the Grey Wolf Optimizer (hereinafter referred to as GWO) Algorithm to identify the optimal location as well as the size of capacitors in RDSs. In order to analyse the efficacy of the proposed research approach, the IEEE-33 bus test system is being used. Furthermore, the obtained results are compared with other contemporary optimization techniques in the power system. In this way, the research outcomes based on the GWO algorithm are compared for highlighting the key advantages of the GWO algorithm in relation to reduced total cost and maximized net savings. It is worth mentioning that obtained results are compared based on three factors including total AP loss reduction, capacitor installation cost, and the value of total cost function. Finally, the research revealed that capacitors should be optimally placed in the appropriate size to attain the best cost function reduction in distribution networks. In this way, the obtained results are encouraging as they are better than other latest techniques available in the literature.

Index Terms—optimum capacitor placement, distribution network, Grey Wolf Optimizer, GWO, radial distribution system, RDS, distribution system

I. Introduction

The vertically integrated utility (after adopting restructuring and deregulation by the power industry) has been sub-divided into some individual entities. These entities are as follows (i) GENCOs (Generation Company) (ii) TRANSCOs (Transmission Company) (iii) DISCOs (Distribution Company) [1]. Due to deregulation, the efficiency of power consumption and power generation has improved. In the deregulated power system, GENCOs are the only entity who is responsible for generating the required amount of electricity. However, TRANSCOs and DISCOs are accountable for supplying generated electricity to

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consumers. Due to the high current and low voltage operating point, the real power losses in the RDS is higher than the transmission system losses [1]. The participation of the distribution network in real power losses is 70% of the whole power losses of the electricity system [2]. Therefore, modern transmission and DS operators always work to maximizing social welfare [3]. The real power losses significantly reduce consumer benefits [3]. Therefore, it is essential to effectively minimize the active power losses of the network for transmission and distribution system operators.

In [2], a sensitivity-based heuristic solution technique has been proposed to capacitor placing problem. For this, the node sensitivity factor has been used to locate a capacitor. A computer-based optimization technique for optimal placement (OP) of fixed as well as switched shunt capacitors on the distribution network to reduce the AP losses have been proposed by [4], [5]. In [6], the authors have proposed a novel optimization technique based on the power loss index for further identifying high potential buses to place the capacitors in radial distribution networks (RDNs). In [7], a novel approach has been presented by the researchers to release system transmission capacity for the reduction of the AP losses in the DS. In addition to that, the research has demonstrated the use of a normalized daily load curve to calculate the net annual energy loss reduction. In [8], a fuzzy multi-objective approach has been proposed based on a genetic algorithm (GA) in order to solve the OP of the capacitor problem. In doing so, the target objectives of maximizing net savings and minimizing total voltage deviations have been used. In [9], a reconfiguration of a redial distribution network, which is based on OCP, has been presented with considering several load stages. Apart from this, the research has been used the primal-dual interior-point method for solving the proposed optimization problem. In [10], the authors have demonstrated successful use of the plant growth simulation algorithm (PGSA) based on loss sensitivity factors to address the Optimal Capacitor Placement (OCP) problem in RDSs. It has been noted that the target objectives of improvement in the voltage profile and loss minimization have been used for getting effective results. In [11], has presented an exact method, which is based on pro-rata (PR) as well as quadratic loss allocation schemes, in order to solve the OCP problem. In [12], the author has proposed a novel optimization algorithm for further presenting the optimal size and location of the capacitors. Subsequently, in the research work [13], a mixed-integer linear programming model used to resolve the OCP problem of the fixed or switched capacitors and voltage regulators in a RDN. In addition to that, in the proposed work [14], the artificial bee colony (ABC) algorithm has been used in the modern distribution network to solve OCP problem. In this context, the authors have used the approach of maximizing voltage stability index, and net yearly savings as the target objective. Furthermore, in [15], the new method as a mixed-integer nonlinear programming methodology has been used by the authors for solving the optimal capacitor placement problem in RDN. While doing so, the research has minimized power losses along with the investment capacitor costs as target objectives.

Apart from this, the other optimization techniques which were used in the past literature are TLBO) algorithm [16], PSO [17], [18], [19], BFOA [20], PGSA [21], GSA [22], flower pollination algorithm [23], [24], WOA [25], [26], CSA [27]. The above-mentioned optimization techniques have been successfully utilised to optimize the capacitor placement in modern RDSs. In [28], the hybrid algorithm known as MSA has been proposed to minimize the AP losses in the DS while using optimal capacitor placement (OCP) technique. In [29], a novel optimization approach based on SSA with loss sensitivity indices has been presented for further determining the optimal locations and sizes of shunt capacitors (SCs) in RDNs) It has been found that the research has used VLSF as well as Reactive Power (RP) loss sensitivity factor to determine candidate buses for capacitor placement technique.

Based on the above literature survey, it can be said that optimal capacitor allocation is having wide scope in any radial distribution network from the researcher perspective. Thus, the proposed paper is going to identify and thereby determine the optimum position of the capacitors in the RDN with the help of the GWO [30] algorithm. In doing so, the total annual cost, which includes AP losses cost and capacitor placement associated cost, is considered as the target objective. It is worth noted that the proposed approach as GWO has been tested on the IEEE-33 bus RDN. In this way, the achieved research outcomes properly demonstrated the performance and effectiveness of the proposed method. Also, the comparative analysis of the results has been carried out.

II. PROBLEM FORMULATION

2.1 Power flow calculation

For further analysis of the DS, the primary need is to determine the power flow in the system efficiently. Thus, the single line diagram (SLD) of the simple RDN is presented as shown in figure 2.1. On the basis of the depicted figure 2.1, the mathematical representation of the power flow equations [25] for the distribution network are as follow:

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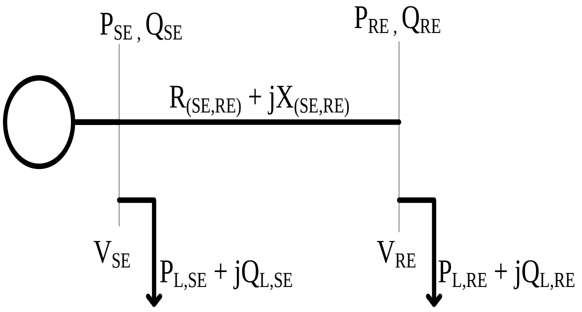

Figure 2.1. Simple radial distribution network

The power flows including AP and RP are calculated using (2.1) (2.2):

$$P_{RE} = P_{SE} - P_{L,RE} - R_{(SE,RE)} * \frac{(P_{SE}^2 + Q_{SE}^2)}{(|V_{SE}|)^2} \tag{2.1}$$

$$Q_{RE} = Q_{SE} - Q_{L,RE} - X_{(SE,RE)} * \frac{(P_{SE}^2 + Q_{SE}^2)}{(|V_{SE}|)^2} \tag{2.2}$$

Line voltages are calculated using (2.3).

$$(|V_{RE}|)^2 = (|V_{SE}|)^2 - 2(R_{(SE,RE)} * P_{SE} + X_{(SE,RE)} * Q_{SE}) + (R_{(SE,RE)}^2 + X_{(SE,RE)}^2) * \frac{(P_{SE}^2 + Q_{SE}^2)}{(|V_{SE}|)^2}$$

(2.3)

AP losses in the line can be calculated using (2.4).

$$P_{loss(SE,RE)}^{line} = R_{(SE,RE)} * \frac{(P_{SE}^2 + Q_{SE}^2)}{(|V_{SE}|)^2} \tag{2.4}$$

Total power losses in the power system have been calculated by summing up all line losses as presented in (2.5)

$$P_{Total\ loss} = \sum_{line=1}^{N_{line}} P_{loss(SE,RE)}^{line} \tag{2.5}$$

Where, P_{SE}, Q_{SE}, and V_{SE} are active power, reactive power and voltage magnitude of the sending end respectively. Similarly, P_{RE}, Q_{RE}, and V_{RE} are active power, reactive power, and voltage magnitude of the receiving end respectively. Furthermore, $P_{L,SE}+jQ_{L,SE}$ and $P_{L,RE}+jQ_{L,RE}$ are complex power at sending end and receiving end, respectively. $R_{(SE,RE)}+jX_{(SE,RE)}$ is a complex impedance of line connected between sending end and receiving end.

2.2 Objective function

The proposed research has considered the operating cost function [25] as the main target objective. The operating cost function can be divided into two parts as depicted in (2.6). It can be said that the first element of the operating cost function represents the cost of the AP, which is provided by the sub-station. Subsequently, the second element of the operating cost function is the cost of the RP, which is provided by the placed capacitors in the power system.

$$cost\ function = K_{P_{T,loss}} P_{T,loss} + \sum_{i=1}^{N_C} K_{Q_i^c} Q_i^c \tag{2.6}$$

Where $P_{T,loss}$ is the total active power loss in KW. $K_{P_{T,loss}}$ is the equivalent cost of power losses in \$/KW. $K_{Q_i^c}$ is reactive power cost of the Q_i^c capacitor in \$/KVAR. Q_i^c is the RP of the i^th capacitor in KVAR. N_C is the total number of capacitor which is placed in the network.

2.3 System constraints

The behaviour of the objective function, as depicted in section 2.2, is bounded by the following constraints.

$$V_i^{min} \le V_i \le V_i^{max};\ i = 1,2,3...N_B$$

$$\sum_{i=1}^{N_C} Q_i^c \le \sum_{j=1}^{N_B} Q_j^L$$

Where, V_i^{min}, V_i^{max} and V_i are minimum, maximum, and actual voltage magnitude at i^th bus. Q_j^L is RP load at j^th bus.

2.4 Constraint handling method

In this paper, a static penalty function technique [31] has been used to handle the system constraints violations. For this, a constant penalty has been applied to the infeasible solution, and the result adds to the objective function. Therefore, $V_{penalty}$ and $Q_{c,penalty}$ are the penalty for voltage violations and RP violation, respectively.

2.5 Augmented objective function

Here, the following equations are representing the mathematical model of the augmented objective function:

$$\text{minimize (F)} = cost\ function + \sum_{i=1}^{N_B} V_{penalty}(V_i - V_{lim}^i)^2 + Q_{c,penalty}(\sum_{j=1}^{N_C} Q_j^c - Q_{lim}^L)^2 \tag{2.9}$$

$$\begin{cases} if \quad V_i \geq V_{\max}^i & ;V_{\lim}^i = V_{\max}^i \\ if \quad V_i \leq V_{\min}^i & ;V_{\lim}^i = V_{\min}^i \\ otherwise & ;V_{\lim}^i = V_i \end{cases} \tag{2.10}$$

$$\begin{cases} if \quad \sum_{i=1}^{N_C} Q_i^c \geq \sum_{j=1}^{N_B} Q_j^L & ;Q_{\lim}^L = \sum_{j=1}^{N_B} Q_j^L \\ otherwise & ;Q_{\lim}^L = \sum_{i=1}^{N_C} Q_i^c \end{cases} \tag{2.11}$$

III. METHODOLOGY

The employed methodology for the proposed work is Grey Wolf Optimization (GWO) algorithm. In this context, GWO is a novel meta-heuristic optimization (MHO) technology based on principle imitated from the behaviour of grey wolves in nature. Here, the optimization algorithm typically works on the basis of the grey wolves' hunting mechanisms. The key difference among optimization algorithms is the model structure of the GWO algorithm.

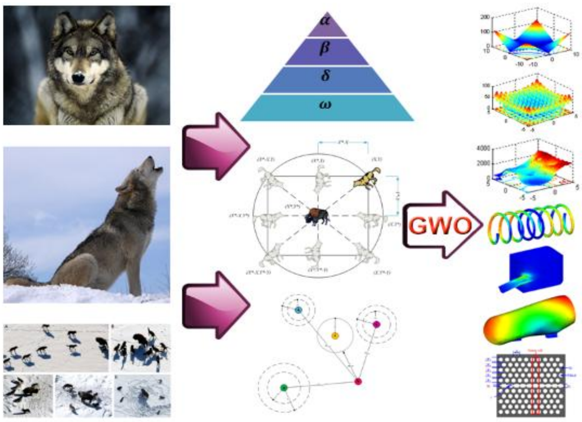

Fig. 3.1. Grey Wolf Optimizer Concept.

Furthermore, GWO is a swarm intelligent technique that is originally developed by Seyedali Mirjalili. The method imitates the leadership hierarchy of the grey wolves as they are well known for their group hunting. On the other hand, the GWO algorithm imitates the hunting mechanism of grey wolves along with the leadership hierarchy from their nature. In this context, it is worth mentioning that four key types of grey wolves' hierarchy are alpha, beta, delta, and omega. Thus, these four types of wolves are usually employed in order to simulate the leadership hierarchy. Besides, three major stages of hunting including searching for prey, encircling prey, and thereby attacking prey. All of the above-mentioned stages are typically implemented in performance optimization functions [30]. Also, The GWO is a swarm intelligent technique originally developed by mimicking the leadership hierarchy of the grey wolves. It is because grey wolves are quite popular for their group hunting mechanism [30]. As per the mathematical form of the GWO algorithm, α is the fittest solution sequenced by the 2nd and 3rd best solutions, β and δ, respectively. On the other hand, ω is always predicted to be the rest of the candidate solutions. Thus, encircling manners can be mathematically represented with the below-listed equation:

$$\vec{D} = \left| \vec{C}.\vec{X}_p(t) - \vec{X}(t) \right| \tag{3.1}$$

$$\vec{X}(t+1) = \vec{X}_p(t) - \vec{A}.(\vec{D}) \tag{3.2}$$

Here, t denotes the most recent iteration. The two-position vectors Xp and X, denote the prey and a grey wolf. Apart from this, coefficient vectors can be estimated by using the following equations:

$$\vec{A} = 2\vec{a}.\vec{r}_1 - \vec{a} \tag{3.3}$$

$$\vec{C} = 2\vec{r}_2 \tag{3.4}$$

In this way, the aforementioned equations will be used for searching the optimized solution for solving the OCP problem in the modern RDNs.

IV. TEST RESULTS

The proposed research method has been performed as well as programming in the MATLAB software domain. In this way, the use of GWO could be demonstrated to solve the OCP problem in the power system. For this, the annual cost minimization function, which is formulated as (1), has been used as a target objective. Also, the proposed approach has been tested on 33 RDN [32]. In this way, the achieved are explained in the following sections.

To obtain desired results, the annual cost per unit of power losses is taken as 168 $/KW. While using the GWO approach for the chosen system, the voltage limits are taken as Vmin = 0.94 (for 33-bus) and Vmax = 1.1. The yearly cost of fixed the capacitors has been adopted from [25]. It is worth mentioning that the programs for assessing the results are coded in MATLAB software. In doing so, the software installed in an Intel® Pentium ® CPU N4200 @ 1.10 GHz with a setup memory of 4.00 GB & 64-bit Operating System.

4.1 Test System: IEEE 33-bus RDN

In this context, the 33 bus system is used for testing the proposed approach that has been taken from the citation [32]. In terms of specifications, the chosen test system consists of 33 Bus, 32 Lines. In addition, the loads are connected to all buses except the substation bus. Moreover, the main loads of the test system are AP load and RP load having values as 3715 kW and

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2300 kVAr respectively. For the given test system, the substation voltage has been taken as 12.66 kV. The SLD of the IEEE-33 bus system is depicted in the following fig. 4.1.

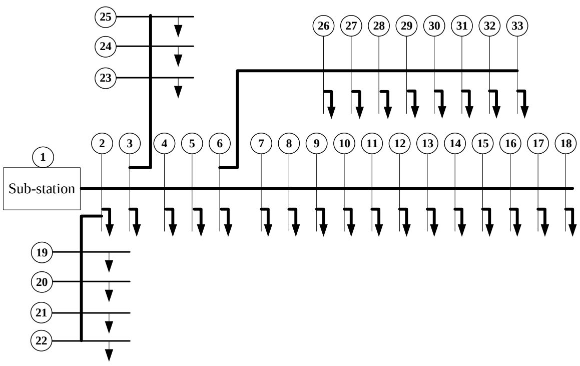

Fig. 4.1. SLD of 33 Bus RDN

As mentioned above, comparative analysis has been carried out with the results available existed in the literature. Therefore, the performed comparative analysis of the obtained results is presented in Table-I. Based on the data of Table-I, it has been observed that the proposed GWO approach effectively reduces AP loss while also improving the voltage profile of the RDN.

TABLE I: COMPARATIVE RESULT ANALYSIS FOR 33 BUS SYSTEM

	Base	PSGA [21]	GSA [22]	FPA [23]	PSO [18]	Proposed approach
Total loss (kW)	202.65	135.4	134.50	134.47	134.07	132.53
Loss Reduction in %	0	33.19	33.63	33.64	33.84	34.60
$C_{Location}$ (bus no.)	nil, nil, nil	6, 28, 29	13, 15, 26	6, 9, 30	8, 13, 30	14, 24, 30
C_{Size} (in kVAR)	0, 0, 0	1200, 760, 200	450, 800, 350	250, 400, 950	450, 300, 900	450, 450, 1200
V_{min} (p.u)	0.9131	0.9463	0.9672	0.9365	0.9400	0.9407
Total connected kVAR	0	2160	1600	1600	1650	2100
Cost of kW loss (A) ($)	34045	22747.2	22596.00	22590.96	22524.18	22265.74
Cost of capacitor (B) ($/(kVAR-year))	0	513.76	334.65	362.55	383.55	431.70
Total cost (C =A +B) ($)	34045	23260.96	22930.65	22953.51	22907.73	22697.44
Net savings ($) (D=base cost – C)	0	10784.24	11114.55	11091.69	11137.47	11347.76
% Savings (E=D/34045)	0	31.68	32.65	32.58	32.71	33.33

In addition to that, the above-mentioned graph in figure 4.2 is showing a comparative representation of the voltage profiles of the base case as well as proposed approach respectively.

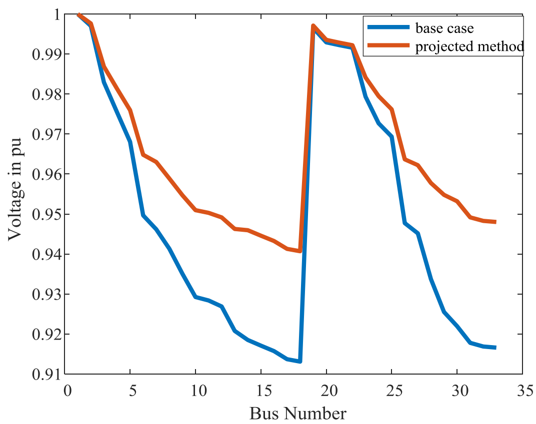

Fig. 4.2. Voltage profile base case and proposed result.

V. CONCLUSION

IN CONCLUSION, THE RESEARCH HAS PROPOSED A NOVEL TECHNIQUE FOR AN EFFECTIVE OPTIMAL CAPACITOR PLACEMENT IN A RADIAL DISTRIBUTION NETWORK. AS A RESULT, THE OPTIMAL CAPACITOR PLACEMENT HAS BEEN DONE BASED ON THE HUNTING MECHANISM AND LEADERSHIP HIERARCHY OF GREY WOLVES. IN ADDITION, THE GWO METHOD HAS BEEN TESTED FOR THE DETERMINATION OF THE OPTIMAL SIZE AND LOCATION OF THE CAPACITORS IN THE 33 BUS RADIAL DISTRIBUTION NETWORK. HENCE, THE RESEARCH HAS PRESENTED AND EXPLAINED A NEW MATHEMATICAL FORMULATION BASED ON THE GWO ALGORITHM. THE IN-DEPTH RESEARCH AND ANALYSIS ON GREY WOLF OPTIMIZER ALGORITHM SUGGEST THAT THE PROPOSED TECHNIQUE IS HIGHLY USEFUL TO FIND THE BEST ALLOCATION AND CAPACITORS RATINGS IN THE RDSS. IN THE FUTURE, THE GWO ALGORITHM CAN BE USED TO MINIMIZE THE ANNUAL COST OF ACTIVE POWER LOSSES PLUS CAPACITOR INSTALLATION. THE RESEARCH HAS SUCCESSFULLY MAXIMIZED THE NET SAVINGS IN TERMS OF THE TOTAL COST FUNCTION.

FINALLY, THE PROPOSED RESEARCH REVEALED THAT THE GWO-BASED ALGORITHM IS FAR SUPERIOR TO THE PSO-BASED ALGORITHM WHILE TESTED ON 33-BUS RDS. SUBSEQUENTLY, THE APPLICATION OF THE PROPOSED OPTIMIZATION TECHNIQUE CAN BE APPLIED FOR OCP BY IMPROVING THE OBJECTIVE FUNCTION. APART FROM THIS, THE PROPOSED METHOD CAN BE USED ON HIGHER BUSES OR REAL SYSTEMS FOR GETTING BETTER RESULTS. THE PROPOSED GWO METHOD FOR OPTIMIZATION CAN ALSO BE USED IN TRANSMISSION SYSTEMS IN THE FUTURE. MOREOVER, A HYBRID OPTIMIZATION TECHNIQUE COMPRISING GWO WITH ANY OTHER EFFICIENT OPTIMIZATION ALGORITHM IS AN IDEA TO BE IMPLEMENTED. IN WHOLE, THE COMPUTATIONAL RESULTS DEMONSTRATED THAT THE PERFORMANCE OF THE PROPOSED APPROACH GWO IS SUPERIOR TO THE REST OPTIMIZATION APPROACHES IN ALL POSSIBLE SCENARIOS.

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