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Resource Scheduling in a Smart Grid with Renewable Energy Resources and Plug-In Vehicles by MINLP Method

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ABSTRACT

This paper presents a formulation of unit commitment for thermal units integrated with wind and solar energy systems and electrical vehicles with emphasizing on Mixed Integer Nonlinear Programming (MINLP). The renewable energy resources are included in this model due to their low electricity cost and positive effect on environment. As well as, coordinated charging strategy of electrical vehicles and reasonable usage of V2G power can reduce the generating cost. Electric vehicles and renewable energy resources are the most promising options for alternative sources in the near future. The proposed method is solved using MINLP solver in GAMS software. The problem is finding a solution which satisfies the constraints and minimizes the objective function. As a case study, results on IEEE ten-unit system are presented in this paper. The numerical tests and results showing that their inclusion with the conventional power generating sources reduces the operational cost and greenhouse gas emissions were presented in electric power industry.

KEYWORDS

Unit commitment, Generation scheduling, Renewable energy resources, Vehicle to grid, MINLP method

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1. INTRODUCTION

The power system and transportation sector are our planet's main sources of greenhouse gas emissions. Renewable energy sources (RESs), mainly wind and solar, can reduce emissions from the electric energy sector; however, they are very intermittent. Likewise, next generation plug-in vehicles, which include plug-in hybrid electric vehicles and electric vehicles with vehicle-to-grid capability, can reduce emissions from the transportation sector [1]. As well as, the coordinated integration of aggregated plug-in electric vehicle (PEV) fleets and renewable energy can decrease the operation cost [2].

Unit commitment scheduling of power generation systems is an important issue in smart grid communications to coordinate energy demand and generation [2]. UC is the problem of selecting the generating units to be put into service during a scheduling period and for how long. The committed units must meet the system load and reserve requirements at minimum operating cost, subject to a variety of constraints. The economic dispatch problem (EDP) is to optimally allocate the load demand among the running units while satisfying the power balance equations and unit operating limits [3]. Methods used to solve the unit commitment problem can be divided into three categories: classic, smart and hybrid. Methods such as dynamic programming, priority list, exhaustive enumeration, lagrange [4,5], optimize internal point, integer linear programming and smart methods such as the tabu search [6], simulated annealing, expert systems, fuzzy systems, genetic algorithm [7], neural networks, shuffled frog leaping algorithm [8] and particle swarm optimization [9] can be used for this purpose. In this paper, Mixed Integer Nonlinear Programming (MINLP) for solving unit commitment problem and economic load distribution have been used. In MINLP method, nonlinear problem includes discrete and continuous variables, which is in accordance with unit commitment problem.

2. PROBLEM FORMULATION

Fuel cost of a thermal unit is usually expressed as a second-order function of the generated power of the unit in that period according to (1).

$$FC_i\big(P_i(t)\big) = a_i + b_i P_i(t) + c_i P_i(t)^2 \qquad (1)$$

Where a_i, b_i and c_i are fuel coefficients of thermal units whose values are for the sample system in Table III; $P_i(t)$ and $FC_i\big(P_i(t)\big)$ are electric power and fuel cost of unit i in period t, respectively.

Emission function is usually expressed as a polynomial function which its order depends on the accuracy required. In this paper, the second order for emissions curve is taken into account.

$$EC_i\big(P_i(t)\big) = \alpha_i + \beta_i P_i(t) + \gamma_i P_i(t)^2 \qquad (2)$$

Where α_i, β_i and γ_i are emission coefficients of thermal units whose values are given in Table IV.

System power balance: One of the main tasks of the ISO in short-term scheduling is balance between production and consumption of electrical energy per hour.

$$\sum_{i=1}^{N} P_i(t)u_i(t) + P_{V2G}(t) + P_{wind}(t) + P_{PV}(t) = D(t) + loss \qquad (3)$$

In (3), $u_i(t)$ is status (off/on) of unit i in period t and is equal to 1 if unit i is committed in period t. $D(t)$ is demand in the period of t and $P_{V2G}(t)$ is V2G power exchanged with the network. As well as, $P_{PV}(t)$ and $P_{wind}(t)$ are power output of solar and wind farms, respectively.

Generation limit: To operate with high efficiency in the long term, the generation of units should be between the minimum and maximum allowed values.

$$P_i^{min} \le P_i(t) \le P_i^{max} \qquad (4)$$

In this equation $P_i^{min}$and P_i^{max} are minimum and maximum power generation of unit i, respectively.

Minimum up and down time: When the unit is turned on, because of the technical considerations must be continuously stay in this situation for a specific time and also when turned off should also remain a specific time in this situation.

$$if\ u_i(t) = 1\ then\ \big(1 - u_i(t+1)\big)MU_i \le x_i^{on}(t) \qquad (5)$$

$$if\ u_i(t) = 0\ then\ u_i(t+1)MD_i \le x_i^{off}(t) \qquad (6)$$

In this equations, MU_i and MD_i are Minimum up and down time of unit i; as well as, $x_i^{on}(t)$ and $x_i^{off}(t)$ are on/off periods of unit i, respectively.

Ramp-rate limit constraints: Considering that power plant, is a mechanical unit, so rate of change in the electric power generation cannot exceed from specific limit.

$$\begin{aligned} &if\ u_i(t) = 1\ and\ u_i(t-1) = 0 \\ &then\ P_i(t) - P_i(t-1) \le RU_i \end{aligned} \qquad (7)$$

$$if\ u_i(t) = 0\ and\ u_i(t-1) = 1$$
$$then\ P_i(t-1) - P_i(t) \leq RD_i \quad (8)$$

Where RU_i and RD_i are ramp up and ramp down of unit i, respectively.

Startup-cost: start-up cost for restarting a decommitted thermal unit, Can be calculated according to (9).

$$Sc_i(t) = \begin{cases} h - cost_i \\ c - cost_i \end{cases} \quad (9)$$

Where $h - cost_i$ and $c - cost_i$ are the hot and cold start costs of unit i, respectively, and $c - cost_i \geq h - cost_i$.

Spinning reserve constraint: So far a variety methods with definitive or probable criterion to determine reserve capacity has been proposed.

Spinning reserve is not loaded part of synchronous generators that in emergency times has ability to respond quickly to load variations [10].

$$\sum_{i=1}^{N} P_i^{max} u_i(t) + P_{V2G}(t) + P_{wind}(t) + P_{PV}(t) = D(t) + R(t) + loss \quad (10)$$

Table I shows the types of reserves with their characteristics. In this paper only the spinning reserve is considered.

TABLE I.
TYPES OF RESERVES WITH THEIR CHARACTERISTICS [9].

Reserve type	Start time	Synchronization?
TMSR	$< 10\,min$	Yes
TMNSR	$< 10\,min$	NO
Thirty minutes Reserve	(10 min, 30min)	NO
Sixty minutes Reserve	(30 min, 60min)	NO
CR	$> 60min$	NO

Power output of PV: The output of a solar photovoltaic (PV) panel given by (11) depends on the area of PV panel A, solar insolation μ(t), and the efficiency of the PV panel β.

$$P_{PV}(t) = A\beta\mu(t) \quad (11)$$

Power output of a wind turbine:

$$P_{wind}(t) = 0.5\alpha\rho(t)AV(t)^3 \quad (12)$$

Where α is the Albert Betz constant, ρ(t) is the air density, A is the area swept by the turbine rotor, and v(t) is the wind speed.

How to estimate the number of electric vehicles connected to the network

For practical applications, the number of GVs in an electric power network can be estimated by (13).

$$N_{V2G} = Q_{V2G} \times V_{REC} \times N_{REC}$$
$$N_{V2G} = \frac{Q_{V2G} \times V_{REC} \times X_{RL} \times D_{min}}{AV_{HLD}} \quad (13)$$
$$AV_{HLD} = \frac{AV_{MEC}}{30 \times 24}$$

D_{min} is minimum load demand in the period, X_{RL} is percentage of residential loads in the power network, V_{REC} is number of GVs of per residential electricity client, Q_{V2G} is the percentage of registered vehicles to participate in the process, AV_{MEC} is average monthly electricity consumption of a domestic home and AV_{HLD} is average hourly electricity load of a residential client.

Power exchanged with the network

$$P_{V2G}(t) = \sum_{j=1}^{N_{V2G}} \xi P_{Vj}(t)(\psi_{pre} - \psi_{dep}) \quad (14)$$

Where ξ is battery efficiency, $P_{Vj}(t)$ is capacity of vehicle j and $\psi_{pre} - \psi_{dep}$ is Initial and final state of charge.

Emission from vehicles

A linear approximate model is used to calculate emission from vehicles in the transportation industry as follows [11]:

$$EC_j(L_j, e_j) = L_j \times e_j \quad (15)$$

Where $EC_j(L_j, e_j)$ is the emission function, L_j is the length of travel by vehicle j in miles, and e_j is the emission per mile from vehicle j.

Objective functions

The objective functions in different scenarios are defined as follows:

$$min\,FC = \sum_i (a_i + b_i P_i(t) + c_i P_i^2(t))u_i(t) + Sc_i(t)(1 - u_i(t-1)) + (x + yP_{V2G}(t) + zP_{V2G}^2(t)) \quad (16)$$

$$min\,EC = \textstyle\sum_i(\alpha_i + \beta_i P_i(t) + \gamma_i P_i(t)^2) + EC_j \quad (17)$$

Min multifunction=

$$W(\textstyle\sum_i \left(a_i + b_i P_i(t) + c_i P_i^2(t)\right) + Sc_i(t)\left(1 - u_i(t-1)\right) + \left(x + yP_{V2G}(t) + zP_{V2G}^2(t)\right)) + (1 - W)(\sum_i (\alpha_i + \beta_i P_i(t) + \gamma_i P_i(t)^2) + EC_j) \quad (18)$$

TABLE II.
HOURLY LOAD DEMAND [10]

Hour	Demand(Mw)	Hour	Demand(Mw)	Hour	Demand(Mw)	Hour	Demand(Mw)
1	700	7	1150	13	1400	19	1200
2	750	8	1200	14	1300	20	1400
3	850	9	1300	15	1200	21	1300
4	950	10	1400	16	1050	22	1100
5	1000	11	1450	17	1000	23	900
6	1100	12	1500	18	1100	24	800

TABLE III.
OPERATOR DATA FOR TEN-UNIT SYSTEM [10]

Parameter	U1	U2	U3	U4	U5	U6	U7	U8	U9	U10
P^{max} (MW)	455	455	130	130	162	80	85	55	55	**55**
P^{min} (MW)	150	150	20	20	25	20	25	10	10	**10**
a ($/h)	1000	970	700	680	450	370	480	660	665	**670**
b ($/MWh)	16.19	17.26	16.6	16.5	19.7	22.26	27.74	25.92	27.27	**27.79**
c ($/MW2h)	0.00048	0.0003	0.002	0.00211	0.00398	0.00712	0.00079	0.00413	0.00222	**0.00173**
MU (h)	8	8	5	5	6	3	3	1	1	**1**
MD (h)	8	8	5	5	6	3	3	1	1	**1**
SCh($)	4500	5000	550	560	900	170	260	30	30	**30**
SCc($)	9000	10000	1100	1120	1800	340	520	60	60	**60**
CST(h)	5	5	4	4	4	2	2	0	0	**0**
I.S(h)	8	8	-5	-5	-6	-3	-3	-1	-1	**-1**

3. CASE STUDY

Operator data and generator emission coefficients for IEEE ten-unit system are summarized in Tables III and IV. As well as, load demand is shown in Table II.

In this paper, solar insolation data for January, April, July and November 2014, are collected from NREL's Solar Radiation Research Laboratory in Golden, CO [12], for the solar farm model. Wind speed data for January, April, July and November 2014, are collected from the National Wind Technology Center in Boulder, CO [13], for the wind farm model. To calculate power output of wind farm, 15 wind turbines model GE's 1.85-87 [14] under ideal conditions is used. As well as, the parameter values for electrical vehicles used in this paper are as follows:

Average vehicle battery capacity, $P_{Vj} = 25$kWh; total number of vehicles of a city$= 50000$ (estimated); charging–discharging frequency=1 per day; scheduling period=24h; system efficiency, $\xi = 85\%$ and cost coefficients of electric vehicles, $x = 0, y = 8.21$, $z = 0.20$.

4. RESULTS AND DISCUSSION

In this paper, production scheduling is done in five scenarios. Different scenarios with the objective functions are summarized in Table V.

TABLE IV.
GENERATOR EMISSION COEFFICIENTS [11]

Unit	$\boldsymbol{\alpha_i(ton/h)}$	$\boldsymbol{\beta_i(ton/Mwh)}$	$\boldsymbol{\gamma_i(ton/Mw^2h)}$
U1	10.33908	-0.24444	0.00312
U2	10.33908	-0.24444	0.00312
U3	30.03910	-0.40695	0.00509
U4	30.03910	-0.40695	0.00509
U5	32.00006	-0.38132	0.00344
U6	32.00006	-0.38132	0.00344
U7	33.00056	-0.39023	0.00465
U8	33.00056	-0.39023	0.00465
U9	35.00056	-0.39524	0.00465
U10	36.00012	-0.39864	0.00470

TABLE V.

DIFFERENT SCENARIOS WITH THE OBJECTIVE FUNCTIONS

scenarios	scheduled in the presence of	objective function
S1	Thermal units	minimizing operation costs
S2	Thermal units	minimizing emissions
S3	Thermal units& renewable energy resources&V2G	minimizing operation costs
S4	Thermal units& renewable energy resources&V2G	minimizing emissions
S5	Thermal units& renewable energy resources&V2G	Multi-Objective Optimization

TABLE VI.

OPERATION COSTS AND EMISSIONS IN S1 AND S2

S1		S2	
operation costs ($)	Emissions (ton)	operation costs ($)	Emissions (ton)
564268.338	26486.006	623254.722	18180.467

TABLE VII.

COMPARISON OF OPERATION COST MINLP WITH OTHER METHODS

Method	Cost($)	Method	Cost($)
MINLP	564268.338	LR [5]	568356
GA [17]	565825	BCGA [17]	567367
DP [17]	565825	ICGA [18]	566404
PSO [19]	564743.5	LRGA [20]	564800
HPSO [21]	564772	LS [22]	564970
SFLA [23]	564769	EP [24]	565352
BF [25]	564842	BPSO [26]	565804
LRPSO [27]	565869		

TABLE VIII.

POWER OUTPUT OF PV AND OF WIND TURBINES

	$P_{wind}(t)$				$P_{PV}(t)$			
time	January	April	July	November	January	April	July	November
1	10.179	27.75	0	2	0	0	0	0
2	5.357	27.75	0	3.75	0	0	0	0
3	27.75	27.75	0	0	0	0	0	0
4	27.75	27.75	0	0	0	0	0.522	0
5	27.75	27.75	0	0	0	1.605	2.808	0.120
6	27.75	19.319	0	0	0	5.015	5.616	2.527
7	27.75	2.50	0	0	2.808	7.622	7.221	6.820
8	27.75	19.319	0	3.75	6.820	7.943	7.943	9.147
9	27.75	20.397	0	4.392	8.425	7.823	8.705	9.748
10	27.75	17.159	0	0	9.427	7.943	8.224	10.029
11	27.75	6.965	0	0	10.350	7.382	6.820	10.109
12	27.75	11.786	0	0	10.109	7.020	6.018	9.628
13	27.75	25.796	3.125	0.5	9.026	7.101	5.536	9.026
14	27.75	6.965	1	0	8.826	6.018	5.416	8.946
15	27.75	1.25	1.25	13.394	8.906	5.095	4.814	8.746
16	0	0	0	25.796	7.221	5.015	3.611	6.820
17	27.75	3.125	3.75	10.179	2.848	4.934	3.209	3.410
18	27.75	5.357	17.159	9.215	0.120	3.089	3.009	0.802
19	27.75	0	0	9.857	0	0.883	1.404	0
20	27.75	0.626	1.25	3.5	0	0	0.201	0
21	27.75	0	0	1	0	0	0	0
22	27.75	0.626	0	6	0	0	0	0
23	27.75	6.965	19.319	6	0	0	0	0
24	25.796	17.159	0	0	0	0	0	0

The results of the scheduling in the absence of V2G have been reported in Table VI. As be expected, costs in the scenario s1 and emissions in the scenario s2 have decreased.

Table VII compares the proposed method to solve the problem with some of the other methods.

It can be seen clearly that the proposed method is very efficient and in addition to having accurate results, it can reduce the operation costs considerably.

The recent trend is to include renewables such as solar, wind turbines and electric vehicles in the modern power systems for energy storages in smart grid in order to reduce the fuel usage and provide an alternate solution for the depleting fuel sources. The next generation plug-in vehicles namely Gridable Vehicles (GV) have become an essential component in the smart grid concept. The interconnection of the vehicle energy storage, communication to the grid and their economic and environmental benefits are the most researched topics in smart grid [28]. Power output of solar and wind farms according to (11) and (12) as well as wind speed data and solar insolation can be obtained. The results for January, April and July 2014 are summarized in Table VIII.

Table IX shows the results of unit commitment and economic dispatch for IEEE ten-unit system in the presence of renewable energy resources and electrical vehicles in scenario S3 and in January.

As can be seen the first and second units that were turned on at the beginning of the scheduling and have lower operation costs remain committed during 24 hours. Because of nine and ten units are relatively expensive, they commitment only in periods that the other units do not meet the load and reserve.

Tables X and XII compare the cost of the operation and emissions for ten unit system in each scenario.

According to Tables VIII and X, we find that in January when the power generated from renewable energy resources is higher, the operation cost is lower and in July that the power generated from them is lower, operation cost has increased.

Table XI shows the results of unit commitment and economic dispatch for IEEE ten-unit system in the presence of renewable energy resources in scenario S4 and in January. This scenario intends to minimize emissions of thermal units.

By comparing the operation cost and emissions in the presence or absence of renewable energy resources the useful role that they play in the smart grid can be realized. For example, in scenario S3 and in January, saving of operating costs in the presence of these resources are 18017.266 $. Also, in the scenario S4 and in January, presence of these resources prevents from 3134.213 tons Additional emissions.

TABLE IX.
RESULTS OF SCHEDULING FOR TEN-UNIT SYSTEM IN JANUARY (S3)

time	U1	U2	U3	U4	U5	U6	U7	U8	U9	U10	Reserve
1	455	248.396	0	0	0	0	0	0	0	0	206.604
2	455	303.133	0	0	0	0	0	0	0	0	151.867
3	455	370	0	0	0	0	0	0	0	0	85
4	455	455	0	0	25	0	0	0	0	0	137
5	455	455	0	0	62	0	0	0	0	0	100
6	455	455	0	130	39.328	0	0	0	0	0	122.672
7	455	392.793	130	130	25	0	0	0	0	0	199.207
8	455	438.710	130	130	25	0	0	0	0	0	153.290
9	455	455	130	130	32	0	0	0	0	0	130
10	455	455	130	130	142	20	25	0	0	0	140
11	455	455	130	130	137	20	25	0	0	0	145
12	455	455	130	130	162	35	25	0	0	10	150
13	455	455	130	130	142	20	25	0	0	0	140
14	455	455	130	130	32	0	0	0	0	0	130
15	455	436.627	130	130	25	0	0	0	0	0	155.373
16	455	316.249	130	130	25	0	0	0	0	0	275.751
17	455	242.985	130	130	25	0	0	0	0	0	349.015
18	455	345.554	130	130	25	0	0	0	0	0	246.446
19	455	425.551	130	130	25	20	0	0	0	0	226.449
20	455	455	130	130	82	20	0	0	0	0	140
21	455	455	130	130	82.250	20	0	0	0	0	139.750
22	455	455	0	130	32.250	0	0	0	0	0	129.750
23	455	317.252	0	0	0	0	0	0	0	0	137.748
24	455	319.202	0	0	0	0	0	0	0	0	135.798

TABLE X.
COMPARISON OF THE OPERATION COST IN EACH SCENARIO

	January	April	July	November
S3	538677.525	545600.527	558402.365	549286.415
S4	734219.386	705140.292	734219.386	737368.294
S5	545756.306	553473.098	559938.293	559132.594

TABLE XI.
RESULTS OF SCHEDULING FOR TEN-UNIT SYSTEM IN JANUARY (S4)

time	U1	U2	U3	U4	U5	U6	U7	U8	U9	U10	Reserve
1	266.227	266.227	0	0	0	80	85	0	0	0	377.545
2	266.227	266.227	0	0	0	80	85	0	0	0	377.545
3	266.227	266.227	0	0	0	80	85	0	0	0	377.545
4	266.227	266.227	0	0	162	80	85	55	55	55	377.545
5	266.227	266.227	0	0	162	80	85	55	55	55	377.545
6	266.227	266.227	130	130	162	80	85	55	55	55	377.545
7	266.227	266.227	130	130	162	80	85	55	55	55	377.545
8	266.227	266.227	130	130	162	80	85	55	55	55	377.545
9	269.647	269.647	130	130	162	80	85	55	55	55	370.705
10	272.628	272.628	130	130	162	80	85	55	55	55	364.743
11	272.628	272.628	130	130	162	80	85	55	55	55	364.743
12	272.628	272.628	130	130	162	80	85	55	55	55	364.743
13	272.628	272.628	130	130	162	80	85	55	55	55	364.743
14	270.792	270.792	130	130	162	80	85	55	55	55	368.416
15	239.304	239.304	130	130	162	80	85	55	55	55	431.391
16	239.304	239.304	130	130	162	80	85	55	55	55	431.391
17	239.304	239.304	130	130	162	80	85	55	0	0	431.391
18	239.304	239.304	130	130	162	80	85	55	55	55	431.391
19	239.304	239.304	130	130	162	80	85	55	55	55	431.391
20	249.198	249.198	130	130	162	80	85	55	55	55	411.604
21	249.198	249.198	130	130	162	80	85	55	55	55	411.604
22	249.198	249.198	0	130	162	80	85	55	55	55	411.604
23	249.198	249.198	0	0	0	80	85	0	0	0	411.604
24	249.198	249.198	0	0	0	80	85	0	0	0	411.604

TABLE XII.
COMPARISON OF EMISSIONS IN EACH SCENARIO

	January	April	July	November
S3	26271.399	26605.649	26916.784	26514.953
S4	13544.422	14580.982	13544.422	۱۳۱۹۱.۴۱۵
S5	21382.101	21588.461	21795.975	21706.439

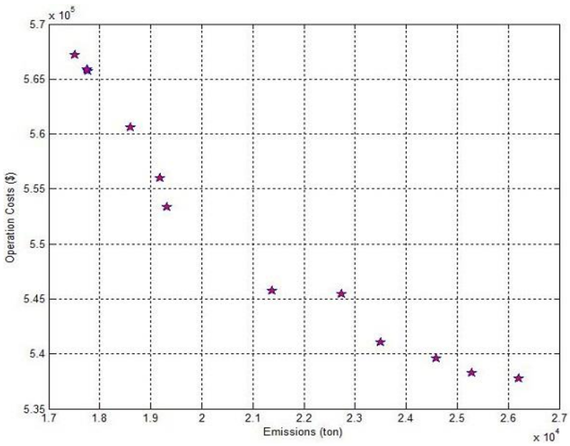

Fig. 1. Pareto chart for S5

In S5, the operation cost and emissions simultaneously with the weight coefficient of W=0.25 are optimized. Figure 1 indicates Pareto chart of Scenario S5. In this chart the optimal points have been obtained from optimization with different weight coefficients for reducing the emissions and cost of operation.

Choose one of these as the optimal points of scheduling depends to importance of each parameters.

5. CONCLUSION

In this paper cost and emission reductions in a smart grid by maximum utilization of electrical vehicles and RESs are presented. As a case study, short-term generation scheduling for IEEE ten-unit system has been done. We propose MINLP method for solving the unit commitment (UC) problem. Constraints such as Generation limit, Minimum up and down time, Ramp-rate limit constraints and Startup-cost is applied in problem solving. The numerical tests and results showing that our scheme can decrease costs and greenhouse gas emissions were presented. As well as, this method is very impressive and the quality of feasible solution is significantly improved.

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