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Optimal Design of an Interruptible Load Program from the Viewpoint of an Industrial Customer

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The interruptible load program (ILP) is one of the most common demand response programs, which is often used by industrial customers. The purpose of implementing this program is to reduce the customer's peak demand in response to the incentives set by a contract. If no attention is paid to characteristics of the industrial customer's production process, the participation in ILP will not be possible. Therefore, complying with customer's technical constraints and optimal design of the program is of great importance. This study aims to present a new model for the optimal design of ILP from the perspective of a cement manufacturing company as an industrial customer. In this regard, the manufacturing process and the constraints of operation of a cement plant are fully modeled and all relevant constraints and requirements are considered. The objective function is the maximum profit, so the ILP is designed such that the cement plant's profit can be maximized without disrupting the normal performance of the production process. The proposed optimization problem is a mixed-integer non-linear one for which a suitable genetic algorithm is designed and used. In the proposed approach, the optimal incentive level is determined by assuming a specific budget level (related to the power company). The implementation of the proposed optimal design will satisfy the power system operator for reducing peak demand and the customer for earning more profit.

Article Info

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I. INTRODUCTION

A. Motivation

In recent years, load management in power system operations has been of great concern. This issue is mainly referred to as demand response (DR) programs. DR is defined as changing customers' consumption patterns in response to changes in electricity prices or to incentives designed when the price is high or the grid reliability is compromised.

About one-third of Iran's electricity demand is consumed in the industrial sector. So, implementing DR programs by industrial customers can play an important role in peak demand management.

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In fact, with the participation of industrial customers in DR programs, the huge cost of building new power plants could be reduced.

Interruptible load program (ILP) is a type of DR program that is often implemented based on a contract between the power company and the industrial customers. In this program, customers will receive incentives to reduce consumption during specified hours, or they will be penalized in the case of failure to comply with it/s obligation. To date, various studies have been conducted on ILP, but little has been done on the optimal design of this program. This paper aims to study the optimal design of ILP.

B. Literature Review

Many research works have investigated the issue of DR

and ILP. The following is a review of some of them, especially those related to industrial loads.

Some references have reviewed the ILP implementation from the viewpoint of industrial customers. For example, in [1], customers' flexible potential in the meat industry in Spain is analyzed. The results indicate that it is possible to reduce the factory's demand by 23%. In [2], the potential of implementing DR programs for major Swedish industries, such as the steel and the paper industries, is determined by considering the characteristics of each one. In [3], it is argued that the goal of a large manageable load modeling is to participate in DR programs and to provide an interruptible load pattern. To this end, the process of vegetable oil production is modeled and the presented interruptible load pattern is implemented on a real data distribution network. In [4], the capacity obtainable from large-scale industries and its role in improving the performance of the German electricity market are studied. Various industrial manufacturing processes, such as steel, have been investigated from technical and economic perspectives to determine this capacity. In [5], the feasibility of implementing ILP in the steel industry has been studied. Four main processes of direct reduction, melting, casting, and rolling are considered as the main processes of the production line. By implementing interruptible load management programs, the steel manufacturer aims to maximize its profit. The model is simulated by taking the constraints of the steel manufacturing process into account.

Reference [6] focuses on ILP and capacity market programs, which are a part of incentive-based programs. The authors develop an economic model for responsive load using the concept of price elasticity of demand and the customer utility function. In [7], energy management techniques are examined in the cement industry. According to the results, monitoring the power of the cement plant will reduce the damage, improve load management, and increase in the power quality. In [8], interruptible load optimization is investigated by taking the uncertainty of the customer response and the total interruptible capacity into account. In [9], a technique is presented for technical, economic, and environmental analysis of the DR program implementation at a paper mill in Germany. In [10], a contract is designed for industrial processes connected to the smart grid. In a case study, a chlor-alkali manufacturing plant is investigated, which has three main sub-processes of thermodynamic, electrochemical and thermal. In [11],[12]-[15], the authors examine the ILP based on modeling in the marketplace with the aim of maximizing the profits of distribution companies and customers.

In the field of demand response, the following can be mentioned. In [16], DR mathematical models, existing problems, and potential future challenges in the field of DR are reviewed comprehensively. In [17], a new economic model is proposed for DR with respect to consumption and budget constraints. In [13], the effect of demand response linear and nonlinear modeling is investigated on different levels of a load of several real electricity markets. In [18]-[19], a price and incentive-based economic model is provided for responsive loads based on the concept of flexibility of price elasticity of demand and customer utility function. The objective in [3] is to model a large manageable load to participate in load management programs and to provide an interruptible load pattern. In [20], an optimal strategic offering model is proposed to maximize the profit of distribution companies. In this model, it is assumed that distribution companies have distributed generation and interruptible load. The proposed model is formulated as a bi-level optimization problem. Table I shows some works on the production process of industrial customers.

TABLE I
RESEARCH WORKS ON PROCESS MODELING IN THE CONTEXT OF ILP

Reference	Case study about ILP
[1]	Meat industry in Spain
[2]	Steel and the paper industries in Swedish
[3]	Vegetable oil production
[4]	Steel industry in German
[5]	Steel industry in Iran
[7]	Cement industry
[8]	A set of industrial loads
[9]	Paper factory
[10]	Chlor-alkali

In [21], an optimization model is presented in which ILP is considered as a reserve source for peak shaving. In the load-scheduling model of [22], both the aggregator and customers participate in the DR program. The authors of [23] investigate the usefulness of DR in a German power system. They conclude that DR has significant potential in the short-term shifts but not in the longer one. In [24], an improved interruptible load management scheme is proposed to maximize social welfare. In [25], a new evolutionary optimization framework for interruptive demand response is introduced to adjust the peak of the demand curve. Reference [26] analyzes the effect of industrial consumer participation in the electricity market. In [27], using the price elasticity concept, ILP is modeled in the energy management problem of integrated energy storage and photovoltaic system.

In [28], a new approach is proposed for designing a time-based DR program. The summary of the recent research works in this area is shown in Table II. The main contribution of our research is proposing an optimization model to design an ILP for an industrial customer, considering the technical constraints of its production process. In addition, we investigate the budget limit effects on the ILP program implementation. This issue has not been studied in previous research.

TABLE II
CATEGORIZATION OF RECENT RESEARCH WORKS

Ref no.	Year	Industrial Case Study	Modeling the Production Process	Analyzing or Designing	Considering Time-based DR	Considering Incentive-based DR	Budget Limits Consideration
[13]	2016	–	–	Analyzing	✓	✓	×
[10]	2016	Chlor alkali	✓	Analyzing	✓	✓	×
[23]	2017	–	–	Analyzing	✓	✓	×
[24]	2018	–	–	Designing	×	✓	×
[21]	2018	–	–	Analyzing	✓	✓	×
[26]	2018	–	×	Designing	✓	✓	×
[25]	2018	Synthetic smart grid	×	Analyzing	×	✓	✓
[22]	2018	Chemical fiber plant Cast steel plant Food factories	–	Designing	✓	✓	×
[27]	2019	–	–	Analyzing	✓	✓	×
[28]	2019	–	–	Designing	✓	×	×
Our paper		Cement factory	✓	Designing	✓	✓	✓

C. Contribution

This study aims to design an optimal ILP from the perspective of a cement manufacturing company as an industrial customer. In this regard, the manufacturing process and constraints of the operation of a cement plant are modeled. The objective function of the industrial customer is to gain the maximum profit, so the program should be designed in such a way that the customer's consumption cost is minimized without damaging the manufacturing process. By adopting DR programs, the customer can gain more income without disrupting its normal performance.

The new model for the optimal design of an ILP is presented from the viewpoint of the industrial customer. In this regard, the manufacturing process of the industrial customer (here the cement plant) is fully modeled and all relevant constraints and requirements are considered. By this optimization, the level of incentives, penalties, and optimal contracts are determined by assuming a certain budget level (for the power company). By implementing the proposed ILP, the industrial customer can participate in the ILP without creating damage to the manufacturing process and enjoy its economic benefits. This will result in peak reduction and the system operator's satisfaction.

It should be noted that the optimal designing of the ILP could be studied from the viewpoint of the system operator or customer. This paper addresses the issue from the viewpoint of the customer, and in another study, the design will be examined from the perspective of the operator.

D. Paper Organization

The rest of this paper is organized as follows. The mathematical formulation of the proposed model is given in Section 2. The case study and the simulation results are represented in Sections 3 and 4. Finally, the paper is concluded in Section 5.

II. THE PROPOSED MODEL

The cement manufacturing process can be modeled as shown in Figure 1. The production line consists of four main processes: Crusher (CR), Raw Mill (RM), Kiln (KL) and Cement Mill (CM) [29]. The storage related to each process is shown with a cylinder. The processes before the crusher and after the cement mill (loading section, etc.) are ignored because of their negligible role in total energy consumption.

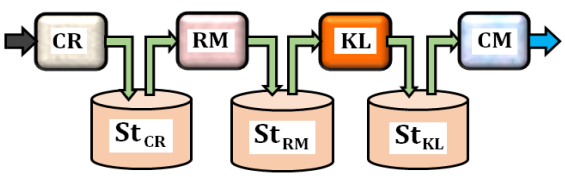

Fig. 1. The cement manufacturing process

A. The Proposed Objective Function

The objective function of the ILP design is proposed based on the profit of the cement company. In the proposed optimal design problem, all the features and constraints of the cement manufacturing process are taken into account. According to Equ. (1), the objective function consists of two parts:

Total profit = The profit of cement sales + The profit of participation in ILP

$$\textbf{Max } \text{Profit}_{\text{Total}} = \underbrace{(\pi_{Cement} - \text{Cost}_{\text{Cement}}) \times \text{Cement}_{\text{Total}}}_{\text{Profit}_{\text{Cement}}} + \text{Profit}_{\text{ILP}} \quad (1)$$

where

$$\text{Cost}_{\text{Cement}} = \underbrace{\sum_{h=1}^{T} \text{Tariff}_{\text{Elec}}(h) \times \text{Energy}_{\text{Elec}}(h)}_{\text{Cost}_{\text{Elec}}} + \underbrace{\beta \times \text{Cement}_{\text{Total}}}_{\text{Cost}_{\text{Non-Elec}}} \quad (2)$$

$$\text{Energy}_{\text{Elec}}(h) = \underbrace{ET_{CR} \times OP_{CR}(h)}_{E_{CR}(h)} + \underbrace{ET_{RM} \times OP_{RM}(h)}_{E_{RM}(h)} + \underbrace{ET_{KL} \times OP_{KL}(h)}_{E_{KL}(h)} + \underbrace{ET_{CMR} \times OP_{CM}(h)}_{E_{CM}(h)} \quad (3)$$

$$\text{Profit}_{\text{ILP}} = \sum_{h=1}^{T} \left\{ \begin{array}{l} \left\{ \begin{array}{l} Aw(h).IL(h) - \\ U(h).\lambda.Aw(h)\left[IL(h) - \text{Contract}\right] \end{array} \right\} \\ +(1-U(h)).Pen(h).\left[\text{Contract} - IL(h)\right] \end{array} \right\} \quad (4)$$

$$U(h) = \begin{cases} 1 & \text{IL(h)} \geq \text{Contract} \\ 0 & \text{IL(h)} < \text{Contract} \end{cases} \quad (5)$$

in which:

$\text{Profit}_{\text{Total}}$: total profit of the cement company

$\text{Profit}_{\text{Cement}}$: profit of cement sales

$\text{Profit}_{\text{ILP}}$: profit of participating in ILP

π_{Cement} : sales price per ton of manufactured cement

$\text{Cost}_{\text{Cement}}$: manufacturing cost per ton of cement (including electrical and non-electric costs)

B : non-electrical cost per ton of cement

$\text{Energy}_{\text{Elec}}(h)$: the electrical energy consumed by manufacturing process per hour (total energy consumption of the crusher, raw mill, kiln, and cement mill processes)

$\text{Profit}_{\text{ILP}}$ includes incentives and penalties based on the comparison of company performance with its obligations as per the contract. Meanwhile, for brevity and simplicity in writing the next equations, the four processes of cement manufacturing are indicated with subscripts i from 1 to 4 corresponding to the processes of crusher, raw mill, kiln, and cement mill, respectively. Other symbols used in the above and next equations are:

Variables:

$OP_i(h)$: the output of the process i performance at the h-th hour (ton/h)

$St_i(h)$: the storage amount of the process i (ton)

$IL(h)$: the amount of load reduction at the h-th hour (kW)

$Aw(h)$: the amount of incentive per hour

$Pen(h)$: the amount of penalty per hour

Contract : the level of contracted load reduction in the ILP of the cement company

$U(h)$: a binary variable to separate two modes of incentives and penalties

$Payment_{Operator}$: the amount paid by the operator to the cement company to reduce the load

Parameters:

ET_i : energy required to manufacture a ton of product in the process i (kWh/ton)

OP_i^{Max} : the rated capacity of the process i in tons per hours of the product manufactured

St_i^{Max} : the rated capacity of storage of the process i (ton)

η_i : the output to input product weight ratio of the process i

OP_i^{Min}, OP_i^{Max} : the minimum and maximum operational capacity of each process (ton/h)

$Energy_{Non-peak}^{Max}$: the amount of contract demand for the cement company

$Energy_{peak}^{max}$: the maximum energy consumption during peak hours by implementing ILP

$Cement_{Plan}$: the amount of planned cement manufacturing

Budget : the maximum budget that an operator can pay to a customer to participate in ILP

$Tariff_{Elec}(h)$: electricity tariff at the h-th hour

$Hours_{specified}$: the hours that the crusher must be off.

λ : incentive reduction coefficient (for when IL is greater than the contract level)

Aw^{Min}, Aw^{Max} : minimum and maximum incentive per hour

Pen^{Min}, Pen^{Max} : minimum and maximum penalty per hour

IL^{Max} : the maximum allowable value of the reduced load

Equ. (4) indicates the amount of money that the cement company receives or is penalized by the implementation of ILP. As such, the customer receives an incentive by participating in the program and reducing its load consumption during peak hours. If it reduces the load more than the contract level, it will receive less incentive (corresponding to λ). Moreover, if it reduces its consumption less than the contract level, it will be penalized according to its violation. According to Equ. (5), the variable U specifies the status of intensive and penalty. In this way, its value is 1 for an IL equal to or greater than the contract level; otherwise, its value is 0.

B. Cement Production Process Constraints

A cement factory has four main production units in the production process chain. Each unit has some technical limitations such as minimum/maximum of the production rate, the constraint of time to be in service or not, and so on [30]. The produced material of each unit is sent to its reservoir as shown in Figure 1. The input material of each production unit is provided from the previous unit reservoir. Therefore, the material stored in each reservoir depends on the operation of the two units around it. This relationship can be expressed by a constraint. In addition, there is a relation between the weights of the output product and the input raw materials of each process. In summary, we can say that an operator should determine the production pattern, while the technical constraints are taken into account for a specified production over a planning horizon.

The total cement manufactured by the company is obtained from Equ. (6). Equ. (7) indicates the relationship between how the processes operate and each storage amount per hour. The constraint of the output product weight to input raw materials weight ratio of each process per hour is given in

Equ. (8). In Equ. (9), the constraint of the minimum and maximum operational capacity of each process is applied. In Equ. (10), the constraint of storage capacity is expressed and according to Equ. (11), the storage capacity at the end of the period should be equal to or greater than the initial amount in the storage. The constraint of the crusher being off at night (according to the real data received from the cement plant) is also given in Equ. (12).

$$\text{Cement}_{\text{Total}} = \sum_{h=1}^{T} OP_{CM}(h) \geq \text{Cement}_{\text{Plan}} \quad (6)$$

$$St_i(h) = St_i(h-1) + OP_i(h) - OP_{i+1}(h) \quad i = 1,2,3 \;\&\; \forall h \quad (7)$$

$$\sum_{h=1}^{T} OP_{i+1}(h) \leq \eta_{i+1} \times \sum_{h=1}^{T} OP_i(h) \quad i = 1,2,3 \quad (8)$$

$$OP_i^{Min} \leq OP_i(h) \leq OP_i^{Max} \quad \forall h \;\; \forall i \quad (9)$$

$$0 \leq St_i(h) \leq St_i^{Max} \quad \forall h \;\; \forall i \quad (10)$$

$$St_i(0) \leq St_i(T) \quad \forall i \quad (11)$$

$$OP_{CR}(h) = 0 \quad h \in \{\text{Hours}_{\text{specified}}\} \quad (12)$$

C. Technical and Economic Constraints of ILP Design

An effective design needs to properly coordinate the economic and technical aspects of the problem. Therefore, we proposed and used some necessary restrictions on ILP designing. In this section, two type constraints are presented as follow:

• Three constraints to limit the interruptible load and the consumed electrical energy.

• Four constraints on the economic aspects of ILP designing.

In this regard, Equ. (13) and (14) indicate the maximum energy consumption in peak and non-peak hours, respectively. The permitted interruptible load is expressed in Equ. (14). According to Equ. (16), the budget allocated for payment to interruptible load by the power company is constrained. Equ. (17) to (19) express the minimum and maximum limits for the variables of the ILP design (i.e., incentive, penalty, and contract level).

$$Energy_{Elec}(h) + IL(h) \leq Energy_{peak}^{Max} \quad h \in \text{Hours}_{\text{peak}} \quad (13)$$

$$Energy_{Elec}(h) \leq Energy_{Non-peak}^{Max} \quad h \in \text{Hours}_{\text{Non-peak}} \quad (14)$$

$$0 \leq IL(h) \leq IL^{Max} \quad \forall h \quad (15)$$

$$\text{Payment}_{\text{Operator}} = \text{Profit}_{\text{DR}} \leq \text{Budget} \quad (16)$$

$$Aw^{Min} \leq Aw(h) \leq Aw^{Max} \quad \forall h \quad (17)$$

$$Pen^{Min} \leq Pen(h) \leq Pen^{Max} \quad \forall h \quad (18)$$

$$Contract^{Min} \leq Contract \leq Contract^{Max} \quad (19)$$

The flowchart of our approach is displayed in Figure 2. As can be seen in this figure, three variables including the amount of incentive/penalty and the level of contracted load reduction are determined based on the GA chromosomes. The other variables are recognized by running the cement production problem. Therefore, the electrical energy consumed by the manufacturing process and hence the cement production cost is identified. Then, the profit of participating in ILP including incentives/penalties based on the contract is calculated. Finally, the objective function as Equ. (1) can be evaluated. This iterative process continues until the stop criterion is satisfied.

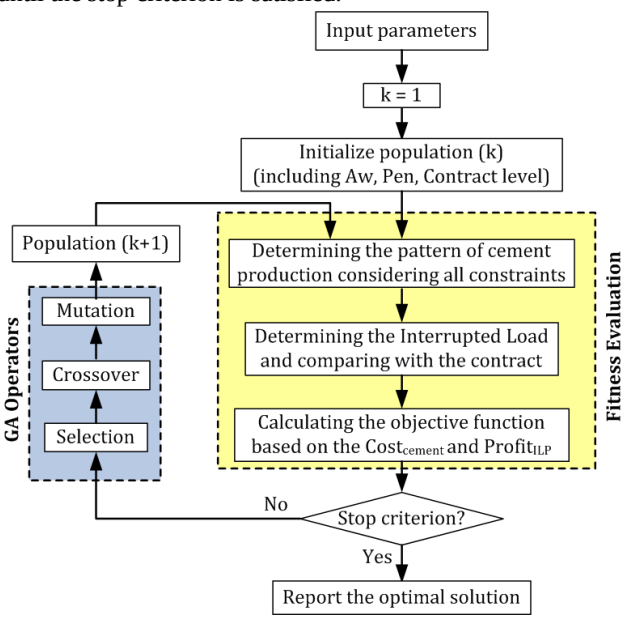

Fig. 2. The flowchart of the research

D. Solution methodology

The designing problem introduced in (1)-(19) is classified as a mixed-integer nonlinear optimization since some variables are discrete while the others are continuous. Therefore, we implement a Genetic Algorithm (GA) to solve the proposed optimization problem. Genetic algorithm is an evolutionary algorithm inspired by natural evolution. GA begins with an initial population (set of some solutions). This algorithm repeatedly updates its population using three main operators: selection, crossover, and mutation. The fitness of each chromosome (i.e. a solution of the problem) is evaluated in each iteration. GA tries to survive better solutions across generations [31-32].

In the fitness evaluation process of the genetic algorithm, a subroutine is called to determine how to operate the cement production process in each hour of the planning horizon. In this subroutine, all technical limitations as presented in (6)-(12) are considered. The outputs of this subroutine are the output of each process of the production chain, the stored materials and the amount of load reduction in each hour. Therefore, the main parameters of ILP designing i.e. the incentive/penalty values and the contracted load reduction level are determined considering the technical cement production constraints.

III. CASE STUDY

The data from a sample cement plant with a manufacturing capacity of 3000 tons of cement per day were used to model and test the method proposed for ILP designing. Table III present the technical characteristics of the four main parts of the cement manufacturing process.

TABLE III
THE TECHNICAL CHARACTERISTICS OF FOUR MAIN PARTS OF THE CEMENT PRODUCTION PROCESS [30]

Process	*Raw Mill*	*Crusher*	*Cement Mill*	*Kiln*
Abbreviation	*RM*	CR	CM	KL
Power rating (kW)	10000	2000	10200	10500
ET_i (kWh/Ton)	20.5	0.65	37	32
$OP_i^{Min}(Ton/h)$	0	0	0	110
$OP_i^{Max}(Ton/h)$	300	800	200	125
η_i	1.2	1	1.04	0.6
St_i^{Max} (Ton)	15000	22000	17600	50000

Figure 3 depicts the contribution of different factors to the cost of manufacturing one ton of cement based on the data of 27 companies [33]. According to Figure 3, with the current electricity tariffs, about 90% of the cost of manufacturing one ton of cement is non-electric and the rest 10% is paid by the cement company for power consumption.

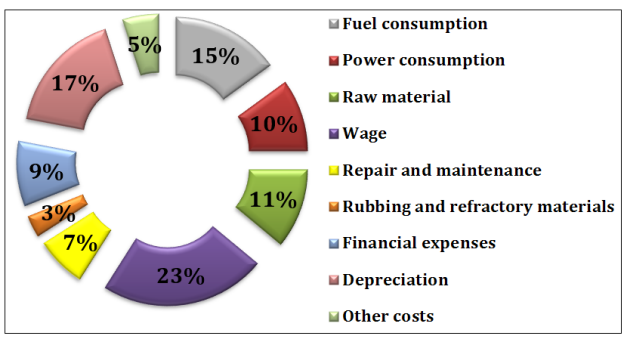

Fig. 3. The contribution of various cost factors to manufacturing one ton of cement

The ILP is usually implemented in the summer days with the highest electrical consumption over the year. Therefore, the peak period will occur in the middle of the day since the maximum demand occurs in the hottest hours. The cost of power consumed is calculated according to the current time-of-use (TOU) tariffs for peak, middle and valley periods. According to the power load pattern in the summer peak days, the low load hours (i.e. valley) are from 10:00 pm to 6:00 am, the peak hours are from 12:00 am to 4:00 pm, and the other hours are assumed to be middle as shown in Figure 4.

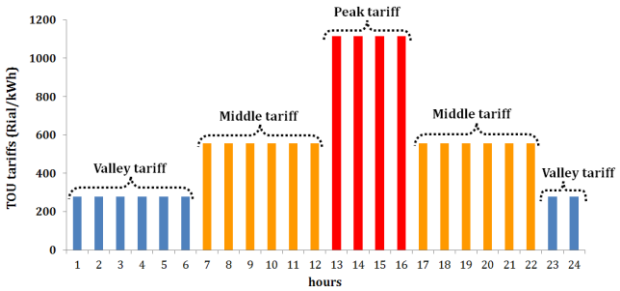

Fig. 4. TOU tariffs for industrial customers

IV. SIMULATION RESULTS

To better understand the power load pattern of the cement company, its manufacture planning and how to perform its main processes are presented firstly regardless of the ILP. Then, the optimal design of the ILP from the perspective of the cement company is done considering its production process.

A. The Cement Production Operation without ILP

The objective function of this section is the first expression of Equ. (1). The problem of cement manufacturing planning is composed of Equ. (2) and (3) with constraints (6)-(12). Simulations are made in four modes separately:

Case 1: Daily operation of the factory with the assumption of fixed electricity prices

Case 2: Daily operation of the factory with the assumption of TOU tariffs

Case 3: Weekly operation of the factory with the assumption of fixed electricity prices

Case 4: Weekly operation of the factory with the assumption of TOU tariffs

In the first and second cases, planning is done to manufacture at least 3000 tons of cement per day. The simulation of these two separate modes is performed and the results are recorded. According to the results, in both cases, cement manufacturing is 3120 tons. The total power load curve in the first and second cases is drawn in Figure 5.

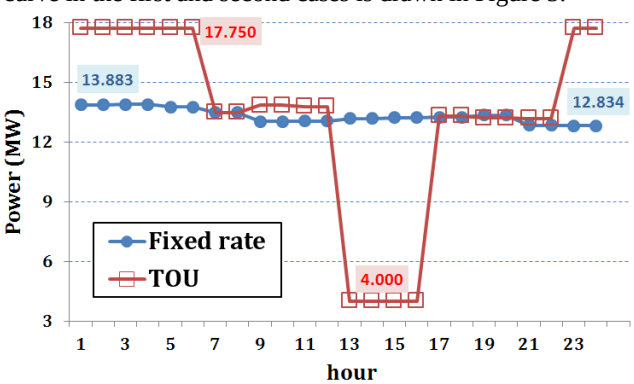

Fig. 5. The total power consumption of the cement plant in a day

The minimum and maximum power consumption is 12.88 MW and 13.88 MW in the first case and 4 MW and 17.75 MW in the second case, respectively. In fact, in a TOU tariff case, the cement company shifts a part of peak loads to middle or low load hours without interrupting the process or reducing manufacturing to pay less electricity cost.

The power consumption of each of the four main processes (crusher, raw mill, kiln, and cement mill) is presented in Figures 6-9, respectively.

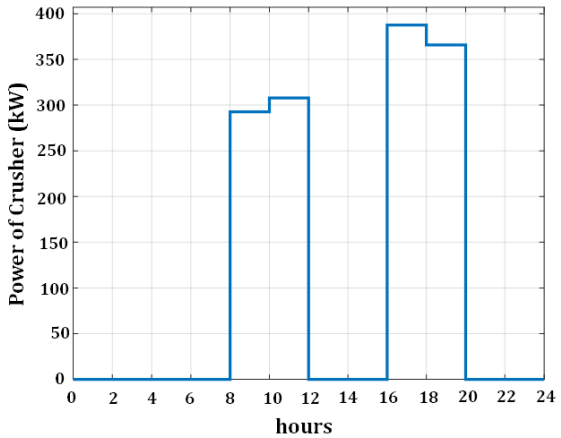

Fig. 6. Crusher power consumption (kW)

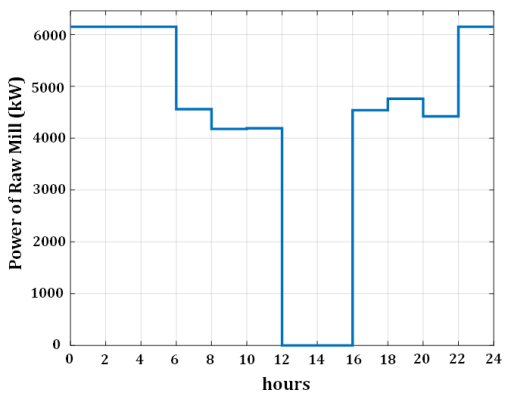

Fig. 7. Raw mill power consumption (kW)

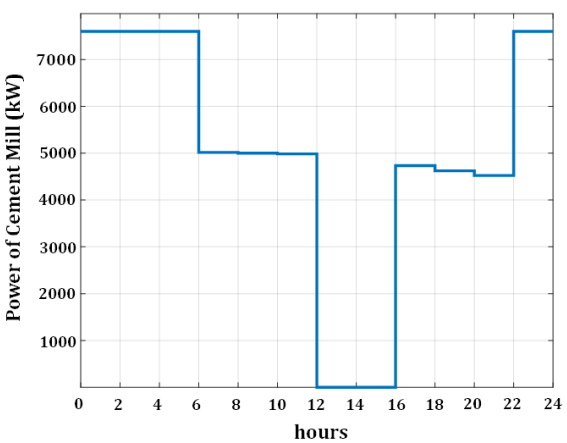

Fig. 8. Cement mill power consumption (kW)

The crusher process is off at 12 hours of the darkness and peak hours of the day. The raw mill and cement mill processes regulate their process based on the TOU tariff and are completely off during peak hours. The kiln process operates according to its constraints constantly and with maximum capacity during the period.

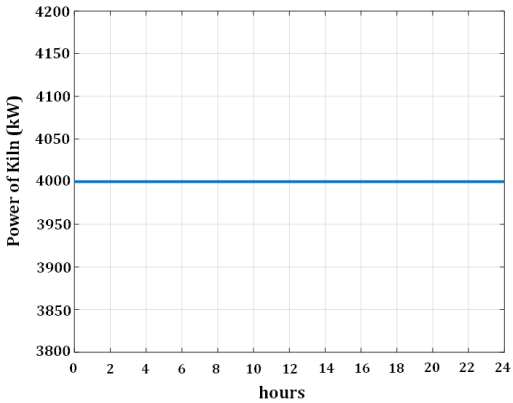

Fig. 9. Kiln power consumption (kW)

The amount of three storages of crusher, raw mill, and kiln is also presented in Figures 10-12, respectively.

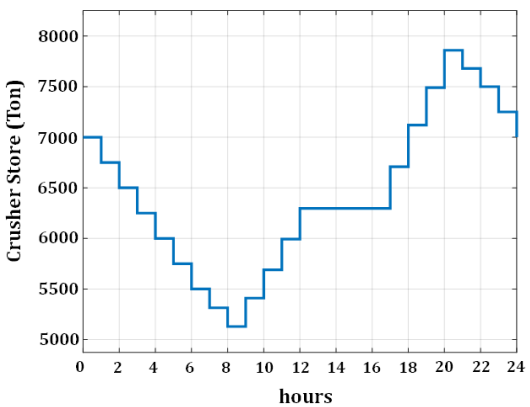

Fig. 10. The amount of storage of the crusher

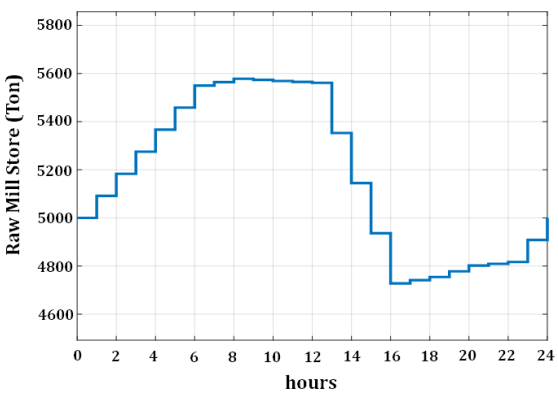

Fig. 11. The amount of storage of raw mill

According to the constraints of the problem, the final storage at the end of each period should not be less than the initial amount. The amount of crusher storage decreases during the initial hours (crusher being off) because the raw mill process is on and consumes materials in this storage. In the hours that the crusher is on, the storage amount will increase. At peak hours of the day (12:00 to 16:00), the amount of storage of the crusher does not change. Because both crusher and raw mill processes are off. The raw mill process is on at other than peak hours, so the amount of storage of raw mill is reduced only at peak hours (because the kiln process is on). The amount of storage of kiln also varies during the period, according to the removal based on the cement mill process operation.

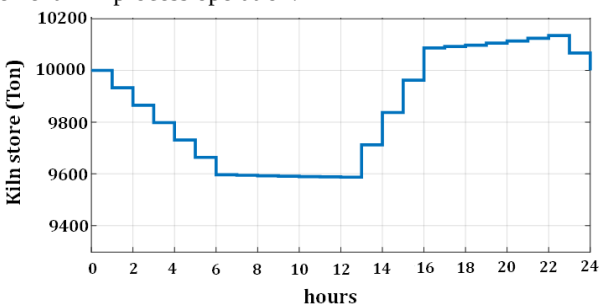

Fig. 12. The amount of storage of Kiln

Subsequently, cement plant operation is implemented on a weekly horizon to manufacture at least 21000 tons per week. The total power consumption chart of the customer in the third case (fixed tariff) is displayed in Figure 13. In this case, the constraint of equal initial and final storage amount is applied for the beginning and end of the week. The minimum and maximum consumptions are 12.57 and 14.23 MW, respectively.

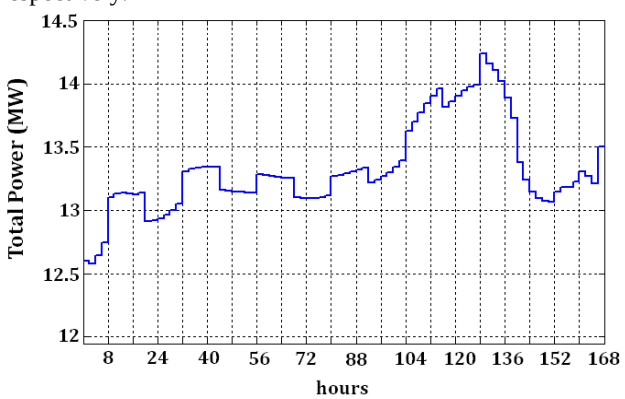

Fig. 13. Total power consumption over a week (Case 3)

The simulation of the fourth case (TOU tariff) yielded the total power consumption curve shown in Figure 14. The consumption pattern is different between the first and the end of the horizon since, according to real data, electricity tariff for peak hours is not considered for Thursdays and Fridays.

B. Optimal Design of ILP Considering Cement Production Process

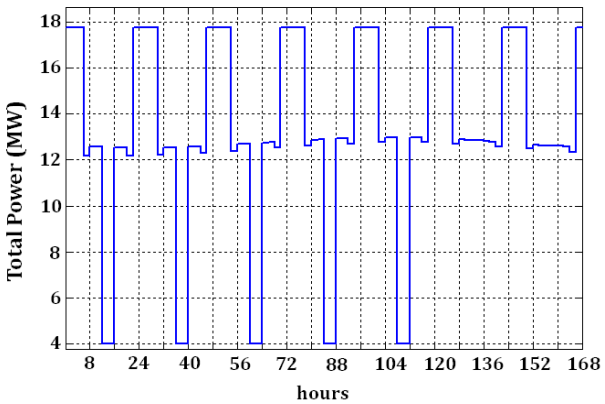

Fig. 14. Total power consumption in a typical week (Case 4)

This section simulates the main objective function proposed by the paper. In this regard, the optimization problem involving all Equs. (1)-(19) is implemented. The budget allocated for incentive pay by the electricity company and hence the customer incentive to reduce peak consumption is an important factor. Therefore, the simulations are separately performed in four scenarios (for the budget level) and the results are recorded. These four scenarios are:

- **Scenario 1**: Very limited budget (incentive coefficient 1)
- **Scenario 2**: Limited budget (incentive coefficient 3)
- **Scenario 3**: Appropriate budget (incentive coefficient 6)
- **Scenario 4**: High budget (incentive coefficient 10)

The ILP incentive rates are usually several times more than electricity tariffs. Therefore, in this study, the maximum incentive rates in four different scenarios are considered equal to the coefficients of ten times the electricity tariff at middle hours (557 IRR per kWh). It is worth noting that in all scenarios supposed for the design, electricity prices are assumed to be TOU tariffs. The total power consumption charts in each scenario are shown below. Then, the data on incentive, the profit of the cement company, etc. are presented and analyzed in a table. Figure 15 shows the total power consumption for Scenario 1.

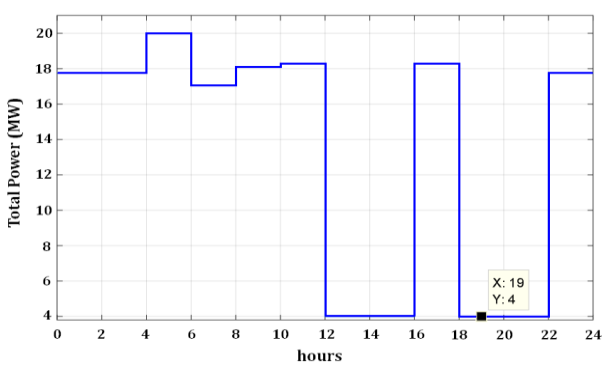

Fig. 15. The total power consumption of the cement company in Scenario 1

Based on the results, with this level of funding, even for the maximum intensive (in Equ. 17), the cement company

refuses to use interruptible load and the customer's minimum consumption is 4 MW.

The total power consumption of the cement company in Scenario 2 can be seen in Figure 16. According to the figure, in this scenario, the customer reduces its consumption at peak hours by 0.026 MW (i.e. 26 kW).

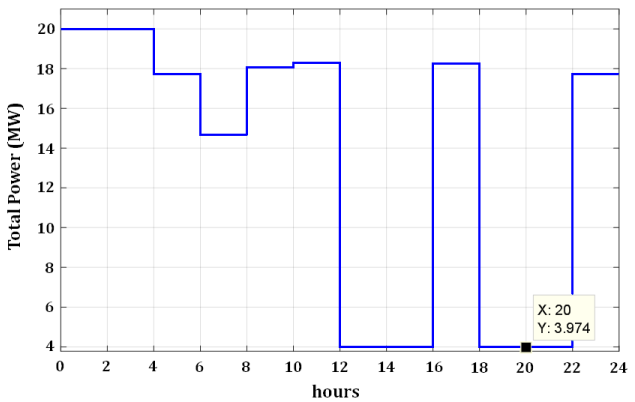

Fig. 16. The total power consumption of the cement company in Scenario 2

The total power consumption in Scenario 3 is shown in Figure 17. In this scenario, the optimal contract value is equal to 50 kW and the customer reduces its consumption at peak hours to this value, and the consumption demand of the company at these hours is 3950 kW. The maximum total power is also 20 MW.

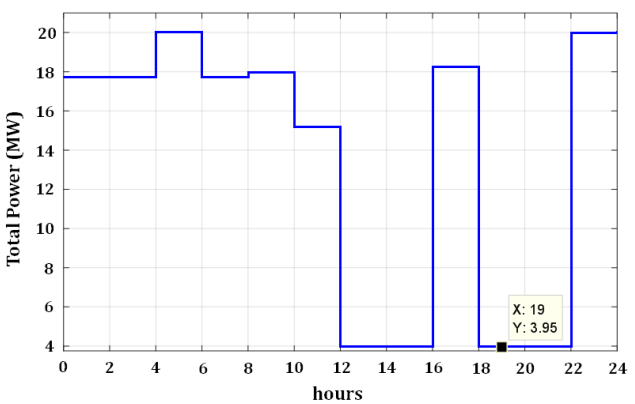

Fig. 17. The total power consumption of the cement company in Scenario 3

Figure 18 illustrates the total power consumption in Scenario 4 in which the highest consumption reduction occurs compared to other ones and the customer will reduce its total consumption by 100 kW at peak hours.

To summarize the results of the four scenarios, the level of load reduction, incentive rate and other additional information for each scenario are summarized in Table IV.

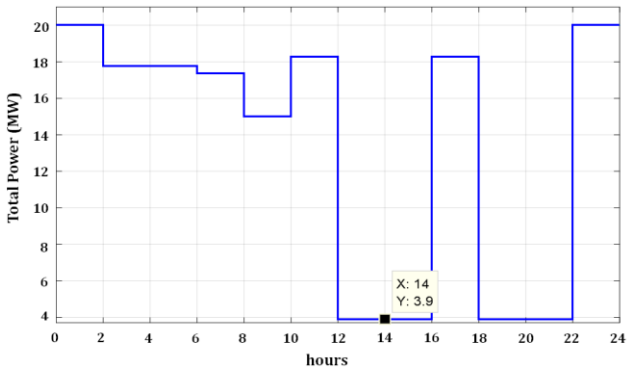

Fig. 18. The total power consumption of the cement company in Scenario 4

TABLE IV

THE SUMMARY OF THE RESULTS OF OPTIMAL ILP IN FOUR SCENARIOS

Sc.	Cement produced (Ton)	Maximum demand (kW)	Interrupted load (kW)	Incentive rate of ILP (IRR/kW)	Total incentive (million IRR)	Total penalty (million IRR)	Total profits (billion IRR)
1	3120	4000	0	5570	0	0.22	2.32
2	3113	3973	4*26	16710	3.5	0.105	2.52
3	3107	3950	4*50	33420	13.3	0	2.81
4	3094	3900	2*50 2*100	44560	30.06	0	3.19

According to Table 4, it can be said that:

• In Scenario 1, since the maximum incentive is low, the cement company does not participate in ILP and does not reduce its consumption. Thus, it does not take any incentive and is only penalized. Therefore, in this case, the ILP contract will not be profitable at all and the cement company will not participate in any ILP. In fact, in this case, despite the penalty, further cement manufacturing is more beneficial for the customer,

• In Scenario 2, with the increase in the incentive level, the cement company reduces its consumption at peak hours by 26 kW, which is less than the contract level. So, it will be penalized, in addition to receiving incentive (due to reducing load less than its obligation),

• In Scenario 3, the cement company reduces its consumption to the contract level, so it receives incentive, and

• In Scenario 4, the cement company reduces its consumption at the first four peak hours to the contract level (50 KW), but at the second four peak hours, it reduces its load by two times as great as the contract level and receives incentive for this scenario too (albeit less than the previous one).

Figure 19 provides a clearer and simpler deduction of the simulation results of the proposed model.

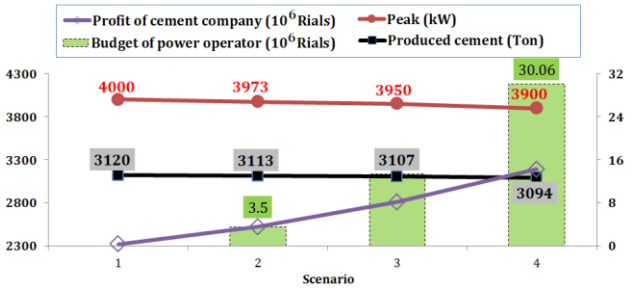

Fig. 19. The summary results of four scenarios of IL design

According to this figure, we can conclude that:

• Only in case of an attractive and profitable ILP, the industrial customer wishes to cooperate and reduce its consumption. Here, the customer has increased its profit by 870 million IRR per day by reducing its cement production from 3120 to 3094 tons and

• The budget needed to encourage the customer to reduce its consumption from 4000 to 3973 kW is 3.5 million IRR, whilst to further reduce the peak demand (reaching to 3900 kW), 30.06 million IRR should be spent. So, the relationship between the required budget and consumption reduction is not linear.

V. CONCLUSION

Since a major part of energy is consumed in the industrial sector, the implementation of demand response programs by industrial customers can play an important role in peak demand management. In this study, a new model is proposed to design an interruptible load program in which all production process constraints of a cement plant as an industrial customer are modeled. The proposed model is simulated in four scenarios of the budget level.

The simulation results show how an attractive and profitable ILP can encourage industrial customers to reduce their consumption. According to the results, the cement company can increase its profit by 870 million IRR per day by reducing its cement production from 3120 to 3094 tons because of the participation in ILP.

REFERENCES

[1] M. Ortega, C. Bel C, G. Escrivá, and A. Domijan, "Evaluation and assessment of demand response potential applied to the meat industry", *Applied Energy*, Vol. 92, pp. 84-91, 2012.

[2] S. Esmailnajad, J.Sundquist, "Demand Side Management in Swedish Indutry," M.S. Thesis in Chalmers University of technology, Sweden, 2014.

[3] H. Safari Faramad, H. Rajabi Mashhadi, "Real modeling of Great sample Manageable loads in order to manage load and participate in Interruptible loads plans", *26th International Power System Conference*, Iran, Tehran, (In Persian), 2011.

[4] M. Paulus, F. Borggrefe, "The potential of demand-side management in energy-intensive industries for electricity markets in Germany," *Applied Energy*, Vol. 88, No.2, pp. 432-441, 2011.

[5] N. Shamloo, M. Aras Nezhad, "The feasibility of using interruptible tariffs in the steel industry through modeling the production process", *31th International Power System Conference*, Iran, Tehran, (In Persian), 2016.

[6] H.A. Aalami, M.P. Moghaddam, and G.R. Yousefi GR. "Demand response modeling considering interruptible/curtailable loads and capacity market programs", *Applied Energy*, Vol. 87, No. 1, pp. 243-250, 2010.

[7] M.W. Leinmiller, "Total power management for the cement Industry", *Cement Industry Technical Conference, IEEE Conferences*, Dallas, TX, USA, pp. 97-107, May 2003.

[8] W. Niu, Y. Li, "Uncertain optimization decision of interruptible load in Demand Response program" *in Innovative Smart Grid Technologies-Asia (ISGT Asia)*, Kuala Lumpur, Malaysia, pp. 675-679, May 2014.

[9] J.R García, C.A. Bel, M.A. Ortega, and E.P. Lopez, "A novel tool for the evaluation and assessment of demand response activities in the industrial sector", *Energy*, Vol. 113, pp. 1136-1146, 2016.

[10] X. Wang, N.H. El-Farra, and A. Palazoglu, "Optimal scheduling of demand responsive industrial production with hybrid renewable energy systems",*Renewable Energy*, Vol. 31, pp. 53-64, 2017.

[11] C.A. Bel, et al. "Technical and economical tools to assess customer demand response in the commercial sector", *Energy Conversion and Management*, Vol. 50, No. 10, pp. 2605-2612, 2009.

[12] H. Safari farmad, H. Rajabi Mashhadi, and S. Biglar, "Risk Modeling in Power Planning for Power Distribution Companies in a Competitive Environment in the Presence of Interruptible loads" *17th Conference on Power Distribution Networks*, (In Persian), 2012.

[13] M. Rahmani-andebili, "Modeling nonlinear incentive-based and price-based demand response programs and implementing on real power markets", *Electric Power Systems Research*, Vol. 132, pp. 115-124, 2016.

[14] M. Rahmani-Andebili, "Nonlinear demand response programs for residential customers with nonlinear behavioral models", *Energy and Buildings*, Vol. 1, pp. 352-362, 2016

[15] C. De Jonghe, B.F. Hobbs, and R. Belmans, "Value of price responsive load for wind integration in unit commitment", *IEEE Transactions on power systems*, Vol. 29, No. 2, pp. 675-85, 2014.

[16] R. Deng, et al. "A survey on demand response in smart grids: Mathematical models and approaches", *IEEE Transactions on Industrial Informatics*, Vol. 11, No. 3, pp. 570-582, 2015.

[17] S. Mohajeryami, Saeed, "A novel economic model for price-based demand response", *Electric Power Systems Research*, Vol. 135, pp. 1-9, 2016.

[18] H.Izad khasti, R.Kipour, "Planning optimal demand response of Electricity Demand Based on Economic Modeling of Flexible Demand Function in Iran", *Iranian Energy Economics Researches*, Vol. 3 , No. 11, pp. 67-90, (In Persian), 2014

[19] M. P. Moghaddam, A. Abdollahi, and M. Rashidinejad, "Flexible demand response programs modeling in competitive electricity markets", *Applied Energy*, Vol. 88, pp. 3257-3269, 2011.

[20] S. Sorkhani, S. Suleimani, and B. Mozafari, "Strategic

bidding for power distribution companies in the electricity market on a day-ahead basis in the presence of Dispersed produce and Interruptible loads", *26th International Power System Conference*, Iran, Tehran, (In Persian), 2011.

[21] Hong Hu, et al., "Research on Peak Load Optimization Model Considering Interruptible Load at Peak Time", *China International Conference on Electricity Distribution (CICED)*,Tianjin, September 2018.

[22] J. Zhang, P. Zhang, H. Wu, X. Qi, S. Yang and Z. Li, "Two-stage load-scheduling model for the incentive-based demand response of industrial users considering load aggregators," *IET Generation, Transmission & Distribution*, Vol. 12, No. 14, pp. 3518-3526, August 2018.

[23] A. Aryandoust, J. Lilliestam,"The potential and usefulness of demand response to provide electricity system services", *Applied Energy*, Vol. 204, pp. 749-766, 2017.

[24] X. Jian, L. Zhang, X. Miao, Y. Zhang, and X. Han, "Designing interruptible load management scheme based on customer performance using mechanism design theory", *International Journal of Electrical Power & Energy Systems*, Vol. 95, pp. 476-489, 2018.

[25] M. Bastani, A.E. Thanos, H. Damgacioglu, N. Celik, and C.H. Chen, "An evolutionary simulation optimization framework for interruptible load management in the smart grid", *Sustainable Cities and Society*, Vol. 41, pp. 802-809, 2018.

[26] M. Habibian, G. Zakeri, A. Downward, et al., "Co-optimization of demand response and interruptible load reserve offers for a price-making major consumer", *Energy System*, Vol. 11, No. 1, pp 45–71, Feb. 2020.

[27] A. Conteh, M.E. Lotfy, K.M. Kipngetich, T. Senjyu, P. Mandal, and S. Chakraborty, "An Economic Analysis of Demand Side Management Considering Interruptible Load and Renewable Energy Integration: A Case Study of Freetown Sierra Leone," *Sustainability*, MDPI, Vol. 11, No. 10, pp. 1-19, May 2019.

[28] M. Samadi, M. Aghamohamadi, A. Mahmoudi, "Optimal time period clustering of time of use schemes based on elastic loads' responsiveness", *International Transactions on Electrical Energy Systems*, First online: November 2019, https://doi.org/10.1002/2050-7038.12275.

[29] M.W. Leinmiller, "Total power management for the cement industry," *in Proc. IEEE Cement Industry Technical Conf.*, pp. 97–107, 2003.

[30] M. Zarif, M. H. Javidi, M. S. Ghazizadeh, "Self-scheduling of large consumers with second-order stochastic dominance constraints", *IEEE Trans. Power Syst.*, Vol. 28, No. 1, pp. 289-299, Feb. 2013.

[31] A. Yari, M. Shakarami, F. Namdari, H. Moradi CheshmehBeigi, "Practical approach for planning of reliability-centered maintenance in distribution network with considering economic risk function and load uncertainly" *International Journal of Industrial Electronics, Control and Optimization*, Vol. 2, No. 4, pp. 319-330, 2019.

[32] H. Moradi CheshmehBeigi, A. Mohamadi, "Torque Ripple Minimization in SRM Based on Advanced Torque Sharing Function Modified by Genetic Algorithm Combined with Fuzzy PSO". *International Journal of Industrial Electronics, Control and Optimization*, Vol. 1, No. 1, pp. 71-80, 2018.

[33] A.M. Bod, "An Analysis of the Cement Industry at the Industry Cement Specialty Roundtable", *8th International Exhibition, Bank and Insurance*, Cement Scientific-Specialized Monthly, (In Persian), July 2014.

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