

Combining both Plug-in Vehicles and Renewable Energy Resources for Unit Commitment studies in Smart Grid

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Abstract: In this Paper, Unit commitment integration with vehicle-to-grid and Renewable Energy Resources (UC-V2G-RES) is developed. The aim of this study is to provide a cost-emission reduction solution to the smart grid. The proposed solution comprised of four steps: data clustering, economic load dispatching, sources' variables optimization and cost-emission values calculation. The Optimization is done using Genetic Algorithm (GA) to fulfill a large number of practical constraints, meet the forecast load demand calculated in advance, plus spinning reserve requirements at every time interval such that the total cost and emissions are minimum. It includes intelligently scheduling on/off states of existing generating units and large number of gridable vehicles with V2G technology in addition to time varying RESs during a full day (24 Hours). The results obtained validated to a reasonable extent the effectiveness of integrating V2G and RESs with the smart grid. The analysis and results are presented and discussed.

Keywords: Genetic algorithms, costs, environmental management, solar power generation, wind power generation, Electric vehicles.

I. INTRODUCTION

Renewable energy is a clean energy source which is relatively cheap. Integrating plug-in hybrid electric vehicles (PHEVs) with vehicle-to-grid (V2G) has the capability, which can reduce emissions from the transportation sector. Linking and scheduling of Renewable Energy Sources (RESs), PHEVs (V2G Vehicles) and existing Power plants (Generation Units) is a very complex problem which needs dynamic adaptive optimization approach to optimize time-varying resources such as RESs and V2Gs in a complex smart grid, this approach is called Unit commitment (UC). The aim of this paper is to study and show the effectiveness of using PHEV-V2G as spinning reserves and RESs (Wind & Solar) as power sources on reducing both emissions and cost. Researches in this field have mainly considered the use of PHEV-V2G either as loads, sources, or energy storages where they assumed that using PHEV-V2G have no cost, they also considered that there is no operation and maintenance cost for wind and solar power production [1]-[2], which affects the accuracy and reliability of the results.

V2G researchers have mainly concentrated on using PHEV-V2G in the ancillary services [3]. The primary contributions of this paper are as follows: (1) reliable and efficient UC with PHEV-V2G, Wind and Solar Energy (UC-V2G-RESs), (2) using PHEV-V2G as Spinning Reserve, (3) calculating the revenue of V2G to the PHEV owner when working as a Spinning Reserve only, (4) including the cost of Wind and Solar energy production in the total cost, and (5) illustration of the reduction effectiveness on both environmental and economical sides when integrating UC-V2G-RESs in Smart grid.

The rest of this paper is organized as follows. The UC-V2G-RESs problem formulation and its related constraints are presented in Section II. A dynamic adaptive optimization method to optimize intelligently time-varying resources such as RESs and V2Gs in a complex smart grid and a new simple logical Economic Load Dispatching (ELD) are described in Section III. Simulation data and results are presented and discussed in Section IV. Finally, the conclusion is given in Section V.

II. PROBLEM FORMULATION

2.1 Objective Function

The objective of the UC-V2G-RESs is to minimize both total running cost and emissions (TCE) simultaneously, as in (1), (2).

$$\begin{aligned} \min TCE = \min f = & \sum_{\text{time}=1}^{\text{Hours}} \text{Fuel Cost} + \text{Start - Up Cost} + \text{V2G (Spinning Reserve)Cost} \\ & + \text{Wind Power O\&M Cost} + \text{Solar Power O\&M Cost} \\ & + \text{Emissions.} \end{aligned} \quad (1)$$

$$\begin{aligned} \min f = & \sum_{i=1}^N \sum_{t=1}^H [FC_i(P_i(t)) + SUC_i(1 - I_i(t - 1))] \cdot I_i(t) \\ & + \sum_{t=1}^H SRSC(t) \\ & + \sum_{t=1}^H W_c(t) + \sum_{t=1}^H S_c(t) + \sum_{i=1}^N \sum_{t=1}^H \epsilon C_i(P_i(t)) \cdot I_i(t) \end{aligned} \quad (2)$$

Where, each term in (2), is the mathematical representation in (1).

$P_i(t)$ is the output power from unit "i" at time "t".

$I_i(t)$ is the output power from V@G unit "i" at time "t".

Subject to [1]-[2] constraints

Constraints

There are a number of constraints that control over the optimization process where the objective function optimization cannot violate any of these constraints as this will affect the reliability and accuracy of the results. Most of the constraints are adapted from previous studies and papers [1]-[2] so that the simulation conditions are the same and the results can be comparable.

III. PROPOSED METHOD

Unit Commitment problems require a computer program to be adaptive and to continue to perform well in a changing environment with many variables to handle. The problem solving approach consists of two consecutive operations: (1) sources' variables optimization using GA, and (2) Economic Load Dispatching, as in **Figure.1** gives a brief description of the two operations is given as the shown:

GA Data Structure for UC-V2G-RESs

In the proposed method, GA chromosomes structures for UC-V2G-RESs problem are as follows:

1) Binary GA: chromosomes of 0s and 1s for the thermal generation units is used to produce the best fit set of combinations. The best sets of combinations' fitness function are reevaluated till the fitness function saturates to a certain fitness value. The best fit set contains a combination of 0s (units are OFF) and 1s (units are ON) which gives the best fit value for the fitness function (lowest cost to meet the system's load demand and constraints).

2) Discrete GA: chromosomes of bits (e.g., 0,1,2,3 ..., ∞) is used with wind and solar energy to determine their energy share to the grid so that it meets the system's constraints and achieve the best fit value (lowest cost and emissions) solution. In addition to that, discrete (integer) GA is used to determine the number of PHEV-V2G that contribute to the grid's spinning reserve so that the best fit integer solution meets the system considerations and achieve the most optimized solution.

Generation units: An $N \times H$ binary matrix;
 Wind energy: A $1 \times H$ integer vector;
 Solar energy: A $1 \times H$ integer vector;
 Number of vehicles: A $1 \times H$ integer vector;

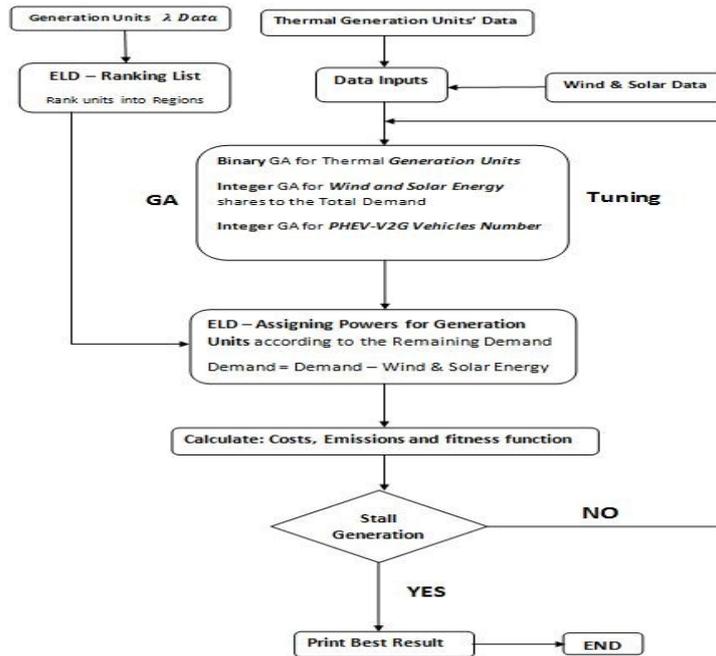


Figure 1. System flowchart.

Economic Load Dispatching Calculation

Economic Load Dispatching (ELD) is the main complex computational intensive part of unit commitment problem as stated in [2]. A New Simple Logical ELD approach is developed. The ELD is based on the units' Incremental fuel costs (Lambda λ) Ranking. The new ELD is composed of two operations:

3) Ranking List: where units' power ranges are divided into regions according to the change in their Lambda-Ranking, in each region the units' power are ranked in an ascending order according to their lambda (λ).

4) Units' power assigning: load demand is satisfied by turning on the committed units according to their Ranking List (Lambda ascending order). In the first Region, the first ranked unit is contributing with power equal to the end of the region's power range and so do all the following ranked units till all the units' power reach the end limits of this region, then doing the same for the following region (according to its new different Lambda-Ranking) and so on till the load demand is satisfied.

Constraints Management

The complexity of UC-V2G-RESs using GA grows exponentially as the number of the variables and elements increases. Due to the high complexity, some constraints might be unexpectedly violated. In order not to violate the constraint, an infinity value (penalty) is assigned to each violated constraint. As a result of that, an invalid infeasible solution will have a fitness value of infinity which cannot be adapted by the GA algorithm so that the GA will keep iterating till it reaches an integer value.

IV. SIMULATION RESULTS

All simulations have been run using MATLAB software. Base 10-generator system is considered for simulation with unlimited number of PHEV-V2Gs which are charged from renewable source in the owner's parking at home. In addition to the Spinning reserve revenue to the owner and in order to encourage the PHEV-V2G owner to keep providing the grid with the spinning reserve service, the PHEV-V2G battery life time is taken into consideration. So the charging – discharging rate is considered 1 per day. This charging-discharging rate maintains a longer battery life time [3]. ELD- Ranking List operation for the 10-generators is done one time only before running the GA optimization algorithm which reduces the optimization complexity. Load demand, unit characteristics of the 10-unit system and emissions data are all collected from [1]-[2], capacity of each vehicle (P_v) = 15 KWh and maximum battery capacity = 25 KWh; departure state of charge, SoC (Ψ) = 60%; efficiency of the converter (η) = 85% and charging-discharging rate = 1 per day. In order to perform simulations on the same condition of [1]-[2], the spinning reserve requirement is assumed to be a minimum of 10% of the load demand and the total scheduling period is 24 hours. Prices for using PHEV-V2G as spinning reserve (owner's revenue) is collected from CAISO's Spinning Reserve cost (SRC) for electricity [4] and costs for Wind (C_w) and Solar (C_s) Energy is collected from California's O&M (fixed + variable) cost for Wind and Solar [5]. Wind and Solar

penetration level (power share) of the load is weighted and adapted according to the Wind & Solar energy generation to the grid's load ratio for CAISO in Fall 2012 [6] so that the load demand to Wind & Solar energy ratio in our model would be the same as the ratio in [6]. In TABLE I, Wind & Solar power share to our model and generation to load ratio for CAISO is listed.

Simulation results for unit commitment of the thermal generation units only are shown in TABLE II. The effectiveness of integrating PHEV-V2G with the 10-base generation units and the reduction effects in both emissions and cost are shown in TABLE III. In TABLE IV, results of unit commitment for the 10-base generation units integrated with wind and solar energy is shown.

The total running cost for the base 10-generator system is 563937\$ and it lowers to 557690\$ when integrating PHEVs-V2G as a spinning reserve service provider. Integrating PHEVs-V2G to the smart electricity grid as a spinning reserve service provider affects both the cost and emissions. Simulation results has shown significant reduction in both fuel cost and total cost when using PHEVs-V2G, achieving 12277\$ reduction in fuel cost and 6247\$ in total cost per day taking into consideration that using PHEVs-V2G bring 5858.1\$ as a revenue to the owners. The revenue is considered as a source of attraction to encourage the PHEVs-V2G owners to be more involved in using their own vehicles as a spinning reserve service provider and as a compensation for their time and battery usage. Emissions reduced as well by 422tons/day when using PHEVs-V2G taking into consideration that cost reduction has a higher priority than emissions reduction in our simulations.

TABLE I. POWER SHARE AND GENERATION TO LOAD RATIO FOR WIND & SOLAR ENERGY.

Hours	Wind-Load Ratio	Max. Wind Level	Solar-Load Ratio	Max. Solar Level
1	0.0929	65	0	0
2	0.0950	71.25	0	0
3	0.0974	82.76	0	0
4	0.0947	90	0	0
5	0.0897	89.74	0	0
6	0.0756	83.17	0	0
7	0.0652	75	0.0043	5
8	0.0592	71.02	0.0184	22.04
9	0.0474	61.66	0.0415	53.95
10	0.0389	54.44	0.0481	67.4
11	0.0393	56.96	0.0464	67.32
12	0.0464	69.64	0.0464	69.64
13	0.0518	72.5	0.0464	65
14	0.0517	67.24	0.0448	58.27
15	0.0586	70.34	0.0448	53.79
16	0.0621	65.17	0.0448	47.06
17	0.0610	61.01	0.0271	27.11
18	0.0633	69.66	0.0100	11
19	0.0639	76.72	0	0
20	0.0645	90.32	0	0
21	0.0633	82.33	0	0
22	0.0684	75.26	0	0
23	0.0784	70.58	0	0
24	0.0870	69.56	0	0

Integrating both wind and solar energy as power sources to partially replace thermal generation units' power share to the grid affects both cost and emissions. Although, wind and solar energy production related costs are considered relatively high and that there is a gradual decrease in the O&M prices, the reductions in both cost and emissions are very encouraging. Integrating wind & solar energy reduced the total cost to be 554436\$ and emissions to 24612tons/day. Reductions in both fuel cost and total cost are significant, fuel cost is reduced by 39550\$ when integrating wind & solar energy to the base 10-generators system model and total cost is reduced by 9501\$ taking into consideration that wind energy production related cost is 21166\$ and solar energy production related cost is 8933\$.

Significant reduction in emissions is achieved when using RESs as power sources, emissions were at the level of 24612 tons/day which makes a reduction by 2379tons/day taking into consideration that emissions reduction was given a higher priority than cost reduction in the simulation (emissions-high priority simulation). Due to the relatively high production cost [5] for solar energy (47.03\$/MW) over wind energy (12.17\$/MW) and even thermal generation units, the solar energy share to satisfy the load demand is the lowest among the three power sources.

TABLE II BASE 10-THERMAL GENERATION UNITS SIMULATION RESULTS COSTS AND EMISSIONS

Hours	U1 MW	U2 MW	U3 MW	U4 MW	U5 MW	U6 MW	U7 MW	U8 MW	U9 MW	U10 MW	Demand MW	Reserve MW	Reserve %
1	455	245	0	0	0	0	0	0	0	0	700	210	30
2	455	295	0	0	0	0	0	0	0	0	750	160	21.33
3	455	370	0	0	25	0	0	0	0	0	850	222	26.12
4	455	455	0	0	40	0	0	0	0	0	950	122	12.84
5	455	390	0	130	25	0	0	0	0	0	1000	202	20.2
6	455	360	130	130	25	0	0	0	0	0	1100	232	21.09
7	455	410	130	130	25	0	0	0	0	0	1150	182	15.83
8	455	455	130	130	30	0	0	0	0	0	1200	132	11
9	455	455	130	130	85	20	25	0	0	0	1300	197	15.15
10	455	455	130	130	162	33	25	10	0	0	1400	152	10.86
11	455	455	130	130	162	73	25	10	10	0	1450	157	10.83
12	455	455	130	130	162	80	25	43	10	10	1500	162	10.8
13	455	455	130	130	162	33	25	10	0	0	1400	152	10.86
14	455	455	130	130	85	20	25	0	0	0	1300	197	15.15
15	455	455	130	130	30	0	0	0	0	0	1200	132	11
16	455	310	130	130	25	0	0	0	0	0	1050	282	26.86
17	455	260	130	130	25	0	0	0	0	0	1000	332	33.2
18	455	360	130	130	25	0	0	0	0	0	1100	232	21.09
19	455	455	130	130	30	0	0	0	0	0	1200	132	11
20	455	455	130	130	162	33	25	10	0	0	1400	152	10.86
21	455	455	130	130	85	20	25	0	0	0	1300	197	15.15
22	455	455	0	0	145	20	25	0	0	0	1100	137	12.45
23	455	425	0	0	0	20	0	0	0	0	900	90	10
24	455	345	0	0	0	0	0	0	0	0	800	110	13.75
Fuel Cost		Start Up Cost					Total Cost					Emissions	
559847 \$		4090 \$					563937 \$					26991 tons	

TABLE III. PHEVs-V2G INTEGRATION AS A SPINNING RESERVE SERVICE PROVIDER'S SIMULATION RESULTS, COSTS AND EMISSIONS

Hours	U1 MW	U2 MW	U3 MW	U4 MW	U5 MW	U6 MW	U7 MW	U8 MW	U9 MW	U10 MW	V2G (Spinning Reserve MWh)	Demand MW	Reserve MWh	Reserve %
1	455	245	0	0	0	0	0	0	0	0	0	700	210	30
2	455	295	0	0	0	0	0	0	0	0	0	750	160	21.3333
3	455	395	0	0	0	0	0	0	0	0	25.0002	850	85.0002	10
4	455	365	0	130	0	0	0	0	0	0	5.0031	950	95.0031	10.0003
5	455	415	0	130	0	0	0	0	0	0	60.0015	1000	100.0015	10.0002
6	455	385	130	130	0	0	0	0	0	0	40.0044	1100	110.0044	10.0004
7	455	435	130	130	0	0	0	0	0	0	95.0028	1150	115.0028	10.0002
8	455	455	130	130	30	0	0	0	0	0	0	1200	132.0	11
9	455	455	130	130	130	0	0	0	0	0	98.0016	1300	130.0016	10.0001
10	455	455	130	130	162	68	0	0	0	0	128.0049	1400	140.0049	10.0004
11	455	455	130	130	162	80	0	38	0	0	128.0049	1450	145.0049	10.0003
12	455	455	130	130	162	80	0	55	33	0	128.0049	1500	150.0049	10.0003
13	455	455	130	130	162	68	0	0	0	0	128.0049	1400	140.0049	10.0004
14	455	455	130	130	130	0	0	0	0	0	98.0016	1300	130.0016	10.0001
15	455	455	130	130	30	0	0	0	0	0	0	1200	132.0	11
16	455	310	130	130	25	0	0	0	0	0	0	1050	282.0	26.8571
17	455	260	130	130	25	0	0	0	0	0	0	1000	332.0	33.2
18	455	360	130	130	25	0	0	0	0	0	0	1100	232.0	21.0909
19	455	455	130	130	30	0	0	0	0	0	0	1200	132.0	11
20	455	455	130	130	162	68	0	0	0	0	128.0049	1400	140.0049	10.0004
21	455	455	130	130	110	20	0	0	0	0	18.0030	1300	130.0030	10.0002
22	455	455	130	0	0	60	0	0	0	0	90.0048	1100	110.0048	10.0004
23	455	445	0	0	0	0	0	0	0	0	80.0037	900	90.0037	10.0004
24	455	345	0	0	0	0	0	0	0	0	0	800	110.0	13.75
Fuel Cost		Start Up Cost				V2G Revenue (Spinning Reserve Cost)						Total Cost		Emissions
547570 \$		4260 \$				5858.1 \$						557690 \$		26569 tons

TABLE IV. WIND & SOLAR INTEGRATION TO THE BASE 10-GENERATORS MODEL SIMULATION RESULTS, COSTS AND EMISSIONS

Hours	U1 MW	U2 MW	U3 MW	U4 MW	U5 MW	U6 MW	U7 MW	U8 MW	U9 MW	U10 MW	Solar MW	Wind MW	Demand MW	Reserve MWh	Reserve %
1	455	180	0	0	0	0	0	0	0	0	0	65	700	275	43
2	455	224	0	0	0	0	0	0	0	0	0	71	750	231	34
3	455	287	0	0	25	0	0	0	0	0	0	83	850	305	40
4	455	380	0	0	25	0	0	0	0	0	0	90	950	212	24.6
5	455	300	130	0	25	0	0	0	0	0	0	90	1000	292	32
6	455	407	130	0	25	0	0	0	0	0	0	83	1100	185	18
7	455	330	130	130	25	0	0	0	0	0	5	75	1150	262	24.5
8	455	367	130	130	25	0	0	0	0	0	22	71	1200	225	20
9	455	455	130	130	48	20	0	0	0	0	0	62	1300	174	14
10	455	455	130	130	121	20	25	0	10	0	0	54	1400	206	15
11	455	455	130	130	158	20	25	0	10	10	0	57	1450	214	15.4
12	455	455	130	130	162	53	25	10	10	0	0	70	1500	177	12
13	455	455	130	130	47.5	20	25	0	0	0	65	72.5	1400	234.5	18.6
14	455	390	130	130	25	20	25	0	0	0	58	67	1300	322	27.4
15	455	389	130	130	25	0	0	0	0	0	1	70	1200	203	18
16	455	244	130	130	25	0	0	0	0	0	1	65	1050	348	35.4
17	455	172	130	130	25	0	0	0	0	0	27	61	1000	420	46
18	455	279	130	130	25	0	0	0	0	0	11	70	1100	313	31
19	455	383	130	130	25	0	0	0	0	0	0	77	1200	209	18.6
20	455	455	130	130	95	20	25	0	0	0	0	90	1400	187	14
21	455	433	130	130	25	20	25	0	0	0	0	82	1300	279	22
22	455	455	0	0	70	20	25	0	0	0	0	75	1100	212	20.7
23	455	349	0	0	25	0	0	0	0	0	0	71	900	242.6	29
24	455	275	0	0	0	0	0	0	0	0	0	70	800	179.6	24.6
Fuel Cost	Start Up Cost	Solar Energy Cost					Wind Energy Cost					Emissions		Total Cost	
520297 \$	4040 \$	8933 \$					21166 \$					24612 tons		554436 \$	

Depending on the simulation conditions and reduction priorities, the use of solar energy can be constructive or destructive to the final results. When adjusting the simulation settings to set cost reduction as high priority, the GA optimization iteratively lower the solar power share to the grid so that the best fit total cost is achieved. Cost–high priority simulation achieve a total cost of 547990\$/day which is lower than emission-high priority simulation by 6446\$/day. The cost reduction effect is due to lowering the solar energy share to the load by 181MW/day as its cost is the highest among all the other power sources.

The spinning reserve (SR) percentage is one of the most important elements in a UC problem optimization. **Figure.2** shows three curves represent the SR percentages for the three modes of simulation. PHEVs-V2G integration gives a full and immediate control of the SR percentage over the day. This can be shown in the period from 3:00 to 15:00 where a SR percentage is almost exactly 10% of the load. SR control ability is expensive and takes more time when thermal generation units are used, but when using PHEVs-V2G it provide full and quick response when needed and saves money when there is no need. The average SR percentage varied over the three modes. For the base 10-units, the average SR percentage is: 16.6% of the load, then it lowers to: 13.7% of load for the PHEVs-V2G integration. The reduction in the average SR percentage is due to the controllability that PHEVs-V2G offer according to the adjustments (Simulation settings: SR percentage is a minimum of 10%). The average SR percentage increases significantly where the average SR is: 24.9% of load when integrating wind & solar energy which makes the system more stable and reliable. The relatively high average SR percentage compensates for the wind and solar day ahead forecasting error which ranges from 5% to 20% of wind & solar energy shared [8]. The uncertainty of wind and solar energy is dependent on many variables such as: geographical area, forecasting models used and period-ahead forecasting, all of these variables affect the uncertainty percentage and the overall accuracy.

As a result of that, two methods were considered to handle the uncertainty challenge:

- (1) The total penetration level of wind & solar energy is less than or equal to 15% of the load demand (average of: 6% wind to load and 1% solar to load) Table. I.
- (2) SR percentage up leveling ranges from 12% to 46% of load with an average of 24.9%. Further enhancement can be done to increase the SR percentage, reliability and stability of the system besides covering up any unexpected uncertainty error for wind and solar energy which includes integrating both PHEV-V2G and RESs (wind & solar energy).

Integrating PHEVs-V2G and RESs slightly increases the cost and emissions as shown in Table. IV, but it provides the system with a higher level of stability where the average SR percentage increases to 30.2% of load. Table. V & **Figure 2** show a summary of different costs elements, emissions and SR average percentage for the four operating modes discussed in this paper.

TABLE V SYMMARY TABLE

Mode	System Elements Costs (\$)				Environmental Effects (tons)	SR %
	Base 10 -Units	V2G revenue	RESs	Total Cost	Emissions	Avg.
10 –units only	563937	0	0	563937	26991	16.6
PHEV- V2G integra- tion	551830	5858	0	557690	26569	13.7
Wind & solar integra- tion	525159	0	25591	550750	24485	24.9
All-in	526819	3578	21893	552290	24637	30.2

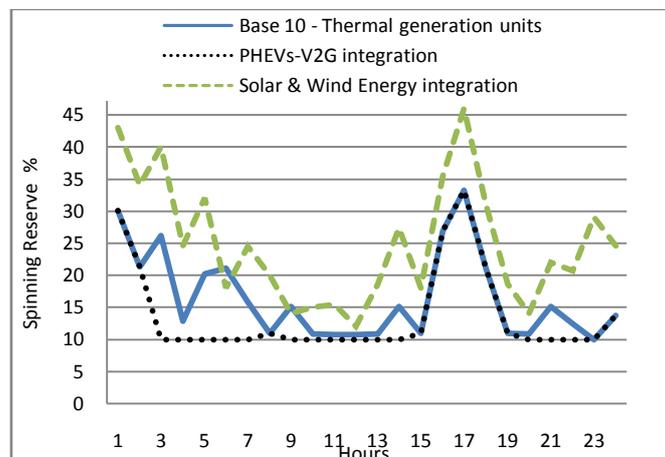


Figure 2. Spining reserve summary versus hours for the the first three modes of operation

V. CONCLUSION

In this paper, the unit commitment problem has been solved in four different modes, provided with results and analysis to illustrate cost and emission reductions for a sustainable integrated electricity and transportation infrastructure. The four modes were: (1) Base 10-generators, (2) PHEVs-V2G integration, (3) wind and solar energy integration, and (4) integrating PHEVs-V2G, wind and solar energy with the base 10-generators model. Binary and integer Genetic Algorithm optimization has been applied on the different dynamic data of the available power sources for the four modes.

GA optimization with a new simple economic load dispatching method has been used in order to generate intelligent and efficient utilization scheduling of the available power resources. PHEVs-V2G has been used as a spinning reserve service provider where profit (revenue) to the owner is taking into consideration. In order to maintain a longer battery life-time for PHEVs-V2G, a 1 charging–discharging/day rate is considered to every vehicle. Wind and solar energy is considered to partially replace the thermal generation units. In order to present a reliable and measurable solution, pricing and costs has been included for PHEVs-V2G spinning reserve revenue, wind and solar power providing.

From this study, it is clear that:

- (1) Integrating PHEVs-V2G in UC problem, gives the operator a fully controllable and quick response service for the spinning reserve.
- (2) Revenue to the user while maintain a policy for a longer battery life-time, encourages vehicles’ users to provide the electricity grid with the needed spinning reserve.
- (3) Integrating wind and solar energy (RESs) only, increases the level of spinning reserve which leads to a more stable and reliable electricity system.

(4) For maximum reliability of the system, both PHEVs-V2G and RESs can be integrated as this up level the spinning reserve average percentage up to 30.2%.

(5) Significant cost and emissions reductions has been achieved when integrating PHEVs-V2G, RESs or both together with the base 10-generators models. In future, there is enough scope to include different load dispatching techniques, cost and emissions oriented optimization, other ancillary services besides the spinning reserve and wind and solar uncertainties calculation methods.

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