Dynamic Combined Economic Emission Dispatch Including Wind Generators by Real Coded Genetic Algorithm

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ABSTRACT

With the growing environmental depletion, the shift in the focus towards minimizing the emissions of gases released in the conventional generators and further incorporation of a cleaner alternate renewable source of energy such as wind or solar to the existing system is of utmost importance. The research paper aims to build an environmentally resilient electric power system. Real coded genetic algorithm powerful optimization technique is employed to solve the dynamic combined economic emission dispatch (i.e., DCEED) strategy for two proposed algorithms. The first proposed DCEED algorithm includes fuel cost of only conventional generators while in the second algorithm along with conventional generators, wind powered generators with varying power output characteristic are added. A comparative analysis of both the algorithms in terms of total combined cost, emission level, and fuel cost is taken into account, and it is observed that in spite of wind uncertainty, the proposed method is more economical.

KEYWORDS

Polynomial Mutation, Price Penalty Factor, SBX Crossover, Valve Point Loading, Wind Power Overestimation Cost, Wind Power Uncertainty, Wind Power Underestimation Cost

1. INTRODUCTION

The ever-increasing population, rapid expansion in economy, growing development and prosperity across the globe, has resulted humongous electricity consumption. Under such circumstances, electric power sector has hit various milestones in terms of advancement in order to cope up with the growing energy demand. But, contrary to the development, the reality of reliance on the traditional fossil fuel based electricity generation is still not completely eliminated. Fossil fuel includes—coal, natural gas, oil etc, and are primarily exhausstible in nature. The conventional system of electricity generation which depends upon these fossil fuels tends to release harmful gases such as carbon dioxide, NOx, SOx etc into the environment, causing serious environmental issues like climate change, air pollution, and further global warming which causes serious impacts on the lives of human and various other forms of life. A major portion of global carbon dioxide emission is contributed by the energy and power sectors (IEA, 2020). Such serious environmental detritions are a matter of utmost concern and
hence a balance between the rate of global development and environmental security has become an essential goal. In order to mitigate the environmental challenges, there is a huge call for the electric power industry to undergo a transition towards cleaner energy system with minimum or net zero carbon-dioxide emission along with the enhanced efficiency, reliability and higher degree of economy.

The classical Economic load dispatch (ELD) aims to allocate power outputs to the committed generator units with the objective of minimizing generation cost in compliance with all constraints of the network satisfied. However, to alleviate the environmental crisis and to make the entire system more resilient, incorporation of environmental factors to electric power system becomes crucial and thus the traditional economic load dispatch problem needs to be modified. The reshaping of the existing economic dispatch problem to match up with the environmental concerns in various forms has been a remarkable area of interest of many research studies (Sharifi et al., 2017) (Mustafa et al., 2018). Mandal et al., (2015) and Sayah et al. (2014) included the pollution level as constraint to the ELD problem, popularly known as ECED, emission constrained economic load dispatch. The objectives of minimizing the fuel cost as well as emission levels are conflicting in nature i.e. minimization of one leads to the, maximization of the other and thus inclusion of both the objectives leads to complexity (Edwin Selva Rex et al., 2019). So, in order to make an equity between fuel cost and emission level, some researchers such as Gherbi et al. (2016) and Ryu et al.(2020) proposed methods which simultaneously takes consideration of both cost of generation and environmental pollution termed as Combined economic emission dispatch (CEED) using price penalty factor. In CEED, the multi-objective optimization is converted into single objective optimization problem and hence reduces the complexity in handling multiple objectives. Modification of the existing dispatch strategy by these approaches resulted in various advantages, however, to make our system more resilient, newer approaches needs to be employed.

The recent trend of inclusion of renewable sources of energy to the traditional energy sector is promising considering today’s scenario to strengthen the environmental security. Renewable sources of energy being environment friendly, inexhaustible in nature, having lesser operation and maintenance cost proves to be an efficient alternative sources of electricity having high potential discussed by Nassar et al., (2019). Among various renewable energy sources, the wind energy and solar energy are vital sources of electricity. They are characterized to have many distinctive features like they are inexhaustible in nature, have low or zero fuel cost, and are zero emission releasing sources of electricity. And thus, the integration of these renewable into the traditional power sector can lead to various advantages including emission control, fuel saving, cost reduction etc (Jin et al., 2014)(Aghaei et al.,2013)(Chenghui et al., 2016) (Elattar, 2018)(Jadoun et., 2018)(Santillán-Lemus et al., 2019) (Chinnadurai et.,2020) (Tariq et al., 2020)

Researchers such as Roy et al., (2014) and Zhou et al., (2011) analyzed economic dispatch of composite power system including traditional fossil fuel and wind based power system. However, along with the various perks that these alternative sources of electricity offers, their integration into the power system encompasses major pitfalls such as high intermittency rate due to its dependence on the nature. To address the problem of uncertainty, various researchers have used different approaches to obtain realistic solutions with these sources. Reddy et al., (2015) considered variation of solar and wind power and evaluated best fit participation factors. Khan et al., (2015) used the solar photovoltaic cost model for incorporating solar photovoltaic into conventional system. Hu et al., (2017) have used wind power uncertainty cost model based on the unbalance between the actual wind power available and the scheduled wind power.

For solving the optimization problem, researchers have used wide range of optimization algorithms. Earlier approaches involved methods like lagrangian relaxation method, dynamic programming, gradient search method, and chance constrained programming. (Senthil et al., 2010) (Dieu et al., 2013) (Bhattacharya et al., 2014)(Cheng et al., 2015). But due to various drawbacks such as approximation used in these techniques and early convergence to local minima, these algorithms proved to be computationally inefficient. To have better solutions to the optimization problem,
algorithms such as differential evolution (Peng et al., 2012), genetic algorithm (Sahay et al., 2018) (Nadakuditi et al., 2019), artificial bee colony (He, et al., 2013) (Jadav et al., 2013), particle swarm optimization (Yao et al., 2012) (Gupta et al., 2020) (Mason et al., 2017) (Chen et al., 2019), gravitational search algorithm (Mondal et al., 2013) (Sarkar et al., 2018), and artificial neural networks has been used by various scholars.

This paper proposes, a short term 24 hr dynamic combined economic emission dispatch (DCEED) for generating units which is implemented via two approaches. The first approach proposes a DCEED model for only conventional generating units with valve point loading and various network constraints. In the second approach DCEED is applied on a composite generating system including both wind powered generators and the conventional generators. A 24 hr varying load demand has been taken for the dispatch with a time interval of 1 hour. The wind power cost model for addressing the uncertainty associated with the wind powered generators is used. A bio–inspired intelligent heuristic optimization algorithm –real coded genetic algorithm (RCGA) has been used for the solving the DCEED problem. In the proposed work a comparative analysis on the DCEED with only conventional generating units and DCEED including conventional and wind powered generators is done based on percentage of fuel saving, emission level reduction, total combined economic cost.

The rest of the paper is organized as: Section 2 deals with the mathematical problem formulation of DCCED for conventional generating units as well as including the wind powered generators. The optimization methodology RCGA and stepwise procedure for the implementation of RCGA for DCEED with conventional generating units as well as including wind powered generators is described in Section 3. Section 4 illustrates the analysis of result obtained through the implementation of RCGA on the test data. And finally Section 5 outlines the conclusion drawn.

2. PROBLEM FORMULATION

2.1. Mathematical Formulation for Dynamic Combined Economic Emission Problem (Only Conventional Generators)

2.1.1 Fuel Cost of Conventional Generators

The cost of operation of generators is predominately given by the fuel cost of the generators. The fuel cost of ith generator is approximated by a quadratic function of the active power output of the generators expressed as:

\[ F_i(P_i) = a_i + b_i P_i + c_i P_i^2 \]  

(1)

To have a practical interpretation of the fuel cost of generating units, the valve point effect needs to be included which arises due to the phenomena of sequential process of opening of valve in the multi-valve steam turbine and makes the cost curve non linear and non smooth. Hence, considering the valve point effect (Rahmat et al., 2014), the fuel cost of generators can be formulated as:

\[ F_i(P_i) = a_i + b_i P_i + c_i P_i^2 + d_i \sin \left( e_i \left( P_i^{\text{min}} - P_i \right) \right) \]  

(2)

\[ FC = \sum_{i=1}^{n} F_i(P_i) \]  

(3)
Where $F_i(P_i)$ denotes fuel cost function, $P_i$, $P_i^{\text{min}}$ is the output power and minimum power capacity of $i^{\text{th}}$ generating unit respectively. $a_i, b_i, c_i$ are the cost coefficient, $d_i, e_i$ are the coefficients of generating unit due valve point effects, $FC$ is the total fuel cost of generating units in Rs/hr, and $N_c$ is the total no. of conventional generators.

### 2.1.2 Emission Cost of Generating Units

The major emissions from conventional generating units are the oxides of sulphur, nitrogen and carbon. The sulphur oxide emission cost is expressed by a quadratic equation similar to the fuel cost function of generating units as it is proportional to the fuel consumed while nitrogen oxide emissions are described by linear and exponential equation. So, the overall cost associated with the emissions of generating units is formulated as the sum of quadratic and exponential terms expressed as:

$$E_i(P_i) = p_i + q_i P_i + r_i P_i^2 + \eta_i \exp(\delta_i * P_i)$$  \hspace{1cm} (4)

$$EC = \sum_{i=1}^{N_c} E_i(P_i)$$  \hspace{1cm} (5)

Where, $E_i(P_i)$ denotes the emission level from $i^{\text{th}}$ generating unit, $p_i, q_i, r_i, \delta_i, \eta_i$ are the coefficients associated with the pollution level. $EC$ is the total emission level released from generating units in kg/hr, and $N_c$ is the total no. of conventional generators.

### 2.1.3 Dynamic Combined Emission Economic Dispatch (DCEED) Objective Function

Since, the fuel cost and the emission cost are incompatible in nature. The best approach towards obtaining a unbiased solution is by finding a pareto optimal solution. Hence, DCEED dynamic combined economic emission dispatch is adopted which deals with the allocation of output power to the committed generating units, aiming towards the minimisation of fuel cost and emission levels simultaneously over a time span in the scheduled horizon expressed as

\[ \text{Min} \left( TC \right) = \sum_{t=1}^{T} f \left( FC, EC \right) \]  \hspace{1cm} (6)

where, $TC =$ total cost of generation of generators, $FC=$total fuel cost of units, $EC=$total emission cost units, $T=$total time span in the scheduled horizon. To obtain the solution for the problem, dual objective function is converted into single objective function by inserting an equivalent price penalty factor (PPF) and a weight coefficient $\lambda$ (Jiang et al., 2019). The range of variation of the weight coefficient is from 0 to 1. Therefore, the DCEED objective function is thus formulated as:

\[ \text{Min} \left( TC \right) = \lambda * FC + (1 - \lambda) * PPF * EC \]  \hspace{1cm} (7)

For finding the value of price penalty factor (PPF) for a particular load demand following steps is taken into account:

Step no.1: Firstly, the fuel cost and the emission level of each generating units are calculated at maximum power capacities i.e. $F_i(P_i^{\text{max}})$ and $E_i(P_i^{\text{max}})$.

Step no. 2: $F_i(P_i^{\text{max}})$ and $E_i(P_i^{\text{max}})$ is divided and $h_i$ is obtained for all for each generating unit.

Step no.3: All $h_i$ of generating units obtained in step ii are sorted in increasing order.
Step no.4: Maximum power capacity of generating units i.e. \( P_i^{\text{max}} \) is added one at a time according to the increasing order of \( h_i \) till the sum of \( P_i^{\text{max}} \) is greater than or equal to load demand.

Step no.5: The value of \( h_i \) associated with the generating unit in the process till the condition satisfies is the equivalent PPF for the particular load demand.

### 2.1.4 Constraints

i. Generator power capacity constraint:

The power output of each generating unit must lie between the maximum and minimum generating capacities:

\[
P_i^{\text{min}} \leq P_i \leq P_i^{\text{max}}
\]  

(8)

Where, \( P_i^{\text{min}} \) and \( P_i^{\text{max}} \) represents the maximum and minimum generating capacity.

ii. Power balance constraint:

The total power generation must be equal to the sum of load demand and the total power loss. The total power loss is given by the transmission loss which is the function of output power of the generating units and loss coefficient.

\[
\sum_{i=1}^{N_i} P_i = P_D + P_L
\]  

(9)

Where, \( P_i \), \( P_D \), \( P_L \) represents the output power of \( i^{th} \) generating unit, power demand and total power loss respectively. Using Kron’s reduction formula, \( P_L \) can be calculated as:

\[
P_L = \sum_{i=1}^{N_i} \sum_{j=1}^{N_j} B_{ij} P_j + \sum_{i=1}^{N_i} B_{io} P_j + B_{oo}
\]  

(10)

\( B_{ij}, B_{io}, B_{oo} \) are the loss coefficients.

### 2.2. Mathematical Formulation for Dynamic Combined Economic Emission Problem Including Wind Generating Systems

#### 2.2.1 Wind Power Cost

Wind energy conversion system is a renewable source of energy with significant features such as there is no fuel cost associated with the wind conversion energy system, no harmful emission released into the environment and thus it is a clean energy source (Sumathi et al., 2015). However, while dealing with the wind power generating system, the main problem lies in its intermittent nature as it depends upon wind speed, wind direction, relative humidity, temperature etc which are highly variable in nature for a particular site and thus wind power output is also random in nature. To address the problem of wind power uncertainty for dispatch problem, penalty cost function associated wind power overestimation and underestimation is considered (Padhi, et al., 2020).

Total cost associated with wind powered generator comprises of three components:
i. Direct wind power cost.

It is fixed cost which any grid operator has to pay for taking wind power from a wind farm. This factor exists only if the wind farm is not owned by the grid operator.

Mathematically represented as,

\[ C_d(w_i) = d_i w_i \]  

Where, \( C_d(w_i) \) represents the direct wind power cost, \( d_i \) is direct cost coefficient of \( i^{th} \) wind power generating unit, \( w_i \) scheduled is the wind power of the \( i^{th} \) wind powered generating unit.

ii. Cost associated with overestimation of available wind power.

This wind power cost component is also known as reserve cost. If at a particular time interval the actual wind power output available of a particular wind powered generator is less than the scheduled wind power, then the overestimated wind power cost needs to accounted. To deal with this scenario, either power needs to be purchased from alternative power sources or load shedding to be exercised. The Cost associated with overestimation is expressed as:

\[ C_{oe}(w_i) = K_{oe}(W_{av} - w_i) \]

Where, \( C_{oe}(w_i) \) represents the cost associated with overestimation of available wind power, \( K_{oe} \) is the overestimation cost coefficient, \( w_i \) scheduled is the wind power, \( W_{av} \) is the actual available wind power of \( i^{th} \) wind powered generating unit.

iii. Cost associated with underestimation of available wind power.

If at a particular time interval the actual wind power output available of a particular wind powered generator is more than the scheduled wind power, then the grid operator needs to pay a penalty cost for not utilising the actual wind power available mathematically expressed as:

\[ C_{ue}(w_i) = K_{ue}(w_i - W_{av}) \]

where, \( C_{ue}(w_i) \) represents the cost associated with underestimation of available wind power, \( K_{ue} \) is the overestimation cost coefficient, \( w_i \) scheduled is the wind power, \( W_{av} \) is the actual available wind power of \( i^{th} \) wind powered generating unit.

This extra wind power generated is either wasted, or used in purposes like charging the batteries or selling to other deficit utilities.

2.2.2 Objective Function Formulation for DCEED Including Wind Powered Generating Units

If \( N_c \) and \( N_w \) is the total no. of conventional and total no. of wind powered generators respectively then total objective function for DCEED can be formulated as:

\[
\text{Min} \{TC\} = \lambda \left[ s + fp + c \sin \left( \epsilon \left( P^n - P \right) \right) + \left(1 - \lambda \right) \left( PP + \epsilon P^n + \eta \exp \left( \lambda \cdot P \right) \right) + \sum_{i=1}^{N_c} d_i w_i + \sum_{i=1}^{N_w} K_{oe}(W_{av} - w_i) + \sum_{i=1}^{N_w} K_{ue}(w_i - W_{av}) \right]^{41}
\]

2.2.3 Constraints

i. Generator power capacity constraint:
The output power must lie between the maximum and minimum generating capacities of both type generators conventional as well as wind powered generators.

\[ P_i^{\text{min}} \leq P_i \leq P_i^{\text{max}} \]  
(15)

\[ w_i^{\text{min}} \leq w_i \leq w_i^{r} \]  
(16)

Where, \( P_i^{\text{min}} \) and \( P_i^{\text{max}} \) represents the maximum and minimum generating capacity of conventional generators, \( w_i^{\text{min}} \) and \( w_i^{\text{max}} \) represents the minimum and rated capacity of wind powered generators.

ii. Power balance constraints:

The total power generation (conventional plus wind power generation) must be equal to the sum of load demand and the total power loss given following expression:

\[ \sum_{i=1}^{N_c} P_i + \sum_{i=1}^{N_w} w_i = P_D + P_L \]  
(17)

Where, \( P_c, w_p, P_{Dp}, P_{Lp} \) represents the output power of \( i^{\text{th}} \) generating unit, \( i^{\text{th}} \) wind power generators, load demand and total power losss respectively.

3. OPTIMISATION METHODOLOGY

3.1. Real Coded Genetic Algorithm (RCGA)

Genetic algorithm (GA) is a modern heuristic intelligent optimisation computational technique which as the name suggests is inspired by the biological evolutionary concept of genetics. The basic ideology of GA is derived from Darwin’s theory of biological evolution through natural selection known as “Survival of the fittest”; according to which the fittest individuals survive better and dominate over the weaker ones or in other words the characteristics or variations in the genotype inherited from genes of parents which increases the organisms chance of survival i.e. have higher fitness, are preserved and is multiplied from the generations to generations and thus become dominant whereas the characteristics which have less survival factor becomes extinct and does not passed on to successive generations. It begins the search for the solution to the problem from a random population which is a set of potential solution (represented by a set of chromosome) to the optimisation problem and uses bio inspired operators like selection schemes, crossover mutation, and survivor operators to evolve from one generation to other and finally an optimal or near optimal population of solution is obtained. Easy programmability and faster computation of real coded genetic algorithm (RCGA) has made it supremely acceptable over binary coded genetic algorithm (BCGA) for real world problems having wider search space.

The basic steps of RCGA are as follows:

a. Initialisation of population:
   In the first step, an initial population of a particular population size \( N_p \) is created via the process of randomisation.

b. Evaluation of fitness value:
Here, the fitness of each decision variable in a population is found out through the fitness function which is the objective function of the optimisation.

c. Selection of parents for mating pool

After evaluation of fitness values of each individual, based on “survival of fittest” theory parents are to be selected for mating pool using suitable selection schemes. In the proposed work, tournament selection method is used.

d. Reproduction

In this step, parents selected in the mating pool are crossed and new population of offspring of size $N_p$ is produced. In the proposed work via suitable crossover operators. Here, in this present work, simulated binary crossover (SBX) operator has been used.

Algorithm for SBX operator is described below:

Let $P_1$ and $P_2$ be the parents in the mating pool, and if $O_1$ and $O_2$ is the offspring generated, following steps are used for SBX operator.

i. In the first step, a random number $u$ is to be generated between 0 to 1 for each decision variable.

ii. Distance between the offspring i.e. spread of the offspring is proportional to the spread of parents i.e.

$$O_1 - O_2 = \delta(P_1 - P_2)$$ (18)

iii. The value $\beta_j$ is computed for the decision variable $j$ through the following relations:

$$\beta_j = \begin{cases} \left(2u_j\right)^{1/(\eta_c+1)}, & \text{if } u_j \leq 0.5 \\ \frac{1}{2\left(1-u_j\right)} & \text{otherwise} \end{cases}$$ (19)

Where, $\eta_c$ is the distribution index for crossover, whose value is non-negative.

iv. The offspring for each decision variable $j$ is given by:

$$O_{1j} = 0.5\left[(1 + \beta_j)P_{1j} + (1 - \beta_j)P_{2j}\right]$$ (20)

$$O_{2j} = 0.5\left[(1 - \beta_j)P_{1j} + (1 + \beta_j)P_{2j}\right]$$ (21)

e. Mutation.

After the crossover operation is completed, each new individual undergoes mutation i.e. a random change is made to the values of some locations in the chromosomes to maintain the diversity.
Polynomial mutation has been used in the present work. In polynomial mutation, to create changes in the newly generated offspring near to the parents, a polynomial probability distribution is used (Deb, et al., 2014).

Algorithm for polynomial mutation operator is described below:

i. In the first step, a random number $r$ is to be generated between 0 to 1 for each decision variable.

ii. $\eta_m$ distribution index for mutation is to defined and then $\delta_j$ is calculated for each decision variable using the following equation:

\[
\delta_j = \begin{cases} 
\left(2r\right)^{\frac{1}{\eta_m+1}}, & r < 0.5 \\
1-\left[2\left(1-r\right)\right]^{\frac{1}{\eta_m+1}}, & r \geq 0.5
\end{cases} \tag{22}
\]

iii. The mutated offspring thus obtained by:

\[
O_{\text{mutated}} = O_j + \left(ub_j - lb_j\right)\delta_j \tag{23}
\]

where $ub, lb$ are upper and lower bounds for a particular decision variable $j$.

f. Combining and sorting:

The population of offspring and the parent population is combined, and the total size becomes $2N_p$ and the combined population are sorted in ascending order and the best fit solutions are taken out and is used as initial population for next generation.

g. Termination

The above steps from 2-6 are repeated till the termination criteria such as fixed no. of generation is reached, maximum iteration limits is reached or if no improvisation in the average fitness of solutions between consequent generations is observed.

h. Attainment of solution

After the termination condition satisfied the solutions in the last generation just before the termination conditions are met, is considered as the solutions to the problem.

3.2. Pseudo-Code

Input: Objective function $f(\text{TC})$, maximum and minimum limits of both type of generators, ($P_{i\text{min}}$ and $P_{i\text{max}}$, $w_{i\text{min}}$ and $w_{i\text{max}}$), population size ($N_p$), tournament size (p), crossover probability and mutation probability ($p_c, p_m$), distribution index for crossover and mutation ($\eta_c, \eta_m$), iteration count ($\text{iter}$), maximum iteration limit ($\text{iter}_{\text{max}}$), random number ($u$ and $r$)

1. Initialise a random population ($N_p$)
2. Obtain fitness function value of $N_p$
3. for \( \text{iter} = 1 \) to \( \text{iter}_{\text{max}} \)

- selection of parents using tournament selection of tournament size, \( p \)
  for \( i = 1 \) to \( N_p/2 \)
  if \( u < p_c \)
  produce offspring using SBX-crossover.
  else
  Copy selected parents as offspring
  end
for \( i = 1 \) to \( N_p \)
  if \( r < p_m \)
  perform mutation using polynomial mutation at selected sites
  else
  No change in offspring
  end
end
evaluate fitness of newly generated offspring
combine and sort
end

3.3. Implementation

3.3.1. RCGA Applied to DCEED with Only Conventional Generators

Step no. 1: The input test data comprising of No. of conventional generators \( N_c \), fuel cost coefficients \( (a_i, b_i, c_i, d_i, e_i) \) and emission cost coefficient \( (p_i, q_i, r_i, \delta_i, \eta_i) \), \( P_i^{\text{min}} \) and \( P_i^{\text{max}} \) of each generating units, loss coefficients, and Power demand \( P_d \) is read.

Step no.2: Price penalty factor (PPF) for a particular load demand is evaluated for combining the fuel cost and emission level objectives.

Step no.3: RCGA parameters including population size \( N_p \), crossover probability \( (p_c) \), mutation probability \( (p_m) \), distribution index for crossover and mutation \( (\eta_c, \eta_m) \), iteration count \( (\text{iter}) \) is set.

Step no.4: The termination condition i.e. the maximum limit of iterations, \( \text{iter}_{\text{max}} \) is set.

Step no.5: A initial random population of \( N_p \) size is created.

Step no.6: Iteration count, \( \text{iter} = 1 \) is set.

Step no.7: Fitness of the population of \( N_p \) size is evaluated using the DCEED objective function.

Step no.8: Parents for the mating pool are selected through tournament selection and mating pool is formed.

Step no.9: A random no. \( (u) \) is generated.

Step no.10: Condition \( u < p_c \) is checked, if the condition comes out to be true new offspring using SBX crossover operator using the selected parents is obtained otherwise the selected parents is copied as the offspring.

Step no. 11: The offspring produced using SBX crossover is bounded within the maximum and minimum power capacity limits.

Step no.11: A random no. \( (r) \) is generated.

Step no. 10: Condition \( r < p_m \) is checked, if the condition comes out to be true, then new offspring is mutated using polynomial mutation operator, otherwise the no mutation is done.

Step no.11: Mutated off springs are bounded and evaluated for fitness.
Step no. 12: The parent population and the newly generated mutated offspring are combined and are sorted according to their decreasing fitness.

Step no. 13: The best fit individuals from the sorted list is taken out and used for successive iterations.

Step no. 14: Step no. 3 to step no. 13 are repeated till the maximum iteration limit is reached and the individuals at the last iteration before the termination conditions is met gives the solution for DCEED problem.

3.3.2. RCGA Applied to DCEED Including Wind Farm

Step no. 1: The input test data comprising of no. of conventional generators $N_c$, fuel cost coefficients $(a_i, b_i, c_i, d_i, e_i)$ and emission cost coefficient $(p_i, q_i, r_i, \delta_i, \eta_i) P_i^{\text{min}}$ and $P_i^{\text{max}}$ loss coefficients of each conventional generating units and wind powered generators $N_w$ overestimation, underestimation
and direct cost coefficients of wind generators, available wind generated power, maximum and minimum capacity of wind generators, power demand is read.

Step no.2: Combine objective function including conventional generating units with fuel cost and emission level function and wind power generator uncertainty cost model is framed along with the various constraints associated with the combined system are

Step no.3: Steps no.3 to step no. 14 in section 3.2 is repeated and optimal power allocation of DCCED including wind powered generators are obtained.

4. RESULT AND DISCUSSION

The computational methodology RCGA is applied to solve the dynamic combined economic emission dispatch for a 6 generating unit test system. The dispatching process of generating units for total duration of 24 hrs with a time span of 1 hr for a time varying load demand has been investigated. The figure 2 presents the load curve for 24 hrs. Results for the two cases has been obtained . The first case dealt with dispatch of only conventional generating units considering the combined fuel and emission cost, while the second case dealt with the inclusion of wind powered generators to the conventional generating system units. Available wind power for a entire dispatch period is used for the wind power cost model estimation. The most expensive conventional generator is replaced with the wind powered generator and optimal allocation of power among the composite system of generators is obtained. A comparison analysis for the two cases based on the percentage of fuel saving, reduction of emission levels and percentage saving of combined economic emission cost with the inclusion of wind powered generators is analyzed. The RCGA parameters are varied for obtaining the best solution for both the cases. The population size is varied from 20,50, 100,200, maximum iteration limit is varied from 100, 200, 300, 500, while a variation ranging from 0.5 -0.9 and 0.01-0.05 for crossover and mutation probability respectively is done for obtaining the best possible dispatch among the generating units with optimal cost, best convergence, and faster computation time. All the results are obtained using compact programming in MATLAB R2013.

4.1 Case 1 (Only Conventional Generating Units)

In this case, a conventional generating unit system is taken as the test case and dynamic economic emission dispatch of the conventional generating units is performed for variable load for 24 hrs. Effects caused due to valve –point loading is considered. For the analysis the data i.e. fuel cost coefficient, emission cost coefficient and transmission loss coefficients of a six conventional generating units is used (Liao, 2011). The combined fuel cost and emission dispatch for the generators are obtained through proper evaluation of penalty factor for each load in the 24 hr dispatch time duration. To have an equal dominance in optimizing the two non-compatible objectives of minimum fuel cost and emission cost simultaneously, the weight factor λ is taken as 0.5. Total of 30 trial runs of the proposed algorithm is done for each load in every time interval for 24 hrs with various combinations in RCGA parameters. Out of the trial runs, the best dispatch solution is taken as the DCEED solution for the particular load demand for a time interval. The converging plot for the total combined generation cost with only conventional generating units in the 9th time interval for the load demand 830 MW is shown in Figure3.

Crossover probability, mutation probability and population size of 0.85, 0.01 and 20 respectively is obtained as a result of tuning RCGA parameters for obtaining the best possible results for this time interval. The total fuel cost, the emission level in the 9th time interval comes out to be 58342 Rs/hr, 915.543 kg/hr respectively while the total combined economic emission cost is 5561408.131 Rs/hr. Table 1 presents the best dispatch solution for DCEED considering only conventional generating units for a time varying 24 hr load demand . Figure 4 shows the curve for the dispatched active power outputs of each generating units for the entire dispatch duration .The average fuel cost, emission level
and the total combined economic emission cost of conventional generating units for entire 24 hrs dispatch period comes out to be 52891.226 Rs/hr, 819.3036 kg/hr and 4253519 Rs/hr respectively.

4.2 Case 2 (Including Wind Powered Generators)

In this case, the most expensive conventional generating unit obtained for each hour in case 1 is replaced by wind powered generators. A wind farm consisting of 50 identical wind turbines each of 2 MW power capacity is considered, therefore making a total wind farm installed capacity as 100 MW. The maximum and minimum power capacity of the wind farm is 15 MW and 100MW. Figure 5 shows the available wind power output characteristics for 24 hrs. For simplicity, it is considered that the wind farm is owned by the grid operator; hence the direct cost coefficient is assumed to be 0. The coefficient associated with wind power uncertainty i.e. coefficient of underestimation and overestimation is taken to be 5 and 30 respectively. The data for load and conventional generator is same as in case 1 for this The converging plot for the total combined generation cost with conventional generating units and wind powered generating units in the 9th time interval for the load demand 830 MW is shown in Figure 6. In the 9th time interval the total fuel cost, emission level is found to be 48195 Rs/hr and 746.871 kg/hr respectively while the total combined cost obtained is 3612073.195Rs/hr. The crossover probability and the mutation probability of 0.7 and 0.01 respectively and the population
### Table 1. DCEED of six conventional generating units for time varying load demand within 24 hrs

| Time period (hr) | Load (MW) | Only conventional generating units (No wind) | Combined converging cost in (Rs/hr) | Total power generated in (MW) | PG1 (MW) | PG2 (MW) | PG3 (MW) | PG4 (MW) | PG5 (MW) | PG6 (MW) |
|------------------|-----------|---------------------------------------------|-------------------------------------|-------------------------------|----------|----------|----------|----------|----------|----------|
| 1                | 425       | Fuel cost in (Rs/hr)                        | 31195                               | 448                           | 28       | 48       | 41       | 76       | 145      | 110      |
| 2                | 476       | Emission level in (kg/hr)                   | 34661.1                             | 599.268                       | 36       | 65       | 74       | 89       | 108      | 126      |
| 3                | 530       | Combined converging cost in (Rs/hr)         | 44433                               | 692.725                       | 34       | 68       | 70       | 119      | 127      | 142      |
| 4                | 580       | Total power generated in (MW)               | 45830                               | 713.67                         | 42       | 67       | 79       | 100      | 166      | 140      |
| 5                | 610       | Fuel cost in (Rs/hr)                        | 48485                               | 800.885                       | 30       | 79       | 88       | 120      | 130      | 166      |
| 6                | 665       | Emission level in (kg/hr)                   | 52709                               | 819.455                       | 70       | 82       | 89       | 132      | 195      | 155      |
| 7                | 735       | Combined converging cost in (Rs/hr)         | 56992                               | 889.276                       | 80       | 94       | 166      | 179      | 137      | 132      |
| 8                | 756       | Total power generated in (MW)               | 57350                               | 895.113                       | 80       | 97       | 187      | 166      | 130      | 146      |
| 9                | 830       | Fuel cost in (Rs/hr)                        | 58342                               | 915.543                       | 85       | 123      | 196      | 187      | 134      | 150      |
| 10               | 875       | Emission level in (kg/hr)                   | 58926                               | 923.67                         | 96       | 130      | 199      | 215      | 136      | 146      |
| 11               | 900       | Combined converging cost in (Rs/hr)         | 61298.453                           | 940.523                       | 114      | 155      | 210      | 225      | 136      | 146      |
| 12               | 910       | Total power generated in (MW)               | 62100.671                           | 945.674                       | 100      | 158      | 210      | 225      | 136      | 146      |
| 13               | 895       | Fuel cost in (Rs/hr)                        | 61023.753                           | 937.663                       | 98       | 155      | 210      | 225      | 136      | 146      |
| 14               | 850       | Emission level in (kg/hr)                   | 58789                               | 915.988                       | 91       | 127      | 197      | 225      | 133      | 150      |
| 15               | 770       | Combined converging cost in (Rs/hr)         | 57776                               | 902.543                       | 82       | 105      | 187      | 182      | 137      | 132      |
| 16               | 730       | Total power generated in (MW)               | 56618                               | 845.234                       | 72       | 95       | 155      | 200      | 145      | 120      |
| 17               | 690       | Fuel cost in (Rs/hr)                        | 53197                               | 824.701                       | 71       | 85       | 92       | 144      | 200      | 140      |
| 18               | 700       | Emission level in (kg/hr)                   | 54651                               | 827.642                       | 72       | 95       | 125      | 150      | 123      | 170      |
| 19               | 745       | Combined converging cost in (Rs/hr)         | 56999                               | 892.452                       | 79       | 95       | 169      | 176      | 134      | 145      |
| 20               | 800       | Total power generated in (MW)               | 58000                               | 900.113                       | 84       | 114      | 189      | 186      | 143      | 132      |
| 21               | 875       | Fuel cost in (Rs/hr)                        | 58926                               | 923.67                         | 94       | 130      | 199      | 215      | 136      | 155      |
| 22               | 890       | Emission level in (kg/hr)                   | 59011.457                           | 937.22                         | 95       | 110      | 190      | 220      | 150      | 140      |
| 23               | 500       | Combined converging cost in (Rs/hr)         | 43358                               | 632.175                       | 52       | 59       | 68       | 80       | 110      | 166      |
| 24               | 460       | Total power generated in (MW)               | 38718                               | 556.795                       | 50       | 40       | 67       | 80       | 122      | 144      |

Figure 4. Plot of dispatched active power outputs of each generating units for the entire dispatch duration.
size of 20 gave the best possible solution for DCEED for this time interval. Table 2 presents the best
dispatch solution for DCEED considering conventional generating units and wind generators. Figure
7 shows the curve for the dispatched active power outputs of each generating units for the entire
dispatch duration. The average fuel cost, emission level and the total combined economic emission
cost of conventional and wind powered generating units for entire 24 hrs dispatch period comes out
to be 44092.54173 Rs/hr, 637.7165 kg/hr and 2992536 Rs/hr respectively.
4.3 Comparison of Case 1 And Case 2

On comparing the two test cases it was observed that there was a significant reduction in cost of fuel, emission level, and total combined economic emission dispatch cost in case 2 in comparison in case 1. On an average, for over 24 hrs dispatch time period the fuel cost saving in test case 2 was 8798.6842688 Rs/hr (16.6354326%), reduction in emission level was 181.5871 kg/hr (22.1636%) and reduction in total combined economic emission cost was 1260983 Rs/hr (29.6456%). A saving of 17.39227% in fuel cost, 18.42317% in emission level and 33.8618% in the total combined economic emission cost was observed in the 9th time interval. Table 3 presents the reduction in cost of fuel, emission level, and total combined economic emission dispatch cost for each time period within 24 hrs dispatch duration. Figure 8, 10, 12 and shows the comparison of both the cases in terms of the total combined economic emission cost, total fuel cost and emission level for entire dispatch duration, while figure 9, 11, 13 shows the percentage of the saving in the combined economic emission cost, total

Table 2. DCEED including wind powered generators for time varying load demand within 24 hr

| Time period (hr) | Available wind power | Fuel cost in (Rs/hr) | Emission level in (kg/hr) | Cost Associated with Wind | Combined converging cost in (Rs/hr) | Total power generated in (MW) | PG1 (MW) | PG2 (MW) | PG3 (MW) | PG4 (MW) | PG5 (MW) | PG6 (MW) |
|-----------------|----------------------|----------------------|---------------------------|--------------------------|-----------------------------------|-------------------------------|-----------|-----------|-----------|-----------|-----------|-----------|
| 1               | 55                   | 26500.8              | 369.4769                  | 350                      | 1374311.953                       | 483                            | 24         | 69        | 82        | 84        | 136       | 41        |
| 2               | 50                   | 27691.80             | 523.627                   | 475                      | 1423684.936                       | 436                            | 46         | 81        | 60        | 105       | 160       | 31        |
| 3               | 65                   | 37048                | 546.1718                  | 425                      | 1641376.774                       | 623                            | 49         | 66        | 111       | 144       | 82        | 94        |
| 4               | 48                   | 37079                | 635.09                    | 425                      | 2332605.963                       | 597                            | 42         | 89        | 60        | 187       | 154       | 65        |
| 5               | 55                   | 43222                | 733.1211                  | 725                      | 2478708.394                       | 626                            | 42         | 85        | 98        | 177       | 84        | 140       |
| 6               | 48                   | 44616                | 745.5486                  | 800                      | 3094363.382                       | 755                            | 55         | 95        | 179       | 197       | 140       | 87        |
| 7               | 55                   | 47957                | 807.2878                  | 800                      | 3293469.156                       | 797                            | 59         | 97        | 185       | 198       | 87        | 149       |
| 8               | 60                   | 48166                | 821.562                   | 675                      | 3293469.156                       | 942                            | 124        | 143       | 220       | 222       | 100       | 133       |
| 9               | 32                   | 48195                | 876.871                   | 842                      | 4381127.195                       | 942                            | 124        | 143       | 220       | 222       | 100       | 146       |
| 10              | 20                   | 48932                | 859.67                    | 850                      | 3823986.853                       | 898                            | 97         | 159       | 215       | 223       | 54        | 150       |
| 11              | 40                   | 49982                | 900.3612                  | 942                      | 4378119.504                       | 942                            | 124        | 143       | 220       | 222       | 100       | 133       |
| 12              | 50                   | 51000                | 900.799                   | 675                      | 4646657.738                       | 964                            | 125        | 158       | 220       | 223       | 77        | 161       |
| 13              | 65                   | 49135                | 889.643                   | 962                      | 4207724.276                       | 925                            | 112        | 162       | 217       | 225       | 100       | 146       |
| 14              | 72                   | 48911                | 842.132                   | 250                      | 3786550.694                       | 866                            | 96         | 131       | 197       | 210       | 82        | 150       |
| 15              | 90                   | 48110                | 795.344                   | 150                      | 3331484.139                       | 798                            | 56         | 115       | 186       | 210       | 147       | 84        |
| 16              | 100                  | 47898                | 772.675                   | 771                      | 2912163.892                       | 751                            | 63         | 85        | 187       | 179       | 150       | 87        |
| 17              | 68                   | 46615                | 765.891                   | 710                      | 2721419.106                       | 700                            | 59         | 95        | 135       | 179       | 165       | 77        |
| 18              | 68                   | 47110                | 759.5611                  | 150                      | 2885921.247                       | 713                            | 57         | 97        | 178       | 210       | 52        | 119       |
| 19              | 60                   | 47994                | 810.99                    | 450                      | 3133142.248                       | 762                            | 58         | 97        | 184       | 196       | 149       | 78        |
| 20              | 70                   | 48176                | 822.342                   | 100                      | 3412606.156                       | 800                            | 82         | 123       | 186       | 212       | 145       | 74        |
| 21              | 20                   | 48932                | 859.97                    | 850                      | 3823986.853                       | 898                            | 97         | 159       | 215       | 223       | 54        | 150       |
| 22              | 90                   | 48976                | 872                      | 850                      | 3997990.053                       | 936                            | 110        | 160       | 200       | 220       | 146       | 100       |
| 23              | 80                   | 33468                | 552.173                   | 625                      | 1564620.676                       | 540                            | 34         | 85        | 98        | 126       | 135       | 31        |
| 24              | 75                   | 32506.4              | 431.8894                  | 325                      | 1378468.568                       | 476                            | 25         | 41        | 35        | 121       | 59        | 195       |
fuel cost and emission level duration, observed in case 2 for entire dispatch duration. The maximum saving in the fuel cost and emission level for the entire dispatch duration was found to be 22.8106% (in the 23rd time interval) and 35.014% (in the 3rd time interval) respectively while the maximum in the total combined economic emission cost was 34.779751%, occurred (in the 19th time interval).

Table 3. Percentage of saving with inclusion of wind powered generators

| Time period (hr) | Most expensive generator obtained from case 2 | Load (MW) | % of saving with wind generators |
|------------------|---------------------------------------------|-----------|----------------------------------|
|                  |                                             |           | Fuel saving | Emission level reduction | Combined cost saving |
| 1                | G6                                          | 425       | 15.047       | 14.332                 | 16.5499              |
| 2                | G6                                          | 476       | 20.106       | 12.62203               | 26.152               |
| 3                | G5                                          | 530       | 16.62053     | 21.156                 | 30.67                |
| 4                | G6                                          | 580       | 19.0944      | 11.431                 | 14.7912              |
| 5                | G5                                          | 610       | 10.8549      | 10.957                 | 18.082               |
| 6                | G6                                          | 665       | 15.354988    | 9.01899                | 25.886425            |
| 7                | G6                                          | 735       | 15.8531      | 9.21965                | 25.48749             |
| 8                | G5                                          | 756       | 16.3452      | 8.29266                | 32.5421              |
| 9                | G5                                          | 830       | 17.39227     | 12.2556                | 33.8618              |
| 10               | G5                                          | 875       | 16.960255    | 6.92888                | 30.06                |
| 11               | G5                                          | 900       | 18.46123     | 5.4367                 | 29.43976             |
| 12               | G5                                          | 910       | 17.87532     | 4.2                    | 26.488               |
| 13               | G5                                          | 895       | 19.481179    | 5.12124                | 30.2528              |
| 14               | G6                                          | 850       | 16.80246     | 8.06298                | 31.7585              |
| 15               | G6                                          | 770       | 16.73        | 11.8774                | 33.8052              |
| 16               | G6                                          | 730       | 15.22484     | 8.5865344              | 29.54388             |
| 17               | G6                                          | 690       | 12.372878    | 9.32723                | 29.75864             |
| 18               | G5                                          | 700       | 13.732594    | 8.22586                | 27.815539            |
| 19               | G6                                          | 745       | 15.79852     | 9.12788                | 29                   |
| 20               | G6                                          | 800       | 16.93793     | 8.64013                | 34.7001              |
| 21               | G5                                          | 875       | 16.960255    | 6.92888                | 30.06                |
| 22               | G6                                          | 890       | 17.0059      | 7                      | 33.285               |
| 23               | G6                                          | 500       | 16.6205      | 24.677                 | 29.4023              |
| 24               | G5                                          | 460       | 16.0431      | 22.432                 | 24.2823              |
Figure 8. Comparison of case 1 and case 2 in terms of total combined economic emission.

Figure 9. Percentage of saving of total combined cost in case 2.

Figure 10. Comparison of case 1 and case 2 in terms of total fuel cost.
5 CONCLUSION

The proposed work aimed to mitigate the problem associated with environmental degradation due to harmful emissions from conventional generation by two approaches. The first approach dealt with the modification of the existing dispatch strategy in which dynamic combined economic emission dispatch model was framed using suitable price penalty factors. In the second approach, to have a greater environmental security, the introduction of wind generator characteristics was added to the system.
The entire dispatch duration of 24 hrs was investigated taking consideration of wind uncertainty as well as load uncertainty in load. To deal with the uncertainty related to wind power availability, wind uncertainty cost model was used where the cost due to wind power uncertainty was addressed using various reserve cost and penalty cost coefficients.

To solve the combined optimisation of fuel cost and emission level in the problem an efficient optimization algorithm – real coded genetic algorithm (RCGA) was successfully implemented. Its ease in programming, multi-point searching feature makes it extraordinarily powerful. RCGA parameters such as crossover and mutation probability were carefully selected for the problem via sensitivity analysis test. Numerous trial runs were performed to obtain the best possible result with the greater optimality and faster convergence.

A comparative analysis of both the cases was done in terms of fuel cost saving, emission reduction and reduction in combined economic emission cost for each period of time. From the analysis, it can be concluded that inclusion of wind powered generators to the system can have excellent optimal impacts in terms of fuel saving, emission control as well as on the total combined cost of generation compared to existing conventional system.
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