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# UNIT COMMITMENT CONSIDERING POSITION OF INTERRUPTIBLE LOAD IN ENERGY AND RESERVE SIMULTANEOUS MARKET

**M. Yousefi Ramandi [1] K. Afshar [2] N. Bigdeli [2]**

*1. Iran Grid Management Company, Tehran, Iran, yousefi.m@igmc.ir*
*2. Electrical Engineering Department, Imam Khomeini International University, Qazvin, Iran*
*afshar@ikiu.ac.ir, bigdeli@ikiu.ac.ir*

**Abstract-** In this paper security constrained unit commitment (SCUC) is employed for simultaneous clearing of energy and reserve markets. Spinning reserve of production units and interruptible loads (IL) are used as system operation reserve. Some restrictions on the use of interruptible loads, such as maximum load curtailed, maximum curtailment hour in a day, maximum length of each curtailment are also considered. Expected energy not supplied (EENS) is considered as a criterion for undesirable load shedding of system and a method is proposed for EENS calculation in presence of interruptible load in the stochastic model. In the proposed model, a two-stage stochastic mixed integer programming (SMIP) is used for considering the uncertainties of the power system. The goal of this program is the unit commitments with their energy production and the scheduled spinning reserve for each production unit and IL for the next day. Monte Carlo simulation is implemented for scenario generation for various production units and transmission lines random outages, the uncertainties in load prediction and refusal of the IL from ISO instructions. Next, the backward scenario reduction method is used for computational burden reduction where the problem accuracy remains desirable. Impact of IL location has been studied on the system reliability, too. It is shown that the IL location will be effective on the power flow of transmission lines at critical moments, congestion and increasing of marginal price. The proposed model is applied to the IEEE reliability test system (IEEE-RTS) to demonstrate its effectiveness.

**Keywords:** Simultaneous Energy and Reserve Market, Interruptible Load Location, Security Constrained Unit Commitment (SCUC), Two-Stage Stochastic Programming, Expected Energy Not Supplied (EENS).

## I. INTRODUCTION

### A. Motivation and Problem Description

In the last thirty years, the demand side management (DSM) solutions used as a way to reduce energy consumption. Traditionally, DSM programs focused on energy efficiency and energy saving programs with the goal of improving system reliability, especially during a network fault [1]. The experiments have shown that with participation of the demand side, electricity markets become more competitive and more efficient and also increases the overall reliability of the power system [2]. In a competitive environment, the independent system operator (ISO) is responsible for managing and clearing of markets. The energy and reserve markets can be cleared by ISO in two ways, which are the sequential dispatch and the simultaneous dispatch [3].

In the sequential method, the determination of market product (energy and reserve) is based on a priority list. In this method, at first, the amount of energy is cleared and next, the reserve market is cleared. Theoretical analyses and practical experiments have shown that this method leads to price reversals (inversions) [4]. In contrast, the simultaneous dispatch of energy and reserve not only prevents the occurrence of price reversals, but also reaches more optimal values of the answer.

### B. Literature Review

As mentioned previously, there are two methods for market clearing of energy and reserve. In [5] and [6] the problems of sequential dispatch have been reviewed and general topic of simultaneous markets for energy and reserve have been emphasized. Ref. [7] is a preceding article in simultaneous energy and reserve markets dispatch that is about demand side bidding. In this ref., initially problems of sequential planning schemes have been discussed and then a simultaneous scheduling model of energy and reserve market has been proposed.

In the later years, this plan has been used by other researchers [8-10].The simultaneous dispatch of energy and reserve markets has been employed by various markets in Ontario [11], New Zealand [12], NYISO [13], PJM [14], ISO-NE [15], and the new California [16] electricity markets, yet. Although, the deterministic criterion is a common method for determination of system required reserve, but it does not consider the uncertainty of power system. As a result, it is difficult to determine the amount of operating risk level. Probabilistic methods can provide a realistic evaluation of the actual amount of risk with consideration of the stochastic behavior of the system components [17-18].

In the recent years, various methods have been proposed for considering the operation reserve in the unit commitment (UC) program [19, 20]. In [21], the authors determined the amount of the unit commitment risk considering the probability of not meeting the load. In [22], the probabilistic nature of units outage rate in providing reserve has been considered, for the first time. Ref. [23] solved the UC problem based on priority list (PL). However, proposed method is capable to consider multi-type operating reserves and system uncertainty of the power system.

However, this method is not suitable for a restructured environment. In [24], the spinning reserve determining and the UC problem has been considered, simultaneously. The problem has been solved via Lagrangian relaxation (LR) approach. In [25], a pool market clearing process with a probabilistic reserve determination has been proposed. In this research, the reliability criteria such as loss of load probability (LOLP) and expected load not served (ELNS) for determination of reserve requirement have been considered.

In [26-28] the electricity market clearing based on security constrained unit commitment (SCUC) with stochastic criteria has been introduced. In this method, both costs of normal state and contingencies in emergency situations in objective function as well as a series of pre-defined events and system load shedding in critical situations have been considered. In [29] a method has been provided based on Bender's Decomposition for solving the SCUC problem. Where, the SCUC problem is divided into a main problem of production unit commitment program and two sub problems to satisfy the constraints of the transmission network in steady-state and emergency.

In addition, the method provided in [30] reduced the time of proposed method in [29] that made possible to be used in the large power systems. In [31], the force outage rate of production units and the uncertainty of the load forecast for determination of spinning reserve in SCUC has been considered and simulated annealing (SA) algorithm has been employed to solve problem. In [32] a method has been presented to make a balance between costs of providing spinning reserve against its benefits.

Many utilities have realized that interruptible loads can help to release the system energy in peak hours of consumption [33]. On the other hand, interruptible load can lead to a reduction in use of spinning reserve requirement [34, 35]. With the restructuring of the electricity industry, many rules designed for participation of interruptible loads in reserve market. In [34] a market-clearing process based on participation of generators and interruptible loads in reserve market with considering its impact on the reliability of the system has been designed.

In [36], the LR technique has been applied to minimize the total cost due to production energy cost and also cost of system risk. Costs of risks come from outages of generating units and the failure of interruptible loads to supply reserve when required. Also a model has presented in [37-40] for determining the reserve requirements with probabilistic method with the aim of minimizing the risk. However, the model in [34-37] is a simple model of interruptible load and regardless of all constraints relating to interruptible load such as the interruption time. On the other hand, the rate of interruptible load participation has been considered regardless of network conditions.

In [40], the market model has been improved based on the reliability-constrained unit commitment (RCUC) taking the sudden outage of production units and the refusal of the interruptible loads from the independent system operator instructions as the system uncertainty into account. Next, a new method for calculating the reliability index of EENS in presence of interruptible loads and interruption time has been developed.

In [34-37], calculation of reliability is done via hierarchical level I (HLI), where, the interruptible loads location is ignored in the network. In this paper, calculation of reliability is (HLII), so that the impacts of the location of interruptible load in system performance including cost and reliability have been studied.

### C. Paper Overview

In this paper, SCUC has been considered for simultaneous clearing of energy and reserve market. In the proposed model, a two-stage stochastic mixed integer programming (SMIP) is used for to include the uncertainties of power system, as well. In the proposed model, a two-stage stochastic mixed integer programming (SMIP) is used for considering the uncertainties of the power system. The goal of this program is the unit commitments with their energy production and the scheduled spinning reserve for each production unit and interruptible load for the next day.

Monte Carlo simulation is implemented for scenario generation for various production units and transmission lines random outages, the uncertainties in load prediction and negative response of the interruptible load to the independent system operator. Next, backward scenario reduction method is used for computational burden reduction where the problem accuracy remains desirable despite the decline in number of scenarios.

Impact of interruptible load location has been studied on the system reliability, too. It is shown that the interruptible loads location will be effective on the power flow of transmission lines at critical moments, congestion and increasing of marginal price. The proposed model is applied to the IEEE reliability test system (IEEE-RTS) to demonstrate its effectiveness. The rest of this paper is organized as follows.

In section II and III an economic load model is presented which considers consumers' response to the electricity price variation. The suggested objective function consists of simultaneous interruptible load contracts and UC program in the 24-hours period. Section IV provides reliability models of generating units and interruptible load. Section V presents the case studies and numerical results and finally the conclusion drawn from the analysis is provided in Section VI.

## II. THE OBJECTIVE FUNCTION

In the traditional power systems, the objective function is the sum of the production, start-up and shutdown costs of units in whole of the period under study. However, in a restructured system, the objective function is the total bid price for power generation, startup of, shutdown and providing operation reserve.

In this paper, the objective function of SCUC has been considered based on two-stage stochastic programming, but it has been modified such that in each scenario, the interruptible load value is considered as a part of the system reserve. This objective function has been shown in Equation (1), as follows:

$$\begin{aligned} EC &= \sum_{t=1}^{N_T} EC_t = \sum_{t=1}^{N_T}\sum_{i=1}^{N_G} C_{it}^{su} + \\ &+\sum_{t=1}^{N_T} d_t \left[ \begin{array}{l} \sum_{i=1}^{N_G}\left(C_{it}^{R^U} R_{it}^U + C_{it}^{R^D} R_{it}^D + C_{it}^{R^{NS}} R_{it}^{NS}\right) \\ +\sum_{j=1}^{N_L}\left(C_{jt}^{R^U} R_{jt}^U + C_{jt}^{R^D} R_{jt}^D\right) \\ +\sum_{k=1}^{N_K}\sum_{seg} ILP_k^c IL_k^{seg} U_{kt}^{ilseg} \end{array} \right] + \\ &+\sum_{\omega=0}^{N_\Omega} \pi_\omega \left\{ \sum_{t=1}^{N_T}\sum_{i=1}^{N_G} C_{it\omega}^{A} + \sum_{t=1}^{N_T} d_t \left[ \begin{array}{l} \sum_{i=1}^{N_G}\sum_{m=1}^{N_{Oit}} \lambda_{Git}(m)\, p_{Git\omega}(m) \\ +\sum_{j=1}^{N_L} \lambda_{Ljt} L_{jt\omega}^{C} + \sum_{j=1}^{N_L} V_{jt}^{LOL} L_{jt\omega}^{shed} \\ +\sum_{k=1}^{N_k}\sum_{seg} ILP_k^e IL_k^{seg} U_{kt\omega}^{ilseg} \end{array} \right] \right\} \end{aligned} \quad (1)$$

where, $EC_t$ is the expected cost of the system, $C_{it}^{R^U}$, $C_{it}^{R^D}$ and $C_{it}^{R^{NS}}$ are the offer costs of the up, down, and non-spinning reserves of unit $i$ in period $t$, respectively. $R_{it}^U$, $R_{it}^D$, and $R_{it}^{NS}$ are, respectively, the up, down and non-spinning reserves scheduled for unit $i$ in period $t$. $C_{jt}^{R^U}$ and $C_{jt}^{R^D}$ represent the offer costs of the up and down spinning reserves of load $j$ in period $t$, respectively. $R_{jt}^U$ and $R_{jt}^D$ are, respectively, the up and down spinning reserve scheduled for load $j$ in period $t$. $\pi_\omega$ is the probability of scenario $\omega$ and $C_{it\omega}^A$ is the cost due to the change in the start-up plan of unit $I$ in period $t$ and scenario $\omega$. $ILP_k^c$ and $ILP_k^e$ are, respectively, the offer cost of the allocation and consumption reserve of interruptible load $k$. $U_{kt\omega}^{ilseg}$ and $U_{kt}^{ilseg}$ are, respectively, the binary variable equal to 1 if interruptible load $k$ is online in period $t$ and scenario $\omega$. $\lambda_{Git}(m)$ and $p_{Git\omega}(m)$ are, respectively, the marginal cost of the $m$th block of energy offered by unit $i$ in period $t$ and Power output corresponding to the $m$th block of energy offered by unit $i$ in period $t$ and scenario $\omega$. The $\lambda_{Ljt}$ and $L_{jt\omega}^C$ are, respectively, the utility of consumer $j$ in period $t$ and power consumed by load $j$ in period $t$ and scenario $\omega$. $V_{jt}^{LOL}$ and $L_{jt\omega}^{shed}$ are, respectively, the value of load shed for consumer $j$ in period $t$ and load shedding imposed on consumer $j$ in period $t$ and scenario $\omega$.

The objective function above includes eight terms (from line 2 to line 4 in Equation (1)):

1. The start-up offer cost of the generating units.
2. The offer cost of contracting up/down spinning and non-spinning reserves from generating units.
3. The offer cost of contracting up/down spinning reserves from loads.
4. The offer cost of contracting reserves from interruptible loads.
5. The cost resulting from the adjustments of the start-up and shut-down plan of generating units previously established by the market clearing.
6. The energy offer cost of the generating units minus the demand utility.
7. The energy offer cost of the interruptible loads.
8. The cost of the load shedding.

Regardless of the loss, the production of power plants and power consumption of loads must be equal to each other. In this paper, the DC load flow has been employed to reduce the computational load. Here, the difference is that in the equation of DC load flow for each scenario, the interruptible load has been considered as part of system reserve, as well. The resulting DC load flow equation will be as follows:

$$\begin{aligned} &\sum_{i:(i,n)\in M_G(t,\omega)} P_{it\omega}^G + \sum_{:(i,n)\in M_G(t,\omega)} r_{it\omega}^U + \\ &+\sum_{i:(i,n)\in M_G(t,\omega)} r_{it\omega}^D + \sum_{i:(i,n)\in M_{IL}(t,\omega)} P_{it\omega}^{IL} + \\ &+\sum_{i:(i,n)\in M_L} L_{jt\omega}^C + \sum_{i:(i,n)\in M_L} L_{jt\omega}^{shedIL} = \\ &= \sum_{r:(n,r)\in \Lambda(t,\omega)} f_{t\omega}(n,r) \end{aligned} \quad (2)$$

where, $P_{it\omega}^G$ and $P_{it\omega}^{IL}$ are, respectively, the power output of unit and interruptible load $i$ in period $t$ and scenario $\omega$, $r_{it\omega}^U$ and $r_{it\omega}^D$ are, respectively, the spinning reserve up and down deployed by unit $i$ in period $t$ and scenario $\omega$. $L_{jt\omega}^C$ and $L_{jt\omega}^{shedIL}$ are, respectively, the power consumed by load $j$ in period $t$ and scenario $\omega$ and load shedding in presence of IL imposed on consumer $j$ in period $t$ and scenario $\omega$ and finally $f_{t\omega}(n,r)$ is the power flow through line ($n$, $r$) from $n$ to $r$.

### A. The Constraints

The constraints of problem are listed as follows:

1- The hourly UC constraints [41]:
- The system power balance constraints
- Real power generation constraints
- Minimum up and down time constraints
- Ramping up and down constraints
- Reserve constraints
- Transmission flow limits

2- Interruptible load constraints according to the IEEE798 Standard [42]
- The interruption time
- The amount of load curtailment for each curtailment

- The maximum Count of Loss of Load (CLOL)
- The Interruptible Load max up time
- The Interruptible Load min down time
- The maximum hour of curtailments per day for each bus

## III. THE RELIABILITY CALCULATIONS

There are two methods for determining the required reserve of the system. The first method is based on the deterministic criteria in which a percentage of load or capacity of the largest unit in the system is considered as the certain reserve of system. However, these methods neither are economically optimal, nor, consider the reliability requirements of the participants.

The other method is based on the probabilistic criteria. In the probabilistic approach, a set of performance indices such as Loss of Load Probability (LOLP), Expected Energy Not Supplied (EENS) and Loss of Load Expectation (LOLE) are chosen to investigate the properties of the system reliability [43]. The main advantage of this approach is the quantities representation of the system reliability in the overall UC cost function which results in more accurate decisions. Besides, it implies that the system reliability costs can be expressed, economically. In this approach, the amount of reserve requirement of the system is achieved via balancing the system costs and the expected reliability.

The total amount of load curtailment in period $t$ and scenario $\omega$ will be equal to:

$$L_{t\omega}^{shed} = \sum_{j} L_{jt\omega}^{shed} \tag{3}$$

where, $L_{t\omega}^{shed}$ and $L_{jt\omega}^{shed}$ are, respectively, the total load shedding in period $t$ and scenario $\omega$ and load shedding imposed on consumer $j$ in period $t$ and scenario $\omega$.

We need to another variable to express the occurrence of interruption at any time for calculation of the reliability indices. This variable is Loss of Load Indicator (*LOLI*) and is a binary variable. The value of *LOLI* is "1" in the event of interruption at any time and is "0", otherwise.

$$LOLI_t^{\omega} = \begin{Bmatrix} 1, & \text{if} & L_{t\omega}^{shed} \neq 0, & \forall t, \forall \omega \\ 0, & \text{if} & L_{t\omega}^{shed} = 0, & \forall t, \forall \omega \end{Bmatrix} \tag{4}$$

Thus, the loss of load probability of interruption at any time can be calculated from Equation (5) as follows:

$$LOLP_t = \sum_{\omega} \pi_{\omega} LOLI_t^{\omega} \tag{5}$$

where, $LOLP_t$ and $\pi_{\omega}$ are, respectively, the loss of load probability in period $t$ and probability of scenario $\omega$. This index is representative of the probability of the failure events leading to load shedding [44].

Another index is Loss of Load Expectation that assesses the expected number of hours during which loss of load events could happen [29].

$$\begin{aligned} LOLE_{\omega} &= \sum_{\omega} prob\left(L_{t\omega}^{shed} \geq 0\right) \\ LOLE &= \sum_{\omega} \pi_{\omega} LOLE_{\omega} \end{aligned} \tag{6}$$

where, $LOLE_{\omega}$ is Loss of Load Expectation in scenario $\omega$. As seen, the two mentioned reliability indices are not indicative of the amount of load shedding. However, in the relating economic issues, it would be better to define a proper quantitative index for calculating the costs of load shedding in the system. For this purpose, EENS has been defined as the sum of load shedding during the evaluated time multiplied by its probability [45] as follows:

$$\begin{aligned} EENS &= \sum_{t} \sum_{\omega} \pi_{\omega} \sum_{j} L_{jt\omega}^{shed} = \sum_{t} EENS_t \\ EENS_t &= \sum_{\omega} \pi_{\omega} \sum_{j} L_{jt\omega}^{shed} \end{aligned} \tag{7}$$

where, $EENS_t$ is Expected Energy Not Supplied in period $t$. As seen, both the *LOLE* and the *LOLP* require the use of binary variables to be considered within a mixed-integer linear programming problem, [36, 46]. On the contrary, the *EENS* can be expressed linearly, without binary variables, which makes the problem solution more simpler.

## IV. UNCERTAINTY IN POWER SYSTEM

The first step in solving a stochastic programming problem, is modeling of the existing uncertainties of the problem. In the literature, the units and transmission lines random outages, the uncertainty in load prediction and negative response of the interruptible load to the independent system operator have been proposed as the uncertainties of the stochastic programming model [45].

Up to knowledge of the authors, not all these uncertainties have been considered, simultaneously, in the related articles. In this paper, simultaneous modeling of these uncertainties based on the reliability model of the power system is proposed. To do this, in the proposed model is day-ahead market and the realistic benchmark of IEEE-RTS have been assumed. The uncertainty conditions for production units and the transmission lines models cope to the system short-term operation.

### A. The Reliability Model of Generating Units and Transmission Lines

Commonly, the two-state model shown in Figure 1 is used for reliability model of generating units and transmission lines [26]. In planning studies that is done in long-term context, forced outage rate (*FOR*) of each element, known as the element unavailability [22], is calculated with failure rate ($\lambda_i$) and repair rate ($\mu_i$) as follows:

$$FOR = \frac{\lambda}{\lambda + \mu} \tag{8}$$

In operation studies, some other models should be utilized based on the model presented in [22]. If failures and repairs come from exponential distributions, unavailability probability of an element $P(down)$ during time $t$ (assuming the availability of units in $t$ = 0) will be as follows:

$$P(down) = \frac{\lambda}{\lambda + \mu}\left(1 - e^{-(\lambda + \mu)t}\right) \tag{9}$$

In this context, if the time $t$ is reasonably small, unit repair rate can be ignored during this time interval ($\mu$=0). In fact, the system recovery time is so small that the damaged unit cannot be repaired or replaced at this time. As a result, Equation (9) can be rewritten as follows:

$$P(down) = \left(1 - e^{-\lambda t}\right) \quad (10)$$

And also if $\lambda t << 1$, (which is true to lead times for several hours), the above equation is approximated into Equation (11).

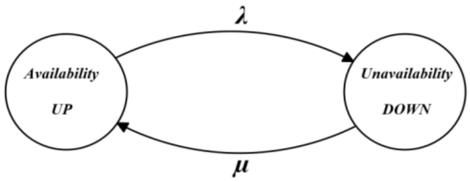


Figure 1. Two-state model of generating units and transmission lines

In this mode the amount of unit, unavailability known as outage replacement rate, is a function of time, which is:

$$ORR^t = U^t = \lambda t \quad (11)$$

where, $ORR^t$ and $U^t$ are, respectively, the outage replacement rate and unavailability of each element in period *t*.

In the proposed model, the unit commitment program is performed, hourly. Therefore, the risk calculation is done hourly, as well. Namely, *FOR* has been considered for calculating the element unavailability in different times. However, this assumption is only for the production units and for transmission lines Equation (9) are employed to calculate the desired element unavailability.

### B. The Reliability Model of Interruptible Loads

In reliability research, interruptible loads can be modeled by two approaches. In the first approach, called load variation approach, after the interruption time, for risk calculation the system load is reduced to the won amount of reserve in the market. In the second approach, called equivalent unit approach, interruptible load is modeled as a unit with specific forced outage rate (zero or non-zero) [45]. These two methods are shown in Figures 2 and 3, respectively.

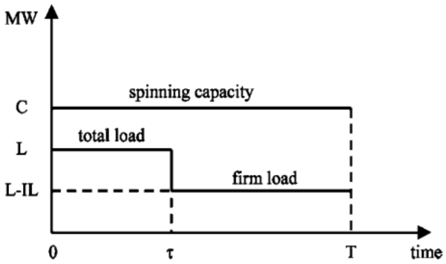


Figure 2. Load variation approach model for interruptible load

In these figures, $\tau$ is the interruption time of interruptible load and *T* is the system lead-time. Also In these figures, *L*, *C* and *IL* are, respectively, system load, spinning capacity of generating units and amount of interruptible load. In this paper, the second approach is employed for modeling of the uncertainties in the interruptible loads.

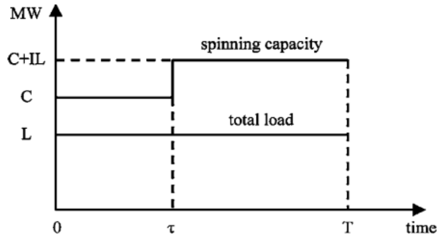


Figure 3. Equivalent unit approach model for interruptible load

## V. SIMULATION RESULTS

In this section, mixed integer linear programming techniques (MILP) is used for implementation of simultaneous security constrained units commitment and participation of demand side for providing reserve. The formulation of the proposed model has been simulated with GAMS [47] software and CPLEX optimization method has been used as an efficient method for solving the MILP [49].

Besides, the well-known Monte Carlo simulation has been performed for scenario generation for various production units and transmission lines random outages, the uncertainty in load prediction and negative response of the interruptible load to the independent system operator, and next, the backward scenario reduction method is used for computational burden reduction.

The simulation procedure is as follows:

1- Implementation of SCUC with mixed integer linear programming where only the spinning reserve of the generators are used for providing system security in the critical condition.

2- Implementation of SCUC with mixed integer linear programming considering the reserve of the generators and interruptible loads to investigate the effectiveness of demand side reserve in reducing the system costs and improving the reliability of power system. In this case, the response of the interruptible load to the independent system operator is assumed positive.

3- Implementation of SCUC with mixed integer linear programming considering the reserve of the generators and interruptible loads to investigate the effect of interruptible load location in reducing the system costs and improving the reliability of the power system.

4- Investigation of the impact of the uncertainties in the interruptible load response to ISO in the previous model.

The 24-node system considered in this paper is based on the single-area version of the IEEE-RTS, 1996 [51]. Information of this case study, including production costs, forced outage rates of generators and transmission lines, generators and load characteristics are extracted from [49].

System load is considered equal to 2850 MW in 44th week of year in the winter and Monday [48]. The load contribution in percentage to the total system demand has been made according to coefficients presented in this reference, as well. Variations of system load during the 24 hours has been shown in Figure 4.

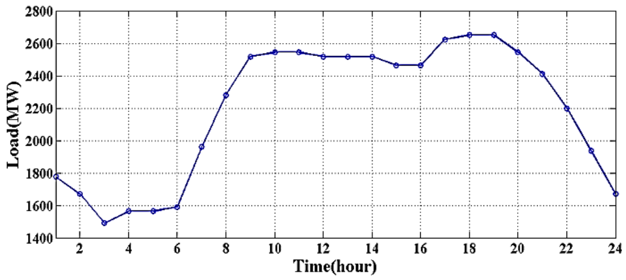

Figure 4. Considered load curve for the IEEE-RTS network [48]

Three interruptible load are considered in the third, fifteenth and eighteenth bus with different outage rates. These loads provide their reserve in three steps of 33%, 67% and 100% of maximum load, which are considered as the interruptible load. These features and their suggested prices for the contract (preparation costs) are shown in Table 1.

Table 1. Interruptible load characteristics and the corresponding suggested prices.

| | ($/MWh) preparation costs | | | |
|---|---|---|---|---|
| Bus number | 33% | 67% | 100% | Force Outage Rate |
| Bus 3 | 3 | 4 | 5 | 0.02 |
| Bus 15 | 3 | 4 | 5 | 0.05 |
| Bus 18 | 3 | 4 | 5 | 0.08 |

### A. Effect of Demand Side Reserve in System Costs

In this section, the SCUC problem has been solved for two cases to examine the system cost and network reliability in presence of the interruptible loads. In the first case, we assume that only spinning reserve of the production units are responsible for providing system reserve and in the second case, the unrestricted participation of the interruptible loads in reserve market to be considered. In addition, it has been supposed that the non-response rate of interruptible loads to request of the operator is zero.

In Table 2, the simulation results are performed from different perspectives. In the second to fifth rows in addition to the total cost of system, Pre contingency, Reserve deployment and Loss of load costs in the above two cases have been also provided. As can be seen, participating of interruptible loads in providing system reserve leads to the significant reduction of the total cost. This is due to a significant reduction in loss of load cost. It should be noted that as expressed in [51], the obtained cost of solving SCUC are not actual costs of system, but are representative of the probable costs of the system.

On the other hand, by the arrival of interruptible loads in the providing reserve, as expected, the amount of customers loss of load is un-voluntarily reduced and system reliability would increase. This issue is shown in the sixth to ninth lines of Table 2 with the help of expected energy not supplied, loss of load probability and loss of load expectation criteria at any hour. As it can be seen, loss of load probability and loss of load expectation at any hour is significantly reduced. To make the results clearer, the effect of interruptible load on reduction of load shedding has been shown in Figure 5.

Table 2. The comparison of effect of demand side reserve in system costs for Cases 1 and 2

| | Case 1 | Case 2 |
|---|---|---|
| Total cost ($) | 1538838.708 | 1336763.154 |
| Pre contingency cost ($) | 15816.06147 | 15797.9851 |
| Reserve deployment cost($) | 613511.9386 | 611654.8158 |
| Loss of load cost ($) | 909510.7076 | 709310.3529 |
| *EENS* (MWh) | 909.5107076 | 709.3103529 |
| Mean *LOLP* (t) | 0.248484706 | 0.198788 |
| LOLE (day/yr) | 4.22424 | 3.379392 |
| LOLE (h/day) | 0.277758247 | 0.222207 |

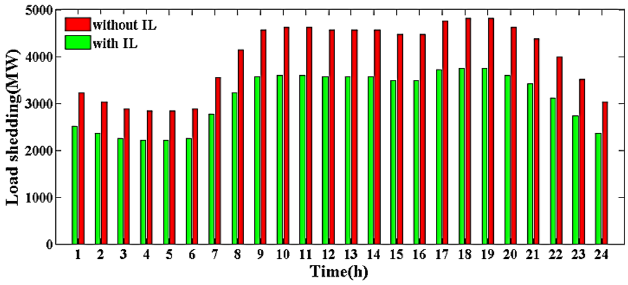

Figure 5. The amount of load shedding in presence and absence of interruptible load during a day (Cases 1 and 2)

### B. The Effect of Refusal of the Interruptible Loads from the ISO Instructions

As mentioned previously, in this paper interruptible loads are modeled as production unit with non-zero outage rate. For considering their response to the request of operator, the outage rate for the production units has been assumed non-zero and new scenarios have been produced, correspondingly. In this case, equivalent unit outage is the meaning of refusal of the interruptible loads from the ISO instructions. Outage rate of any interruptible load has been assumed according to the data given in Table 3. In Table 3 and Figure 6, the results of this section are compared the results of the case 2 in the previous section.

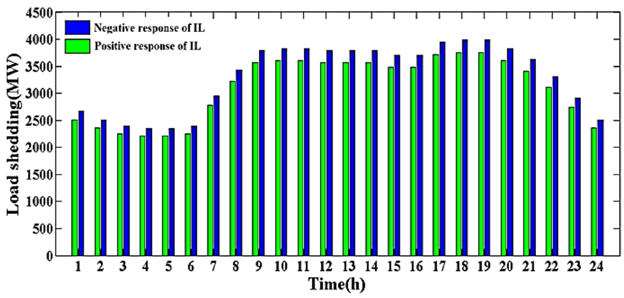

Figure 6. The amount of load shedding for positive/negative response of IL to ISO instructions

As expected, the amount of network reliability has been reduced compared to its previous state and so the amount of energy not supplied has been increased. This issue is due to the increases of loss of load and total cost with respect to its previous state. From Table 3 and compared to Case 1 of Table 2, it is also demonstrated that in absence of interruptible load, the network is capable of more favorable conditions in terms of reliability.

However, this result is compatible with our expectations, the increase in outage rates of equivalent unit for interruptible load would results in reduction amount of reserve load and increment of system costs. In order for investigating the effect of outage rate, its value has been changed via some multiplication factor and various scenarios has been re-generated with new outage rates [45]. The impacts of interruptible loads outage rate variability in system response has been shown as in Figures 7 to 9.

Table 3. The comparison of effect of the negative response of IL to the ISO instructions (Case 3) with the Cases 1 and 2

| | Case 1 | Case 2 | Case 3 |
|---|---|---|---|
| Total cost ($) | 1538838.708 | 1336763.154 | 1338578.024 |
| Pre contingency cost ($) | 15816.06147 | 15797.9851 | 15796.03874 |
| Reserve deployment cost ($) | 613511.9386 | 611654.8158 | 611654.8158 |
| Loss of load cost ($) | 909510.7076 | 709310.3529 | 711127.1694 |
| EENS (MWh) | 909.5107076 | 709.3103529 | 711.1271694 |
| Mean *LOLP*(t) | 0.248484706 | 0.198788 | 0.199190294 |
| LOLE(day/yr) | 4.22424 | 3.379392 | 3.386235 |
| LOLE(h/day) | 0.277758247 | 0.222207 | 0.222656548 |

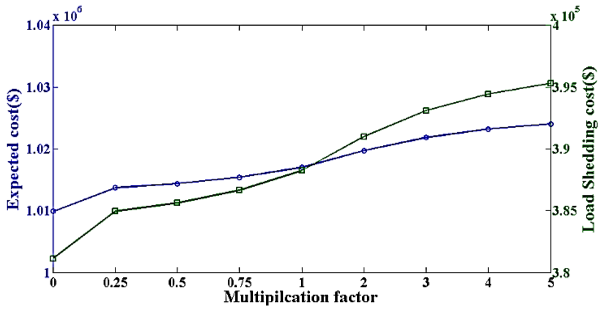


Figure 7. The effect of interruptible loads outage rates on system costs

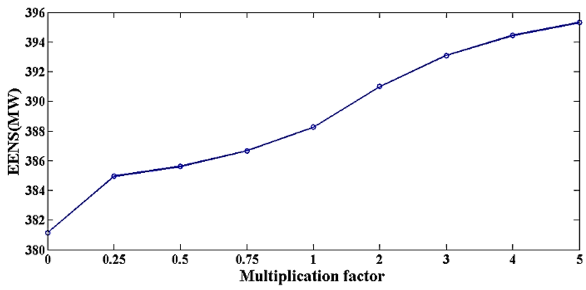


Figure 8. The effect of interruptible loads outage rates on EENS

As seen, by reducing the use of interruptible load, the energy not supplied and load shedding have been increased, monotonically.

### C. The Effect of IL Location in System Costs and Reliability

As stated earlier, the location of the interruptible loads in the power system would affect the power flow of the transmission lines at critical moments, the congestion status and the value of marginal price. In this paper, the optimal location of the interruptible loads has been found in terms of reliability and cost constraints. In order to find and implement these cases, the GAMS software has been linked with MATLAB program via the method in [51].

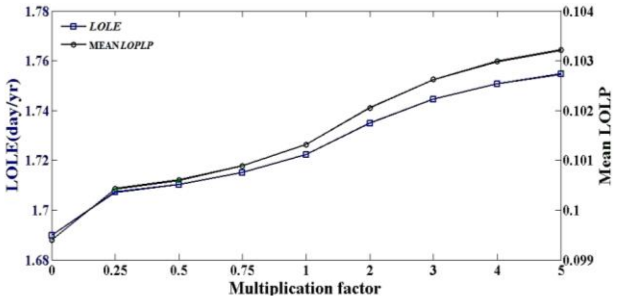


Figure 9. The effect of interruptible loads outage rates on LOLP and LOLE

To examine the effects of IL location on system cost and reliability four states has been considered four states which the first state represents the system in absence of IL that is case 1 of the simulation results and cases 4-6 represents the system in presence of IL's in their optimal locations. The results have been shown in Table 4 and Figure 10. That is, in case 4, one IL exists at Bus 8, in case 5, two IL's are located at Buses 8 and 6 and finally in case 6, three IL exist at buses 8, 6 and 20.

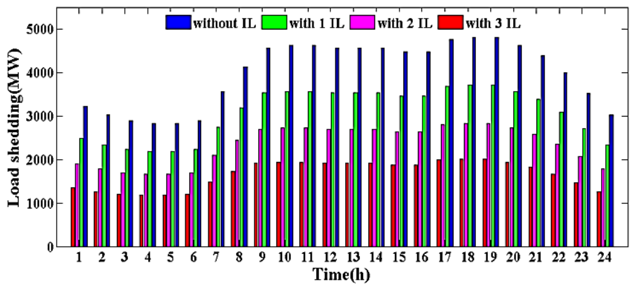


Figure 10. The amount of load shedding in presence of IL at its optimal location

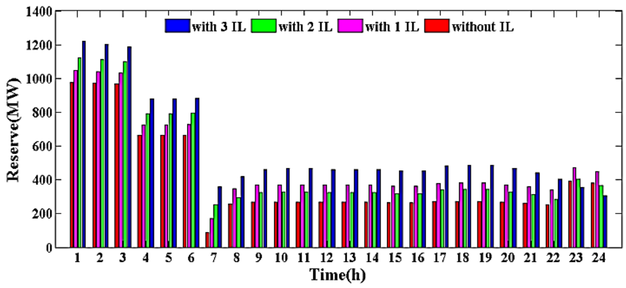


Figure 11. The amount of scheduled reserve in presence of IL at its optimal location for each hour

According to Table 4, we see that the total cost of "1336763.154" of case 2 in which, interruptible loads were at buses 3, 15 and 18 has been decreased to "1014363.602" which in this case interruptible loads are located in the optimal location at Buses 8, 6 and 20. In addition, it can be observed according to Table 4 that all in case 6, the three indices of reliability have been significantly improved with respect to other cases.

Table 4. The effect of IL location in system cost and reliability for various cases

| | Case 1 | Case 2 | Case 4 | Case 5 | Case 6 |
|---|---|---|---|---|---|
| Total cost ($) | 1538838.708 | 1336763.154 | 1375862.245 | 1214363.816 | 1014363.602 |
| Pre contingency cost ($) | 15816.06147 | 15797.9851 | 16042.26179 | 16340.44589 | 16769.03745 |
| Reserve deployment cost ($) | 613511.9386 | 611654.8158 | 613485.6095 | 614033.2494 | 611987.9817 |
| Loss of load cost ($) | 909510.7076 | 709310.3529 | 746334.374 | 583990.121 | 385606.5829 |
| *EENS* (MWh) | 909.5107076 | 709.3103529 | 746.334374 | 583.990121 | 385.6065829 |
| Mean *LOLP*(*t*) | 0.248484706 | 0.198788 | 0.19919 | 0.149896 | 0.100602 |
| *LOLE* (day/yr) | 4.22424 | 3.379392 | 3.386235 | 2.54823 | 1.710225 |
| *LOLE* (h/day) | 0.277758247 | 0.222207 | 0.222657 | 0.167555 | 0.112453 |

In Figure 10, the results of load shedding for both cases of with/without interruptible loads have been brought. The results indicate that the IL location has a significant impact in decreasing of load shedding at any hour.

Table 5. The amount of scheduled reserve in presence of IL at its optimal location

| | Case 1 | Case 2 | Case 3 | Case 4 | Case 5 | Case 6 |
|---|---|---|---|---|---|---|
| Reserve (MW) | 9768.2 | 12009.6 | 12009.5 | 11601 | 11905 | 14425 |

In Table 5 and Figure 11, the scheduled reserve of system has shown in whole and for each hour. Scheduled reserve is the maximum amount of reserve that will be used in the next day. As it is observed, in presence of IL, the amount of the scheduled reserve has been increased, significantly. From these results, it is concluded that the location of the interruptible loads have a significant impact on the overall reliability performance of the power system.

## VI. CONCLUSIONS

In this paper, a stochastic model for simultaneous energy and reserve market clearing has been proposed. It is assumed that the spinning reserve of production units and interruptible loads are both present in the system. In this model, the common objective functions in the literature, have been extended to include the power production costs, the cost of reserve scheduling and consumption of each supplier plus the cost of EENS for different hours.

Also Monte Carlo simulation has been implemented for scenario generation and modeling of production units in conjunction with the transmission lines random outages, uncertainty in load prediction and refusal of interruptible loads from the ISO instructions. Next, the backward scenario reduction method is used for computational burden reduction where problem accuracy remains desirable despite decline in total size of calculations.

Finally, the impacts of interruptible load location has been also studied on the system reliability. From the performed simulations, the following observations and conclusions may be drawn:

1- Simultaneous clearing of energy and reserve markets considering the stochastic nature of power system and the value of loss load in each hour, prevented from scheduling the extra amount of spinning reserve and considered the optimal amount of reserve for each hour. In addition, this amount of reserve is related to cost of production and amount of system load in each hour.

2- Stochastic programming based on scenario generation helped us to considering the simultaneous outages of power system without increasing the calculation. On the other hand, scenario reduction methods are leading to consideration of the only critical state and outages with high probability.

3- Participation of demand side in simultaneous markets of energy and reserve decreased the costs of energy market, spinning reserve market and middle cost of involuntary load shedding which in turn reduced the operation costs.

4- Employing the interruptible load reserve, especially in optimal location, improved the system reliability to higher levels and decreased the total cost.

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## BIOGRAPHIES

**Mostafa Yousefi Ramandi** was born in Tehran, 1985. He received his B.Sc. degree in Electrical Engineering from Islamic Azad University, Saveh, Iran in 2009 and the M.Sc. degree in Electrical Engineering from Imam Khomeini International University, Qazvin, Iran in 2013. His research interests are included power system and restructured power system.

**Karim Afshar** was born in Iran, 1978. He received his Ph.D. degree in Electrical Engineering Majoring in Power Systems from Sharif University of Technology, Tehran, Iran in 2007. He is with Electrical Engineering Department of Imam Khomeini International University, Qazvin, Iran as an Associate Professor. His research interest includes reliability issues, economic operation and forecasting as well as bidding strategy in power markets.

**Nooshin Bigdeli** was born in Iran, 1978. She received her Ph.D. degree in Electrical Engineering Majoring in Control from Sharif University of Technology, Tehran, Iran in 2007. She is with Electrical Engineering Department of Imam Khomeini International University, Qazvin, Iran as an Associate Professor. Her recent research interest includes data mining, chaotic systems, analysis and forecasting as well as bidding strategy in power markets.