Load Shifting Implementation in a Laundry Room under Demand Response Program

Mahsa Khorram [1], Pedro Faria [1], Zita Vale [1]
[1] Polytechnic of Porto, Porto, Portugal
makgh@isep.ipp.pt, pnf@isep.ipp.pt, zav@isep.ipp.pt

Abstract— **In order to overcome the consequences of high energy consumption, renewable energy resources advancement, smart grids development, and demand response programs effectiveness should be noticed and surveyed. Regarding the important role of buildings in energy consumption, another important factor is equipping the buildings and houses with automation. For this purpose, this paper presents an optimization algorithm based on demand response program which is concerning about time of use for ancillary service and also is based on energy price in different periods. In the case study of this paper, the power consumption of two washing machines and one dryer are considered to achieve the demand response program goal. Since it is not reasonable to use dryer before washing machines, the sequence of operation cycle of devices is important for the algorithm. The obtained results of the algorithm show the applied load shifting based on energy price, demand response requirements and remuneration.**

Keywords— Buildings, Demand Response, Load shifting, Time of Use, Optimization, Rstudio.

I. Introduction

Power system stability is the ability of an electric power system, for a given initial operating condition, to recover a state of operating balance after being subjected to a physical disturbance. However, the electrical power systems are known as a nonlinear system where the changing of generation and the loads are in a continues state [1]. The efforts have been increased in the last decades to maintain the stability of the electrical power systems, due to the characteristic of the modern electrical power systems from the complex dynamical properties to the small stability margins, which mainly caused by the expansion of the power grids and the huge implementation of renewable energy sources [2]. However, the most common mechanisms which used for controlling emergency states in electrical grids are load shedding, generators rescheduling, optimal power flow, and Flexible Alternating Current Transformer System devices [3]. And with the development new methods have been established to achieve that target. One of these methods is the Demand Response (DR) programs, which defined as the programs that lead to change the electric usage of the final customers from their normal consumption patterns as a response to the variation of the electricity prices or to the incentive payments from the grid operators or when the stability of the power system is in a critical situation [4]. In other words, the demand response programs (DR) are the modification of electricity consumption profiles, which customer is paid by the grid operator due to the several economic or technical reasons [5]. The objective of these programs is load curve smoothing (peak shaving), or simply keep the balance between generation and demand. However, Demand response programs can be categorized into two main groups, Price-based methods, and Incentive-based methods [6] [7]. Price-based methods: It refers to the variation of the consumptions to response to the price variations, such as: Time-of-use (TOU), Real-time pricing (RTP), Critical-peak pricing (CPP) rates, Critical peak rebates (CPR); Demand Bidding/Buyback (DB) programs, Emergency Demand Response Program (EDRP), Capacity Market program (CAP). Incentive-based methods: It refers to the programs that give the customers incentives for changing their consumption models, including: Direct Load Control (DLC), Interruptible/Curtailable Service (IC), In Demand Bidding/Buyback (DBB), Emergency Demand Response (EDR), In Capacity Market (CM), Ancillary Services Market (ASM).

The DR programs have already demonstrated to be an important mechanism to ensure the reliability of the electrical system [8], furthermore, DR use to control the frequency and maintain the frequency stability [9]. Indeed, with the growth of renewable energy sources and distributed energy resources in the grid, the possibility of congestion issues is significantly increasing, and they may cause serious system damages, here the demand response can play the role to manage and provide the needed power for ancillary service (AS). In this context, DSR services include: Frequency Response, Short Term Operating Reserve (STOR), and Fast Reserve.

There are many presented studies to achieve those services by providing Ancillary Services such as the work in [10] when they proposed a model for deep peak regulation , also, the work in [11] when they proposed control method for grid-interactive smart buildings, according to the characteristics of the aggregated smart buildings will have power tracking and energy recovery capability, which can effectively improve the system frequency response [11]. Authors in [12] have been proposed an optimization-based Supervisory Control And Data Acquisition (SCADA) system under real time pricing tariff due to DR program.

This paper proposes an optimization algorithm to implement the load shifting based on priority of the loads, DR program requirements, incentives, and energy price. Three non-deferrable loads are considered to implement the loads shifting in different scenarios. It should be noted that the operating sequence of loads are important point in the algorithm. After this section, the methodology is explained in Section II. The case study is demonstrated in Section III and the obtained results will be compared in section IV. Finally, Section VI describes the main conclusions of the work.

II. Materials and Methods

This section presents the implemented optimization methodology for shifting the power consumption of two WMs and one dryer in order to response to the DR program event. Fig. 1 shows the overall view of the present methodology.

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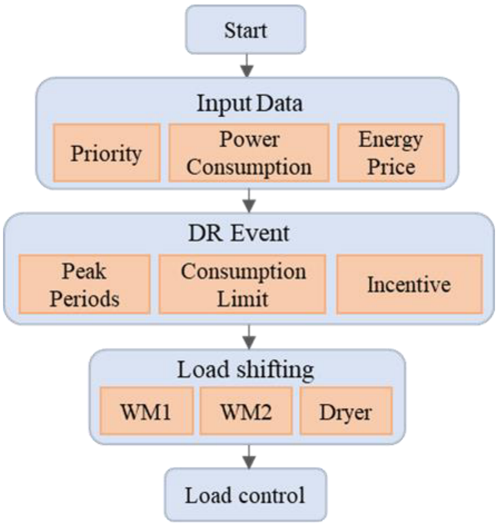

Fig. 1. Overall view of proposed methodology.

From the perspective of program coding, the purpose is load shifting of 3 appliances. However, from the realistic perspective of users, the operation cycle of dryer must be after finishing the operation cycle of two WMs. It means that, two WMs are free to have interference in their operation cycle, but the starting time of dryer should be after the complete operation cycle of two WMs. This optimization algorithm considers the priority of devices to operate, and also considers the energy prices and incentives prices in different periods. Regarding to DR program specifications, the power consumption of WMs should be shifted to desired periods with considering operation cycle of dryers.

The present methodology is implemented in Rstudio® software with using OMPR package which is one of the available packages in Rstudio for implementing mixed integer linear problems (www.rstudio.com). Equation (1) shows the Objective Function (OF) of present optimization algorithm.

$$Min\ OF = \sum_{t=1}^{T}\Bigg[\sum_{o=1}^{O}(Pr\_WM1_o \times Price_t \times Incentive_t \times Power\_WM1_{(o,t)} \times WM1_o) + (Pr\_WM2_o \times Price_t \times Incentive_t \times Power\_WM2_{(o,t)} \times WM2_o) + \sum_{od=1}^{OD}(Pr\_D_{od} \times Price_t \times Incentive_t \times Power\_D_{(od,t)} \times Dryer_{od})\Bigg] \quad (1)$$

Pr_WM1, Pr_WM2, and Pr_D shows the priority of WM1, WM2, and dryer respectively. Priority numbers are decimal numbers between 0 and 1, which represents the priority of each device to participate in DR event based on user preference. Devices with priority numbers close to 0 have less priority than devices with higher priority number. Price means the energy price in different periods of time. Incentive is the financial motivation in each period that should be offered by DR entity to consumers to make changes in their consumption pattern. Power_WM1, Power_WM2, and Power_D indicates the power consumption of WM1, WM2, and dryer respectively. All above parameters are defined as coefficients of variables for algorithm to choose the optimum solution based on different priorities, different prices, different incentive, and available power. It means that algorithm should select the period with low price and high incentive with respecting to the defined priorities and available power. According to (1), WM1is a binary variable related to first washing machine. WM2 is a binary variable related to second washing machine, and Dryer indicates the binary variable related to dryer. The binary variables show the operation state of devices so that 1 is related to ON situation, and 0 is related to OFF. It should be noted that T indicates the number of periods, O means the Operation modes of WMs, and OD is operation mode of dryer.

Equations (2), (3), and (4) are the constraints to bound the algorithm for choosing only one operation mode for WM1, WM2, and dryer respectively.

$$\sum_{o=1}^{O} WM1_o = 1 \quad (2)$$

$$\sum_{o=1}^{O} WM2_o = 1 \quad (3)$$

$$\sum_{od=1}^{OD} Dryer_{od} = 1 \quad (4)$$

Equation (5) shows the allowed power consumption in each period based on DR program specifications.

$$\sum_{o=1}^{O}(WM1_o \times Power\_WM1_{(o,t)}) + (WM2_o \times Power\_WM2_{(o,t)}) + \sum_{od=1}^{OD}(Dryer_{od} \times Power\_D_{(od,t)}) \le P\_max_t \ \forall\, t \in \{1, \dots, T\} \quad (5)$$

P_max shows the maximum allowed power consumption in each period based on DR program requirements. It should be mentioned that P_max is related to total power consumption of controllable devices.

Regarding to rational use of dryer, (6) and (7) are defined to adjust the starting time of dryer after finishing of WM1 and WM2 respectively.

$$\sum_{t=1}^{T} t \times WM1_t \leq \sum_{t=N+1}^{T} t \times Dryer_t \tag{6}$$

$$\sum_{t=1}^{T} t \times WM2_t \leq \sum_{t=N+1}^{T} t \times Dryer_t \tag{7}$$

N represents the number of periods that WMs need to finish their operation cycle which is considered equal to 3.

III. Case Study

This section is prepared to test and validate the proposed methodology in a real case study for optimizing power consumption of building based on DR programs requirements. In order to study about the impact of DR programs, the dataset from Federal Energy Regulatory Commission (FERC) [14] has been selected as the reference. The selected program is voluntary named as (AEP-Variable Pricing), its goal to provide full-time energy price incentive for the customer to shift the loads from peak to off-peak. The incentives are 10.1 Cent/kWh for peak periods, 3.4 Cent/kWh for mid-peak periods, 0.4 Cents/kWh for off-peak periods and for critical peak is 29 Cent/kWh. Regarding to load shifting implementation, there are no changes in annual energy use, each peak period is 2 hours, whereas the dispatchable critical peak is up to 176 hours per year. This program kept going all over the year with 25000 costumers participating, with power reduction up to 45 MW. The peak demand is 59% and 1.5- 3 kW per customer which should be shifted to off-peak periods. The algorithm controls the equipment in the private laundry room of a building which is working from 10 am to 6 pm. This building is equipped with a SCADA system for controlling and monitoring several parameters in the building such as power consumption of controllable devices. In fact, the building is able to manage the electricity consumption and also to record the data in a database. More detailed information about present SCADA system can be found in [13].

The present study considers two WM and one dryer as controllable loads for load shifting. Regarding to non-flexibility of these kind of domestic loads, the algorithm should observe their operation cycle. The algorithm focuses on 8 periods of a day from 10 am to 6 pm. It means each period is equal to 1 hour. The complete operation cycle for WMs has been reported as 3 hours, and the operation cycle of dryer has been considered as 2 hours. This case study includes 6 scenarios for surveying about the impact of different parameters on the results. The number of devices and their operation cycle periods are the same in all periods.

Scenario 1 implements the load shifting based on P_Max, normal electricity price, and incentives for peak periods and off-peak periods. All parameters are considered in this scenario and all constraints are observed.

In terms of parameters, scenario 2 is the same as scenario 1. However, constraints (6) and (7) are ignored to verify the role of constraints (6) and (7) for observing the sequence of devices which is an important factor for the users.

In scenario 3, the algorithm will be implemented based on P_Max, normal electricity price, and incentives. In this scenario, periods 5 and 6 considered as critical periods and the incentives should be applied based on critical periods. It should be noted that all constraints are included.

In Scenario 4, electricity prices are reduced by 50% in periods 5 and 8. The incentive prices and power consumption limitation are the same as scenario 1.

Scenario 5 is the implementation of algorithm based on power limitation. Energy price and incentive price are ignored in this scenario and the results are based on P_Max.

Scenario 6 is opposite of scenario 5. In this scenario there is no limitation for power consumption in all periods, however, the algorithm implements the load shifting based on energy prices and incentives in each period.

The Electricity Bill (EB) will be calculated by (8) with considering the actual power consumption of devices, energy price and received money due to incentives.

$$\begin{aligned} EB = [(&\sum_{o=1}^{O}(WM1_o \times Power\_WM1_{(o,t)}) \\ &+ (WM2_o \times Power\_WM2_{(o,t)}) \\ &+ \sum_{od=1}^{OD}(Dryer_{od} \times Power\_D_{(od,t)}) \times Price_t] \\ &- Incentive_t;\ \forall\, t \in \{1, \dots, T\} \end{aligned} \tag{8}$$

Fig. 2 shows the power consumption of building in detail before optimization. The maximum allowed power consumption in each period has been compared to total power consumption of the building.

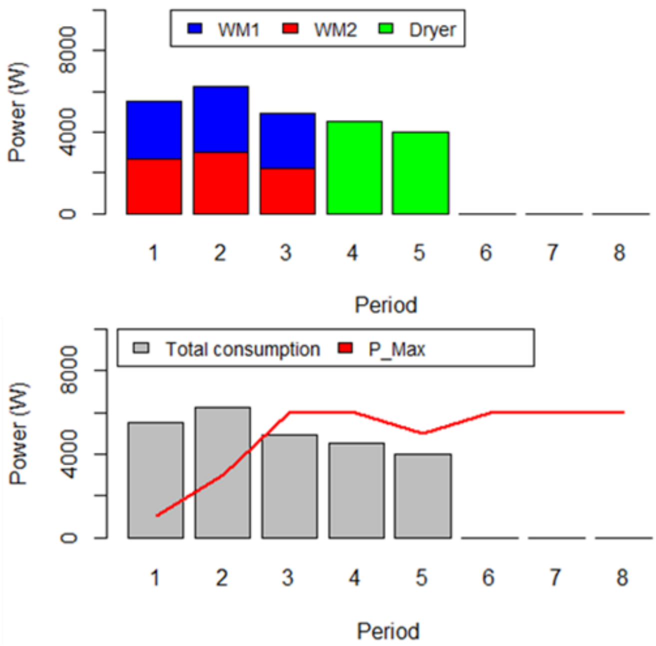

Fig. 2. Power consumption of the laundry room before load shifting.

As it can be seen in Fig. 2, the operation cycle of WMs can have interferences in all period, however this is not allowed for the dryer even for one period.

According to received DR, the maximum allowed power consumption in each period is defined. It can be seen in the Fig. 2 that there are restrictions in power consumption in periods 1-2. However, the maximum allowed power consumption in periods 6-8 are more than actual power consumption of the building. Priority of devices is a effective factor to control the devices in the same category. In this study the priority numbers of two WMs determine the destination periods of their shifting. Table I shows the priority od devices in each period. The priorities are constant parameters in all scenarios.

TABLE I. DEFINITION OF PARAMETERS IN PRESENT CASE STUDY.

Period	1	2	3	4	5	6	7	8
Pr_WM1	0.7	0.1	0.5	0.6	0.9	1	0.9	0.9
Pr_WM2	0.1	0.7	0.4	0.6	0.9	1	0.9	0.9
Pr_D	1	1	1	1	1	1	1	1

As it can be seen in Table I, the WMs have differences in priority numbers in some periods. In each period, the device with high priority number is the first participant in DR program and should be cut.

In addition to P_Max, and priorities the electricity price has an important role in the load shifting. The maximum allowed power consumption in each period may provide several choices for the algorithm to shift the load, however, the electricity price is the factor to limit the load shifting based on economical purposes. Incentive prices are also another economic factor that affect on consumption behavior of devices. More incentives encourage the consumers to cut their loads to gain more benefits. The algorithm will be implemented several times to surveys about the impact of DR program in consumption pattern, impact of constraints (6) and (7) on dryer power consumption, and the impact of incentive prices in time of use of consumers. The obtained results of proposed cased study will be illustrated in next section. Table II shows the energy price and incentives in different scenarios. The electricity prices and incentive prices presented in the table are in cent/kWh.

TABLE II. ENERGY PRICE AND INCENTIVES IN DIFFERENT SCENARIOS.

Period		1	2	3	4	5	6	7	8
Scenario 1,2,6	P	16	16	9	9	16	9	9	16
	I	10	10	3	3	10	3	3	10
Scenario 3	P	16	16	9	9	16	9	9	16
	I	10	10	3	3	29	29	3	10
Scenario 4	P	16	16	9	9	8	9	9	8
	I	10	10	3	3	10	3	3	10
Scenario 5	P	-	-	-	-	-	-	-	-
	I	-	-	-	-	-	-	-	-

IV. RESULTS

The main purpose of this section is to propose the obtained results of the optimization algorithm based on the case study descriptions. The following figures present the results of 6 different scenarios based on different purposes. Fig. 3 shows the implemented load shifting method for responding to received DR program in scenario 1.

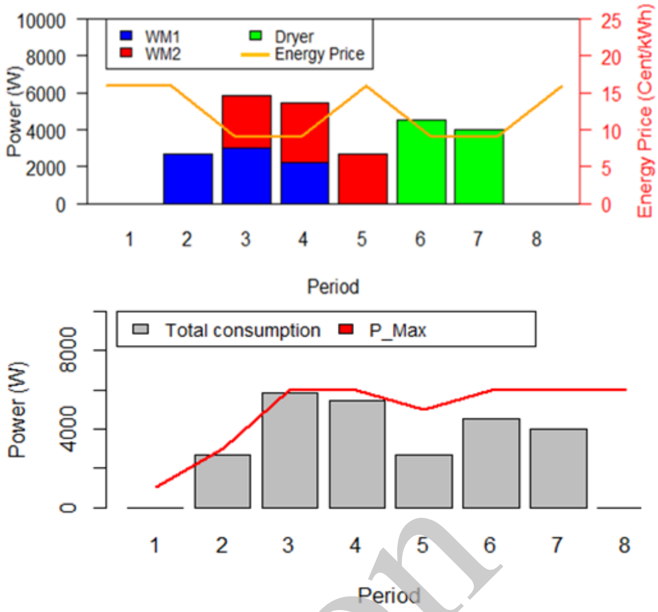

Fig. 3. Power consumption of devices in scenario 1.

According to comparison of Fig. 3 and Fig. 2, power consumption of WM1 has been shifted 1 period ahead, power consumption of WM2 has been shifted 2 periods ahead, and power consumption of dryer is shifted 2 periods ahead. Regarding to freedom of the algorithm in some periods based on P_MAX, electricity price, and incentive reasons, the power consumption of WM1 and WM2 is overlapped in periods 3 and 4. It can be seen that in periods 3 and 4 the power consumption is in the highest range; however, the energy price is low. Also, the remuneration of load reduction in periods 3-4 and 6-7 is low. The difference in starting time of WM1 and WM2 can be justified by proposed priority numbers in Table 1. Regarding to P_Max in Fig. 2, the maximum allowed consumption for laundry room in period 1 is announced 1000 W. It means that any of devices cannot operate in this period due to their high consumption. However, in second period, the P_Max has been increased and the device with lower priority to participate in DR program is the first device to operate.

In order to verify the validity of the algorithm for achieving DR program requirements, Fig. 3 also shows the total power consumption of the laundry room based on maximum allowed power consumption in each period. According to comparison of Fig. 3 and Fig. 2, it can be seen that the consumption pattern has been modified based on DR request. There is no change in the total power consumption of the users, however time of use has been changed based on technical and economic reasons.

Constraints (6) and (7) are defined to set the operation cycle of dryer after WMs. For ensuring the effectiveness of those constraints, Fig. 4 illustrates the obtained results of scenario 2 when constraints (6) and (7) are not considered. It can be seen in Fig. 4, the dryer has been operated first, and its operation cycle has been overlapped with WM2. This is not reasonable to use the dryer before washing anything. Regarding to the DR program description, the incentives rate may change based on the network conditions. The incentive price in critical periods has been reported as 29 Cent/kWh. It is considered that DR program announced critical periods in 5-6 with 29 Cent/kWh remuneration.

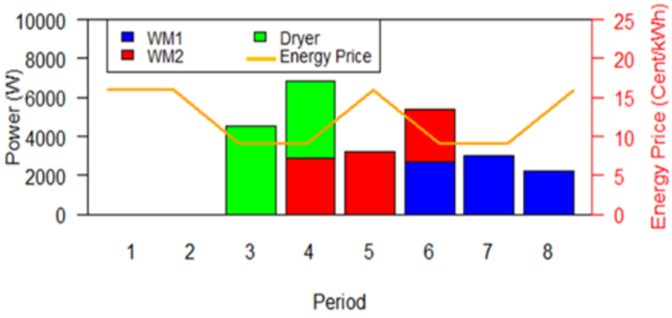

Fig. 4. Power consumption of devices in scenario 2.

Fig. 5 presents the obtained results of the algorithm in scenario 3. The consumption of dryer has been shifted one period ahead due to consider the incentive price increment. The consumption of WMs have not been changed in critical periods in order to respect to maximum allowed consumption.

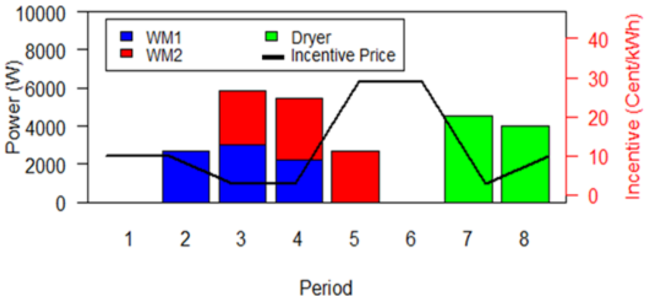

Fig. 5. Power consumption of devices in scenario3.

Fig. 6 shows the results of algorithm related to scenario 4 with different energy prices in periods 5 and 8. The obtained results of scenario 4 in Fig. 6 shows the power consumption periods 5 and 8 to take advantage of low electricity price. According to scenario 5, the energy price and incentive price are ignored and the optimization in based on power limitations. Fig. 7 shows the results of scenario 5. Comparing Fig. 7 with previous results, it can be seen that the absence of energy price and incentives in this scenario caused dryer operation in periods 7-8.

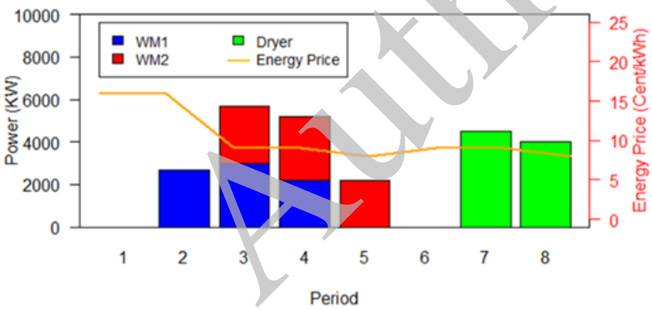

Fig. 6. Power consumption of devices in scenario 4.

Fig. 8 presents the consumption of laundry room when there is no limitation for consumption. It means that the results of scenario 6 are based on energy price and incentive prices. WM1 started to operate in first period, however, in previous scenarios, the first period had power consumption limitation equal to 1000W. In order to compare the scenarios in economic aspects, the EB of each scenario is calculated based on (8). The EB of the laundry room before DR is calculated 337.24 Euro/kWh. Table III shows the EB of each scenario dedicated to 8 hours working of laundry room.

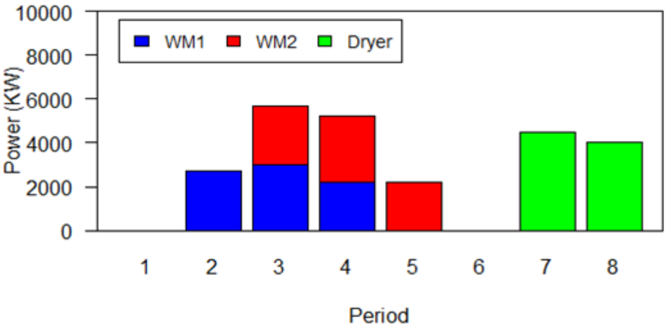

Fig. 7. Power consumption of devices in scenario 5.

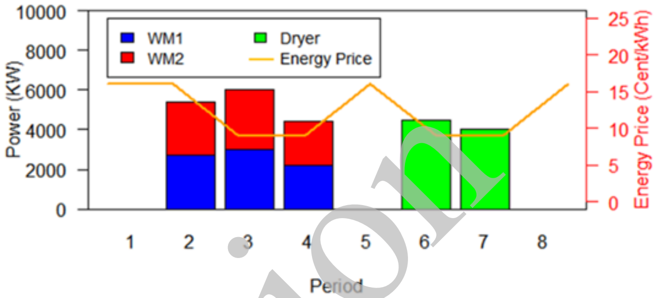

Fig. 8. Power consumption of devices in scenario 6.

TABLE III. ELECTRICITY BILL IN EACH SCENARIO.

	Scn1	Scn2	Scn3	Scn4	Scn5	Scn6
EB	160.61	138.09	163.91	110.3	182.66	163.16

The EB is decreased in all scenarios. Scenario 4 has the lowest EB by its flexibility to change the consumption pattern to take advantage of off-peak periods. Scenario 1 also is considered an efficient one observing DR requirements.

V. CONCLUSIONS

This paper proposed an optimization algorithm for minimizing the energy consumption of a laundry room based on determinant parameters such as priority of devices, electricity price, incentives, and available loads. The algorithm has been designed to achieve the demand response program goals and requirements. The case study of the paper considered 2 washing machines and one dryer in the laundry room to apply the load shifting based on demand response program and defined parameters of algorithm. Proposed demand response has declared a specific power consumption limit for each period, and different incentive price as well. Six different scenarios have been considered to propose the impact of each parameter in the outcome of algorithm.

The obtained results of proposed methodology have been shown by several figures to verify the functionality of the algorithm in different scenarios. In scenario 1, the obtained results were based on the specified power consumption limit and electricity price and incentives. Scenario 2 presented the capability of the algorithm to manage the sequences of device operations based on defined constraints. Scenarios 3-6 have been focused on impact of electricity price and incentive prices in different ways such as increasing the tariffs, ignoring the prices and incentives, or conversely, paying special attention to the price and ignoring the power consumption limit. However, it should be noted that all scenarios were led to decrease the electricity bill by changing the consumption pattern.

This paper has been focused on 8 hours of a day to implement the load shifting, however, it can be extended to several consecutive days to be a multiperiod algorithm in future works. Also, 3 shift-able loads can be considered as more flexible loads beside interruptible, and reducible loads to participate in various demand response programs. Also, the load management can be improved by future methodology based on defining specific constraints and specific purposes.

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