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Research Article

Electrical Energy Management of Industrial Consumers to Increase Profitability with an Optimal Control Strategy - A case study

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Abstract

Mutual cooperation between the power distribution companies and industrial consumers is of special importance in promoting efficient load management. Due to this, the purpose of this paper is to study the effects of load management practices on consumers using an optimal control strategy. By using this strategy, the distribution company controls consumption of industrial consumers in two ways: time transfer of load and optimization of consumption. For this study, the distribution company is assumed as the controller and two industrial consumers are considered as the consumers controlled of the problem. First, using this strategy, the load management of consumers is studied static. In static load management, industrial consumers (controlled) present the amount of power consumption needed for the next day to the distribution company (controller) from the day before and determine how the power consumption changes during the day and night. In this case, the controller offers suggestions to minimize the financial loss or increase the benefit for the consumers. Then the controller determines the pattern of power consumption for two industrial consumers during 24 hours a day and obtains the optimal power consumption for each of consumers. In the following, load management is examined dynamic. In this case, unlike static load management, electricity distribution companies determine how and the pattern of power consumption for consumers during 24 hours a day. In this way, according to the electricity market price in the next half hour and also the information provided by the consumers controlled ones from their factories, the controllers get the optimal amount of power consumption for each of the industrial consumers. The controller then encourages consumers to follow this optimal consumption reference by defining incentives. In order to investigate the role of mutual cooperation between distribution companies and industrial units, two different scenarios are considered. One is complete cooperation between the controller and the consumer, and the other is non-cooperation between them. Finally, using the simulation results, the effects of load management in improving power consumption in two scenarios will be investigated in terms of consumer profitability.

Keywords: Cost function; Production function; Optimal control strategy; Consumption load management; Controlled consumers.

1. Introduction

With the increasing consumption of electric energy, need to supply load seems necessary. There are several solutions for this purpose: Establishment of new power plants: this action is done to increase the production of electricity in order to compensate for the increase in load. - Expanding the electricity network: this operation is done in order to serve the growing areas. - Use of FACTS tools: This action is done in order to reduce the losses of transmission lines and make optimal use of the available capacity in the network. - Use of Distributed Generators: This action is done to increase the reliability of the network locally and also to serve the areas with limited population. The methods mentioned above are time-consuming and costly. For this purpose, another solution is proposed which requires less cost and time and can solve the problem of load compensation and also power price adjustment to a considerable extent. This solution is called load management. Load management has a very important position both in traditional networks and in restructured networks. One of the important factors that can be effective in promoting and efficiency of a load management program is the mutual cooperation that can be between industrial consumers and the distribution company as a power supplier. Unfortunately, our country does not yet have a specific planning on how to consume electricity in various sectors, especially industry. (Bgork et al., 1989), provides a load management program in which the consumer voluntarily participates in the load management program. In (Dranka et al., 2020), the optimal control strategy has been applied sequentially for dynamic systems with several stages in decision-making, and it examines how to coordinate in an interconnected system. The concept of optimal incentive strategy has been studied by using this strategy in the (Fernando et al., 1998), and it has dealt with the necessary restrictions related to it. In a system, when there is more than one decision maker in order to achieve the goals of the system, it is very difficult to find an optimal control that leads to the optimization of the system. When a system inherently has the necessary conditions to implement an optimal control strategy, the selection of an optimal control to optimize the system can be adopted (Mignoni et al., 2023). In (Halrvarian et al., 2002), an optimization using the controller - controlled strategy (Steckelberg) has been done for a system in a time discrete state, in which the studied system is considered as a time discrete linear equation. In (Jose B et al., 2022), the leader-follower

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strategy has been used to formulation a solution to control and organize the electricity market with regard to system reliability. In this reference, the structure intended to control the electricity market in this system is based on an MMB monitoring center. The main task of MMB is to create the necessary coordination between energy producers and consumers. MMB takes into account the reliability of the system as well as the amount of rotating storage, it plays a role in determining the amount of energy pricing. On the other hand, other market players who play the role of market competitive functions (MCF) in determining the production rate of power plants can play a significant role in the performance and price of the electricity market. In this reference, MMB, which is at the top of the market, is considered as the leader and MCFs as the followers of the issue. Finally, the necessary optimization has been done to make the actors more profitable. In (Martin et al., 1978), the authors have tried to use a proposed strategy in the motivational management of industrial loads. For this purpose, two industrial consumers are considered as controlled consumers and the energy distribution company as controller. In this article, it has been studied by changing the assumptions and also taking into account a series of limitations to continue the work in the previous references. In this research, the form of the profit function considered for the controller is different, also all the coefficients and powers related to the profit function, power price and problem data are considered different. In the previous references, the controller obtains the amount of power purchased from the market by his utility function, while in this article it is assumed that the leader uses the total power consumption of the followers as the basis for purchasing power from the market. In the previous references, the power price is considered in two different scenarios, and in the second scenario, the power price is assumed to be different for follower one and two. In this article, the price of power is considered the same for both consumers. In this article, in order to use the controller - controlled theory to solve the load management problem, a region is considered, which includes a regional electricity distribution company and two large industrial consumers. The distribution company is considered as the controller because it can have more complete information about the system and the electricity market than the consumers. Also, each follower knows only the information related to him and has no information about other followers. Due to the possession of this information as well as the information of the followers, the leader optimizes the parameters of the service and profit functions of all actors in a way that is both for his own benefit and for the benefit of the followers. In this case, the follower can act or not act on the optimization suggested by the leader. The action of the follower in the optimization proposed by the leader increases the reliability of the system as well as its profitability. On the other hand, not paying attention to the leader's suggestion may cause irreparable losses such as reducing the reliability of the system and the financial loss of the consumers. In this paper, considering the several advantages mentioned in using load management, we decided to study a method of applying load management using optimal control strategy. As it was said at the beginning, or this purpose, the distribution company is assumed as the controller and two industrial consumers are considered as the consumers controlled. Then the mutual cooperation between the distribution company and the industrial units is examined. The goal is to determine the extent to which mutual cooperation between the distribution company and the industrial units reduces consumer costs. First, at the suggestion of the controller, by changing the shift work of the consumers and transferring the power consumption time from peak to non-peak time, it will increase the benefit for them. Then, based on the information provided by the consumers, the controller obtains an optimal power consumption reference for each of the consumers and encourages them to follow it by defining incentives. Using simulations, the effects of load management in improving power consumption and the amount of profit obtained for each of the consumers, as well as the appropriate solution for making more profit for the consumers, are determined.

2. Research Objectives and Motivations

Reducing the cost of investment to provide the peak load of the network and reducing the price of electric energy for consumers is the main motivation of the research on load management methods. In general, the objectives of applying load management are: Reduction of peak load, which reduces the need for production units and equipment needed in these conditions - Reducing the operating cost by limiting the use of more expensive units and also reducing the number of units that must be placed in the circuit - Increasing the reliability of the system by increasing the network rotating reservation in peak load - Reducing the price of electric energy for consumers by adopting appropriate policies in electricity consumption. Unfortunately, in our country, there is still no specific planning on how to consume electrical energy in different sectors, especially industry. Considering the many advantages mentioned above in the use of load management, in this article we decided to study a method of applying load management by using a new strategy.

3. Problem Statement

The existence of different conditions in different countries and regions has caused different techniques and strategies to be proposed in load management. One of the important factors that can be effective in the advancement and effectiveness of a consumer load management program is the mutual cooperation that can exist between industrial consumers and energy distribution companies, as power providers. Considering this issue, in this article, we want to study the effects of load management by using the controller - controlled strategy. For this purpose, the distribution company is considered as controller and two industrial consumers as controlled consumers. Its purpose is to determine to what extent the mutual cooperation between the distribution company and the industrial units will reduce the cost of the consumers. Also, we would like to know whether it is cost-effective to equip the factories in order to provide the possibility of more cooperation with the power distribution company.

4. Literature Review

4.1 The Results of Load Management in some Countries

The use of various load management tools is different in different conditions. It is obvious that all load management tools cannot be used simultaneously or in the same way in all countries. Each country and each region can use different methods for load management according to the production and distribution system, legislative structure, market conditions, consumer characteristics, economic and climatic conditions. Therefore, it is necessary to adopt a suitable schedule to achieve the desired goals in long-term load management. In this section, we intend to have an overview of the results of load management practices in other countries, relying on other references. In Brazil, after two years, despite the fact that the need for power consumption in industries is increasing, we have not seen any increase in the peak of the load curve in this country. This pricing reform, which continued despite the opposition of most consumers and some companies, quickly established itself and is now planned to extend these principles to all subscribers. After two years, when the time-of-use tariff for industrial purposes was implemented in Brazil, the deputy energy department of this country published the results of this decision, whose results are given in table 1 (Ming et al., 2002).

Table 1
The results of the implementation of the load management program in Brazil (Ming et al., 2002).

Economic benefit for the network (billion dollars)	Reducing costs (billion dollars)	Bill reduction (billion dollars)	Modeling MW	Utility (billion dollars)
Voltage <= 69 Kv	96	45.8	1200	50.2
Voltage > 69 Kv	22.4	9.4	280	13
Sum	118.4	55.2	1420	63.2

According to the numbers mentioned in the table, the savings made by better use of the electrical system are divided between the production network and consumption in the proportions of 53% and 47%. In French (Ming et al., 1997), for a country like France with a history of more than 30 years of management, it is very difficult to compare the use or non-use of load management because many factors have affected the changes in the shape of the load curve in this country. (Growth of new applications of electricity consumption, change in production technology,...) However, the following salient points can be pointed out: In 1985, more than 379 billion dollars had been invested to install load management equipment for 7 million consumers. The amount of investment for each consumer was $54, including $13 for communications, $28 for two-tariff registrants. In this year, due to residential load management, less than 2000 MW of reduction in peak power was estimated. According to the investment made, the cost of reducing each KW is more than $200. Now, for comparison, it should be mentioned that in 1984, the investment cost for a 100 MW gas turbine amounted to 300 $/KW and for a 600 MW coal-burning unit, it amounted to 600 $/KW. From the operational point of view, the savings resulting from this management were estimated at 35 $/KW in production and 10 $/KW in transmission. These results indicate that load management can be used as a useful tool for the efficiency of the entire system. However, before implementing a load management system, a careful study should be done because repeating what has been done in another place cannot guarantee success. In Denmark (Shavell et al., 1989), load management project was carried out with the cooperation of 500 consumers, which lasted for a year and a half. In this part, the principles and results of this project are mentioned. The result of this project shows that the multi-tariff system based on the time of consumption of electric energy creates a suitable change in the consumption pattern of customers (especially household consumers) as well as other consumers such as industrial and commercial. From the middle of 1986 to the end of 1987, in Denmark, two large electric companies named NEAS A/S and SEAS A/S carried out a load management project with the cooperation of several other electric companies. In this project, the act of communicating is the responsibility of two independent elements. The connection from the electricity company to the 50/10 KV or (132/10 KV) substations is made through telephone lines. If communication with a specific customer was done through power transmission lines (two-way). This part is the most important and technical part of this project (Xiaoping et al., 1992).

5. Load Management using an Optimal Control Strategy

The optimal control strategy was first proposed in 1930 by H. Von. Stackelberg . In this strategy, one of the actors has more ability than the other actors and can make the necessary decisions for them. The powerful actor whose strategies are executed by the rest of the actors is called the controller, and the other actors who react to the controller’s strategies and decisions are called controlled. In this paper, in order to use the optimal control strategy to solve the load consumption management problem, an area is considered that includes a distribution company and two large industrial consumers. In this area, the distribution company is assumed the controller and two industrial consumers are considered as the consumers controlled. Each controller can have more complete information about the system and the electricity market than the consumers, but it does not have information about other controllers. Also, each consumer only knows information about itself and does not have information about other consumers. With this information, as well as the information of the consumers, controller optimizes the parameters of the service functions and the benefit of all the actors in order to benefit both itself and the consumers. In this case, the consumers can act or not on the optimization suggested by the controller. Following the optimization proposed by the controller will increase the reliability of the system as well as its benefit, and conversely, not paying attention to it may cause irreparable losses such as reduced system reliability and financial loss of the consumers (Shavell et al., 1992& Z.bagheri et al., 2017).

5.1 Static load management of consumers

5.1.1 Static load control

The assumption of the problem is that industrial consumers (controlled) do not have any information about the price and electricity market. Rather, this is energy distribution company(controller) that has complete control over the market and power price. In order to buy consumption power from the market, consumers must act through the controller and buy their requested power. Therefore, first, the industrial consumers or the controlled of the problem should predict the amount of power they need in the future according to their history and consumption records. Then, through the controller, this amount of power will be provided for them through the electricity market. It is emphasized again that in this method (static), each consumer alone is not able to provide the requested power from the market and this must be done by the controller. It should be mentioned that it is assumed that the controller provides this amount of power for the consumers in any possible way. In long-term contracts, the quantity and price of electric energy is fixed. Therefore, these contracts are similar to common contracts for buying and selling other goods or common long-term contracts between companies. The customer should take into account that he buys electricity with such a contract, and when the time of the contract finally comes, the customer is the owner of the specified amount of energy for a fixed price (independent of the actual current price at that time). Despite this, if the hourly spot price is higher than the contract price at that time, the customer can use less energy than the contract amount and sell his right to the company, which will bring him a profit (Erichsen et al., 1989).

5.1.2 Total benefit of consumers

In order to find the total profit of consumers, it should be considered that the profit of consumers consists of two parts: The profit from the sale of extra power, which is the result of savings, or in other words, the effect of consumption management - Profit from power consumption that leads to factory productions. In order to obtain profit from power consumption that leads to factory production (for consumers), a profit function should be considered for them (Kiani et al., 2023).

5.1.2.1 Benefit function

Economic benefit is the difference between the firm’s receipts and the costs incurred by the firm. It is important to know that all costs must be included in the benefit calculation. For example, if a shopkeeper works in his shop, his salary as a worker should be taken into account in calculating the cost. Both the revenue and the expenses of the firm depend on the activities of the firm. These activities can take several forms. Real production activities, purchasing of production agents and advertising are examples of the activities of the firm. According to the above, the benefit of each company or production unit consists of two parts: revenue and cost. The relationship between these two parameters in the benefit function is expressed as follows: (Krauter et al., 2017)

Cost – Revenue = Benefit (1)

According to the relationships stated above and according to the profit relationship of each company, the profit relationship for each of the industrial units considered in this paper for one day and night are stated as follows: (Trinh et al., 2021)

$$B^{F1} = \sum_{k=1}^{24} \{ G_{F1} \times (x_{11}^k)^{0.19} \times (x_{12}^k)^{0.21} \times (x_{13}^k)^{0.32} - (w_{11}^k \cdot x_{11}^k + w_{12}^k \cdot x_{12}^k + w_{13}^k \cdot x_{13}^k) - K_{F1} \} \tag{2}$$

$$B^{F2} = \sum_{k=1}^{24} \{ G_{F2} \times (x_{21})^{0.22} \times (x_{22})^{0.18} \times (x_{23}^k)^{0.39} - \left(w_{21}^k \cdot x_{21}^k + w_{22}^k \cdot x_{22}^k + w_{23}^k \cdot x_{23}^k \right) - K_{F2} \} \tag{3}$$

G_{F1}: Price of manufactured goods by industrial unit one (consumer 1)

G_{F2}: Price of manufactured goods by industrial unit two (consumer 2)

Table 2 shows the values of X and W for consumers one and two. Also, the value of G for consumers is selected as follows (Ildarabadi et al., 2017). $G_{F2} = 12800$, $G_{F1} = 23500$

Table 2
Values of X and W for each consumer

Hours	1-7	7-14	14-19	19-23	23-24
x_{11} (Manpower/Hours)	10	8	10	9	11
x_{12} (Ton/Hours)	22	40	45	23	20
w_{11} (Rial/Manpower)	10000	7500	8400	9500	10000
w_{12} (Rial/Ton)	9000	7300	8000	8800	9000
x_{21} (Manpower/Hours)	29	48	40	27	19
x_{22} (Ton/Hours)	52	230	180	135	92
w_{21} (Rial/Manpower)	13000	7500	8800	7400	10000
w_{22} (Rial/Ton)	8500	3500	3650	3400	5500

5.1.2.2 Revenue function

The revenue of each company or production unit is defined as multiply its production function (amount of production) by the price of each unit produced by them and is shown as $P \times f(x)$. Here P is the price of each production unit and $f(x)$ is the revenue function. The production function shows an Input (raw material) – Output (product) relationship. In other words, the production function determines the conversion rate of resources into products (Trinh et al., 2021). A production function can be expressed in different ways. including in writing, counting and explaining the inputs that are effective on the amount of outputs, by preparing a list of inputs and outputs numerically in a table, in the form of a picture and finally in the form of an algebraic equation. A production function can be written as follows: (Payedar et al., 2015)

$$Y = f\left(X_1, X_2, X_3, ..., X_n\right) \tag{4}$$

Where Y is output and $X_n......X_1$ is output that participate in the production of the product or output. ‘ f ’ indicates the type of relationship that converts inputs into outputs. The production function considered in this dissertation for two industrial units is expressed as follows:

$$Y = f\left(X_1, X_2, X_3\right) = (X_1)^a \times (X_2)^b \times (X_3)^c \tag{5}$$

Where:
X_1: Number of factors and manpower, X_2: The amount of raw materials consumed by the industrial unit.
X_3: The amount of power consumed by the industrial unit.
$\{a, b, c\}$: Positive real values.

The above relationship currently shows the importance and participation of each of the inputs in the production process (hommixay et al., 1989).

5.1.2.3 Cost function

Costs are expenditures paid to organize and carry out the production process. Costs include expenditures on inputs and services used in production. In short term, total costs include fixed and variable costs. In the long run, all costs are variable because all inputs are variable. A resource or input is called fixed if its value does not change during the period of production and a resource or input is called variable if its value changes during the period. In general, costs related to variable inputs are called variable costs. When the amount of production changes, the amount of fixed costs does not change, even if there is no production, the fixed costs will not change. Fixed costs are independent of the amount of production. Fixed costs are usually related to fixed inputs (technical units) because when an input is fixed, the related expenses are also fixed. Care should be taken in this case because this ruling is not always fixed (Liu et al., 2022). In practice, there are two ways to estimate the cost function of production units. The first way is to estimate the cost functions directly. For example, by observing the figures related to the output values and the cost of a number of the sample production unit, it is possible to determine the relationship between the costs and the output amount. The second way is to estimate the cost functions directly from the production function. If the production function is known, the cost functions can be obtained by using fixed costs and input prices. The cost function of the two industrial consumers considered in this paper is as follows:

$$Cost(X) = W^T \cdot X = W_1 X_1 + W_2 X_2 + W_3 X_3 + K_F \tag{6}$$

Where:
W_1: Salary paid to manpower
W_2: The cost of purchasing the required raw materials
W_3: Purchase price of consumed power
K_F: Fixed cost of the company (such as the cost of repair and maintenance of equipment, etc.)

According to the relations (5) and (6) and according to the benefit relation of each firm (1), the benefit relation for each of the industrial units considered in this paper for a day and night are expressed as follows: (Adewumi et al., 2022)

$$B^{S1} = \sum_{k=1}^{24} \{G_{S1} \times (x_{11}^k)^{0.19} \times (x_{12}^k)^{0.21} \times (x_{13}^k)^{0.32} - (w_{11}^k \cdot x_{11}^k + w_{12}^k \cdot x_{12}^k + w_{13}^k \cdot x_{13}^k) - K_{S1}\} \quad (7)$$

$$B^{S2} = \sum_{k=1}^{24} \{G_{S2} \times (x_{21})^{0.22} \times (x_{22})^{0.18} \times (x_{23}^k)^{0.39} - \left(w_{21}^k \cdot x_{21}^k + w_{22}^k \cdot x_{22}^k + w_{23}^k \cdot x_{23}^k\right) - K_{S2}\} \quad (8)$$

Where,

G_{S1}: Price of manufactured goods by industrial unit 1(consumer 1)

G_{S2}: Price of goods produced by industrial unit 1 (consumer 2)

K_{S1}: Fixed cost of consumer 1 , K_{S2}: Fixed cost of consumer 2

Industrial consumers or consumers controlled of the problem should predict the amount of power they need in the future according to their consumption history and records. Then the controller provides them with this amount of power through the electricity market. It is assumed that the amount of requested power that each of the Industrial consumer 1 and 2 to the controller for 24 hours a day, to be provided for them from the market, is according to Figure 1.

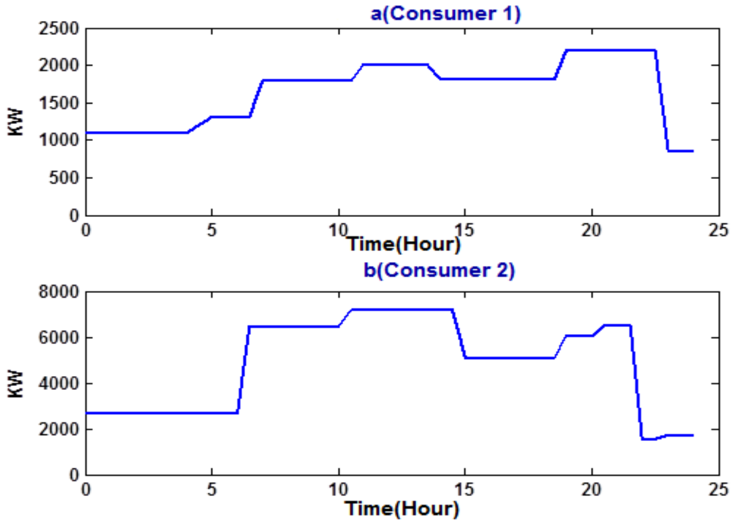

Fig**. 1.** Power consumption reference by the consumers for 24 hours

Therefore, the controller considers this amount of requested consumption power as the consumption reference of each of the consumers. As it was said, the controller buys this amount of power from the market for them through a long-term 24-hour contract. It is assumed that the power price that the controller or the distribution company buys from the electricity market to supply to its consumers is according to figure2.

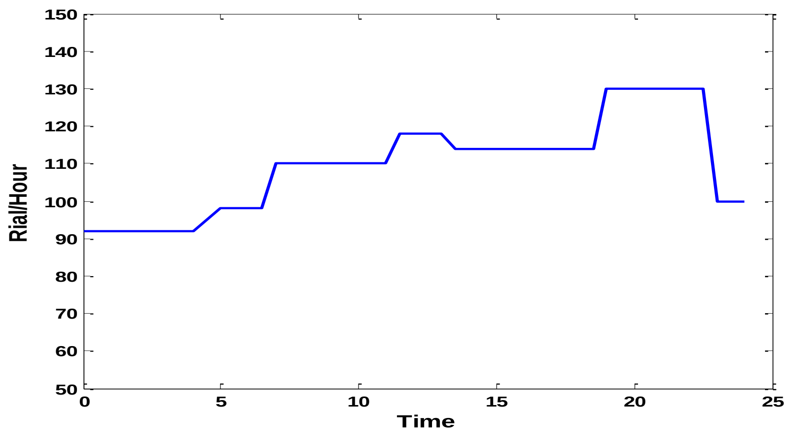

Fig. 2. Power price in the market for 24 hours a day

If M is the amount of power purchased by the controller at the price λ from the electricity market, the cost that the controller must pay to buy this amount of power is $M.\lambda$. K_L Fixed costs, such as equipment repair and maintenance costs, etc., are considered. Assuming that the controller sells this amount of power to the consumers at the price P, the profit function of the controller is obtained as follows:

$$B_f = M.(P - \lambda) - K_L \tag{9}$$

According to its profit function, the price of buying electricity from the market and the amount of power requested by the consumers, the controller must determine the price to provide power to its consumers in order to obtain its desired profit. Therefore, according to the conditions of the market day and the amount of its desired profit in each time period, the controller offers a price to provide power to its consumers, which is shown in figure3.

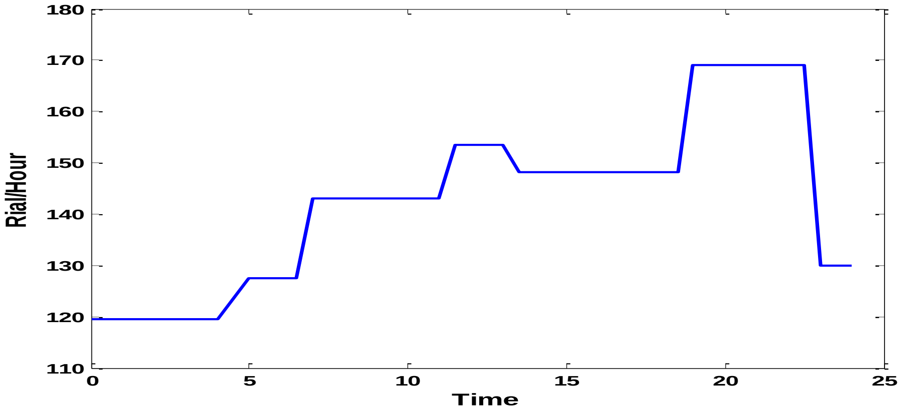

Fig. 3. Energy price Specified by controller to supply to the consumers

In this paper, it is assumed that if the controller has excess power over his reference consumption, after comparing the actual consumption of the consumers with the expenditures of their clients that they ordered the day before, he can sign contracts with them to sell their excess consumption in another market (such as reservation). To encourage consumers to participate in the load management program, the benefit from the sale of this excess power is returned to them. Conversely, if the consumption of a consumer is more than the reference, the controller is forced to buy additional power from the production market at a higher price to compensate for this shortage. It should also be noted that the provision of this power may be less reliable. The actual consumption of each consumer relative to their consumption reference is shown in Figure 4.

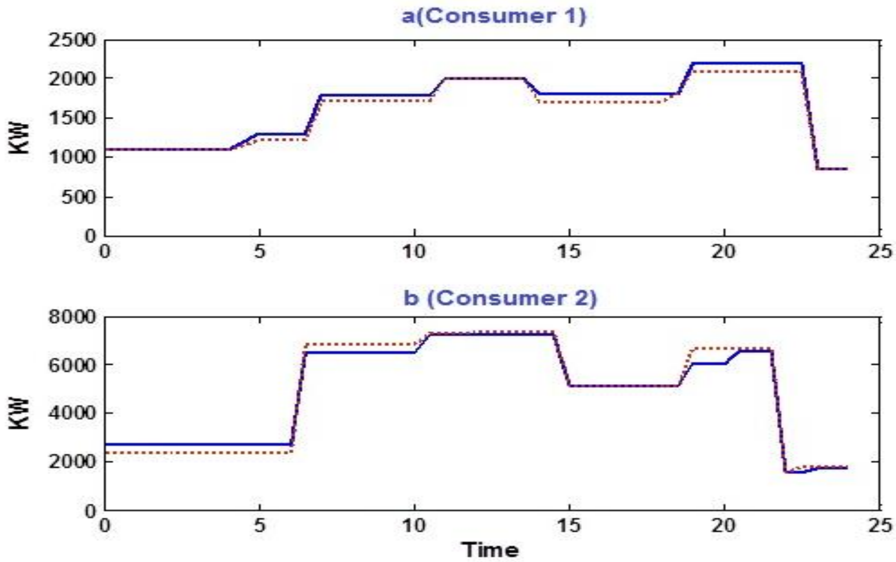

Fig. 4. The actual consumption each consumer compared to their reference consumption
(Reference consumption _ actual consumption...)

By comparing the actual consumption of the consumers during 24 hours a day, as can be seen in Figure 4, the consumer 1 has additional power over its consumption reference, and the controller can sell his surplus consumption in another market at a higher price through a contract with consumer 1. To encourage the consumer 1, a benefit from the sale is returned to it. The amount of this extra power and the resulting gain for 24 hours a day for consumer 1 is shown in Figure 5.

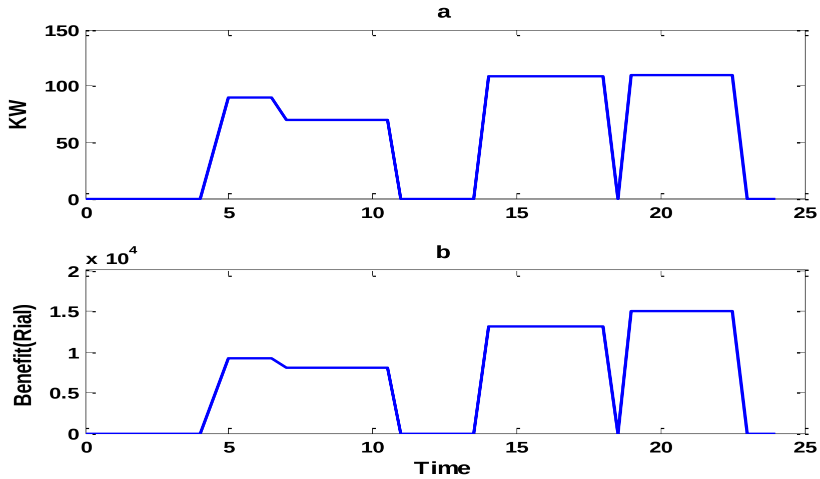

Fig. 5. a) The amount of power in excess of the reference consumption of consumer 1 during 24 hours a day b) Benefit from the sale of additional power of consumer 1 during 24 hours a day

Also, according to Figure 4, it can be seen that the power consumption of the consumer 2 has increased more than the reference consumption during 24 hours of the day and night. In this case, the controller is forced to buy this amount of power from the reservation market at a higher price. The amount of additional purchased power as well as the cost of this operation for consumer 2 is shown in Figure 6.

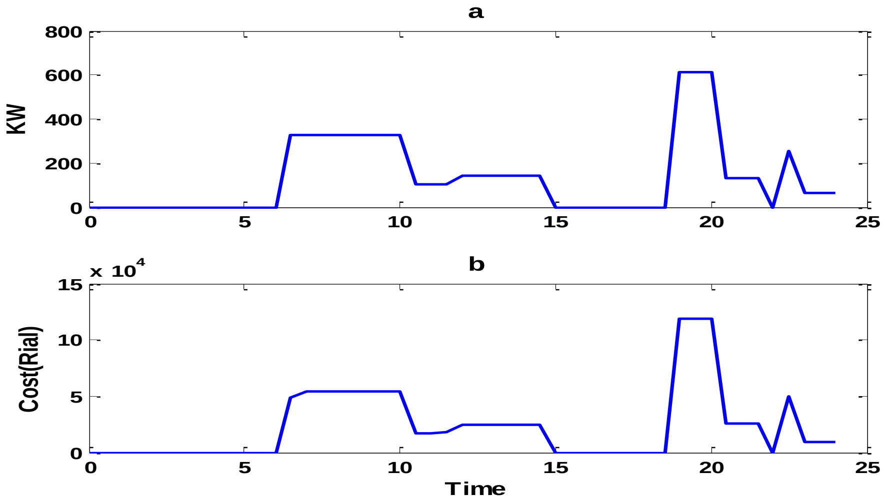

Fig. 6. The amount of additional purchased power for the consumer 2 and the associated cost during 24 hour

3.3 Consumers reference benefit

Consumers are expected to consume exactly the amount of power they have ordered. In other words, it is expected that they will not have any additional power to sell to the market and also no lack of power to buy from the market. By calculating the total benefit (according to relations 7 and 8) by the consumers in Figure 8, it is observed that the consumer 1 gains more benefit compared to the reference benefit due to following its reference and also having excess power to offer in the market. But consumer 2 suffers a lot of financial loss due to the violation of the consumer reference in the hours of the day and night. Of course, it should be noted that, consumer 2 earns more benefit than the reference benefit during these hours, because it has more power than the reference consumption for sale in the early hours of the day.

4. The Controller's Proposal to Minimize the Financial Loss of the Consumer 2

As shown in Figure4, consumer 2 has excess power over reference consumption during some hours. In this case, they can transfer some of their consumption from the hours when they have a lack of power to the hours that they have excess of power. This compensates for some of the losses incurred by purchasing power from the reservation market. Figure 8 shows the actual consumption of the consumer 2 in normal mode and in time transfer mode, compared to the consumption reference

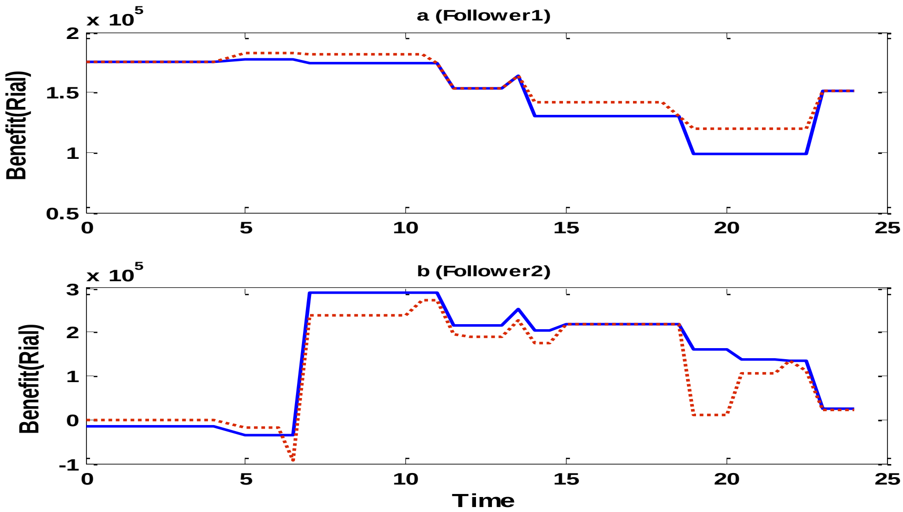

Fig.7. The actual benefit earned by each of the consumer compared to the reference benefit (Reference benefit – Real obtained benefit)

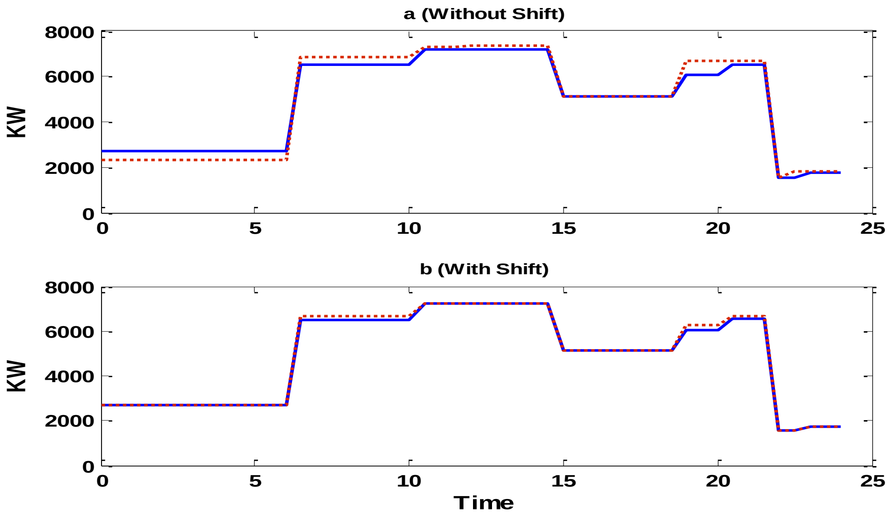

Fig. 8. a) The actual consumption of consumer 2 compared to the reference consumption in normal mode b) The actual consumption of the consumer 2 compared to reference consumption in the time transfer mode

As can be seen in Figure (8.a), the consumer 2 has a shortage of power in some half-day and peak hours and is forced to buy this power from the reservation market at a high price by the controller. The consumer 2 can compensate the extra power by transferring consumption from hours when they have a lack of power to the hours that they have more than the reference consumption. This operation is shown in Figure (8.b). As can be seen, the amount of power consumption in the early hours of the day by this power transfer is equal to the reference consumption, and this additional consumption is transferred to the hours when there is a lack of power. Therefore, power consumption has increased during these hours and is close to the reference consumption. However, power consumption is lacking in some hours due to the lack of additional power in other hours to transfer consumption and consumer 2 has to buy this extra power from the market. The amount of power shortage by consumer 2 in the time transfer mode and the cost associated with its purchase compared to normal consumption are shown in Figure 9.

The total benefit obtained for the consumer 2 in normal consumption and consumption with time transfer are compared in Figure (10). As can be seen, the benefit of consumer 2 in the time transfer mode of consumption is less than normal consumption in the early hours of the day. Because the consumer 2 does not have the excess power to sell to the market during these hours after consumption time transfer, and therefore there is a drop in benefits during these hours. However, the amount of benefit earned for this consumer has increased significantly in other hours of the day and night.

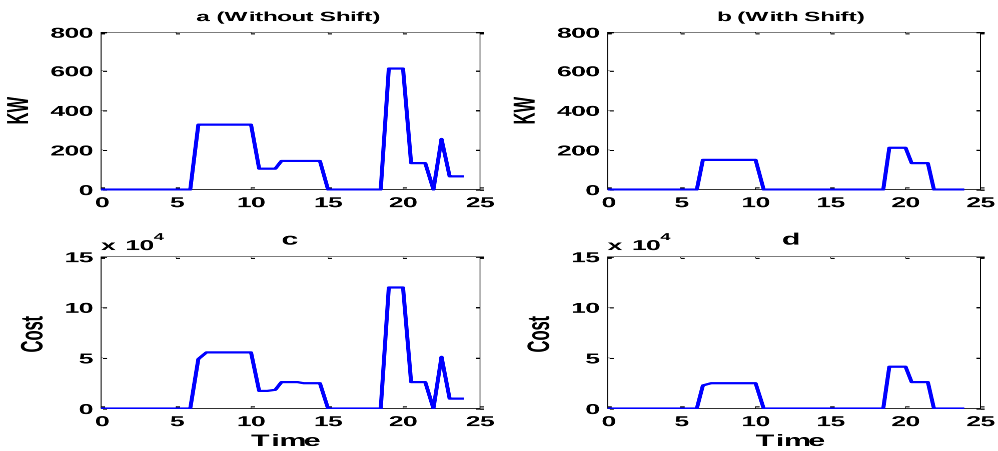

Fig. 9. The amount of power shortage by the consumer 2 and the related cost in both modes of time transfer and normal consumption

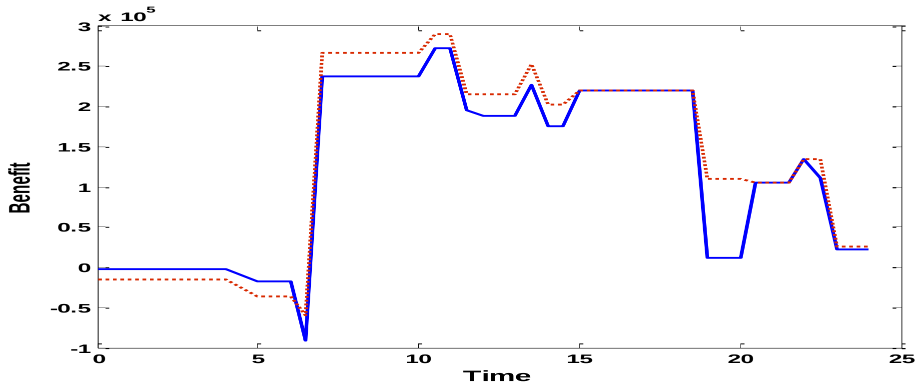

Fig. 10. The total benefit obtained for the consumer 2 in the time transfer mode and the normal mode
(Normal mode _ time transfer mode...)

5. Providing Solutions by the Controller to Bring More Profit to Consumers

If the consumers have full cooperation with the controller and provide it with all the information about their company, it means that the controller has enough information about the profit function, power consumption, costs and parameters of each of his consumers, then the controller can obtain the optimal power consumption of them based on this information. The optimal value of a variable input is the value that maximizes the profit of the production process. When the optimal amount of variable inputs is applied in the short term, the only possible way to increase profits is to change technology or change the amount of fixed inputs [20]. Given this, the basic assumption of most analyzes is that the firm operates for maximum profit, that is, the firm chooses its activities $(a_1,\dots\dots,a_n)$ in a way that maximizes $R(a_1,\dots\dots,a_n)-C(a_1,\dots\dots,a_n)$. Here R stands for Revenue and C stands for Cost. Despite this general assumption, a basic principle is derived from maximizing the profit function resulted from the simple application of the differential calculus. The issue of maximizing profits that the firm is facing is written as follows:

$$\max_{a_1,\dots,a_n} R(a_1,\dots\dots,a_n)-C(a_1,\dots\dots,a_n) \tag{10}$$

The simple application of the differential calculus shows that the optimal set of activities is determined by the following condition:

$$\frac{\partial R(a^*)}{\partial a_i}=\frac{\partial C(a^*)}{\partial a_i} \qquad i=1,2,\dots\dots,n \tag{11}$$

According to the above, the controller derives from the profit function stated before in relation to the power consumption parameter in order to find the optimal power consumption. So we have:

$$\begin{gathered}\frac{\partial B^{F1}}{\partial x_{13}}=0 \;\Rightarrow\\ \frac{\partial B^{F1}}{\partial x_{13}}=0.32\cdot x_{13}^{-0.68}\,23500\cdot x_{11}^{0.19}\cdot x_{12}^{0.21}-w_{13}=0\\ x_{13}^{*}=\left(\frac{w_{13}}{0.32\cdot 23500\cdot x_{11}^{0.19}\cdot x_{12}^{0.21}}\right)^{\frac{1}{-0.68}}\end{gathered} \tag{12}$$

$$\frac{\partial B^{F2}}{\partial x_{23}} = 0 \quad \Rightarrow$$
$$\frac{\partial B^{F2}}{\partial x_{23}} = 0.39 \cdot x_{23}^{-0.61} 1280 \quad \cdot x_{21}^{0.22} \cdot x_{22}^{0.18} - w_{23} = 0 \qquad (13)$$
$$x_{23}^{*} = \left(\frac{w_{23}}{0.39 \cdot 1280 \quad \cdot x_{21}^{0.22} \cdot x_{22}^{0.18}} \right)^{\frac{1}{-0.61}}$$

By replacing and considering the price of power, the optimal consumption of each of the consumers can be achieved. The optimal power consumption of each of the consumers is shown in Figure 11.

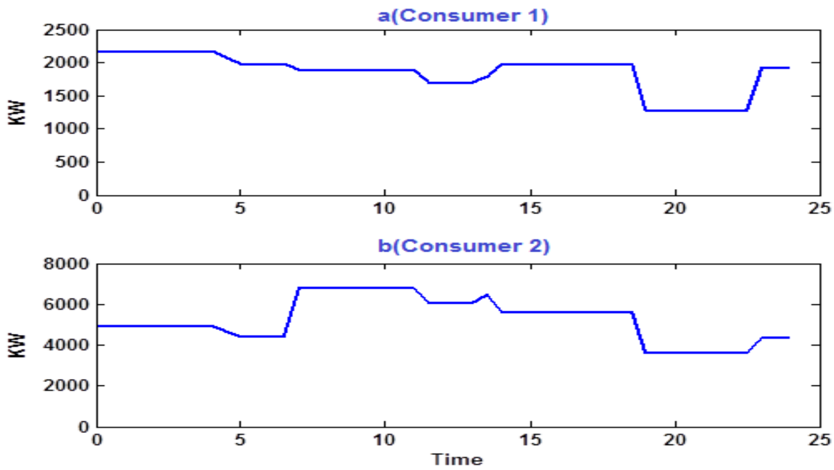

Fig. 11. The amount of optimal power consumption determined by the controller for each of the consumers

Figure (12) shows the amount of optimal power consumption determined by the controller with the amount of normal power consumption obtained from the history of each consumer. As shown in the figure, the policy regarding the optimal consumption mode is that the amount of power consumption by the consumers reduce by increasing the price of power (network peak hours) and most of their activities and power consumption are during non-peak hours.

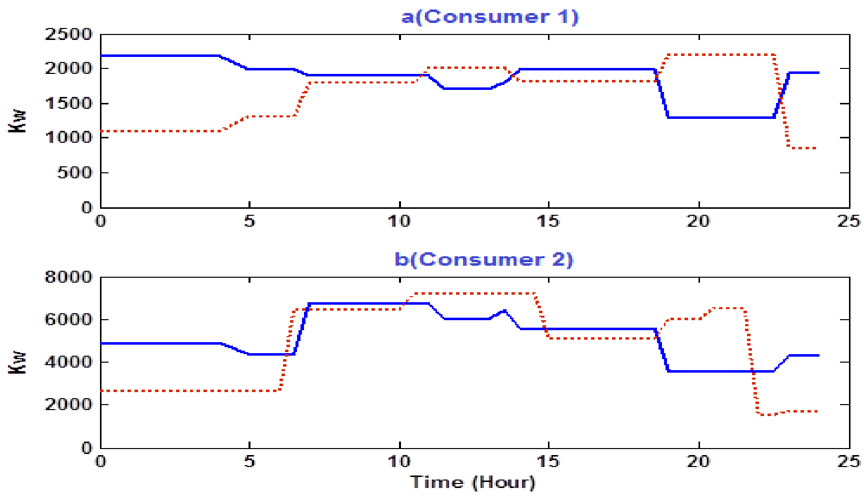

Fig. 12 . The amount of optimal power consumption determined by the controller compared to normal consumption (Optimal consumption _ normal consumption...)

If the consumers follow this type of consumption, their total benefit compared to the previous reference consumption mode is shown in Figure (13), as seen in this figure, by following the optimal costs announced by the controller, the benefit of both of them has increased compared to the benefit of their normal costs. Especially consumer2,which has had a significant increase in benefit in this case.

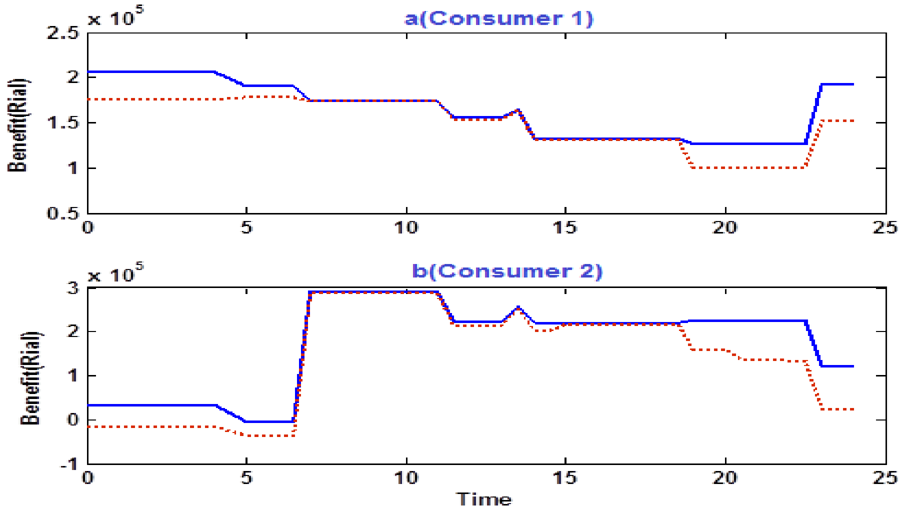

Fig. 13. Benefit from normal consumption compared to the optimal consumption determined by the controller for each of the consumers (Optimal profit _ Normal profit...)

6. Dynamic Load Management of Consumers

As it was studied in non-dynamic load control, each of the consumers of the problem provided the requested power needed for the next day to the controller. The controller was obliged to provide this amount of power requested by the consumers through a long-term 24-hour contract for them from the electricity market. One of the long-term benefits is that the customer is able to buy the right to consume energy in the future at a fixed price, independent of the actual current price at that time, in the form of insurance and guarantee. However, this type of power purchase contract has a number of disadvantages for the consumers of the issue, the most obvious of which is its high risk tolerance. This means that it is true that the consumers buy the guaranteed power for tomorrow at a fixed price one day before, but as we know, the price of power in the market changes momentarily according to the demand (Ferahtia et al., 2022). What is certain is that the price they bought power for tomorrow may be higher than the current price of that hour, which will reduce the profit of the factory. Assuming that the current price of power for consumers may be lower than the price of buying power with a long-term contract, the controller suggests another solution for followers. In this section, the energy market is modeled as a dynamic system and the controller - controlled strategy is used for the distribution company(controller) and industrial consumers (controlled), which is called dynamic load management. Therefore, according to the agreement that is made between the consumers and the controller, according to the controller's proposal, the consumers of the issue no longer need to present their requested power to the controller from one day before. Rather, the controller predicts the price of electricity in the market in the next half hour at any moment (the controller has this ability) and by using the profit function of the consumers at his disposal, determines the optimal consumption rate for the next half hour. With this method, the controller optimizes the profit function of the followers for the next half hour based on their decision variables. Therefore, the optimal consumption power of the consumers is obtained by the controller taking into account the security of the power network and the reliability constraint. Then the controller considers this optimal amount of consumption as a consumption reference that should be followed by the consumers to get the maximum profit. Therefore, the controller considers the sum of the optimal consumption power of follower one and two as the basis for purchasing power from the market. If in the previous references, the controller buys a certain amount of power from the electricity market to provide to the followers before doing the optimization for the followers, that this amount of power in some hours exceeds the total optimal consumption of consumers. According to the mentioned materials, to investigate the role of mutual cooperation between the leader and the consumer, two different situations are considered for the consumers of the subject: The first case: providing real information to the controller by followers (cooperation). The second case: not providing or providing false information to the controller by the consumers (non-cooperation) (Junzhe et al., 2022).

6.1 Dynamic load control

In order to obtain an optimal response for the cost of consumers, the controller needs to solve the optimal consumption equation, which is a function of the control parameters. By solving these functions, a series of control parameters that have the ability to minimize the cost are obtained. There are different methods to solve this equation, one of which is called dynamic programming. Dynamic planning is defined in such a way that at each stage, the actor considers a decision that minimizes the total cost of the current stage and the cost of the future stages. In order to solve the cost function, a dynamic system can be defined as follows: (Zhihang et al., 2022)

$$x_{k+1} = f_k(x_k, u_k, w_k) \qquad k = 0,1,2,..., N-1$$
(14)

Where,
K : Time step
x_k : It shows the state of the system and also includes past information for optimization used in the future.
u_k : The control element that can be selected in time and with information.
w_k : Variable parameter
N : Time limit

The cost function is considered as follows for optimization using dynamic programming.

$$J(x) = g_N(x_N) + \sum_{k=0}^{N-1} g_k(x_k, u_k, w_k) \qquad (15)$$

Here, $g_N(x_N)$ is the cost that is applied to the system at the end of the process. Due to the presence of the w_k parameter, the cost function changes randomly and the function cannot be optimized comprehensively. Therefore, the problem is formulated in a way that minimizes the $u_0, u_1, u_2, ..., u_{N-1}$ elements of the cost function. In this case, a function is obtained as $u_k = \mu_k(x_k)$.
and field,

$$\varphi = \{\mu_0, \mu_1, \mu_2, \mu_3, ..., \mu_{N-1}\} \qquad (16)$$

It is considered as control. In this case, for each φ, the cost for the initial value of x_0 is defined as follows.

$$J(x_0) = g_N(x_N) + \left\{\sum_{k=0}^{N-1} g_k(x_k, \mu_k(x_k), w_k)\right\} \qquad (17)$$

The goal of minimizing this cost function is for all values of φ.

6.1.1 Objective function

The objective function for each of the industrial consumers is generally considered as follows:

$$J_k^{Fi}(x_k) = (x_N - x_N^D)^T Q_N^{Fi}(x_N - x_N^D) + \sum_{j=k}^{N-1}\{(x_j - x_j^D)^T Q_j^{Fi}(x_j - x_j^D) + (u_j^{Fi} - u_j^{Fi,d})^T R_j^{Fi}(u_j^{Fi} - u_j^{Fi,d})\} \qquad (18)$$

These cases are considered for $i = 1,..., p$, where p is the number of consumers. The overall consumption dynamics that is considered for each of the consumers is as follows.

$$x_{k+1} = f_k(x_k, u_k^L, u_k^{F1}, ..., u_k^{Fp}) \qquad (19)$$

Here, $J_k^{Fi}(x_k)$ is the quadratic objective function of consumer i. Expressions of Q_j^{Fi}, R_j^{Fi} are symmetric and positive matrices for $i = 1,..., n$ and are defined in distance $j \in [0, N]$.

In equation (18), x_j^D is the desired values of the state for distance $j \in [0, N]$ is the desired $)\, i = 1,..., p$ ($u_j^{Fi,d}$) ، control values for consumers in distance $j \in [0, N-1]$.

Also, in equation (19), $f_k(x_k, u_k^1, ..., u_k^p)$ is a non-linear dynamic relationship of state variable (x_k) and ($u_k^L, u_k^{Fi},\ i = 1,..., p$) control of the energy distribution company and consumers.

The optimal strategy ($u_k^{L*}, u_k^{Fi*},\ i = 1,..., p$) must satisfy the following relations: (Sutikno et al., 2023)

$$J_k^{Fi}(x_k, u_k^{L*}, u_k^{F1*}, ..., u_k^{Fi*}, ..., u_k^{Fp*}) \le J_k^{Fi}(x_k, u_k^{L*}, u_k^{F1*}, ..., u_k^{Fi}, ..., u_k^{Fp*}),\ \forall\ u_k^{Fi} \in U^{Fi} \qquad (20)$$

6.2. Providing a consumption dynamic and optimization by the controller

In this section, the proposed strategy is modeled as a dynamic tracking problem. In order to implement the dynamic tracking problem, the optimal control value is obtained by first defining a consumption dynamic and then using the dynamic programming method. For this purpose, if the objective cost function that should be optimized for each of the consumers is considered as equation (21), then the desired closed form can be achieved by using the following steps: (Eskandari et al., 2022)

$$J(x) = \min_{u_k}\{(x_N - x_N^{Di})^T Q_N(x_N - x_N^{Di}) + \sum_{k=0}^{N-1}\{(x_k - x_k^{Di})^T Q_k(x_k - x_k^{Di}) + u_k{}^T R_k u_k\}\} \qquad (21)$$

Where,

x_k^{Di} : Reference value of the optimal consumption of the *ith* consumer at the *kth* hour

x_k : The actual consumption of the *ith* consumer at the *kth* hour

u_k : control values

Q_k , R_k : Symmetric and positive matrices

For this purpose, a consumption dynamic is defined in the form of equation 22.

$$x_{k+1} = x_k + u_k \tag{22}$$

Also, the restriction that is considered for the control values is as follows:

$$U_{\min} \le u_k^i \le U_{\max} \tag{23}$$

Using mathematical induction and dynamic programming algorithm, the closed form of the follow-up problem defined in this article for $K = 1,2,...., N-1$ is obtained as follows:

$$u_k^* = D_k z_k + E_k \quad (24)$$

$$\begin{aligned} D_k &= -(R_k + F_{k+1})^{-1} F_{k+1} \\ E_k &= D_k \left(w_k + F_{k+1}^{-1} G_{k+1} \right) \end{aligned} \tag{25}$$

(26)

$$J_k^*(z_k) = z_k^T F_k z_k + G_k^T z_k + z_k^T G_k + H_k$$

$$\begin{aligned} F_k &= Q_k + D_k^T R_k D_k + (I + D_k)^T F_{k+1} (I + D_k) \\ G_k &= (I + D_k)^T F_{k+1} (E_k + w_k) + D_k^T R_k E_k + G_{k+1} \\ H_k &= (E_k + w_k)^T F_{k+1} (E_k + w_k) + E_k^T R_k E_k + G_{k+1}^T (E_k + w_k) + (E_k + w_k)^T G_{k+1} + H_{k+1} \end{aligned} \tag{27}$$

$$\begin{aligned} J_N(z_N) &= z_N^T F_N z_N \\ F_N &= Q_N \\ G_N &= 0 \\ H_N &= 0 \end{aligned} \tag{28}$$

It is necessary to explain that in each step after u^* is obtained, it is checked according to the limitation of equation (23), if $u^* \ge U_{\max}$ then $u^* = U_{\max}$ is considered and if it is $u^* \le U_{\min}$, then $u^* = U_{\min}$ is considered. In this article, the values related to $U_{\max}$ and $U_{\min}$ of consumers are considered as follows:

$$,U_{\min}^{L!} = -200, U_{\max}^{L2} = 1000, U_{\min}^{L2} = -1000$$

$$U_{\max}^{L1} = 200$$

After providing the optimal consumption reference power value for the consumers by the controller, in order to obtain the maximum profit, the consumers should adjust their parameters in such a way to achieve this important, the consumption dynamics that the controller for each of the consumers in It was considered as relation 22. Here, more explanation is given in connection with this consumption dynamic. Each consumer has an initial consumption of x_0, which corresponds to the last hour of the previous day (24). In order for the actual consumption of consumers in state x_1 to correspond to x_1^D (reference), the controller provides a u_0^* to the consumers, which causes the consumption in state x_1 to correspond to x_1^D (reference). After the consumers have reached the actual consumption x_1, the controller provides them with the control element u_1^* to make their actual consumption x_2 match x_2^D, and so on until we reach stage N (24 hours).

In general, it can be said that u_k^* is the amount of changes that consumers must make in their consumption at the *kth* hour so that, their actual consumption matches the reference consumption at the $k+1$ hour. As mentioned, two effective parameters in the selection of u_k^* are coefficients R_k and Q_k. How these coefficients affect the follow-up of consumers from the reference announced by the controller for two different values of these coefficients and for a period of 24 hours a day for consumer 1 is shown in Fig14.

As seen in figure14, the control values of u^* for consumer1 are between 200 and -200 according to the limit that was assumed for it. This restriction indicates that a consumer1 cannot have more than 200 KW changes in the consumption of his plant during half an hour. Of course, it should be noted that the amount of Q_k and R_k may change for each of the consumers during the day and night. This means that the rate of power changes in factories during day and night hours, depending on the conditions of the factory, can be different. For example, Figure 15 shows the tracking of consumer 1 from the optimal reference for constant value and variable R_k =1 values Q_k during day and night.

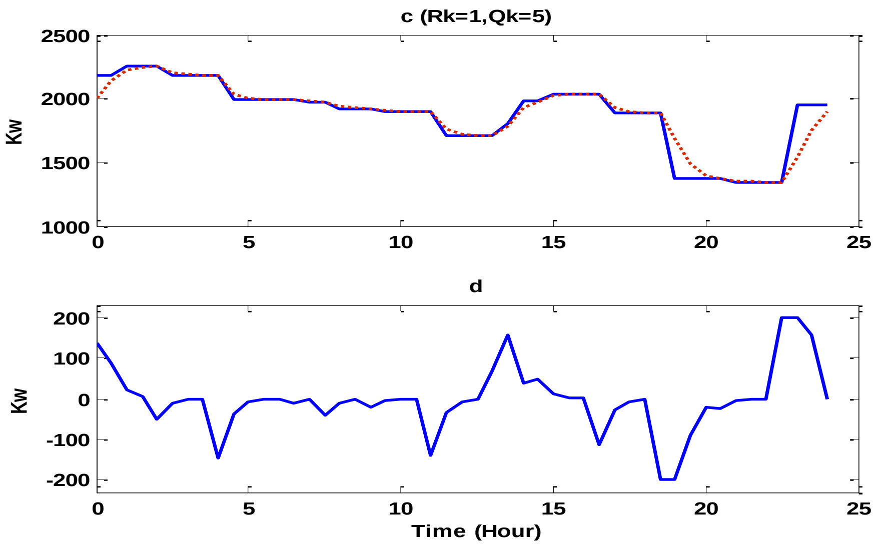

Fig. 14. a) The actual power consumption of consumer 1 compared to the reference power in $(R_K = 1, Q_K = 5)$ b) Control values(u^*) for consumer 1 in 24 hours a day $(R_K = 1, Q_K = 5)$ (Reference _Tracking…)

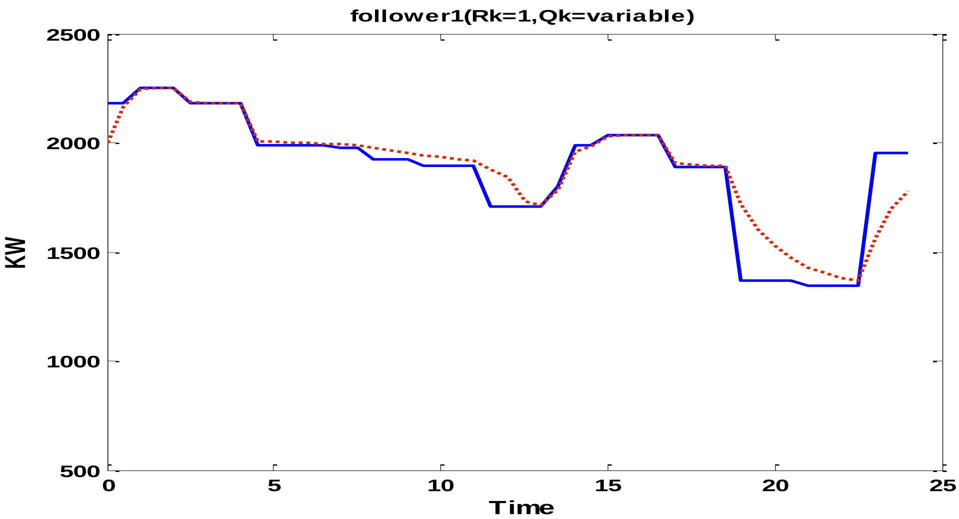

Fig. 15. Tracking of consumer 1 from the optimal reference for constant value Q_k and variable values R_k =1

In order to understand more about the ability of factories in rapid changes in consumption, an example of a large industrial customer, such as a metal smelting factory, is briefly examined. This metal smelting factory has metal working machines (from 1 to 100 kilowatts), electric metal melting machines (from 1 to 10 megawatts), lighting and ventilation, etc. This factory has a computer equipped for production planning (every hour and hours of the following week) and direct control of planned processes. The production planner and the production manager of this factory can have different reactions in the market. The production manager is interested in long-term issues (months to years) and concludes long-term contracts. In these long-term contracts, the long-term price forecast, the future needs of the factory and the existing capital are considered. The production planner is interested in hourly and daily operation and provides the necessary input for the computer control and planning of the production process. In planning for the operation of facilities, short-term forecast of price and certain amount of production is used. It is necessary to mention that if consume more than the reference consumption by consumers , each of them will face a heavy fine from the energy distribution company, because the controller itself is under pressure from the market not to consume more than the specified amount. However, as seen in figures 15, consumers have power shortages in some hours of the day and night compared to the consumption reference. And they have to procure this amount of power shortage through the controller from the market at a high price. The amount of this power shortage and its related cost for two different values of R_k and Q_k coefficients for consumer 2 are shown in figure 16.

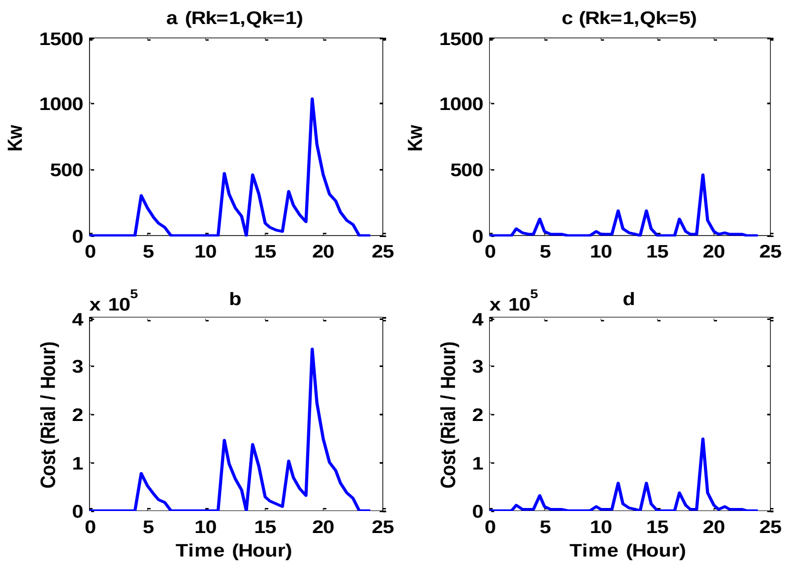

Fig. 16. a,c) The amount of power deficiency of consumer 2 for two different values of coefficients R_k and Q_k .b,d) The cost related to the purchase of additional power for the consumer 2 for two different values of coefficients R_k and Q_k

As can be seen in Figure 16, with the increase of the Q_k coefficient and the decrease of the R_k coefficient, the amount of power shortage and the related cost for the consumer will decrease. According to the presented materials and considering the amount of power consumption by consumers and the costs involved, the total profit received by each of the consumers for two different values of coefficients R_k and Q_k for 24 hours a day compared to the profit from consumption the reference power is shown in figures 17 and 18.

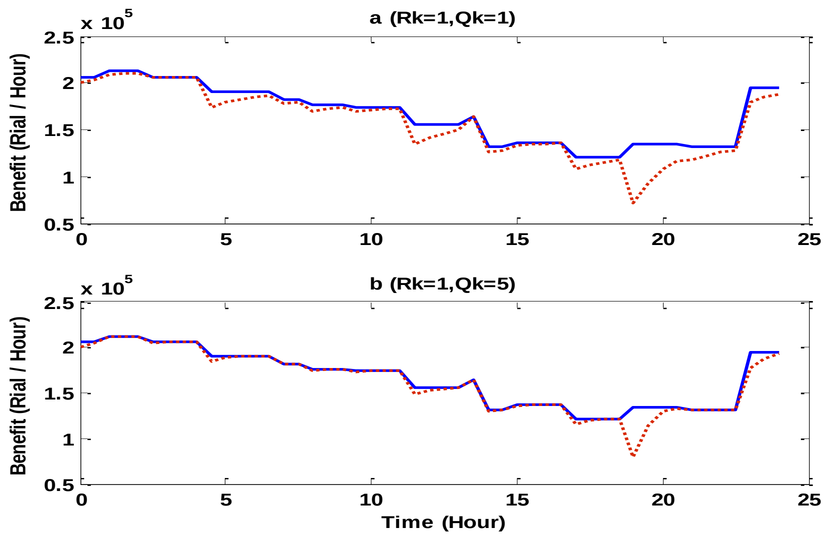

Fig. 17. The total profit obtained by the consumer 1 compared to the profit obtained from the reference power consumption for two different values of coefficients R_k and Q_k (Reference _Tracking…)

As we can see from figures 17 and 19, by decreasing the coefficient R_k and increasing the coefficient Q_k , the total profit obtained for consumers will increase. In the other scenario, two cases are considered, one is that the consumers do not give any information about their factory to the controller. And the other is that the consumers provide a series of incorrect and unreal information about the factory to the controller. In this case, because the controller does not have access to the profit function of its consumers, it cannot determine the optimal amount of consumption for consumers. Therefore, the controller is forced to use the records and consumption history of consumers to provide a reference power for consumption.

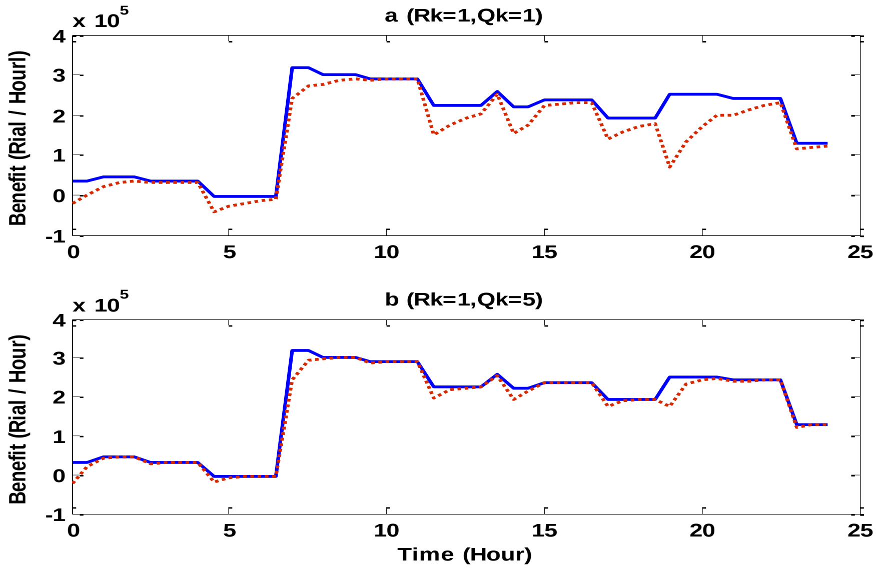

Fig. 18. The total profit obtained by the consumer 2 compared to the profit obtained from the reference power consumption for two different values of coefficients R_k and Q_k (Reference _Tracking…)

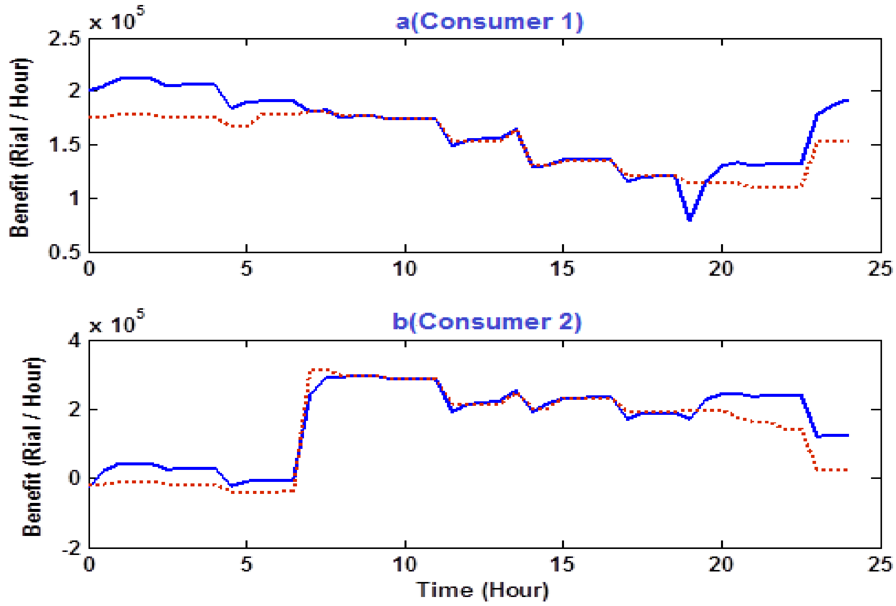

Fig. 19. The profit obtained for consumers with their historical power consumption in comparison with the optimal power consumption in state $R_k = 1$ and $Q_k = 1$ (Historical profit _ Optimum profit …)

In figure 19, the profit obtained for the consumers according to their consumption history compared to the optimal power consumption with coefficients $R_k = 1$ and $Q_k = 1$ (worst case) are compared with each other. Assuming that in the second scenario, the best possible situation for consumers occurs (that is, consumers should follow the optimal consumption reference set by the controller so that they have the least power deficit in order to buy from the market), in this case, the profit The sum obtained by each of the consumers in the second scenario in the best case and the profit obtained from the first scenario are compared with each other in figures 20 and 21 respectively.

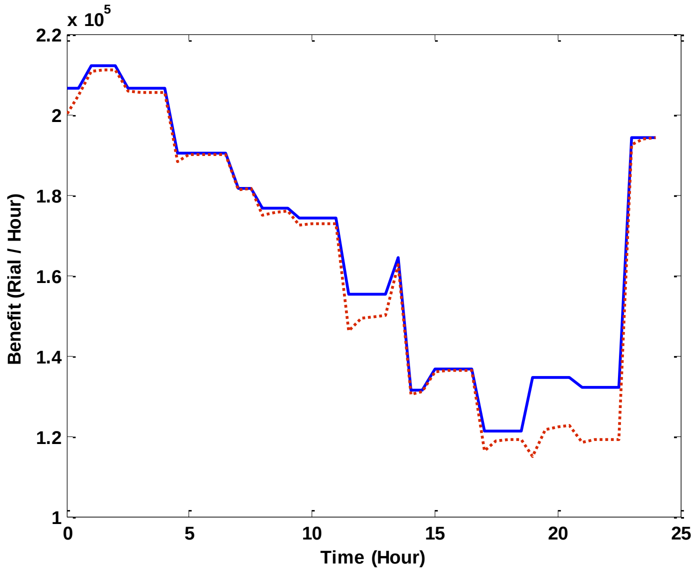

Fig. 20. Profit obtained for consumer 1 in the first and second scenario

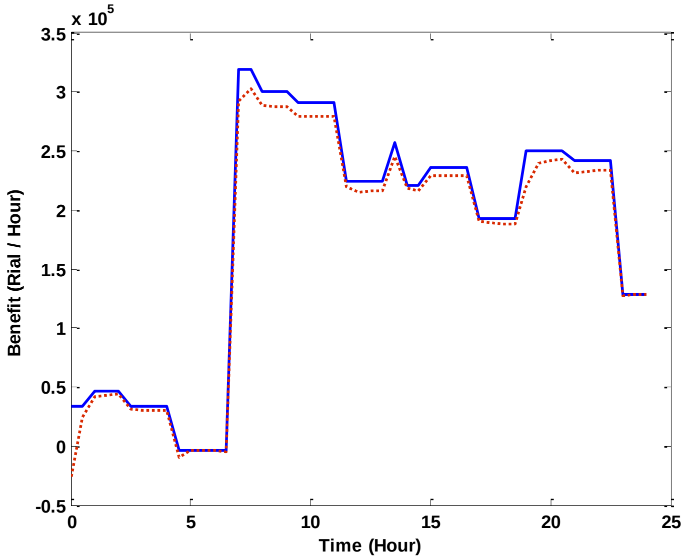

Fig. 21. Profit obtained for consumer 2 in the first and second scenario

As can be seen in figures 20 and 21, the profit obtained for consumers in the first scenario is more than the profit obtained in the second scenario. The reason for this is that in the second scenario, due to the fact that consumers provide incorrect information to their controller, the optimal consumption amount that the controller obtains for them is not their actual optimal consumption. Therefore, as the results of the simulations show, the consequences of this non-cooperation is that the real profit obtained for them will be less.

7. Conclusion

In this paper, we study the effects of load management practices on two industrial consumers using the optimal control strategy. For this study, the distribution company was considered as the controller and two industrial consumers as the consumers controlled of the problem. Using this strategy, consumer load management was examined. In this case, the controller controls the load consumption of consumers (controlled) by transferring load from peak to non-peak time and optimizing power consumption. The results of the simulation showed that load management using this method, in addition to saving power consumption and adjusting the price of power, also increases consumer profits. For example, if a consumer (at the suggestion of the controller) transfers some of his load from hours of power shortage to hours of excess power, it can reduce the cost of purchasing its additional power by 70%. This method is based on the real information of the actors (participants in the electricity distribution market) about the system and the electricity generation market. Also, all tariffs for the price of electricity consumption and the amount of consumption of the consumers result from the optimization of the profit functions of the distribution company (controller) and consumers (industrial producers). Therefore, this method can be more efficient and provide more reliable electricity to consumers than the previous methods presented in the articles. It should be noted that consumers cannot respond to the change of load requested by the controller (they cannot follow the optimal consumption reference). According to the simulation results, it is in the interest of the consumers to cooperate with their controller and provide his with complete information about the factory to determine the optimal consumption power, and finally to follow this optimal consumption reference. In the optimization of consumption load, the proposed strategy was modeled as a dynamic tracking problem. In order to calculate the optimal values of load change every half hour by each of the controlled ones, a consumption dynamic is defined for each consumer. Then, by using dynamic programming, a closed form was obtained to determine the optimal control value (optimal load change value) of each of the consumers. By defining appropriate incentives, the controller encourages consumers to follow the optimal consumption reference. The results of the simulation show that if the consumers follow the optimal reference announced by the controller, their profit will increase significantly. As the closed form obtained for the optimal control shows, two parameters R_k and Q_k play a great role for the consumers to follow the optimal consumption reference. By reducing the R_k coefficient and increasing the Q_k coefficient, the amount of following from the reference announced by the controller will be improved by each of the consumers. The values of Q_k and R_k basically indicate the factory's ability to follow the requested load change (u_k^*) from the controller. In other words, Q_k and R_k are subject to the change rate of the factory load, which is announced by the consumer to the controller. According to the conducted research, recognizing the problems and shortcomings in this field, the following items are suggested for future research.

- Optimum distribution of the limited amount of power between consumers
- Considering reliability for the studied system
- Implementation of load management using this strategy for a case study

The consumption reference controller obtains the optimal power for each of the consumers, and provides this amount of power completely from the market for them. To continue the work, we can consider a situation in which the controller divides the limited amount of power between the consumers in such a way that both of them achieve the maximum possible profit. Also, in this article, the reliability of the fixed system is assumed. To continue the work, it is suggested to consider a situation where the reliability of the system is a random variable.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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