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Smart Grid Unit Commitment with Considerations for Pumped Storage Units Using Hybrid GA-Heuristic Optimization Algorithm

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Abstract

A host of technologies has been developed to achieve these aims of the smart grid. Some of these technologies include plug-in electric vehicle, demand response program, energy storage system and renewable distributed generation. However, the integration of the smart grid technologies in the power system operation studies such as economic emission unit commitment problem causes two major challenges. Pumped storage unit with the capability of storing energy can provide spinning reserve and consequently decrease total cost and environmental emission. The goal of this study is to develop and examine a hybrid GA-heuristic and deterministic optimization algorithm for solving the UC problem for a smart grid with considerations for pumped storage as an energy storage system. Simulation results show improvements in total cost and environmental emission by 1.27 and 4.09%, respectively.

Keywords: Smart grid, Pumped storage, Unit commitment, Optimization

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1. Introduction

The smart grid is conceived as an electric power system which is able to enhance existing power grids to ones which are more economical, ecological, flexible, and reliable. A host of technologies has been developed to achieve these aims of the smart grid. Some of these technologies include plug-in electric vehicle (PEV), demand response program (DR), energy storage system (ESS) and renewable distributed generation (DG). However, the integration of the smart grid technologies in the power system operation studies such as economic emission unit commitment (UC) problem causes two major challenges. Firstly, the integration of the smart grid in the generation scheduling problem requires new methodologies for linking the demand-side and supply-side resources scheduling to fully benefit from the advantages of the smart grids. On the other hand, resource scheduling task of the conventional power grid becomes more complex [1].

In the literature, there are limited studies that focus on solving UC problem for smart grid systems. It is noted that, UC requires an optimization of generation resources to satisfy power demand at the least cost [2-5].

A) Literature Review

In [1], a new model of robust optimization consist of two-stage for solving UC problems with the objective of reducing of the worst-case cost, is presented. In this formula, impact of Uncertainty of wind power is a main parameter. In first stage UC decisions are made without regard to Wind data and in second stage after the observation of wind data, economic dispatch decisions are made. Similarly, in [6], the stochastic dynamic program is used with the same condition.

Based on a developed heuristic method, A new computation method for minimizing total cost of UC considering effect of various renewable generations and electric vehicles is presented in [7]. This study, to solve the charging and discharging of PEVs is used combination of a hybrid topology binary particle swarm optimization, self-adaptive differential evolution method and lambda iteration method. The consequence of this study showed that using PEV in power system schedule and different weather condition that cause the uncertainty of RGs, have a significant effect on reducing economic cost.

Optimal day-ahead scheduling in UC considering hourly demand shift with maximizing the social welfare and reducing total generation cost as objective function is developed by [8].

Using thermal plants to provide loads demand have two disadvantages including environmental problems and fuels cost. On the other hand renewable generation can reduce the negative effects on thermal plants, but this combination create a duck curve problem which makes a large gap between peak and off peak curve. In [9] to solve duck curve problem proposed a new scheme for optimal UC to reduce the fuel cost of thermal plant in turn on and turn off time. Also other objectives such as increased amount of renewable energy to supply the demand and decrease the CO2 emission is presented.

Optimal Transmission Congestion Management with PEV in smart Grid is proposed in [10] for minimize the cost of generating plants. Using EVs and injection power in smart grid decrease the generation of units by. On the other hand, the ability of EVs movement cause to reduce the line congestion that finally decreases the generation units cost.

In [11] Smart house-based optimal operation of thermal UC for a smart grid considering transmission constraints is presented. In that study, each nod includes different number of Smart house and each house has EV, SC, HP and PV. The result showed connection of EV to the smart house can reduce the total cost of thermal unit and provide a good situation in transmission lines.

Simultaneous employment of PEV and wind power in scheduling and operation of power systems considering the uncertainty of wind generation is presented in [12]. The significant point in this study is, determination of optimal number of vehicles in parking. Based on the results, using vehicles which connected to the grid, the operation cost in power system is decreased.

One of the important effect of presence of wind unit is reducing thermal units generation cost. But experts because of uncertainly of wind unit, has a challenge to manage sources to supply the demand. Therefore, UC in smart Grids with Wind Farms Using Virus Colony Search Algorithm and Considering Adopted Bidding Strategy is discussed in [13] to solve the problem.

In [14], Combined Heat and Power UC with Smart Parking Lots of PEVs is presented. This study proposed a new approach for combination of Heat and Power UC problem considering optimal charging/discharging scheme of PEVs.

B) *Contributions*

As a heuristic optimization method is used to solve smart grid UC problem, the effects of pumped storage unit is studied in this paper.

The goal of this study is to develop and examine a hybrid genetic algorithm (GA) for solving the UC problem for a smart grid with considerations for pumped storage as an energy storage system.

The organization of this study is as follows. Section 2 introduces the UC problem formulation for smart grid and, Section 3 explains the heuristic optimization algorithm proposed in this study. In Section 4, the parametric values and data are presented and, simulation results are analyzed. Finally, in Section 5, conclusion and recommendations are given.

2. Problem Formulation

The goal of UC problem is to allocate the duty of generating power to smart grid system so that total cost is minimized. For evaluation, 2 cases are considered in this study:

Case (a): (For validation) Smart grid UC for integrated thermal-DG-DR-PEV system with considerations for environmental emission

Case (b): The effects of pumped storage on smart grid UC

A) *Thermal units*

For thermal units, the objective function is,

$$\min\left\{TC_{THE}\right\} \tag{1}$$

Where

$$TC_{THE} = FC_{THE} + SC_{THE} + EMC_{THE} \tag{2}$$

$$FC_{THE} = \sum_{t=1}^{T}\sum_{i=1}^{N}\left\{ f(P(i,t))I(i,t)\right\} \tag{3}$$

$$\begin{aligned} f(P(i,t)) &= a_i P^2(i,t) + b_i P(i,t) + c_i \\ &+ \left| d_i \sin\left(e_i (P_{\min}(i) - P(i,t))\right)\right| \end{aligned} \tag{4}$$

where the last term in Eq. (4) represents the valve-point effects modeled as a non-convex term.

If spinning reserve cost is considered, FC_{THE} is modified as

$$\begin{aligned} FC_{THE} &= (1-re)\sum_{t=1}^{T}\sum_{i=1}^{N}\left\{ f\left(P(i,t)\right) I(i,t)\right\} + \\ & re\sum_{t=1}^{T}\sum_{i=1}^{N}\left\{ f\left(P(i,t)+R(i,t)\right) I(i,t)\right\} \end{aligned} \tag{5}$$

$$SC_{THE} = \sum_{i=1}^{N}\left\{SUC(i,t)I(i,t)(1-I(i,t-1))\right\} \tag{6}$$

$$SUC(i,t) = \begin{cases} HSC(i) & T^{OFF}(i,t) \le CST(i) + MDT(i) \\ CSC(i) & T^{OFF}(i,t) > CST(i) + MDT(i) \end{cases} \tag{7}$$

$$I(i,0) = IS(i) \tag{8}$$

Note that $IS(i) > 0$ if thermal unit i has been ON before first time period and, $IS(i) < 0$ if thermal unit i^{th} has been OFF before first time period.

Constraints

The objective function for thermal units given by Eq. (1) is subject to the following constraints,

I. Generation capacity

$$P_{\min}(i)I(i,t) \le P(i,t) \le P_{\max}(i) \tag{9}$$

II. Minimum up time

$$T^{ON}(i,t) \ge MUT(i) \tag{10}$$

III. Minimum down time

$$T^{OFF}(i,t) \ge MDT(i) \tag{11}$$

B) DG units

In this situation, the sum of DG acts as a special unit if an aggregator is considered as discussed in [29]. This special unit has its own cost coefficients and cost function

$$f(P(j,t)) = a_j P(j,t)^2 + b_j P(j,t) + c_j \tag{12}$$

Two constraints of DG are taken into account. Firstly, since DG's output is subject to natural resource and weather condition, so an upper limit on available DG at each hour is considered (13). Secondly, now that DG tends to be intermittent and volatile, an upper limit on its penetration rate should be set (14), to ensure a reliable operation of the power system

$$P(j,t) \le DG_{\max}(t) \tag{13}$$

C) Demand response

This paper focuses on the incentive-based DR considering current state of electricity market. A load aggregator exists to interact with tens of thousands of scattered power users [15-17]. It gathers all the distributed DR resources and signs contract with the system operator. Consequently, the total contribution of DR is treated as a special unit in our UC model. DR's cost function is also assumed to be a quadratic function

$$f(P(k,t)) = a_k P(k,t)^2 + b_k P(k,t) + c_k \tag{14}$$

There are two constraints on DR in our model for the sake of power users' habits and interests. Upper limits are set on demand curtailment at each hour and within a day as follows:

$$P(k,t) \le DR_{\max}(t) \tag{15}$$

$$\sum_{t=1}^{T} P(k,t) \le DR_{d\max} \tag{16}$$

D) Electric vehicles

With the related techniques getting mature, it is feasible for EV to sold electricity back to the grid. There is supposed to be an aggregator to communicate between the system operator and a great number of EV owners [19-22]. If an EV is inactive for a certain period, its owner can sign a contract with the system operator for commitment via the load aggregator. The sum of PEV can be treated as a special unit. Considering there is an increasing marginal cost to involve more EV owners, the cost function of PEV is assumed to be a quadratic function.

$$f(P(m,t)) = a(m)P(m,t)^2 + b(m)P(m,t) + c(m) \tag{17}$$

Some basic constraints should be taken into account. Firstly, in case of emergent use of EV's owners, a lower limit of SoC is considered (2). Secondly, for the sake of safe operation of the gird, an upper limit on total output of EVs at each hour should be stipulated (4). Thirdly, now that EV may not be connected to the grid all the 24 h, it is sensible to set a time range limit when EV is available for the system operator (5). Fourthly, the available capacity of PEV at each hour has an upper limit, respectively.

$$SOC(t,m) \ge SOC_{\min} \tag{18}$$

$$PEV(t) = \sum_{m=1}^{M} P(t,m) \le PEV_{\max} \tag{19}$$

E) Pumped storage

Pumped storage fuel consumption is zero and theore, the operation cost is negligible and not considered in this study. However, the following constraints must be satisfied.

a. Lower and upper limits of generation

$$0 \le P_g(m,t) \le P_{g-\max}(m) \tag{20}$$

b. Lower and upper limits of pumping

$$0 \le P_p(m,t) \le P_{p-\max}(m) \tag{21}$$

c. Lower and upper limits of spinning reserve

$$0 \le P_{g-SR}(m,t) \le P_{g-\max}(m) \tag{22}$$

$$0 \le P_{p-SR}(m,t) \le P_p(m,t) \tag{23}$$

d. Summation of energy and spinning reserve in a specific hour must be less than $P_{g-\max}(m)$

$$P_g(m,t) + P_{g-SR}(m,t) \le P_{g-\max}(m) \tag{24}$$

e. For a pumped storage unit, it is impossible to have pumping and generation, simultaneously.

$$u_p(m,t) + u_g(m,t) \le 1 \tag{25}$$

f. Energy storage balance for upper reservoir

$$\begin{aligned} E(m,t) &= E(m,t-1) - P_g(m,t) + \eta_{PS} P_p(m,t) \\ &- \left(\eta_{PS}.P_{p-SR}(m,t) + P_{g-SR}(m,t)\right) re \end{aligned} \tag{26}$$

g. Energy storage limits for upper reservoir

$$E_{\min}(m,t) \le E(m,t) \le E_{\max}(m) \tag{27}$$

h. Initial energy stored in upper reservoir

$$E(m,T) = E(m,0) \tag{28}$$

k. Minimum energy stored in upper reservoir

$$E_{\min}(m,t) = E_{\min}(m) + re\left(P_{p-SR}(m,t+1) + P_{g-SR}(m,t+1)\right) \tag{29}$$

F) Integrated system

When thermal, DG, DR and PEV units are operated as one integrated system, the objective function is,

$$\min\{TC_{INT}\} \tag{30}$$

$$TC_{INT} = TC_{THE} + TC_{DG} + TC_{DR} + TC_{PEV} \tag{31}$$

G) Constraints

The objective function of UC problem given by Eq. (24) is subject to the following constraints,
System power balance:

$$\sum_{i=1}^{N} P(i,t) + \sum_{j=1}^{J} P(j,t) + \sum_{k=1}^{K} P(k,t) + \sum_{m=1}^{M} P(m,t) = P_D(t) \tag{32}$$

System power spinning reserve inequality:

$$\sum_{i=1}^{N} R(i,t) + \sum_{j=1}^{J} R(j,t) + \sum_{k=1}^{K} R(k,t) + \sum_{m=1}^{M} R(m,t) \geq R(t) \tag{33}$$

Units constraints:

All units' constraints must be met.

3. Optimization

In this section, the heuristic optimization algorithm developed for optimal scheduling of smart grid for minimizing environmental emission and total cost is presented. The steps of the heuristic optimization algorithm are as follows:

- The pumped storage unit is responsible for meeting spinning reserve [4], therefore

$$P_{gs}(l,t) = R(t)\text{, } t=1,\ldots,T \tag{34}$$

then, spinning reserve met by thermal unit is

$$P_{th}(t) = 0 \tag{35}$$

If

$$R(t) > P_{gs}(l,t) \Rightarrow P_{gs}(1,t) = P_{g\max}(1) \tag{36}$$

Then

$$R_{th}(t) = R(t) - P_{gs}(1,t) \tag{37}$$

and required pumping is

$$P_p(1,t^{'}) = \sum_{t=1}^{24} R(t).re/\eta \tag{38}$$

- After scheduling of pumped storage unit, new demand and spinning reserve should met by thermal and DG units. Then, UC problem is solved for thermal and DG units using the heuristic optimization algorithm discussed in [23-25]. It is noted that to fined the optimal output power of units, GA is used as discussed in [26-28].

4. Simulation Results

The simulation results are presented for the two cases to examine the environmental emission and total cost reductions achieved based on the heuristic optimization algorithm proposed in this study.

A) (For validation) Smart grid UC for integrated thermal-DG-DR-PEV system with considerations for environmental emission

An integrated 6 thermal units (Table I), DR (Tables II-III), DG (Tables II-III) and PEV (Tables II-III) system [1] is used. The demand is illustrated in Table IV.

For simulation of UC problem of Case (a) and the results are used for comparison with those available from literature under equal conditions, as discussed later in this section.

The simulation results for comparison of environmental emission and total cost reduction are presented in Tables V and VI under 4 scenarios:

- Smart grid UC for thermal units only without consideration for environmental emission cost
- Smart grid UC for thermal units, DR , DG and PEV without consideration for environmental emission cost
- Smart grid UC for thermal units only with consideration for environmental emission cost
- Smart grid UC for thermal units, DR, DG and PEV with consideration for environmental emission cost where improvements are 12.5 and 34.8% for environmental emission and total cost, respectively, as compared with [1].

B) The effects of pumped storage on smart grid UC

In this case, a 240 MW Pumped storage unit [4] is responsible for meeting spinning reserve to shut down thermal units and therefore, to reduce environmental emission and total cost. It is noted that required pumping is considered to compensate used spinning reserve.

In Table VII , environmental emission and total cost improvements with considerations for pumped storage unit are presented. It is noted that pumping power is met by thermal unit 1.

As shown in Table VII, environmental emission and total cost reduction are 4.09 and 1.27, respectively, when pumped storage unit is utilized.

As discussed in section III, GA is used to find $P^*(i,t)$. For example, the GA convergence curve for thermal unit 1 at hr 1. ($P^*(1,1) = 69$) is shown in Fig. 1.

5. Conclusion

In this study, a hybrid algorithm including GA and heuristic and deterministic optimization algorithm for solving the UC problem for a smart grid is developed and examined with considerations for pumped storage as an energy storage system. As a heuristic optimization method is used to solve smart grid UC problem, the effects of pumped storage unit is studied in this paper.

Table.1.
Thermal unit characteristics

Unit	$P_{\min}$	$P_{\max}$	*a*	*b*	*c*	*HSC*	*HSC*
1	0	200	0.00375	2.00	0	70	176
2	0	80	0.01750	1.70	0	74	187
3	3	0	0.06250	1.00	0	50	113
4	9	35	0.00834	3.25	0	110	267
5	8	30	0.02500	3.00	0	72	180
6	10	40	0.02500	3.00	0	40	113
Unit	α	β	γ	*IS*	*CST*	*MUT*	*MDT*
1	0.0126	-0.9000	22.983	-1	2	1	1
2	0.0200	-0.1000	25.313	-3	1	2	2
3	0.0270	-0.1000	25.505	2	1	1	1
4	0.0291	-0.0050	24.900	3	1	1	2
5	0.0290	-0.0040	24.700	-2	1	2	1
6	0.0271	-0.0055	25.300	2	1	1	1

Table.2.
DG, DR, PEV characteristics

Hr	*PEV max*	*DG max*	*DR max*	*Hr*	*PEV max*	*DG max*	*DR max*
1	0	5	7	13	0	10	13
2	0	5	7	14	0	10	12
3	0	5	8	15	0	10	11
4	0	5	9	16	0	10	10
5	0	5	10	17	0	10	10
6	0	5	10	18	0	5	10
7	0	10	11	19	0	5	11
8	0	10	11	20	18	5	13
9	0	10	12	21	17	5	12
10	0	10	13	22	16	5	10
11	0	10	14	23	15	5	9
12	0	10	14	24	14	5	8

Table.3.
DG, DR, PEV characteristics

Type	$P_{\min}$	$P_{\max}$	*a*	*b*	*c*
DR	0	Table III	0.05	2.2	4
DG	0	Table III	0.01	2.6	10
PHEV	0	Table III	0.03	2.4	8

Table.4.
Demand characteristics

Hr	*Demand*	*Hr*	*Demand*
1	134	13	267
2	143	14	248
3	162	15	229
4	181	16	200
5	191	17	191
6	210	18	210
7	219	19	229
8	229	20	267
9	248	21	248
10	267	22	210
11	277	23	172
12	286	24	153

Table.5.
Total cost and emission comparison under 4 scenarios

Scenario	*Algorithm*	*Cost ($)*	*Improvement (%)*	*Emission (TOC)*	*Improvement (%)*
1	IPSO [1]	17644	---	7304.0	---
	proposed	13497	23.5	7225.5	1.1
2	IPSO [1]	15076	---	6454.0	---
	proposed	13752	8.84	6371.0	1.3
3	IPSO [1]	22998	---	7094.0	---
	proposed	14992	34.8	6204.0	12.5
4	IPSO [1]	19909	---	6232.0	---
	proposed	15329	23.0	5586.0	10.3

Table.6.
Units output power under scenario 4

Hr	***Output power (MW)***								
	1	***2***	***3***	***4***	***5***	***6***	***DR***	***DG***	***PHEV***
1	69	34	28	0	0	29	7	5	0
2	50	34	25	0	0	22	7	5	0
3	57	34	28	0	0	29	8	5	0
4	50	34	27	29	0	27	9	5	0
5	56	34	28	29	0	29	9	5	0
6	50	34	27	29	28	28	9	5	0
7	51	34	28	29	28	29	9	10	0
8	61	34	28	29	28	29	9	10	0
9	80	34	28	29	28	29	9	10	0
10	99	34	28	29	28	29	9	10	0
11	109	34	28	29	28	29	9	10	0
12	118	34	28	29	28	29	9	10	0
13	99	34	28	29	28	29	9	10	0
14	80	34	28	29	28	29	9	10	0
15	61	34	28	29	28	29	9	10	0
16	60	34	28	29	0	29	9	10	0
17	51	34	28	29	0	29	9	10	0
18	50	34	27	29	28	28	9	5	0
19	66	34	28	29	28	29	9	5	0
20	88	34	28	29	28	29	9	5	16
21	69	34	28	29	28	29	9	5	16
22	59	34	28	29	0	29	9	5	16
23	51	34	28	0	0	29	9	5	15
24	63	34	28	0	0	0	8	5	14

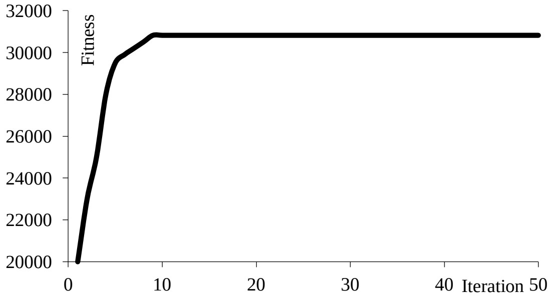

Fig. 1. The GA convergence curve for thermal unit 1 at hr 1.

Table.7.
Total cost and emission comparison-pumped storage is operated

Operation	*Cost ($)*	*Improvement (%)*	*Emission (TOC)*	*Improvement (%)*
Without pumped storage	564250	-	17524	-
With pumped storage	557070	1.27	16807	4.09

The simulation results show that using the capability of pumped storage for meeting spinning reserve, environmental emission and total cost are reduced. For future works, the operation of CHP units detailed in [29, 30] and hybrid PV and solar thermal systems [31-33] in smart grid environment is suggested. Also, complete modeling of a PEV parking lot is recommended.

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