

Article

Modeling and Optimization of Wind Turbines in Wind Farms for Solving Multi-Objective Reactive Power Dispatch Using a New Hybrid Scheme

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Abstract: Reactive Power Dispatch is one of the main problems in energy systems, particularly for the power industry, and a multi-objective framework should be proposed to solve it. In this study, we present a multi-objective framework for the optimization of wind turbines in wind farms. We investigate a new combined optimization method with Chaotic Local Search, Fuzzy Interactive Honey Bee Mating Optimization, Data-Sharing technique and Modified Gray Code for discrete variables. We use the proposed model to select optimal energy system parameters. The optimization process is based on simultaneous optimization of three functions. Finally, we improve a new method based on Pareto-optimal solutions to select the best one among all candidate solutions. The presented model and methodology are validated on energy systems with wind turbines. The evaluated efficiency is compared with the real system.

Keywords: MORPD problem; hybrid optimization; fuzzy theory; multi-objective; wind farms



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1. Introduction

Reactive Power Dispatch (RPD) is tightly coupled to bus voltages throughout a distribution power network [1–12]. Hence, it has a noteworthy effect on system security [13–24]. One of the important reasons for some of the recent blackouts in the power distribution systems around the world, such as those that occurred in Canada, the United States, Sweden, Denmark, and Italy, was reported as inadequate reactive power resources of the system, resulting in voltage collapse [25–36]. The RPD problem is a non-differentiable optimization problem with a multidimensional search space. This is due to the size of control parameters, which minimize the non-commensurable and conflicting objective functions via finding control variables while fulfilling certain system constraints [37–48]. Renewable systems, including hybrid renewable energy systems, have increased quickly in recent years. Principally, wind energy penetration (from large wind farms) is much larger compared with other renewable energy sources worldwide and is one of the most promising options for future energy [49,50]. Large-scale wind farms impact the power network in 2 ways [51–62]:

- (i) Areas with valuable wind energy are used for power network terminals [63–70];
- (ii) Wind energy has inherent uncertainties regarding the wind speed variable.

1.1. Literature Review

Recently, a large number of studies have been devoted to this problem of energy power systems and solutions have been presented for RPD problems. Nonlinear programming (NLP), linear programming (LP) and quadratic programming (QP) methods have been applied to solving RPD problems [71–80]. Many models have been presented in previous research studies [81–90] and have been applied to resolving the RPD problem. Optimization models used in a distributed generation have been found to be important [90–95]. In [96], optimization models of wind power generation were used to select wind turbine (WT) points in wind farms (WF). However, analysis has shown that when the objective function is epistatic, numbers of optimized variables are large, and the above-mentioned techniques' efficiency is degraded to select global solutions, as well as results that do not approach the global optimum.

1.2. Motivations and Contributions

The important aims of this study are as follows:

- (i) We present power requirements for Wind Turbine to find active power control.
- (ii) We propose a power dispatch model for wind farms via HBMO search.
- (iii) We propose some modifications in discrete search and local and global search.
- (iv) We propose a procedure based on the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) to select a compromise solution via fuzzy interactive honey bee mating optimization (FIHBMO).
- (v) We test the efficiency of the mentioned method via simulations and validated using available data.

In Sections 2 and 3, we introduce the RPD formulation with and without the WT Effect. In Section 4, we introduce the proposed scheme. We detail the application of FIHBMO to the proposed problem in Section 5. Results are compared to previous works in Section 6, and finally, Section 7 concludes with the results of this paper.

2. Problem Formulation without WT Effect

The power system's goals are voltage stability and deviation, system transmission loss and security. Commonly, the RPD method is presented as follows.

2.1. Problem Objectives

- *Objective 1: Power loss minimization*

Transmission losses are economic losses, and minimization of them is important. Transmission losses for bus voltages are presented via Newton–Raphson:

$$J_1 = P_{loss}(x, u) = \sum_{k=1}^{N_L} g_k [V_i^2 + V_j^2 - 2V_i V_j \cos(\theta_i - \theta_j)] \quad (1)$$

The g is line conductance, V and θ are line voltage and angles, N_D is power demand bus, N_j is bus number adjacent to bus j . P_{loss} is transmission power loss.

- *Objective 2: Voltage deviation (VD) minimization*

The second function of RPD is presented as follows:

$$J_2 = VD(x, u) = \sum_{i=1}^{N_d} |V_i - 1.0| \quad (2)$$

The N_d is the load bus number.

- *Objective 3: L-index voltage stability minimization*

Voltage collapse is abrupt [95–97]. L-index, L_j of the bus, is presented via:

$$\begin{cases} L_j = \left| 1 - \sum_{i=1}^{N_{PV}} F_{ji} \frac{V_i}{V_j} \right|, j = 1, 2, \dots, N_{PQ} \\ F_{ji} = -[Y_1]^{-1}[Y_2] \end{cases} \quad (3)$$

The N_{PV} and N_{PQ} are the number of PV and PQ bus, and Y_1 and Y_2 are sub-matrices of Y_{BUS} that are produced after segregation of PQ and PV bus bar, as presented in Equation (4):

$$\begin{bmatrix} I_{PQ} \\ I_{PV} \end{bmatrix} = \begin{bmatrix} Y_1 & Y_2 \\ Y_3 & Y_4 \end{bmatrix} \begin{bmatrix} V_{PQ} \\ V_{PV} \end{bmatrix} \quad (4)$$

The L for system stability is presented via:

$$L = \max(L_j), j = 1, 2, \dots, N_{PQ} \quad (5)$$

The objective function is obtained via:

$$J_3 = VL(x, u) = L_{\max} \quad (6)$$

2.2. Objective Constraints

• Constraints 1: Equality Constraints

The constraints for the bus are obtained via:

$$\begin{cases} P_{G_i} - P_{D_i} = V_i \sum_{j=1}^{N_B} V_j [G_{ij} \cos(\theta_i - \theta_j) + B_{ij} \sin(\theta_i - \theta_j)] \\ Q_{G_i} - Q_{D_i} = V_i \sum_{j=1}^{N_B} V_j [G_{ij} \sin(\theta_i - \theta_j) - B_{ij} \cos(\theta_i - \theta_j)] \end{cases} \quad (7)$$

The N_B is bus number; Q_{G_i} is reactive power of bus; P_{D_i} and Q_{D_i} are load real and reactive power. The G_{ij} and B_{ij} are transfer conductance and susceptance between buses i and j . The V is voltage magnitude and θ is voltage angle at buses.

• Constraints 2: Generation Capacity Constraints

Generator power and bus voltage are obtained via:

$$Q_i^{\min} \leq Q_i \leq Q_i^{\max}, v_i^{\min} \leq v_i \leq v_i^{\max} \quad (8)$$

where Q_i^{\min} and Q_i^{\max} are power minimum and maximum, and v_i^{\min} and v_i^{\max} are i th transmission line voltage. The thermal curve is presented in Figure 1.

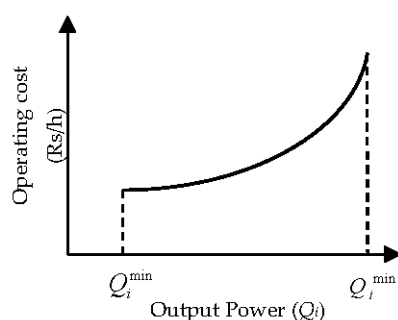


Figure 1. Operating costs curve.

- *Constraints 3: Line flow constraints*

Here, RPD solution is discussed via the proposed algorithm, and this constraint is presented as follows:

$$|S_{Lf,k}| \leq S_{Lf,k}^{\max}, k = 1, 2, \dots, L \quad (9)$$

The $S_{Lf,k}^{\max}$ is the flow limit, and L is lines [77].

- *Constraints 4: Discrete control variables*

The shunt susceptance (B_{sh}) and transformer tap settings (T_i) values are obtained as discrete values, and they are restricted via limits in Equation (10):

$$\begin{cases} T_i^{\min} \leq T_i \leq T_i^{\max} \\ B_{sh_i}^{\min} \leq B_{sh_i} \leq B_{sh_i}^{\max} \end{cases} \quad (10)$$

2.3. Problem Formulation

RPD is represented by:

$$\begin{aligned} J_{Final} &= \min_{P_G} [VL(x, u), VD(x, u), P_{loss}(x, u)] \\ \text{subject to :} \\ g(x, u) &= 0 \\ h(x, u) &\leq 0 \\ \text{where, } x^T &= [V_L]^T, [Q_G]^T, [S_L]^T, \\ u^T &= [V_G]^T, [T]^T, [Q_C]^T \end{aligned} \quad (11)$$

The g and h are equality and inequality constraints. $[V_L]$, $[Q_G]$, and $[S_L]$ are vectors of load bus voltages, generator outputs, and transmission line loading. $[V_G]$ and $[Q_C]$ are vectors of generator bus voltages and reactive compensation devices. The x and u are control variable vectors.

3. Problem Formulation with Wind Turbine Effect

3.1. Power Capacity in Wind Farms

The WT expansion concepts are important in variable speed wind turbines, and DFIG usually pertains to wind generation technology [98].

Here, the double-fed induction generator (DFIG) method is used, and P–Q qualities of WTs are presented in Figure 2. The data of wind turbine Gamesa WT G80-2.0MW is given in [99], and in this WT, the power ability is bounded (red color). WF P–Q properties are similar to WTs but transferred to the capacitive side (green color) which is presented in Figure 3.

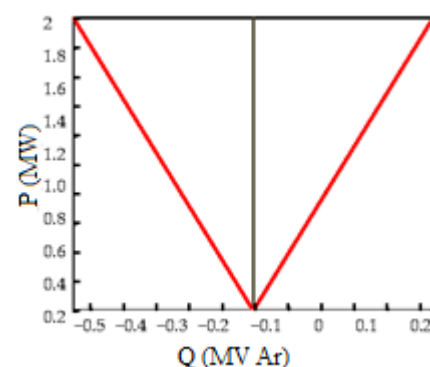


Figure 2. Q characteristic for WT in G80-2.0 MW.

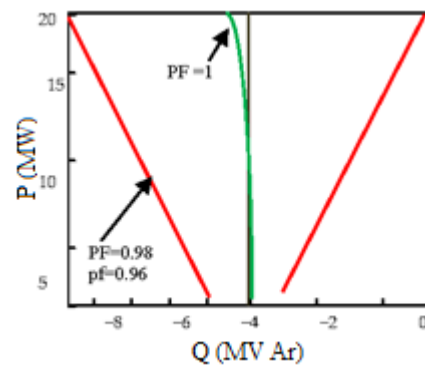


Figure 3. Q characteristic for WF in G80-2.0MWTs.

When WF takes capacitive power in low power WTs are changed to inductive.

3.2. Objective Function

Control of STATCOM and capacitor bank for RPD optimization via FIHBMO algorithm are used. The suggested fitness is taken to minimize power loss via WF cables as follows:

$$\text{Minimize } J(\text{Var}_x, \text{Var}_y) = \text{Min } P_{\text{losses}} \quad (12)$$

The Var_y represents transformer tap, and Var_x refers to dependent variables, which are WT power outputs. The j is optimized variables and each i is the solution.

3.3. Objective Constraints

The WT power, transformers tap, and STATCOM are limited via their minimum and maximum capacity, respectively:

$$Q_{WT_i}^{\min} \leq Q_{WT_i} \leq Q_{WT_i}^{\max}, i = 1, 2, \dots, N_G \quad (13)$$

$$T_i^{\min} \leq T_i \leq T_i^{\max} \quad (14)$$

$$Q_{Statcom}^{\min} \leq Q_{Statcom} \leq Q_{Statcom}^{\max} \quad (15)$$

where

The power prerequisite in PCC models is as follows:

$$Q_{PCC}^* = Q_{PCC}^{meas} \quad (16)$$

where Q_{WT_i} , $Q_{Statcom}$ and T_i are wind reactive power, STATCOM output and transformers tap position, respectively. Solutions searching are employed, and limitations are presented via:

$$S_i^{k+1} = \begin{cases} S_i^k + v_i^{k+1}, & S_i^{\min} \leq S_i^k + v_i^{k+1} \leq S_i^{\max} \\ S_i^{\min}, & S_i^{\min} > S_i^k + v_i^{k+1} \\ S_i^{\max}, & S_i^k + v_i^{k+1} > S_i^{\max} \end{cases} \quad (17)$$

where S indicates the feasible solution. With the above equation, the inequality restraints are satisfied, and equality restraint (16) remains solved. To decrease the CPU time searching, the equality constraint is increased, and error is presented via:

$$|Q_{PCC}^* - Q_{PCC}^{meas}| < \varepsilon \quad (18)$$

4. The Suggested Scheme

4.1. Briefly Review of Standard HBMO Algorithm

The honeybee has a single queen and thousands of workers [100]. For algorithm development, workers are limited to squab care, which acts to increase the broods. The drone mates use the following function [101]:

$$\text{prob}(Q, D) = e^{\frac{-\Delta(f)}{S(t)}} \quad (19)$$

The $S(t)$ and $E(t)$ decay by these equations:

$$S(t+1) = \alpha_{HBMO} \times S(t) \quad (20)$$

$$E(t+1) = E(t) - \gamma_{HBMO} \quad (21)$$

where $\text{Mate_Prob}(Q, D)$ is the probability function of adding the sperm of drone D to the spermatheca of queen Q . $\Delta(f)$ is the absolute difference between the fitness of D (i.e., $f(D)$) and the fitness of Q (i.e., $f(Q)$). $S(t)$ is queen's speed at time t . $E(t)$ is queen's energy at time t .

The HBMO steps are the following:

- Step 1: This step is controlled by several parts and the start of the HBMO procedure. Then, the drone is selected from generated broods.
- Step 2: Algorithm is started via Equation (19), and the mating flight is finished when spermatheca is complete.
- Step 3: Broods are produced via Equation (22), and they transfer genes of drones and queen to j th, which is obtained via

$$\text{brood} = \text{drone} + \beta_{HBMO}(\text{queen} - \text{drone}), \beta_{HBMO} = (0, 1) \quad (22)$$

- Step 4: The community of broods increases by applying the mutation operators as follows:

$$\begin{aligned} \text{brood}_i^k &= \text{brood}_i^k \pm (\delta_{HBMO} + \varepsilon_{HBMO}) \text{brood}_i^k \\ 0 &< \varepsilon_{HBMO}, \delta_{HBMO} < 1 \end{aligned} \quad (23)$$

β_{HBMO} is the decreasing factor, ε_{HBMO} is the growing factor and δ_{HBMO} is the growth factor.

- Step 5: If finish criteria are satisfied, the algorithm is complete; if it happens for the old criteria, go to stage 2. Otherwise, choose the current one and go to stage 2.

4.2. Fuzzy Chaotic Interactive HBMO

The HBMO includes a flexible structure for developing global exploration potential. The HBMO algorithm utilizes the independent randomly such that it affects algorithm stochastic nature Equation (22). To overcome this problem in this study, the Newtonian law of universal gravitation is added to Equation (22) as follows:

$$\begin{aligned} F_{ik_j} &= G \frac{F(\text{parent}_i) \times F(\text{parent}_k)}{(\text{parent}_{kj} - \text{parent}_{ij})^2} \cdot \frac{\text{parent}_{kj} - \text{parent}_{ij}}{|\text{parent}_{kj} - \text{parent}_{ij}|}, \\ \text{brood}_{ij}(t+1) &= \text{parent}_{ij}(t) + F_{ik_j} \cdot [\text{parent}_{ij}(t) - \text{parent}_{kj}(t)] \end{aligned} \quad (24)$$

where, $F(\text{parent}_i)$ is the fitness value of the queen i . $F(\text{parent}_k)$ is the fitness value of the drone k . In IHBMO, the gravitational force attracts drones to others, and if premature convergence occurs, there is no recovery in the algorithm. So, a new operator is added to IHBMO to improve its flexibility in solving problems. Then, a new operator is presented:

$$c_{i+1}^j = \begin{cases} 2c_i^j \times (1 + \frac{g_{best}^{k-1}}{g_{best}^k}) \times \cos(2\pi \frac{g_{best}^{k-1}}{g_{best}^k}), & 0.5 < c_i^j \leq 1 \\ 0.1c_i^j \times (1 - \cos((1 + \frac{g_{best}^{k-1}}{g_{best}^k}))), & 0 < c_i^j \leq 0.5 \end{cases} \quad (25)$$

N_{chaos} is the number of individuals for CLS. g_j^{best} is the best answer for the j th iteration. Where C_i^j is the chaos variable. The $g_{best}^{k-1} / g_{best}^k$ reports that fine-tuning is necessary to obtain a gyration sequence. The chaotic search on IHBM0 is obtained via the following steps.

Step 1: Produce the initial chaos population in CLS.

$$\begin{aligned} X_{cls}^0 &= [X_{cls,0}^1, X_{cls,0}^2, \dots, X_{cls,0}^{Ng}]_{1 \times Ng} \\ cx_0 &= [cx_0^1, cx_0^2, \dots, cx_0^{Ng}] \\ cx_0^j &= \frac{X_{cls,0}^j - P_{j,min}}{P_{j,max} - P_{j,min}}, j = 1, 2, \dots, Ng \end{aligned} \quad (26)$$

Chaos variable is obtained via

$$\begin{aligned} X_{cls}^i &= [X_{cls,i}^1, X_{cls,i}^2, \dots, X_{cls,i}^{Ng}]_{1 \times Ng}, i = 1, 2, \dots, N_{chaos} \\ x_{cls,i}^j &= cx_{i-1}^j \times (P_{j,max} - P_{j,min}) + P_{j,min}, j = 1, 2, \dots, Ng \end{aligned} \quad (27)$$

Step 2: Chaotic variables

$$\begin{aligned} cx_i &= [cx_i^1, cx_i^2, \dots, cx_i^{Ng}], i = 0, 1, 2, \dots, N_{chaos} \\ cx_{i+1}^j &= \text{base CLS } j = 1, 2, \dots, Ng \\ cx_0^j &= \text{rand}(0) \end{aligned} \quad (28)$$

The *Rand* [0,1] produces a number from 0 to 1.

Step 3: Map variables

Step 4: Chaotic variables to variables

Step 5: Solution via variables.

To develop the performance of IHBM0, the ϵ_{HBMO} and δ_{HBMO} adapt via

$$\begin{aligned} \epsilon_{HBMO}^{iter+1} &= \epsilon_{HBMO}^{iter} + \Delta \epsilon_{HBMO}^{iter}, \Delta \epsilon_{HBMO}^{iter} \in [-1, 1] \\ \delta_{HBMO}^{iter+1} &= \delta_{HBMO}^{iter} + \Delta \delta_{HBMO}^{iter}, \Delta \delta_{HBMO}^{iter} \in [-1, 1] \end{aligned} \quad (29)$$

$\Delta \epsilon_{HBMO}^{iter}$ and $\Delta \delta_{HBMO}^{iter}$ are obtained via a fuzzy mechanism as follows:

$$Nor_Fit^{iter} = \frac{F(g_{best}^{iter}) - F_{min}}{F_{max} - F_{min}} \in [0, 1] \quad (30)$$

Nor_Fit^{iter} , ϵ_{HBMO} , and δ_{HBMO} contain input variables, and changes in growth are output variables. To select the best growth factors, the triangular functions are considered.

4.3. Modified Gray Code (MGC)

Gray code is suggested via Frank Gray for shaft encoders [102], and its mathematical methods are presented in [103]. In integer parameter $m \in \mathbb{N}$, $[m]$ shows set $\{0, 1, \dots, m\}$, and in n -tuple, $b \in \mathbb{N}n$:

- $[b]$ denotes the produce set $[b_1] \times [b_2] \times \dots \times [b_n]$, and
- $||b|| = \sum_{i=1}^n b_i$.

The MGC in creation $[b]$, shown here by $G_n(b)$, is obtained via:

$$G_n(b) = \begin{cases} 0, & \text{if } n = 0 \\ 0G_{n-1}(b'), 1\overline{G_{n-1}(b')}, 2G_{n-1}(b') \\ \dots, G'_{n-1}(b'), & \text{if } n > 0 \end{cases} \quad (31)$$

$b' = b_2b_3 \dots b_n$ and $\overline{G_{n-1}(b')}$ are reverse for $G_{n-1}(b')$, and $G'_{n-1}(b')$ is $G_{n-1}(b')$. Two-tuple $G_n(b)$ differs by +1 or -1; note that in Gray code method [28], a new ordering scheme linearly builds piecewise and more precisely, since overall, J_{Final} is smoother and “jumpy”.

B_{sh} (shunt) and T tap include a small capacity change for numbers, and J_{Final} function is obtained via one variable; a Gray code assists in reducing piecewise the J_{Final} function to one-dimension.

4.4. Non-Dominated Sorting (NDS)

In sorting, the agent chooses method in the population or not in it:

$$Obj.1[i] < Obj.1[j] \text{ and } Obj.2[i] < Obj.2[j], i \neq j \quad (32)$$

This method continues until shared fitness is obtained, and these values are obtained via

$$Share(d_{ij}) = \begin{cases} 1 - (\frac{d_{ij}}{\mu_{share}})^2, & \text{if } d_{ij} < \mu_{share} \\ 0, & \text{otherwise} \end{cases} \quad (33)$$

$$d_{ij} = \sqrt{\sum_{a=1}^{P_1} (\frac{x_s^i - x_s^j}{x_s^{\max} - x_s^{\min}})^2} \quad (34)$$

The p_1 refers to variable numbers, x_s is the s th variable, and μ_{share} is the maximum distance between agents, and *Nichecount* (N) is obtained via

$$Nichecount_i = \sum_{j=1}^N Share(d_{ij}) \quad (35)$$

A. TOPSIS mechanism

A fuzzy set is obtained to handle the dilemma; let (R_{ij}) be the efficiency rating of X_j with respect to A_i . To obtain objective weights via entropy, a model matrix is needed for each A_j using the following equation:

$$P_{ij} = \frac{R_{ij}}{\sum_{p=1}^n R_{pj}}, \begin{cases} i = 1, 2, \dots, N_p \\ j = 1, 2, \dots, N_o \end{cases} \quad (36)$$

A normalized decision matrix showing alternative performance is obtained via:

$$P = \begin{bmatrix} P_{11} & P_{12} & \dots & P_{1m} \\ P_{21} & P_{22} & \dots & P_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ P_{n1} & P_{n2} & \dots & P_{nm} \end{bmatrix} \quad (37)$$

The decision quantity is obtained Equation (37), and for A_j ($j = 1, 2, \dots, m$), it can be obtained as follows:

$$e_j = \frac{-1}{\ln n} \sum_{i=1}^n P_{ij} \ln P_{ij} \quad (38)$$

The d_j of the average intrinsically controls for A_j via this equation:

$$d_j = 1 - e_j \quad (39)$$

The objective weights for A_j are:

$$w_j = d_j / \sum_{k=1}^m d_k \quad (40)$$

v_{ij} was calculated via:

$$v_{ij} = w_j P_{ij} \quad (41)$$

The subsequent step is aggregated to generate the performance of A_j , which it obtains via:

$$\begin{cases} A^+ = (\max(v_{i1}) \max(v_{i2}) \dots \max(v_{im})) = (v_1^+, v_2^+, \dots, v_m^+) \\ A^- = (\min(v_{i1}) \min(v_{i2}) \dots \min(v_{im})) = (v_1^-, v_2^-, \dots, v_m^-) \end{cases} \quad (42)$$

A^+ and A^- are the + and—solution, and alternatives are obtained via:

$$\begin{aligned} d_j^+ &= \left\{ \sum_{i=1}^m (v_{ji} - v_i^+) \right\}, j = 1, 2, \dots, n \\ d_j^- &= \left\{ \sum_{i=1}^m (v_{ji} - v_i^-) \right\}, j = 1, 2, \dots, n \end{aligned} \quad (43)$$

The relative closeness for X_j in A^+ is obtained via:

$$C_j = \frac{d_j^-}{d_j^- + d_j^+}, j = 1, 2, \dots, n \quad (44)$$

The d_j^- and $d_j^+ \geq 0$ and $C_j \in [0, 1]$.

The X_j was closer to A^+ and steps need via this models:

- Step 1: Select pareto-optimal for functions.
- Step 2: Find attributes for cost.
- Step 3: List pareto-optimal.
- Step 4: Compute significance by Equation (40).
- Step 5: Made P_{ij} and v_{ij} .
- Step 6: Compute A^+ , A^- .
- Step 7: Pareto-optimal and select C_j for maximum ranking.

B. Data Sharing (DS)

Usage of optimizers is feasible to guide engineers. DS consider D drones, S_1, S_2, \dots , and SD in N to optimize M functions. The f_1 and f_2 are obtained via D_1 and D_2 , and drones are obtained via respective functions. The D_2 queen is used to obtain a new D_1 queen colony, and X_1 queen is used to obtain D_2 queen.

5. Applying the FIHBMO to the Proposed Problem

Here, the application of the suggested model for solving RPD is illustrated. The process of RPD optimization using the proposed technique is as follows:

Step 1: The population of state variables is randomly produced. It can be calculated via:

$$D = [D_1, D_2, D_3, \dots, D_n] \quad D_i = (d_i^1, d_i^2, \dots, d_i^m) \quad (45)$$

The D_i is calculated.

- Step 2: Randomly produce population of bees for variables.
- Step 3: Calculate functions and sort the population and data for fitness.
- Step 4: Use the suggested method for the best solution obtained for CLS, when the best solution is obtained via CLS as a new solution.
- Step 5: When broods are produced, solutions are improved with a mutation method.
- Step 6: If the iteration number obtains its maximum, the algorithm is finished; go to step 2.

The process of the algorithm is reported in Figure 4.

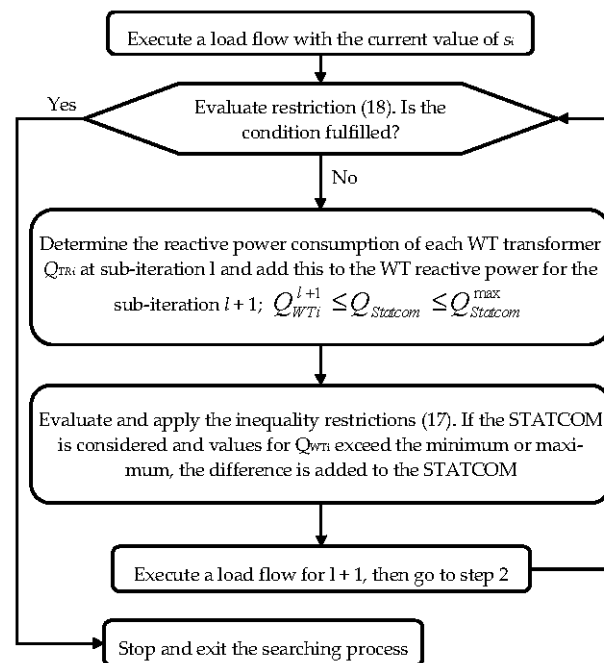


Figure 4. The flowchart of the suggested model.

6. Simulation and Discussion

The proposed technique was applied in MATLAB(9.5/Mathworks, New York, NY, USA) to solve RPD, and simulations were done using a computer. To evaluate the effectiveness and robustness of this strategy, simulations were done for systems and in different cases using the following scenarios:

Scenario I: RPD without the effect of wind.

Scenario II: Classic RPD in the presence of wind farms.

Scenario III: Proposed optimized dispatch based on Section 3.

6.1. Scenario I: RPD without Effect of WT

For this subsection, the suggested algorithm of IEEE 30-bus was used, as presented in Figure 5, for obtaining algorithm suitability via the system in [104–108]. The output list is in Table 1.

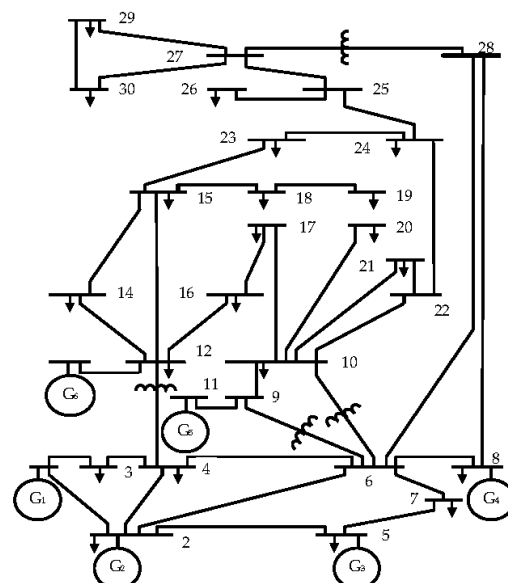


Figure 5. IEEE 30-bus system.

Table 1. Output Control Variables Obtained After Optimization For IEEE 30 Bus.

Control Variable Settings	Case I in Scenario I	Case II in Scenario I	Case III in Scenario I	Case IV in Scenario I
	Proposed Method	Proposed Method	Proposed Method	Proposed Method
V ₁ p.u	1.0919	1.0509	1.0831	1.0812
V ₂ p.u	1.0094	0.9552	1.0584	0.9254
V ₅ p.u	0.9277	1.0359	1.0919	1.0827
V ₈ p.u	0.9299	1.0310	1.0311	1.0265
V ₁₁ p.u	0.9515	0.9325	0.9071	0.9195
V ₁₃ p.u	1.0681	0.9238	1.0698	0.9557
T ₁₁	0.9509	0.9997	1.0868	1.0094
T ₁₂	1.0629	1.0919	1.0357	1.0915
T ₁₅	0.9487	0.9681	1.0515	1.0930
T ₃₆	1.0859	1.0171	1.0486	0.9315
QC ₁₀ p.u	2.9765	0.0448	4.9784	4.0941
QC ₁₂ p.u	3.9393	0.0503	4.0311	4.0914
QC ₁₅ p.u	2.9502	3.9510	3.9342	3.9971
QC ₁₇ p.u	2.0232	2.0012	4.0412	3.0601
QC ₂₀ p.u	1.0662	1.0514	5.000	0.9108
QC ₂₁ p.u	1.0171	1.0507	5.000	1.0062
QC ₂₃ p.u	1.0099	0.9761	5.000	1.0558
QC ₂₄ p.u	1.0834	1.0136	5.000	1.0868
QC ₂₉ p.u	1.0662	0.9152	5.000	0.9266
Power losses MW	4.4433	6.6423	6.661	4.9033
voltage deviations p.u	0.8343	0.0453	0.894	0.2432
L_{max}	0.1332	0.1343	0.118	0.1332

To find the effectiveness for the suggested model, the four cases are suggested as follows:

Case (I) Function of real power losses is suggested (Figure 6A).

Case (II) Function of improvement voltage is suggested (Figure 6B).

Case (III) System was suggested as voltage stability (*L-index*) (Figure 6C).

Case (IV) Constraints were used for voltage stability and profile and transmission loss constraints (Figure 6D).

Results confirmed the potential of the suggested model for solving a real-world constrained optimization problem.

The results of the analyzed cases are reported in Table 2.

The FIHBMO was applied to 30-bus.

The transmission losses were reduced from 5.934 MW to 4.9593 MW via the proposed model. Data for the reduction system are compared to methods in [106,107]. In these methods, CLPSO is used for solving the optimization problem. Table 3 shows the RPD solution if four compensation devices are installed after changing constraints in [108], and the problem was solved in comparison to SARCGA.

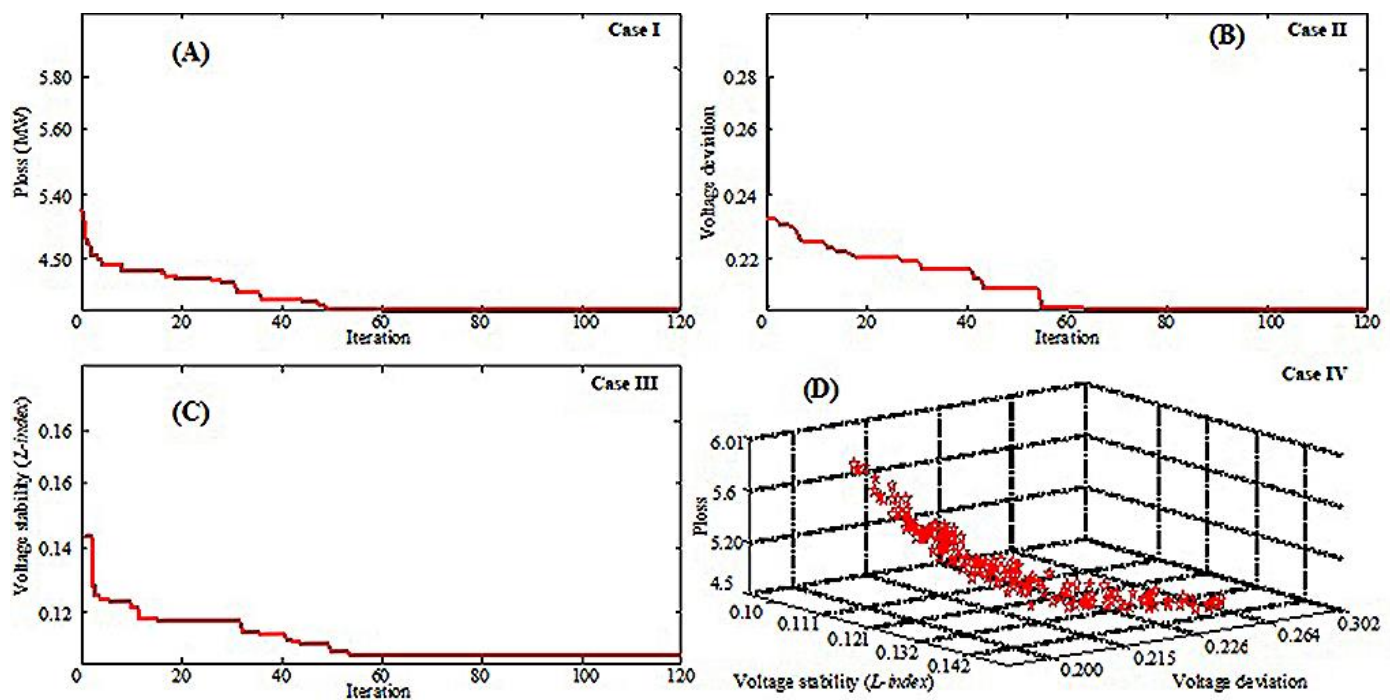


Figure 6. Pareto-optimal front of proposed technique, (A) case 1, (B) case 2, (C) case 3, and (D) case 4.

Table 2. Comparison of transmission losses for different algorithms based on the optimization of the IEEE 30-bus system. Reproduced from [109], International Research Publication House: 2010.

Compared Item	SGA [109]	PSO [109]	HAS [109]	FIHBMO
Best P_{loss} (MW)	4.9408	4.9239	4.9059	4.9876
Worst P_{loss} (MW)	5.1651	5.0576	4.9653	5.8755
Average P_{loss} (MW)	5.0378	4.9720	4.9240	4.4356
Psave (%)	16.07	17.02	17.32	17.43

Table 3. Comparison of the proposed method with the literature results. Reproduced from [106], Elsevier: 2009.

Solving with Constraints According to [106]					
Method	CLPSO [106]	EP [31]	CGA [106]	AGA [106]	PSO [106]
Ploss	5.988	4.963	4.980	4.926	4.8136
Method	CLPSO [106]	HSA [108]	HBMO	FIHBMO	
Ploss	4.7208	4.7624	4.7693	4.432	

Moreover, the results of solving the RPD problem are reported in Table 4. The FIHBMO has better problems, and data in FIHBMO are simple and acceptable in comparison to GA and PSO.

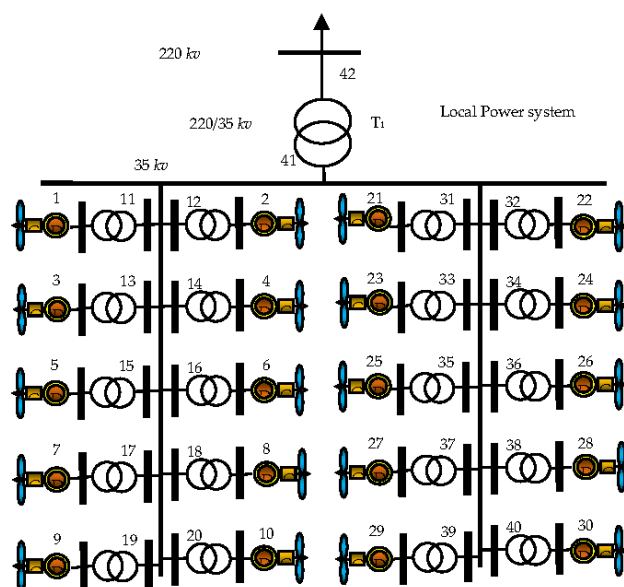
Table 4. Comparison of the proposed method with the literature results. Reproduced from [106], Elsevier: 2009 and from [107] Elsevier: 2011.

Solving with Constraints According to [105]		Solving with Constraints According to [107]	
Method	Power Loss	Method	Power Loss
PSO [108]	4.6723	PSO [11]	5.092
HAS [108]	4.6403	HAS [108]	5.007
SARCGA [107]	4.5913	GQ-GA [110]	5.04
GSA [109]	4.5143	DE [111]	5.011
BBO [112]	4.551	IPM [111]	5.101
FIHBMO	4.432	FIHBMO	4.989

The results indicate that the suggested model has superiority and better results for power loss and solution quality than other models.

6.2. Scenario II: Classic RPD in WF

WF has 403 node [113–121], and only 42 nodes are presented in Figure 7. Table 5 is reported data between TGA, IGA and the suggested model. The IGA has decreased network losses that are better than TGA. The advantage of the suggested model is confirmed via a 4% reduction of VAR cost and a 9% decreasing in power loss. It can be concluded in Table 5, voltage stability of the conventional model is better than the suggested approach.

**Figure 7.** Model of wind farm with 42 nodes.**Table 5.** Compared results of reactive power optimization in wind farms. Reproduced from [39], Springer: 2020.

Project	Investment of Reactive Power Compensation (Million Yuan)	The System Loss(kW)		
		V = 4m/s	V = 8m/s	V = 12m/s
TGA [39]	338	1872	2480	3129
IGA [39]	336	1731	2292	2892
FIHBMO	297	1711	2256	2498

6.3. Scenario III: Proposed Optimized Dispatch Based on Section 3

The dispatch model tested for WF is presented in Figure 8. The WF has 12 WTs in the sketch, and WF and WT characteristics are presented. The purpose is to obtain a power setpoint for PCC and to minimize power losses. The suggested model was applied to six strategies for reactive power control for WF, and data are presented in Figure 9. These strategies are as follows:

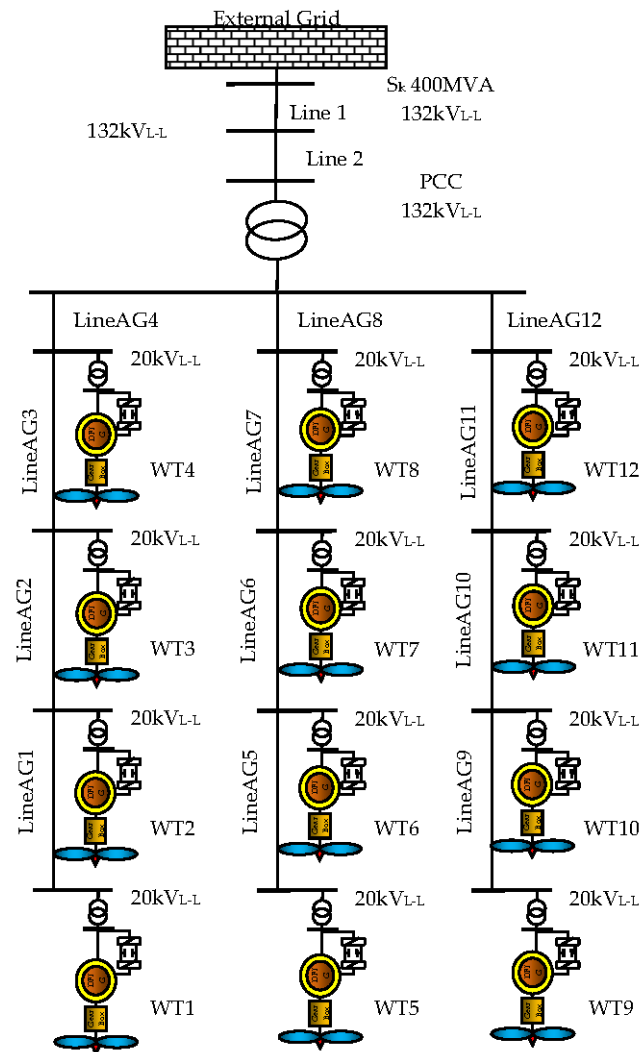


Figure 8. Structure of the tested wind farm.

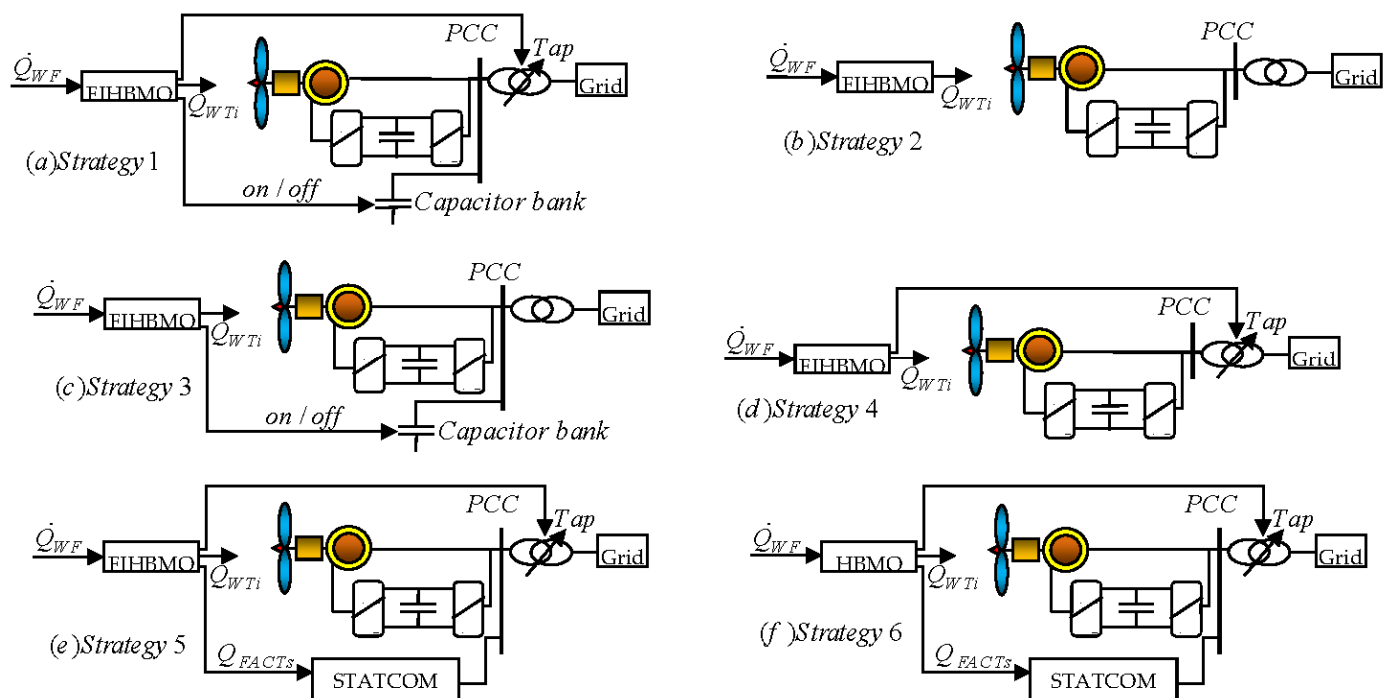


Figure 9. Feasible solution search FIHBMO and basic HBMO. (a) C.1. Strategy 1: Control variables are the power of WT QWTi, te tap situation of the PCC transformer, and capacitor bank. (b) C.2. Strategy 2: The model uses the power of WT QWTi as the control variable. (c) C.3. Strategy 3: RPD is done via power injection of WT QWTi and the use of a capacitor bank. (d) C.4. Strategy 4: Control variables are the power of WT QWTi and the tap position. (e) C.5. Strategy 5: STATCOM is installed in PCC and reactive power of STATCOM with QWTi. (f) C.6. Strategy 6: Finally, strategy 5 is employed to HBMO without Q*PCC.

Table 6 shows the RPD values (MVar) obtained with the FIHBMO for power productions.

Table 6. Results of option I for reactive power WTs, tap position, and compensation equipment.

Q*PCC	PWF 100%		PWF 80%		PWF 50%		PWF 20%		PWF 10%	
	4	3.5	3.5	2	3	1	0.5			
QWT1	0.147	0.091	0.053	0.032	0.062	0.038	0.008			
QWT2	0.173	0.072	0.187	0.036	0.168	0.084	0.020			
QWT3	0.407	0.394	0.325	0.032	0.204	0.080	0.040			
QWT4	0.407	0.407	0.325	0.204	0.205	0.082	0.040			
QWT5	0.127	0.082	0.094	0.022	0.036	0.033	0.006			
QWT6	0.254	0.072	0.147	0.034	0.155	0.084	0.033			
QWT7	0.405	0.406	0.323	0.035	0.206	0.083	0.041			
QWT8	0.405	0.405	0.323	0.204	0.206	0.083	0.041			
QWT9	0.123	0.067	0.086	0.025	0.075	0.033	0.011			
QWT10	0.162	0.154	0.126	0.035	0.124	0.083	0.020			
QWT11	0.407	0.407	0.325	0.043	0.204	0.084	0.040			
QWT12	0.407	0.407	0.325	0.204	0.204	0.084	0.040			
Tab	−2	−2	−2	−2	−2	−2	−2			
Comp	ON	ON	ON	ON	ON	OFF	OFF			

P_{losses} and power for proportional distribution are reported and compared in Table 6, since for the FIHBMO model, maximum error is allowed via E and E is reduced. Reduction in P_{losses} is greater for WF output power in Table 7.

Table 7. Results for Strategy I; comparison between proportional distribution and proposed FIHBMO Method.

P_{WF}	Proportional Distribution (PD)		
	Q_{PCC}^*	P_{losses} (MVar)	$Q_{PCC}^* - Q_{PCC}^{meas}$ (%)
100%	4	0.113	14.446
100%	3.5	0.1133	10.8922
80%	3.5	0.0733	8.0349
50%	2	0.029	2.0973
50%	3	0.0304	33.3397
20%	1	0.0049	11.4268
10%	0.5	0.0013	28.2564
P_{WF}	FIHBMO		
	P_{losses} (MVar)	$Q_{PCC}^* - Q_{PCC}^{meas}$ (%)	Reduction P_{losses} %
100%	0.1121	4.2312	0.07964
100%	0.1125	4.2403	0.70609
80%	0.0720	4.2342	1.7735
50%	0.0284	4.2374	2.0689
50%	0.0285	4.2356	6.25
20%	0.0044	4.2403	10.2041
10%	0.0012	4.2352	6.9231

Simulation data for strategies 2 to 6 are presented in Table 8. Table 8 indicates that power percentage is decreased for the case in which voltages and taps are 1 p.u.

Table 8. Results of option I for reactive power WTs, tap position, and compensation equipment.

WT Units	Strategy				
	2	3	4	5	6
QWT1	0.2953	0.0768	0.4063	0.1754	0.0033
QWT2	0.4062	0.3272	0.2563	0.2923	0.2143
QWT3	0.4063	0.4058	0.4063	0.2886	0
QWT4	0.4063	0.4060	0.4064	0.4005	0.4056
QWT5	0.3053	0.0768	0.3297	0.1823	0.0989
QWT6	0.4063	0.3147	0.4064	0.3016	0
QWT7	0.4064	0.4054	0.4064	0.1873	0.1545
QWT8	0.4063	0.4054	0.4064	0.4057	0.4067
QWT9	0.3582	0.0757	0.4064	0.1665	0
QWT10	0.4064	0.2811	0.2913	0.1365	0.1246
QWT11	0.4062	0.4063	0.4064	0.4065	0.3564
QWT12	0.4066	0.4064	0.4064	0.4065	0
Comp	–	1	–	–	–

Table 8. Cont.

WT Units	Strategy				
	2	3	4	5	6
Tab	–	–	–2	–2	–2
Q_{ST}	–	–	–	1.218	1.219
P_{losses}	0.1233	0.1219	0.1131	0.1123	0.1126
$Q_{PCC}^* - Q_{PCC}^{meas}$ (%)	4.9813	4.9503	4.9678	4.0394	40.726

7. Conclusions

The optimal multi-objective RPD problem is effective on secure and power networks, which include both discrete and continuous control variables. The major drawback of previous works is that optimal RPP load demand and wind power uncertainties at the same time are not examined. In this study, the RPP is investigated to decrease the cost of reactive power, minimize power loss, maximize voltage stability, and increase load ability. The generators' voltage, transformers tap settings and output power of VAR are considered as control variables.

Here, CLS, FIHBMO, Gray code, and data-sharing model are proposed, which include three conflicting objective functions: voltage stability, power losses, and L -index are optimized simultaneously while satisfying various practical system constraints. The proposed hybrid approach is changed in two RPDs, including 6 thermal units and 30 wind turbines whose three objective functions are calculated. Furthermore, problem equality is taken into account. The proposed method always provides solutions that satisfy the problem constraints. The robustness performance analysis of the proposed optimization technique is also presented for optimal solutions of RPD problem on a six-unit test system for 100 trial runs. The suggested model shows computational efficacy, and a promising tool for RPD solutions in power systems is suggested. The RERs incorporated in systems can provide a novel solution from an environmental and technical perspective. The inclusion of RERs can minimize the dependence on fossil fuel, decrease greenhouse gases and noxious emissions, and improve the operation. Furthermore, the power loss is reduced by the inclusion of renewable energy resources by about 3%.

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