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Priority List Method Aided Artificial Bee Colony Algorithm for Optimal Operation Off-grid Microgrid

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ABSTRACT

Micro Grid (MG) is defined as an assembly of renewable energy sources (RES) such as wind energy and non-RESs (micro sources) such as micro turbine and fuel cells. MG can provide electrical power for rural and remote areas where supplying the from the grid is not economical and feasible. MG can be operated either as connected to a grid or independent from it. The work proposes a two-stage methodology for the cost-effective operation of off-grid MG systems. The incremental cost-based unit selection and artificial bee colony algorithm are utilized for the determining the real power outputs of online power sources. The developed methodology is implemented on two off-grid MG systems and the attained best feasible dispatch schedules are various scenarios are presented.

KEYWORDS: *Economic operation, Micro grid, Artificial bee colony algorithm.*

I. Introduction

The deregulation in electric power industry and concern over the environmental issues as well as increasing in an electrical energy consumption an have led to an increase in installation capacity of distributed generation and energy storage systems. These sources comprise several energy conversion technologies, such as diesel generators (DG), micro turbines (MT), fuel cells (FC), photovoltaic (PV), small wind turbines, hydro turbines etc. the coordinated operation and control of distributed generation resources is central of the concept of micro grids (MG) [1-2].

MG is defined as an assembly of renewable energy sources (RES) such as wind solar energy and non-RESs (micro sources) such MT, FC energy storage system and loads [3]. MG can provide electrical power for rural and remote areas where supplying the power from the grid is not economic [4]. MGs have some advantages in power systems such as: improving the power quality, reducing the power loss and improving the efficiency of power system, economic benefits related to

power exchange with utilities, black start capability, etc [5-7].

MG can be operated either as connected to a grid or independent from it. Since the wind and solar energy are intrinsically intermittent, the presence of back-up power supply resources is essential to ensure the continuity of power supply [8]. Diesel generators and battery energy storage systems can operate as back-up resources. Recent development and advantages in energy storage and power electronics technologies are making the MG operation as more flexible and economical. The optimal management and operation of MG involves optimum sizing and scheduling of distributed generation resources as per the demand pattern. Various researchers have working towards for the optimal management and operation of MG and is summarized as follows. An overview of solving an economic dispatch problem in MG is presented [8]. A stochastic energy and spinning reserve scheduling approach for the MG considering different types of demand side reserve offers is detailed [9]. The optimal operation of MG which comprises of cogeneration units and renewable energy sources is presented [10]. The sizing and control strategy of MG is formulated as an optimization problem and was solved using particle swarm optimization technique [11]. An improved artificial bee colony algorithm was used as a main optimization tool for modelling and managing an MG with battery energy storage system [12]. Zhao et al., detailed the optimal operation model of stand-alone MG including renewable resources, energy storage devices and diesel generation. This operational model includes operation and fuel costs and non-dominated sorting genetic algorithm had been used as an optimization tool. The hybrid differential evolution and harmony search algorithm was used for the optimal operation of microgrid comprises of MT, FC and renewable resources [14]. Chen et al., utilized matric real code genetic algorithm for developing smart energy management system in MG [15].

A method that optimizes both size of battery storage system and operation strategy of a grid-connected PV system has been discussed in [16]. For solving the proposed problem, multi-objective genetic algorithm has been adopted. Fossati et al. [17] introduced a genetic algorithm based method for optimal size of energy storage systems in an MG containing an MT, FC, wind turbine (WT), two diesel generators and an battery storage system. The grey wolf optimization algorithm has been used in [18] for the optimal sizing of the storage system in an MG. This method tested on a typical MG consisting of MT, FC, WT, PV and battery. Bahramirad et al. presented a model for determining the optimal size of the battery in an MG considering the reliability criterion [19]. The optimal size was determined by minimizing investment and operating costs. Chakraborty et al. proposed a cost-benefit method for optimal sizing of storage system with thermal power system [20]. The benefit of proposed method consists of a number cost saves such as production costs, distribution network costs and etc. The proposed problem has been solved by tabu search (TS) algorithm. As well as, the proposed method has been applied in two power systems with different thermal units. A method based on net present value for optimal allocation and economic analysis of the battery storage system in a grid-connected MG [21]. The presented method consists of two parts, the optimal size of energy storage and economic analysis. To solve the optimization problemself-adaptive bee swarm optimization was used. Morteza Zolfaghari et al, used convex method for the optimal operation of off-grid MG [22]. Most papers in the literature have used evolutionary methods such as particle swarm optimization, genetic algorithm, tabu search and so on for determining the optimal operation of MGs. These evolutionary algorithms are inspired from the nature and are based on population size and maximum iterations. This means that converge of these methods and their solutions depends on the population size, the number of iterations, and other parameters of algorithms. The application of meta-heuristic algorithms for the optimal operation of MG is still an interesting research task. The main objective of the work is to develop an effective two-stage methodology for the optimal operation of MG considering various operational constraints. In the first the best economical units are identified for meeting the forecasted load demand and followed by determining the real power schedules of the on-line units.

The rest of the paper is organized as : section 2 details the problem formulation; section 3 details the implementation of proposed methodology; the numerical simulation results are detailed in section 4 and conclusion is presented in section 5.

II. Problem Formulation

A. *Nomenclature*

f_t^{dis} cost function of DG.
f_t^{MT} cost function of micro turbine.
f_t^{FC} cost function of fuel cell.
$\alpha_0,\alpha_1,\alpha_2$ fixed coefficients related to DG cost function
β_0,β_1 cost coefficients of MT.
γ_0,γ_1 cost coefficients of FC.

P_t^{dis}, P_t^{MT}, P_t^{FC} generated power of DG, MT, FC at t (kw)

λ_t^{dis}, λ_t^{MT}, λ_t^{FC} on/off status of DG, MT, FC, at t

μ^{dis},μ^{MT},μ^{FC},μ^{WT},μ^{PV} operation and maintenance factors of DG, MT,FC,WT, PV.

δ^{dis},δ^{MT},δ^{FC} startup costs of DG, MT and FC.x^{dis},x^{MT},x^{FC} shutdown costs of DG, MT and FC.

σ_0,σ_1 fuel consumption power curve coefficients

Ψ_j,$\zeta_{i,j}$ price coefficients and emission factor of pollutant j by unit i.

$P_{dis,r}$ rated power of DG at the time t.

Φ_R reserve cost ratio.

P_t^D load demand at the time t (kW).

U^{dis},U^{MT},U^{FC} minimum up time of DG, MT and FC.

$U^{dis,0}$,$U^{MT,0}$,$U^{FC,0}$minimum initial up time DG, MT and FC.

D^{dis},D^{MT},D^{FC}minimum down time of DG, MT and FC.

$D^{dis,0}$,$D^{MT,0}$,$D^{FC,0}$ minimum initial down time of DG, MT, FC

$P_t^{dis,max}$,$P_t^{MT,max}$,$P_t^{FC,max}$ maximum available power of DG, MT and FC at the time t

$P^{dis,min}$,$P^{dis,max}$ generation limits of DG (kw)

$P^{MT,min}$,$P^{MT,max}$ generation limits of MT (kw)

$P^{FC,min}$,$P^{FC,max}$ generation limits of FC (kw)

$P^{WT,min}$,$P^{WT,max}$ generation limits of WT (kw)

$P^{PV,min}$,$P^{PV,max}$ generation limits of PV (kw)

Δi time interval that is one hour

RU^{dis},RU^{MT},RU^{FC} ramp up limit of DG, MT and FC

SU^{dis},SU^{MT},SU^{FC} startup ramp limits of MT and FC

$P^{dis,r}$,$P^{MT,r}$,$P^{FC,r}$ rated power of DG, MT and FC

RD^{dis},RD^{MT},RD^{FC} ramp down limits of DG, MT and FC

SD^{dis},SD^{MT},SD^{FC} shut down ramp limit of DG,MT,FC

$f_t^{microgrid}$ cost function of MG at the time t

$EC_t^{microgrid}$ emission cost of MG at the time t

$SUC_t^{microgrid}$, start up cost of MG at the time t

$SDC_t^{micro\ grid}$ shutdown cost of MG at the time t

CF_t^{dis} consumption of DG (l)

RC_t reserve costs of the system at the time t

R_t amount of spinning reserve at the time t

TC total cost of MG in time horizon

I index denotes the MG sources

Ξ the set indicates MG sources, indicating diesel generator, MT, FC, WT and PV

t time indicator

τ set of time slots in the MG operation

T the last one the last one-hour duration of operation time of MG

J the index denotes pollutant substances, including CO2, SO2, NOx

B. Objective function

The objective of the problem is to a minimize the operation costs of the MG by determining the optimal size of the while respecting the imposed constraints. The representation of each cost is as follows

$$f_t^{dis} = \alpha_2\ P_t^{dis\,\wedge 2} + \alpha_1\ P_t^{dis} + \alpha_0 (1)$$

$$f_t^{MT} = \beta_1 P_t^{MT} + \beta_0 (2)$$

$$f_t^{FC} = \gamma_1 P_t^{MT} + \gamma_0 (3)$$

$$f_t^{microgrid} = f_t^{dis}.\lambda_t^{dis} + f_t^{MT}.\lambda_t^{MT} + f_t^{FC}.\lambda_t^{FC}\ (4)$$

Operation and Maintenance Cost

The installation and fuel costs of the diesel generator, MT, FC can be approximated based on their produced power expressed as follows.

$$O\&MC_t^{microgrid} = \mu^{dis}.P_t^{dis}.\lambda_t^{dis} + \mu^{MT}.P_t^{MT}.\lambda_t^{MT} + \mu^{FC}.P_t^{FC}.\lambda_t^{FC} + \mu^{WT}.P_t^{WT} + \mu^{PV}.P_t^{PV} (5)$$

Emission Cost

The emission of the DG, MT and FC units are considered as a cost. This assumption is in line with imposition of carbon tax in many jurisdictions. These units emit gases such as CO_2, SO_2, NOx. Emission costs of these units can be evaluated as follows

$$EC_t^{micro\ grid} = \sum_{j=1}^{3}\varphi^j.\left(\sum_{j=i}^{3}\zeta^{ij}\ P_t^j.\lambda_t^i\right) = P_t^{dis}.\lambda_t^{dis}\left(\Psi^{NO_x}\zeta^{dis,NO_x} + \Psi^{SO_2}\zeta^{dis,SO_2} + \Psi^{CO_2}\zeta^{dis,CO_2}\right) + P_t^{MT}.\lambda_T^{MT}.\left(\Psi^{NO_x}\zeta^{MT,NO_x} + \Psi^{SO_2}\zeta^{MT,SO_2}\Psi^{CO_2}\zeta^{MT,CO_2}\right) P_t^{FC}.\lambda_t^{FC}.\left(\Psi^{NO_x}\zeta^{FC,NO_x} + \Psi^{SO_2}\zeta^{FC,SO_2} + \Psi^{CO_2}\zeta^{FC,CO_2}\right)(6)$$

Startup and shutdown costs

In this study, start up and shutdown costs are considered for the diesel generator, MT and FC. These costs are obtained by multiplying a cost multiplier by the squared difference of unit status in two consecutive time periods. These costs will be zero if a unit is on or off for two successive hours. Thus, these costs for each unit and the MG are formulated as the following.

$$SDC_t^i = \chi^i\left(\lambda_t^i - \lambda_{t-1}^i\right)^2\ \ i \in \Xi, t \in \tau (7)$$

$$SUC_t^i = \delta^i\left(\lambda_t^i - \lambda_{t-1}^i\right)^2 i \in \Xi, t \in \tau (8) SUC_t^{microgrid} = SUC_t^{dis} + SUC_t^{MT} + SUC_t^{FC} (9) SUC_t^{microgrid} = \delta^{dis}(\lambda_t^{dis} - \lambda t{-}1dis)2{+}\delta MT(\lambda tMT{-}\lambda t{-}1MT)2{+}\delta FC(\lambda tFC{-}\lambda t{-}1FC)2 (10)$$

$$SDC_t^{microgrid} = SDC_t^{dis} + SDC_t^{MT} + SDC_t^{FC} (11)$$

$$SDC_t^{microgrid} = \chi^{dis}(\lambda_t^{dis} - \lambda_{t-1}^{dis})^2 + \chi^{MT}(\lambda_t^{MT} - \lambda_{t-1}^{MT})^2 + \chi^{FC}(\lambda_t^{FC} - \lambda_{t-1}^{FC})^2 \quad (12)$$

Fuel Consumption of Diesel Generator

Fuel consumption of diesel generators is a function of type, size, rated power and other specifications of the unit. The amount of fuel consumed by a diesel generator can be formulated as,

$$CF_t^{dis} = (\sigma_0 P^{dis,r} + \sigma_1 P_t^{dis}).\lambda_t^{dis} \quad (13)$$

The values of 60 and 61 are 0.06 and 0.024 respectively.

Reserve Cost

The reserve cost is formulated as follows:

$$RC_t = \varphi^R.R_t \quad (14)$$

The reserve costs ratio is considered as 1.2.

Therefore, the total cost of the MG, the objective function of the model, is as follows:

$$TC = MOC \quad (15)$$

Minimize

$TC = \sum_{t=1}^{T}(f_t^{microgrid} + SUC_t^{microgrid} +$ *SDCtmicro gridVt€τ+O&MCtmicrogrid+ζdisFCtdis+RCt)* (16)

C. **_Constraints_**

Power Generation Limits

The output of each generating unit is limited between its lower and upper limits. This constraint is originating from the physical limitations of the units. This set of constraints can be written as follows.

$$P^{dis,min} \le P_t^{dis} \le P^{dis,max} \quad (17)$$
$$P^{MT,min} \le P_t^{MT} \le P^{MT,max} \quad (18)$$
$$P^{FC,min} \le P_t^{FC} \le P^{FC,max} \quad (19)$$
$$P^{WT,min} \le P_t^{WT} \le P^{WT,max} \quad (20)$$
$$P^{PV,min} \le P_t^{PV} \le P^{PV,max} \quad (21)$$

Load Balance

The sum of the generated power by the DG, MT, FC, WT, PV and the must be equal to the demand (P_t^D). This constraint has an important role in power management in the MG.

$$P_t^{dis}.\lambda_t^{dis} + P_t^{MT}.\lambda_t^{MT} + P_t^{FC}.\lambda_t^{FC} + P_t^{WT} + P_t^{PV} = P_t^D \quad (22)$$

Minimum Up Time

This constraint states that if a unit is on, it cannot be shut down for at least MUT hours. In this study, it is assumed that the diesel generator, MT and FC have an MUT. This constraint formulated as detailed in [21].

Minimum Down Time

Similarly, if a unit is off, it cannot be started up for at least MDT hours. The mathematical formulation of this constraint for the diesel generator, MT and FC is as formulated as detailed in [21].

Ramp Capabilities

Due to the physical limitations of the units, the rate of change of their output level is limited. These ramping constraints limit the ability of units to change the power generation in short

times. In this work, for the diesel generator, MT, and FC three ramp constraints are imposed. The ramp capabilities are formulated as detailed in [21].

Spinning Reserve

The mathematical relationship of the spinning reserve is as follows:

$(P^{dis}.\lambda_t^{dis} - P_t^{dis}) + (P^{MT}.\lambda_t^{MT} - P_t^{MT}) + (P^{FC,r}.\lambda_t^{FC} -$ *PtFC* (23)

III PROPOSED METHODOLOGY

A. *Two Stage Methodology*

The cost-effective operation of MG is performed as two stages. In the first stage, the best feasible dispatchable units have been selected for meeting load demand. Then, economic dispatch is performed for the on-line power sources. This two-stage methodology comprises the selection of dispatch power sources and real power scheduling of committed dispatchable power sources.

The unit commitment problem is inherently complex in nature. The unit commitment process is formulated mathematically as a non-linear, large scale, mixed integer combinatorial optimization problem, which is quite difficult due to its inherent high-dimensional, non-convex, discrete and nonlinear nature. The inclusion of ramp rate limits and pollutant emissions increases further the complexity of the problem. The solution methods being used to solve unit commitment problem are priority list method, dynamic programming, branch and bound method, etc. Among the analytical methods, priority list method is simple and computationally efficient. In this method, the units are committed in the ascending order of the unit full load average cost. In MG environment, the cost function of power source is expressed either as linear or quadratic function of their real power outputs. Hence, the priority list is identified based on the incremental cost.

After obtaining the unit commitment schedule, economic dispatch is performed. Various analytical and soft computing aided methods have been reported for the solving economic dispatch problems. The meta-heuristic algorithms are more attractive for solving economic scheduling problems as they are having high exploration and exploitation characteristics. In this work, a bio-inspired algorithm namely, artificial bee colony (ABC) algorithm has been used.

The solution procedure involves unit selection and dispatch among the selected units. The desirable power sources are identified based on the incremental cost and ABC algorithm is applied for determining the real power outputs online dispatchable sources.

B. *Artificial Bee Colony Algorithm [22]*

The foraging bees are classified into three categories; employed bees, onlookers and scout bees. All bees that are currently exploiting a food source are known as employed. The

employed bees exploit the food source and they carry the information about food source back to the hive and share this information with onlooker bees. Onlookers bees are waiting in the hive for the information to be shared by the employed bees about their discovered food sources and scouts' bees will always be searching for new food sources near the hive. Employed bees share information about food sources by dancing in the designated dance area inside the hive. The nature of dance is proportional to the nectar content of food source just exploited by the dancing bee. Onlooker bees watch the dance and choose a food source according to the probability proportional to the quality of that food source. Therefore, good food sources attract more onlooker bees compared to bad ones. Whenever a food source is exploited fully, all the employed bees associated with it abandon the food source, and become scout. Scout bees can be visualized as performing the job of exploration, whereas employed and onlooker bees can be visualized as performing the job of exploitation.

In the ABC algorithm, each food source is a possible solution for the problem under consideration and the nectar amount of a food source represents the quality of the solution represented by the fitness value. The number of food sources is same as the number of employed bees and there is exactly one employed bee for every food source. This algorithm starts by associating all employed bees with randomly generated food sources (solution). In each iteration, every employed bee determines a food source in the neighbor- hood of its current food source and evaluates its nectar amount (fitness). The i^{th} food source position is represented as X_i where i=1, 2… N is a D-dimensional vector. The nectar amount of the food source located at X_i is calculated by using the following equation,

$$fit_t = \frac{1}{1+f_1} \qquad (24)$$

After watching the dancing of employed bees, an onlooker bee goes to the region of food source at Xi by the probability p_i defined as,

$$p_t = \frac{fit_1}{\sum_{n=1}^{N} fit_n} \qquad (25)$$

The onlooker finds a neighbourhood food source in the vicinity of X_i as,

$$v_{if} = x_{ij} + \emptyset_g(x_{ij} - x_{ij}) \qquad (26)$$

Where k∈{1,2,…N} and j∈{1,2,…D} are randomly chosen indexes. Although k is determined randomly, it has to be different from i. ϕ_{ij} is a random number between [-1, 1]. If its new fitness value is better than the best fitness value achieved so far, then the bee moves to this new food source abandoning the old one, otherwise it remains in its old food source. When all employed bees have finished this process, they share the fitness information

with the onlookers, each of which selects a food source according to probability. With this scheme, good food sources will get more onlookers than the bad ones. Each bee will search for better food source around neighborhood patch for a certain number of cycles (limit), and if the fitness value will not improve then that bee becomes scout bee.

It is clear from the above explanation that there are three control parameters used in the basic ABC: The number of the food sources which is equal to the number of employed or onlooker bees (N), the value of limit and the maximum cycle number (MCN).

C. *Implementation of Two Stage Methodology*

The computational flow of the proposed methodology is as follows.

Step 1: Read the number of dispatchable power sources, load demand and operational characteristics of all power sources.

***Step 2:* Perform Unit Selection**

Step a: Determine the priority order of all units. Sort the unit in the ascending order based on the incremental cost.

Step b: Repeat the following step for all intervals.

Step c: Commit the unit one by one as per the priority order, till the total available generation is greater than or equal to sum of load demand at the interval and required spinning reserve.

Step d: Obtain the unit commitment schedule for the entire scheduling period.

***Step 3:* Perform Economic Dispatch**

Step a: Initialize the control parameters of the algorithm.

Step b: An initial population of N solution is generated.

Step c: Evaluate the fitness value of each individual in the colony.

Step d: Produce neighbour solutions for the employed bees and evaluate them.

Step e: Apply the selection process.

Step f: If all onlooker bees are distributed, ise, go to the next step.

Step g: Calculate the probability values p_i for the solutions.

Step h: Produce neighbour solutions for the selected onlooker bee, depending on the p_i value and evaluate them.

Step i: Determine the abandoned solution for the scout bees, if it exists and replace it with a completely new randomly generated solution and evaluate them.

Step j: Memorize the best solution attained so far.

Step k: Stop the process if the termination criterion is satisfied. Otherwise, go to step *d*.

Step 4: Print the optimal dispatch schedules.

IV. Simulation and Results

A. *Test System and Case Studies*

The developed methodology is coded in MATLAB platform on a quad core processor laptop machine with 1.6GHz clock frequency and 4 GB of RAM. The desirable control parameters of [22] ABC are N = 100, MCN =100 and Limit = 30

The proposed methodology has been implemented on the two different off-grid MG systems. The MG is assumed in the islanded mode and thus there is no selling or buying of electric power from the utility to this system.

The test system 1 comprises of two conventional generators, one cogeneration unit and renewable sources such as PV and wind [9]. The 24 hours load demand profile which includes the industrial and residential loads. The total generation of the MG is assumed to be higher than the peak demand and includes enough spinning reserve for reliability. The cost function for the cogeneration and two conventional generators are expressed as second order polynomial function. The availability of PV and wind powers for the entire scheduling interval are specified.

The test system 2 comprises of DG, FC, MT and RES such as PV and wind [21]. The scheduling period covers one day and the load demand for each interval is specified. The characteristics include the installation and fuel costs, operation and maintenance cost, emission cost, minimum up / down time, start-up and shut down costs of diesel generator, FC and MT are specified. The availability of RES for the entire scheduling period is also specified.

B. *Microgrid I*

This test system comprises of two conventional generators, one cogeneration unit and renewable sources such as PV and wind and one day scheduling is considered. The wind and solar power generation must be always adopted when it is generating, since there is no generation cost for them compared to the fossil fuel cost and thus it is ignored in the optimization process. But their cost functions are used while computing the total generation cost. Also, they are considered as non-dispatchable DGs and they are intermittent sources too. The program computes the economic dispatch among the cogeneration and the two conventional generators only.

The cost function of wind generation considers the investment cost of the equipment and also the operation and maintenance costs of the generated energy, but it does not consider the capital cost of land since it is a community based micro-grid where land is owned by them. The cost function is defined as,

$$F(P_W) = aI^P P_w + G^E P_W \quad (27)$$

$$a = \frac{r}{[1-(1+r)-N]} \quad (28)$$

Where, P_w is the wind generation (kW), a is the annuitization coefficient (dimensionless), r is the interest rate (taken as 0.09), N is the investment lifetime (taken as 20 years), I^P is the investment costs per unit installed power ($/kW) and G^E is the operation and maintenance costs, per unit generated energy ($/kW). This equation is used to calculate the total generating cost of the wind energy considering the depreciation of all the equipment for generation. In this system, it is assumed that the investment costs per unit installed power and operation and maintenance costs per unit generated energy is approximately equal to $1400 and 1.6cents per kW respectively.

The cost function of solar generation considers the investment cost of the equipment and also the operation and maintenance costs of the generated energy, but it does not consider the capital cost of land since it is a community based microgrid where land is owned by them. The cost function is defined as,

$$F(P_s) = aI^P P_s + G^E P_s \quad (29)$$

$$a = \frac{r}{[1-(1+r)-N]} \quad (30)$$

Where, P_s is the wind generation (kW), a is the annuitization coefficient (dimensionless), r is the interest rate (taken as 0.09), N is the investment lifetime (taken as 20 years), I^P is the investment costs per unit installed power ($/kW) and G^E is the operation and maintenance costs, per unit generated energy ($/kW). This equation is used to calculate the total generating cost of the wind energy considering the depreciation of all the equipment for generation. In this system, it is assumed that the investment costs per unit installed power and operation and maintenance costs per unit generated energy is approximately equal to $5000 and 1.6cents per kW respectively. The economic dispatch operations are carried out for the scenario: All generators except solar energy; All generators except wind energy and All generators. The attained numeric results are presented in Tables I, II and III.

TABLE I

BEST FEASIBLE DISPATCHES FOR SCENARIO 1 OF MG I

Time (Hours)	P_D (kW)	P_{FC} (kW)	P_{G1} (kW)	P_{G2} (kW)	P_{wind} (kW)	P_{PV} (kW)
1	140	40.51	39.33	58.45	1.7	0
2	150	37.33	36.36	64.6	8.5	0
3	155	27.01	46.81	64.48	9.27	0
4	160	42.41	46.26	49.63	16.66	0
5	165	28.54	58.74	51.02	7.22	0
6	170	50.22	34.43	53.66	4.91	0
7	175	31.73	47.98	58.59	14.66	0
8	180	67.83	32.96	36.09	26.56	0
9	210	28.58	44.23	65.48	20.88	0
10	230	29.87	46.87	61.55	17.85	0
11	240	35.01	32.62	70.66	12.8	0
12	250	45.25	35.44	57.61	18.65	0
13	240	32.92	46.24	59.14	14.35	0
14	220	45.03	46.69	46.58	10.35	0
15	200	49.16	32.05	57.08	8.26	0
16	180	26.62	45.86	65.81	13.71	0
17	170	43.2	44.2	50.9	3.44	0
18	185	47.44	31.86	58.99	1.87	0
19	200	47.13	38.19	52.98	0.75	0
20	240	34.56	41.97	61.77	0.17	0
21	225	46.95	35.91	55.44	0.15	0
22	190	53.3	34.18	50.82	0.31	0
23	160	41.53	49.1	47.68	1.07	0
24	145	38.86	46.49	52.95	0.58	0
Total cost: $148287.97						

TABLE II

BEST FEASIBLE DISPATCHES FOR SCENARIO2 OF MG I

Time (Hours)	P_D (kW)	P_{FC} (kW)	P_{G1} (kW)	P_{G2} (kW)	P_{wind} (kW)	P_{PV} (kW)
1	140	38.91	50.77	50.3	0	0
2	150	38.66	38.19	63.1	0	0
3	155	49.65	39.64	50.7	0	0
4	160	29.36	49.43	61.2	0	0
5	165	27.65	47.76	64.5	0	0
6	170	20.99	53.45	65.5	0	0.03
7	175	26.17	49.35	64.4	0	6.27
8	180	53.29	12.92	73.6	0	16.98
9	210	45.36	35.52	59.1	0	24.05
10	230	36.42	50.62	52.9	0	39.37
11	240	48.01	35.38	56.6	0	7.41
12	250	36.12	44.52	59.3	0	3.65
13	240	46.68	48.22	45.1	0	31.94
14	220	37.19	57.02	45.8	0	26.81
15	200	34.02	54.03	51.9	0	10.08
16	180	37.62	49.93	52.4	0	5.3
17	170	36.63	48.12	55.2	0	9.57
18	185	42.05	49.64	48.3	0	2.31
19	200	42.89	47.82	49.2	0	0
20	240	31.21	53.74	55.0	0	0
21	225	37	40.14	62.8	0	0
22	190	33.76	44.44	61.8	0	0
23	160	49.95	28.47	61.5	0	0
24	145	42.95	42.6	54.4	0	0
Total cost $147988.40						

C. *Microgrid II*

This MG comprises of diesel generator, FC, MT and RES such as PV and wind and one day scheduling is considered. The two-stage methodology has been applied for the cost-effective operation. The desirable unit selection is completed in the first stage and the dispatches among the committed units are carried out in second stage. The proposed methodology is implemented for two scenarios: (i) cost effective operation neglecting ramp rates and (ii) cost effective operation considering ramp rates. The attained numeric results are presented in Tables IV and V.

TABLE III

Best Feasible Dispatches for Scenario 3 of MG I

Time (Hours)	P_D (kW)	P_{FC} (kW)	P_{G1} (kW)	P_{G2} (kW)	P_{wind} (kW)	P_{PV} (kW)
1	140	31.47	40.32	66.51	1.7	0
2	150	42.29	43.75	55.47	8.5	0
3	155	39.39	40.03	66.32	9.27	0
4	160	31.34	43.21	68.78	16.66	0
5	165	34.99	63.78	59.01	7.22	0
6	170	48.75	51.15	65.16	4.91	0.03
7	175	50.21	45.99	57.87	14.66	6.27
8	180	26.53	52.22	57.71	26.56	16.98
9	210	45.13	50.15	69.79	20.88	24.05
10	230	52.94	58.4	61.44	17.85	39.37
11	240	94.77	28.11	94.7	12.8	7.41
12	250	70.06	79.29	78.35	18.65	3.65
13	240	74.31	52.17	67.23	14.35	31.94
14	220	61.9	44.73	76.2	10.35	26.81
15	200	51.69	62.39	67.58	8.26	10.08
16	180	41.08	52.74	67.17	13.71	5.3
17	170	44.36	58.63	54	3.44	9.57
18	185	49.69	53.92	77.21	1.87	2.31
19	200	78.72	89.79	30.55	0.75	0
20	240	74.09	72.14	93.6	0.17	0
21	225	75.8	68.09	80.96	0.15	0
22	190	47.42	53.13	89.14	0.31	0
23	160	47.23	59.13	52.57	1.07	0
24	145	34.68	48.03	61.71	0.58	0
Total cost $169394.80						

TABLE IV

Best Feasible Dispatches for Scenario 1 of MG II

t (h)	P_D kW	P_{Diesel} kW	P_{MT} kW	P_{FC} kW	P_{wind} kW	P_{PV} kW
1	48	0.000	30.5	16.45	1	0
2	47	0.000	35.0	11.00	1	0
3	49	0.000	34.3	13.69	1	0
4	50	0.000	35.0	14.00	1	0
5	53	0.000	35.0	16.99	1	0
6	60	0.000	35.0	23.00	2	0
7	66	4.080	35.0	24.92	2	0
8	70	8.847	34.3	23.78	1	1
9	71	7.366	34.3	18.30	2	4
10	75	2.587	28.3	23.06	3	8
11	75	0.000	24.0	11.93	9	11
12	73	0.000	24.9	3.000	11	12
13	73	0.000	14.9	3.059	4	24
14	73	0.000	24.0	3.993	2	21
15	76	6.463	35.0	15.53	2	8
16	80	11.74	34.9	23.28	1	4
17	86	21.18	34.8	25.00	2	1
18	87	24.29	34.7	24.97	2	0
19	90	27.07	34.9	25.00	2	0
20	89	26.12	35.0	24.87	2	0
21	84	21.28	35.0	24.71	2	0
22	79	16.02	34.9	25.00	2	0
23	74	16.85	34.8	21.28	1	0
24	68	7.370	35.0	24.62	1	0
Total Installation and Fuel Costs(KW)					378.75	
Total O&M Costs(kw)					153.32	
Cost for Emission(kw)					44.43	
Reserve Cost(kw)					699.59	
Total Cost(ect)					1284.22	

TABLE V

Best Feasible Dispatches for Scenario 2 of MG II

Time (Hour)	P_D (kW)	P_{Diesel} (kW)	P_{MT} (kW)	P_{FC} (kW)	P_{wind} (kW)	P_{PV} (kW)
1	0.0000	29.5752	17.4247	1	0	48
2	0.0000	35.0000	11.0000	1	0	47
3	0.0000	34.9919	13.0081	1	0	49
4	0.0000	30.7442	18.2556	1	0	50
5	0.0000	35.0000	17.0000	1	0	53
6	0.0000	35.0000	23.0000	2	0	60
7	5.2808	34.9193	23.8011	2	0	66
8	14.4474	27.6939	24.8571	1	1	70
9	2.5972	35.0000	22.4015	2	4	71
10	7.4744	29.9956	16.5321	3	8	75
11	0.0000	27.5976	8.4027	9	11	75
12	0.0000	19.7348	8.2652	11	12	73
13	0.0000	15.0000	3.0000	4	24	73
14	0.0000	23.0463	4.9536	2	21	73
15	7.0620	35.0000	14.9392	2	8	76
16	10.3033	35.0000	24.7029	1	4	80
17	21.2845	34.9919	24.7229	2	1	86
18	24.0122	35.0000	24.9879	2	0	87
19	27.0475	34.9488	25.0000	2	0	90
20	26.0723	34.9278	25.0000	2	0	89
21	21.1923	34.8807	24.9277	2	0	84
22	16.3223	35.0000	24.6820	2	0	79
23	13.0744	34.9244	25.0000	1	0	74
24	10.8717	31.2513	24.8773	1	0	68
Total Installation and Fuel Costs(kw)				384.63		
Total O&M Costs(kw)				154.31		
Cost for Emission(kw)				45.69		
Reserve Cost(kw)				699.59		
Total Cost(£ct)				1284.22		

V. CONCLUSION

This work details a two-step methodology for the cost-effective operation of off-grid MG systems. In the intended method incremental cost-based unit selection is performed and ABC algorithm is used for determining the best real power settings among the online dispatchable power sources. The developed methodology has been implemented on two off-grid MG systems with one day scheduling horizon. The cost-based operational framework comprises installation and fuel costs, operation and maintenance costs, emission cost, reserve cost, etc. The minimum up and down time and ramp up and down constraints have also been incorporated in the framework. The best feasible dispatch schedules for various scenarios are presented. This work will be extended for the optimal sizing battery energy storage systems for the off-grid MG system

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