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Optimum Location and Parameter Setting of STATCOM Based on Improved Differential Evolution Harmony Search Algorithm

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ABSTRACT Identification of the optimum location and capacity of Static Synchronous Compensator (STATCOM) in power grids has been given much attention to maximize its technical performance while minimizing operational cost. In this regard, a new multi-objective optimization model that minimizes power loss, enhances system stability and reduces operational cost of STATCOMs is presented in this paper. To overcome the issue of the harmony search (HS) optimization algorithm in solving high-dimensional multi-objective optimization problem, an improved differential evolution harmony search (DEHS) algorithm is proposed. In this algorithm, mutation and crossover operations are adopted instead of the original pitch adjustment operation adopted in the HS optimization algorithm, which enhances the algorithm global search ability. Moreover, opposition-based learning technique is incorporated to the process to broaden the diversity of variables and hence improving the search efficiency of the algorithm. The proposed algorithm is employed to identify the optimal allocation and sizing of multiple STATCOMs within the IEEE 30-bus system. Results reveal the superiority of the proposed optimization algorithm over the conventional multi-objectives adaptive harmony search algorithm.

INDEX TERMS Flexible ac transmission systems, static synchronous compensator, system optimization, harmony search algorithm.

I. INTRODUCTION

Flexible Alternating Current Transmission Systems (FACTS) have been widely adopted in power grids to control power flow, regulate voltage profile, increase lines power transfer capability, reduce active power losses and improve system stability [1]–[3]. Due to the high cost of FACTS devices, their capacity and placement in power grids should be identified precisely through adopting robust optimization techniques to solve a preset objective function [4]. STATCOM is one of the FACTS devices that received much attention in research and industry fields due to its several advantages that include wide operational range, rapid response and improved filtering performance [5]–[7]. Improper placement and capacity of the STATCOMs may result in adverse effects on

system stability and reliability along with the additional cost it incurs [8]. Majority of the current research in the literature has tackled this point through identifying the optimum location after which the optimum capacity of the STATCOM is calculated [9]. However, this decoupled method does not necessarily result in global optimal solution. Therefore, considering the installation site and device capacity simultaneously has been given much concern to optimize the FACTS installation [10].

Due to the day-by-day increase in the load demand, the issue of voltage stability which is highly dependent on the reactive power balance has been elevated as a new challenge to power system planning and operation [11]–[13].

Reactive power optimization is a typical nonlinear, discontinuous and mixed integer optimization problem. In recent years researchers have increasingly employed artificial intelligence optimization methods to solve this problem [12].

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In [13], Quantum Particle Swarm Optimization (QPSO) algorithm is adopted to optimize the installation site and capacity of the STATCOM. Results of this investigation indicate that STATCOM can increase system loadability. In [14], voltage deviation, device capacity and power loss are combined into a single objective function to optimize the STATCOM location and capacity using Particle Swarm Optimization (PSO) technique. Results show that two STATCOMs connected to the investigated system at specific locations are adequate to optimize system performance. The optimal location of STATCOM on different transmission networks has been investigated using various evolutionary algorithms namely Particle Swarm Optimization, Bacterial Foraging Optimization and Plant Growth Optimization techniques [15]. The published results attest that STATCOM is a very effective FACTS device in regulating the voltage profile of the studied systems.

This paper is aimed at introducing a new cost-effective optimization technique based on improved differential evolution harmony search algorithm to optimize the capacity and location of the STATCOMs within the IEEE 30-bus system. Harmony Search (HS) is a global heuristic search algorithm proposed by Geem Korean in 2001 [16]. This algorithm emulates the process of a music player adjusting various instrument pitches to reach the most pleasant harmonies status [17], [18]. The HS algorithm features several advantages including simple structure, requirement of few parameters, rapid convergence and robustness, [19]. This facilitates the algorithm to be used to optimize systems of continuous as well as discrete variables. HS algorithm has been widely used in solving problems of multi-parameters and multi-extreme optimization functions and engineering applications, and has achieved good application in the study of power grid optimization [20]–[22]. A Pareto-based grouping discrete harmony search algorithm is proposed to solve the multi-objective flexible job shop scheduling problem (FJSP) [23]. The comparison results show that the proposed PGDHS algorithm for solving multi-objective flexible job-shop scheduling problem. Literature [24] develop a new rule for the improvisation to produce a new harmony according to the characteristic of FJSP and the coding strategies, and several local search methods are embedded to enhance the algorithm's local exploitation ability.

A hybrid harmony search (HHS) algorithm with efficient job sequence mapping scheme and variable neighborhood search (VNS) is proposed to solve the PFFSP in [25]. The recommended values of parameters adopted in HHS are presented.

The pitch trims in HS algorithm are replaced by differential mutation operator to enhance the global search ability of the algorithm and eliminate the issue of converging into local optimum solution instead of a global solution [26]. A difference operator is also used to improve the harmony search algorithm in [27]. This improved algorithm utilizes opposite learning strategies [28] and is proposed in this paper to broaden the diversity of variables. The improved algorithm has been applied to optimize the installation of STAT-

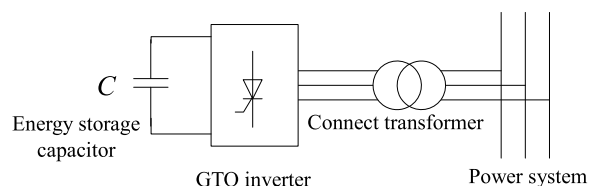


FIGURE 1. Schematic diagram of voltage type STATCOM device.

COM in the standard IEEE 30-bus system. The superiority of this algorithm is validated through comparing its results with the results of conventional adaptive multi-objective HS algorithm.

II. MATHEMATICAL MODEL OF OPTIMAL PLACEMENT AND SIZING OF STATCOM

A. STATCOM MODELING

STATCOM is a second-generation FACTS device that is used as a shunt reactive power compensator in power grids and wind energy conversion systems. The basic principle of STATCOM is to connect a voltage or current type inverter to the grid in parallel by connecting a transformer or a reactor. By adjusting the amplitude and phase of the inverter output voltage, or controlling the size of the reactive current output from the AC side of the inverter, STATCOM can output or absorb certain reactive power, the adjustment of the system node voltage is completed to achieve the effect of dynamic reactive power compensation [29]. STATCOM is a dynamic reactive power compensation device which can adjust the reactive power at the point of common coupling, suppress voltage flicker and maintain voltage stability with advantages of fast response and smooth regulation [30]. The principle of the voltage type STATCOM device is shown in Figure 1:

Because STATCOM is a parallel FACTS element, it can be equivalent to a tunable capacitor or reactor connected in parallel to the node, or a reactive current source or voltage source connected in parallel to the node, injected or absorbed into the system to meet the requirements of reactive power. In the steady state power flow calculation model, the node installed with STATCOM can add a reactive power control variable equivalently. In this paper, STATCOM is modeled as an ideal controllable reactive power source that can inject or absorb reactive power with the following constraints [13].

$$Q_{STATCOM \min} \leq Q_{STATCOM} \leq Q_{STATCOM \max} \quad (1)$$

where $Q_{STATCOM \max}$ and $Q_{STATCOM \min}$ are the the maximum and minimum values of the STATCOM volt ampere reactive (Var) capacity, respectively.

B. OBJECTIVE FUNCTION

A multi-objective optimal model is developed to identify the best location and optimum capacity of the STATCOM in power systems. Minimizing the active power loss, cost of reactive power compensation and minimizing the voltage stability index are taken into consideration in the proposed objective function as elaborated below.

1) MINIMIZATION OF ACTIVE POWER LOSS

Minimizing the active power loss is formulated as below [31]:

$$\min P_{loss} = \sum_{i,j \in N_L} G_{ij}(U_i^2 + U_j^2 - 2U_i U_j \cos \theta_{ij}) \quad (2)$$

where N_L is the number of branches in the power system; U_i is the voltage amplitude at bus i ; G_{ij} and θ_{ij} are the conductance and the voltage phase difference between buses i and j , respectively.

2) MINIMIZATION OF REACTIVE POWER COMPENSATION COST

The overall cost of STATCOM installation comprises capital cost of the hardware equipment and running cost for operation and maintenance expenses. The total cost is minimized using the below equation [32]:

$$\min Cost = C_T + C_Y \quad (3)$$

where C_T is the one-time capital cost; C_Y is the operating and maintenance expenses. In this paper, C_T is calculated using the year-equivalence method as follows:

$$C_T = \sum_{i=1}^{N_C} Q_{Ci} \times C_p \times \frac{1}{(1 + \tau)^t} \quad (4)$$

where N_C is the number of installed STATCOM; Q_{Ci} is the reactive power compensation capacity at node i ; C_p is the price of the STATCOM per kVar capacity, (200 yuan/kVar); τ is the discount rate (10%); durable years t is equal to 20.

The operating and maintenance expenses C_Y is calculated from:

$$C_Y = H \times C_T \quad (5)$$

Operation and maintenance costs are calculated as a percentage of the investment cost. The operating cost is assumed to be 5% of the investment cost and is represented by H matrix [33].

3) MINIMIZATION OF VOLTAGE STABILITY INDEX

Kessel proposed a voltage stability index L to reflect the steady state of the power systems [34]. In this regard, the nodes of the power system are divided into two groups: one group contains all of the load (PQ) buses and is defined as: $\alpha_L = \{1, 2, \dots, n_L\}$; the other group includes all the generation (PV) buses and is defined as: $\alpha_G = \{n_L + 1, n_L + 2, \dots, n\}$. The bus current-voltage equation can be written as:

$$\begin{bmatrix} I^L \\ I^G \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{bmatrix} \begin{bmatrix} U^L \\ U^G \end{bmatrix} \quad (6)$$

Using partly inverting methods, the following equation can be derived:

$$\begin{bmatrix} U^L \\ I^G \end{bmatrix} = \begin{bmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{bmatrix} \begin{bmatrix} I^L \\ U^G \end{bmatrix} = \begin{bmatrix} Z^{LL} & F^{LG} \\ K^{GL} & Y^{GG} \end{bmatrix} \begin{bmatrix} I^L \\ U^G \end{bmatrix} \quad (7)$$

where Z^{LL} , F^{LG} , K^{GL} and Y^{GG} are the sub matrices of the H -matrix; U^G and I^G are vectors of the voltage and current

at the PV buses, respectively; U^L and I^L are vectors of the voltage and current at the PQ buses, respectively.

For each load bus $j \in \alpha_L$, local indicator L_j is defined as follows:

$$L_j = \left| 1 - \frac{\sum_{i \in \alpha_G} F_{ji} U_i}{U_j} \right| \quad (8)$$

where L_j is the local voltage stability index of the i th load node or bus, U_i is the complex voltage of the i th PV bus, U_j is the complex voltage of the j th PQ bus, $j \in \alpha_L$, F_{ji} is the i th row- j th column element of the F^{LG} matrix.

The system voltage stability index L is defined as follows:

$$L = \max_{j \in \alpha_L} (L_j) \quad (9)$$

The value of L is between 0~1. The lower the value of L , the better is the voltage stability of the power system. The difference $1.0 - L$ can be regarded as the voltage stability margin of the system. Hence, increasing voltage stability can be achieved through minimizing the voltage stability indicator L -index as below.

$$\min L = \max_{j \in \alpha_L} (L_j) \quad (10)$$

C. CONSTRAINTS

The constraints of the optimization problem are identified based on the characteristics of the power system and the expected voltage profile. Each of the constraint as elaborated below represents a limit in the search space.

1) EQUALITY CONSTRAINTS

At each bus, power balance must be achieved as below [32], [34].

$$\begin{cases} P_{Gi} - P_{Li} = U_i \sum_{j=1}^N U_j (G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij}) \\ Q_{Gi} + Q_{Ci} - Q_{Li} = U_i \sum_{j=1}^N U_j (G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij}) \end{cases} \quad (11)$$

where P_{Gi} and Q_{Gi} are the generator active and reactive power of node i , respectively; P_{Li} and Q_{Li} are the load active and reactive power at bus i , respectively; G_{ij} and B_{ij} are the real and imaginary parts of node admittance matrix, respectively; θ_{ij} is the voltage phase difference between buses i and j ; U_i is the voltage amplitude at bus i ; N is the number of nodes.

2) INEQUALITY CONSTRAINTS

These constraints include control variables and state variables. Control variables include generator terminal voltage U_G , tap position of transformer T and reactive power compensation capacity Q_C . On the other hand, state variable include the reactive power of generators Q_G and the load bus voltage U_L [33]–[35].

These constraints are formulated as below:

$$\begin{cases} U_{Gi \min} \leq U_{Gi} \leq U_{Gi \max} & i = 1, 2, \dots, N_G \\ T_{i \min} \leq T_i \leq T_{i \max} & i = 1, 2, \dots, N_T \\ Q_{Ci \min} \leq Q_{Ci} \leq Q_{Ci \max} & i = 1, 2, \dots, N_C \end{cases} \quad (12)$$

$$\begin{cases} U_{Li \min} \leq U_{Li} \leq U_{Li \max} & i = 1, 2, \dots, N_L \\ Q_{Gi \min} \leq Q_{Gi} \leq Q_{Gi \max} & i = 1, 2, \dots, N_G \end{cases} \quad (13)$$

where U_{Gi} is the terminal voltage of the i th generator; T_i is the tap position of the i th transformer; Q_{Ci} is the reactive power compensation capacity of the i th compensation point; U_{Li} is the voltage amplitude of the i th load bus; Q_{Gi} is the reactive power of the i th generator bus; N_G , N_T , N_C and N_L are respectively the number of generators, transformers, reactive power compensation devices and load buses.

III. PROPOSED APPROACH

A. MULTI-OBJECTIVE HS ALGORITHM

In the multi-objective HS algorithm, each instrument is analogous to a component of the solution vector and the pitch of the instrument is regarded as the value of solution vector. Harmonies of all instruments constitute a solution vector. The objective function of the optimization problem can be regarded as the evaluation of the music. Musician adjusts various instruments in the band repeatedly to achieve a pleasing harmony pitch with memory [36].

The details of multi-objective harmony search (MOHS) algorithm can be summarized in the below 6 steps [37]:

Step1: Initialization of the parameters

In this step the Harmony memory size (HMS), harmony memory considering rate ($HMCR$), pitch adjusting rate (PAR) and arbitrary distance band width (BW) are initialized.

Step2: Initialization of the harmony memory

The harmony memory (HM) can be expressed as:

$$\begin{aligned} HM &= \{X_1, X_2, \dots, X_{HMS}\} \\ X &= \{x_1, x_2, \dots, x_m\} \\ &(i = 1, 2, \dots, HMS; J = 1, 2, \dots, m) \end{aligned}$$

where HMS is the harmony memory size; m is the pitch of the harmony.

Step3: Generation of non-dominated solutions

In this step the objective function of each harmony variable in the HM is calculated and the harmonies are ranked using non-dominated sorting approach. Harmonies with the first rank are conserved in Pareto solution set.

Step4: Improvise a new harmony from the HM.

A new harmony vector is produced following three rules: memory consideration, pitch adjustment and random selection. This procedure works as follows:

$$x_{i,j}^{new} = \begin{cases} x_{rnd,j} & rnd < HMCR \\ x_{j,\min} + rand \times (x_{j,\max} - x_{j,\min}) & else \end{cases} \quad (14)$$

where $rand$ is a uniformly distributed random integer number between $1 \sim HMS$; $x_{j,\max}$ and $x_{j,\min}$ are the upper and lower

boundaries of the j th pitch, respectively; $rand$ is a uniformly distributed random number between $0 \sim 1$; $HMCR$ is the harmony memory considering rate.

For any new vector generated from HM , pitch adjusting is carried out with PAR parameter. Pitch adjustment and random selection are identified as follows:

$$x_{i,j}^{new} = \begin{cases} x_{i,j} \pm rand \times BW & rand < PAR \\ x_{i,j} & else \end{cases} \quad (15)$$

where PAR is the pitch adjusting rate; BW is an arbitrary distance band width.

To overcome the issues associated with the conventional HS algorithm that include unstable convergence and easy to run into local optimum solution instead of global solution, adaptive strategy is adopted to adjust the control parameters and improve the performance of the search algorithm. The adopted strategies can be formulated as below [38], [39]:

$$HMCR_k = HMCR_{\max} - \frac{(HMCR_{\max} - HMCR_{\min})}{it_{\max}} k \quad (16)$$

$$PAR_k = PAR_{\min} + \frac{PAR_{\max} - PAR_{\min}}{\pi/2} \arctan k \quad (17)$$

$$BW_k = (BW_{\max} - BW_{\min})e^{-k} + BW_{\min} \quad (18)$$

where $HMCR_{\max}$ and $HMCR_{\min}$ are the maximum and minimum values of harmony memory considering rate, respectively; k is the current iteration number; it_{\max} is the maximum number of iterations; PAR_{\max} and PAR_{\min} are the maximum and minimum values of the pitch-adjusting rate, respectively; BW_{\max} and BW_{\min} are the maximum and minimum values of bandwidth, respectively.

Step 5: Updating harmony memory

This step is to generate new harmonies and sort them with fast non-dominated sorting approach after which a solution vector from 1 to HMS remained in the HM according to the ranking is chosen.

Step 6: Checking the termination criterion

The process is terminated if the maximum number of iteration is reached otherwise, go to Step 4.

Step7: Obtain the Pareto solution set.

B. IMPROVED DIFFERENTIAL EVOLUTION HARMONY SEARCH ALGORITHM

Harmony search algorithm presents good search capabilities in solving low dimensional function optimization problems. However, with the increase of variables dimension, the search space becomes large and the coupling degree between variables increases, which results in a decrease of the global searching ability. Thus, the algorithm may fall into local optimum solution with low efficiency. Most of the decision variables in the new harmony vector are obtained by perturbing the variables from the vectors in the harmony memory. The multiple harmony vectors and the information of the optimal solution are not fully used for the new harmony vector. Optimization makes the algorithm's evolution speed slower and easily falls into a local optimum.

The differential evolution algorithm is an optimization algorithm based on the theory of swarm intelligence. The swarm intelligence generated by cooperation and competition among individuals in the swarm guides the optimization of the search. It retains the population-based global search strategy and has strong global convergence and robustness. In differential evolution algorithm, mutation operator can speed up the convergence search process and cross operation can increase the diversity of the population and avoid local optimum solution. To make full use of the available information of the HM, this paper introduces a differential evolution vector in the HS which is inspired by the mutation of differential evolution algorithm. It is worth mentioning that differential evolution harmony search algorithm does not change the search framework of the HS algorithm [26]. Under the guidance of the difference vector and the optimal solution, DEHS algorithm can not only search for better solutions, but it also ensures the diversity of HM, which can improve the search efficiency for complex optimization problems.

1) DIFFERENTIAL EVOLUTION HARMONY SEARCH ALGORITHM

The differential evolution algorithm comprises three operations: mutation, crossover and selection. This paper introduces mutation and crossover of differential evolution in harmony search algorithm to generate new harmonies [26]. The mutation operation is formulated as below:

$$v_{ij} = x_{g_{best},j} + F \times rand(x_{r_1,j} - x_{r_2,j}) \quad (19)$$

where r_1 and r_2 are two different random individuals in the population; $x_{g_{best}}$ is the best individual of the current population; $F > 0$ is a variation constant; F is used to control the zoom of difference vectors to avoid search stagnation.

The cross operation in differential evolution algorithm intends to maintain the diversity of the population. The i th individual x_i crosses to corresponding variation v_i to get the test individual x_i^{new} in each generation as below:

$$x_{ij}^{new} = \begin{cases} v_{ij} & rand < CR \\ d_{j,\min} + rand * (d_{j,\max} - d_{j,\min}) & else \end{cases} \quad (20)$$

where $rand$ is a random number between [0,1]; CR is the crossover probability.

In order to balance the local and global search performance of the improved differential harmony search algorithm proposed in this paper, the coefficient of variation and crossover probability dynamic changes are expressed as:

$$F_k = F_{\min} + \frac{F_{\max} - F_{\min}}{\pi/2} \arctan k \quad (21)$$

$$CR_k = CR_{\max} - \frac{CR_{\max} - CR_{\min}}{it_{max}} k \quad (22)$$

where k is the current iteration number; it_{max} is the maximum number of iterations; F_{\max} and F_{\min} are the maximum and minimum values of the variation coefficient, respectively;

CR_{\max} and CR_{\min} are the maximum and minimum values of crossover rate, respectively.

2) OPPOSITION-BASED LEARNING PRINCIPLE

Opposition-based learning principle as an intelligent computing strategy was proposed and applied to individual initialization process of intelligent algorithms by Tizhoosh [28].

Let $x = (x_1, x_2, \dots, x_N)$ be a point of N -dimensional space, $x_1, x_2, \dots, x_N \in R, x_i \in [a_i, b_i]$. The opposite number x' is defined as follows:

$$x' = a_i + b_i - x_i \quad (23)$$

In order to avoid blind search and to speed up the convergence process, this article introduces opposition-based learning strategy to the differential evolution harmony search algorithm. To make the algorithm running in a relatively reasonable space, the minimum and maximum values of each variable in the searching space is used in the opposition-based learning as below.

$$x_j^{new} = \begin{cases} x_{j\max} + x_{j\min} - x_j^{new} & rand < CR \\ x_{j\min} + rand * (x_{j\max} - x_{j\min}) & else \end{cases} \quad (24)$$

where $x_{j\max}, x_{j\min}$ are the maximum and minimum values of the j th dimensional variable, respectively.

If the reverse learning solution x_j^{new} dominates the new solution x_j^{new} , the new solution is equal to x_j^{new} , otherwise the new solution remains unchanged.

The update of a variable in the HS algorithm is only related to an individual variable, and the information of population evolution is not fully used. The proposed improved algorithm makes full use of the information of multiple evolutionary individuals and the optimal solution to generate the next generation of individuals. The full use of the information of multiple individuals in the population to update will help enhance the algorithm's global search ability and make full use of the information of the Pareto optimal solution to update can help speed up the convergence of the algorithm.

IV. APPROACH IMPLEMENTATION

Each harmonic component in the search space corresponds to a control variable of the optimization problem. The harmonies are coded as follows:

$$x_i = [U_{G1}, \dots, U_{GN_G}, T_1, \dots, T_{N_T}, L_1, \dots, L_{N_L}, Q_{C1}, \dots, Q_{CN_C}] \quad (25)$$

where U_G is the voltage amplitude of the generator G , T is the tap position of transformer, L is the location point of the STATCOM and Q_C is the reactive power compensation capacity.

The constraints of generator terminal voltage, transformer tap position and reactive power compensation capacity can be self-satisfied in the power flow calculation process. In this paper, a penalty function is considered in the objective function to handle the off-limit state variable is developed as

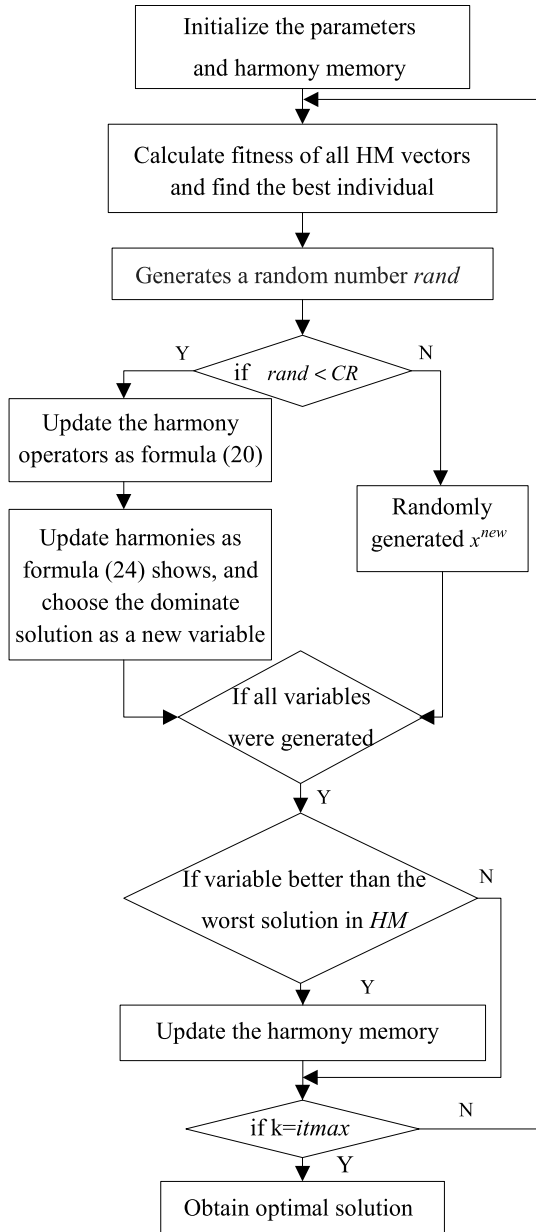


FIGURE 2. Flowchart of the proposed DEHS.

below [40]:

$$f = \lambda_U \sum_{i=1}^{N_L} \left(\frac{\Delta U_i}{U_{i\max} - U_{i\min}} \right)^2 + \lambda_G \sum_{i=1}^{N_G} \left(\frac{\Delta Q_{Gi}}{Q_{Gi\max} - Q_{Gi\min}} \right)^2 \quad (26)$$

$$\text{where } \Delta U_i = \begin{cases} U_{i\min} - U_i & U_i < U_{i\min} \\ 0 & U_{i\min} \leq U_i \leq U_{i\max} \\ U_i - U_{i\max} & U_{i\max} < U_i \end{cases}$$

$$\Delta Q_{Gi} = \begin{cases} Q_{Gi\min} - Q_{Gi} & Q_{Gi} < Q_{Gi\min} \\ 0 & Q_{Gi\min} \leq Q_{Gi} \leq Q_{Gi\max} \\ Q_{Gi} - Q_{Gi\max} & Q_{Gi\max} < Q_{Gi} \end{cases}$$

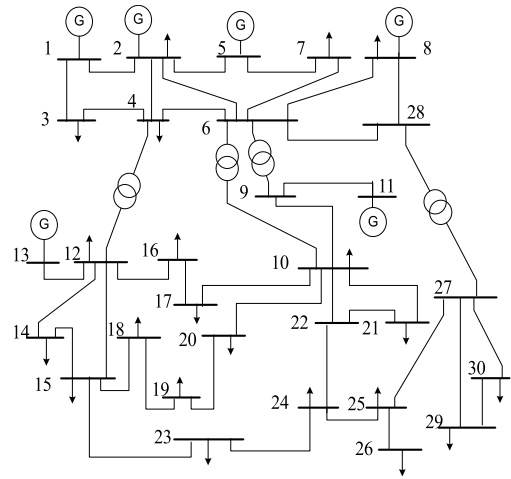


FIGURE 3. IEEE 30-bus system.

where λ_G and λ_U are respectively the penalty coefficients of the reactive power over limit of generators and the voltage violations of the load node, in this paper these values are set as $\lambda_G = 5$, $\lambda_U = 10$; U_i is the voltage amplitude of the i th load node; Q_{Gi} is the reactive power of the i th generator.

The flow chart of the proposed improved differential evolution harmony search algorithm is shown in Fig. 2.

V. CASE STUDY AND DISCUSSION

In order to verify the effectiveness of the algorithm proposed in this paper, the improved differential evolution harmony search algorithm is applied to optimize the installation of STATCOMs in the IEEE 30-bus system shown in Fig. 3 [41]. The obtained results are compared to the results obtained using conventional adaptive multi-objective harmony search algorithm. The IEEE 30-bus system comprises 6 generators, 41 transmission lines and 4 transformers [41]. Power flow calculation is performed based on a base power of 100 MVA using Newton-Raphson method.

Optimization parameters are set as: size of HM is 100; maximum iteration number is 250; PV buses voltages are set within the range 0.9 pu to 1.1 pu; PQ buses voltages are set within the range 0.95 pu to 1.05 pu; transformers tap positions are set on taps 1 to 5, that is $1 \pm 2.5\%$. The installed capacity of the STATCOM is assumed within the range $-200\text{MVar} \sim 200\text{MVar}$. The parameters of the two algorithms are set as follows: $HMCR_{\max} = 0.95$, $HMCR_{\min} = 0.85$; $PAR_{\max} = 0.2$, $PAR_{\min} = 0.15$; $CR_{\max} = 0.95$, $CR_{\min} = 0.85$; $F_{\max} = 0.2$, $F_{\min} = 0.15$.

Using the improved differential evolution harmony search algorithm and multi-objective harmony search algorithm to optimize the location and capacity of STATCOMs in the IEEE 30-bus system based on the above-mentioned optimization functions leads to the optimum results shown in

Fig. 4. According to Fig. 4, the Pareto solution set of MODEHS algorithm is better than MOHS algorithm. The solutions of MODEHS algorithm present less power loss, lower compensation costs and better stability.

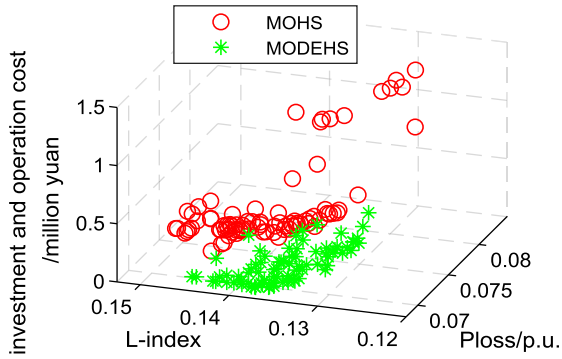


FIGURE 4. The optimal solution of the two investigated algorithms.

In order to provide a final solution for the decision-makers after obtaining the optimal solution set, fuzzy comprehensive evaluation and decision method [42] are adopted to compromise the solution while considering three objective functions. Fuzzy membership function is developed to reflect the satisfaction of each solution corresponding to each target function as below:

$$\mu_i = \frac{f_{i\max} - f_i}{f_{i\max} - f_{i\min}} \tag{27}$$

where, f_i is the fitness value of the i th objective function; $f_{i\max}$ and $f_{i\min}$ are maximum and minimum value of the i th objective function, respectively.

The compatibility of the solution in the optimal solution set is assessed as below.

$$\mu = \frac{1}{N} \sum_{i=1}^N \mu_i \tag{28}$$

where, N is the number of objective functions. High value of μ means better solution.

Fuzzy decision theory is used to identify the most compromised solution. Fitness values and variables for the two investigated optimization algorithms are listed in Table 1

From the optimal compromises calculated by the two optimization algorithms in Table 1, the power loss and L index calculated by Newton-Raphson method for power flow are 7.253MW and 0.145 without STATCOM respectively. However, the power loss and L index calculated by the MODEHS algorithm are reduced by 0.3212MW and 0.0087 respectively. The STATCOM is installed on the 24th and 27th nodes, with the installed capacities of 0.6281MVar and 0.8384MVar respectively. While the power loss and L index are only reduced by 0.0328MW and 0.0079 by using the MOHS algorithm and the cost is higher than that calculated by the MODEHS algorithm.

From the comprehensive comparison of Figure 4 and Table 1, it can be seen that the optimization effect of the MODEHS algorithm proposed in this paper is better than the MOHS algorithm, and the solution is better.

Table 2 shows the bus voltage profile of the fuzzy satisfaction solution for the IEEE 30-bus system. Table 2 reveals

TABLE 1. Fuzzy satisfaction solution of the two optimization algorithms.

| Variable | Initial | MOHS | MODEHS |
|-------------------|---------|---------|--------|
| U_{G1} | 1.0500 | 1.0469 | 1.0740 |
| U_{G2} | 1.0338 | 1.0320 | 1.0614 |
| U_{G5} | 1.0058 | 0.9968 | 1.0335 |
| U_{G8} | 1.0230 | 1.0151 | 1.0416 |
| U_{G11} | 1.0913 | 1.0662 | 1.0961 |
| U_{G13} | 1.0883 | 1.0563 | 1.0677 |
| T_{6-9} | 1.0155 | 0.975 | 1 |
| T_{6-10} | 0.9629 | 0.95 | 0.975 |
| T_{4-12} | 1.0129 | 1 | 1 |
| T_{27-28} | 0.9581 | 0.95 | 0.95 |
| L_1 | 0 | 16 | 24 |
| L_2 | 0 | 24 | 27 |
| Q_{C1} | 0 | -0.3101 | 0.6281 |
| Q_{C2} | 0 | 13.7042 | 0.8384 |
| Ploss/MW | 7.2530 | 7.2202 | 6.9318 |
| L - index | 0.1450 | 0.1371 | 0.1363 |
| Cost/million yuan | 0 | 0.4375 | 0.0458 |

TABLE 2. Bus voltage profile for different algorithms of fuzzy satisfaction solution for the IEEE 30-bus system.

| Bus no. | Initial | MOHS | MODE HS | Bus no. | Initial | MOHS | MODE HS |
|---------|---------|--------|---------|---------|---------|--------|---------|
| 1 | 1.0500 | 1.0469 | 1.0740 | 16 | 1.0318 | 1.0123 | 1.0295 |
| 2 | 1.0338 | 1.0320 | 1.0614 | 17 | 1.0230 | 1.0067 | 1.0247 |
| 3 | 1.0272 | 1.0226 | 1.0488 | 18 | 1.0140 | 0.9976 | 1.0131 |
| 4 | 1.0218 | 1.0170 | 1.0429 | 19 | 1.0101 | 0.9941 | 1.0106 |
| 5 | 1.0058 | 0.9968 | 1.0335 | 20 | 1.0135 | 0.9978 | 1.0147 |
| 6 | 1.0177 | 1.0123 | 1.0384 | 21 | 1.0145 | 1.0035 | 1.0186 |
| 7 | 1.0046 | 0.9977 | 1.0284 | 22 | 1.0151 | 1.0053 | 1.0194 |
| 8 | 1.0230 | 1.0151 | 1.0416 | 23 | 1.0129 | 1.0056 | 1.0142 |
| 9 | 1.0447 | 1.0186 | 1.0488 | 24 | 1.0041 | 1.0098 | 1.0112 |
| 10 | 1.0270 | 1.0122 | 1.0303 | 25 | 1.0119 | 1.0174 | 1.0291 |
| 11 | 1.0913 | 1.0662 | 1.0961 | 26 | 0.9941 | 0.9997 | 1.0116 |
| 12 | 1.0478 | 1.0259 | 1.0415 | 27 | 1.0255 | 1.0307 | 1.0488 |
| 13 | 1.0883 | 1.0563 | 1.0677 | 28 | 1.0130 | 1.0072 | 1.0324 |
| 14 | 1.0316 | 1.0122 | 1.0270 | 29 | 1.0057 | 1.0110 | 1.0295 |
| 15 | 1.0259 | 1.0089 | 1.0228 | 30 | 0.9943 | 0.9997 | 1.0184 |

the improvement in the voltage profile using MODEHS algorithm when compared to the MOHS algorithm.

Fig. 5 -Fig. 7 shows the distribution of the optimal solution set. It can be observed that results with minimum power loss, minimum L -index and minimum investment and operating costs are distributed in the edge of the solution set (called outer solutions). Considering the randomness of the algorithm, the distribution of outer solutions after running the optimization several times are compared. The improved multi-objective difference evolution harmony search algorithm and adaptive multi-objective harmony search algorithm are run 30 times to get 30 outer solutions for each objective function.

The central location of box plot [43] represents the median value and the middle box contains 50% of the samples.

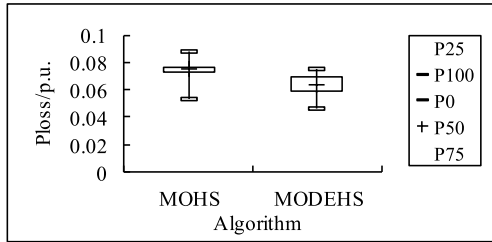


FIGURE 5. Distribution of outer solutions for system total active power loss.

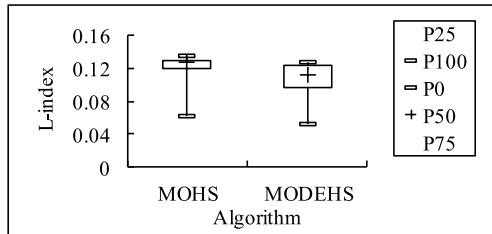


FIGURE 6. Distribution of outer solutions for system L index.

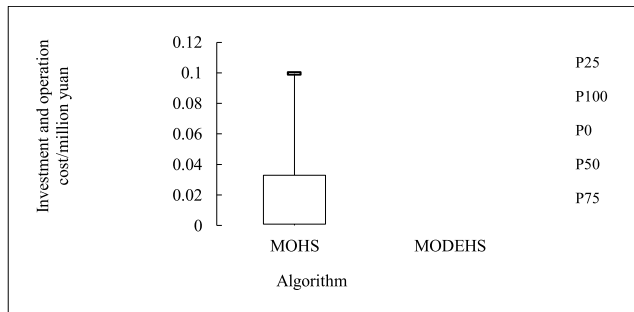


FIGURE 7. Distribution of outer solutions for system investment and operational cost.

The upper and lower edges of the box are the upper and lower quartiles of sample. The distribution of outer solutions is shown by box plots in Figs.5, 6 and 7. According to the distribution shown in these figures, the outer solutions of MODEHS algorithm are better and more concentrated than that of the MOHS algorithm. This indicates that the MODEHS algorithm presents better performance than the MOHS.

The domination of the optimal solution sets of the two algorithms are further compared using *C*-index [44]. The *C*-index of two solution sets is calculated as:

$$C(Q_1, Q_2) = \frac{|\{b \in Q_2; \exists a \in Q_1 : a < b\}|}{|Q_2|} \quad (29)$$

where $C(Q_1, Q_2)$ is the *C*-index used to measure the ratio of solutions of Q_2 being dominated by solution of Q_1 .

Both algorithms are run 30 times and the distribution of *C*-index is plotted as shown in Figs.8, 9. The 5 box plots in each figure represent the comparison results of 50, 100, 150, 200, 250 iteration times.

Figs. 8 and 9 show that improved differential evolution harmony search algorithm performs better. The solutions of

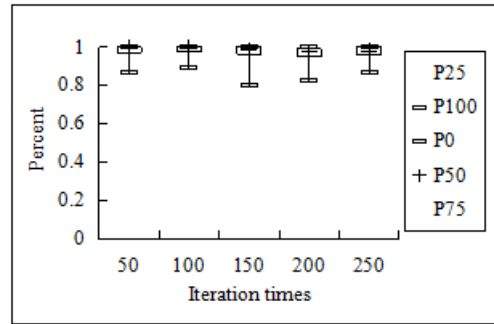


FIGURE 8. Distributions of C (MODEHS, MOHS).

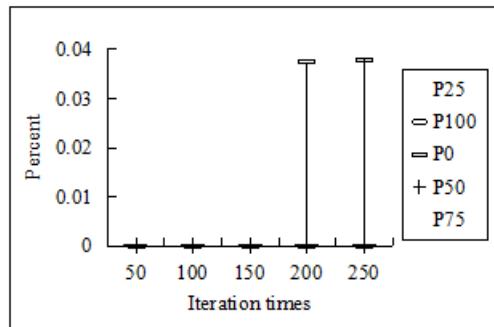


FIGURE 9. Distributions of C (MOHS, MODEHS).

MODEHS algorithm dominate 80% to 100% of the solutions of the MOHS algorithm in the iteration process; while the solutions of the MOHS algorithm dominate less than 4% of the solutions.

VI. CONCLUSION

This paper presents a new application of the improved differential evolution harmony search algorithm to solve the problem of optimal placement and sizing of multiple STATCOM units in power systems. While conventional harmony search algorithm features simple structure, few parameters, high solving speed, it exhibits some drawbacks that include premature convergence. To enhance the global search ability, the pitch trims in the harmony search algorithm are replaced by the differential mutation operator. The improved algorithm employs the opposite learning strategies to update and increase the diversity of variables. The proposed algorithm is used to solve a multi-objective optimization problem of the STATCOM installation in the IEEE 30-bus system. Obtained results reveal the proposed algorithm can effectively identify the optimum location and capacity of the STATCOM which improves the voltage profile of the investigated system and reduces power losses. In order to evaluate the obtained optimal solution, fuzzy decision theory is employed to help decision makers find the best compromised solution. According to the obtained results, the proposed differential evolution harmony search algorithm is of high accuracy and good convergence stability.

In the future, our research work will focus on continuing to explore how to use the optimization strategy of the differential search algorithm to improve the pitch adjustment and random

mutation operation of the harmony search algorithm, preventing the harmony search algorithm from falling into a local optimum and speeding up the convergence rate. We will also compare the DEHS algorithm with other optimization algorithms in order to solve practical multi-objective optimization problems.

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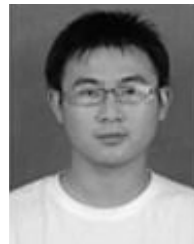
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