Real-Time Simulation of a Curtailment Service Provider for Demand Response Participation

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***Abstract*—The daily increment of the electricity use, obligates the network operators to utilize the new concepts, such as demand response programs. These programs have a minimum capacity in the consumption reduction, therefore, the small and medium consumers cannot participate in such programs individually. Curtailment Service Provider is a new concept that can overcome this barrier, by aggregating the small and medium consumers. However, testing and validating the concepts of Curtailment Service Provider with real data in realistic scenarios is required before the massive implementation of the business models. Therefore, this paper represents a real-time simulation of a Curtailment Service Provider including 220 consumers, and 68 distributed generation. In the case studies, the reactions of two small and medium prosumers are surveyed based on different decisions of Curtailment Service Provider.**

***Index Terms*— Curtailment Service Provider, Demand Response, Hardware-In-the-Loop, Real-Time Simulation.**

I. INTRODUCTION

Demand Response (DR) program became a reality in the nowadays power system [1]. DR program is defined as the modification in the consumption patterns of the end-users in order to response to the incentive paid from the network operator due to some technical or economic reasons [2]. There are two main classifications for the DR: incentive based, and price based.

The incentive based DR are related to the programs that the customers are paid with the fixed or time varying incentive, which is provided by the grid operator [3]. The price based DR programs are referred to the changes in the consumption of the customers based on the electricity price variations. By this way, the end-users can reduce their monthly electricity bills if they reduce their consumption while the electricity price is high, and shift it to moments that the electricity price is lower [4].

In this context, if the Renewable Energy Resources (RERs) are integrated with the DR programs; both consumers and grid operators will fully benefit from the advantages of smartgrids and microgrids [5]. However, both consumption and generation resources should have enough capacity in order to be able to participate in DR programs. According to [6], [7], the minimum reduction capacity for consumers to participate in a DR program is typically 100 kW. Small typical consumers, namely residential or commercial are not able to participate in DR programs individually. Curtailment Service Provider (CSP) can overcome the mentioned barriers [8].

A CSP is referred to a grid player that aggregates the small and medium consumers, who do not have enough capacity of consumption reduction for participating in the DR programs. In other words, a CSP aggregates the small and medium consumers and participate them in the DR program as one [9].

Few research works implemented or simulated the CSP in real-time. This motivates the author to focus on this area. Therefore, this paper represents a real-time simulation of a CSP that consists of 220 consumers, and 68 distributed generation. The focus is given to small and medium prosumers (a consumer that can also produce energy), which cannot participate in the DR program individually since they do not have enough 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 resources.

There are some relevant works surveyed in this area. In [10], the authors present the CSP as a mechanism for the demand to participate in the Colombia wholesale electricity market. [11] developed a model for the thermostatically controlled load aggregators for participating in the DR programs. Reference [9] provides a multi-agent model that simulates a smartgrid and test the DR programs with several players including CSP and virtual power players. In [12], the authors utilize a multi-agent system for the simulation of small and medium consumers' strategic demand response events, which are aggregated by a CSP. [13] provides a real-time simulation model of microgrid by using real generation and consumption resources. However, the main focus of this paper is to simulate the CSP in real-time, providing a DR event to real small and medium prosumers, and survey their behaviors during the event, as detailed in Figure 1.

After this introductory section, the CSP concepts are described in Section II. The real-time simulation model used in the paper is illustrated in Section III. There are three case studies explained in Section IV, and finally, Section V clarifies the main conclusions of the work.

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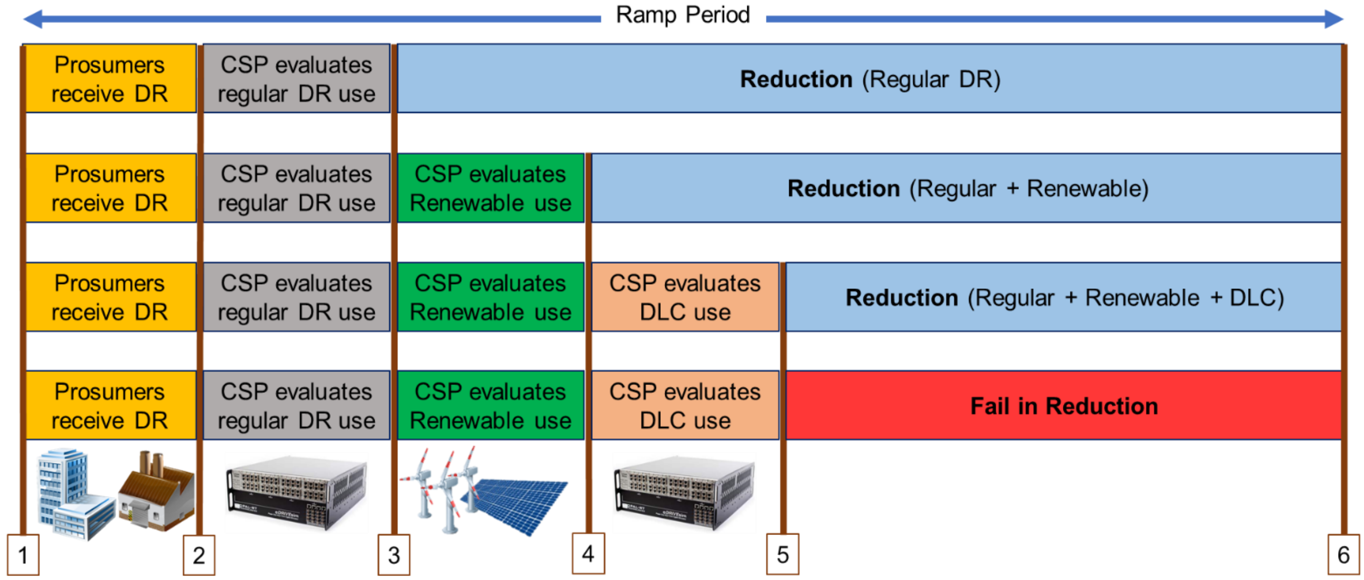

Figure 1. CSP procedure during the ramp period of a real-time DR event.

II. 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 paper is adapted and improved from [9].

Generally, for applying a DR event in a power distribution network, if a particular customer has adequate amount of energy to cut and attain the minimum required reduction of the DR event, can establish direct contract with the DR program managing entity, which usually is an Independent System Operator (ISO). For the players who intent to participate in the DR event but are not able to provide the sufficient reduction, they will make a contract with the CSP, in order to be aggregated and participated in the DR events.

In this paper, it is considered that the players are equipped with the 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 the loads that CSP is able to directly turn them off. (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 value and the amount of renewable use to the CSP at the beginning of the event. Figure 1 illustrates the procedure done by CSP during the ramp period of a real-time DR program.

As Figure 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 the both values of regular and renewable. 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 the 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 stuffiest 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.

III. REAL-TIME SIMULATION ARCHITECTURE

In this part, the real-time simulation model, and the network players and 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™/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 distributed generation units (including RERs), which has been developed by the author in the scope of his previous works [14]. This distribution network was implemented in the MATLAB™/Simulink, in order to be compatible with the OP5600. Figure 2 illustrates the developed distribution network.

As it was mentioned, the main focus of this paper is to survey the behavior 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 #12 and #13 of the distribution network are dedicated respectively to a medium and a small prosumer. As Figure 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 as consumer and a 1.2 kW wind turbine emulator as generator.

All of this hardware equipment used for the small and medium prosumers are real and laboratorial equipment that have been merged in the real-time simulator (OP5600) by the HIL methodology. More information and details on how they are integrated in the OP5600 is available on [13], [15].

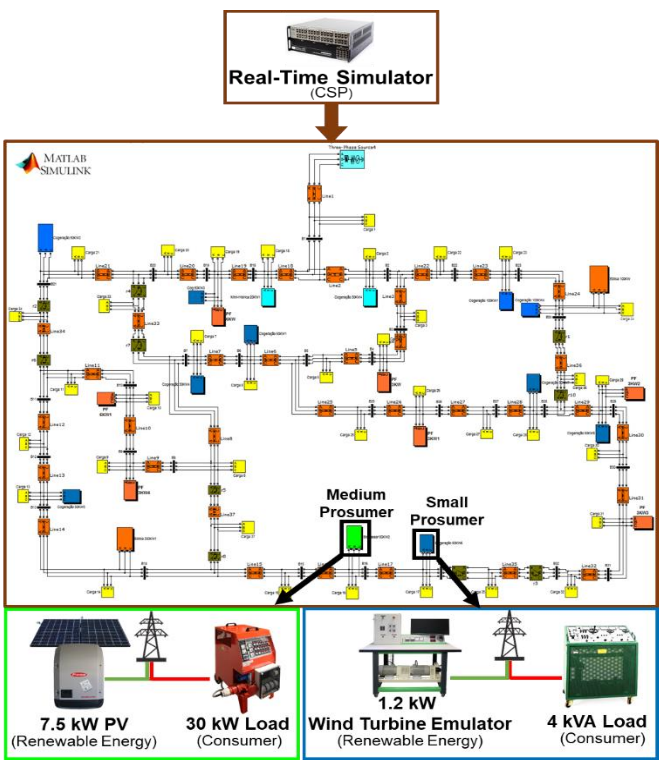

Figure 2. Real-Time simulation of CSP using real hardware resources.

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.

IV. 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 the all case studies, it is considered that the medium prosumer is a little 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 are demonstrated in Figure 3, somehow each period represents one minute. The consumption profile of the factory (Figure 3 – (a)) has been adapted from [16], and its generation profile is the real production curve of the PV system installed in GECAD research center, ISEP/IPP, Porto, Portugal. Moreover, the consumption pattern of the office building (Figure 3– (b)) is the real consumption profile of the GECAD research center, and the wind speed data for the wind generation profile were chosen from ISEP Meteorology website [17].

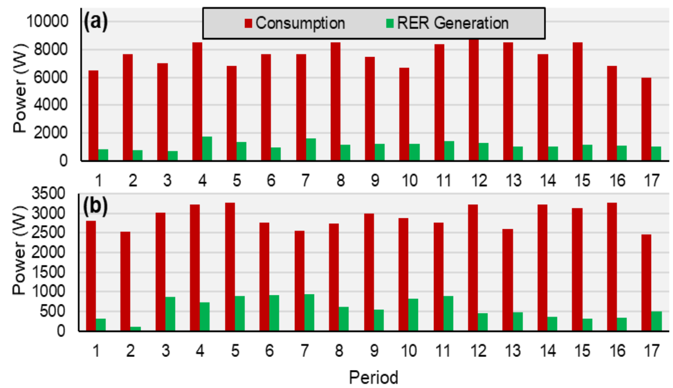

Figure 3. Consumption and generation profiles of: (a) factory - (b) office.

The established contract between the two presented prosumers and the CSP is shown on the Table 1.

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		

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.

A. *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 Figure 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 behaviors of the factory and office building during the DR event are illustrated in the Figure 4. The results showed in Figure 4 are for 1020 seconds (17 periods, one minute per period), provided by the real-time simulator (OP5600) in MATLAB^{TM}/Simulink. As Figure 4 shows, the DR event starts from 60 to 960 seconds, which is period 2 to 16. In Figure 4 – (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 of these two lines demonstrates the regular reduction (3 kW). Also, in Figure 4 – (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).

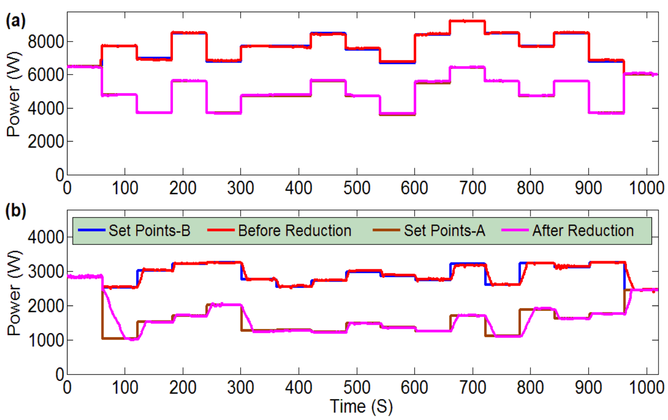

Figure 4. The reactions of the two CSP prosumers in the case study 1: (a) factory - (b) office building.

The blue and brown lines in Figure 4 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.

B. 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 the 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 Figure 5.

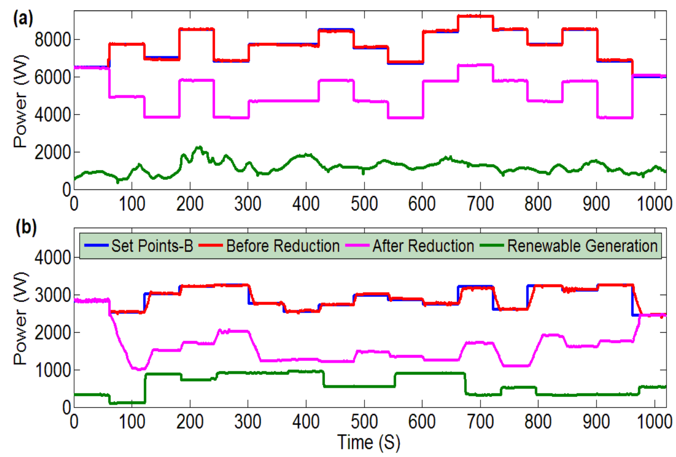

Figure 5. The behavior of the two CSP prosumers in the case study 2: (a) factory - (b) office building.

Similar to the case study 1, in Figure 5 the DR event starts from the period 2 to 16, which is 60 to 960 seconds. The amount of reduction in the both prosumers are as 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 center, 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 produce power and transmits the real-time generation data to the OP5600 with one second time interval.

C. 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. Figure 6 illustrates the final results of the case study 3. As it is clear in Figure 6, 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.

During these three case studies, the energy that the CSP sold to the two prosumers are illustrated in Figure 7.

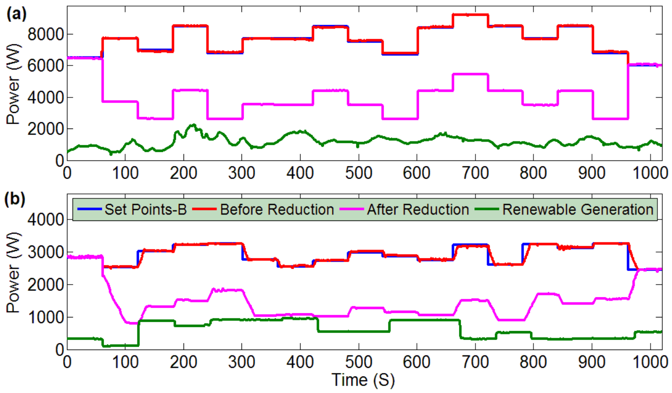

Figure 6. The reactions of the two CSP prosumers in the case study 3: (a) factory - (b) office building.

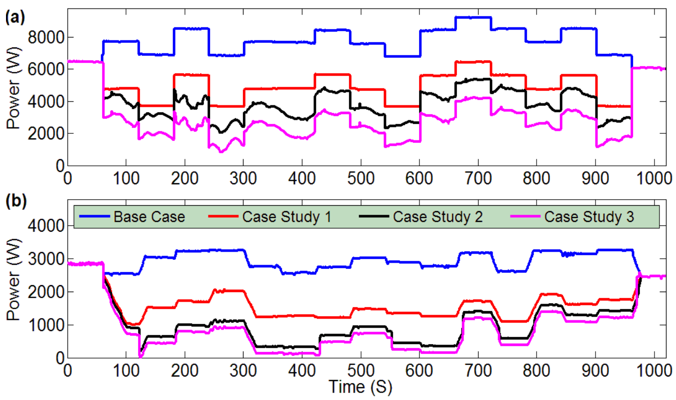

Figure 7. The energy consumption of the two prosumers during the three case study from the CSP stand point: (a) factory – (b) office building.

As you can see in Figure 7, 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 are 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.

V. Conclusions

Demand response programs and the renewable energies are very relevant in the scope of microgrids and smartgrids. For the small and medium prosumers that do not have enough consumption reduction capacity to participate in a DR event, a Curtailment Service Provider would enable them to participate in the event.

In this paper, a realistic model of a Curtailment Service Provider consists of 220 consumers, and 68 distributed generation is simulated in real-time, which supports decision making for DR testing and validating. The presented model has been executed by a real-time digital simulator (OP5600) using several real and laboratorial 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 Curtailment Service Provider makes various decisions for participating in a real-time DR event. The presented results are the real measured data from the loads and generators, which validate the concepts of the Curtailment Service Provider by enabling the small and medium prosumer to participate in a DR event.

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