Optimal Resource Utilization in Micro-grids: A Whale Optimization-based Environmental Economic Dispatch with Distributed Generation and Energy Storage

Dr. S. Naveen Prakash[1], Dr. S. Vasantharaj[2], K. C. Gayathri[3] and V. Vaishnavi[4]
[1,2] *Assistant Professor, Kings College of Engineering, Punalkulam, Thanjavur, Pudukkottai Dt – 613 303*
[3,4]*UG Students, Kings College of Engineering, Punalkulam, Thanjavur, Pudukkottai Dt – 613 303*
E-mail: naveeneee.kce@gmail.com, vasantharaj118@gmail.com, 20gayathri23@gmail.com and vaishnaviligam@gmail.com

***Abstract*—With the depletion of fossil fuel resources and a rising demand for power, the micro-grid (MG) system has seen increased interest in distributed generation (DG) technology. The integration of DG in MG not only improves power quality but also reduces both generation and emission costs. This study addresses the environmental economic dispatch problem by minimizing the total cost objective function, which encompasses both generation and emission costs. Various DG technologies, such as Photo-voltaic (PV), fuel cell (FC), wind turbine (WT), gas-turbine (GT), and diesel engine (DE), are incorporated into the MG, along with battery energy storage (BES). The optimization of the environmental economic dispatch in MG is tackled as an optimization problem, and in this study, the Whale Optimization Algorithm (WOA) is employed for its solution. The proposed methodology is validated on a typical MG system, and the effectiveness of WOA is demonstrated through a comparative analysis with other optimization techniques.**

Keywords—Micro-grid, Distributed Generation, Battery Energy Storage, Environmental Economic Dispatch, Whale Optimization Algorithm, Total cost reduction

I. INTRODUCTION

Distributed generation (DG) comprises small-scale generation units installed near consumers. The renewable energy resources are widely used now a days and the integration of distribution technology in MG [1-3] provides an effective way for comprehensive usage of natural renewable energy resources. On other hand the integration of DGs in MG causes several challenges. In the literature various researches have focused and explained the MG operations and the optimal scheduling problem of MG involving various optimization techniques. The optimal scheduling problem of MG was solved using optimization algorithms while optimizing either generation cost or emission cost objective. The various optimization that are used to solve scheduling of DG in environmental economic dispatch problem are Genetic Algorithm [4], Particle Swarm Optimization [5,6] and Ant Colony System [7]. In this Study WOA is used for solving the environmental economic dispatch of MG. The proposed WOA has fine balance between exploration and exploitation capabilities in the search space. Due to this, it has very good convergence behavior and achieved better global optimum solution. The effectiveness of the results obtained using proposed WOA is concluded by comparing the results attained with other optimization algorithm. The remaining of this paper is organized in the following manner. Section 2 proposes the problem formulation. section 3 explains the implementation of proposed whale optimization algorithm and its fundamental particulars. Section 4 presents the simulation results followed by conclusion.

II. PROBLEM FORMULATION

A. Objective Function

Minimization of total cost that contains generation cost and emission cost is taken as the main objective. Mathematically the objective function is formulated as follows:

$$Min\ F(P_i) = \left(\sum_{i=1}^{n_{DG}} C_{g,i}(P_i)_{DG} + \sum_{i=1}^{n_{BES}} C_{g,i}(P_i)_{BES} \right) + \left(\sum_{i=1}^{n_{DG}} C_{e,i}(P_i)_{DG} \right) \tag{1}$$

where, $F(P_i)$ is the total operating cost (¥/h); n_{DG} is the total number of DG units; n_{BES} is the total number of BES; $(C_{g,i})_{DG}$ is generation cost of i^{th} unit of DG; $(C_{g,i})_{BES}$ is Generation cost of i^{th} unit of BES; $(C_{e,i})_{DG}$ is emission cost of i^{th} unit of DG; $(P_i)_{DG}$ is generation power of i^{th} unit of DG.

B. Generation Cost

The generation cost involves fuel cost and operational and maintenance cost and it is formulated as follows:

$$C_{g,i}(P_i)_{DG,BES} = C_{f,i}(P_i)_{DG} + C_{o,i}(P_i)_{DG} + C_{o,i}(P_i)_{BES} \tag{2}$$

where, $(C_{g,i})_{DG}$ is Generation cost of i^{th} unit of DG; $C_{f,i}(P_i)_{DG}$ is fuel cost (¥/h) of i^{th} unit of DG; $C_{o,i}(P_i)_{DG}$ is the operating and maintenance cost of i^{th} unit of DG; $C_{o,i}(P_i)_{BES}$ is the operating and maintenance cost (¥/h) of i^{th} unit of BES. $(P_i)_{DG}$ is generation power of i^{th} unit of DG.

1) Fuel cost: The fuel cost for different DG units integrated to the MG is formulated as follows:

$$C_{f,i}(P_i)_{DG} = (K_{f,i})_{DG} \times (P_i)_{DG} \tag{3}$$

where $C_{f,i}(P_i)_{DG}$ is fuel cost (¥/h) of i^{th} unit of DG; $(K_{f,i})_{DG}$ is fuel coefficient of i^{th} unit of DG (¥/kwh).

2) Operational and maintenance cost: The operational and maintenance cost for different DG units and BES integrated to the MG is formulated as follows:

$$C_{o,i}(P_i)_{DG} = (K_{o,i})_{DG} \times (P_i)_{DG} \quad (4)$$

$$C_{o,i}(P_i)_{BES} = (K_{o,i})_{BES} \times (P_i)_{BES} \quad (5)$$

$C_{o,i}(P_i)_{DG}$ and $C_{o,i}(P_i)_{BES}$ are the operating and maintenance cost (¥/kwh) of DG and BES respectively; $(K_{o,i})_{DG}$ and $(K_{o,i})_{BES}$ are the operating and maintenance coefficient for DG and BES respectively. $(P_i)_{DG}$ is generation power of i^{th} unit of DG; $(P_i)_{BES}$ is the generation power of i^{th} unit of BES.

C. Emission Cost

The formulation of emission cost is given as follows:

$$C_{e,i}(P_i)_{DG} = (K_{e,i})_{DG} \times M_e \times (P_i)_{DG} \quad (6)$$

$C_{e.i}(P_i)_{DG}$ is the emission cost (¥/h) of i^{th} unit of DG; $(K_{e,i})_{DG}$ is the emissions coefficient of i^{th} unit of DG (¥/kwh); M_e is the greenhouse gas emissions cost (¥/Kg); $(P_i)_{DG}$ is Generation power of i^{th} unit of DG.

D. Technical Constraints

The objective function expressed in (1) is optimized subjected to following technical constraints.

1) Load demand balance constraints: Electrical load demand P_D, at time t, should be equal to the summation of total generated power of DE, GT, FC, PV and WT and also total absorbed or injected power of BES and utility. Thus the electrical load demand balance operation can be expressed as follows:

$$\left.\begin{array}{l} P_{DE,t}u_{DE,t} + P_{GT,t}u_{GT,t} + P_{FC,t}u_{FC,t} \\ +P_{PV,t} + P_{WT,t} + P_{BES,t}u_{BES,t} + P_{grid,t} \end{array}\right\} = P_{D,t} \quad (7)$$

where, $P_{DE,t}$, $P_{GT,t}$, $P_{FC,t}$, $P_{PV,t}$, $P_{WT,t}$, $P_{BES,t}$, and $P_{grid,t}$ are the output power of DE, GT, FC, PV, WT, BES and grid respectively at time t.

2) Operating power constraints of DG units: The operating output of each DG unit should be within its minimum and maximum limits. The generating capacity constraints of DG units are expressed as follows:

$$P_{DE,\min} \le P_{DE,t} \le p_{DE,\max} \quad (8)$$

$$P_{GT,\min} \le P_{GT,t} \le p_{GT,\max} \quad (9)$$

$$P_{FC,\min} \le P_{FC,t} \le p_{FC,\max} \quad (10)$$

$$P_{PV,\min} \le P_{PV,t} \le p_{PV,\max} \quad (11)$$

$$P_{WT,\min} \le P_{WT,t} \le p_{WT,\max} \quad (12)$$

Where, $P_{DE,min}$, $P_{GT,min}$, $P_{FC,min}$, $P_{PV,t,min}$, $P_{WT,t,min}$, minimum output power of DE, GT, FC, PV and WT respectively; $P_{DE,max}$, $P_{GT,max}$, $P_{FC,max}$, $P_{PV,t,max}$, $P_{WT,t,max}$, maximum output power of DE, GT, FC, PV and WT respectively.

3) Grid Constraints: Power supplied by utility should be within its minimum and maximum limits in each time step and is given by:

$$P_{grid,\min} \le P_{grid,t} \le P_{grid,\max} \quad (13)$$

where, $P_{grid,t}$ is the power of utility of grid at time t; $P_{grid,min}$, $P_{grid,max}$ are the minimum and maximum of power of utility.

The charging and discharging constraints of BES are given in [10].

III. Implementation of Whale Optimization Algorithm

In this proposed approach, a nature-inspired algorithm utilizing the physical phenomenon observed in whales is employed to tackle optimization problems [8]. This work introduces a novel nature-inspired algorithm called the whale optimization algorithm, which mimics the hunting behavior of humpback whales. The algorithm's behaviors are modeled after the unique hunting techniques employed by humpback whales.

A. Encircling Prey

Humpback whales can recognize the location of prey and encircle them. Since the position of the optimal design in the search space is not known a priori, the WOA algorithm assumes that the current best candidate solution is the target prey or is close to the optimum. After the best search agent is defined, the other search agents will hence try to update their positions towards the best search agent. This behavior is represented by the following equations:

$$D = |C.X^*(t) - X(t)| \quad (14)$$

$$X(t+1) = X^*(t) - A.D \quad (15)$$

t indicates the current iteration; A and C coefficient; X^* position of the best solution obtained so far; X is the position of whale. The A and C are calculated as follows:

$$A = 2a.r - a \quad (16)$$

$$C = 2.r \quad (17)$$

Where, a is linearly decreased from 2 to 0 over the course of iterations; r is a random vector in [0,1].

B. Bubble-net Attacking Method

Two approaches are utilized to figure the air bubble net conduct of humpback whales as mentioned below:

1) Shrinking encircling mechanism: Eq. (16) has explained this approach. The fluctuation scope of A is additionally diminished by a. As such A will be random in the interval $[-a, a]$, where 'a' is diminished from 2 to 0 throughout iterations. A is in $[-1, 1]$, the new position of a search operator has been estimated between the first position of the agent and the position of the present best agent.

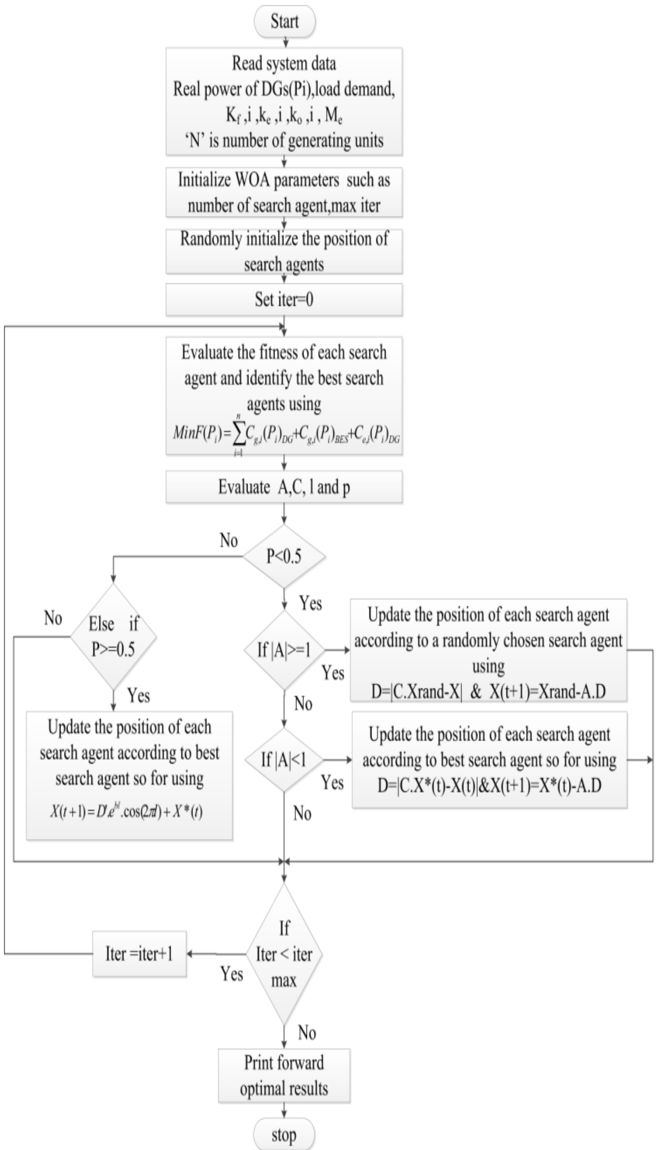

Fig. 1. Flowchart for environmentak economic disptch of MG using WOA algorithm.

2) Spiral updating position: This approach depends on determining the distance between the whale situated at (X,Y) and prey situated at (X^*, Y^*). Eq (18) represents the spiral path between the position of whale and prey.

$$X(t+1) = D'.e^{bl}.\cos(2\pi l) + X^*(t) \tag{18}$$

Where, $D' = | X^*(t) - X(t) |$ and demonstrates the separation of the i^{th} whale to the prey (best solution), b is a constant for characterizing the state of the logarithmic spiral , l is an random number in [−1,1]. Whales swim around the prey inside shrinking circle and along a spiral form. There is a probability of half to select one of two approaches as shown:

$$X(t+1) = \begin{cases} X^*(t) - A.D & if p < 0.5 \\ D'e^{bl}.COS(2\pi l) + X^*(t) & if \geq 0.5 \end{cases} \tag{19}$$

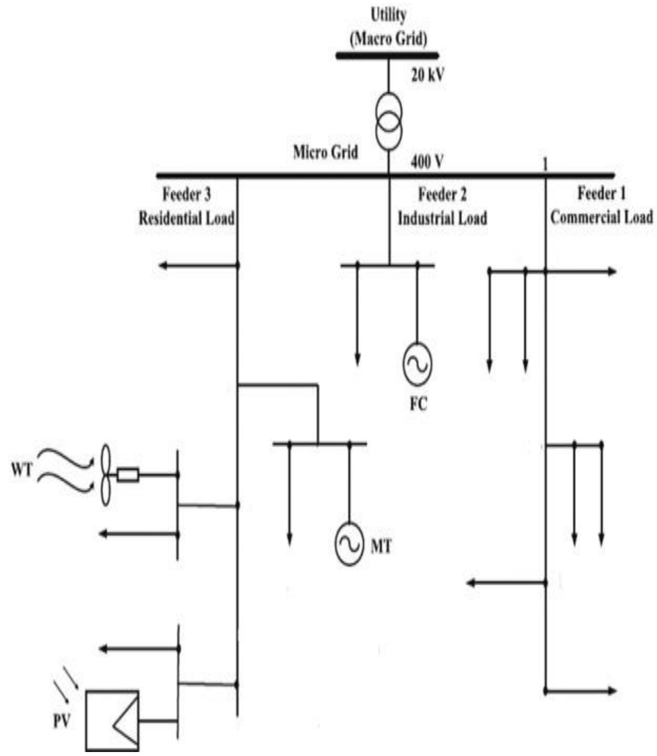

Fig. 2. Typical MG.

Where, p is a random number in [0, 1]. In addition to the bubble-net method, the humpback whales search for prey randomly. The mathematical model of the search is as follows.

3) Search for Prey: Whales pursue randomly as per the position of each other. Thus, A is utilized with the random values more than 1 or under −1 to make search agent to move far from a reference whale. The position of search agent has been updated in the investigation stage as per a randomly picked search agent rather than the best pursuit agent discovered in this way. This scheme and $|A| > 1$ highlight investigation and tolerate the WOA calculation to perform a global pursuit. The mathematical model is as per the following.

$$D = | C.X rand - X | \tag{20}$$

$$X(t+1) = X rand - A.D \tag{21}$$

The flowchart describing various computational steps involved in WOA for environmental economic dispatch of MG is shown in Fig.1.

IV. Simulation Results and Discussion

The environmental economic dispatch problem is verified on a typical MG system as shown in Fig.2. The minimum and maximum output power generation limits, cost coefficients and emission coefficients are taken from [9,10]. The forecasted output power of PV and WT are taken from [9,10]. The scheduling of different DG units and BES using WOA for 24 hours time period is shown in Fig 3. Form Fig.3, it is observed that, when the demand is higher than the total output of PV and WT, the DG units with lower cost and emission coefficients supplies the excees power demand, therby resulting in reduced total cost of the MG system. The negative and positive values of BES denotes the charging mode and discharging mode of BES. The battery gets charged when total generation of DG units is greater than the demand and it gets discharged when total generation of DG units is lesser than the demand. The negative value of utility grid denotes the power consumed by the grid and the positive value of utility grid denotes the power injected by the ultility grid into the MG system. The excess generation of power from the DG units gets injected into the grid, whereas if the total generated power of DG units is not sufficient to supply the demand then the utility grid supplies power to the excessive load in the MG system. The generation cost, emission cost and total cost of the MG for each hour of a day is given in Fig.4, Fig.5 and and Fig.6 respectively.

In order to show the effectiveness of WOA, the results are compared with cuckoo search algorithm as shown in Table I. From, Table I, it is evident that the proposed WOA results in reduced generation and emission cost, thereby making it highly suitable for solving environmental economic dispatch problem of MG. The convergence characteristics of WOA and CSA are shown in Fig.7. From Fig.7 it is evident that WOA shows greater convergence speed by providing optimal solutions within much reduced iterations.

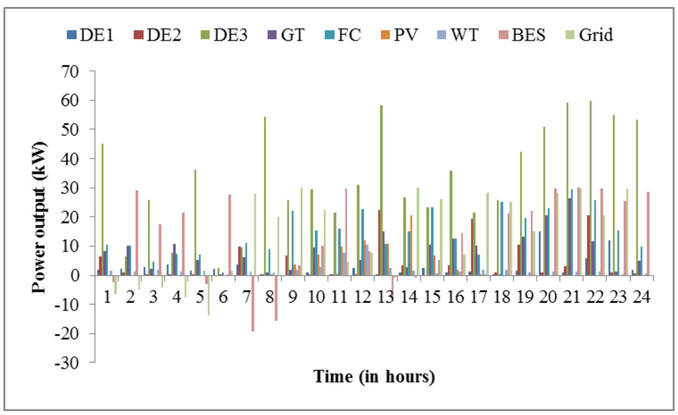

Fig. 3. Optimal dispatch of MG using WOA.

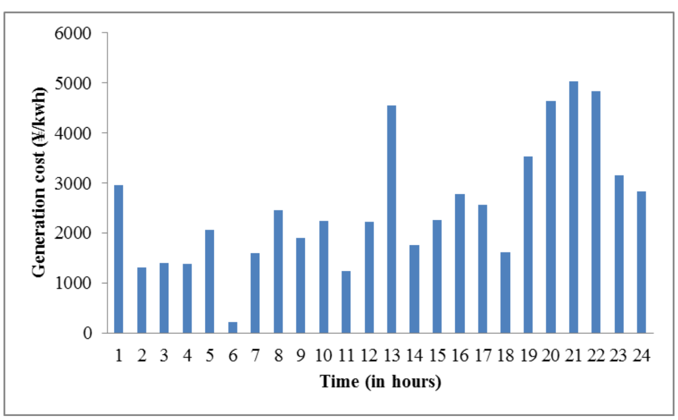

Fig. 4. Generation cost of MG in each hour of a day.

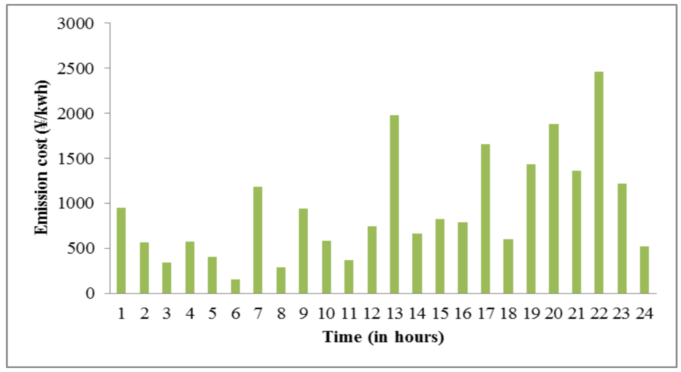

Fig. 5. Emission cost of MG in each hour of a day.

V. Conclusion

In this research, a nature-inspired algorithm known as the Whale Optimization Algorithm (WOA) has been effectively applied to address the environmental economic dispatch problem in Microgrids (MGs). The MG dispatch problem involves the integration of various Distributed Generation (DG) units and Battery Energy Storage (BES) systems. The primary objective is to minimize the total operation cost, comprising generation and emission costs. Simulation results demonstrate that the WOA leads to decreased generation and emission costs. A comparative analysis with the Cuckoo Search Algorithm (CSA) indicates that the proposed WOA achieves superior minimization of the total cost objective and exhibits faster convergence, providing optimal solutions in fewer iterations.

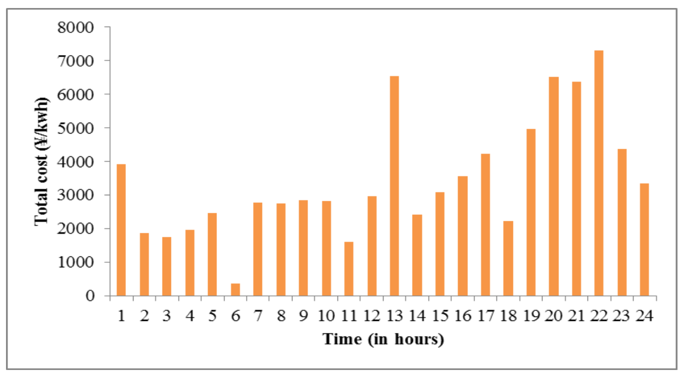

Fig. 6. Total cost of MG in each hour of a day.

TABLE I. Comparative Study

Technique	CSA	WOA
Fuel cost	59368.54704 (¥/day)	58960.52 (¥/day)
Operational & maintenance cost	1128.20536 (¥/day)	1198.16 (¥/day)
Generation cost	60496.75240 (¥/day)	60158.68 (¥/day)
Emission cost	22509.92778 (¥/day)	22471.63 (¥/day)
Total Operation cost	83006.68017 (¥/day)	82630.32 (¥/day)

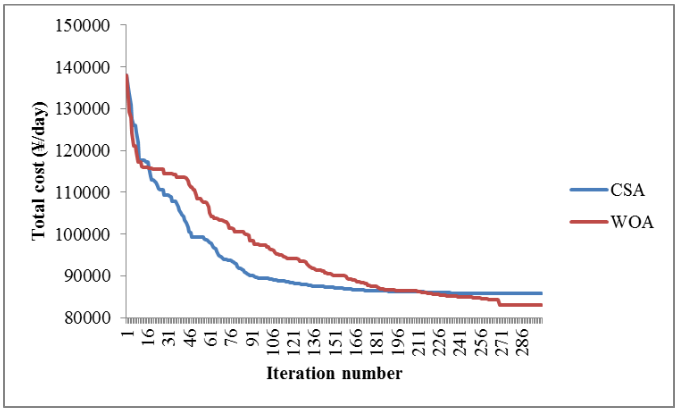

Fig. 7. Convergence characteristics.

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