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INVESTIGATION OF SIMULTANEOUS DEMAND RESPONSE RESOURCES AND VEHICLES TO GRIDS IMPACTS ON UNIT COMMITMENT

S. Mobasheri M. Tabrizi A. Khajehzadeh H. Zayandehroodi

Department of Electrical Engineering, Kerman Branch, Islamic Azad University, Kerman, Iran
sahar.mobasheri@yahoo.com, mahla_tabrizi@yahoo.com, alikhajezadeh@yahoo.com, hadi.zayandehroodi@yahoo.com

Abstract- In recent years, load management (LM) programs are contemplated as a crucial option in all energy policy decisions. Under deregulation, the scope of LM programs has considerably been expanded to include demand response (DR) programs. Here, the DR programs are regarded as a virtual resource for reserve provision. Furthermore, Vehicle to Grids (V2Gs) as one of the new technology can reduce dependencies on small expensive units in new environment which can be used as energy storage. Unit Commitment (UC) scheduling of generating units is addressed as a short-term generation scheduling in power system studies which is affected by DR programs as well as charging/discharging scheme of V2Gs. In this paper, a new structure for UC scheduling associated with DR program and V2Gs are suggested. In order to scrutinize the economic- and environmental-driven measures of DR programs and V2Gs, a new linearized formulation of cost-emission based unit commitment problem is presented. Here, the proposed framework is structured as a mixed-integer programming (MIP) problem and solved using CPLEX solver. This model would schedule reserves provided by Demand Response Programs (DRPs), and commitment status of generating units. Values of energy and reserves over the scheduling time horizon are also determined simultaneously in this paper. The standard IEEE-10 unit system is utilized to demonstrate the effectiveness of the proposed structure to declines emissions as well as expenditures.

Keywords: Demand Response Programs (DRPs), Vehicle to Grids (V2Gs), Unit Commitment, Energy and Reserve Scheduling, Economic and Environmental Measures.

I. INTRODUCTION

The International Energy Agency (IEA) introduces demand side activities as the first option in all energy policy decisions due to affecting on operation, economic and emissions levels. Under restructured power systems, the scope of demand side management is developed to demand response (DR) programs. The DR is a program which is established to change electric use by demand-side resources from their normal consumption patterns in response to changes in the price of electricity, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized.

Demand response [1] programs provide many potential benefits such as cost and emission reduction, decline of overseas fuel dependency, power system reliability improvement as well as increasing revenues due to differing commitment of units. According to Federal Energy Regulatory Commission (FERC), DR programs had been classified into two major categories namely time-based rate (TBR) and incentive-based programs (IBPs). More detailed explanations of demand response programs are provided in [2].

Moreover, renewable energy resources play an important role in new smart environment due to capability of reducing emitted pollutions as well as fossil fuels consumption. One of the main policies is utilizing the energy storage of Vehicles to Grids (V2Gs) in electricity sector. In fact, V2Gs as portable source of electricity storages have undeniable benefits through intelligent charging and discharging scheme in a smart grid environment.

Optimal charging and discharging scheme of V2Gs provides many potential such as load curve flattening, minimizing load curtailment by discharging V2Gs in peak time and charging at off-peak periods, decreasing dependencies on small expensive units, reducing emissions, and decreasing operation expenditures [3-4]. V2Gs are also useful for ancillary services such as supplying spinning reserve to improving reliability as well as energy efficiency and frequency regulation due to their fast responsiveness [5-6].

In order to scrutinize the economic and environmental benefits of demand side programs as well as vehicles to grids, the cost-emission based unit commitment scheduling associated with DR programs and V2Gs is addressed in this paper. Unit Commitment (UC) is an important issue in power system studies, where it determines when to start-up or shut-down units and how to dispatch online generators over a given scheduling horizon to minimize the operating costs, satisfying the prevailing constraints such as power balance, system reserve requirement, ramp rate limits, & min. up/down time limits.

Several deterministic, heuristic, and hybrid methods have been proposed in the last decades for solving the UC as a large scale, non-convex, and mixed-integer combinatorial optimization problem [7-8]. Deterministic methods in general are unable to find a solution within the available time frame, when the problem is medium or large size. These limitations have been redounded to introduce the heuristic methods [9-10]. Heuristic optimization algorithms may have some advantages to solve such a complicated optimization problem, while the main drawback of heuristic methods is that they cannot guarantee the optimal solution [11]. Since there exists a need for more improvement to the existing unit commitment solution techniques, hybrid methods have been experienced [12-13]. Currently, in most cases general algebraic modeling system (GAMS) commercial solver is utilized to solve such complicated problems [2-14].

This paper investigates the impacts of DR programs as well as V2Gs on unit commitment problem. Here, DR programs are contemplated as virtual resources to procure system reserve necessity in PMS problem. Moreover, it is assumed that V2Gs are charged via renewable resources which imposed no expenditures to the system. In fact, V2Gs are merely considered as a storage source in the system. Therefore, a new cost-emission based structure for unit commitment scheduling problem associated with market-based DR programs and V2Gs is presented. Besides the prevailing constraints of UC problem and V2Gs limitations, maximum load curtailment per day and the potential of implementing demand response program per period are also considered as DR limits.

The proposed framework determines commitment status of generating units, energy and reserve scheduling, demand side reserve scheduling and V2Gs discharging scheme so that the system total expenditures as well as emission are both minimized over the scheduling time horizon. The suggested framework is developed as a combinatorial optimization problem which is linearized and structured as a mixed integer programming (MIP) problem. The advantages of MIP method include global optimality, direct measure of the optimality of a solution and more flexible and accurate modeling capabilities. Here, CPLEX as a sophisticated and computationally efficient MIP solver is applied for solving the proposed model [15].

The rest of this paper is organized as follows. Section II provides the MIP based structure of unit commitment scheduling associated with DR programs as well as V2Gs. Section III conducts the numerical simulations and finally, the concluding remarks are explained in section IV.

II. MODEL DESCRIPTION AND FORMULATION

In the proposed structure, the crucial point is to link demand- and supply-side resources to the unit commitment in a way that the economic and environmental benefits of DR programs as well as V2Gs are observable. Here, the characteristics of generating units, vehicle to Grids, as well as signed contracts to participate in demand response programs are submitted to the ISO. The ISO runs the UC associated with DRRs as well as V2Gs over the scheduling time horizon while the system total cost and emission are both minimized. The suggested framework determines the commitment status of generating units, energy and reserve scheduling, V2Gs cooperation in demand satisfaction, as well as offers of DR programs participants to procure system reserve simultaneously. Here, an alternative mixed-integer programming formulation, suitable for available MIP software is presented for the suggested structure. One of the main features of the MIP method includes direct measure of optimality of a solution and more flexible and accurate modeling capabilities. The employed optimization software is General Algebraic Modeling System (GAMS) and CPLEX as a commercial and computationally efficient MIP solver is used for solving the problem.

The linearized objective function for the proposed framework is presented as:

Minimize O.F.

$$w_c\begin{pmatrix} Cost_{OP}+Cost_{ST}+ \\ Cost_{RE}+Cost_{DR} \end{pmatrix}+w_e\left(Emitted_{PO}\right) \quad (1)$$

where: $w_e+w_c=1$

where, w_c and w_e are considered to include or exclude cost and emission in the objective function. More explanations about each parameter of the objective function are outlined in the following.

A. Fuel Cost [19]

The quadratic fuel cost function utilized in scheduling problems is formulated as Equation (2).

$$Cost_{OP}:\sum_{t=1}^{T}\sum_{i=1}^{N_G}\left(a(i)+b(i)P(i,t)+c(i)P^2(i,t)\right) \quad (2)$$

Equation (2) can be correctly approximated by a set of piecewise blocks which can't be recognizable from the nonlinear model if enough segments are utilized. An analytic representation of the piecewise linear function is provided in Equation (3).

$$Cost_{OP}:\sum_{t=1}^{T}\sum_{i=1}^{N_G}\left(\underline{F}(i)u(i,t)+\sum_{m=1}^{N_{SF}}P_m(i,t)b_m(i)\right) \quad (3)$$

In Equation (3), the *i*th unit on/off status is symbolized by $u(i,t)$ which is one when the generator is on and otherwise it takes zero. The start-up cost is related to either hot or cold conditions, where it can be written as:

$$Cost_{ST}:\left[1-u(i,t-1)\right]\begin{cases} HSC(i);\ \text{if}:T_{i,t}^{D}\le MD_i^{ON}\le T_{i,t}^{D}+C_i^{ST} \\ CSC(i);\ \text{if}:\ T_{i,t}^{D}>T_{i,t}^{D}+C_i^{ST} \end{cases} \quad (4)$$

The reserve provision expenditure in *i*th unit is symbolized by $\pi(i)$. Each unit participation level in reserve provision, i.e. $url(i,t)$, is determined so that the system total expenditure and emission are both minimized.

$$Cost_{RE}:\sum_{t=1}^{T}\sum_{i=1}^{N_G}url(i,t)\pi(i) \quad (5)$$

A mixed-integer model of the DR program bid-quantity is presented in Equation (6). The minimum customers' participation level in DR programs, i.e. $\underline{\sigma}(t)$, should be greater than the minimum curtailment level of the DR programs which is specified by the ISO. The status of customers' offer package to cooperate in DR programs at point ν is labeled as $\vartheta(\nu,t)$ which is one when the point is scheduled by the ISO and otherwise takes zero. The discrete DR reserve levels are symbolized by $\lambdabar(\nu,t)$ with the associated cost of $\lambdabar(\nu,t)$.

$$Cost_{DR}:\ \sum_{t=1}^{T}\left(\underline{\lambdabar}(t)\underline{\sigma}(t)\underline{\vartheta}(t)+\sum_{\nu=1}^{N_{SDR}}\sigma(\nu,t)\lambdabar(\nu,t)\vartheta(\nu,t)\right) \tag{6}$$

where: $\hbar_{DR}(t)=\underline{\sigma}(t)\underline{\vartheta}(t)+\sum_{\nu=1}^{N_{SDR}}\sigma(\nu,t)\vartheta(\nu,t).$

Emission effect is taken into consideration for environmental friendly power production [18]. Typically, emissions produced by generating units are presented as a polynomial function of their power production. In this paper, quadratic function is considered for the emission curve as Equation (7).

$$Emitted_{PO}:\sum_{t=1}^{T}\sum_{i=1}^{N_G}\left(\alpha(i)+\beta(i)P(i,t)+\gamma(i)P^2(i,t)\right) \tag{7}$$

Emission function can also be accurately approximated by a set of piecewise blocks. The analytic representation of this linear approximation is similar to (3) and formulated as Equation (8).

$$Emitted_{PO}:\sum_{t=1}^{T}\sum_{i=1}^{N_G}\left(\underline{e}(i)u(i,t)+\sum_{m=1}^{N_{SE}}\Upsilon_m(i,t)e_m(i)\right) \tag{8}$$

B. Economic Unit Commitment Constraints

The objective function is subjected to the following constraints.

○ Power balance: Generated power from committed units must satisfy the required demand and system losses. $\hbar_{DR}(t)$ is considered as the customers participation level in market-based DR programs.

$$\sum_{i=1}^{N_G}P(i,t)+P_v(t)N_{v2g}(t)=P_D(t)-\hbar_{DR}(t) \tag{9}$$

○ Power generation constraint:

$$\underline{P}(i)u(i,t)+\sum_{m=1}^{N_{SF}(i)}P_m(i,t)\le\bar{P}(i)u(i,t)-url(i,t) \tag{10}$$

○ Reserve Constraint:

$$\sum_{i=1}^{N_G}u(i,t)\bar{P}(i)+P_{v\max}N_{v2g}(t)\ge P_D(t)-\hbar_{DR}(t)+SR(\mathrm{t}) \tag{11}$$

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

$$\begin{aligned}&P(i,t)-P(i,t-1)\le u(i,t)\{1-u(i,t-1)\}\underline{P}(i)+\\&+\left[1-u(i,t)\{1-u(i,t-1)\}\right]RU(i)\end{aligned} \tag{12}$$

$$\begin{aligned}&P(i,t-1)-P(i,t)\le u(i,t-1)\{1-u(i,t)\}\underline{P}(i)+\\&+\left[1-u(i,t-1)\{1-u(i,t)\}\right]RD(i)\end{aligned} \tag{13}$$

○ Minimum up/down time [19]: Once a unit is committed, it must remain "on" for a minimum number of hours, and accordingly if a unit is shutdown, it must remain "off "for a minimum number of hours given in (14).

$$\begin{aligned}&\left\{X_{ON}^{i}(t-1)-T_{ON}^{i}\right\}\left(u(i,t-1)-u(i,t)\right)\ge 0\\&\left\{X_{OFF}^{i}(t-1)-T_{OFF}^{i}\right\}\left(u(i,t)-u(i,t-1)\right)\ge 0\end{aligned} \tag{14}$$

C. Vehicle to Grids Constraints

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

$$\sum_{t=1}^{T}N_{v2g}(t)=NT_{v2g}^{\max} \tag{15}$$

○ Parking lots limitation: Due to limited parking lot's capacity, maximum number of V2Gs which can be in parking lots per period is limited.

$$N_{v2g}(t)\le N_{v2g}^{\max}(t) \tag{16}$$

○ Charging/discharging frequency is assumed once a day.

○ Integrated efficiency for charging/discharging plus inverter is defined by ξ.

○ Each vehicle should have a desired departure State of Charge (SOC) level which symbolized by ψ.

D. Demand Response Constraints

○ The amount of load curtailment at a period must be lower than the pre-specified level.

$$\hbar_{DR}(t)\le\eta(t) \tag{17}$$

○ The customers' participation level in DR programs per year, i.e. $\bar{D}_{LC}$, is restricted as Equation (18).

$$\sum_{t=1}^{T}\hbar_{DR}(t)\le\bar{D}_{LC} \tag{18}$$

III. SIMULATION RESULTS AND DISCUSSIONS

In this study, a standard IEEE 10-unit system has been utilized for simulation studies and the peak load is considered equal to 1500 MW. The fuel cost and emissions curves for generating units given as a quadratic function are approximated by twenty linear segments between the minimum and maximum generating units' capacity. More required data including operating insights of the generating units are provided in [2].

Spinning reserve requirement is assumed to be 10% of the hourly load demand in 24 h scheduling time period. The potential of implementing DR programs, i.e. $\eta(t)$, is considered 5% of the total load in per period. The daily load curtailment is assumed equal to 3% of the total daily load. The offer packages are presented in Table I. DRPs data are composed of three discrete points, i.e. 33%, 66%, and 100% of the total response of the customers [16]. The number of available V2Gs in system is considered equal to 50000.

Moreover, according to [14], the following parameters are presumed for V2Gs: maximum battery capacity 25 kWh; minimum battery capacity 10 kWh; average battery capacity 15 kWh; charging/discharging frequency 1 per day; departure state of charge 50%; total efficiency 85%. It should be mentioned that V2Gs are charged via renewable resources which causes to have no operating costs for V2Gs [17].

Table 1. Demand Response Programs' offer package

ν	$\sigma(\nu)$	$\bar{\lambda}(\nu)$
0	33% of total Response	11
1	66% of total Response	12
2	100% of total Response	13

The following case studies are conducted to investigate the impacts of demand response programs as well as V2Gs on unit commitment scheduling. A trade-off between cost and emission minimization is considered. Multifarious weighting factors can be assigned for cost and emission which depend on the system operator demand. Here, w_e and w_c are both considered equal to 0.5 in Equation (1).

In case #1, the unit commitment scheduling is addressed without considering vehicles to girds as well as DR programs. In the second case, case #2, the V2Gs impact is contemplated while DR programs are disregarded. Finally V2Gs as well as DR programs are evaluated in case #3.

Applying CPLEX 12.4.0 [15], system operating expenditures, reserve cost, DR expenditures, as well as emissions are provided in Table 2, for cases #1, #2 and #3. It can be concluded from Table 2 that V2Gs and DR programs causes to decrease system expenditure, considerably. The system total expenditures in cases #2 and #3 is decreased 1.83% and 6.02% in comparison with case #1. Furthermore, the emissions is declined in case #2 in comparison with case #1, while the emission is increased in case #3 in comparison with case #1 due to emission and cost coefficients.

The participation level of V2Gs in demand satisfaction in cases #2 and #3 over the time horizon is presented in Table 3. Referring to Table 3, it is concluded that V2Gs participation is more in peak periods in comparison with other ones.

Table 2. Total expenditures and emissions in cases #1, #2 and #3

	Scenario 1	Scenario 2	Scenario 3
generation	574207.693	562816/03	540470.97
Power reserve	46207.329	46217.855	35061.28
resource DR	---	---	7518.575
Total reserve	46207.329	46217.855	42579.855
Total system	620415.022	609033.885	583050.825
Emissions	22445.58	22313.418	23341.621
target	321430.301	315673.651	303196.223

Table 3. V2Gs cooperation level in demand satisfaction (MW)

hour	Scenario 2	Scenario 3	hour	Scenario 2	Scenario 3
3	25	25	13	31.875	31.875
4	5	5	14	31.875	31.875
6	13.75	24	15	---	9.75
9	31.875	31.875	20	31.875	31.875
10	31.875	31.875	21	31.875	31.875
11	31.875	31.875	22	20	---
12	31.875	31.875			

The participation level of customers as well as share of generating units in system reserve provision in case #3 are provided in Table 4. All the reservation level is supplied by conventional generating units during off-peak periods since the customers do not participate in DR programs. Demand response resources satisfy part of the system reserve during the peak periods to decline the system expenditures. As an example, the required reservation level is equal to 110 MW in period #6, while 18.15 MW, i.e. 16.5%, of the system reservation level is supplied by DRRs and the remained part is procured via conventional units in hour #6.

Utilizing demand response programs, consumers' consumption is altered during the time. The load curve of IEEE-10 unit system before and after implementing DR programs is displayed in Figure 1.

Table 4. Participation level (%) of DRRs and generating units in reserve procurement

hour	Unit	DR	hour	Unit	DR
1	100	---	13	50	50
2	100	---	14	58.55	41.45
3	100	---	15	19.48	80.52
4	100	---	16	100	---
5	100	---	17	100	---
6	83.5	16.5	18	100	---
7	83.5	16.5	19	79.22	29.87
8	76.5	23.5	20	50	50
9	58.55	41.45	21	58.55	41.45
10	50	50	22	83.5	16.5
11	50	50	23	100	---
12	50	50	24	100	---

As shown in Figure 1, the participation of customers in peak periods is more in comparison with the other periods in order to decline the system total cost more tangible.

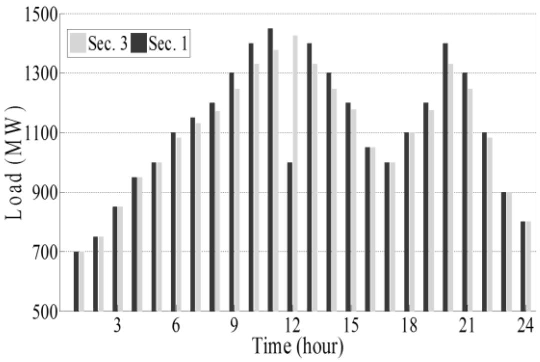

Figure 1. The impact of DR programs on load profile

In the following, the generation pattern and reserve scheduling of generating units for the maximum level of demand are examined in Figures 2 and 3, respectively in cases #1, #2 and #3. Referring to Figure 2, it is concluded that the generation pattern of generating units is nearly similar in cases #1 and #2, and merely the generation pattern in 7th and 10th units are different. This issue is because of V2Gs' participation in demand satisfaction in case #2. However, due to simultaneous presence of V2Gs and DRRs, the generation pattern is completely different in case #3 in comparison with other cases.

The generation level of economical units, i.e. 1st and 2nd units, and most expensive units, i.e. 7th to 9th units, are respectively increased and decreased in case #3 in comparison with cases #1 and #2. Furthermore, referring to Figure 3, the reservation level of generating units in case #3 are declined considerably in comparison with cases #1 and #2 due to participation of customers, i.e. 75 MW, in DR programs in the peak period.

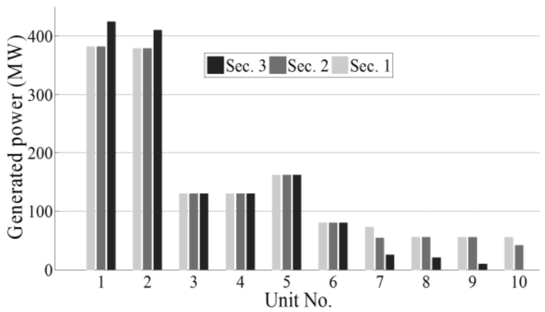

Figure 2. Generation units participation in demand satisfaction in peak period

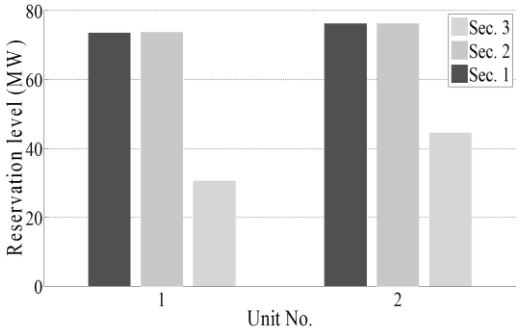

Figure 3. Generating units participation in reserve provision in peak period

IV. CONCLUSIONS

This paper makes a bridge between unit commitment problem and vehicles to girds as well as demand response resources by introducing new structure. In this paper, demand side resources have been introduced as a virtual resource to provide system reserve requirement. Furthermore, discharged power of V2Gs is also contemplated as virtual power plant to procure portion of requested demand.

Here, in order to investigate the economic and environmental driven measures of demand response programs as well as vehicles to grids, a new MIP-based structure for cost-emission based unit commitment scheduling associated with DR programs has been suggested. Utilizing the proposed framework; commitment status of generating units, energy and spinning reserve scheduling as well as scheduled reserve of DRPs and V2Gs discharging scheme are simultaneously determined over the scheduling horizon.

The applicability of the proposed model has been illustrated using the standard IEEE 10-unit system. It is concluded that implementing DR programs as well as V2Gs discharging scheme reduce the system total cost as well as produced emission considerably. Demand response resources also affect commitment scheme of power plants.

NOMENCLATURES

$a(.), b(.), c(.)$: Fuel cost coefficient

$b_m(.)$: Slope of *m*th segment in linearized fuel cost curve

$CSC(.)$ Cold start-up cost of a unit

$\bar{\lambda}(.)$: Capacity cost in a point of DRPs in a period

$\hbar_{DR}(.)$: Scheduled reserve of a demand response programs in a period

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

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

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

$HSC(.)$: Hot start-up cost of a unit

i : Unit index

$\sigma(.)$: Demand response level in a point of offer package in a period

m : Segment index for linearized fuel cost and emission curves

N_G : Number of generating units

N_{SDR} : Number of discrete points in offer package

N_{SF} : Number of segment for the piecewise linearized fuel cost curve

N_{SE} : Number of segment for the piecewise linearized emission curve

$N_{v2g}(.)$: Number of vehicles that discharging connected to the grid at a period

$N_{v2g}^{\max}(.)$: Maximum number of discharging vehicles in a period

$NT_{v2g}^{\max}$: Total vehicles in the system

$P(.)$: Output power of a unit in a period

$P_D(.)$: Load demand of a bus in a period

$\bar{P}(.) / \underline{P}(.)$: Maximum / minimum generating capacity of a unit

$P_m(.)$: Generated power in *m*th segment of linearized fuel cost curve

$RU(.) / RD(.)$: Ramp up/down rate of a unit

$SR(.)$: System reserve requirement in a period

t : Period index

T : Scheduling time horizon

$u(.)$: Commitment status of a unit in a period

$url(.)$: Unit reservation level in reserve acquisition in a period

w_c, w_e : Weighting coefficient for generating cost / emission in objective function

$\bar{D}_{LC}$: Maximum daily load curtailment

$\alpha(.), \beta(.), \gamma(.)$: Emission coefficient of a unit

$\Upsilon_m(.)$: Generation of *m*th segment in linearized emission curve

$\vartheta(.)$: Binary variable associated with a point offer package

$\pi(.)$: Offered capacity cost of a unit for providing system reserve

$\eta(.)$: The potential of DRPs implementation

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BIOGRAPHIES

Sahar Mobasheri received the B.Sc. degree in Electronic Engineering from Shahid Bahonar University of Kerman, Kerman, Iran in 2011. She is currently pursuing the M.Sc. degree in Electrical Engineering from Kerman Branch, Islamic Azad University, Kerman, Iran. Her research interests include power system optimization, economic, energy management, and smart grids.

Mahla Tabrizi received the B.Sc. degree in Electronic Engineering from Kerman Branch, Islamic Azad University, Kerman, Iran in 2009. She is currently pursuing the M.Sc. degree in Electrical Engineering in the same university. Her research interests are power system and distributed generation.

Alimorad Khajehzadeh received the Ph.D. from University of Technology of Malaysia, Malaysia. He has been a Faculty Member in Dept. of Electrical Engineering at Kerman Branch, Islamic Azad University, Kerman, Iran. His main research interests are power electronics, optimization and planning in power system.

Hadi Zayandehroodi received the Ph.D. in Power Systems Engineering from National University of Malaysia, Malaysia in 2011. Since 2004, he has been a Faculty Member in Department of Electrical Engineering at Kerman Branch, Islamic Azad University, Kerman, Iran. His main research interests are power system protection, power management and distributed generation.