

# Effects of Interruptible Load on Decision Making of a Distribution Company in Competitive Environments

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**Abstract:** The main goal of this paper is to present a new day-ahead energy acquisition model for a distribution company (Disco) in a competitive electricity market environment with Interruptible Load (IL). The work formulates the Disco energy acquisition model as a bi-level optimization problem with some of real issues, and then studies and designs a Genetic Algorithm (GA) of this optimization problem too. To achieve this goal, a novel two-step procedure is proposed. At the first step, a realistic model for an industrial interruptible load is introduced, and it is shown that Interruptible load model may affect the problem modeling and solving. At the second step, Disco energy acquisition program is formulated and solved with this realistic model. As a result, this paper shows energy acquisition programming model with ILs, by considering real assumptions. The introduced method shows a good performance of problem modeling and solving algorithm both in terms of solution quality and computational results. In addition, a case study is carried out considering a test system with some assumptions. Subsequently results show the general applicability of the proposed model with potential cost saving for the Disco.

**Keywords:** Bi-Level Optimization, Distribution Company, Electricity Market, Interruptible Load.

## 1 Introduction

### 1.1 Motivation

In a deregulated electricity market environment, and unlike the traditional vertical utility structure, both economic and technical decisions are treated with the same level of importance and are usually handled simultaneously in the same time frame [1]. Disco usually buys energy from the wholesale market to meet the requirement of its end customers. However, a Disco will have more choices to acquire energy if it possesses ILs. ILs can be used by Disco to improve its market response capabilities, and accordingly change the passive position of it in the market. Real or physically based model and formulation for industrial loads (as IL) has considerable effects on solution quality and computational results of the problem.

### 1.2 Literature Review

So far, IL services have attracted significant attention from both academia and industry. The existing research broadly falls into two main categories. A major research problem of IL services is to design appropriate

incentive rate structures for customers to participant voluntarily into the IL programs. In [2] and [3], optimal incentive-rate structures are designed for IL contracts using mechanism-design theory. Another category of IL research focuses on evaluating the influences of IL services on the whole market. Moreover, the impact of IL on the price volatility is proposed in [4]. Also in [5], it is constrained that IL can provide price spikes without any proposed solution for IL contract type. IL contracts have been widely practiced in many countries through their reserve markets. According to North America Electricity Reliability Council (NERC), Interruptible Load Management (ILM) is recognized as one of the contingency reserve services [6]. A Disco energy acquisition market model with DGs and ILs is presented in [7] under a market structure based on pool and bilateral contracts. The energy acquisition model in [7] is a static single period model. Furthermore, in [8] a multiperiod energy acquisition model for a distribution company with DG and IL is introduced. However, the energy acquisition model in [8] assumes some assumptions such as quadratic form of cost functions (both of DGs and ILs), considering only one type of ILs, only one type IL contract (fixed for all IL types), meanwhile it doesn't consider impact of real situations, and avoids constraints that link successive hours, etc.

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This paper develops a multiperiod energy acquisition model for a Disco with multiple options including:

- Interruptible load with low price compensation before supply unavailability, that is independent of power supply unavailability.
- Interruptible load with high price compensation after supply unavailability that is performed only after actual power supply unavailability.
- Realistic model for interruptible load, and wholesale market purchase.

### 1.3 Approach and Contributions

The main aim of this paper is to model interruptible load in the electricity market with real considerations, and develop a multiperiod energy acquisition model for Disco. The focus is to study the roles of ILs in demand side response. Disco with ILs can use this model to increase its flexibility in energy acquisition, improve the demand side response, and maximize its benefit. Disco acquisition market can be formulated for each period as a mathematical optimization problem and the resulting problem can be solved using proposed Genetic Algorithm Bi-Level Optimization (GABLO) method. In addition, an 8-bus system is employed to illustrate the proposed method and algorithm. By performing realistic modeling for IL, the obtained results show that traditional approaches do not lead to good consequences.

### 1.4 Paper Organization

This paper is organized as follow: market structure is introduced in section 2, Modeling of the IL with real considerations is presented in section 3, and Disco Energy acquisition model is described in section 4. Sections 5 and 6 contain solution to the acquisition of Disco and simulation results of test system respectively. Finally, paper summarized and concluded in section 7.

## 2 Structure Of Electricity Market

The general structure of the day-ahead market considered in this work is shown in Fig. 1. In this structure, Gencos sell energy to the market by bidding into the market.

The information Gencos submit to the Independent system operator (ISO) includes:

- Lower and upper generation limits,
- Bidding price, and
- Generation ramping up/down limits.

Disco buys energy either financial bilateral contracts or in the pool. If necessary, Disco may interrupt low price interruptible loads (LIL) and finally in emergencies, Disco can interrupt high price interruptible loads (HIL). LIL contract, allows the Disco to interrupt a given percentage of a customer's load a fixed number of times over the life of the contract. In exchange, the customer receives a discount on the retail price for the customer's load covered by the LIL contract.

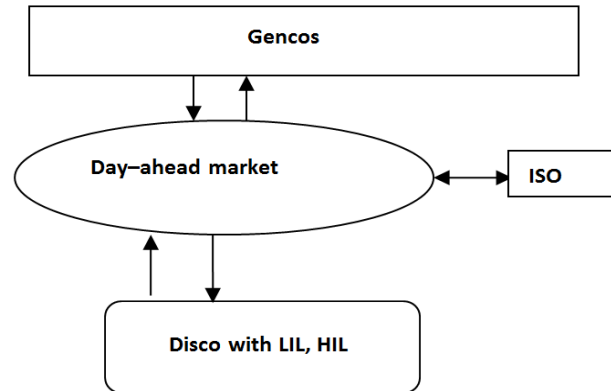


Fig. 1 General market structure.

HIL contract, allows the Disco to interrupt part of a customer's load a fixed number of times in exchange for compensation. This compensation is typically chosen to be considerably higher than the retail price. LIL contract is executed from the time of committing, in which power supplier gives a discount on the retail price of electricity for the customer's load under the LIL contract in exchange for the right to interrupt a given amount of customer's load a fixed number of times over the life of the LIL contract. The customer's load under the LIL contract is billed at a discounted price, but for the load outside the LIL contract is billed at the retail price. From the point of view of financial options, HIL can be regarded as a unilateral optional forward contract. The implementation of HIL contract depends on whether the spot price is above or below the interrupted compensation price, which is stipulated in the HIL contract. If spot price is higher than the interrupted compensation price, power supplier will interrupt or curtail the customers' load under HIL contract, otherwise will supply power to customers. The information Disco submits to the ISO includes:

- Maximum demand for each hour and at each bus,
- Lower and upper limits of LILs, and
- Cost information (or curves) for LILs.

The day-ahead market serves as a platform for Gencos and Disco to sell and buy energy. The objective of Disco is to maximize its profit by determining the amount of ILs and the quantity of the energy purchased from the day-ahead market.

## 3 Modeling of the Industrial load as IL

Since the industrial sector accounts for a significant proportion of the total electricity consumption, and the average electricity consumption per consumer is high, Industrial Load Management (ILM) is an important option for utilities to manage their peak deficit. Industrial loads can be classified into: a) controllable loads, which can be subjected to any type of load management actions, and b) fixed time loads, that occur at specified time periods and cannot be controlled or subjected to LM actions (e.g., lighting load).

Controllable loads can be grouped into process independent loads, process interlocked loads, storage constraint loads and sequential loads. Here formulation is based on discrete time representation of the entire time horizon of interest [9]. Events such as start or end of processes only allowed at the interval boundaries.

$$\sum_{i=1}^{N_I} t_i = T \quad (1)$$

The decision variable will be 1 or 0 as in Eq. (2), and it shows that a subprocess (Sp) is active in an interval or not.

$$I_{mi} = \begin{cases} 0 & \text{the subprocess } m \text{ isn't active} \\ & \text{on the interval } i \\ 1 & \text{the subprocess } m \text{ is active} \\ & \text{on the interval } i \end{cases} \quad (2)$$

It is required to have a specified minimum output (Q) of the final product in the time horizon. Then

$$\sum_{i=1}^{N_I} \sum_{m=1}^{N_{sp}} (P_{mi} * t_{mi} * I_{mi}) \geq Q \quad (3)$$

Process loads with storage space with maximum capacity limitations can be modeled as in Eq. (4).

$$\sum_{i=1}^T \sum_{m=1}^{N_{sp}} (P_{mi} * t_{mi} * I_{mi}) - \sum_{r=1}^{N_{sp}} (q_{ri} * t_{ri} * I_{ri}) \leq S_m \quad (4)$$

for  $T = 1 \text{ to } N_I$

Peak demand limit is an important factor to be considered in load scheduling since many industries are subjected to maximum demand restrictions. For interval  $i$ :

$$\sum_{m=1}^{N_{sp}} \left( \frac{EP_{mi}}{pf_{mi}} \right) * I_{mi} \leq KVA_{mi} \quad (5)$$

The electrical power input in kW for any machine at any interval  $i$  as in Eq. (6).

$$EP_{mi} = \{(R_m * UF_{mi}) / E_{mi}\} * I_{mi} \quad (6)$$

The objective function is the minimization of the electricity cost as in Eq. (7).

$$\min \sum_{i=1}^{N_I} \sum_{m=1}^{N_{sp}} [(EP_{mi} * t_{mi} * I_{mi} * C_i) + \{C_{ai} * I_{ai}\} * t_i] \quad (7)$$

$$I_a = \begin{cases} 1 & \text{LM action corresponding to } C_{ai} \text{ is taking place} \\ 0 & \text{otherwise} \end{cases} \quad (8)$$

The decision variable  $I_a$  will be 1 or 0 as in Eq. (8), indicating which machines should be on or off in the corresponding interval.

#### 4 Acquisition Market Modeling

A bi-level optimization formulation is developed wherein the upper sub problem maximizes the Disco's revenue, while, the lower sub problem addresses the ISO's market clearing by minimizing generation costs and compensation costs for ILs.

#### 4.1 Market Clearing Model

It is assumed that the ISO clear the market using a security-constraint economic dispatch model to minimize the generation costs and compensation costs for LILs, subject to the bids, line flow constraints, and LIL constraints too as in Eq. (9).

$$\min \left[ \sum_{i \in GS, k \in TS} C_{G,ik}(P_{G,ik}) + \sum_{i \in BLI, k \in TS} C_{LIL,ik} \right] \quad (9)$$

We assume that a Gencos' bid function is given as Eq. (10).

$$p_{G,ik}(p_{G,ik}) = 2\alpha_{ik} p_{Gik} + \beta_{ik} \quad i \in GS, k \in TS \quad (10)$$

Accordingly, generation cost function assumed as Eq. (11).

$$C_{G,ik}(p_{G,ik}) = (\alpha_{ik} p_{Gik}^2 + \beta_{ik} p_{Gik} + \gamma_{ik}) u_{ik} \quad (11)$$

$$u_{ik} = \begin{cases} 0 & \text{unit has no generation} \\ 1 & \text{unit generates} \end{cases} \quad (12)$$

$$i \in GS, k \in TS$$

Generation capacity constraint is as in Eq. (12).

$$p_{G,ik}^{\min} \leq p_{G,ik} \leq p_{G,ik}^{\max} \quad i \in GS, k \in TS \quad (13)$$

Transmission line flow constraint is as Eq. (13).

$$-p_{ij,k}^{\min} \leq p_{ij,k} \leq p_{ij,k}^{\max} \quad i, j \in BS, k \in TS \quad (14)$$

Ramping Up and Ramping Down constraints are as in Eqs. (15) and (16).

$$p_{G,ik} - p_{G,i(k-1)} \leq Ru_{G,ik} \quad i \in GS, k \in TS \quad (15)$$

$$p_{G,i(k-1)} - p_{G,ik} \leq Rd_{G,ik} \quad i \in GS, k \in TS \quad (16)$$

The Gencos' bidding curves are reached using game theory [10] and neural network method [11], which are based on the predicted load or locational marginal price (LMP) published on the ISO website. Load balance constraint is as in Eq. (17).

$$p_{G,ik} - (p_{D,ik}^{\max} - p_{ILL,ik} - p_{ILH,ik}) + \sum_{j=1}^{B(i)} p_{ij,k} = 0 \quad (17)$$

$$j \in B(i), i \in B, k \in TS$$

Based on DC power flow equation, the summation of branch voltages for any independent loop should be zero as in Eq. (18).

$$\sum_{i,j \in BSL, k \in TS} p_{ij,t} x_{ij} = 0 \quad i, j \in BSL, t \in TS \quad (18)$$

The ramping constraints (15) and (16) makes the ISO market clearing model a linked multiperiod optimization problem and the unit commitment constraint links successive hours. LIL bids are evaluated along with generation supply bids in day-ahead market. However, to the best of the authors' knowledge, no research has been conducted to integrate LIL and HIL methods until now. The decision variables in this model include  $p_{G,ik}$ ,  $p_{ij,k}$  and  $p_{LIL,ik}$ .

### 4.2 Disco Energy Acquisition Model

The operational aspects of a Disco are considered over a 24-hour demand cycle. The distribution substation transformer represents the main connection point of the Disco with the bulk power system. HIL decisions are included at this stage. In this model, the first energy provision component is the power purchased from the grid, which is the power, imported via the substation and is priced at electricity market price on an hourly basis. We assume that a Disco does not bid its HILs into the day-ahead market but serves them according to estimated LMPs in emergencies, and, if the load of a Disco (LIL) is interrupted, the Disco will be paid according to LMP and load reduction. Disco returns all the compensation collected from the interruption of load (LIL) to the interrupted end customer and does not benefit from the LIL compensation. A Disco's profit only comes from the difference between the revenue it collects from customers and the cost it pays for the same amount of energy. Disco profit is as in Eq. (19).

$$R = \sum_{i \in BD, k \in TS} (\lambda_k (P_{D,ik}^{\max} - P_{LIL,ik} - P_{HIL,ik})) - \sum_{i \in BD, k \in TS} [\rho_{Dik} (P_{D,ik}^{\max} - P_{LIL,ik} - P_{HIL,ik})] - \sum_{i \in BD, k \in TS} (C_{HIL,ik}) \quad (19)$$

Disco intends to maximize its own profit subject to IL constraints is as Eq. (20).

$$\begin{aligned} & \max R \\ & s.t. \end{aligned} \quad (20)$$

$$P_{HIL,ik}^{\min} \leq P_{HIL,ik} \leq P_{HIL,ik}^{\max}$$

and constrains (12)-(16)

The decision variable in this model is  $P_{HIL,ik}$ .

### 5 Solution to the Acquisition of Disco

The Disco energy acquisition model, Eqs. (9)-(20), is a bi-level optimization problem, where the upper level represents the decision maker Disco, while the lower level is for the ISO's market clearing. GABLO is used to solve this model. For the convenience of description, we first introduce the basic idea of GABLO, and then derive the solution approach.

#### 5.1 Bi-Level Optimization

Bi-level Problem (BP) is one of the basic types of optimization systems in that for the objective function of the upper-level problem is decided by the solution function of the lower-level problem which, generally speaking, as shown in Fig. 2, is neither linear nor differentiable.

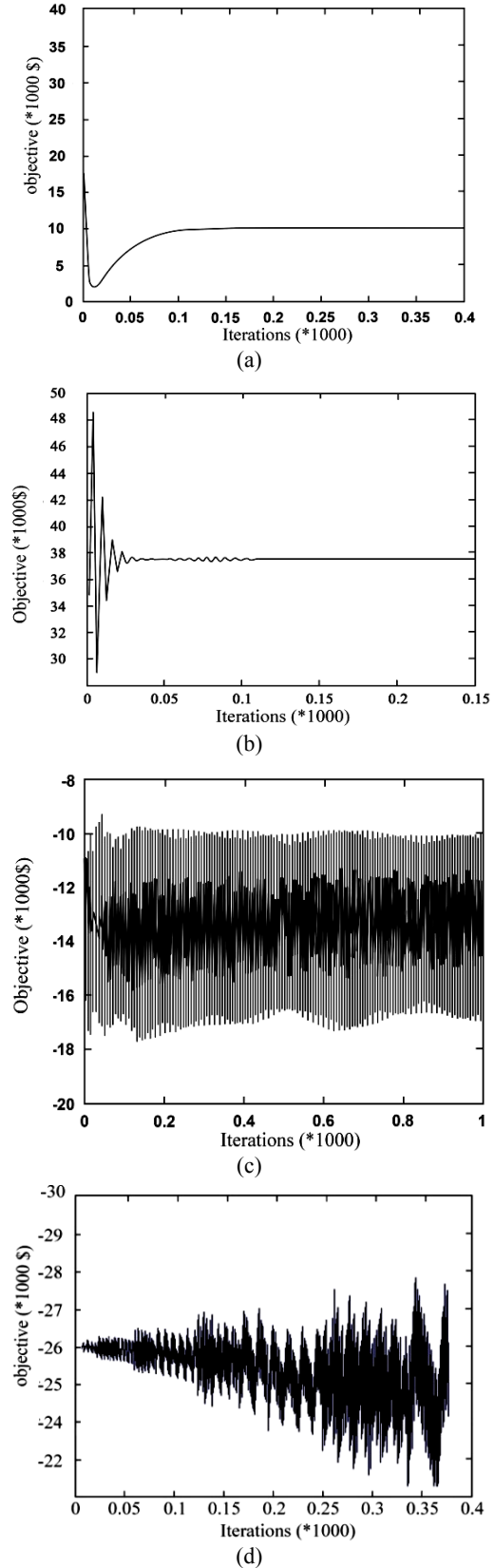


Fig. 2 Four possible behaviors of the search trajectory.

Although the objective function and the constraints of the upper subproblem and lower subproblems include linear constraints, the BP is neither continuous everywhere nor convex. When constraints or cost functions are quadratic, the problem can be solved by a large number of mathematical approaches [12] that can be classified into local and global searches such as gradients descent, Newton's method, conjugate-gradient method, Lagrange multiplier method, etc. When constraints or cost functions are linear, discrete or special forms, as shown in Fig. 2; convergence or unconvergence and convergence speed reduction can be occurred. Four possible behaviors of the search trajectory are:

- (a). The trajectory converges without oscillations (when cost functions are quadratic, case 2A in section 6.2);
- (b). The trajectory gradually reduces its oscillations and eventually converges (When some cost functions are linear, case 2B in section 6.2);
- (c). The trajectory oscillates within some range but never converges (When cost functions are discrete form, case 2C in section 6.2 with cement factory);
- (d). The magnitude of oscillations increases and the trajectory eventually diverges (When cost functions are discrete form). Obviously, the first two cases are desirable, and the other two are not.

This work studies and completes GA of BP that avoids the use of penalty function to deal with the constraints, by changing the randomly generated initial population into an initial population satisfying the constraints in order to improve the ability of the GA to deal with the constraints [13].

### 5.2 Using Genetic Algorithm Bi-level Optimization (GABLO)

The solution strategy named GABLO shown in Fig. 3. The basic idea solving BP by GA is as follow: firstly, choose the initial population satisfying the constraints, and then the lower-level decision maker creates the corresponding optimal reaction and evaluates the individuals according to the fitness function constructed by the feasible degree, until the optimal solution is searched by the genetic operation repeatedly. After the initialization of the Upper Subproblem population (US), the members represented are copied from the Lower Subproblem (LS) into the population. Selection, crossover and mutation operations are similar to conventional simple GA technique. The sort operator is designed to give a larger selective preference to the fitter members of the population when the co-evolutionary operator is invoked. It sorts the population in descending order of fitness with the fittest member towards the front end of the population and the less fit members towards the back end of the population. An external elite population is maintained to identify the elite members of both populations after the co-evolutionary operator for every generation. Members in

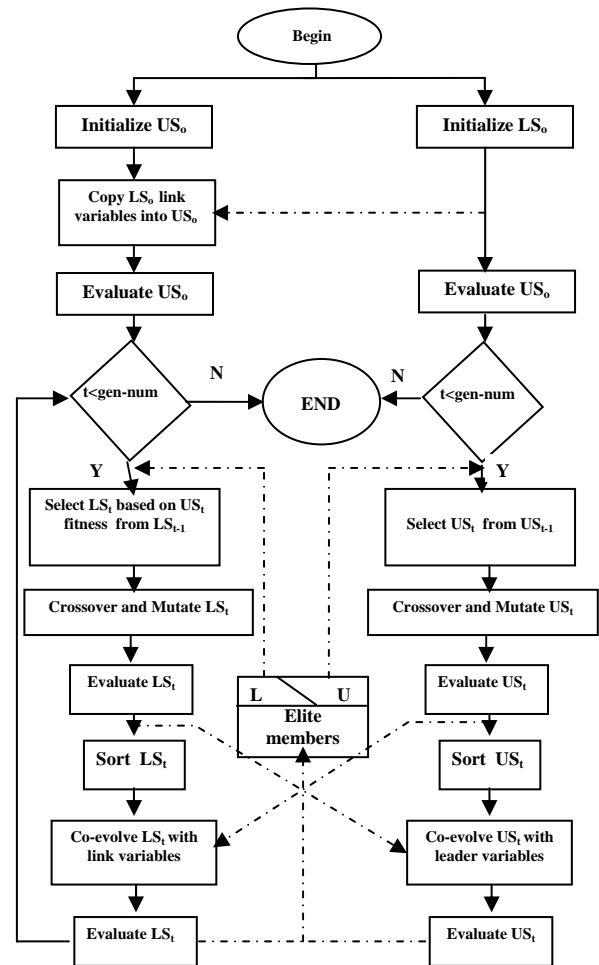


Fig. 3 GABLO flowchart.

the elite population are replaced with the best members from current generation if best members are fitter than the elites are.

### 5.3 Distribution Company Energy Acquisition Model as a GABLO

In this section, Disco energy acquisition model will be formulated as a bi-level optimization problem, the upper subproblem represents Disco's profit problem, and the lower subproblem, which shows the ISO's market clearing model. The final equilibrium point is the point on that Disco's profit is maximized. Lower subproblem (LS problem) can be formulated as in Eqs. (21)-(27).

$$\min \left[ \left( \sum_{i=1}^{N_g} \sum_{k=1}^{24} (\alpha_{ik} p_{Gik}^2 + \beta_{ik} p_{Gik} + \gamma_{ik}) u_{ik} \right) \right] \quad (21)$$

$$+ \left( \sum_{i=1}^{N_{UL}} \sum_{k=1}^{24} CLIL_{i,k} \right) \quad (22)$$

s.t.  $p_{G,ik}^{\min} \leq p_{G,ik} \leq p_{G,ik}^{\max}$

$$-p_{ij,k}^{\min} \leq p_{ij,k} \leq p_{ij,k}^{\max} \quad (23)$$

$$p_{G,ik} - p_{G,i(k-1)} \leq Ru_{G,ik} \quad (24)$$

$$p_{G,i(k-1)} - p_{G,ik} \leq Rd_{G,ik} \quad (25)$$

$$\sum_{i=1}^B \sum_{j=1}^B p_{ij} x_{ij} = 0 \quad (26)$$

$$P_{LIL,ik}^{\min} \leq P_{LIL,ik} \leq P_{LIL,ik}^{\max} \quad (27)$$

The decision variables in this model include  $p_{G,ik}$  and  $p_{ij,k}$ . Upper subproblem (US problem) can be formulated as Eq. (28).

$$\begin{aligned} \max & \left[ \left( \sum_{i=1}^{BD} \sum_{k=1}^{24} (\lambda_k (P_{D,ik}^{\max} - P_{LIL,ik} - P_{HIL,ik})) \right) \right. \\ & \left. - \left( \sum_{i=1}^{BD} \sum_{k=1}^{24} [\rho_{Dik} \cdot (P_{D,ik}^{\max} - P_{LIL,ik} - P_{HIL,ik})] \right) \right] \\ & - \sum_{i=1}^{BD} \sum_{k=1}^{24} (C_{HIL,ik}) \end{aligned} \quad (28)$$

s.t.

$$P_{HIL,ik}^{\min} \leq P_{HIL,ik} \leq P_{HIL,ik}^{\max}$$

and constrains (22)-(27)

## 6 Application to a Real Network

An eight-bus system, Mashhad electric distribution company (MEDC) is used to illustrate the proposed model and solution algorithm.

### 6.1 System Description

A scheme showing the main features of MEDC and central interconnected system is presented in Fig. 4. This system includes three Gencos, and six interruptible loads. The Disco is fed by four step-down substations from the central interconnected system.

In MEDC region, as shown in Table 1, there are six interruptible loads. For analyzing the effects of realistic model of interruptible loads, Mashhad Cement factory is considered. Model of other interruptible loads assumed to be as described in section 6.2.

Cement production process generally, as shown in Fig. 5 includes three main parts:

1. Before the furnace, includes Grinding, Crushing, Raw mill, homogenizing silos and pre blending bin.
2. Baking system includes Furnace, Cooler, and Pre heaters.
3. Final system includes Rotary Klin, silos, and dispatching.

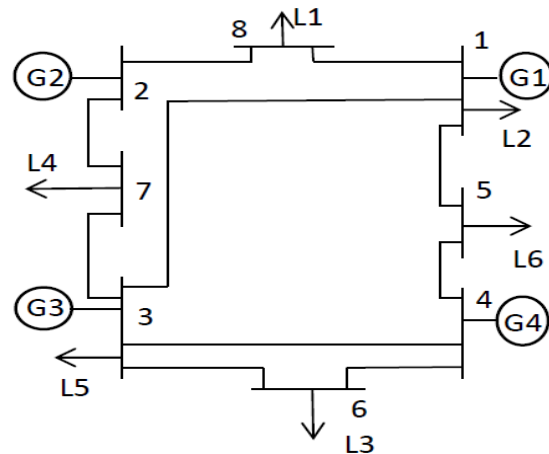
First, Raw materials arrive in part 1 and in this part; they are converted to a compound powder. In part 2, this compound powder converted to clinker that is bullet form. In part 3, this clinker is converted to final cement

and prepared for transporting. Here, we have 4 intervals and 11 sub-processes. Equipment is categorized into five groups based on their controllability. Table 2 shows the plant equipment ratings and details.

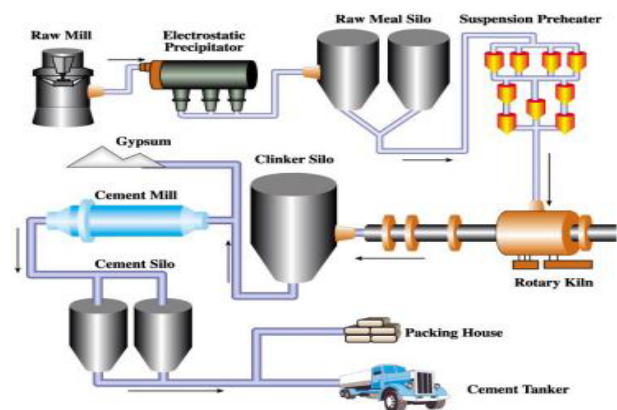
Solving of the optimization problem, Equations (1)-(8), shows that Mashhad Cement manufacturer can participate in IL programs as shown in Fig. 6 in which  $t_1$  is start time of ILM program.

**Table 1** Interruptible load programs in test system.

Name	IL type	Minimum Curtailment (MW)	Maximum Curtailment (MW)	Bus
Ghods agriculture industries	HIL	2.5	12	8
Part lastic factory	LIL	1.75	11.2	5
Pegah factory	LIL	1	11.3	5
Mashhad Cement factory	HIL	1.26	2.83	7



**Fig. 4** Real case study.



**Fig. 5** Cement production process.

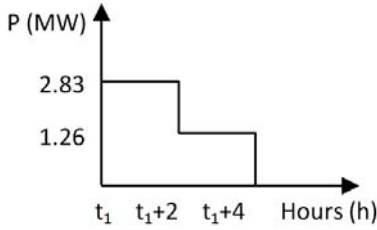


Fig. 6 Cement factory (as IL) offer for interruption.

Table 2 Plant equipment for LM actions.

Description	Production capacity t/hr	Rated kWh/t	Capacity utilization (u)	Efficiency (E)
Sp <sub>1</sub> , Sp <sub>2</sub>	200	2.4	0.95	0.9
Sp <sub>3</sub>	175	28	0.9	0.85
Sp <sub>4</sub> , Sp <sub>5</sub> , Sp <sub>6</sub>	170	14.6	0.9	0.9
Sp <sub>7</sub> , Sp <sub>8</sub>	165	23.4	0.85	0.75
Sp <sub>9</sub> , Sp <sub>10</sub>	150	43.5	0.9	0.9
Sp <sub>11</sub>	120	1.1	0.98	0.95

Table 3 Transmission Lines Data.

Line	From bus	To bus	X (p.u.)	Power limit (MW)
1	1	3	0.090	34
2	1	5	0.020	120
3	1	8	0.025	40
4	2	7	0.025	20
5	2	8	0.020	32
6	3	4	0.055	12
7	3	6	0.025	120
8	3	7	0.012	16
9	4	5	0.020	23
10	4	6	0.023	32

Table 4 Gencos' Data.

Genco	P <sub>min</sub> (MW)	P <sub>max</sub> (MW)	a (\$/(MWh) <sup>2</sup> h)	b (\$/MWh)	g (\$/h)
G1 (Toos)	0	600	0.09	54.76	685
G2 (Shariati)	0	160	0.13	65.57	712
G3 (Mashhad)	0	160	0.21	76.53	840
G4 (Ferdowsi)	0	450	0.07	46.94	650

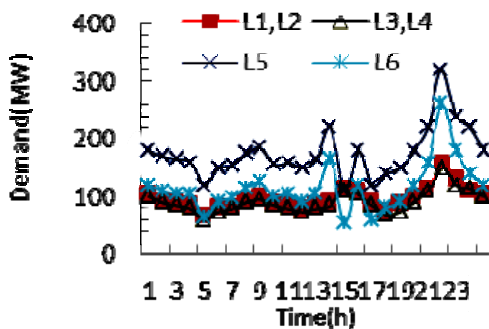


Fig. 7 MEDC Demand Profile.

Detailed information on test system, IL types, Gencos, DGs, and transmission lines are shown in Tables 1-4, which are assumed the same for all hours. Demand profile for 24 trading periods is shown in Fig. 7 as well.

## 6.2 Comments

MEDC 8-bus system shown in Fig. 7 is used to illustrate proposed model and solution algorithm. In this work, it is assumed that:

- price that Disco charges its customers for energy is
 
$$\lambda = \begin{cases} 50 \$ / MWh \text{ at } 6:00 - 19:00 \\ 70 \$ / MWh \text{ at } 19:00 - 23:00 \\ 30 \$ / MWh \text{ at } 23:00 - 6:00 \end{cases} \quad (29)$$
- All generator's ramping-up and ramping-down rates are  $Ru_G = Rd_G = 20$  MW/h (for G2, G3), and  $Ru_G = Rd_G = 50$  MW/h (for G1, G4)
- The costs for power suppliers to implement LIL management are as in Eq. (30).

$$C_{LIL} = \delta \lambda (P_{LIL} - p_{LIL}) t_{LIL} + \lambda p_{LIL} t_{LIL} \quad (30)$$

- The costs for power suppliers to implement HIL management are as in Eq. (31).

$$C_{HIL} = \lambda p_{HIL} t_{HIL} + \rho_D p_{HIL} t_{HIL} \quad (31)$$

The strategy of Disco depends on the demand and LMPs of day-ahead market. From Fig. 7, we can see that demand increases slowly for the hours before 18:00 and after 23:00. Therefore, the impact of ramping-up and ramping-down limits on LMPs can be ignored and the optimal solutions for those hours do not depend on other hours.

**Case 1:** Considering three continuous periods 18:00–19:00–20:00. In this case, ramping limits for some generators are active and flow limits for some lines are also active. Three periods are linked with each other too.

1) G3 is an expensive unit compared with G1, G2, and G4. Its generation will be as small as possible if ramp limits are not considered. When there is another 1 MW of load increment at Bus 3 in the system, G3's generation increases by more than 1 MW while the generations of other cheap units decrease due to transmission congestion, which leads to high LMPs.

2) However, generation of G3 increases at 18:00 once ramp limits are enforced. When the same 1 MW load increment occurs at Bus 1, G3's generation does not change at all. Thus, LMPs are lower although ramping limits are active. This also indicates that the decrease of cheaper power or the increase of more expensive power can cause less congestion to a certain extent. Because the LMPs at 18:00 are lower, the Disco would like to purchase more energy from the day-ahead market. Thus, their LIL programs are less than those are when no ramping limits are enforced. Ramping limits have smaller impact on the LMPs at 19:00. With the

increase of demand and due to ramping-up limits, the LMPs at 20:00 are much higher. So more LILs are utilized in order to maximize Disco's profits. The same analysis can be made to the trading periods 21:00–22:00–23:00, where ramping-down limits are active.

**Case 2:** This case is to analyze the roles of LIL and HIL when congestion occurs in the system. Ramping limits are not considered in this case. Demands in the system are at their peak with L1, L2=165 MW; L3, L4=150 MW; L5 =310 MW, and L6=245 MW. Three subcases are considered as follows:

- 2A. Disco has no LIL and HIL;
- 2B. Disco has LIL but no HIL;
- 2C. Disco has both HIL and LIL.

The comparisons of Disco's optimal strategy, Disco's profit, LMPs, cost for Gencos, and IL's costs are shown in Table 5.

From Table 5, the following observations can be made.

1) In Case 2A, congestion leads to much high LMPs. Disco's profit is negative since it has no LIL and HIL and can only purchase energy from the day-ahead market with high prices.

2) In Case 2B, Disco would prefer to use LIL when market prices are high. The net demand decreases and LMPs decrease significantly compared to those in Case 2A so that its profit increases accordingly. This means that congestion offers potential incentive to Disco to be developed using of LILs.

**Table 5** Results.

Case	2A	2B	2C
LIL (MW)	0	32.5	21.2
HIL (MW)	0	0	14.83
DAM (MW)	1185.2	1152.7	1149.17
Total (MW)	1185.2	1185.2	1185.2
Profit (\$)	-17217.41	13563.57	21738.64
Gencos' Cost (\$/h)	100165.73	974761.27	81235.52
LMP at Bus1 (\$/MWh)	25.34	24.39	21.86
LMP at Bus2 (\$/MWh)	162.84	92.57	74.61
LMP at Bus3 (\$/MWh)	135.42	96.64	82.14
LMP at Bus4 (\$/MWh)	32.87	26.31	24.12
LMP at Bus5 (\$/MWh)	23.64	22.57	22.01
LMP at Bus6 (\$/MWh)	27.46	23.82	20.57
LMP at Bus7 (\$/MWh)	125.37	87.23	67.24
LMP at Bus8 (\$/MWh)	28.97	29.34	27.21

3) Besides LIL, HIL is a useful resource to mitigate congestion as shown in Case 2C. When Disco's demand is interrupted, LMPs are lower than those are in Case 2A. This means that Disco will be encouraged to sign flexible HIL contracts with the end customers. It should be pointed out that the cost of HIL is usually higher than the cost of LIL. So in general, LIL is more suitable to be used in emergency states. Where there are HILs and LILs in the system, the proposed model can help Disco make its energy purchase plan to maximize its profit.

4) When LIL and HIL participate in the competition of day-ahead market (Cases 2B-2C), the ISO pays less money to Gencos, which can restrict Gencos' capabilities of earning more profits by means of capacity withholding and strategic bidding.

## 7 Conclusion

In this paper, a novel day-ahead energy acquisition-programming model for a distribution company was proposed. One of the most important concepts introduced was considering real assumption for interruptible load modeling. The proposed concept can be employed to gain good understanding of interruptible load modelling. Therefore, it can be useful in studies of the energy acquisition programming for distribution companies. The achieved results can assist the market operator and distribution companies to make the best decisions. In this paper, it is shown that a Disco can obtain the best mix of energy acquisition from the Gencos and Interruptible loads. Results showed that increasing in Disco's profit and decreasing in ISO payments to Gencos (decreasing the generation cost) could be happened. Moreover, the proposed concept could be used with distributed generation units (DG's), in the future researches.

## Appendix

The nomenclature is as follows.

$K$	Index for hours.
$i, j$	Index for buses.
$\alpha, \beta, \gamma$	Generation bid coefficients.
$P_G$	Generation awarded to a Genco.
$P_G^{min}$	Lower limit on bid quantity submitted by a Genco.
$P_G^{max}$	Upper limit on bid quantity submitted by a Genco.
$R_{uG}$	Ramping up limit submitted by a Genco.
$R_{dG}$	Ramping down limit submitted by a Genco.
$U$	Unit commitment variable.
$P_{ij}$	Line flow of line $i-j$ .
$P_{ij}^{min}$	Lower flow limit on line flow of line $i-j$ .
$P_{ij}^{max}$	Upper flow limit on line flow of line $i-j$ .
$X_{ij}$	Reactance of line $i-j$ .
$N_g$	Set of Genco buses.



$P_D^{max}$	Maximum demand of Disco.
$B$	Set of all buses.
$B(i)$	Set of buses connected to bus $i$ .
$l$	Set of independent loops.
$BS$	Set of all branches.
$BSl$	Set of branches in independent loop $l$ .
$BD$	Set of Disco buses.
$BLI$	Set of LIL buses.
$BHI$	Set of HIL buses.
$GS$	Set of Gencos.
$TS$	Set of hours.
$\rho_G$	LMP paid to a Genco.
$\rho_D$	Electricity market price (LMP paid by Disco).
$P_D$	Net demand of Disco.
$p_{LIL}$	LIL granted to Disco.
$P_{LIL}^{min}$	Lower limit of LIL.
$P_{LIL}^{max}$	Upper limit of LIL.
$\delta$	Discount factor.
$P_{LIL}$	Maximum curtailed amount signed under LIL contract.
$t_{LIL}$	The hours of the LIL to be interrupted.
$P_{HIL}$	HIL curtailed by Disco.
$P_{HIL}^{min}$	Lower limit of HIL.
$P_{HIL}^{max}$	Upper limit of HIL.
$t_{HIL}$	The hours of the HIL to be interrupted.
$\lambda$	Disco's retail energy rate.
$N_t$	Set of time intervals.
$t$	Time interval.
$i$	Subprocess binary decision variable
$P_{mi}$	Production rate of machine $m$ in the interval $i$ .
$q_{mi}$	Output of machine $m$ in the interval $i$
$E_{mi}$	Efficiency of the machine or device.
$UF_{mi}$	Utilization factor of the device.
$KVA_{mi}$	Maximum demand limit.
$EP_{mi}$	Electrical power input in kW.
$R_{mi}$	Rated capacity of the machine/device in kW.
$pf_{mi}$	Power factor of the machine for the interval.
$S$	Storage at the end of a sub-process.
$C_i$	Cost of energy for the interval $i$ .
$C_{ai}$	Additional cost of LM actions for the interval $i$ .

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