International Journal on
"Technical and Physical Problems of Engineering"
(IJTPE)
Published by International Organization of IOTPE

ISSN 2077-3528
IJTPE Journal
www.iotpe.com
ijtpe@iotpe.com

| March 2014 | Issue 18 | Volume 6 | Number 1 | Pages 39-45 |
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# INCORPORATING VEHICLE TO GRID INTO UNIT COMMITMENT PROBLEM - A CASE OF COST VS EMISSION OPTIMIZATION

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**Abstract-** Smart power grids are expected to involve an increasing level of intelligence and incorporation of new information and communication technologies. Gridable Vehicles (GVs) are one of the interesting programs, which can be utilized in the smart grid environment. GVs can be used as small portable power plants to enhance the reliability as well as security of the power system. This paper formulates a Mixed-Integer Programming (MIP) approach for solving the cost emission based Unit Commitment (UC) problem with GVs. The formulation of the UC problem has been modified to incorporate GVs. A mixed-integer representation of GVs is used in the proposed unit commitment model. The proposed method is carried out on the conventional 10-unit test system to demonstrate the impacts of smart grid environment on the UC problem and the benefits of implementation of GVs in smart grid environment.

**Keywords:** Smart Grid, Mixed-Integer Programming, Unit Commitment, Vehicle-to-Grid.

## I. INTRODUCTION

The power and energy industry (in terms of a. economic importance, and b. environmental effect) is one of the most important sectors in the world since nearly every aspect of industrial productivity and daily life, is affected by that. Unit Commitment (UC) involves the determination of on/off status of generation units and the value of generators power production to meet the forecasted demand for a specified time horizon [1].

The optimal schedule should minimize the system production costs during the scheduling period, while satisfying load demand, spinning reserve requirements as well as physical and operational constraints of each individual unit [2-4]. Being a non-convex, mixed-integer combinatorial optimization problem several mathematical, heuristic and hybrid methods have been proposed for solving the UC problem. The mathematical approaches include Priority List (PL), Dynamic Programming (DP), Integer and Mixed-Integer Programming (IP/MIP), Linear Programming (LP), Branch and Bound (BB) [5-8].

Due to some limitations in application and results of the mathematical methods, heuristic approaches have been proposed [9-13]. The Smart Grid is a set of software and hardware tools capable of routing power more proficiently, and therefore reducing the need for excess capacity and upgrade of the existing system. The main difference between the current grid and the smart grid is that the last is a transformed electricity and distribution network, which uses two-way communications, advanced intelligent technologies to enhance the efficiency and reliability of power supply.

Being equipped with ICT-based (Information and Communication Technologies) optimization technology, smart grids are capable of communicating with demand side loads that offer a variety of options to make the grid load and the production more predictable and adaptable [14]. The focuses of Vehicle-to-Grid (V2G) researchers have mainly been on interconnection of energy storage of vehicles and grid [15-19]. Their aim is to educate about the environmental and economic benefits of V2G and improvement of the power market.

However, success of V2G technology mainly depends on the efficient scheduling of Gridable Vehicles (GVs) considered restricted number of parking lots. Ideally speaking, gridable vehicles for V2G technology should be charged from renewable sources. A gridable vehicle can be considered as a small portable power plant [20]. Reference [21] simulated a parallel HEV based on faulty condition, the obtained results demonstrated that proper Kalman Filter Gain might cause best fault detection.

In this paper, UC problem in smart grid environment is investigated considering both financial and environmental issues. V2Gs as one of the main programs of the smart grid are considered in UC problem. In [22] authors addressed the incorporation of V2G into unit commitment, however, these mobile storage devices were used to supply spinning reserve. Modeling V2G involves intelligently scheduling existing units and large number of GVs in limited and restricted parking lots. In [20, 23] the consideration of V2G in the UC problem was proposed. They used evolutionary algorithms to solve aforementioned problem.

However, the evolutionary algorithms have many advantages, they have several disadvantages such as achieving the optimal solution is not guaranteed, obtaining same solution after each run of method is highly unlikable and if so the execution time would be relatively high. Therefore, in this study, a mixed-integer programming is proposed and is applicable for practical purposes. A mixed-integer programming (MIP) framework is proposed in this study, which formulates the cost-emission based unit commitment problem with V2G. A mixed-integer representation of GVs has been modeled.

The proposed model is used to determine loads supported by the GVs and schedule commitment status of generating units. The obtained results demonstrate that operation cost can be significantly reduced in the presence of DRPs and GVs with proper and intelligent optimization. The proposed approach is conducted on the conventional 10-unit test system to demonstrate the influences of GVs on the UC problem and electricity market. The rest of this paper is organized as follows. Section II provides a primer of V2Gs. The proposed mathematical formulation is expressed in detail in Section III. Section IV conducts the numerical results and discussions. Finally, concluding remarks are drawn in Section V.

## II. VEHICLE-TO-GRID

Plug in Hybrid Electric Vehicles (PHEVs) are hybrid electric vehicles that can draw and store energy from an electric grid to supply propulsive energy for the vehicle energy consumption. This simple functional change enables a PHEV to displace energy from petroleum with multi-source electric energy [24]. This has important and generally beneficial influence on petroleum consumption, pollution, as well as on the performance and makeup of the electric grid. Because of these characteristics and their near term availability, PHEVs are seen as one of the most promising means to enhance the sustainability of the energy sectors [25].

A widespread adoption of electric vehicles will need to be taken into account in all activities within power systems. However, some activities will more likely be subject to more severe modifications in technical as well as in operational terms, than others will. This can easily be understood since the vehicles will be connected to lower network levels and hence entities active on these levels will be affected more [26]. Among which UC problem is one of activities that is considerably influenced by PHEVs.

## III. PROPOSED MATHEMATICAL FRAMEWORK

### A. Conventional Unit Commitment Formulation

UC involves determining generating outputs of all units from an initial hour to satisfy load demands associated with startup and shutdown schedule over a time horizon. The objective function is to find the optimal schedule such that the total operating costs are minimized while satisfying the load demand, spinning reserve requirements, emission allowance limit, as well as other operational constraints. The objective function for unit commitment problem comprises the startup costs, shutdown costs of de-committed units, the fuel costs, as well as the emission level of generating units, which can be presented as follows:

$$\min \sum_{i=1}^{N}\sum_{t=1}^{T}[F(i,t)\,u(i,t)+SU(i)\,u(i,t)(1-u(i,t-1))+ \\ +SD(i)u(i,t-1)(1-u(i,t))] \quad (1)$$

### B. Gridable Vehicles Model

Only predefined registered/forecasted GVs are considered for determining the optimum solution (scheduling) in the UC problem. Total number of registered GVs is considered to be fixed and it is assumed that they were charged from renewable sources and not from the grids. All the vehicles will discharge to the grid during the scheduling period [20].

$$\sum_{t=1}^{T} N_{GV}(t) = N_{GV}^{\max} \quad (2)$$

Vehicles are assumed to be charged from renewable sources and discharge to the grid. Multiple charging/discharging facilities of GVs may be available however since it is very dependent on lifetime and type of batteries. In this study, for sake of simplicity, charging/ discharging frequency is one per scheduling horizon.

### C. MIP-Based Unit Commitment with Gridable Vehicles

In this study, the objective function is a nonlinear mixed-integer optimization problem that is difficult to solve by standard nonlinear programming methods. Therefore, we describe an alternative mixed-integer linear formulation, MILP-UC, suitable for available MILP software [27, 28]. The MILP-based model of objective function for unit commitment problem with GV can be formulated as follows:

$$\min \sum_{t=1}^{T}[W_F[\sum_{i=1}^{N}[\underline{F}(i)u_i(t)+\sum_{m=1}^{NSF(i)} p_m(i,t)b_m(i)+ \\ +SC_n(i)\left[u(i,t)-\sum_{n=1}^{k}u(i,t-n)\right]-z(i,t)SD(i)]]+ \\ +W_E\{\underline{Em}(i)u_i(t)+\sum_{m=1}^{NSE(i)} q_m(i,t)e_m(i)\}] \quad (3)$$

More explanation about each parameter of Equation (3) is outlined in the following.

### C.1. Fuel Cost

The quadratic fuel cost function typically used in scheduling problems can be formulated as:

$$F(i,t)=a(i)+b(i)P(i,t)+c(i)P^2(i,t) \quad (4)$$

The cost function in Equation (4) can be accurately approximated by a set of piecewise blocks [27]. For practical purposes, the piecewise linear function is indistinguishable from the nonlinear model if enough segments are used. The analytic representation of this linear approximation is as follows:

$$\underline{F}(i)\,u_i(t)+\sum_{m=1}^{NSF(i)} p_m(i,t)\,b_m(i) \quad (5)$$

**C.2. Emission**

Emission effects should be taken into account for environment friendly power production. The total emission of fossil fuelled units also mathematically modeled as a second order Taylor expansion and given in a quadratic form as:

$$Em(i,t)=\alpha(i)+\beta(i)P(i,t)+\delta(i)P^2(i,t) \quad (6)$$

which can be accurately approximated by a set of piecewise blocks. The analytic representation of this linear approximation is similar to Equation (5) and can be formulated as follows:

$$\underline{Em}(i)u_i(t)+\sum_{m=1}^{NSE(i)} q_m(i,t)e_m(i) \quad (7)$$

**C.3. Startup Cost**

Since the time span has been discretized into hourly periods, the startup cost is also a discrete function. The discrete startup cost can be asymptotically approximated by a stair wise function, which is more accurate as the number of intervals increases [28]. A mixed-integer linear formulation for the stair wise startup cost was proposed in [28].

$$\begin{cases} SU(i)\geq SC_n(i)\left[u(i,t)-\sum_{n=1}^{k}u(i,t-n)\right] & \forall i,\forall t \\ \forall k=1,...,NS(i) \end{cases} \quad (8)$$

$$SU(i)\geq 0 \quad \forall i,\forall t \quad (9)$$

Note that Equations (8) and (9) only depend on the binary variables associated with the on/off status of generating units.

**C.4. Shutdown Cost**

Shutdown cost is constant for each unit and is modeled by using a shutdown indicator as presented in Equation (3).

**C.5. Unit Output limit**

$$\underline{P}(i,t)u(i,t)+\sum_{m=1}^{NSF(i)} p_m(i,t)\leq \overline{P}(i,t)u(i,t) \quad \forall i,\forall t \quad (10)$$

**C.6. Ramping Up/Down Constraints**

$$P_i(t+1)-P_i(t)\leq RUR_i \quad \forall i,\forall t \quad (11)$$

$$P_i(t)-P_i(t+1)\leq RDR_i \quad \forall i,\forall t \quad (12)$$

**C.7. Minimum On/Off Time Constraints**

Once a unit is committed, it must remain 'on' for a minimum number of hours given in Equation (12). Formulation of minimum on/off time constraints is given as [27]:

$$\sum_{t=1}^{UT(i)}(1-u(i,t))=0, \quad \forall i \quad (13)$$

$$y(i,t)+\sum_{m=t+1}^{\max[T,t+MU(i)-1]} z(i,m)\leq 1, \quad \forall i,\forall t=UT(i)+1,...,T \quad (14)$$

$$UT(i)=\max\{0,\min[T,MU(i)-TU(i,0)u(i,0)]\} \quad (15)$$

Accordingly, if a unit is shutdown, it must remain 'off' for a minimum number of hours given as [27].

$$\sum_{t=1}^{DT(i)}u(i,t)=0, \quad \forall i \quad (16)$$

$$z(i,t)+\sum_{m=t+1}^{\max[T,t+MD(i)-1]} y(i,m)\leq 1, \quad \forall i,\forall t=DT(i)+1,...,T \quad (17)$$

$$DT(i)=\max\{0,\min[T,MD(i)-TC(i,0)(1-u(i,0))]\} \quad (18)$$

The relationship between startup and shutdown indicators and unit status is [27].

$$y(i,t+1)-z(i,t+1)=u(i,t+1)-u(i,t), \quad \forall i,\forall t \quad (19)$$

The hourly relationship among unit status, startup, and shutdown indicators is enforced by Equation (19). A unit may not be started up and shutdown at a given hour, therefore [27].

$$\begin{cases} y(i,t)+z(i,t)\leq 1 & \forall i,\forall t \\ 0\leq z(i,t)\leq 1 & \forall i,\forall t \end{cases} \quad (20)$$

**C.8. Spinning Reserve**

Spinning Reserve (SR) must be sufficient to maintain the desired reliability of a power system. SR is usually a pre-specified amount that is either equal to the largest unit or a given percentage of the forecasted load, which can be given by the following equation:

$$\sum_{i=1}^{N}\overline{P}(i,t)u(i,t)+P_{GV}^{\max}N_{GV}(t)\geq SR(t) \quad \forall t \quad (21)$$

**C.9. State of Charge**

This constraint express that each vehicle should have a desired departure state of charge level.

**C.10. Number of Discharging Vehicles Constraint**

Not all the vehicles can be discharged at the same time because of power transfer, current limit. For reliable operation and control of GV, only a limited number of vehicles are assumed able to discharge at a time.

$$N_{GV}(t)<N_{GV}^{\max}(t) \quad (22)$$

**C.11. Efficiency**

Charging and inverter efficiencies should be considered.

## IV. SIMULATION RESULTS AND DISCUSSION

The conventional 10-unit test system has been used for the simulation of this study. Figure 1 depicts the load curve of the 10-unit test system. Parameter values regarding GV are presented in the following [20]:

- Maximum battery capacity = 25 kWh
- Minimum battery capacity = 10 kWh
- Average battery capacity, $P_{GV}$ = 15 kWh
- Maximum number of vehicles for power provision at each hour, $N_{GV}^{\max}(t)$ = 10% of total GVs
- Total number of GVs in the system, $N_{GV}^{\max}$ = 50000
- Charge/Discharge freq. = one per study horizon (24h)
- Departure state of charge = 50%
- Efficiency = 85%

Three different case studies have been considered in order to evaluate the effect of GVs on the unit commitment problem. The first case study focuses on the conventional unit commitment problem without consideration of GVs. In the second case, the effect of GVs on the cost based UC problem has been studied. In the third case, impact of GVs on cost emission based UC problem has been investigated.

### A. Case Study 1, Conventional Unit Commitment Problem

In this case, the system includes 10 units with a scheduling time horizon of 24 hours. The generating units data are given in [1]. Twenty linear segments between the minimum and maximum generating units' capacity approximate the cost curves for generating units given as a quadratic function in [1]. Table 1 gives the MIP-based solutions (outputs) of units for 24 h period for 10-unit based system. The total cost of the system in this case is 565,283.9537 $ and the total emission is equal to 12,824.4927 tones.

Table 1. Units output power for the conventional 10-unit test system

| Hours | Units | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 1 | 455 | 245 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 455 | 295 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 455 | 370 | 0 | 0 | 25 | 0 | 0 | 0 | 0 | 0 |
| 4 | 455 | 455 | 0 | 0 | 40 | 0 | 0 | 0 | 0 | 0 |
| 5 | 455 | 455 | 0 | 0 | 70 | 20 | 0 | 0 | 0 | 0 |
| 6 | 455 | 455 | 0 | 130 | 40 | 20 | 0 | 0 | 0 | 0 |
| 7 | 455 | 390 | 130 | 130 | 25 | 20 | 0 | 0 | 0 | 0 |
| 8 | 455 | 440 | 130 | 130 | 25 | 20 | 0 | 0 | 0 | 0 |
| 9 | 455 | 455 | 130 | 130 | 100 | 20 | 0 | 10 | 0 | 0 |
| 10 | 455 | 455 | 130 | 130 | 162 | 33 | 25 | 10 | 0 | 0 |
| 11 | 455 | 455 | 130 | 130 | 162 | 73 | 25 | 10 | 10 | 0 |
| 12 | 455 | 455 | 130 | 130 | 162 | 80 | 25 | 43 | 10 | 10 |
| 13 | 455 | 455 | 130 | 130 | 162 | 33 | 25 | 10 | 0 | 0 |
| 14 | 455 | 455 | 130 | 130 | 100 | 20 | 0 | 10 | 0 | 0 |
| 15 | 455 | 455 | 130 | 130 | 30 | 0 | 0 | 0 | 0 | 0 |
| 16 | 455 | 310 | 130 | 130 | 25 | 0 | 0 | 0 | 0 | 0 |
| 17 | 455 | 260 | 130 | 130 | 25 | 0 | 0 | 0 | 0 | 0 |
| 18 | 455 | 360 | 130 | 130 | 25 | 0 | 0 | 0 | 0 | 0 |
| 19 | 455 | 455 | 130 | 130 | 30 | 0 | 0 | 0 | 0 | 0 |
| 20 | 455 | 455 | 130 | 130 | 162 | 23 | 25 | 10 | 10 | 0 |
| 21 | 455 | 455 | 130 | 130 | 85 | 20 | 25 | 0 | 0 | 0 |
| 22 | 455 | 445 | 0 | 130 | 25 | 20 | 25 | 0 | 0 | 0 |
| 23 | 455 | 420 | 0 | 0 | 25 | 0 | 0 | 0 | 0 | 0 |
| 24 | 455 | 320 | 0 | 0 | 25 | 0 | 0 | 0 | 0 | 0 |

### B. Case Study 2, Unit Commitment Considering Gridable Vehicles

The MIP-based solutions for the UC problem with GVs are provided in Table 2. The output powers of generation units are presented in this table after implementing GVs. like before, the shaded boxes highlight the difference in the output power of generating units comparing to the base case. The total generation cost of generation units is 552,464.6172 $. It shows considerable reduction in the UC problem after including GVs comparing to the 565,283.9537 $ for the case 1. As mentioned earlier it is assumed that GVs are charged from renewable resources.

In case GVs are charged via power grid, their charging power consumption should be considered in the load curve and therefore simulations. Implementation of GVs has decreased the generation costs by turning off the expensive generating units at peak interval.

Table 2. 10-unit output power with GVs in case 2

| Hours | Units | | | | | | | | | | GV |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
| 1 | 455 | 245 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 455 | 295 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 455 | 395 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 455 | 455 | 0 | 0 | 38.70 | 0 | 0 | 0 | 0 | 0 | 1.3 |
| 5 | 455 | 455 | 0 | 0 | 58.12 | 20 | 0 | 0 | 0 | 0 | 31.87 |
| 6 | 455 | 455 | 0 | 130 | 37.57 | 20 | 0 | 0 | 0 | 0 | 22.42 |
| 7 | 455 | 410 | 130 | 130 | 25 | 20 | 0 | 0 | 0 | 0 | 0 |
| 8 | 455 | 455 | 130 | 130 | 30 | 20 | 0 | 0 | 0 | 0 | 0 |
| 9 | 455 | 455 | 130 | 130 | 78.12 | 20 | 0 | 10 | 0 | 0 | 31.87 |
| 10 | 455 | 455 | 130 | 130 | 143.12 | 20 | 25 | 10 | 0 | 0 | 31.87 |
| 11 | 455 | 455 | 130 | 130 | 162 | 41.12 | 25 | 10 | 10 | 0 | 31.87 |
| 12 | 455 | 455 | 130 | 130 | 162 | 80 | 25 | 11.12 | 10 | 10 | 31.87 |
| 13 | 455 | 455 | 130 | 130 | 143.12 | 20 | 25 | 10 | 0 | 0 | 31.87 |
| 14 | 455 | 455 | 130 | 130 | 78.12 | 20 | 0 | 10 | 0 | 0 | 31.87 |
| 15 | 455 | 455 | 130 | 130 | 30 | 0 | 0 | 0 | 0 | 0 | 0 |
| 16 | 455 | 310 | 130 | 130 | 25 | 0 | 0 | 0 | 0 | 0 | 0 |
| 17 | 455 | 260 | 130 | 130 | 25 | 0 | 0 | 0 | 0 | 0 | 0 |
| 18 | 455 | 360 | 130 | 130 | 25 | 0 | 0 | 0 | 0 | 0 | 0 |
| 19 | 455 | 455 | 130 | 130 | 30 | 0 | 0 | 0 | 0 | 0 | 0 |
| 20 | 455 | 455 | 130 | 130 | 158.12 | 20 | 0 | 10 | 10 | 0 | 31.87 |
| 21 | 455 | 455 | 130 | 130 | 78.12 | 20 | 0 | 0 | 0 | 0 | 31.87 |
| 22 | 455 | 445 | 0 | 130 | 31.85 | 20 | 0 | 0 | 0 | 0 | 8.150 |
| 23 | 455 | 420 | 0 | 0 | 25 | 0 | 0 | 0 | 0 | 0 | 0 |
| 24 | 455 | 320 | 0 | 0 | 25 | 0 | 0 | 0 | 0 | 0 | 0 |

Table 3. Cost and emission based 10-unit output power with GVs in case 3

| Hours | Units | | | | | | | | | | GV |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
| 1 | 412.75 | 287.25 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 439.75 | 310.25 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 455 | 395 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 455 | 365 | 0 | 130 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 455 | 395 | 0 | 130 | 0 | 20 | 0 | 0 | 0 | 0 | 0 |
| 6 | 455 | 365 | 130 | 130 | 0 | 20 | 0 | 0 | 0 | 0 | 0 |
| 7 | 455 | 415 | 130 | 130 | 0 | 20 | 0 | 0 | 0 | 0 | 0 |
| 8 | 455 | 424.5 | 130 | 130 | 38.7 | 20 | 0 | 0 | 0 | 0 | 1.8 |
| 9 | 455 | 455 | 130 | 130 | 78.125 | 20 | 0 | 0 | 0 | 0 | 31.875 |
| 10 | 455 | 455 | 130 | 130 | 143.125 | 20 | 25 | 10 | 0 | 0 | 31.875 |
| 11 | 455 | 455 | 130 | 130 | 162 | 41.125 | 25 | 10 | 10 | 0 | 31.875 |
| 12 | 455 | 455 | 130 | 130 | 162 | 80 | 25 | 11.125 | 10 | 10 | 31.875 |
| 13 | 455 | 455 | 130 | 130 | 143.125 | 20 | 25 | 10 | 0 | 0 | 31.875 |
| 14 | 455 | 455 | 130 | 130 | 78.125 | 20 | 0 | 0 | 0 | 0 | 31.875 |
| 15 | 455 | 416.225 | 130 | 130 | 38.7 | 0 | 0 | 0 | 0 | 0 | 30.075 |
| 16 | 447.25 | 317.75 | 130 | 130 | 25 | 0 | 0 | 0 | 0 | 0 | 0 |
| 17 | 424.50 | 290.5 | 130 | 130 | 25 | 0 | 0 | 0 | 0 | 0 | 0 |
| 18 | 455 | 360 | 130 | 130 | 25 | 0 | 0 | 0 | 0 | 0 | 0 |
| 19 | 455 | 414.425 | 130 | 130 | 38.7 | 0 | 0 | 0 | 0 | 0 | 31.875 |
| 20 | 455 | 455 | 130 | 130 | 158.125 | 20 | 0 | 10 | 10 | 0 | 31.875 |
| 21 | 455 | 455 | 130 | 130 | 78.125 | 20 | 0 | 0 | 0 | 0 | 31.875 |
| 22 | 455 | 365 | 130 | 130 | 0 | 20 | 0 | 0 | 0 | 0 | 0 |
| 23 | 452.25 | 317.75 | 130 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 24 | 398 | 272 | 130 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

### C. Case Study 3, Cost Emission Based Unit Commitment Considering GVs

In this case, both cost and emission are considered in the UC problem with GVs. In this case, $W_E$ and $W_F$ are considered to be 0.5 in Equation (3). The value of objective function in this case is equal to 290,174.4388. In case GVs are not considered in the simulations the value of objective function will be 295,909.3994 $.

The output powers of generation units are presented in Table 3 after implementation of GVs for the cost emission based UC problem in the smart grid environment. The shaded boxes show the difference in the output power of generating units comparing to the cost emission based UC problem without GVs.

### D. Discussion

In order to validate the advantages of the proposed method the obtained results by the proposed MIP-based approach are compared with those drawn from other methods reported in the literature. In [20, 23] the impact of GV on unit commitment problem employing Particle Swarm Optimization (PSO) was studied. Shown in Table 4 is the comparison of the proposed method with those of PSO form [20].

Table 4. Comparison of the results of the proposed method with PSO for UC with GVs

| Method | Best | Worst | Average |
|---|---|---|---|
| PSO [23] | 557,180.7 | 561,593.6 | 558,917.6 |
| BPSO [20] | 554,509.5 | 559,987.8 | 557,584.4 |
| MIP | 552,464.6 | 552,464.6 | 552,464.6 |

As shown in Table 4 the proposed MIP-based solution always renders the optimal solution, while the results obtained by other methods vary significantly. Moreover, proposed approach result in better solution in comparison with the other two approaches reported in the literature.

## V. CONCLUSIONS

A mixed-integer programming approach for solving the UC problem with consideration of GVs has been addressed in this paper. Both cost and emission has been considered as objective function. The objective function of the UC problem has been modified to incorporate GVs. The proposed method has been carried out on the conventional 10-unit test system. Three different cases have been considered to investigate the impact of GVs on cost and emission separately and simultaneously. The results obtained show the effectiveness of the GVs on the UC problem in terms of cost and emission. Obtained results also demonstrate the capability of the proposed mixed-integer framework in finding the optimal solution in different cases.

## NOMENCLATURES

$a()$ , $b()$ , $c()$ : Fuel cost coefficients of a unit

$b_m$ : Slope of segment *m* in linearized fuel cost curve

$D()$ : Power demand of an hour

$Em()$ : Emission function of a unit

$\underline{Em}()$ : Lower limit on the emission of a unit

$e_m()$ : Slope of segment *m* in linearized emission curve

$F()$ : Fuel cost function of a unit

$\underline{F}()$ : Lower limit on the fuel cost of a unit

$IC()$ : Contract level of Incentive-based programs of an hour

$i$ : Denotes a unit

$MU()$, $MD()$ : Minimum up/down time of a unit

$m$ : Segment index for linearized fuel cost and total incentive curve

$N$ : Number of units

$N_{GV}$ : Number of gridable vehicles

$N_{GV}^{\max}$ : Maximum number of gridable vehicles

$NSE()$ : Number of segments for the piecewise linearized emission curve

$NSF()$ : Number of segments for the piecewise linearized fuel cost curve.

$n$ : Segment index for stair wise emission curve

$P()$ : Generation of a unit

$\underline{P}(), \overline{P}()$ : Minimum/maximum generating capacity

$P_{GV}$ : Power obtainable from one GV

$P_{GV}^{\max}$ : Maximum power obtainable from one GV

$p_m()$ : Generation of segment *m* in linearized fuel cost curve

$q_m()$ : Generation of segment *m* in linearized emission curve

$RDR()$ : Ramping down limit of a unit

$RUR()$ : Ramping up limit of a unit

$SC_n()$ : Cost of the interval *n* of the stair wise startup cost function of unit *j*

$SU()$ : Startup cost of a unit

$SD()$ : Shutdown cost of a unit

$T$ : Number of hours for the scheduling period

$t$ : Hour index

$TU(,0)$, $TC(,0)$ : Number of hours a unit has been on/off at the beginning of the scheduling period

$UT(), DT()$ : Number of hours a unit needs to remain on/off if on/off at the beginning of the scheduling period

$u()$ : Unit status indicator where 1 means on and 0 means off

$W_E$ : Weight coefficient of emission in objective function

$W_F$ : Weight coefficient of generation cost in objective function

$y()$ : Startup indicator

$z()$ : Shutdown indicator

$\alpha()$ , $\beta()$ , $\delta()$ : Emission coefficients of a unit

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