Abstract—Wind power being one of the sustainable forms of renewable energy resources will bear significant role in future clean energy generation. Combined heat and power method of power and heat generation in a single process not only yields more than 80% efficiency but also reduces emission of \( \text{CO}_2 \), \( \text{NO}_x \), and \( \text{SO}_2 \). This paper utilizes a new bio-inspired krill herd algorithm to solve economic emission dispatch optimization problem of wind power integrated combined heat and power system. Herding behavior of individual krill is considered to formulate this algorithm. The distance of each individual krill from food and from highest density of the herd is considered as the objective function. At any instant, position of an individual krill is determined by: i) movement induced by neighboring krill individuals, ii) foraging activity of it and iii) its random diffusion motion. A test system has been considered in this paper to illustrate this algorithm. The result shows that this algorithm is capable of solving such multi-objective optimization problem of hybrid power system with better convergence consuming less computation time.

Keywords—Combined Heat and Power (CHP), Cogeneration, Combined heat and power economic dispatch (CHPEED), Feasible operation region (FOR), Krill herd (KH) algorithm, Optimization.

I. INTRODUCTION

Technological advancement and reduction of production cost has encouraged increased installed capacity of wind power generation worldwide. Being one of the alternatives to fossil fuel, wind power is the renewable form of abundant and clean source of energy which does not produce greenhouse gas during its operation and hence does not affect the environment unlike other sources of energy. More than 83 countries around the world have been producing wind power to supply to their respective electric power grid and this production of wind power is growing rapidly at the rate of more than 25% per year. In India wind power production by the year 2030 has been projected to be 39GW. Total share of wind power by the end of 2030 has been projected to be 30%.

On the other hand, combined heat and power system of power and heat generation in a single process has emerged as another matured form of distributed energy resource (DER) which not only yields more than 80% efficiency [1] but also helps to reduce emission level, primary energy usage and production cost. This paper presents a hybrid test system consisting of cogeneration units (CGU) and wind power unit which will primarily use wind power to supply the power demand depending on the availability of wind speed and the remaining power and heat demand to be serviced by utilizing the cogeneration units so that the total cost of production is minimum and the emission level is also at minimum. Penalty is imposed if available wind power is not utilized fully. Penalty is also imposed if scheduled wind power is not available. Hence, the projected problem is intrinsically a non-linear multi-objective optimization problem which has to supply the demand satisfying all equality and non-equality constraints. The projected system may supply to conventional grid or micro-grid and may also operate in islanding mode.

Optimum utilization of different units of conventional power generating stations and wind power integrated in to it, has been handled by different researchers for solving economic dispatch (ED) and economic emission dispatch (EED) respectively using different heuristic optimization techniques such as particle swarm optimization [2], craziness based particle swarm optimization [3], differential evolution [4], krill herd [5] etc.

Some researchers solved CHPEED problem effectively using multi-objective strength pareto evolutionary algorithm (SPEA) [6], multi-objective particle swarm optimization [7], fuzzy cluster-based particle swarm optimization [8], non-dominated sorting genetic algorithm II (NSGA II) [9]-[10] etc. But real coded genetic algorithm (RCGA) [11] applied to solve economic dispatch and emission dispatch separately. But few work of EED on such a hybrid system incorporating CHP with wind power have been reported [12]-[13] so far.

Focus of this research work is to use a recently developed biological inspired meta heuristic krill herd algorithmic technique [14] for simultaneous optimization of cost and emission level of the hybrid test system considering transmission loss. Result shows that the algorithm is capable of handling such non-linear multi-objective optimization problem efficiently.

Remaining portion of the paper is organized as follows: section II presents wind power unit modeling in to the system, section III presents the CHPEED problem formulation, section IV presents the methodology of krill herd algorithm, section V presents simulation on the test system and finally section VI presents the concluding discussion and future possibilities.
II. WIND POWER MODELLING

Power generation from wind power cannot be controlled and scheduled with high degree of accuracy as it can start and stop suddenly depending on the availability of wind speed suitable for such generation. Thus the wind speed ($W_r$) is a random variable and the relationship between power generated from wind generator and the wind speed is highly non-linear. Hence, this research work emphasizes on integration of combined heat and power units with wind power unit and priority of usage of available wind power generation. To ensure this a penalty factor is imposed for not using the available full wind power generation. This situation arises when scheduling underestimates wind power generation. On the other hand, ambitious scheduling of wind power generation may also be penalized if the wind power is not available during the scheduled period. Under such situation demand is served by utilizing combined heat and power unit. Improved forecasting method, historical wind profile data of the location and historical load demand profile may help to improve accuracy of scheduling method of wind power generation.

The relation between the wind power generated and the wind speed is highly non-linear. Hence, this research work emphasizes on relation between power generated from wind generator and the wind speed which is defined as follows:

$$P_W = \begin{cases} \frac{(W_r - V_{in})(V_{cut-in} - V_{in})}{W_{cut-in}}, & V_{cut-in} \leq W_r < V_{in} \\ W_r, & V_{in} \leq W_r < V_{cut-out} \\ 0, & W_r \leq V_{cut-out} \end{cases}$$

(1)

where $W_r$ is the wind speed, $W_r$ is the rated wind power, $V_{in}$ is the cut-in wind speed, $V_{cut-out}$ is the cut-out wind speed, $V_{cut-in}$ is the rated wind speed and $P_W$ is the power generated by wind power generator. It is evident that when wind speed is within the cut-in speed and rated wind speed then only the power generated by the wind power is continuous and otherwise the power generated is discrete. Because when the wind speed is less than cut-in wind speed and when it is more than cut-out wind speed, the power generated by wind generator is zero. And when the wind speed is within the rated wind speed and cut-out wind speed, the power generated by the wind power is the rated wind power.

III. CHPEED PROBLEM FORMULATION

Integration of cogeneration units in power system introduces complicacy as in these units power and heat production depends mutually on each other. In cogeneration units, this dependency of heat production on power production and vice versa is well defined by the feasible operation region (FOR). The feasible operation region as shown in fig. 1 for a cogeneration unit is enclosed by the curve $a_1$, $a_2$, $a_3$, $a_4$, $a_5$. The test system considered contains cogeneration units and wind power unit. The objective of combined heat and power economic emission dispatch problem is to optimize production cost and emission level simultaneously through optimal unit power and heat production satisfying all inequality and equality constraints so as to cater the power and heat demand of the system. The cost of production function, emission estimation function and the constraints are mathematically stated as below:

$$PC = \min \sum_{j=1}^{Nq} (C_j(P_j, H_j) + C_{wp})$$

(2)

Where $PC$ is the total cost of production of power and heat, $C_{wp}$ is the cost of wind power production, $C_j$ is the cost function co-efficient of respective units of power and heat production, $P$ is the power generation of cogeneration units, $H$ is the heat generation by cogeneration units. The cost of wind power $C_{wp}$ is defined as:

$$C_{wp} = d_i \times P_w + C_{wpp} + C_{wpr}$$

(3)

where $d_i$ is the direct cost co-efficient factor, $C_{wpp}$ is the underestimation penalty cost due to available wind power generation being more than the scheduled wind power ($W_s$) and $C_{wpr}$ is overestimation reserve cost due to available wind power generation being less than the scheduled wind power. $C_{wpp}$ is defined using penalty cost co-efficient $K_p$ as:

$$C_{wpp} = K_p \times (P_s - W_s)$$

(4)

$C_{wpr}$ is defined using reserve cost co-efficient ($K_r$) as:

$$C_{wpr} = K_r \times (W_s - P_s)$$

(5)

Emission is minimized using this equation:

$$Em = \min \sum_{j=1}^{Nq} E_j(P_j)$$

(6)

Subject to the constraints:

$$\sum_{j=1}^{Nq} P_j + P_w = p_d + p_L$$

(7)

$$\sum_{j=1}^{Nq} H_j = h_d$$

(8)

$$P_j \leq P_j^h \leq P_j^m, H_j \leq H_j^h \leq H_j^m, j = 1, 2, \ldots, N_q$$

(9)

The transmission loss $p_L$ of the system is calculated using the loss co-efficient as in (11).

$$p_L = \sum_{j=1}^{N_q} P_j B_j P_j$$

(11)

Where $Em$ is the total emission generated by cogeneration units of the system, $p_d$ is the active power transmission loss of the system, $p_L$ and $h_d$ are the power and heat demand to the system, $P_j^m$ and $P_j^m$ are the power generation capacity limits of individual cogeneration units, $H_j^m$ and $H_j^m$ are the heat generation capacity limits of the individual cogeneration units, $j$ is the indices of cogeneration units respectively; $N_q$ are the numbers of cogeneration units; $B_j$ are the transmission loss co-efficients between $i$-th and $j$-th generators of wind power only and cogeneration units.
Fig. 1. FOR on heat and power plane of a Co-generation unit (CGU).

IV. KRILL HERD ALGORITHM

The main objective of Krill herding is to reach the food location and the highest density of swarm. Hence, the fitness of each krill is defined as its distance from food and highest density of swarm. The time dependent position of each krill individual is determined by three factors such as: 1) movement induced by other krill, 2) its own foraging activity and 3) its random diffusion motion. Thus at each moment the motion of krill individual tries to
1) find the location and the highest density of swarm. Thus at each moment the motion of krill individual tries to
1) find the location and the highest density of swarm. Hence, the fitness of each krill individual using (17):

\[ S_d = \frac{1}{5N} \sum_{i=1}^{N} \|X_i - X_f\| \]  

where \( N \) is the number of krill individuals and \( S_d \) is the sensing distance for the \( i-th \) krill individual. The lowest fitness of an individual krill is its known target vector. The effect of the individual krill with best fitness to the global optima and is more effective than other neighboring krill individuals. The value of \( C_{best} \) is determined as:

\[ C_{best} = 2 \left( \text{rand} + \frac{1}{I_{max}} \right) \]  

where \( I_{max} \) is the actual iteration number, \( I_{max} \) is the maximum number of iterations and \( \text{rand} \) is a random value between 0 and 1.

\[ \frac{dX_i}{dt} = O_{mi} + F_{mi} + D_{mi} \]  

where \( O_{mi} \) is the motion induced by other krills; \( F_{mi} \) is the foraging motion of the \( i-th \) krill individual, and \( D_{mi} \) is the physical diffusion of the \( i-th \) krill individual.

A. Motion Induced by Other Krill Individuals

The motive of krill individuals is to stay within the high density of swarm and move due to mutual effects [14] of the neighboring krill. The local swarm density, the target swarm density and the repulsive swarm density together dictate the direction \( \beta \) of this induced motion of the \( i-th \) krill individual. This movement for the \( i-th \) krill individual is defined as:

\[ O_{mi}^{max} = O_{mi}^{max} [\beta] + \omega_{mi} O_{mi}^{old} \]  

where,

\[ \beta = [\beta_{m}^{best}] + [\beta_{m}^{rep}] \]  

and \( O_{mi}^{max} \) is the maximum induced speed whose value is taken as 0.01 ms\(^{-1}\) [14], \( O_{mi}^{old} \) is the last motion induced, \( \beta_{m}^{best} \) is the local effect provided by the neighboring krill individuals and \( \beta_{m}^{rep} \) is the target direction effect provided by the best krill individual and \( \omega_{mi} \) is the inertia weight of the motion induced in the recommended range \((0, 1)\) [14]. The attractive or repulsive effect of the neighbors on an individual krill movement for local search is determined using (15):

\[ \beta_{m}^{best} = \sum_{j=1}^{N} \frac{K_j - K_{best}^{j}}{K^{j} - K_{best}^{j}} \cdot \frac{X_j - X_i}{\|X_j - X_i\| + \epsilon} \]  

where \( \epsilon \) is added to the denominator to avoid the singularities. In each iteration, neighbors of a krill individual are determined based on a sensing distance around the krill individual using (17):

\[ C_{best} = \frac{K_j - K_{best}^{j}}{K^{j} - K_{best}^{j}} \]  

and \( K_i \) represents the fitness of the \( i-th \) krill individual; \( K_j \) is the fitness of \( j-th \) neighbor; \( X \) represents the related positions; \( N \) is the number of the neighbors and \( K_{best}^{j} \) and \( K^{j} \) are the best and the worst fitness values of the krill individuals so far. A small positive number, \( \epsilon \), is added to the denominator to avoid the singularities.

The right side of each of (15) and (16) contains unit vector and normalized fitness value. The vectors show the induced directions by different neighbors which may be either attractive or repulsive since the normalized value can be negative or positive. In each iteration, neighbors of a krill individual are determined based on a sensing distance around the krill individual using (17):

\[ S_d = \frac{1}{5N} \sum_{i=1}^{N} \|X_i - X_f\| \]  

where \( N \) is the number of krill individuals and \( S_d \) is the sensing distance for the \( i-th \) krill individual. The lowest fitness of an individual krill is its known target vector. The effect of the individual krill with best fitness to the global optima and is more effective than other neighboring krill individuals. The value of \( C_{best} \) is determined as:

\[ C_{best} = 2 \left( \text{rand} + \frac{1}{I_{max}} \right) \]  

where \( I_{max} \) is the actual iteration number, \( I_{max} \) is the maximum number of iterations and \( \text{rand} \) is a random value between 0 and 1.

B. Foraging Motion

The food location and the previous experience about the food location are the two main effective parameters based on which the foraging motion is formulated for the \( i-th \) krill individual as:

\[ F_{mi} = F_{yi} [\gamma_i] + \omega_{mi} F_{mi}^{old} \]  

where \( [\gamma_i] = [\gamma_{i}^{food}] + [\gamma_{i}^{best}] \) and \( F_{mi}^{old} \) is the last foraging motion, \( F_{yi} \) is the foraging speed, \( \omega_{mi} \) is the inertia weight of the foraging motion in the range \([0,1]\) [14], \( [\gamma_{i}^{food}] \) is the food attractive and \( [\gamma_{i}^{best}] \) is the effect of the best fitness of the \( i-th \) krill so far. The value of the foraging speed [14] is taken as 0.02 (ms\(^{-1}\)). To define the food effect, the virtual centre of food concentration is estimated according
to the fitness distribution of the krill individuals per iteration using (22):

$$X_{food} = \sum_{i=1}^{NK} \frac{1}{C_i} X_i \left/ \sum_{i=1}^{NK} \frac{1}{C_i} \right.$$  \hspace{1cm} (22)

And the food attraction of the $i$-th krill individual is determined as:

$$[y^\text{food}] = C_{food} \left( \frac{K_{best} - K_{i,food}}{K_{i,food} - K_{best}} \right) \overline{X},_{i,\text{best}}$$  \hspace{1cm} (23)

where $C_{food}$ is the food coefficient. The effect of food in krill herding diminishes with time and the food coefficient is determined as:

$$C_{food} = 2 \left( 1 - \frac{t}{t_{\text{max}}} \right)$$  \hspace{1cm} (24)

After some iterations, the krill individual normally herd around the global optimum point as the food attraction leads krill swarm to the global optima. This is considered to be an efficient global optimization strategy which helps improving the globality of the KH algorithm. The effect of the best fitness of the $i$-th krill individual is estimated using (25):

$$[y^\text{best}] = \left( \frac{K_{best} - K_{i,\text{best}}}{K_{i,\text{best}} - K_{best}} \right) \overline{X},_{i,\text{best}}$$  \hspace{1cm} (25)

where $K_{i,\text{best}}$ is the best previously visited position of the $i$-th krill individual.

C. Physical Diffusion

The physical diffusion of krill individuals being a random process can be expressed in terms of a maximum diffusion speed and a random directional vector as:

$$D_m = D_{m_{\text{max}}} \left[ \delta \right]$$  \hspace{1cm} (26)

Where $D_{m_{\text{max}}}$ is the maximum diffusion speed and $[\delta]$ is the random directional vector array having random values between -1 and 1. Suggested range for the maximum diffusion speed $D_{m_{\text{max}}}$ of the krill individuals is (0.002, 0.010) (ms$^{-1}$) [14] and this range has been used in this paper. As the position of the krill becomes better and better, its motion becomes less random. This effect is considered by adding another term to the physical diffusion formula. With passage of time (iterations), the effects of motion induced by other krill individuals and foraging motion gradually decrease. Physical diffusion being a random vector and does not steadily reduce with the increase of the iteration number, another term is added to (26) to linearly decrease this random speed with time which works as a geometrical annealing schedule.

$$D_m = D_{m_{\text{max}}} \times \text{floor} \left\{ \left[ \frac{K_{best} - K_{i,\text{best}}}{K_{i,\text{best}} - K_{best}} \right] \left[ 1 - \frac{t}{t_{\text{max}}} \right] \right\}$$  \hspace{1cm} (27)

where $\text{floor}$ rounds the element to the nearest integer less than or equal to it.

D. Motion Process of KH Algorithm

The time dependent position of krill individual changes frequently, due to the effect of the above defined three motions, for attaining the best fitness value. Each of motion induced by neighboring krill and foraging motion contains a local and a global searching strategy which works in parallel. This makes KH a powerful algorithm. The position vector of a krill individual during the interval $(t)$ and $(t+\Delta t)$, using different abovementioned effective parameters of the three motions during the time, is given by (28):

$$X_i(t + \Delta t) = X_i(t) + \Delta t \frac{dX_i}{dt}$$  \hspace{1cm} (28)

The parameter $\Delta t$ acts as a scale factor of the speed vector, and is to be chosen carefully as per the optimization problem. This parameter depends solely on the search space and is given by:

$$\Delta t = C, \sum \frac{|y - L b|}{L b}$$  \hspace{1cm} (29)

where $C_i$ is a constant number between (0, 1) and $L b$ are lower and upper bounds respectively of the search space. A small value of $C_i$ helps the krill individuals to search the space carefully which should be considered for the complex problems. These powerful features help this algorithm to converge effectively to a global minima which has encouraged authors to use this KH method in solving the CHPEED problem.

E. Methodology Of KH Algorithm

Based on the motion characteristics of the krill individuals the flow of the KH algorithm is defined by the following phases:

Phase1 : Data Structures Definition: Search space identification, determination of constants etc.
Phase2 : Initialization: Random initial population creation.
Phase3 : Fitness evaluation: based on individual Krill position.
Phase4 : Motion calculation:
   I. Motion induced by surrounding Krill individuals,
   II. Foraging motion of individual Krill
   III. Physical diffusion of krill individual
Phase5 : Go to phase 6 if all constraints are satisfied else go to phase 4.
Phase6 : Update position of Krill individual in search space.
Phase7 : Go to phase 4 until the stop criteria is reached.
Phase8 : End.

Flow of the KH algorithm is shown in Fig. 2.

V. NUMERICAL EXAMPLE

In this section, a test system, modified from that of [15], has been used to show the validity and effectiveness of the KH algorithm. The power and heat demands of the system are 200 MW and 115 MWh (modified from 80 MW and 70 MWh of [15]) respectively. The algorithm is implemented using Matlab7.7 on 3GHz, 500GB Pentium IV PC and is used to minimize cost of production and the emission level.

Test system : consists of three co-generation units (replaced 1st CGU of [15] by a higher capacity CGU, kept the 2nd CGU same and added another CGU) and a wind power unit. System unit data (modified from [15]), cost function, emission function, transmission power loss co-efficient, feasible operation region (FOR) of heat and power of the co-generation units used in the system, cost and emission convergence characteristics and results are given in Appendix.

In arriving at the results of KH as shown in Table I, tuning of time interval parameter $C_i$ is done to achieve the optimal point.
Initially, the number of iterations per trial is kept 100 and \( C_i \) is set at recommended value [14] of 0.5. Production cost and emission converged to a value of 11685.7045, 0.6788 Kg respectively and the computation took 0.197486 seconds only for a population size of 10. It has been observed that for higher population sizes such as 50, 100, 200, 500, 1000 the converged value remains the same but the computation time increases accordingly. Variation of two other parameters \( w_a \) and \( w_f \) within recommended range of 0.9 and 0.1 have been taken care of dynamically in the program. It has also been observed that for a particular krill population size computation time increases with reduction of \( C_i \) values because lower value of \( C_i \) allows krill to search the space more carefully as the scaling factor of speed vector \( \Delta t \) depends on the search space defined by the tuned value of \( C_i \). All these values are obtained considering \( D^{\max} \) as 0.009. With reduction of this value of \( D^{\max} \) in steps within the recommended range (0.010, 0.002) as 0.008, 0.007, 0.006, 0.005, 0.004, 0.003, 0.002 the convergence time remains same and convergence is also 100\% i.e. out of 100 trials convergence occurs each time. For population size above 1000 and \( D^{\max} \) value from 0.005 to 0.002, the convergence is 80\% and the convergence time is much more. And the solution quality differs marginally only in decimal part. Moreover, with increase of iteration number beyond 100, in all cases, the convergence time increases, solution quality remains the same as convergence occurs within few iterations only. As the iteration progresses, the motion induced in a krill by neighboring krill and its foraging motion gradually decreases and the random nature of the physical diffusion motion of it is linearly reduced due to the effect of (27). All other parameters in (27) change dynamically in the course of the program except the parameter \( D^{\max} \) (maximum diffusion speed) which is set manually.

The proposed KH method simultaneously minimizes cost and emission to 11685.7074\$ and 0.6788 Kg.

VI. CONCLUSION

This paper presents a hybrid system consisting of cogeneration units integrated with wind power unit and a bio-inspired krill herd algorithm to solve combined heat and power economic emission dispatch problem of the system. The objective of this research work is to optimize cost of production and emission level of the system simultaneously. The strength of this algorithm lies in the fact that the search space is explored locally and globally by the first two motions by exploiting the position of the Krill individual having best fitness value for a probable better solution locally as well as globally. And the physical diffusion motion randomly explores the search space around that global location for further probable better optimal point of solution. Result shows that KH algorithm successfully provided minimum cost of production and emission level simultaneously utilizing less computation time as the fitness consumed 5 iterations only for cost and emission to converge which is evident from fig. 6 and 7. This encourages to use this algorithm for solving other optimization problems as well in future.

APPENDIX

I. Network active power transmission loss co-efficients:

\[
B = \begin{bmatrix}
49 & 14 & 15 & 15 \\
14 & 45 & 16 & 20 \\
15 & 16 & 39 & 10 \\
15 & 20 & 10 & 40 \\
\end{bmatrix} \times 10^{-6}
\]

\[
B_0 = [-0.3908 -0.1297 0.7047 0.0591] \times 10^{-3}; \quad B_0 = 0.056
\]

II. Cost and Emission functions of each unit of Test System

Cogeneration units:

\[
C_{cg1} = 1250 + 36 P_1 + 0.0435 P_1^2 + 0.6 H_1 + 0.027 H_1^2 + 10.011 P_1 H_1
\]

\[
E_{m1}(cg1) = 0.00165 P_1
\]

\[
C_{cg2} = 2650 + 14.5 P_2 + 0.0345 P_2^2 + 4.2 H_2 + 0.03 H_2^2 + 0.033 P_2 H_2
\]

\[
E_{m2}(cg2) = 0.0022 P_2
\]

\[
C_{cg3} = 1565 + 20 P_3 + 0.072 P_3^2 + 2.3 H_3 + 0.821 H_3^2 + 0.04 P_3 H_3
\]

\[
E_{m3}(cg3) = 0.0011 P_3
\]

Wind Power unit:

\[
C_{wp} = di \times WPav + C_{wpb} + C_{wpw}
\]

Subject to fulfillment of the following equality constraints:

\[
P_1 + P_2 + P_3 + P_4 = P_d ; \quad H_2 + H_3 + H_4 = h_d
\]

1.1584415842 H_1 - P_1 = 46.88118181 \leq 0; \quad 0.151162791 H_1 + P_1 - 130.6976744 \leq 0

45.07614213 - P_2 - 0.067681895 H_2 \leq 0; \quad P_2 + 0.2727272727 H_2 - 60 \leq 0

20 - P_3 - 0.25 H_3 \leq 0; \quad 2.333333333 H_3 - P_3 - 83.333333333 \leq 0

\[
P_1 + 0.6 H_1 - 1.05 \leq 0; \quad 2.2 H_2 - P_1 - 9 \leq 0
\]
TABLE I. Result of KH algorithm for the Test system

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<th>Trial No =&gt;</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
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<td>$P1(cgu1)_{mW}$</td>
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<tr>
<td>$H2(cgu2)_{mWth}$</td>
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<td>Time (sec)</td>
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REFERENCES