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# INCORPORATING ELECTRIC VEHICLES AND SPINNING RESERVE INTO THE UNIT COMMITMENT PROBLEM

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**Abstract-** Ancillary services play a vital role for maintaining security and reliability of power systems. Spinning Reserve (SR) is one of the most important ancillary services, which can provide power system stability and integrity response to contingencies, and disturbances that may occur in the power systems continuously. Although reliability is one of the most important sequences in power system, price of maintaining to it should be economical. Therefore, a trade-off between reliability and operating cost must be taken into consideration. In this paper, a Unit Commitment (UC) incorporating spinning reserve cost is presented. Furthermore, Plug in Electric Vehicles (PEVs) as mobile storage devices have additional power that can be used for different aspects such as supplying spinning reserve. Therefore, integration of PEVs, the so-called parking lots, has been added to mentioned UC problem to attain some saving. The proposed methodology is applied to IEEE 10-unit test system. The results obtained from simulation analysis show a significant techno-economic saving.

**Keywords:** Plugin Electric Vehicles, Unit Commitment, Smart Grid, Spinning Reserve, Ancillary Services, Reliability, Generating Scheduling, Discharging.

## I. INTRODUCTION

In a Smart Grid (SG) environment, by utilizing bidirectional connection between consumers and generating resources, acquiring communication information concerning consumers' behavior as well as other available generating resources system facilitates. SGs also may improve energy efficiency, reliability, and sustainability of electric grid whilst decreasing operating costs [1]. By providing such real time information, Independent System Operators (ISOs) achieve ability to handle supply-demand equilibrium in a real time fashion and better integration of renewable energies associated with electricity storages [2]. PEVs as portable source of electricity storages have undeniable benefits through intelligent charging and discharging scheme in a smart grid environment.

One of the techno-economic achievement of PEVs is flattening load curve and minimizing load curtailment by discharging PEVs in peak time and charging at off-peak periods[3, 4]. Furthermore, they can decrease the operating costs incurred at peak hours through connecting Vehicle to Grid (V2G) [5-7]. Moreover, PEVs can reduce emission by decreasing total generation of polluting units [8, 9]. PEVs are also useful for ancillary services such as supplying spinning reserve to improve reliability as well as energy efficiency and frequency regulation because of their fast response[10-12].

Also PEVs can diminish transmission line congestion as a result of Dispersed Generation (DG) as well as decreasing real power losses and improving power quality [13-16]. Reference [17] simulates a parallel hybrid electric vehicle based on the faulty condition. A Particle Swarm Optimization with Improved Inertia Weight (PSO-IIW) is proposed in [18] to solve the UC problem between thermal generating units with wind impact an electricity market, the objective is to minimize the total cost of the system.

In this paper, the impact of parking lots penetration on spinning reserve has been investigated. A term considering spinning reserve cost has been added to objective function of conventional unit commitment problem. Mathematically, unit commitment is a non-convex, nonlinear, and mixed integer optimization problem. For sake of improvement in solving this problem, the fuel costs of generators are linearized. The problem has been modeled in GAMS platform and an IEEE 10-unit test system is considered for the numerical studies and simulation analysis. The rest of the paper is organized as follows. Section 2 proposes the problem formulation. Section 3 presents the simulation and results and finally conclusions are discussed in section 4.

## II. MODELLING AND FORMULATION

### A. Objective Function

The objective function of UC in this paper is to minimize total operating costs comprising fuel costs, start-up and shut down costs and spinning reserve cost.

$$\sum_{i=1}^{N}\sum_{t=1}^{h} [F_i(P_i^t)\ u_i^t + SUC_i\ (1-u_i^{t-1}) + +SDC_i\ (1-u_i^{t+1})] + \sum_{i=1}^{N}\sum_{t=1}^{h} SPC_i^t \tag{1}$$

**A.1. Fuel Cost**

Fuel cost of a thermal unit is expressed as a second order function of generated power of the unit.

$$F_i(P_i^t) = a_i + b_i P_i^t + c_i (P_i^t)^2 \tag{2}$$

where, $a_i$, $b_i$, and $c_i$ are positive fuel cost coefficients of thermal unit $i$. The unit fuel cost function is nonlinear in nature. It can be approximated accurately by a set of piecewise blocks [19]. For practical implementation, the piecewise linear function is indistinguishable from the nonlinear model if enough segments are used. The analytic representation of this linear approximation is:

$$F_i^t = F_i^{\min} \times u_i^t + \sum_{m=1}^{NSF(i)} Pm_i^t \times bm_i \tag{3}$$

**A.2. Startup Cost**

The startup cost is related to either hot or cold conditions, where it can be expressed as follows:

$$SUC_i = \begin{cases} HSC_i & MD_i \le XD_i^t \le HD_i \\ CSC_i & XD_i^t > HD_i \end{cases} \tag{4}$$

$$HD_i = MD_i + CSH_i \tag{5}$$

A typical exponential startup cost function is shown in Figure 1, where the time span has been divided into hourly periods [20]. The discrete startup cost can be approximated asymptotically by a stair wise function, which is more accurate as the number of intervals increases.

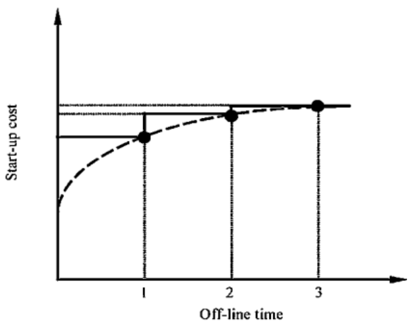


Figure 1. Exponential, discrete, and stair wise startup cost functions [20]

**A.3. Spinning Reserve Cost**

Spinning reserve cost of a unit can be described as follows [21]:

$$SPC_i^t = PR_i^t \times SR_i^t \tag{6}$$

$$PR_i^t = 0.1 \times \left( \frac{F(P_i^t) - F(P_i^t - 2)}{2} \right) \tag{7}$$

**B. Constraints**

The essential power supplied from committed units subjected to their generation limits, associated with PEVs must satisfy the load demand:

$$D^t = \sum_{i=1}^{N}\sum_{t=1}^{h} [P_i^t\ u_i^t] + \sum_{t=1}^{h} [pv\ N_{dsch}^t] \tag{8}$$

$$P_i^{\min} \le P_i^t \le P_i^{\max} \tag{9}$$

On the other hand, spinning reserve requirement, $R(t)$, must be sufficient enough to prevent any undesirable load shedding in case of an outage or unexpected increasing of demand. It is usually a pre-specified amount that is either equal to the largest unit or a given percentage of the forecasted load [22]. Mathematically, $R(t)$ at each hour is the total amount of maximum capacity of all synchronized units minus the total generating output in that hour which can be given by the Equation (11).

$$D^t + R^t \le \sum_{i=1}^{N}\sum_{t=1}^{h} [P_i^{\max}\ u_i^t] + \sum_{t=1}^{h} [pv\ N_{dsch}^t] \tag{10}$$

Once a unit is committed, it must remain "on" for a minimum number of hours given in Equation (11), and accordingly if a unit is shutdown, it must remain "off "for a minimum number of hours given in Equation (12).

$$\text{if } u_i^t = 1 \text{ then } (1-u_i^{t+1})\ MU_i \le XU_i^t \tag{11}$$

$$\text{if } u_i^t = 0 \text{ then } u_i^{t+1}\ MD_i \le XD_i^t \tag{12}$$

The variation of a unit output is limited by ramp up/down rate at each hour:

$$\text{if } u_i^t = 1\ \&\ u_i^{t-1} = 1 \text{ then } P_i^t - P_i^{t-1} \le RU_i \tag{13}$$

$$\text{if } u_i^t = 1\ \&\ u_i^{t-1} = 1 \text{ then } p_i^{t-1} - p_i^t \le RD_i \tag{14}$$

In order to have a reliable operation, limited number of PEVs should charge/discharge at the same time over a predefined horizon.

$$\sum_{t=1}^{h} N_{dsch}^t = N^{\max} \tag{15}$$

For sake of simplicity, charging/discharging frequency is assumed once a day, respectively. Each vehicle should have a desired departure State Of Charge (SOC) level, while $\eta$ is defined as integrated efficiency for charging/discharging plus inverter [23].

## III. SIMULATION STUDIES AND RESULTS ANALYSIS

A standard IEEE 10-unit system presented in Table 1 is considered for simulation study with 50000 PEVs. Spinning reserve requirement is assumed 10% of hourly load demand in 24-hour scheduling period. According to [24], the following parameters are presumed for PEVs, maximum battery capacity=25 kWh, minimum battery capacity=10 kWh, average battery capacity ($pv$)=15 kWh, charging/discharging frequency=1 per day, departure state of charge ($\delta$)=50%, total efficiency ($\eta$)=85%.

Three different scenarios are studied in this paper (Table 2). First scenario consists typical unit commitment problem, while an integration of spinning reserve cost into UC problem is second one. Third scenario comprises of integration 50000 PEVs charged by renewable sources and discharged to power grid to conventional UC problem considering spinning reserve cost. Maximum number of discharging vehicles at each hour ($N_{dschv2g\max}(t)$) for scenario 3 is 10% of total vehicles.

## A. Scenario 1

The result of UC without PEVs and spinning reserve cost is presented in Table 3. As it can be seen from Table 3, two least expensive units 1 & 2 are committed in 24 hour while unit 1 always generates its maximum power. Additionally, units 7, 9 and 10, which are the most expensive units always supply spinning reserve as well as power at their minimum limits.

Table 2. Details of scenarios

| Scenarios | Details |
|---|---|
| Scenario 1 | Thermal units without PEVs and spinning reserve cost |
| Scenario 2 | Thermal units with spinning reserve cost without PEVs |
| Scenario 3 | Thermal units with spinning reserve cost and 50,000 PEVs |

Table 1. Unit characteristics of the 10-unit system

| Parameters | Unit 1 | Unit 2 | Unit 3 | Unit 4 | Unit 5 | Unit 6 | Unit 7 | Unit 8 | Unit 9 | Unit 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| $P^{max}$ (MW) | 455 | 455 | 130 | 130 | 162 | 80 | 85 | 55 | 55 | 55 |
| $P^{min}$ (MW) | 150 | 150 | 20 | 20 | 25 | 20 | 25 | 10 | 10 | 10 |
| $a$ ($\$h^{-1}$) | 1000 | 970 | 700 | 680 | 450 | 370 | 480 | 660 | 665 | 670 |
| $b$ ($\$MWh^{-1}$) | 16.19 | 17.26 | 16.6 | 16.5 | 19.7 | 22.26 | 27.74 | 25.92 | 27.27 | 27.79 |
| $c$ ($\$MWh^{2\ -1}$) | 0.00048 | 0.00031 | 0.002 | 0.00211 | 0.00398 | 0.00712 | 0.0079 | 0.00413 | 0.00222 | 0.00173 |
| *MUT* (h) | 8 | 8 | 5 | 5 | 6 | 3 | 3 | 1 | 1 | 1 |
| *MDT* (h) | 8 | 8 | 5 | 5 | 6 | 3 | 3 | 1 | 1 | 1 |
| Cold Start cost ($) | 9000 | 10000 | 1100 | 1120 | 1800 | 340 | 520 | 60 | 60 | 60 |
| Hot start cost ($) | 4500 | 5000 | 550 | 560 | 900 | 170 | 260 | 30 | 30 | 30 |
| Cold start hour (h) | 5 | 5 | 4 | 4 | 4 | 2 | 2 | 0 | 0 | 0 |
| Shut down cost ($) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Initial status (h) | 8 | 8 | -5 | -5 | -6 | -3 | -3 | -1 | -1 | -1 |

Table 3. Schedule and dispatch of generating units for Scenario 1

| Hour | $P_1$ (MW) | $P_2$ (MW) | $P_3$ (MW) | $P_4$ (MW) | $P_5$ (MW) | $P_6$ (MW) | $P_7$ (MW) | $P_8$ (MW) | $P_9$ (MW) | $P_{10}$ (MW) | Demand (MW) | Spinning reserve (MW) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 455 | 245 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 700 | 210 |
| 2 | 455 | 295 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 750 | 160 |
| 3 | 455 | 370 | 0 | 0 | 25 | 0 | 0 | 0 | 0 | 0 | 850 | 222 |
| 4 | 455 | 455 | 0 | 0 | 40 | 0 | 0 | 0 | 0 | 0 | 950 | 122 |
| 5 | 455 | 390 | 0 | 130 | 25 | 0 | 0 | 0 | 0 | 0 | 1000 | 202 |
| 6 | 455 | 360 | 130 | 130 | 25 | 0 | 0 | 0 | 0 | 0 | 1100 | 232 |
| 7 | 455 | 410 | 130 | 130 | 25 | 0 | 0 | 0 | 0 | 0 | 1150 | 182 |
| 8 | 455 | 455 | 130 | 130 | 30 | 0 | 0 | 0 | 0 | 0 | 1200 | 132 |
| 9 | 455 | 455 | 130 | 130 | 85 | 20 | 25 | 0 | 0 | 0 | 1300 | 197 |
| 10 | 455 | 455 | 130 | 130 | 162 | 33 | 25 | 10 | 0 | 0 | 1400 | 152 |
| 11 | 455 | 455 | 130 | 130 | 162 | 73 | 25 | 10 | 10 | 0 | 1450 | 157 |
| 12 | 455 | 455 | 130 | 130 | 162 | 80 | 25 | 43 | 10 | 10 | 1500 | 162 |
| 13 | 455 | 455 | 130 | 130 | 162 | 33 | 25 | 10 | 0 | 0 | 1400 | 152 |
| 14 | 455 | 455 | 130 | 130 | 85 | 20 | 25 | 0 | 0 | 0 | 1300 | 197 |
| 15 | 455 | 455 | 130 | 130 | 30 | 0 | 0 | 0 | 0 | 0 | 1200 | 132 |
| 16 | 455 | 310 | 130 | 130 | 25 | 0 | 0 | 0 | 0 | 0 | 1050 | 282 |
| 17 | 455 | 260 | 130 | 130 | 25 | 0 | 0 | 0 | 0 | 0 | 1000 | 332 |
| 18 | 455 | 360 | 130 | 130 | 25 | 0 | 0 | 0 | 0 | 0 | 1100 | 232 |
| 19 | 455 | 455 | 130 | 130 | 30 | 0 | 0 | 0 | 0 | 0 | 1200 | 132 |
| 20 | 455 | 455 | 130 | 130 | 162 | 33 | 25 | 10 | 0 | 0 | 1400 | 152 |
| 21 | 455 | 455 | 130 | 130 | 85 | 20 | 25 | 0 | 0 | 0 | 1300 | 197 |
| 22 | 455 | 455 | 0 | 0 | 145 | 20 | 25 | 0 | 0 | 0 | 1100 | 137 |
| 23 | 455 | 425 | 0 | 0 | 0 | 20 | 0 | 0 | 0 | 0 | 900 | 90 |
| 24 | 455 | 345 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 800 | 110 |

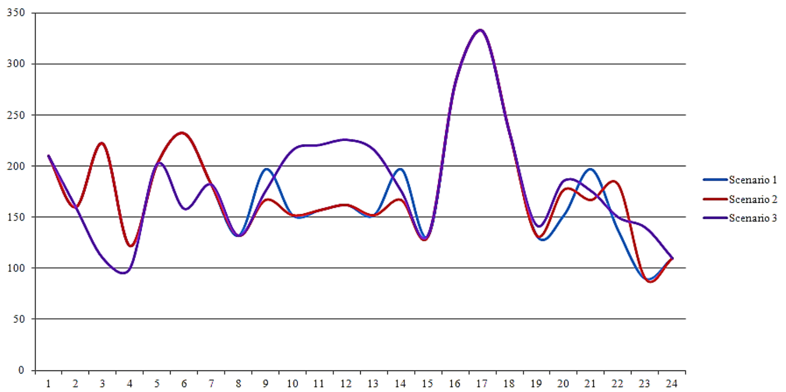


Figure 2. The value of spinning reserve for different scenarios

Table 4. Schedule and dispatch of generating units for Scenario 2

| Hour | $P_1$ (MW) | $P_2$ (MW) | $P_3$ (MW) | $P_4$ (MW) | $P_5$ (MW) | $P_6$ (MW) | $P_7$ (MW) | $P_8$ (MW) | $P_9$ (MW) | $P_{10}$ (MW) | Demand (MW) | Spinning reserve (MW) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 455 | 245 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 700 | 210 |
| 2 | 455 | 295 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 750 | 160 |
| 3 | 455 | 370 | 0 | 0 | 25 | 0 | 0 | 0 | 0 | 0 | 850 | 222 |
| 4 | 455 | 455 | 0 | 0 | 40 | 0 | 0 | 0 | 0 | 0 | 950 | 122 |
| 5 | 455 | 390 | 0 | 130 | 25 | 0 | 0 | 0 | 0 | 0 | 1000 | 202 |
| 6 | 455 | 360 | 130 | 130 | 25 | 0 | 0 | 0 | 0 | 0 | 1100 | 232 |
| 7 | 455 | 410 | 130 | 130 | 25 | 0 | 0 | 0 | 0 | 0 | 1150 | 182 |
| 8 | 455 | 455 | 130 | 130 | 30 | 0 | 0 | 0 | 0 | 0 | 1200 | 132 |
| 9 | 455 | 455 | 130 | 130 | 100 | 20 | 0 | 10 | 0 | 0 | 1300 | 167 |
| 10 | 455 | 455 | 130 | 130 | 162 | 33 | 25 | 10 | 0 | 0 | 1400 | 152 |
| 11 | 455 | 455 | 130 | 130 | 162 | 73 | 25 | 10 | 10 | 0 | 1450 | 157 |
| 12 | 455 | 455 | 130 | 130 | 162 | 80 | 25 | 43 | 10 | 10 | 1500 | 162 |
| 13 | 455 | 455 | 130 | 130 | 162 | 33 | 25 | 10 | 0 | 0 | 1400 | 152 |
| 14 | 455 | 455 | 130 | 130 | 100 | 20 | 0 | 10 | 0 | 0 | 1300 | 167 |
| 15 | 455 | 455 | 130 | 130 | 30 | 0 | 0 | 0 | 0 | 0 | 1200 | 132 |
| 16 | 455 | 310 | 130 | 130 | 25 | 0 | 0 | 0 | 0 | 0 | 1050 | 282 |
| 17 | 455 | 260 | 130 | 130 | 25 | 0 | 0 | 0 | 0 | 0 | 1000 | 332 |
| 18 | 455 | 360 | 130 | 130 | 25 | 0 | 0 | 0 | 0 | 0 | 1100 | 232 |
| 19 | 455 | 455 | 130 | 130 | 30 | 0 | 0 | 0 | 0 | 0 | 1200 | 132 |
| 20 | 455 | 455 | 130 | 130 | 162 | 38 | 0 | 10 | 10 | 10 | 1400 | 177 |
| 21 | 455 | 455 | 130 | 130 | 100 | 20 | 0 | 10 | 0 | 0 | 1300 | 167 |
| 22 | 455 | 455 | 0 | 130 | 40 | 20 | 0 | 0 | 0 | 0 | 1100 | 182 |
| 23 | 455 | 425 | 0 | 0 | 0 | 20 | 0 | 0 | 0 | 0 | 900 | 90 |
| 24 | 455 | 345 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 800 | 110 |

Table 5. Schedule and dispatch of generating units for Scenario 3

| Hour | $P_1$ (MW) | $P_2$ (MW) | $P_3$ (MW) | $P_4$ (MW) | $P_5$ (MW) | $P_6$ (MW) | $P_7$ (MW) | $P_8$ (MW) | $P_9$ (MW) | $P_{10}$ (MW) | $N_{v2g}$ | $P_{v2g}$ (MW) | Demand (MW) | Spinning reserve (MW) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 455 | 245 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 700 | 210 |
| 2 | 455 | 295 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 750 | 160 |
| 3 | 455 | 370 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3922 | 25 | 850 | 110 |
| 4 | 455 | 360 | 0 | 130 | 0 | 0 | 0 | 0 | 0 | 0 | 784 | 5 | 950 | 100 |
| 5 | 455 | 390 | 0 | 130 | 25 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1000 | 202 |
| 6 | 455 | 455 | 0 | 130 | 31.85 | 0 | 0 | 0 | 0 | 0 | 4416 | 28.15 | 1100 | 158.3 |
| 7 | 455 | 410 | 130 | 130 | 25 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1150 | 182 |
| 8 | 455 | 455 | 130 | 130 | 30 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1200 | 132 |
| 9 | 455 | 455 | 130 | 130 | 78.125 | 20 | 0 | 0 | 0 | 0 | 5000 | 31.875 | 1300 | 175.75 |
| 10 | 455 | 455 | 130 | 130 | 143.125 | 20 | 25 | 10 | 0 | 0 | 5000 | 31.875 | 1400 | 215.75 |
| 11 | 455 | 455 | 130 | 130 | 162 | 41.125 | 25 | 10 | 10 | 0 | 5000 | 31.875 | 1450 | 220.75 |
| 12 | 455 | 455 | 130 | 130 | 162 | 80 | 25 | 11.125 | 10 | 10 | 5000 | 31.875 | 1500 | 225.75 |
| 13 | 455 | 455 | 130 | 130 | 143.125 | 20 | 25 | 10 | 0 | 0 | 5000 | 31.875 | 1400 | 215.75 |
| 14 | 455 | 455 | 130 | 130 | 78.125 | 20 | 0 | 0 | 0 | 0 | 5000 | 31.875 | 1300 | 175.75 |
| 15 | 455 | 455 | 130 | 130 | 29.4 | 0 | 0 | 0 | 0 | 0 | 94 | 0.6 | 1200 | 133.2 |
| 16 | 455 | 310 | 130 | 130 | 25 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1050 | 282 |
| 17 | 455 | 260 | 130 | 130 | 25 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1000 | 332 |
| 18 | 455 | 360 | 130 | 130 | 25 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1100 | 232 |
| 19 | 455 | 455 | 130 | 130 | 25 | 0 | 0 | 0 | 0 | 0 | 784 | 5 | 1200 | 142 |
| 20 | 455 | 455 | 130 | 130 | 158.125 | 20 | 0 | 10 | 10 | 0 | 5000 | 31.875 | 1400 | 185.75 |
| 21 | 455 | 455 | 130 | 130 | 78.125 | 20 | 0 | 0 | 0 | 0 | 5000 | 31.875 | 1300 | 175.75 |
| 22 | 455 | 365 | 130 | 130 | 0 | 20 | 0 | 0 | 0 | 0 | 0 | 0 | 1100 | 150 |
| 23 | 455 | 425 | 0 | 0 | 0 | 20 | 0 | 0 | 0 | 0 | 0 | 0 | 900 | 140 |
| 24 | 455 | 345 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 800 | 110 |

### B. Scenario 2

The result of scenario 2 is presented in Table 4. As shown in Table 4, by adding spinning reserve cost term to the objective function, committed hours of unit 7, which is most expensive unit decreases significantly. In scenario 1 at hours 9 and 14 for supplying spinning reserve requirement unit 7, which is more expensive and has ability to produce more power than units 8 to 10 has been turned on. But in scenario 2 and by adding cost term of spinning reserve to objective function at hours 9 and 14, unit 8 which is less expensive than unit 7 has been turned on, consequence has been happened at hours 20 to 22 too.

### C. Scenario 3

Table 5 presents results of scenario 3. As it can be seen from Table 5, by integrating 50000 PEVs, committed hours of units 5, 8 and 10, which are relatively expensive decreases significantly. In addition, total generation of unit 6 reduces. According to Tables 3 and 4 at hour 3 unit 5 has been turned on to supply spinning reserve but as it can be seen from Table 5 at hour 3 generating 25 MW by PEVs causes to turn unit 5 off. Figure 2 demonstrates the values of spinning reserve for different scenarios.

As it can be seen from this figure by integrating PEVs the amount of spinning reserve at hours 9 to 14 increases significantly which leads to improvement of reliability. Therefore, it can be concluded that the spinning reserve is higher in the attendance of PEVs through the parking lot in the UC problem, which shows the effectiveness of V2G parking lot consideration in the reserve market and its role in maintaining reliability of the power system.

Table 6 shows the result of the proposed methodology for different scenarios. As it can be seen from this Table, by adding spinning reserve cost term to the objective function of UC problem (scenarios 2 and 3), spinning reserve cost decreases significantly. Also total costs of Scenario 3 is lower than other scenarios which shows the effectiveness of integrating PEVs for decreasing total operation costs.

Table 6. The operating, spinning, and total costs of proposed method for different scenarios

| Cost ($) | Scenario 1 | Scenario 2 | Scenario 3 |
|---|---|---|---|
| Operating | 562838.2 | 563171.4 | 559346 |
| Spinning reserve | 8985.442 | 8861.61 | 7578.127 |
| Total | 571823.6 | 572033 | 566924.2 |

Table 7 shows a comparison between results of scenarios one with recent methods addressed in literature. As Table 7 shows, the proposed approach produces better results than other methods.

Table 7. Comparison of total cost of the proposed method with recent researches for 10-unit system

| | Methods | | Scenario 1 | Methods | | Scenario 1 |
|---|---|---|---|---|---|---|
| Total Cost ($) | Proposed method | Best | - | SFLA [25] | Best | - |
| | | Worst | - | | Worst | - |
| | | Average | 562838.2 | | Average | 564769 |
| | PSO [23] | Best | 563741.8 | LR [26] | Best | 565825 |
| | | Worst | 565443.3 | | Worst | - |
| | | Average | 564743.5 | | Average | - |
| | ICGA [27] | Best | - | EP [28] | Best | 564551 |
| | | Worst | - | | Worst | 566231 |
| | | Average | 566404 | | Average | 565352 |
| | LRGA [29] | Best | - | HPSO [30] | Best | 563942 |
| | | Worst | - | | Worst | 565785 |
| | | Average | 564800 | | Average | 564772 |
| | GA [26] | Best | 565825 | LS [31] | Best | - |
| | | Worst | 570032 | | Worst | - |
| | | Average | - | | Average | 564970 |

## IV. CONCLUSIONS

In this paper, an involving integration of PEVs and spinning reserve cost term to the unit commitment problem has been presented. This complex mixed integer nonlinear problem has been linearized, modeled and solved by GAMS software. The proposed model has been successfully applied to IEEE 10-unit system. From the results obtained, it can be concluded that integrating PEVs reduces the operation costs significantly. Also the proposed methodology demonstrates the capability of V2G to improve power system reliability.

## NOMENCLATURES

$a_i$, $b_i$, $c_i$ : Fuel cost coefficients of unit $i$
$bm_i$ : Slope of segment $m$ in linearized fuel cost curve
$CSH_i$ : Cold start hour of $i$th unit
$CS$ : Cold startup cost of $i$th unit
$D^t$ : Load demand at time $t$
$F_i(P_i^t)$ : Fuel cost function
$F_i^{\min}$ : Lower limit on the fuel cost of a unit
$h$ : Scheduling hours
$HS$ : Hot startup cost of $i$th unit
$MU_i$ / $MD_i$ : Minimum up/down time of unit $i$
$N$ : Number of units
$N_{dsch}^t$ : Number of vehicles that discharge when connected to the grid at hour $t$
$N^{\max}$ : Total vehicles in the system
$N_{dsch}^{\min}$ : Minimum number of discharging vehicles at hour $t$
$N_{dsch}^{\max}$ : Maximum number of discharging vehicles at hour $t$
$NSF(i)$ : Number of segments for the piecewise linearized fuel cost curve
$P_i^t$ : Output power of $i$th unit at time $t$
$P_i^{\min}$ / $P_i^{\max}$ : Maximum/minimum output limit of $i$th unit
$Pm_i^t$ : Generation of segment $m$ in linearized fuel cost curve
$PR_i^t$ : Bidding price for spinning reserve of unit $i$ at time $t$
$pv$: Capacity of each vehicle
$R^t$ : System reserve requirement at hour $t$
$RU_i$ / $RD_i$ : Ramp up/down rate of unit $i$
$SPC_i^t$ : Spinning reserve cost of unit $i$ at time $t$
$SR_i^t$ : Value of spinning reserve supply by unit $i$
$SUC_i$ : Startup cost of unit $i$
$SDC_i$ : Shutdown cost of unit $i$
$u_i^t$ : $i$th unit status at hour $t$ (1/0 for on/off)
$XU_i^t$ : Duration of continuously on of unit $i$ at time $t$
$XD_i^t$ : Duration of continuously off of unit $i$ at time $t$
$\eta$ : Efficiency
$\delta$ : State of charge

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