A hybrid optimization-based approach to solve environment constrained economic dispatch problem on microgrid system

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Abstract

Generation of electricity comes with the emission of toxic gases into the atmosphere by the fossil fueled generators. Along with the promotion in the utilization of renewable energy sources (RES), it is also the duty of the power engineers to arrive at a compromised solution such that less emission of toxic gases occurs with economic generation of electricity. This paper proposes a balanced trade-off method for solving environment constrained economic dispatch (ECED) problems. A novel comparative analysis is performed among proposed ECED method with existing price-penalty-factor (PPF) and fractional programming (FP) methods for solving combined economic emission dispatch (CEED) problems on a 3-unit dynamic test system to sort out the method, which yields a better trade-off solution between generation cost and pollutants emitted. An algorithm, following the hunting strategy of wolves, is improvised by incorporating strategies from population-based sine-cosine algorithm along with position updating methods of crows to form a robust hybrid algorithm, which was used as the optimization tool for the study. Involvement of RES diminished the generation cost to 5.5% for both economic dispatch and PPF based CEED, and 6.5% decrease in emission of pollutants was observed due to the same. The generation cost and amount of emitted pollutants, evaluated using proposed ECED approach, were much closer to the economic dispatch and emission dispatch values respectively compared to PPF based and FP based CEED solution. Furthermore, statistical analysis endorses the superiority of the proposed hybrid optimizer over other algorithms presented in the state-of-art literature.

Keywords:
- Microgrid
- Energy management
- Grey wolf optimizer
- Sine cosine algorithm
- Crow search algorithm

1. Introduction

In the field of electricity industries, the efficacious and optimal operation and planning of electric power generating systems is of utmost importance. Problems based on cost efficient load dispatch (Economic Load Dispatch, ELD) are the most concerning issues in the field of control and operation of power system. Power system optimization problems employing ELD helps us determine the most appropriate, flawless and cost-effective operation by regulating the output of various generating units supplying the load demand. The sole ambition of ELD is reduction of the overall cost related to generation of power without violating any constraint.

On the basis of the power demand, generally referred as load, economic dispatch problems are broadly categorized into two parts: Static ELD, where the load demand is fixed for large intervals of time, which results in the fixed generator outputs for the duration in case of static load economic dispatch. The sole purpose is to obtain the minimum cost of generation and transmission, for every epoch of time, such that the total power generated can be exactly equal to the power required without violation of any constraint; Dynamic ELD, where the demand of the power system is consistently varying due to which the generators need to correspondingly adapt. In other words, with the increase in the load demand, the generator output needs to be increased and vice-versa. Thus, in dynamic load dispatch, the scheduling of generators committed to the grid is done as per the varying load at regular intervals of time with the intention of least cost of generation.

However, emission problems corresponding to the fossil fuels-based power plants cannot be neglected. With increasing environmental concern, it is our duty to not just optimize the operation of these power plants for our economic benefits but also, tackle the increasing emission problems as well. The major portion of the pollution is governed by the operation of thermal power plants which utilize fossil fuels for power generation. To deal with these serious environmental problems, Distributed Generation (DG) methodology is also adopted. DGs are combination of small power plants along with various other small scale...
renewable energy sources which include wind turbine (WT), photovoltaic (PV) systems, Diesel engine, etc., which are installed at location near to user end. These help in reducing transmission losses due to reduction in the distance between the user and the plant and reduce environmental degradation as the load is now shared among various generating units, including renewable sources of energy. Despite of the aforementioned benefits of the DGs, issues like reliability and stability due to their large-scale incorporation cannot be neglected. To eliminate the issues related to DGs, the concept of microgrid was coined which provides the advantages of DGs and reduces their negative impact.

Every utility tries to fulfill the load demand with least cost of generation as well least value of emission. Being contradictory to each other, it is not possible to obtain, at the same time, the least value of both generation as well as emission. This leads to the concept of Combined Economic and Emission Dispatch (CEED). Unlike ELD, where the sole target is to minimize the cost of generation, the objective of CEED includes the concerns regarding pollution and emission along with the aim to minimize the overall cost. These calls, for certain rules and regulations, that need to be followed by both private and government firms, e.g., to reduce the various toxic effluents.

Ma et al. (2017) propose load dispatch model for charging plug-in electric vehicles to obtain the reduced cost of generation and environmental emissions. Research was carried on three case studies: 6-unit without PEV; 6-unit with PEV, and; 10-unit with PEV. Levenbergh Marquardt Back-Propagation Algorithm (LMBP) based Artificial Neural Network (ANN) was used by Daniel et al. to solve Dynamic Economic Load Dispatch (DELD) problems (Daniel et al., 2018). Tests were carried on 9 generating unit considering ramp rate limit constraints (RRL). Hybridized algorithm constituted with the amalgamation of Artificial Algae Algorithm (AAA) and classical Simplex Search method (SSM) having dynamically tuned parameters was proposed by Kumar and Dhillon (2018), where AAA executes overall optimization while SSM searches locally. The proposed algorithm was applied on various test systems, considering 13 generating units, 40 generating units and 80 generating units and the effects of Valve Point Effects (VPE), 140 generating units and the prohibited operating zones (POZs) and VPE and transmission losses. DELD problems considering VPE is solved using improved PSO (IPSO), proposed by Yuan et al. (2009). The technique to solve optimization problems considering time varying emission dispatch (MODEED). The DSM approach is based on day ahead load shifting and tested on 6 units considering, ramp rate limits, coefficients related to fuel and emission and 24 h forecasted demand considering shifting and tested on 6 units considering, ramp rate limits, coefficients related to fuel and emission and 24 h forecasted demand considering different cases using DSM. DELD problems considering VPE is solved using improved PSO (IPSO), proposed by Yuan et al. (2009). The inequality constraints are handled using feasibility-based selection technique, and power balance constraint using heuristic strategies without use of penalty factors. Tests were performed on 10- generator system with cases of inclusion and exclusion of transmission losses and
triplled ten-unit system to obtain 30 units data. Xu et al. (2014) compared Genetic Algorithm (GA) and Dynamic Programming (DP) for ELD of 26 hydro units of the three Gorges Reservoir. Hybridized Bacterial Foraging (BF) algorithm with simplified swarm optimization combined with opposition-based initialization and new mutation operator is proposed by Azizipanah-Abarghooye (2013), and tested on test systems comprising different generators sets: 5 units, 10 units, 30 units and 100 units, considering POZs as well as VPE. Modified group search algorithm is presented by Daryanian and Zare (2018) for solving problem based on the combination of economic and emission dispatch on IEEE 30 bus system with cases of inclusion and exclusion of system loss along with the other constraints. Solution to stochastic DELD system incorporating WT and PV based generation systems by Improved FireWorks Algorithm (IFWA) is presented by Jadoun et al. (2018). Table 1 shows a summarized of the state of the art in economic emission dispatch for dynamic systems. The Table is dissected with respect to the optimization algorithms used, dimension of the test system, and type of RES implemented and year of publication.

1.1. Research gap and objective of the paper

A detailed in-depth literature review performed above highlights the innovative research going on with respect to CEED problems on dynamic system considering various test systems and entities. However, it was also noticed that every research article emphasized on a particular multi-objective optimization algorithm to perform a fixed type of CEED on dynamic test systems. Most of the papers are based on the pareto-front using multi-objective technique of performing CEED. The literature review shows that there is a gap in a fair comparative analysis among two or more methods of CEED, and the reason of choosing the multi-objective type over the others is not studied enough.

The objective of the paper is the production of electricity power in a way such that the generation cost is minimized and the atmosphere remains clean, i.e., least possible amount of toxic gases is emitted from the combustion of fossil fuels by the generators. Three methods of combined economic emission dispatch are compared and contrasted among themselves to sort out the way, which delivers the better compromised solution between minimized generation cost and pollutants emission. All the methods are theoretically defined and mathematically formulated in the succeeding sections of the paper.

Recent literature considers algorithms such as Grey Wolf Optimizer (GWO), Sine Cosine Algorithm (SCA) and Crow Search Algorithm (CSA) in tackling multi-modal and complex optimization problems. The advantages of GWO in a large search space is its outstanding facet, it avoids premature convergence, it has lesser number of control parameters and gives the same accurate result consistently even after many trials. SCA presents the advantage of extraordinary exploration potential, and its toggling between sine and cosine functions generates an adequate trade-off between diversification and intensification process. While CSA has the prominent feature of exploitation potential, which ensures handling enormous population size with ease and results in rapid convergence.

This paper proposed a hybrid of these three algorithms as GWOSCA-CSA, which would ensure adaptation of the best attributes of all the three thereby delivering optimal solutions.

1.2. Contributions

The main contributions of this paper to the state of the art on CEED studied above are listed as follows:

i. Three different types of CEED methods are studied on a 3-unit RES integrated low voltage microgrid systems.

| Optimization tools used | System Description | RES | Year | Ref |
|-------------------------|-------------------|-----|------|-----|
| MO-DE with self-adaptive parameter | 10 units with EV | WT | 2020 | Qiao and Liu (2020) |
| Two-stage compensation algorithm | IEEE-118 bus test system & provincial power grid | WT | 2017 | Xie et al. (2017) |
| Gradient based JAYA | Multi-area with 6, 10, 16, 40 & 120 units | NA | 2016 | Azizipanah-Abarghooe et al. (2016) |
| Tent-Map DE | 6 units and microgrid with ESS | WT | 2020 | Mandal and Mandal (2020) |
| BBO | 6, 13 & 40 units with TL | NA | 2012 | Rajasomashekar and Aravindhababu (2012) |
| CSA with PPF | 3, 5 units | WT, PV | 2020 | Dey et al. (2020a) |
| ISA with PPF | 3 units | WT, PV | 2018 | Trivedi et al. (2018) |
| Modified HSA with PPF | 3 units | WT, PV | 2018 | Elattar (2018) |
| WOA with PPF | 3 units | WT PV | 2019 | Dey et al. (2019) |
| CCSA | 6 units | NA | 2018 | Rizk-Allah et al. (2018) |
| Dinklake’s Algorithm | 6 units with TL | NA | 2016 | Chen et al. (2016) |
| Hybrid GWO-PSO | 10 unit-three areas | NA | 2020 | Azizivahed et al. (2020) |
| PSO with clone selection | 5-unit, 10-unit, 15-unit | NA | 2020 | Qian et al. (2020) |
| WOA | 5-unit, 10-unit, 30-unit | PV | 2020 | Padhi et al. (2020) |
| MO-NN based DE | 5, 10, 15 units | NA | 2018 | Mason et al. (2018) |
| Θ-modified KHA | Grid-connected MG with MT, FC, ESS | PV | 2020 | Yin et al. (2020) |
| Modified ISA | Grid-connected MG with MT, FC, ESS and DSG | WT | 2018 | Rabiee et al. (2018) |
| Improved PSO | Grid-connected MG with MT, FC, DSG and 3 EVs | PV | 2018 | Lu et al. (2017) |
| Improved PSO | Grid-connected MG with MT, FC, DSG, EV and Load Variance as third objective | WT | 2018 | Lu et al. (2018) |
| E-constrained method | Grid-connected MG with MT, CHP EV and frequency deviation as third objective | PV | 2018 | Tabar et al. (2018) |
ii. A comparative analysis among the three is performed to sort out the method that yields the best compromised solution between the generation cost and pollutants emitted.

iii. HMGWO is proposed for the first as the optimization tool for this problem, the efficiency and robustness of which is measured and compared with original GWO.

The rest of the paper is presented as follows; Section 2 defines the problem formulation; Section 3 highlights the implementation of the proposed hybrid algorithm in the current problem; Section 4 gives a detail account of simulation results, with the work being concluded in Section 5.

2. Objective function formulation

2.1. Cost function for DG units

Fuel comes with a price. Generation cost refers to the cost of the fuel utilized (or combusted) by the fossil fueled generator to produce per unit of power. The equation of the generation cost function in case of DG units is not a linear equation. It is a quadratic equation (Dey et al., 2020a; Trivedi et al., 2018; Elattar, 2018) represented by equation (1).

\[
ECD = \sum_{t=1}^{24} \sum_{j=1}^{n} \left( a_j G_j t^2 + b_j G_j t + c_j \right)
\]  

(1)

where \( a_j, b_j \) and \( c_j \) are the cost coefficients, \( G_j \) is the power output of \( j \)th DG unit. Hence, the total cost is \( ECD \), while \( n \) is the total number of involved DG units. In the case of dynamic economic load dispatch, the total cost for 24 h is calculated, where \( t \) is indication of hour.

2.2. Emission dispatch for DG units

The non-conventional fossil fueled generators emits toxic gases into the atmosphere while generating electricity. These toxic gases are usually oxides of carbon, sulphur and nitrogen which are released into the atmosphere as dark and dense smoke. Emission dispatch (EMD) is the scheduling of the generators in such a way so as to minimize the release of this harmful toxic gases. The objective function of emission dispatch can be calculated by equation (2) depending on the availability of the emission coefficients,

\[
EMD = \sum_{t=1}^{24} \sum_{j=1}^{n} \left( x_j G_j t^2 + y_j G_j t + z_j \right)
\]  

(2)

where \( x_j, y_j \) and \( z_j \) are the emission coefficients, and EMD is the total emission (Dey et al., 2019, 2020a; Trivedi et al., 2018; Elattar, 2018).

2.3. Combined economic emission dispatch using PPF method

ECD deals with the minimization of the fuel costs, while EMD deals with the minimization of the emission of harmful pollutants from the conventional fossil fueled generators to the atmosphere. Hence, a compromised solution must arrive at that can achieve both reduced fuel costs releasing fewer pollutants in the atmosphere. This is achieved by formulating a CEED by combining equations (1) and (2) and also the Price Penalty Factor (PPF), a parameter used to get a mixed objective function involving both ECD and EMD as mentioned in equation (3) (Dey et al., 2020a; Trivedi et al., 2018; Elattar, 2018).

\[
CEED_{ppf} = \sum_{t=1}^{24} \sum_{j=1}^{n} \left( a_j G_j t^2 + b_j G_j t + c_j \right) + p_{ppf} \cdot \left( x_j G_j t^2 + y_j G_j t + z_j \right)
\]  

(3)

Various types of price penalty factors (PPF) are given in equations (4)–(9) according to references (Dey et al., 2020a) and (Dey et al., 2019). Here \( p_{max/min} \) denotes the maximum and minimum values of the

\[
ppf_{max-min} = \frac{ECD\left(p_{max}\right)}{EMD\left(p_{max}\right)}
\]  

(4)

\[
ppf_{min-min} = \frac{ECD\left(p_{min}\right)}{EMD\left(p_{min}\right)}
\]  

(5)

\[
ppf_{max-min} = \frac{ECD\left(p_{max}\right)}{EMD\left(p_{min}\right)}
\]  

(6)

\[
ppf_{min-max} = \frac{ECD\left(p_{min}\right)}{EMD\left(p_{max}\right)}
\]  

(7)

\[
ppf_{avg} = \frac{ppf_{max-min} + ppf_{min-min} + ppf_{max-min} + ppf_{min-max}}{4}
\]  

(8)

\[
ppf_{com} = \frac{ppf_{max}}{no. \ of\ DGs}
\]  

(9)

2.4. Combined economic emission dispatch using FP method

This method considers two different competing and conflicting objective functions, comprising of the same decision and control variables and are solved as a ratio of each other. For instance, ECD is considered as the economic dispatch equation mathematically expressed by equation (1), and EMD is the emission function given by equation (2). Then, a compromised solution can be obtained by FP method by minimizing the ratio \( EMD : ECD \). This is mathematically expressed by equation (10) (Rizk-Allah et al., 2018; Chen et al., 2016).

\[
CEED_{fp} = \frac{\sum_{t=1}^{24} \sum_{j=1}^{n} \left( x_j G_j t^2 + y_j G_j t + z_j \right)}{\sum_{t=1}^{24} \sum_{j=1}^{n} \left( a_j G_j t^2 + b_j G_j t + c_j \right)}
\]  

(10)

2.5. Environment constrained economic dispatch (CEED)

The above two methods of CEED focused on reducing the emission of harmful pollutants to the atmosphere. In the process the generation cost of the system rises much more than the best value obtained during economic dispatch. Rajasomashekar and Aravindhababu (2012) presented a simple equation to bring together two differently aimed objective functions and attain a better-quality compromised solution, given by equation (11). It depends, whether unimodal or multimodal, upon the nature of the economic dispatch and emission dispatch equations expressed in (1) and (2) respectively.

\[
CEED = \mu \left[ \frac{ECD - ECD_{min}}{ECD_{max} - ECD_{min}} \right] + (1 - \mu) \left[ \frac{EMD - EMD_{min}}{EMD_{max} - EMD_{min}} \right]
\]  

(11)

where \( \mu \) lies in the range of 0 and 1, \( ECD_{min} \) is the best value of generation cost obtained by minimizing (1), \( EMD_{min} \) is the best value of pollutants emitted obtained by minimizing equation (2), \( ECD_{max} \) is the generation cost obtained by substituting the optimal parameters of \( EMD_{min} \) in equation (1), \( EMD_{max} \) is the amount of pollutants emitted obtained by substituting the optimal parameters of \( ECD_{min} \) in equation (2). Results obtained in (Rajasomashekar and Aravindhababu, 2012) also points toward three important steps and assumptions as follows:
i. It is to be noted that the swift and successful steps to obtain the best compromised solution can be attained by setting the value of $\mu$ as 0.5, i.e., giving equal emphasis to both the objective functions.

ii. A better quality compromised solution will have the least value of absolute difference between cost performance index (CPI) and emission performance index (EPI). Equations (12) and (13) expresses the formulae of CPI and EPI respectively.

$$CPI = \left[ \frac{ECD - ECD_{\text{min}}}{ECD_{\text{max}} - ECD_{\text{min}}} \right] \times 100\%$$  \hspace{1cm} (12)

$$EPI = \left[ \frac{EMD - EMD_{\text{min}}}{EMD_{\text{max}} - EMD_{\text{min}}} \right] \times 100\%$$  \hspace{1cm} (13)

iii. The better-quality compromised solution will have the value of generation cost nearer to $ECD_{\text{min}}$ and amount of pollutants emitted nearer to $EMD_{\text{min}}$.

2.6. Equality and inequality constraints

Equations (14) and (15) are the equality constraints for without including RES and including RES problems respectively. Equation (16) is the inequality constraint restricting the DERs within their limits.

$$\sum_{j=1}^{n} G_{ij} = D_i$$  \hspace{1cm} (14)

$$\sum_{j=1}^{n} G_{ij} + P_{RES,i} = D_i$$  \hspace{1cm} (15)

$$G_{i,\text{min}} \leq G_i \leq G_{i,\text{max}}$$  \hspace{1cm} (16)

where $D_i$ is the demand of $t$th hour, $P_{RES,i}$ is RES output in terms of power.

2.7. Utilization percentage

The utilization percentage, UP, is given by equation (17) (Kumar and Saravanan, 2019; Dey et al., 2020b).

$$UP = \frac{\sum G_i}{24G_{\text{max}}}$$  \hspace{1cm} (17)

UP is normally used when it is an unclear and confusing attempt to represent the hourly outputs of test systems which have larger number of DERs.

2.8. Uncertainty modelling

Due to the stochastic nature of RES, the day ahead forecasted values of the RES are modelled to evaluate the uncertainty in them using equations (18) and (19) (Dey et al., 2020b; Jamshidi and Askarzadeh, 2019; Li et al., 2008):

$$PV_{\text{in}} = dPV_{\text{in}} + n_1 + PV_{\text{f},r}$$

$$dPV_{\text{in}} = 0.7* \sqrt{PV_{\text{f},r}}$$  \hspace{1cm} (18)

$$W_{\text{in}} = dP_{\text{in}} + n_2 + W_{\text{f},r}$$

$$dP_{\text{in}} = 0.8* \sqrt{W_{\text{f},r}}$$  \hspace{1cm} (19)

where $dPV_{\text{in}}$ is the standard deviation of the PV output, $PV_{\text{in}}$ is the is PV output considering the uncertainty, and $PV_{\text{f},r}$ is the day ahead forecasted PV output. Similarly, $W_{\text{in}}$ is uncertainty of wind, $dP_{\text{in}}$ is standard deviation of wind power and $W_{\text{f},r}$ is the day ahead forecasted wind output. $n_1$ and $n_2$ are randomly evaluated normal distribution function with mean 1 and standard deviation 0.

3. Hybrid grey wolf optimizers

The proposed optimization tool for this study is a robust and powerful hybrid of modified version of GWO (Mirjalili et al., 2014), SCA (Mirjalili, 2016) and CSA (Askarzadeh, 2016). Proposed hybrid, called HMGWO, has already outperformed other hybrids and modifications of GWO when realised on benchmark functions (Dey and BhattacharyyaRamesh, 2021) and have been useful in solving energy management and electricity market pricing problems on microgrid systems (Dey et al., 2020b; Dey and BhattacharyyaRamesh, 2021; Dey et al., 2020c).

The mathematical formulation of GWO and HMGWO are detailed below:

3.1. Grey Wolf Optimizer (GWO)

GWO is a recently developed optimization algorithm based on the hunting behaviour of the wolves. Wolves hunts in packs of 10 or 12. The leader wolf is known as alpha ($\alpha$), and is the most nearer to the prey. Alpha is followed by its successor beta ($\beta$), responsible for maintaining harmony in the group. Then, in hierarchy, comes the delta ($\delta$) wolves, which acts as scapegoat. Rest of the wolves are termed as omega ($\Omega$).

GWO algorithm mainly involves the top three class of wolves for which acts as scapegoat. Rest of the wolves are termed as omega ($\Omega$).

Equation (21) shows the positing updating formulation of the GWO algorithm,

$$\begin{align*}
\vec{Y}_1 &= \vec{Y}_a - R_1 \cdot (\vec{P}_a - \vec{P}_b) \\
\vec{Y}_2 &= \vec{Y}_b - R_2 \cdot (\vec{P}_b - \vec{P}_c) \\
\vec{Y}_3 &= \vec{Y}_c - R_3 \cdot (\vec{P}_c - \vec{P}_a) \\
\vec{Y}_{(\text{iter}+1)} &= \frac{\vec{Y}_1 + \vec{Y}_2 + \vec{Y}_3}{3}
\end{align*}$$  \hspace{1cm} (21)

The value of vectors $R$ and $Q$ can be calculated by equation (Qian et al., 2020),

$$\begin{align*}
\vec{R} &= 2 \cdot \vec{\alpha} - \vec{r}_1 - \vec{r}_2 \\
\vec{Q} &= 2 \cdot \vec{r}_2
\end{align*}$$  \hspace{1cm} (23)

Mathematically, the value of R converges or diverges the wolves towards or away from its prey. The vector ‘a’ changes with respect to iteration as mentioned in equation (24) and, thereby, controls the value of ‘R’ throughout the search.

$$\vec{\alpha} = 2 * \left(1 - \frac{\text{iter}}{\text{Max_iter}}\right)$$  \hspace{1cm} (24)

3.2. HMGWO

The three major modifications in GWO to formulate HMGWO are listed as follows:

a. Involvement of omega set of wolves (Khandelwal et al., 2018).

b. Tossing the Manhattan distance calculation between wolves with sine and cosine functions (Dey and Bhattacharyya, 2019; Dey and
Dey, 2019; Devarapalli et al., 2020; Devarapalli and Bhattacharyya, 2020).

c. Using the CSA strategy of position updating procedure (Dey and Bhattacharyya, 2019; Dey and Das, 2019; Devarapalli et al., 2020; Devarapalli and Bhattacharyya, 2020).

The mathematical formulation of MGOWSCACSA are as follows:

\[
\begin{align*}
\mathbf{P}_a & = \text{rand} \times \sin(\text{rand}) \times \left[\mathbf{Q}_a, \mathbf{Y}_a - \mathbf{Y} \right] \quad \text{if rand} > 0.5 \\
\mathbf{P}_a & = \text{rand} \times \cos(\text{rand}) \times \left[\mathbf{Q}_a, \mathbf{Y}_a - \mathbf{Y} \right] \quad \text{otherwise}
\end{align*}
\]

(25)

\[
\begin{align*}
\mathbf{P}_1 & = \text{rand} \times \sin(\text{rand}) \times \left[\mathbf{Q}_1, \mathbf{Y}_1 - \mathbf{Y} \right] \quad \text{if rand} > 0.5 \\
\mathbf{P}_1 & = \text{rand} \times \cos(\text{rand}) \times \left[\mathbf{Q}_1, \mathbf{Y}_1 - \mathbf{Y} \right] \quad \text{otherwise}
\end{align*}
\]

(26)

If \( T \) is the time period for optimal scheduling, \( D \) is the number of DERs involved in powering the microgrid system on which the energy management is to be performed, and \( N \) is the number of search agents of the population, then the matrix depicting the population is given by equation (33), wherein every search agent of the population follows the system constraints mentioned in equations (2)-(14).

\[
S = \begin{bmatrix}
S_{1,\text{DER}}1 & S_{1,\text{DER}}2 & \cdots & S_{1,\text{DER}}D \\
S_{2,\text{DER}}1 & S_{2,\text{DER}}2 & \cdots & S_{2,\text{DER}}D \\
\vdots & \vdots & \ddots & \vdots \\
S_{N,\text{DER}}1 & S_{N,\text{DER}}2 & \cdots & S_{N,\text{DER}}D
\end{bmatrix}
\]

(33)

The position of the wolves is depicted by particles in the population matrix which acts the control variables. The distance of wolves from the prey is taken as the fitness value for the objective function. Considering the proposed work as a constrained minimization approach, the position of search agent with least fitness value function is the best solution among all search agents in the search space and is termed as \( x_{cr} \).

4. Case studies

4.1. Overview of the subject test system

A dynamic test system of 3 fossil fueled generating units are considered on which CEED is performed using PPF, FP and proposed ECED methods. It is to be noted that the cost and emission equation of 3-units contains only quadratic terms and are unimodal in nature. The cost coefficients, emission coefficients and the maximum and minimum limits of operation of the DERs are shown in Table 2.

Table 3 shows the load demand of the test system and highlights the forecasted values of RES contribution for the system. Uncertainty evaluations have been done based on these forecasted values based on the equations mentioned in Section 2. The cost of the RES were not considered for the test system. The optimization was coded and executed in a laptop configured with Intel Core i5 8th Gen processor 8 GB RAM on a MATLAB R2013a software. The population size of the optimization.
4.2. Descriptive analysis on the results obtained

The detailed analysis of the CEED based study on the test system are listed below:

a. Initially ECD was conducted on the test system with and without considering the RES using proposed HMGWO as the optimization tool. Table 4 shows that the generation cost of the system was 176165 USD without RES and 166792 USD considering the RES. This marked a savings of 5.5% if RES was considered for the generation of power to suffice the load demand. It can also be seen from Table 4 that proposed HMGWO outperformed a long list of population-based swarm intelligence metaheuristic optimization algorithms to yield the minimum value of ELD.

b. When EMD was evaluated for the test system with and without RES, there was a 6.5% decrease in the emission of harmful pollutants in the atmosphere when the power output from RES was utilized. Table 5 shows that the generation cost without RES was 2282 kg after considering the involvement of RES in delivering power to the system. The superiority of the proposed optimization tool can be noticed in this case too.

c. It was evident from (Dey et al., 2020a) and (Dey et al., 2019) that min-max price penalty factor was the best and least for this test system. As per the records mentioned in the aforementioned articles, the PPF values for G1, G2 and G3 are 25.1597 USD/kg, 11.9948 USD/kg and 4.6750 USD/kg respectively. Thereafter, PPF based CEED was conducted on the test system and the generation cost was reduced to 2142 kg after considering the involvement of RES in delivering power to the system. It can also be seen from Table 4 that proposed HMGWO outperformed a long list of population-based swarm intelligence metaheuristic optimization algorithms to yield the minimum value of ELD.

d. FP based CEED was evaluated using equation (10) for the test system with and without considering RES. The generation cost when evaluated based on the optimal variables obtained after minimizing equation (10) was 177011 USD without considering RES and 167398 USD when RES was considered thus saving 5.6% in the generation cost. This cost reduced to 2142 kg after considering the involvement of RES in delivering power to the system. The superiority of the proposed optimization tool can be noticed in this case too.

e. The amounts of pollutants emitted using PPF based CEED method were 2453 kg and 2243 kg without and with RES respectively. The amounts of pollutants emitted using PPF based CEED method were 2453 kg and 2243 kg without and with RES respectively. The amounts of pollutants emitted using PPF based CEED method were 2453 kg and 2243 kg without and with RES respectively. The amounts of pollutants emitted using PPF based CEED method were 2453 kg and 2243 kg without and with RES respectively. The amounts of pollutants emitted using PPF based CEED method were 2453 kg and 2243 kg without and with RES respectively.
USD when RES outputs were involved. The amount of toxic emissions in this case was 2136 kg and 2263 kg with and without RES respectively. FP was evaluated using GWO and HMGWO and the best value of fitness function is displayed in Table 6.

e. From the aforementioned points (a) and (b) and from the steps mentioned in Section 2, the following data to conduct ECED were obtained.

| Parameters | Without RES | With RES |
|------------|-------------|----------|
| $ECD_{min}$ (USD) | 176165 | 166792 |
| $ECD_{max}$ (USD) | 176900 | 167382 |
| $EMD_{min}$ (kg) | 2282 | 2142 |
| $EMD_{max}$ (kg) | 2805 | 2602 |

Thereafter, ECED was performed with and without considering RES for different values of $\mu$ ranging from 0.1 to 0.9. The generation cost and amount of toxic emissions were noted down for every value of $\mu$ and 2D graph was plotted for the values when ECED was evaluated without considering RES. The graph is shown in Fig. 1. It can be seen that the best compromised solution obtained at $\mu = 0.5$ without RES is (176356 USD, 2418 kg).

Likewise, a 3D graph was plotted when ECED was evaluated using proposed HMGWO with RES for different values of $\mu$. The value of $\mu$ was in the X axis, generation cost was plotted in the Y-axis and emission value in the Z axis. It can be seen from Fig. 2 that the best compromised value in this case was (0.5, 166944 USD, 2136 kg). GWO was also implemented as the optimization tool to evaluate ECED and the results are recorded in Table 6.

Fig. 3 shows a graph of the value of ECED fitness function and the absolute difference between CPI and EPI for various values of $\mu$. It can be seen that the least difference was obtained at $\mu = 0.5$. 

![Fig. 1. Cost vs. Emission using HMGWO (without RES).](image1)

![Fig. 2. Cost vs. Emission for different $\mu$ values using HMGWO (with RES).](image2)
Further an attempt was made to assemble the absolute difference between CPI and EPI for all the three aforementioned methods of evaluating CEED, and the same is shown in Fig. 4. It can be seen that among the PPF based CEED, FP based CEED and ECED methods, the least difference was obtained for proposed ECED method. The above study proves the discussion in Section 2 that the best compromised solution is obtained when the absolute difference between CPI and EPI is the least and when the value of $\mu$ is 0.5.

Table 7 shows the best values of generation cost and amount of pollutants emitted throughout the study using proposed hybrid HMGWO algorithm.

Fig. 5 shows the utilization of the three fossil fueled generators when RES was considered for evaluating all the fitness functions mentioned in Section 2 using proposed HMGWO algorithm. Generator unit G1 was utilized the least when ELD was performed as G1 have the maximum values of cost coefficients. Generator unit G3 was utilized least when EMD was evaluated as it has the highest value of emission coefficients. A reasonable balance between the utilization of all the three generators can be seen in ECED method when compared to all the other fitness functions evaluated.

Fig. 6 shows the convergence curve when proposed HMGWO yielded the best quality results for various objective functions evaluated considering the involvement of RES. The convergence curves shows the value of the objective function attained by the algorithm during each iteration until the maximum number of iteration is reached.

Since the objective of the paper was to evaluate ECED, GWO along with proposed HMGWO was used as the optimization tool to evaluate ECED on the test system with and without RES for 30 individual trials and the results and execution time was recorded for every trial. Table 8 shows the statistical analysis data when ECED was evaluated for 30 different individual trials with $\mu = 0.5$ using both GWO and HMGWO algorithms. The least value of standard deviation claims the robustness of proposed HMGWO algorithm. The decrease in the value of algorithm execution time to attain 500 iterations can also be seen from Table 8 compared to original GWO algorithm.

Based on the values mentioned in Table 8, the box plot figure was formed and is shown in Fig. 7. The boxplot is a summary of 30 sets of results obtained by each algorithm while evaluating ECED for the considered test system. The median is the line dividing the box, the upper and lower quartiles of the data define the ends of the box. The minimum and maximum data points are drawn as points at the ends of the lines (whiskers) extending from the box. These box-plots show the distribution of quantitative data in a way that facilitates comparisons between ECED between GWO and HMGWO. From these plots, it is seen that the chances of getting minimum ECED is very high as the median from HMGWO is nearer to the lower quartile.

5. Conclusions

This paper proposed a unique and novel approach of performing a comparative analysis among three different methods of evaluating CEED on a 3-unit dynamic test system configured with RES. Uncertainty calculation of the forecasted values of RES was employed to attend the
Fig. 5. Utilization Percentage of G1, G2 and G3 for various objectives (with RES).

Fig. 6. Convergence curve characteristics obtained for various objective functions using HMGWO.
stochastic behavior of the same. The major distinct findings of the paper are listed below:

a. There was a decrease in the generation cost while economic dispatch and PPF based CEED was evaluated by approximately 5.5% each due to the involvement of the RES. Also, the emission of toxic pollutants in the atmosphere diminished by 6.5% for the same reason.

b. The difference between the values of EPI and CPI was least for the proposed ECED method amongst the three, which indicates that the proposed approach yields a better compromised solution than the other two. The fact that the generation cost and amount of emitted pollutants, evaluated using proposed ECED approach, were much closer to the economic dispatch and emission dispatch values respectively compared to PPF based and FP based CEED solution also verifies the same.

c. HMGWO outperformed a number of optimization algorithms in providing better quality solutions throughout the study. This is a satisfactory reason of choosing the hybrid optimization algorithm for further solving large dimensioned complex optimization problems.

The values of ECD and EMD are needed to be calculated before evaluating ECED. This might be a disadvantage of the proposed approach compared to FP based CEED and PPF based CEED, but the satisfactory results in delivering a compromised solution with the least possible value of generation cost and toxic emissions make up for the aforementioned disadvantage. The proposed hybrid optimization technique might be somewhat cumbersome while coding given the number of equations, but the algorithm is robust enough in yielding consistently better and superior quality solutions for any number of trials.

As a scope of future work, the horizon of the study based on ECED approach can be expanded by solving large dynamic and multimodal test systems including MG energy management problems given the availability of cost and emission coefficients.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix

Table A1

| Algorithms | Min            | Max            | Mean          | STD       | Time (s) |
|------------|----------------|----------------|---------------|-----------|----------|
| With RES   |                |                |               |           |          |
| GWO        | 0.26393        | 0.26442        | 0.26410       | 0.00024   | 210.95   |
| HMGWO      | 0.26146        | 0.26152        | 0.26146       | 1.52e-05  | 180.36   |
| Without RES|                |                |               |           |          |
| GWO        | 0.26202        | 0.26280        | 0.26254       | 0.000364  | 223.52   |
| HMGWO      | 0.25984        | 0.26001        | 0.25986       | 6.44e-05  | 202.68   |

Fig. 7. Box plot evaluation for ECED calculations a) Without RES b) With RES.

Table 8

ECED evaluated for 30 trials with $\mu = 0.5$

| Algorithms | Min            | Max            | Mean          | STD       | Time (s) |
|------------|----------------|----------------|---------------|-----------|----------|
| With RES   |                |                |               |           |          |
| GWO        | 0.26393        | 0.26442        | 0.26410       | 0.00024   | 210.95   |
| HMGWO      | 0.26146        | 0.26152        | 0.26146       | 1.52e-05  | 180.36   |
| Without RES|                |                |               |           |          |
| GWO        | 0.26202        | 0.26280        | 0.26254       | 0.000364  | 223.52   |
| HMGWO      | 0.25984        | 0.26001        | 0.25986       | 6.44e-05  | 202.68   |
Table A1 (continued)

| Hours | G1      | G2      | G3      |
|-------|---------|---------|---------|
| 15    | 51.4657 | 57.0821 | 73.1122 |
| 16    | 44.5121 | 51.3204 | 65.1575 |
| 17    | 43.1638 | 50.2039 | 63.6223 |
| 18    | 51.1867 | 56.8485 | 72.7848 |
| 19    | 57.3902 | 61.9835 | 79.8763 |
| 20    | 71.0561 | 73.2856 | 95.4882 |
| 21    | 66.0113 | 69.1096 | 89.7291 |
| 22    | 54.1766 | 59.3134 | 76.2000 |
| 23    | 43.8131 | 50.7505 | 64.3664 |
| 24    | 38.9384 | 46.7010 | 58.7807 |

Table A2

Hourly outputs of generators (in MW) when best value of EMD was obtained using HMGWO

| Hours | G1      | G2      | G3      |
|-------|---------|---------|---------|
| 1     | 48.2955 | 40.0000 | 50.0045 |
| 2     | 48.3209 | 42.6476 | 50.5315 |
| 3     | 53.4013 | 42.1053 | 50.2233 |
| 4     | 52.7740 | 40.2442 | 50.3218 |
| 5     | 67.3749 | 40.3534 | 50.0517 |
| 6     | 68.0801 | 46.7422 | 50.2377 |
| 7     | 63.1215 | 40.8447 | 50.1039 |
| 8     | 45.7068 | 41.2861 | 50.2671 |
| 9     | 69.3990 | 45.9613 | 50.0997 |
| 10    | 70.9331 | 51.6635 | 50.1834 |
| 11    | 95.0519 | 73.7666 | 50.9714 |
| 12    | 94.2403 | 79.9026 | 53.5571 |
| 13    | 90.4377 | 56.7981 | 51.6042 |
| 14    | 80.2214 | 46.7596 | 50.7290 |
| 15    | 79.6775 | 51.7999 | 50.1825 |
| 16    | 65.3710 | 45.3587 | 50.2603 |
| 17    | 65.2901 | 41.2797 | 50.4202 |
| 18    | 74.1806 | 55.9488 | 50.6070 |
| 19    | 84.0169 | 64.9413 | 50.2918 |
| 20    | 98.7570 | 85.5441 | 55.5289 |
| 21    | 97.8798 | 74.1834 | 52.7868 |
| 22    | 78.0132 | 61.2699 | 50.4070 |
| 23    | 67.8189 | 40.5823 | 50.5288 |
| 24    | 52.3253 | 42.0431 | 50.0516 |

Table A3

Hourly outputs of generators (in MW) when best value of PPF based CEED was obtained using HMGWO

| Hours | G1      | G2      | G3      |
|-------|---------|---------|---------|
| 1     | 48.2991 | 40.0004 | 50.0005 |
| 2     | 51.4998 | 40.0001 | 50.0001 |
| 3     | 55.7287 | 40.0011 | 50.0002 |
| 4     | 53.3390 | 40.0001 | 50.0009 |
| 5     | 64.9868 | 42.7319 | 50.0613 |
| 6     | 65.8771 | 49.0278 | 50.1551 |
| 7     | 62.5719 | 41.4986 | 50.0076 |
| 8     | 47.2591 | 40.0005 | 50.0004 |
| 9     | 66.6405 | 48.0352 | 50.6942 |
| 10    | 67.8585 | 51.3637 | 53.5579 |
| 11    | 74.2552 | 66.4967 | 79.0831 |
| 12    | 74.9518 | 70.0631 | 82.6853 |
| 13    | 71.8914 | 60.1474 | 66.8012 |
| 14    | 68.4856 | 53.1018 | 56.1226 |
| 15    | 69.1135 | 55.6661 | 56.8804 |
| 16    | 65.9934 | 44.9680 | 50.0286 |
| 17    | 64.5816 | 42.4068 | 50.0015 |
| 18    | 68.6636 | 55.5676 | 56.5889 |
| 19    | 71.2575 | 61.0768 | 66.9157 |
| 20    | 77.3478 | 73.2830 | 89.1992 |
| 21    | 74.4825 | 69.9037 | 80.4638 |
| 22    | 70.0646 | 57.8047 | 61.8207 |
| 23    | 65.2457 | 43.6549 | 50.0294 |
| 24    | 54.4187 | 40.0012 | 50.0001 |
### Table A4
Hourly outputs of generators (in MW) when best value of FP based CEED was obtained using HMGWO

| Hours | G1       | G2       | G3       |
|-------|----------|----------|----------|
| 1     | 47.5521  | 40.6998  | 50.0481  |
| 2     | 50.9773  | 40.4611  | 50.0616  |
| 3     | 55.5374  | 40.1023  | 50.0503  |
| 4     | 51.4409  | 41.8709  | 50.0282  |
| 5     | 67.2639  | 40.4378  | 50.0506  |
| 6     | 68.3415  | 46.6678  | 50.0218  |
| 7     | 63.7018  | 40.3464  | 50.0506  |
| 8     | 47.0286  | 40.1835  | 50.0479  |
| 9     | 69.6940  | 45.6220  | 50.0686  |
| 10    | 74.1663  | 48.5451  | 50.0068  |
| 11    | 95.7270  | 70.5148  | 53.5484  |
| 12    | 94.6252  | 82.3143  | 50.7335  |
| 13    | 84.2946  | 40.3464  | 50.0218  |
| 14    | 73.7501  | 53.4926  | 50.4673  |
| 15    | 72.9463  | 50.1023  | 50.1389  |
| 16    | 69.0070  | 41.8626  | 50.0867  |
| 17    | 65.8635  | 41.0119  | 50.1146  |
| 18    | 82.0755  | 48.6933  | 50.0512  |
| 19    | 84.7533  | 64.4092  | 50.0874  |
| 20    | 160.4495 | 53.8613  | 55.5192  |
| 21    | 98.1673  | 74.5988  | 52.0839  |
| 22    | 77.8654  | 61.5551  | 50.2695  |
| 23    | 68.1709  | 40.6490  | 50.1101  |
| 24    | 54.1873  | 40.2232  | 50.0905  |

### Table A5
Hourly outputs of generators (in MW) when best value of ECED was obtained using HMGWO

| Hours | G1       | G2       | G3       |
|-------|----------|----------|----------|
| 1     | 45.6568  | 42.6407  | 50.0025  |
| 2     | 47.4941  | 44.0555  | 50.0004  |
| 3     | 49.8204  | 45.9806  | 50.0018  |
| 4     | 54.2826  | 51.9885  | 51.5089  |
| 5     | 56.0277  | 70.7248  | 72.7871  |
| 6     | 57.1287  | 53.5692  | 54.3621  |
| 7     | 53.7327  | 50.1723  | 50.1651  |
| 8     | 45.4166  | 41.8399  | 50.0035  |
| 9     | 57.9916  | 53.5397  | 53.8387  |
| 10    | 60.0026  | 55.9600  | 56.8174  |
| 11    | 78.4809  | 73.6212  | 75.5979  |
| 12    | 69.0228  | 60.1474  | 65.6423  |
| 13    | 62.0349  | 57.4882  | 58.1868  |
| 14    | 63.1637  | 58.4556  | 59.4047  |
| 15    | 56.0277  | 52.0910  | 52.8714  |
| 16    | 54.8036  | 51.0521  | 51.1343  |
| 17    | 62.6443  | 58.6812  | 59.4945  |
| 18    | 69.0372  | 64.3516  | 65.8611  |
| 19    | 82.9531  | 77.0748  | 79.0201  |
| 20    | 77.6485  | 72.5340  | 74.6764  |
| 21    | 66.2958  | 60.9224  | 62.4719  |
| 22    | 55.4805  | 51.4703  | 51.9791  |
| 23    | 48.7232  | 45.6928  | 50.0040  |

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