Dynamic Economic Load Dispatch in Isolated Microgrids with Particle Swarm Optimisation considering Demand Response

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***Abstract*—A viable option for electrification of remote areas far from power grids is to set up microgrids and feed them with local generation. Such microgrids are referred to as isolated microgrids and due to the lack of possibility of power exchange with the grid, their operation is different from grid-connected microgrids. Isolated microgrids, similar to grid-connected microgrids are equipped with energy management systems including unit commitment and economic dispatch modules. In this paper, the aim is to formulate the dynamic economic load dispatch (DELD) in isolated microgrids, while curtailment of responsive loads and curtailment of renewable power is allowed and load shedding is used as the last resort for balancing generation and demand. The generated power of dispatchable distributed generators (DGs), curtailed power of renewable DGs, curtailed demand and shed power are determined for each time period. The formulated DELD problem is solved with the well-established particle swarm optimisation (PSO) algorithm. The results for a microgrid with four dispatchable DGs and two renewable DGs show the performance of PSO over grey wolf optimisation (GWO) and also indicate the significant effect of demand response in reducing the operation cost of isolated microgrids.**

***Keywords*—Microgrids, demand response, optimisation, energy management.**

I. INTRODUCTION

According to IEA report, a significant portion of world population, especially in developing countries have no access to electricity. In 2018, the number of people without electricity access was 860 millions [1].

A viable option for electrification of areas which are far from power grids is to set up microgrids (MGs) and feed them with local generation. Such microgrids are referred to as isolated microgrids. The operation of isolated microgrids is different from grid-connected microgrids.

- From security perspective, the inertia of isolated microgrids is much smaller than grid-connected microgrids, so a relatively small unbalance between generation and demand may lead to frequency instabilities. On the other hand, in isolated microgrids, where the possibility of exchange with grid does not exist, establishing the balance between generation and demand is more difficult than grid-connected microgrids. In microgrids, due to the high penetration of renewable generation resources and their uncertainties, establishing the balance of generation and demand is crucial.
- From reliability perspective, in isolated microgrids due to lack of access to the grid, the probability of resorting to load shedding for balancing generation and demand is higher than grid-connected microgrids, so the reliability of isolated microgrids is lower than their grid-connected counterparts.
- From environmental perspective, since the emission treatment cost of local generation units are typically lower than grid [2], isolated microgrids are more environmentally friendly grids than their grid-connected counterparts.
- From economic perspective, in grid-connected microgrids, microgrid operator can import power from grid during low market price hours and export power to the grid during high price hours. In both cases, the exchange with grid reduces the operation cost of the microgrid, while in isolated microgrids there exists no possibility of exchange with grid. Therefore, the operation cost of an isolated microgrid is higher than its grid-connected counterpart with the same demand.

Isolated microgrids, similar to grid-connected microgrids are equipped with energy management systems (EMS) including unit commitment and economic dispatch modules [3-5]. EMS determines the schedule of distributed energy resources, curtailed power and shed power.

In literature, energy management of isolated microgrids has been done in some research papers [6-11].

In [12], unit commitment in isolated microgrids with energy storage system (ESS) has been formulated as a mixed-integer nonlinear programming (MINLP), while voltage stability index of the microgrid, power flow constraints and generation contingencies have been taken into account and SBB solver in GAMS has been used to solve the formulated optimisation problem.

In [13], energy management of isolated microgrids has been formulated as a mixed-integer linear programming (MILP) and

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has been solved both with and without microgrid network constraints. In [14], with piecewise linearization of cost function of DGs, energy management problem in ESS-integrated isolated microgrids has been formulated as a mixed-integer linear programming problem. Power and voltage constraints of the microgrid have been taken into account and the uncertainties of demand and renewable generation have been dealt with affine arithmetic method. In [15], genetic algorithm (GA) has been used for energy management of isolated microgrids and the effect of uncertainties of photovoltaic (PV) and wind generation on EMS and schedule of distributed energy resources have been investigated.

In this paper, the aim is to formulate dynamic economic load dispatch in isolated microgrids, while curtailment of responsive loads and curtailment of renewable power is allowed and load shedding is used as the last resort for balance of generation and demand. The generated power of dispatchable DGs, curtailed power of renewable DGs, curtailed demand and shed power are determined for each time period. The formulated DELD problem is solved with the well-established particle swarm optimisation algorithm.

The rest of the paper is organised as follows; section II includes the formulation of the problem. Section III describes the proposed methodology for solving DELD in isolated microgrids. Section IV includes the results and analysis of the results. Eventually, section V contains the conclusions.

II. Problem Formulation

In this section, dynamic economic load dispatch in an isolated microgrid is formulated as (1)-(7). The decision vector includes the power of dispatchable DGs, power curtailed through demand response (DR) program, curtailed power of renewable generation units and power not supplied to consumers.

Cost of power generated by dispatchable DGs is given by (1).

$$Cost_i(P_{i,t}) = a_i(P_{i,t})^2 + b_iP_{i,t} + c_i \quad \$/h \quad (1)$$

where $P_{i,t}$ denotes power of ith DG at time t and a_i, b_i and c_i denote the cost coefficients of ith DG.

Operation cost of the isolated microgrid is determined as below.

$$J = \sum_{i=1}^{NG}\sum_{t=1}^{T} Cost_i\left(P_{i,t}\right) + \sum_{t=1}^{T} inc_tP_{DR,t} + \sum_{t=1}^{T} VOLL_tP_{shed,t} \quad (2)$$

where T is the total number of time periods and NG is the number of dispatchable DGs, inc_t and $P_{DR,t}$ are respectively the incentive and curtailed load in DR program for t th time period, $P_{shed,t}$ and $VOLL_t$ denote the shed power and value of lost load at time t.

As the equality constraints of the problem, the power balance equation must be held at all times.

$$D_t = P_{shed.t} + P_{DR,t} + \sum_{i=1}^{NG} P_{i,t} + \sum_{p=1}^{Nren} P_{p,t} - \sum_{p=1}^{Nren} curtail_{p,t} \quad (3)$$

where $P_{p,t}$ and $curtail_{p,t}$ respectively represent the available and curtailed power of pth renewable DG unit at time t and $Nren$ represents the number of renewable DGs.

At each time, there is a maximum curtailable power in DR program.

$$0 \le P_{DR,t} \le hD_t \quad (4)$$

where h is the ratio of curtailable demand to microgrid demand [3]. The power of each DG must be bounded within its specified range as (5).

$$P_{i,min} \le P_{i,t} \le P_{i,max} \quad (5)$$

where $P_{i,min}$ and $P_{i,max}$ respectively represent the minimum and maximum power of ith dispatchable DG.

In order to prevent sharp changes in power of DG units, constraints (6)-(7) are applied.

$$P_{i,t} - P_{i,(t-1)} \le RU_i \quad (6)$$

$$P_{i,(t-1)} - P_{i,t} \le RD_i \quad (7)$$

where RU_i and RD_i respectively denote ramp-up and ramp-down rate limits of ith dispatchable DG unit.

Assuming T as the total number of time periods and NG as the number of dispatchable DGs, in DELD of an isolated microgrid, the number of decision variables is $T(NG + Nren + 1)$ and there exists $2T + \left((3T-2).NG\right)$ constraints. Among the constraints, T constraints are equality constraints.

III. Methodology

Particle swarm optimisation (PSO) is the first swarm intelligence-based metaheuristic optimisation algorithm that has been successfully applied for solving a very diverse set of engineering optimisation problems.

In PSO, a swarm of particles traverse search space and try to find a near-global feasible solution for the optimisation problem. The best position visited by a particle is named its personal best and the best position visited by the whole swarm is named global best.

The jth particle is represented by (8).

$$X_j = \left[X_{j_1}, X_{j_2}, \dots, X_{j_d}, \dots, X_{j_n}\right] \quad (8)$$

All the particles are randomly initialised. During each iteration it, the velocities and positions of particles are updated based on their current velocity, current position, personal best and global best as (9)-(10) [16].

$$V_j(it+1) = \omega V_j(it) + C_1 r_1 \left(best_j - X_j(it)\right) + C_2 r_2 \left(best_g - X_j(it)\right) \quad (9)$$

$$X_j(it+1) = X_j(it) + V_j(it+1) \quad (10)$$

where V_j denotes the velocity vector of jth particle, C_1 and C_2 are respectively cognitive and social acceleration coefficients, $best_j$ denotes the personal best of jth particle and $best_g$ denotes global best. The notation ω denotes inertia weight and r_1 and r_2 are two random numbers in [0,1] [17, 18].

It has been proved that bounding particles' velocities within a pre-determined interval improves the performance of PSO [19]. At each iteration, once the positions are updated, the particles are evaluated and their personal bests and global best are updated. As a result, global best as the solution of the optimisation problem improves over iterations. The intelligent traverse of particles within search space continues until the predefined stopping criterion is met [17]. In this paper death penalty method and repair method are used for dealing with constraints wherein the infeasible particles are converted into feasible particles [20]. Each particle that violates ramp-up/down rate limits is repaired, while other constraints of the problem are dealt with death penalty.

IV. Results And Analysis

In this section, PSO is applied to DELD problem in an isolated microgrid. In subsection A, DELD is solved without integration of demand response in MG and in subsection B, it is solved with responsive loads. The performance of PSO is compared with grey wolf optimisation as another swarm intelligence-based metaheuristic optimisation algorithm [21].

The case study is a microgrid with four dispatchable DGs whose specifics are tabulated as Table I and two renewable power DGs whose day-ahead power forecast can be found in Table II. Table II also contains day–ahead demand forecasts. Hourly incentives of DR program can be seen as Fig.1. Value of lost load (VOLL) has been taken as 200 \$/MWh. In this paper, for solving dynamic DELD problem, time horizon is 24 hours and time resolution is 1 hour. Due to their stochastic behavior, both optimisation algorithms have been run for 30 runs. Maximum number of iterations and number of search agents have been respectively set as 100 and 10000.

A. DELD in isolated MG without demand response

Here, PSO and GWO are used for DELD in studied isolated microgrid for 30 independent runs. The best operation cost achieved by PSO is \$10914, while the best operation cost achieved by GWO is as high as \$10993.

TABLE I. Particulars of dispatchable DGs in the microgrid [3, 22]

Unit	a	b	c	Minimum power (MW)	Maximum power (MW)	Ramp-up (MW/h)	Ramp-down (MW/h)
DG1	0	27.7	0	1	5	2.5	2.5
DG2	0	39.1	0	1	5	2.5	2.5
DG3	0	61.3	0	0.8	3	3	3
DG4	0	65.6	0	0.8	8	3	3

TABLE II. Forecasts of demand and renewable power [22]

Hour	Demand (MW)	renewable #1 (MW)	renewable #2 (MW)
1	8.73	0	0
2	8.54	0	0
3	8.47	0	0
4	9.03	0	0
5	8.79	0.63	0
6	8.81	0.80	0
7	10.12	0.62	0
8	10.93	0.71	0
9	11.19	0.68	0
10	11.78	0.35	0
11	12.08	0.62	0
12	12.13	0.36	0.75
13	13.92	0.40	0.81
14	15.27	0.37	1.20
15	15.36	0	1.23
16	15.69	0	1.28
17	16.13	0.05	1.00
18	16.14	0.04	0.78
19	15.56	0	0.71
20	15.51	0	0.92
21	14.00	0.57	0
22	13.03	0.60	0
23	9.82	0	0
24	9.4500	0	0

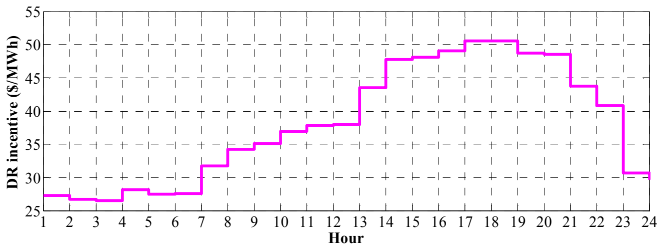

Fig. 1. DR incentives

The average of operation costs given by PSO and GWO are respectively $11030 and $11032. The best optimal solution achieved by PSO and GWO have been respectively illustrated as Fig.2 and Fig.3. For both PSO and GWO, at all times, shed load is zero. With the best solution achieved by PSO, generation curtailment at all hours is equal to zero, however, the best optimal solution achieved by GWO has generation curtailment for hours 1, 5, 7, 9 and 12 respectively with 9 kW, 57.3 kW, 8.4 kW, 30.1 kW and 10.6 kW. Convergence curve of PSO can be seen in Fig.4.

As per Fig.2, for t=1 where demand is 8.73 MW and renewable generators produce nothing, the best dispatch is to fully load DG1 as the most affordable DG, load DG3 and DG4 as the most expensive sources of power with minimum power, namely 0.8 MW and supply the remaining 2.13 MW with DG2. Actually, at this time, DG2 is the marginal generator and sets system shadow price at 39.1 $/MWh. At the second hour, when demand decreases to 8.54 MW, again DG1 is fully loaded, DG3 and DG4 are loaded with their minimum power and DG2 as the marginal generator produces the remaining 1.94 MW and sets system shadow price. Until the end of hour 12, DG2 must serve as marginal generator.

At hour 14, when demand reaches 13.7 MW and renewable DGs respectively produce 0.37 MW and 1.2 MW, DG1 and DG2 must be fully loaded, DG4 as the most expensive DG must be loaded with minimum power and DG3 must operate as marginal generator. At this time, shadow price reaches 61.3 $/MWh. From 15-20, due to the increase in demand, DG4 as the most expensive DG serves as marginal generator and shadow price reaches 65.6 $/MWh. At hour 24, when demand is 9.45 MW and the power of both renewable DGs are zero, the best dispatch is to fully load DG1, load DG3 and DG4 with minimum power and supply the remaining 2.85 MW with DG2. Therefore, at this hour DG2 sets the system price at 39.1 $/MWh.

B. DELD in isolated MG with demand response

In this subsection, demand response is integrated into microgrid, while at most 40% of demand may be curtailed and load curtailment incentives paid to consumers at different hours are as in Fig.1 The best optimal solution achieved by PSO and GWO have been respectively tabulated as Fig. 5 and Fig. 6. The microgrid operation cost given by PSO and GWO are respectively $10416 and $10425. For both PSO and GWO, at all times, curtailed power of renewable DGs and shed load is zero. Convergence curve of PSO has been drawn as Fig.7.

The results show that the integration of demand response into microgrid reduces its operation cost. The integration of DR increases the number of power resources and thereby decreases operation cost.

For example, at hour 1, when load curtailment incentive is 27.30 $/MWh and is less than bid of all DGs, the maximum curtailable demand, namely 3.4920 MW is curtailed, DG2, DG3 and DG4 are loaded with minimum power and DG1 as the marginal generator produces the remaining power to supply the demand. At this hour, shadow price is 27.7 $/MWh and is less than shadow price of the case without DR integration.

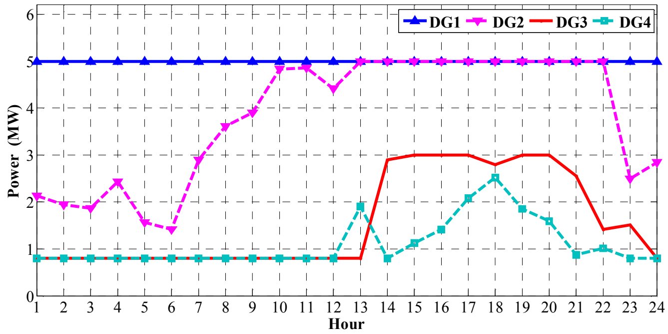

Fig. 2. Optimal schedule of DGs with PSO.

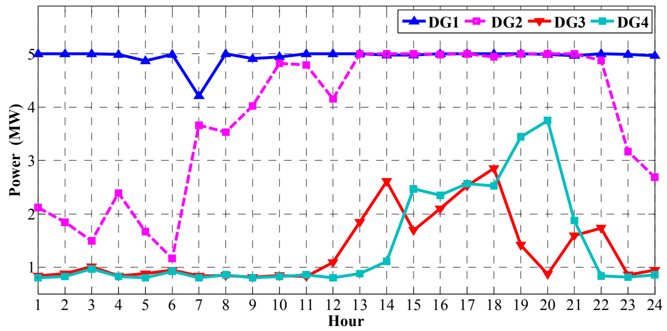

Fig. 3. Optimal schedule of DGs with GWO.

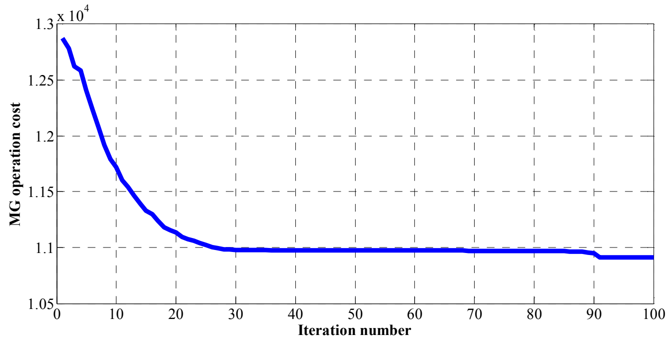

Fig. 4. Convergence curve of PSO in DELD of isolated MG.

As another example, at hour 2, when load curtailment incentive is 26.70 $/MWh and is less than bid of all DGs, the maximum curtailable demand, namely 3.4160 MW is curtailed, DG2, DG3 and DG4 are loaded with minimum power and DG1 as the marginal generator produces the remaining 2.5240 MW to supply the demand and sets shadow price at 27.7 $/MWh.

At hour 24, when load curtailment incentive is 29.60 $/MWh, DG1 as the cheapest resource is fully loaded, DG2, DG3 and DG4 are loaded with their minimum power and DR is the marginal power resource, so shadow price is 29.60 $/MWh. For the case without DR, the shadow price at this hour was as high as 39.1 $/MWh.

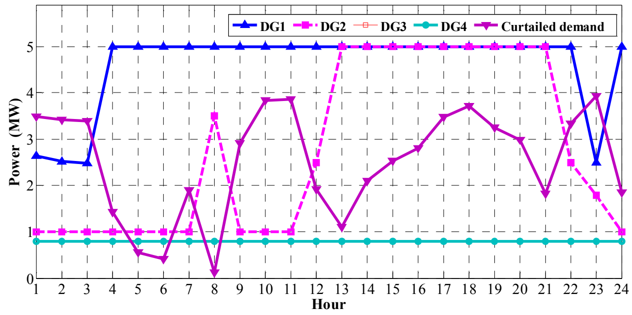

Fig. 5. Optimal schedule of DGs and curtailed power in DR-integrated isolated MG with PSO.

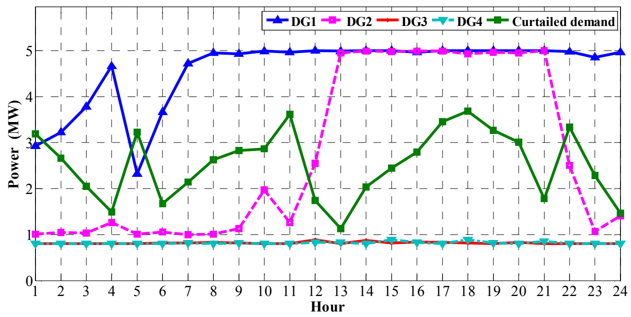

Fig. 6. Optimal schedule of resources in DR-integrated MG with GWO.

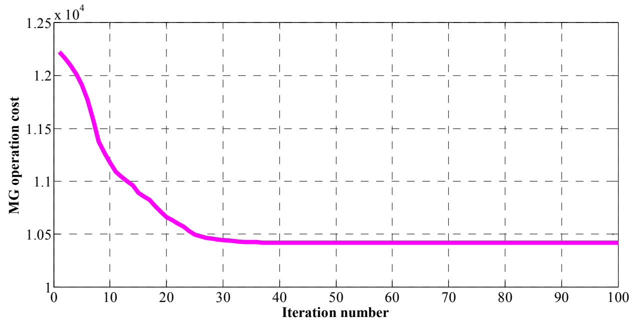

Fig. 7. Convergence curve of PSO in DELD of DR-integrated isolated MG.

V. Conclusions

In this paper, dynamic economic load dispatch in isolated microgrids has been formulated as a linear programming problem while curtailment of responsive loads and curtailment of renewable power is allowed and load shedding was used as the last resort for balancing generation and demand. The generated power of dispatchable DGs, curtailed power of renewable DGs, curtailed demand and shed power have been determined for each time period. PSO has been used to solve the formulated problem. The results for the studied microgrid with four dispatchable DG and two renewable DG demonstrated the performance of PSO over GWO. The results also demonstrated the significant effect of incentive-based demand response in reducing the operation cost of the isolated microgrid.

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