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Real-Time Demand Response Program Implementation Using Curtailment Service Provider

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Abstract

Nowadays, electricity network operators obligated to utilize the new concepts of power system, such as demand response program, due to peak shaving or reducing the power congestion in the peak periods. These types of management programs have a minimum capacity level for the consumers who tend to participate. This makes small and medium scale consumer incapable to participate in these programs. Therefore, a third party entity, such as a Curtailment Service Provider, can be a solution for this barrier since it is a bridge between the demand side and grid side. This paper provides a real-time simulation of a curtailment service provider that utilize real-time demand response programs for small and medium consumers and prosumers. The case study of the paper represents a network with 220 consumers and 68 distributed generations, which aims at the behavior of two small and medium scale prosumers during a real-time demand response program.

Keywords: real-time simulation, hardware-in-the-loop, demand response, aggregator, curtailment service provider.

1. Introduction

Demand Response (DR) programs and Distributed Generation (DG) are two concepts that widely discussed in the state of the art [1]. DR programs are efficient tools for both sides of the network, since it can reduce the electricity bills of the demand side consumers, and also provides flexibility for the grid operators [2]. Briefly, DR program is referred to the change of electricity consumption profiles of the demand side consumers in order to response to the electricity prices changes or the incentives paid by the DR managing entities [3]. All DR programs are classified into the two categories of price-based and incentive based [4], [5].

It is clear that if the use of DR programs integrated with the DG, it enables the network operator to have more flexibility in the energy management [6]. However, both DR and DG units should have adequate capacity in order to have a significant role in the grid management. According to [7-9], the minimum capacity of reduction for the demand side consumers in order to participate in DR programs are 100 kW. Therefore, this is a barrier for the small and medium scale consumers and prosumers to participate in the DR programs individually [10]. Curtailment Service Provider (CSP) can be considered as a third party entity, which aggregates the small and medium scale consumers and prosumers and participate them in the electricity market negotiations as a unique resource [11-13]. However, before the massive implementation of CSP, it should be well tested and validated in order to identify future problems [14]. The simulation of an electricity network by computational resources, would be non-affordable and the results may be far from the reality [15]. Real-time simulation methods using Hardware-In-the-Loop (HIL) can be a verified methodology in this context, since it merged the results of both reality and simulation environments [16].

This paper represents a real-time simulation of a CSP that consists of 220 consumers, and 68 DG. The focus is given to the reactions of small and medium prosumers, while the CSP is managing the resources in real-time including DR programs and DG units. The small and medium prosumers are the ones that cannot participate in the DR program individually since they do not have adequate reduction capacity for the DR, and they established a contract with the CSP. The CSP model is executed in real-time digital simulator, and both prosumers are emulated by the real and laboratorial hardware equipment.

The rest of the paper is organized as follow. Section 2 describes the CSP model and DR programs. The real-time simulation model developed for the CSP is represented in Section 3. Section 4 concerns about the case studies considered for the developed model and its results are described in the same section. Section 5 provides the main conclusions of the paper.

2. Curtailment Service Provider

In this section, the theory of CSP and its operation in a real-time DR program will be proposed. The CSP demand response procurement model presented in this section is adapted and improved from [13]. Generally, if a particular customer has an adequate amount of energy to attain the minimum required reduction of a DR event, then it can establish a direct contract with the DR program managing entity (which usually is an ISO). On the other hand, players that are not able to provide the sufficient reduction by themselves can make a contract with the CSP to be aggregated and participated in DR events. In this model, it is considered that the players are equipped with the Renewable Energy Resources (RERs) and Energy Storage System (ESS), and they are capable to store their own generation in the ESS as well as inject energy to the main grid. When a contract is made between a prosumer and the CSP, the prosumer should specify three specific values. These values are ordered in below based on the incentives paid by the CSP to the prosumers:

• Regular reduction – is the amount of energy that the prosumer can reduce it in real-time (cheapest reduction from CSP stand point);

• Renewable use – is the real-time amount of RER generation, that the prosumer should inject it to the grid, and it is not allowed to store it in ESS;

• Direct Load Control (DLC) – is related to the loads that CSP is able to directly control (most expensive reduction from CSP stand point).

During a DR event, the CSP has a specific time to achieve the amount of consumption reduction mentioned in the contracts. This specific time is called ramp period. If the proposed event is a real-time DR program, the prosumers should transmit their regular reduction values and the amount of renewable use to the CSP at the beginning of the event. Fig. 1 illustrates the procedure done by CSP during the ramp period of a real-time DR program.

As Fig. 1 shows, the procedure done by CSP during the ramp period of a real-time DR program consists of six steps. In the first step, the CSP informs the prosumers from the DR event. After that, in the second step, the prosumers transmit both values of regular and renewable energy. In the third step, the CSP evaluates the amount of the regular reduction. If the regular reduction cannot provide the minimum reduction for the event, the CSP evaluates the amount of renewable use. In the fourth level, the CSP transmits the final decisions of the evaluation to the prosumers. If both regular and renewable use are not adequate for DR reduction, in fifth level, the CSP estimates the DLC reduction, and evaluates the three mentioned resources (Regular + Renewable + DLC). Finally, in the last step, the CSP decides concerning the players that can participate in the DR event or not, and the players that cannot provide the sufficient reduction, will be excluded from the DR event.

In fact, the minimum reduction for a CSP to participate in a DR event always should be a value higher than the defined minimum DR reduction. For example, if the DR program managing entity defines the minimum reduction as 100 kW, the CSP should consider 120 kW in order to overcome the possible failures.

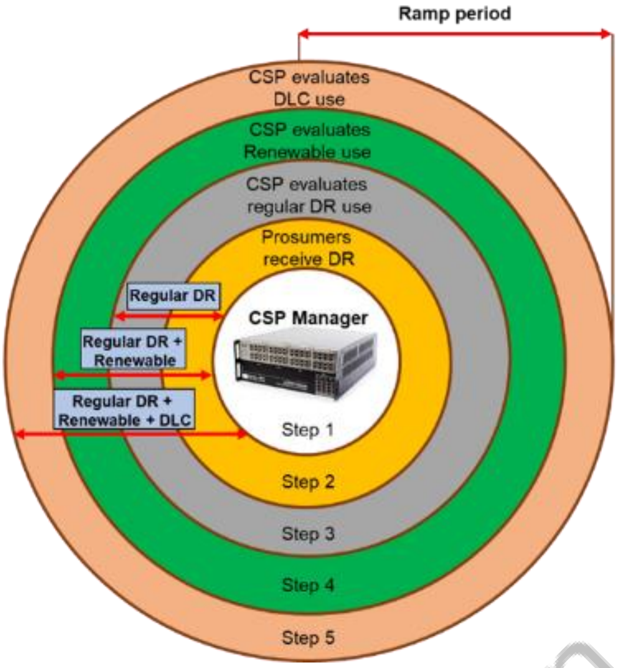

Fig. 1: CSP procedure during the ramp period of a real-time DR event.

3. Real-Time Simulation Architecture

In this part, the real-time simulation model and the network (with their hardware structures) proposed for the CSP will be demonstrated and explained in detail. The main core of the CSP model is OP5600 (www.opal-rt.com), which is a real-time digital simulator. In the presented model, the OP5600 is the main controller of the CSP, and is based on MATLAB^{TM}/Simulink. Moreover, the Hardware-In-the-Loop (HIL) capability of the OP5600, enables the model to integrate and control the real hardware resources from the Simulink environment.

The power distribution network presented for the CSP is a 33 buses distribution grid with 220 consumers and 68 DG units (including RERs) [17]. This distribution network was implemented in the MATLAB^{TM}/Simulink, in order to be compatible with the OP5600. Fig. 2 illustrates the developed distribution network.

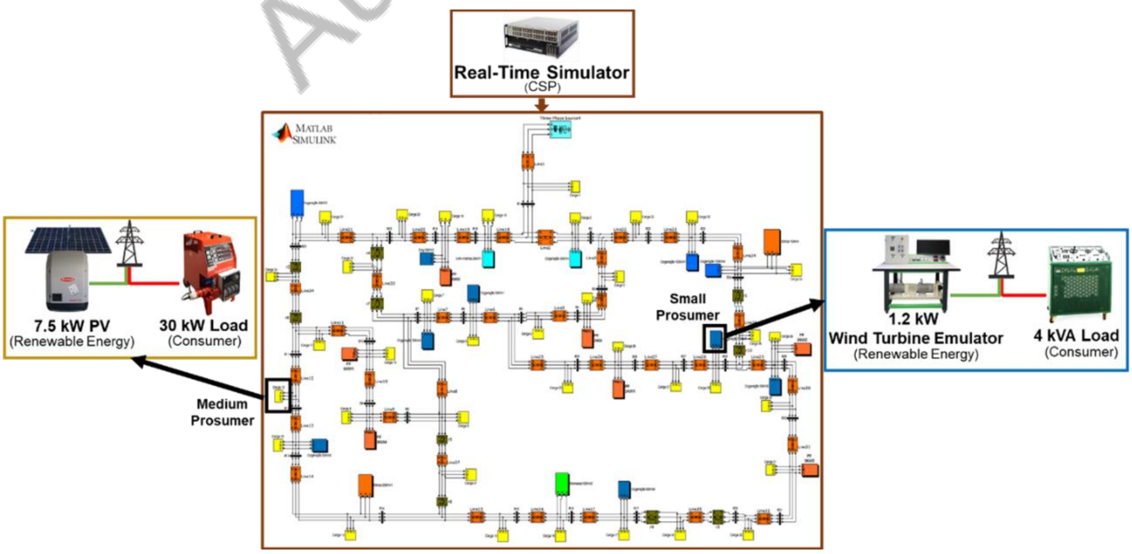

Fig. 2: Real-Time simulation of CSP using real hardware resources.

As it was mentioned, the main focus is to survey the behaviour of the small and medium prosumers while they have been aggregated by the CSP in order to participate in the DR event. For this purpose, bus

#10 and #24 of the distribution network are dedicated respectively to a medium and a small prosumer. As Fig. 2 shows, the medium prosumer consists of a 30 kW resistive load emulating the consumption of the player, and a 7.5 kW PV unit as a renewable energy producer. Additionally, the small prosumer includes a 4 kVA load and a 1.2 kW wind turbine emulator.

The hardware equipment used for small and medium prosumers simulator are physical equipment connected, in real-time, with the real-time simulator (OP5600) by the HIL methodology. Fig. 3 and Fig. 4 illustrate the details on how these medium and small prosumers have been integrated in the OP5600. From the CSP stand point, these prosumers are capable to deliver the produced energy to the grid, and also, they can store it in the ESS.

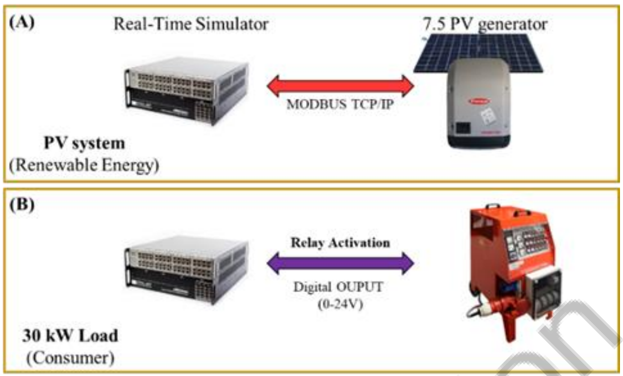

Fig. 3: HIL methodology for medium prosumer.

As it is clear in Fig. 3-(A), for acquiring and monitoring the real-time generation data from the PV system to OP5600 and Simulink model, Modbus/TCP protocol has been used. Also, for the 30 kW load, (Fig. 3-(B)), the OP5600 applies several Digital outputs in order to activate the related relays installed on load [16].

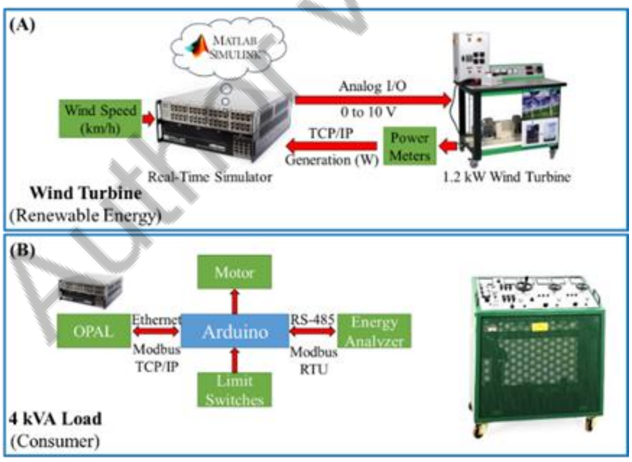

Fig. 4: HIL methodology for small prosumer [16].

As Fig. 4-(A) shows, for controlling the wind turbine emulator of the small prosumer, the analog input terminal of the speed controller unit has been integrated to the analog output board of the OP5600. Then, the wind speed data have been converted from km/h to a value in the range of 0 to 10 V, provided to the analog output board of the OP5600. The computations of this conversion have been done in the Simulink environment. In the last stage, the related power meter of the wind turbine emulator has been connected to the OP5600 via Ethernet interface, with Modbus/TCP protocol. Moreover, for the consumption of the small prosumer, the 4 kVA load is used. The 4 kVA load consists of three independent parts: resistive, inductive, and capacitive. The resistive part is automatically varied through a controlling process that is illustrated in Fig. 4 (B), using a 12 V DC motor to control the motion of the resistive gauge. Therefore, by controlling the direction of the rotation in this small motor (clockwise or counterclockwise) the resistive gauge can be moved upward or downward in order to increase or decrease the load consumption. Moreover, a power meter was used for measuring the real-time consumption of the 4 kVA load. An Arduino®

(www.arduino.cc) equipped with an Ethernet shield and a Relay module has been employed for controlling the 4 kVA load [16].

4. Case Studies

In order to test and validate the system capabilities, three case studies are designed to be applied in the CSP developed model. For all the case studies, it is considered that the medium prosumer is a small factory equipped with the PV arrays, and the small prosumer is an office building with small-scale wind turbine.

The consumption and generation profiles regarding these two players during 17 periods of one minute each are demonstrated in Fig. 5. The consumption profile of the factory (Fig. 5 – (a)) has been adapted from GECAD database, and its generation profile is the real production curve of the PV system installed in GECAD research centre, ISEP/IPP, Porto, Portugal. Moreover, the consumption pattern of the office building (Fig. 5 – (b)) is the real consumption profile of the GECAD research centre, and the wind speed data for the wind generation profile were chosen from ISEP meteorology. Also, the established contract between the two presented prosumers and the CSP is shown on Table 1. For the case studies, we considered that the CSP receives a real-time DR program from the DR managing entity, such as ISO, for 15 minutes with the minimum reduction capacity of 100 kW. Therefore, the CSP considers 120 kW as the minimum reduction in order to overcome the possible failures.

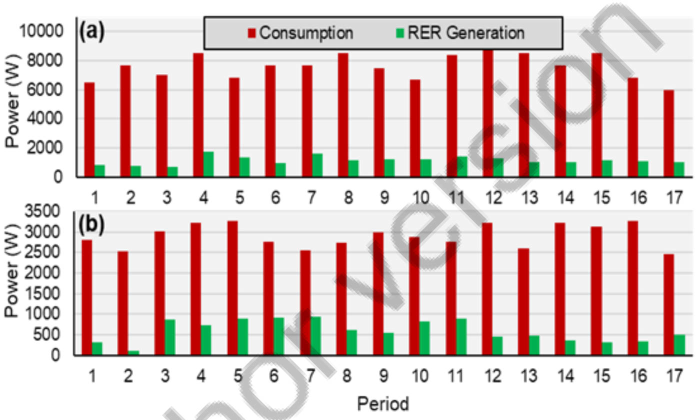

Fig. 5: Consumption and generation profiles of: (a) factory - (b) office.

Table 1. CSP information during the DR events in the case studies (All values are in kW).

	Case Study 1			Case Study 2			Case Study 3		
	Reg	***RER***	***DLC***	***Reg***	***RER***	***DLC***	***Reg***	***RER***	***DLC***
Factory	3	~1	1	3	~1	1	3	~1	1
Office	1.5	~0.5	0.2	1.5	~0.5	0.2	1.5	~0.5	0.2
Others	124.5	~20.4	9	88.3	~40.9	13	88.3	~24.3	13
Total	129	~21.9	10.2	92.8	~42.4	14.2	92.8	~25.8	14.2
	161.1			149.4			132.8		

4.1. Case Study 1

In this case study, it is assumed that the factory player has 3 kW capacity in the regular reduction (Reg. in Table 1), and it can provide around 1 kW renewable use (RER in Table 1) to the CSP, and finally, 1 kW capacity in the DLC reduction (DLC in Table 1). Moreover, the office player has 1.5 kW capacity in the regular reduction, around 0.5 kW renewable use, and 0.2 kW capacity in the DLC reduction. Additionally, the other players available in the CSP provide 124.5 kW in regular, 20.4 kW in renewable use, and 9 kW in the DLC. These values are transmitted from the players to the CSP during the ramp period (as Fig. 1 showed), consequently, the CSP can achieve the minimum required reduction by the regular reductions provided by the players, which is the cheapest one.

The behaviours of the factory and office building during the DR event are illustrated in the Fig. 6. The results shown in Fig. 6 are for 1020 seconds (17 periods, one minute per period), provided by the real-time simulator (OP5600) in MATLAB™/Simulink. As Fig. 6 shows, the DR event starts from 60 to 960 seconds, which is period 2 to 16. In Fig. 6 – (A), the consumption profiles of the factory are emulated by the 30 kW load, where the red line is the consumption before the reduction, and the purple line indicates the consumption after the reduction. The difference between these two lines demonstrates the regular reduction (3 kW). Also, in Fig. 6 – (B), the consumption profiles of the office building are emulated by the 4 kVA load, and the difference of the red line (consumption without DR event), and the purple line (consumption during DR event) indicates the amount of the regular reduction by the office building (1.5 kW).

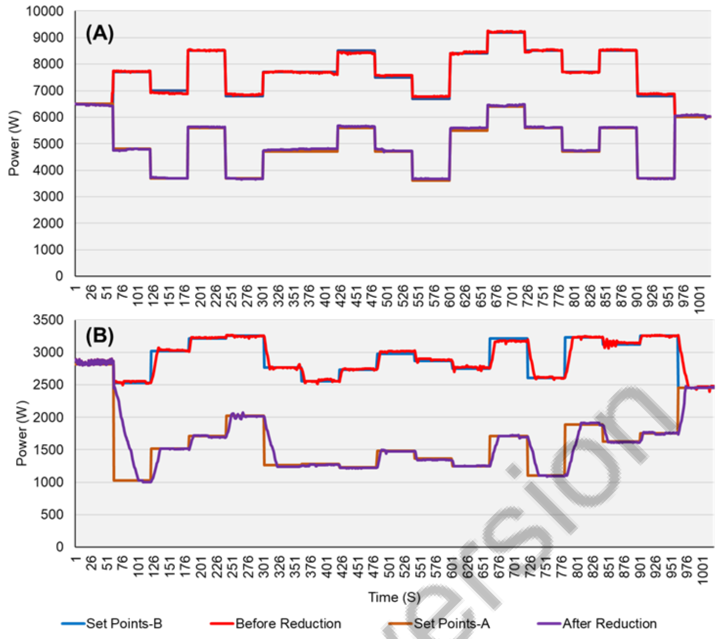

Fig. 6: The reactions of the two CSP prosumers in the case study 1: (A) factory - (B) office building.

The blue and brown lines in Fig. 6 are related to the real-time simulation and HIL methodology. In other words, these lines are the values that OP5600 transmits from the Simulink to 30 kW and 4 kVA load with one minute time interval, and the red and purple lines are the real-time consumption values transmitted by the devices to the Simulink environment with one second time interval.

4.2. Case Study 2

In the second case study, it is considered that all the conditions explained in the case study 1 will be equal, except the amount of reductions that the other players of the CSP will provide. As Table 1 shows, for the case study 2 it is assumed that the other players provide 88.3 kW in the regular reduction, 40.9 kW in the renewable use, and 13 kW in the DLC. In this moment, the CSP computes the provided reductions in the ramp period, and since the sum of regular reductions are not sufficient for participating in the DR event, it decides to use the second reduction resource, which is renewable use. Therefore, by using both reduction resources (Reg. + RER in Table 1), the CSP achieves the minimum reduction with 135.2 kW, and there is no need to use the DLC resource. In the next step, the CSP transmits its decision to the players, which is reducing their consumption until the regular reduction, and do not storing their produced renewable energy in the ESS, however, inject it to the main grid. While the players inject their own produced energy to the main grid, the CSP will see a reduction. The reactions of the factory and the office building during the DR event in this case study are shown on Fig. 7.

Similar to the case study 1, in Fig. 7 the DR event starts from the period 2 to 16, which is 60 to 960 seconds. The amount of reduction in both prosumers is the same as the case study 1, which is around 3 kW and 1.5 kW in the factory and office respectively. However, in this case study, all CSP players including these two prosumers are bounded to inject their own produced energy to the grid.

The generation profile of the factory is related to the real PV production of GECAD research centre, with one second time interval. Also, the generation profile of the office building is related to the generation of the wind turbine emulator, somehow the OP5600 transmits the real-time wind speed data with one minute time interval to the emulator, and the emulator produces power and transmits the real-time generation data to the OP5600 with one second time interval.

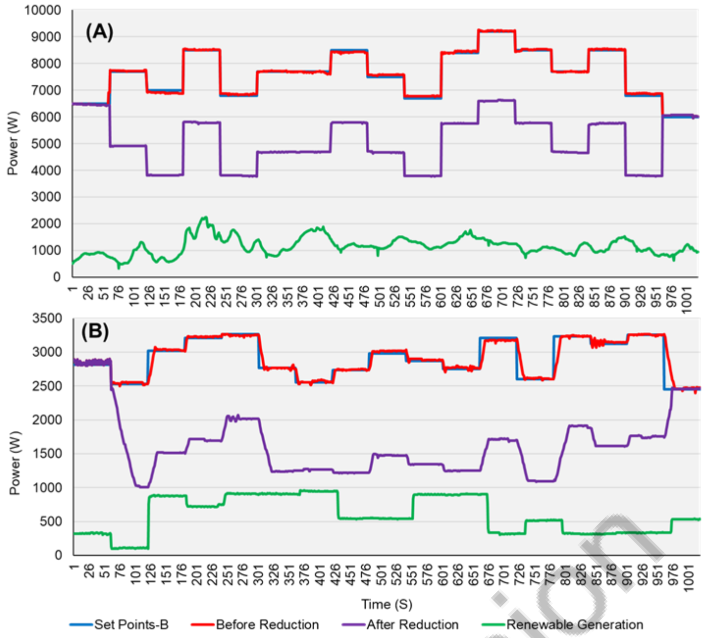

Fig. 7: The behaviour of two CSP prosumers in the case study 2: (A) factory - (B) office building.

4.3. Case Study 3

In the case study 3, we considered that the CSP encountered with significant reduction in the RER generation by the players. Therefore, as Table 1 showed, the regular reduction and renewable use will not be adequate for the CSP to achieve 120 kW reduction. Consequently, the CSP should use the DLC contracts, which enable the CSP to directly turn off the loads that are involved in the contract. Fig. 8 illustrates the final results of the case study 3. As it is clear in Fig. 8, the CSP utilizes its DLC reduction, which is the last and most expensive resource, in order to reach the minimum reduction capacity for participating in the DR event.

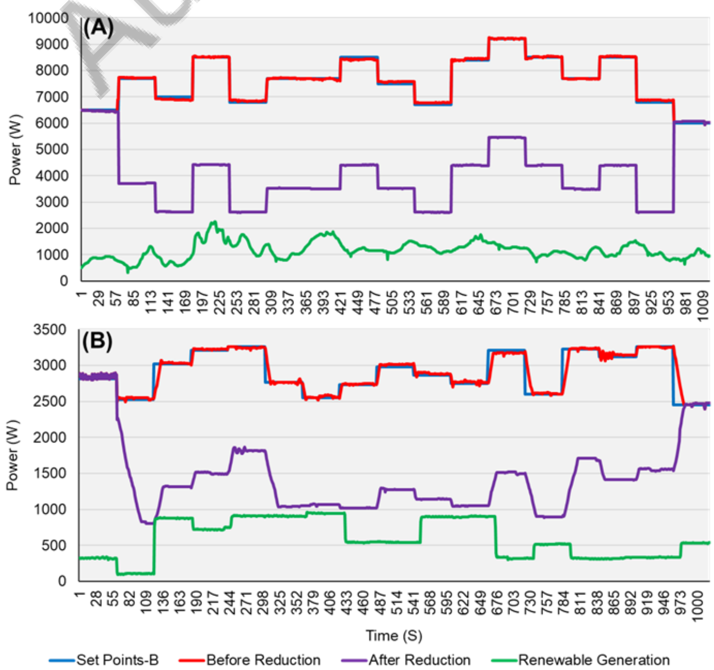

Fig. 8: The reactions of the two CSP prosumers in the case study 3: (a) factory - (b) office building.

During these three case studies, the energy that the CSP sold to the two prosumers is illustrated in Fig. 9, and also the voltage variations during the real-time simulation of the three case studies are shown on Fig. 10.

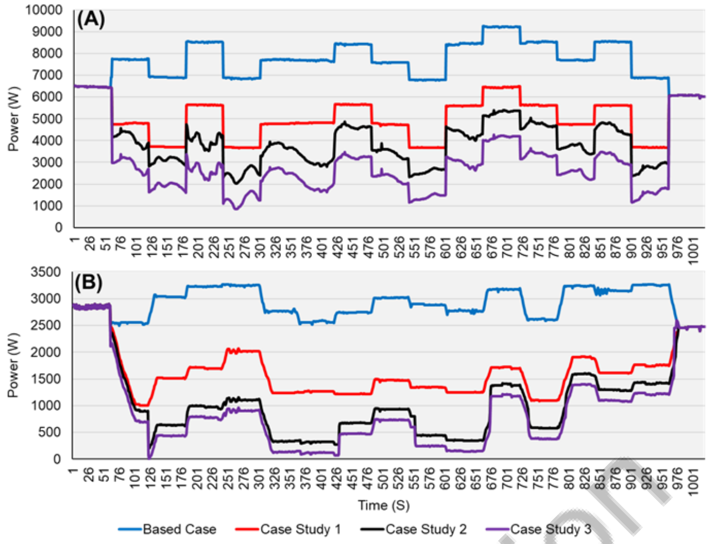

Fig. 9: The energy consumption of the two prosumers during the three case studies from the CSP stand point: (A) factory – (B) office building.

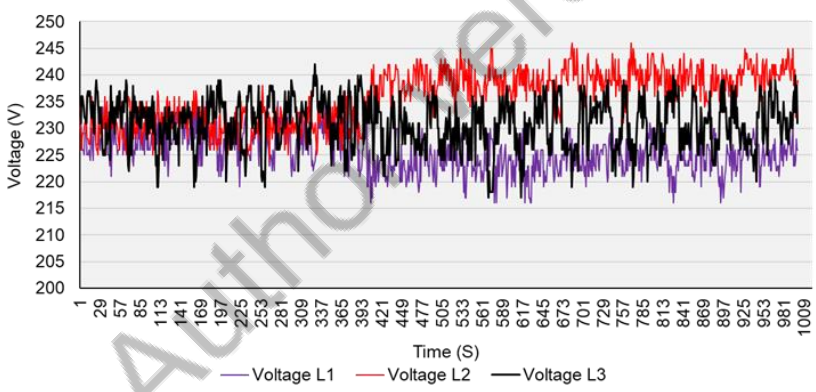

Fig. 10: Voltage variations during the real-time simulation of three case studies.

As you can see in Fig. 9, the blue line indicates the consumption of the prosumers while there was no DR event. When the DR event starts, in the case study 1, the transmitted energy from CSP to the prosumers is reduced based on the regular reduction. Also, in the case studies 2 and 3, by the involvement of the produced renewable energy by the prosumers, the CSP sold less energy to them. Therefore, it sees a reduction in the consumption and consequently, the CSP was able to participate in the DR event. The most important novelty showed by the case studies, is when the load schedule is changed, the actual and real consumption devices take a while to reach the desired consumption level. This is the fact that was not considered in the electrical network simulation models, and has been addressed by the real-time simulation test bed using HIL methodology.

5. Conclusions

This paper represents a real-time simulation of a Curtailment Service Provider consisted of 220 consumers, and 68 distributed generations, which supports decision making for demand response programs testing and validating. The presented model executed by a real-time digital simulator (OP5600) using several real and laboratory hardware resources by Hardware-In-the-Loop methodology.

In the case studies, the reactions of a small and medium prosumers have been investigated while the CSP makes various decisions for participating in a real-time DR event. The results of the case studies are the real measured data from the loads and generators, which validate the concepts of the CSP by enabling the small and medium prosumer to participate in a DR event. Also, the results demonstrated that whenever the rate of consumption changed, the loads require some times to reach the desire consumption rate. This is one of the main differences between the experimental works and simulation works, which in simulation environment the consumption rate changed immediately, however, in real world all consumers need a period to adapt and reach the desired consumption.

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