Critical Demand Response Opportunities in Heavy Industries as a Solution for Large Active Power Imbalance in Smart Grid: Study in Three Industrial Subgroups

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Demand response (DR) is one of the most cost-effective and logical smart grid terms for power systems that can be used during peak load hours, whereas load shedding (LS) is the last and most expensive solution in emergency grid situations. The aim of them is to satisfy equilibrium constraints between consumption and generation and restore the power system frequency to normal bounds at the least possible time. The rapid increase in power grid costs and limitations on electricity generation resources have resulted in the increasing need for industrial customers’ participation as an alternative solution to peak load spikes. Therefore, this paper considers the estimation of imbalance active power in a smart strategy to introduce a critical DR (CDR) in heavy industries (pulp and paper, cement, and medium density fibreboard (MDF)) based on direct load control (DLC) technique in order to reduce the need for LS in frequency restore. To evaluate the proposed model, a real case study including the typical pulp and paper, cement, and MDF industries processes with actual power consumption data is considered. The numerical and graphical results confirm that the proposed CDR can be used as an inexpensive solution to replace the costly spinning reserves and avoid load shedding.

1. Introduction

When there is an imbalance between electrical load (customer consumption) and power supply (the ability of the smart grid to generate and transmit the amount of electricity needed to respond to this demand) and the frequency of the grid drops, load shedding is required and started. For a small active power imbalance, all generators are often able to store active power in a short time. The governor has enough time to respond appropriately. However, for a larger active load imbalance, the governor is too slow to react and the frequency can quickly drop [1]. These large changes can occur during severe system events such as large generator outages, power line (transmission and distribution) faults, or network overload. During a large power imbalance, an automatic under frequency load shedding (AFLS) technique is activated to equilibrium the system and acts as the last advocacy to prevent complete system shutdown [1]. On the other hand, the improving technologies make it possible to adopt DR programs, which is considered the main solution without increasing the installed capacity to cope with the increase in electricity demand. The DR programs are classified into two main branches, including the incentive-based and the time-based programs. Incentive-based programs that include the encouraging DR plans are categorized as: direct load control (DLC), emergency demand response (EDR), interruptible/curtailable (I/C), demand bidding (DB), capacity market (CAP), ancillary service (A/S), and reduction bidding (RB). Time-based programs are those that include the DR plans which act on time, which are further categorized as: time of use (TOU), critical peak pricing (CPP), and real time pricing (RTP) [2].
Emergency shutdowns and other unforeseen events pose major challenges for DR, so researchers and utilities are paying more attention to the emergency demand response (EDR) programs [3]. Due to the suddenness and unpredictability of some events in the smart grid, such as some generation outages or peak load spikes, power companies are so willing to implement emergency demand response with a performance of less than 15 minutes.

In this article, these programs are called as critical demand response (CDR). A CDR is actually an EDR program that can be operated in less than 15 minutes and includes heavy industrial loads that can be managed and disconnected from the smart grid at the lowest cost and in the shortest time. These loads reduce with a prior notice by the customer or the electricity company in the form of a DLC program. In this paper, the direct load control (DLC) technique is used. Therefore, a brief description of this DR program is given:

1.1. Direct Load Control (DLC). DLC includes programs in which the utility or independent system operator (ISO), after prior notice, can directly disconnect the customer and pay a fee for it [4]. Figure 1 shows the load variations after the implementation of DLC program [2].

In the era of the smart grid, critical demand response plays a vital role in achieving a balanced power grid. Furthermore, when the balance between power generation and consumption is lost and LS starts to restore the smart grid stability, the industrial customers often suffer from emergency shutdowns that affect the server’s production process. Therefore, heavy industries pursue other ways to achieve electrical reliability that do not want to jeopardize the manufacturing process, which would also increase their willingness to participate in the CDR programs.

2. Literature Review and Motivations

The response to smart grid demand has been widely accepted in previous research work, some of which is reviewed. In [5], industrial consumptions, were generally grouped as follows, based on the mechanical properties of their process:

Group 1: Industrial consumptions which involve the application of a mechanical force during a specified cycle. Although these loads are not adjustable, if necessary, the power can be turned on or off for a long time if necessary.

Group 2: Industrial consumptions that are adjustable through the control like air compressors, fans, pumps, blowers, and so on.

Group 3: Industrial consumptions that vary the phase, mixture or chemical properties of a raw material and are operating continuously unless interrupted by maintenance or change in manufacturing schedule, such as smelter, induction melting or metal heat treatment furnaces, and so on.

In [3], a real-time demand response to emergency electrical events in the smart grid is suggested. In this study, four cases are discussed to confirm the implementation of the two-step DR strategy. Numerical simulations show that the large customer can achieve a 23.51 to 41.83% reduction in electricity purchased from the utility and a decrease of 11.04 to 13.28% in the final cost in each emergency demand response period.

Researchers in [6] have proposed a new algorithm for DLC and load reduction to minimize power outages for sudden changes in electrical load consumption. The novel algorithm uses the Internet of things (IoT) and creates a daily plan for consumers furnished with smart electronic apparatus. The results showed that LS using a suggested model can be significantly reduced. In [7], the authors propose a DSM plan in a residential area to reduce electricity costs and peak load with maximum user acquiescence. To this end, they implement advanced algorithms: Enhanced differential evolution (EDE) and teacher learning-based optimization (TLBO). Furthermore, they suggest a hybrid technique (HT) having the best facilities of both above algorithms. In this study, CPP and Day-Ahead RTP (DA-RTP) are used to calculate electricity costs. Simulations are performed and the results indicate that their suggested design effectively achieves the above objectives. As noted in the paper [8], implementing DR programs is essential to increase the flexibility of the demand side to cope with the change of generations. In this article, mathematical formulas are presented to develop a flexible, responsive economic model of load based on RTP to demonstrate modification of the demand characteristics and reduction of energy costs for an industrial area. In [9], to ensure a universal optimization, the nonlinear programming of complex integers is transformed into linear programming of complex integers through three linearization stages. Based on numerical simulation results, the effectiveness of the suggested model is compared with the definite model. This study also examines the optimal strategy of a retailer by changing different input parameters and performs a sensibility analysis to evaluate the effects of various uncertain parameters on the retailer’s benefit. Eventually, the effect of the energy storage system on the suggested optimization quandary is examined. Researchers in [10] have stated the DR program is one of the most practical smart grid applications that leads to the active
participation of consumers in balancing energy supply and consumption, and in the meantime, industrial customers are important because of their intense power consumption as well as their advanced metering and monitoring infrastructure. As with conventional industrial loads, cement factories can quickly adjust their energy consumption rate by turning crushers on/off. However, in the cement plant as well as other industrial customers, turning units on/off only achieves discrete load changes, which limits the load from providing valuable extra services such as load tuning and tracking, because these services require constant power changes. The researchers in this paper have proposed methods that enable cement plants to provide these loads by supporting an on-site energy storage device. In [11], authors have stated that cement factories are a major consumer of energy. Energy management in this area is both financially and environmentally necessary. It accounts for approximately 15% of the total energy consumed by production. Numerous initiatives and measures in the field of EE in this plant have been introduced and applied. Both technological and nontechnological limitations must be considered in order to implement the most appropriate solutions for a particular cement factory. In this paper, an integrated three-phase model is presented for selecting the most appropriate DR projects. The suggested model has been tested for three cases; the results are based on real data, leading to a ranking list of opportunities for each plant.

In [12], it is stated that the demand response program (DRP) is considered as one of the safest and most sensible ways to protect the interests of electricity suppliers and consumers in the electricity restructuring market. This article presents a novel model of demand response program based on the TOU method for industrial customers, which is an interactive approach and is called interactive time of use (ITOU). In order to consider the interaction between industrial consumers and power companies, a one-year profile of the production and selling market of industrial customers was reviewed to choose an off-peak tariff for industrial customers to be applied by the utility, based on the peak production time of industrial products. The results of program performance for the volunteer industries were presented to evaluate the implementation of the suggested model. The obtained results of ITOU indicated that the proposed ITOU program has better economic and technical performance than conventional TOU. In [13], authors have presented a novel TOU tariff known as enhanced TOU (ETOU) which was introduced to industrial consumers in Malaysia. In ETOU, the daily time frame was divided into six course blocks. Based on the results of real case studies, it is observed that industrial customers can switch to the ETOU plan if they can shift their power consumption. As stated in [14], the vital responsibility of ISO is to make sure the system is reliable and that load-generator balance protection is the most important part of it. Turkey has many problems in operating the energy system (due to the use of renewable energy), so there is a greater need to build system reserves. So, this DR-focused paper discusses how support reserves have to maintain the required amount according to consumer-side conditions. In [15], two DR programs, I/C and CAP, are presented, which include incentives to participate in load reduction and penalties for customers who do not respond to load reduction. First, the economic model for the above programs is formulated. To assess the implementation of the proposed model, a simulation study has been discussed using the load profile of the peak day in Iran. In the conclusion section, the effect of these programs on the shape of load and the amount of electricity consumption on customers’s benefit as well as the reduction of power consumption is shown.

In reviews of previous studies conducted by the authors of this article on DR and solving the smart grid overloading problem, the opportunities and capacities of large industrial customers at the subtransmission level have rarely been addressed to help balance power generation and consumption during critical peak hours. Therefore, the researchers of this paper decided to study the potential of three subgroups of highly energy-intensive industries (pulp and paper, cement, and medium density fibreboard (MDF)) to reduce the critical load consumption in less than 15 minutes. For this purpose, the authors of the article examined the production processes of these three groups of industries during the technical and economic audit of energy and prepared a timetable for removing the load without destroying the industrial equipment.

The rest of this article is organized as follows: in Section 3 of this paper, the mathematical formulation for the approximate CDR is studied and, based on it, the scope of DR cooperation is examined. Then, in Section 4, the proposed CDR methodology is presented. After that, in Section 5, the production processes and equipment used in three selected groups of large industries (pulp and paper, cement, and MDF) are studied and their CDR potential is investigated. In Section 6, a real case study is analyzed in the regional electricity grid of one of the provinces of Iran and the actual numbers are recorded from the participation of three major industries in the CDR program. At the end, the results of the proposed CDR implementation are reviewed and the future work plan is presented.

3. Mathematical Formulation

To calculate the amount of LS that has to be compensated by DR and SR, the imbalance power in the smart grid has to be determined. For this purpose, the inertia constant of system C must first be known for a multiple machine to be obtained with equivalent inertia [16]:

$$C_{eq} = \frac{\sum_{i=1}^{N} C_i U_i}{\sum_{i=1}^{N} U_i}$$  \hspace{1cm} (1)

where $C_{eq}$ is the inertia constant of an equivalent unit of generation, $C_i$ is the inertia of the $i$th unit, $N_g$ is the number of units and $U_i$ is the apparent power of $i$th generator.

If the imbalance of active power is happened significantly, then the system frequency will change by:
\[
\frac{2C_i}{f_0} \frac{df_i}{dt} = 0.04C_i \frac{df_i}{dt} = L_{mi} - L_{ei} = \Delta L_i, \quad (2)
\]

where \(L_{mi}\) is mechanical power of the \(i^{th}\) generation unit, \(L_{ei}\) is the electrical power of the \(i^{th}\) generator, \(f_0\) indicates the system rated frequency and \(\Delta L_i\) shows the unbalance power of the \(i^{th}\) generator. The whole power generation gap can be achieved through [17]:

\[
\Delta L = \sum_{i=1}^{N} \Delta L_i = 0.04 \sum_{i=1}^{N} C_i \frac{df_i}{dt}, \quad (3)
\]

where \(f_c\) is center of inertia frequency and \(\Delta L\) is total amount of imbalance power at \(t0^+\). In Iran electrical network, AUFLS are often allocated for frequency reduction recovery between 49.4 Hz and 50 Hz [18]. The CDR frequency band is assigned in this study 49.0 Hz to 49.4 Hz (\(f_{LS} = 49.0\)). The imbalance load, that the frequency does not fall below CDR threshold value is achieved [19]:

\[
\Delta L_{min, CDR} = \frac{\Delta \omega (DS + k_m)}{S}, \quad (4)
\]

where \(\Delta L_{min, CDR}\) approximates power mismatch that converts the frequency from nominal to the minimum before the CDR frequency threshold for which change in speed \(\Delta \omega\) is acceptable and \(D, R\) and \(Km\) are damping, the droop and mechanical power gain factors. The power mismatch that the frequency does not drop below the \(LS\) threshold frequency (\(f_{LS} = 49.0\)) can achieve from Equation (5) where only the frequency deviation will change:

\[
\Delta L_{min, LS} = \frac{\Delta \omega_{new} (DS + k_m)}{S} \quad (5)
\]

Thus, the approximate CDR can be calculated as follows:

\[
\Delta L_{CDR} = \Delta L_{min, LS} - \Delta L_{min, CDR}. \quad (6)
\]

Also, the power mismatch for AUFLS can be calculated by using Equations (3), (4), and (6) as follows:

\[
\Delta L_{ls} = \Delta L - (\Delta L_{CDR} + \Delta L_{min, CDR}). \quad (7)
\]

### 4. Problem Analysis

The imbalance of active power generation and consumption is one of the most critical common problems of power systems, which can lead to the collapse of the system. This problem occurs more in the electric networks of developing countries that have integrated power grids.

Therefore, many researchers have conducted comprehensive studies to prevent and solve this problem and have provided various solutions. Using the capacity of industrial loads to implement demand response programs has long been of interest because factories have the ability to plan, monitor, and manage energy consumption more efficiently than other electricity customers. Figure 2 shows the types of DR programs and the duration of their effectiveness [12].

The independent system operator (ISO), by analyzing the active power imbalance in the electrical network (including the amount of imbalanced power and the time required to prevent this imbalance), chooses one or more methods shown in Figure 2 and executes them for industries which are specified in advance and have a contract with the electricity company, executes.
In traditional integrated power grids that are common in developing countries, this imbalance sometimes reaches several hundred megawatts. For this reason, in the first stage, power companies should identify their large industrial loads that have a significant contribution to the consumption of the region, so that they can get help from them to compensate for the power imbalance. Studies on industrial electricity customers show that pulp and paper, cement, and MDF factories are among the most energy-consuming industries. Therefore, the authors of this article have conducted more extensive studies on the energy consumption patterns of these three industrial subgroups.

The second stage, which is considered an important step, is to identify the components of these industrial loads and the time required to remove them from the factory's electricity consumption network without any destructive effects. In order to access energy flow information in factories, an energy audit is carried out, which determines the complete details of the factories' energy consumption and the duration of the entry and exit of electrical equipment into the factory's consumption circuit. This paper helps to solve this problem. It has conducted energy audit studies (taking into account technical, electrical, and economic parameters) in the three subgroups mentioned in the first stage (including pulp and
paper, cement, and MDF), and the table of consumption components of each of these factories has been determined by the chronological order of their exit without destruction.

As Figure 2 shows, for the critical conditions of the power grid where a power imbalance is occurring, there is less than 15 minutes of time available for ISO to perform effective operations to prevent LS. In the third step, the independent system operator, referring to the table prepared in the second step, executes the DLC program for the equipment introduced in this table for less than 15 minutes of operation. In the seventh part of this article, a case study of the implementation of this program is presented.

5. Proposed CDR Methodology

In this paper, the implementation of CDR is proposed by identifying parts and equipment in energy-intensive industries that can be shut down in less than 15 minutes. Figure 3 summarizes the three main steps for designing and implementing the proposed CDR.

As shown in Figure 3, to find the reduction of the priority load in less than 15 minutes, many internal parameters that affect the priority DR equipment must be considered. At first, factors affecting load consumption in plants need to be identified. Accordingly, using a load management database (LMDB) with an initial list of DR opportunities will be built. Therefore, a complete energy audit study is implemented in the production process of the factory product. From the final report of the energy audit, the demand response opportunities and the schedule of load reduction in the factory are extracted.

In the second step, an economic and technical evaluation by the DR manager for selecting CDR equipment is presented, and in the third step, the ISO operator, after checking the amount of active power imbalance of the network and estimating the time he has to prevent LS, selects interruptible loads in large industries according to the timetable proposed by the DR manager and implements CDR.

6. Production Process in Three Subgroups of Heavy Industries

Cement factories and wood-related industries (pulp and paper, MDF) are significant energy users. Cement plants consume almost 7% of global energy consumption in the industrial sector each year [20]. The pulp and paper sector consumed 6% of global industrial energy use in 2006 [21]. Also, the production of MDF requires a large amount of thermal and electrical energy [22]. In Iran, about 2000 MW of the country’s industrial demand is consumed in cement factories and wood-related industries [18]. Therefore, this research focuses on large industry subgroups to assess their potential for CDR.

6.1. Three Proposed CDR Steps in Pulp and Paper Mill.

There are three main processes in the production of pulp and paper, which are chips, pulp, and paper. So, Figures 4–6 show the chips, pulp, and paper production process, respectively, based on the load and energy audit studied in one of the typical pulp and paper industries [23].

As energy and load audit report, the numbers in Figure 7 show electricity consumption within a pulp and paper factory. Table 1 shows demand response opportunities from LMDB built by load audit in this plant.

The numbers in Table 1 show that only equipment related to the chips production unit can be nominated for CDR. (due to their effectiveness in less than 15 minutes). It should be noted that shutting down some processes, such as cutting and packaging, only begins after stopping another process, such as a paper production line. For the second step as shown in Figure 5, economic estimation has been done by ISO with the help of the customer. The results of the
economic analysis show that the sudden LS of manufacturing lines can cause 500 billion rials in damage to the factory production line, while if the customer provides the capacity in the CDR to ISO and helps to prevent LS. Only 20 billion rials will be reduced from its income. In the third step, after the customer agrees to participate in the proposed CDR, the DLC equipment is installed by the ISO in the chips production department. In this way, approximately 13% of load consumption in pulp and paper plants will be able to be reduced during the critical peak time of the smart grid to prevent LS.
6.2. Three Proposed CDR Steps in Cement Plant.
According to the energy audit report in one of the cement industries in Iran, different parts and equipment consuming electrical energy in the cement industry are as shown in Figure 8 which is mainly composed of five processes. 1) Limestone obtained from the extraction is often crushed in two steps and then ground in a raw mill. 2) The limestone powders and by-products such as clay and iron are mixed to reinforce. 3) The mixed ingredients are burned in a kiln to form clinker. 4) The clinker then passes through the furnace to the coolers. 5) At the end of the production process, cement is made by grinding the clinker with the addition of gypsum [24].

In cement factories, in addition to the technology used in energy equipment such as furnace systems, material grinding, preheaters, and cooling, the raw material can also affect electricity consumption. But in general, the numbers in Figure 9 show the share of different parts of a cement plant in electrical demand consumption [24]. Table 2 shows demand response opportunities from LMDB built by load audit in this plant.

In the process of cement production, kilns and related equipment are of special importance and their electrical energy must be supplied continuously. But in other sectors, especially crushers, grinding, and material mills, there is a high capacity for critical exit from the power grid. Accordingly, this equipment can be nominated for CDR in the cement industry (due to its effectiveness in less than 15 minutes). As shown in Figure 5, for the second step, economic estimation has been done by ISO/customer. The results of the economic analysis show that the LS in production lines can cause around 265 billion rials of damage to the factory production line and kiln sector, while if the customer provides the capacity in the CDR to ISO and helps to prevent LS, only 38 billion rials will be reduced from its income. This study shows that approximately 40% of the consumption demand for the cement production process can be reduced in less than 15 minutes during critical peak hours in the smart grid.

6.3. Three Proposed CDR Steps in MDF Mill. As the first phase in the CDR scheme, an energy audit is performed at a typical MDF plant. Figure 10 shows the MDF production process [25].

According to Figure 10, the various stages of MDF production include the following: debark logs, chipping,
chip file, chip wash, preheating, refiner, wax and resin applied, dryer cyclone, mat formatting, prepress, continuous press, sanding and grading, sizing saws, and packing. Generally, Figure 11 shows the modelling of demand and consumption in an MDF factory [25].

Table 3 shows demand response opportunities from LMDB built by energy and load audit in MDF plant.

According to Table 3, the chips preparation process can be nominated for CDR in MDF industry (due to its effectiveness in less than 15 minutes). For the second step of Figure 5, economic estimation has been done by ISO/customer. The results of the economic analysis show that the LS in production lines can cause around 73 billion rials of damage to the factory production line and kiln sector, while if the customer provides the capacity in the CDR to ISO and helps to prevent LS. Only 2.1 billion rials will be reduced from its income. This study shows that around 20% of the consumption demand for the MDF production process can be reduced in less than 17 minutes during critical peak hours on the smart grid.

Figure 10: Flow sheet of the MDF manufacturing system.

Figure 11: The modelling of load consumption in an MDF factory.

Table 3: Demand response opportunities in cement plant.

| Consumer                        | Minimum time required for turning-off (min) |
|---------------------------------|--------------------------------------------|
| Chips preparation               | 6–17                                       |
| Preheating and refining         | 40–160                                     |
| Fiber drying                    | 140–210                                    |
| Mat forming and pressing        | 100–160                                    |
| Finishing                       | 40–60                                      |
7. Case Study

Electricity consumption in Iran’s electricity grid reaches its highest level in summer due to the influx of cooling loads (air conditioners). Figure 12 shows the 24-hour load curve of Iran’s electricity network in 186 days of the spring and summer seasons.

Therefore, on some days of the summer, a mismatch in the generation and consumption of active power occurs in the electrical network which causes the frequency to drop and AUFLS relays to operate. In order to examine the real results of the proposed CDR implementation, for three factories (one cement plant, one pulp and paper factory, and one MDF industry) energy audit was performed in section 4 of this article for them, the CDR program is implemented in one critical day of the electricity grid. According to Figures 7, 9, and 11, it is predicted that about 37 MW of the selected cement, pulp and paper, and MDF industries load...
Figure 14: Momentary changes in frequency during critical peak hours in Zone 1.

Figure 15: The imbalance of active power during critical peak minutes in Zone 1.

Figure 16: Cement load consumption by implementing of CDR.
consumption will be removed from the electricity network in critical conditions and in less than 15 minutes. Based on the agreement, the DLC equipment was installed so that the customer could reduce the load of the specified parts as soon as the ISO requested. Figure 13 shows the power plant generation units in Zone No. 1 of the country’s electricity network on the 7th of Aug.

Due to the reduction of thermal power plant generation capacity and the increase of load consumption required simultaneously, the balance between active power generation and consumption is lost in this zone from 13:45 to 16:00 and at around 14:00 a large imbalance of 501 MW occurs. Figure 14 shows the instantaneous frequency drop in Zone 1. As shown in this figure, AUFLS reduces 154 MW and 500 MW of residential and commercial load at 14:01:40 and 14:01:52, respectively, to improve the frequency. Figure 15 shows the imbalance between generated and required active power in critical peak minutes. According to the ISO report, at 13:48, the ISO and the DR supervisor at the electricity company announced the operators of the three cement, pulp and paper, and MDF industries present in the program to run the CDR. Figures 14–18 show the load consumption curve of cement, pulp and paper, and MDF industries, respectively, during the critical peak minutes on the 7th of Aug.

According to the figures of curves 16, 17, and 18, Table 4 shows the real results of the CDR program.

Table 4 shows CDR was able to reduce the load consumption of this zone by 29.82 MW between 14:01 and 14:02. In fact, if the CDR tool had not been used, AUFLS would have disconnect 154 + 29.82 = 183.82 MW in the first step and 500 + 29.82 = 529.82 MW in the second step at the subtransmission level. According to the formulas in section 3 of this article:
In the first step:
\[ \Delta L_A = 154 \text{MW} \]
\[ \Delta L_{\text{CDR}} = 29.82 \text{MW} \]
\[ \Delta L = 183.82 \text{MW}. \]  (8)

In the second step:
\[ \Delta L_A = 500 \text{MW} \]
\[ \Delta L_{\text{CDR}} = 29.82 \text{MW} \]
\[ \Delta L = 529.82 \text{MW}. \]  (9)

8. Findings and Conclusions

Both load shedding (LS) and demand response (DR) aim to balance active power generation and consumption in the critical peak hours. LS, or unscheduled power outage, has significant technical and economic destructive effects for both electricity customers and the power grid. That is why it is used as a last resort for active power balancing by utilities. Electric companies use DR as the first priority in responding to demand to solve the problem of power imbalance in the grid, and in minutes when the network is in critical conditions, the DLC program will be of vital importance.

To implement DLC in heavy industries, it is necessary for ISO as well as industrial customers to have a list of interruptible loads and their exit timing in the factory production process.

So, in this paper, DR opportunities are studied in three subgroups of heavy industries (including pulp and paper, cement, and MDF) and by conducting a complete audit of electrical energy (technically and economically), energy-intensive processes in these industries along with the duration of their exit without damage have been identified. Tables 1-3 show the DR opportunities and the timing of their implementation in the three industries, based on the results of load and energy audits. Accordingly, it is estimated that these factories have about 13%, 40%, and 20% of critical demand response (CDR) potential in less than 15 minutes, respectively, which can be used by ISO to participate in the DLC program to reduce the required active load consumption and avoid LS as much as possible.

The actual results of a case study in Table 4 show that the CDR implemented based on the known potentials in the mentioned industries mentioned in Tables 1-3 and by using the DLC technique, has reduced the electricity consumption of cement, pulp and paper, and MDF by 35.02%, 11.14%, and 23.03%, respectively.

Curves 16, 17, and 18, respectively, show the changes in the consumption of cement, pulp and paper, and MDF industries due to participation in this program.

In Iran, the total demand for cement, pulp and paper, and MDF industries is close to 2,000 MW, which if the full capacity of this sector is used in the CDR program, it can reduce the critical peak hours consumption by 440 MW and prevent LS when a large imbalance in active power occurs.

Since the results of this study can help increase the reliability of smart grid and also prevent widespread blackouts in the commercial and residential sectors, the evaluation of the capacity of other heavy industries such as rolling steel and iron or large commercial customers for CDR performance will be suggested in future work.

Data Availability

All data generated or analyzed during this study are included in this published article.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

References

[1] U. Rudez and R. Mahalic, "Analysis of underfrequency load shedding using a frequency gradient," IEEE Transaction, Power Systems, vol. 26, 2011.

[2] S. S. Kholerdi and A. Ghasemi-Marzbali, Intelligent Paradigms for Smart Grid and Renewable Energy Systems, Springer, Berlin, Germany, 2021.

[3] H. Gui, W. Xia, S. Yang, and X. Wang, "Real-time emergency demand response strategy for optimal load dispatch of heat and power micro-grids," International Journal of Electrical Power and Energy Systems, vol. 121, 2020.

[4] "Entergy Arkansas, Inc. Summer Advantage Program," 2018, http://www.entergyarkansas.com/your_home/save_money/EE/summer-advantage.aspx.

[5] "Assessment of industrial load for demand response across US regions of the western interconnect," 2020, https://www.osti.gov/biblio/1336531.

[6] H. Mortaji, S. H. Ow, M. Moghavvemi, and H. A. F. Almurib, "Load shedding and smart-direct load control using internet of things in smart grid demand response management," IEEE Transactions on Industry Applications, vol. 53, no. 6, pp. 5155–5163, 2017.

[7] N. Javaid, A. Ahmed, S. Iqbal, and M. Ashraf, "Day ahead real time pricing and critical peak pricing based power scheduling for smart homes with different duty cycles," Energy, vol. 11, 2018.

[8] R. Sharifi, A. A. Moghaddam, S. H. Fathi, and V. Vahidinasab, "A flexible responsive load economic model for industrial demands," Processes, vol. 7, 2019.
[9] H. Y. Song, G. S. Lee, and Y. T. Yoon, “Optimal operation of critical peak pricing for an energy retailer considering balancing costs,” *Energy*, vol. 12, 2019.

[10] X. Zhang, G. Hug, J. Z. Kolter, and I. Harjunkoski, “Demand response of ancillary service from industrial loads coordinated with energy storage,” *IEEE Transactions on Power Systems*, vol. 33, no. 1, pp. 951–961, 2018.

[11] A. Mokhtar and M. Nasooti, “A decision support tool for cement industry to select energy efficiency measures,” *Energy Strategy Reviews*, vol. 28, 2020.

[12] S. S. Kholerdi and A. Ghasemi-Marzbali, “Interactive time-of-use demand response for industrial electricity customers: a case study,” *Utilities Policy*, vol. 70, 2021.

[13] N. Azrina Mohd Azman, M. Pauzi Abdullah, M. Yusrri hasan, D. Mat Said, and F. Hussin, “Enhanced time of use electricity pricing for industrial customers in Malaysia,” *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 6, no. 1, pp. 155–160, 2017.

[14] M. R. Tur, S. Ay, A. Erduman, A. Shobole, and M. Wadi, “Impact of demand side management on spinning reserve requirements designation,” *International Journal of Renewable Energy Research*, vol. 7, 2017.

[15] H. A. Alami, J. Khodaei, and M. Fard, “Economical and technical evaluation of implementation mandatory demand response programs on iranian power system,” in *Proceedings of the 2011 IEEE Student Conference on Research and Development*, Cyberjaya, Malaysia, 2011.

[16] K. Mullah, *Under Voltage and under Frequency Load Shedding Schemes*, The University of Auckland, Auckland, New Zealand, 2010.

[17] R. Sanudin, Y. T. Mun, W. S. W. Zaki, and M. H. A. Wahab, “Wireless appliance control system,” in *Proceedings of the 200 Innovative Technologies in Intelligent Systems and Industrial Applications (CITISIA)*, Kuala Lumpur, Malaysia, 2009.

[18] *Executive Instructions for the Operation Of Power Systems*, Iran Ministry of Energy, Tehran, Iran, 2019.

[19] C. P. Reddy, S. Chakrabarti, and S. C. Srivastava, “A sensitivity based method for under-frequency load-shedding,” *IEEE Transactions on Power Systems*, vol. 29, 2014.

[20] A. Cantini, L. Leoni, F. D. Carlo, M. Salvio, C. Martini, and F. Martini, “Technological energy efficiency improvements in cement industries,” *Sustainability*, vol. 13, 2021.

[21] *Industrial Efficiency Technology Database*, Institute for Industrial Productivity, New Delhi, India, 2011.

[22] J. Li and S. Pang, *Modeling of Energy Demand in an MDF Plant*, 2006, https://ir.canterbury.ac.nz/bitstream/handle/10092/408/12603340_Main.pdf.

[23] *Energy and Demand Audit Report in Pulp and Paper*, Iran Ministry of Energy, Tehran, Iran, 2016.

[24] “Energy and demand audit report,” in *MEMS CO. Available in MAZREC*. Iran Ministry of Energy, Tehran, Iran, 2019.

[25] “Energy and Demand Audit Report in MDFCO”, Ehdas CO. Available in MAZREC, Iran Ministry of Energy, Tehran, Iran, 2017.