Impact of wired telecommunication network latency on demand-side management in smart grids

Adrien Gougeon*, Benjamin Camus*, Anne Blavette†, Anne-Cécile Orgerie*
*Univ. Rennes, Inria, CNRS, IRISA, Rennes, France, Email: {adrien.gougeon, benjamin.camus, anne-cecile.orgerie}@irisa.fr
†Univ. Rennes, CNRS, SATIE, Rennes, France, Email: anne.blavette@ens-rennes.fr

Abstract—**Demand-side management relies on the flexibility of consumers' load to avoid electrical network issues, including grid congestion. Recent advances in smart grid systems (also called Energy Internet) allow using demand-side management reactive strategies based on the dynamical shedding of residential consumers appliances. Both centralized and decentralized approaches are considered in literature, depending on the considered system size, but only few contributions consider the potential impact of the telecommunication network on their performance. In this paper, we conduct a comparative analysis on a realistic scenario based on representative power consumption time series of a residential power system. Our results show that latency may have a significant impact on energy management strategies in terms of performance for the smart grid, and that it should be considered when designing such strategies.**

I. INTRODUCTION

The ever-increasing individual electricity consumption, the electrification of transport and the grid connection of variable, and somewhat uncertain, decentralized renewable energy sources (e.g. wind, solar) may raise congestion issues on the electrical network [26]. Congestion occurs when the current flowing through a piece of electrical equipment (e.g. a transformer) exceeds its rated value, which would lead to thermal overloading: it must therefore be avoided. In the past, conservative sizing and reinforcement of the electrical network used to represent the sole option to prevent this issue. However, nowadays, the advent of the smart grid, a cyber-physical system based on a ubiquitous and fast communication network (also called the Energy Internet [28]), renders demand-side management technically feasible. Demand-side management implies to adjust the power consumption of so-called "flexible loads" (e.g. smart heaters, electric vehicles) in order to prevent or mitigate grid issues in a considered area. This approach may represent a cost-effective alternative to expensive and time-consuming grid reinforcement measures, and it is therefore enthusiastically considered by grid operators.

However, the large number of flexible loads to be controlled, as well as the short timescale at which they should be controlled, will render the traditional centralized approaches obsolete [22], [7]. Under such conditions, these approaches would indeed require a prohibitive computing effort, as well as raise potential privacy issues due to the transmission and centralization of short timescale, and therefore highly sensitive, consumers electricity consumption data.

978-3-903176-32-4

Hence, decentralized management approaches are now considered [14], [22]. Among them, anticipatory and reactive approaches may be distinguished. The anticipatory approach is intended to generate a load power consumption schedule preventing grid issues, based on forecasts (e.g. of the power consumption and generation in the considered network) and on sufficient knowledge of the network characteristics such as topology and impedance for instance. However, forecasts inherently present a certain level of error, thus impacting the performance of such an approach, and sufficient information on the network characteristics may be unavailable. Contrary to the anticipatory approach, the reactive approach is envisaged as a mitigation measure once an issue in the grid (e.g. a congestion) is detected or is close to occur [23], [29], [13]. Therefore, it does not require any knowledge on the future and needs only limited to no information on the electrical network characteristics. Such an approach relies on short period measurements in the problematic area (e.g. short period measurements of the electrical current in the potentially congested piece of equipment), and on equally short period flexible loads control.

This paper presents a comparative analysis of the performance between two such reactive energy management algorithms, one being decentralized and the other being centralized, both based on short frequency measurements and control, and both intended to mitigate congestion in a low-voltage electrical network, whose model is publicly available, and will be detailed later in the paper. The algorithms are based on the successive and repeated shedding (called "cascado-cyclic shedding") of a sufficiently important number of direct-acting smart electric heaters [25]. These loads can be reasonably shed during a short amount of time without impacting noticeably their owners' comfort due to the significant thermal inertia in typical households [25].

However, decentralized management approaches are expected to be more sensitive to communication delays, jitter and bottlenecks, as experienced in the Internet, than centralized ones [9]. Hence, this comparative analysis, between a centralized and a decentralized approach, is performed for a range of communication latency values typical of local area networks. The impact of latency on the performance of demand-side management algorithms for congestion prevention/mitigation is generally not covered in papers dealing with this approach [14]. Yet, this impact may have significant consequences even for small-sized power systems, as we will show in our study, notably in terms of performance and in terms of the necessary number of messages for each approach. The numerical simulations are performed based on an open-source co-simulation platform combining telecommunication network simulators (SimGrid, ns-3) and power system simulator pandapower [3]. The impact of wired telecommunication network latency between the centralized and the decentralized approaches is very significant, the latter being more affected than the former.

The paper is organized as follows. Section II details the state of the art. The studied use-case is presented in Section III and the validation framework is detailed in Section IV. The results are discussed in Section V. Section VI concludes this work and presents future work.

II. STATE OF THE ART

A. Demand-side management

The emergence of smart grids renders more and more urgent the need for adopting a holistic view on the power system and on its supervision telecommunication network. Combining both systems aims at making the power system more flexible in order to integrate variable, less-dispatchable renewable energy sources into the grid [17]. It also aims at operating the power system in a more efficient way, increasingly closer to its physical limits, by adopting less conservative security margins [18], [29]. This should contribute in postponing, or even avoiding, the need for costly grid reinforcement.

However, this combination renders the power system performance dependent on the design and management of its telecommunication supervising infrastructure [2]. The performance of the former can of course be enhanced by using the additional amount of information provided by the latter [27]. Energy Internet communications make use of various wired (Ethernet, DSL, Power Line Communications) and wireless (Wi-Fi, ZigBee, LoRaWAN, etc.) technologies [7], [28]. In particular, wired Ethernet-based networks are praised for their reliability and energy efficiency [7], contrary to power line communications that present severe channel conditions and are unable to accommodate a massive number of clients [5]. Hence, this renders wired telecommunications particularly suitable to the requirements of residential demand-side management in terms of bandwidth, latency, reliability and coverage area [2], [7].

However, recent works have shown that communication delays, inherent to the transmission of information, could degrade dramatically the performance of a smart grid [9]. Hence, communication latencies should be taken into account when designing control algorithms with a significant share of information transmission, such as distributed energy management strategies. Yet, many work consider perfect telecommunication conditions, without latency constraints [10], [20], [23], although the implied reaction time required for such a scenario is in the order of seconds or lower [2], [7], [29].

Additionally, the need for integrating disparate, intermittent and widely geographically distributed energy sources (i.e. renewable sources) and flexible loads (i.e. heaters, electric vehicles) presenting individual constraints calls for a decentralization of the power system management [20], [22]. However, without centralization, demand-side management strategies may be even more sensitive to telecommunication latencies. To explore this assumption, we conduct a comparative analysis of two approaches, a centralized and a decentralized one, on a single realistic scenario representative of residential conditions. The benefits of residential demand-side management for reducing network congestion have been assessed in the literature [10], [20].

B. Simulation of smart grid infrastructures

Electrical grid studies usually rely on power system simulators that numerically reproduce the dynamics of an electrical network and perform power flow calculations for a considered network. Such simulators represent the necessary alternative to performing tests on the actual network, which may cause disturbances detrimental to customers. Several tools exist for power system simulations, such as pandapower [16] and PowerFactory [6].

On the other hand, event-based packet-level simulators, such as ns-3 [11] and OMNeT++ [24], are widely used in the telecommunication network community. They implement a large range of communication protocols (e.g. TCP/IP, UDP, Wi-Fi) that may be deployed in smart grids, thus making them good candidates for simulating the smart grid supervision telecommunication network. The highly-efficient SimGrid platform [4] is dedicated to the simulation of large-scale distributed systems, which makes it perfectly suitable to simulate a smart grid control system.

Co-simulation consists in coupling different stand-alone simulation tools, so that they simulate together a whole cyber-physical system in a consistent way. In this work, we employ our own open-source co-simulation tool relying on pandapower on the power system side, ns-3 on the telecommunication side and SimGrid for the co-simulation framework. While our previous study using this framework [3] employed PowerFactory for the power system, we developed, for the study presented in this paper, an interface for pandapower as this simulation tool is not license-dependent and thus allows for multiple simulations to be launched at the same time on the same machine. Consequently, our co-simulation framework for cyber-physical systems based on SimGrid, ns-3 and pandapower greatly shortens the experimental campaign's duration, and as all the software pieces are freely available, it is easily reusable by others.

III. DEMAND-SIDE MANAGEMENT SCENARIO

Grid operators tend to operate their electrical networks increasingly closer to their physical limits [18]. In particular, despite the fact that consumption is ever-increasing, grid operators are reluctant to carry out grid reinforcements, as they are costly, time-consuming and may give rise to strong public opposition. Hence, it is expected that intelligent load shedding strategies will be developed and applied in order to solve any congestion issues that may have arisen from the electrical current exceeding maximum allowed values in lines and transformers.

Such congestion issues may occur during peak period times, when consumption is at its highest, that is in the early evening in most countries, especially in winter times when electrical heaters are used. This type of appliance is power and energy intensive, but can be interrupted for a short period without disturbing the consumers. This is why we consider controllable electrical heaters in this case study in order to analyze the influence of the telecommunication network's performance on the smart management of the electrical grid.

A. Power system

Real data from existing power systems are scarce, especially when considering not only few isolated loads, but an entire network, its topology and its loads. We chose to base our study on the publicly available electrical network IEEE model "European Low Voltage Test Feeder" (ELVTF) [12]. This network includes a 3-phase, low voltage (230/400 V) distribution grid with multiple feeders connected to a 11 kV/416 V substation typical of the United Kingdom [21]. The model also provides time series of one-minute averaged consumption. Each time series corresponds to the consumption of a single household, for a total of 55 time series for 55 households. In this study, for the sake of simplicity and as a first step, it is assumed that the electrical network is ideally balanced over the three phases while future studies will consider a larger scale, unbalanced network. Our study focuses on the peak hour, between 5:30 pm and 6:45 pm for the ELVTF model, as it constitutes the most stressful hour for power system management.

Gas boilers and electric storage radiators are commonly used in the UK [15]. So, we supposed that domestic direct-acting electric heating was not included in the ELVTF traces for the considered peak period. Nevertheless, our scenario considers a context where direct-acting electric heating is widely used, as it is the case in France [1], in order to provide flexibility to the power system management. Thus, for our scenario, 3 electric heaters are added in each household. Each heater power consumption is modeled as a cyclic profile alternating between typical values of 2 kW and 0 kW. Used values rely on an experiment performed on an electric radiator located in the Rennes region, France on Feb, 11 2019 between 7:15 pm and 8:30 pm, during the French consumption peak period (or more exactly to its second, descending part) [19]. Each radiator has a power profile based on real data on which random time-delays are applied. Each time-delay is equal to the sum of two random time-delays which represent respectively the dephasing between radiators belonging to the same household (arbitrarily-selected to be equal to 30 seconds maximum to illustrate variability within a single house) and the dephasing between two households (arbitrarily-selected to be equal to 15 minutes maximum to showcase the variability among the houses of the same district). It must be pointed out that a simple heater model is considered due to the absence of additional experimental data. In the considered model, the post-shedding rebound effect on the power consumption is not taken into account. It is assumed that the rebound effect due to a relatively short shedding duration is negligible.

B. Computing system

In this scenario, we consider that each household has a smart electricity meter that can send on/off instructions to the electrical heaters. A TCP/IP telecommunication network is considered in our scenario of automated and intelligent shedding in the electrical network. In order to be managed and monitored, the electric line Line1, feeding the 11 kV/416 V substation, and the households are equipped with computing devices. We assume that these devices belong to the same LAN (local area network), connected through Ethernet links following a star topology, each computing device being linked to a central switch that can be the district DSLAM (digital subscriber line access multiplexer). For the sake of simplicity, homogeneous bandwidths and latencies are considered for each link.

C. Smart grid management

In order to automate the shedding of the electric heaters in the different households, we consider the *cascado-cyclic* policy. In the cascado-cyclic policy, a shedding process is initiated when the current in Line1 goes above an upper threshold Θ. Then, several households are selected to be shed. We considered that, on average, at least one heater per household is in the on-duty part of its cycle. Assuming that the current I_{Line1} flowing in the considered line is mostly active (i.e. its reactive part is considered as negligible), then, it can be expressed as:

$$I_{Line1} \approx \frac{\sum_i P_{H,i}}{\sqrt{3} V_{Line}} \tag{1}$$

where $P_{H,i}$ is the instantaneous power consumption of household i and V_{Line1} the line phase-to-phase voltage. Following this, the number n_H of households to shed is approximated using Equation 2 according to the current in Line1 I_{Line1}, the maximum consumption P_h of a single heater of an household and the phase-to-phase voltage V_{Line1}.

$$n_H = \left\lceil \frac{(I_{Line1} - \Theta) \times \sqrt{3} \times V_{Line1}}{P_h} \right\rceil \tag{2}$$

where Θ is the maximum rated current that the line may transmit on a permanent basis. The shedding process stops when the current I_{Line1} in Line1 goes below a current threshold θ (lower than Θ) determined with Equation 3. In this equation, we consider the worst case scenario where all the households that stop shedding switch all their three heaters back on at the same time. The resulting power consumption increase would be then of $3 \times P_h$ per household. Hence, the lower threshold θ can be expressed as:

$$\theta = \Theta - \frac{n_H \times P_h \sqrt{3}}{V_{Line1}} \tag{3}$$

where the lower threshold θ is dynamically adapted during the cascado-cyclic process when the current number of shed households n_H varies. During the shedding process, the group of shed households is regularly modified, avoiding an household being shed for too long consecutively. For the same reason, and also to balance the shedding among the different households, the selection of households to be shed is done in a cyclic way, described hereafter. Indeed, as we do not consider pricing mechanisms to incentivize users to accept shedding policies, we target a fair shedding policy balancing the shedding duration among the users. The cascado-cyclic policy may be implemented by multiple algorithms. In this work, we propose two representative and simple algorithms: a centralized and a decentralized one. Both rely on the telecommunication network among the households previously described to exchange information. We opted for simple algorithms to highlight the telecommunication network impact without hiding its effects over complex optimizations.

D. Centralized Cascado-cyclic approach

The major component of the centralized approach in the cascado-cyclic process consists in the master node. It is in charge of managing the households in order to keep the current below its upper threshold in Line1. It periodically receives information from the power and current probes positioned in each household. According to this data, it decides whether or not electric heaters should be shed. As a consequence, it sends commands to shutdown or switch on electric heaters in households. Taking advantage of the amount of information it receives, the master selects in priority the households that have the highest average power consumption over the last δ seconds, but still balances the shedding among the different households, as stated previously. The reactivity of the centralized approach strongly depends on the frequency at which it receives information when no prediction algorithm is used. Consequently, we employ in our scenario a high frequency to guarantee the performance of the power system management: one message per second for each household and for Line1 is sent to the master node. The master node can be located either near the Line1 substation or in a remote location connected through wired telecommunication networks.

In subsequent work, we explored various lower frequencies for information exchange and concluded that decreasing the frequency increases both the cumulative peak duration and its variability, thus leading to closer performance between centralized and decentralized approaches, as expected.

E. Decentralized cascado-cyclic approach

The decentralization of the cascado-cyclic shedding process removes the ability to sample and compare the power consumption of each household. Thus, the only value monitored is the current at the Line1 substation, which is periodically sampled by a probe. For this approach, the households are considered sorted in a predefined and arbitrary order. Whenever the current in Line1 goes above the upper threshold, shedding commands are sent to the first household. The first household then decides whether or not it will handle the command. If it does, the household is shed for a specific duration, and it sends the command to the next household afterward. If it does not, the command is directly forwarded to the next household which will decide whether or not it will handle the command, and so on. A cycle is completed whenever the last household forwards the command to the Line1 probe. The probe keeps track of the number of completed cycles (i.e. a cycle is finished when all sheddable households have handled one command) and adds this information in the shedding commands. Each household may handle a command only if the command has a number of cycles equals to the number of times the household has been shed. This token-based strategy ensure that each household handles the same number of commands. Whenever the current in Line1 goes below the lower threshold a command is sent to stop the shedding process. This command goes through each household in a similar way than the shedding command. At the time the command reaches the Line1 probe, it ensures that the shedding process has stopped for each household. The cycle is resumed when a new cascado-cyclic process starts, thanks to this decentralized algorithm. This decentralized algorithm is a classical token-based algorithm whose main advantage consists in its simplicity. Indeed, it does not require complex computation or heavy data storage for each node: it simply requires each node to keep track of its number of executed shedding and to compare this number with the cycle number included in the shedding command.

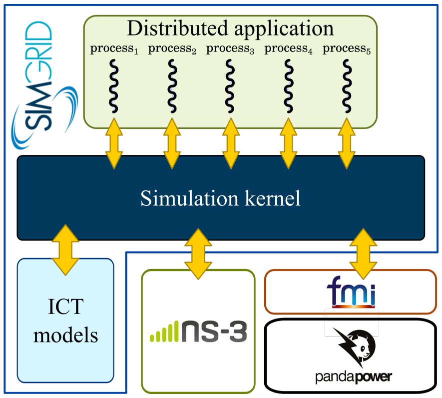

Fig. 1: The proposed experimentation set-up.

IV. VALIDATION FRAMEWORK

A. Validation means

We propose to study the impact of ICT systems on smart grids operations by using the set-up of Figure 1. It makes SimGrid, ns-3 and pandapower co-evolve and interact to rigorously model and simulate a smart grid, while taking into account the electrical and telecommunication intertwined systems.

We use the programming interface of SimGrid to model the distributed control application of the smart grid and its computing infrastructure. We can use then the unique ICT performance models of SimGrid to simulate the execution of this distributed ICT system. Thanks to an ad-hoc coupling between SimGrid and ns-3, we use the telecommunication models of ns-3 to simulate message exchange in the smart grid. We benefit then from the high accuracy of ns-3 and from its various communication models.

As part of this work, we developed an open-source dedicated tool to export pandapower as an FMU, which is available online[1]. Thanks to the open-source SimGrid-FMI plug-in developed in our previous work [3] and officially certified by the FMI standard[2], these FMUs can be imported into SimGrid. During the simulation, the distributed control system modeled in SimGrid can then interact directly with the electric grid modeled in pandapower (e.g. get the current in a line, or set the consumption of a load) and the telecommunication network modeled in ns-3. For this study, we rely on SimGrid v3.24, pandapower v2.1.0 and ns-3 v3.29.

B. Experimental plan

We compare the two approaches for three metrics: 1) Cumulative overcurrent duration: cumulative duration during which the current in Line1 is above the upper threshold. It is computed by SimGrid and is a measure of our approach efficiency from the Distribution System Operator's perspective; 2) Cumulative household shedding duration: cumulative duration of shedding required to solve the congestion problem. It is computed by SimGrid and indicates the efficiency of the approach from the smart grid consumers perspective; 3) Total amount of data sent through the telecommunication network. It is computed by SimGrid and indicates the impact of the smart grid control system on the telecommunication network.

Table I summarizes the fixed parameters in our experiments: the network bandwidth (voluntarily oversized as its impact for wired network is not a limiting factor in our context), the sampling frequency at which the power and current values are monitored and sent to the master node in the case of the centralized approach, the duration of a single shedding if not interrupted by a switching on command, and the duration for averaging the household consumption in order to select in priority the highest consuming households. Table II summarizes the variable parameters: the number of sheddable households, the upper current threshold on Line1, the communication latency for each telecommunication link and the size of each command and monitoring message. During a simulation, only one parameter varies from the default parameters. The default parameters are indicated in the last column of Table II and their choice is explained throughout the simulation results.

To compare the approaches with a given parameters set, we run three simulations: (1) a co-simulation with the centralized approach, (2) a co-simulation with the decentralized one, and (3) a simulation of the electrical network without shedding, in order to build baseline results. When switching to a new set of parameters, a new electric heater power profile with random time-delays (as described on Section III-A) is generated for each household. Each set of parameters is simulated 50 times and the results present mean and standard deviation values. The simulations were run in parallel using several machines on the Grid'5000 [8] platform. We performed a total of 4,200 simulations to execute this experimental plan.

TABLE I: Co-simulations fixed-parameters.

Network bandwidth	10Gb
Power and current probes sampling frequency	1 sec
Duration of a single shedding (if not interrupted)	60 sec
Duration δ considered to average households consumption	300 sec

TABLE II: Co-simulations variable-parameters.

	Range	Step	Default
Number of sheddable households[3]	15 to 55	5	30
Upper current threshold	410 to 450 A	10 A	440 A
Communication latency[4]	0 to 20 ms	5 ms	5 ms
Messages size	1024 to 10240 kb	1024 kb	1024 kb

V. RESULTS

In this section, we explore the impact of:

- the upper current threshold, that is of uttermost importance for the electricity distribution system operator, and that can include a safety margin depending on the expected reactivity of the system;
- the number of sheddable households, that depends on the consumers' willingness to help the electricity operator, and in our case, this effort is fairly shared among the voluntary users;
- the communication latency and message sizes that are used for implementing the demand-side management and that depend on the telecommunication network topology and communication protocols.

A. Cascado-cyclic behavior assessment

Figure 2 shows the typical evolution of current in Line1 over time for a single simulation run with the centralized approach (the decentralized one follows a similar trajectory). From this figure, we can see that, during peak time, the current progressively increases to reach the upper current threshold of 440 A at 5.49 pm. Then, the cascado-cyclic process starts shedding household heaters to keep the current below the upper threshold. We can see from the variations of the lower current threshold that the cascado-cyclic process dynamically adapts the shedding effort to successfully remain below the upper threshold (i.e. the lower the threshold is, the more important the shedding effort needs to be).

---

[1] https://framagit.org/Adrien.Gougeon/pandapower-fmu

[2] https://fmi-standard.org/tools/

[3] The number of households in the simulation stay the same, 55. However, the number of households that can be shedded varies.

[4] The configuration with 1 ms latency was also explored.

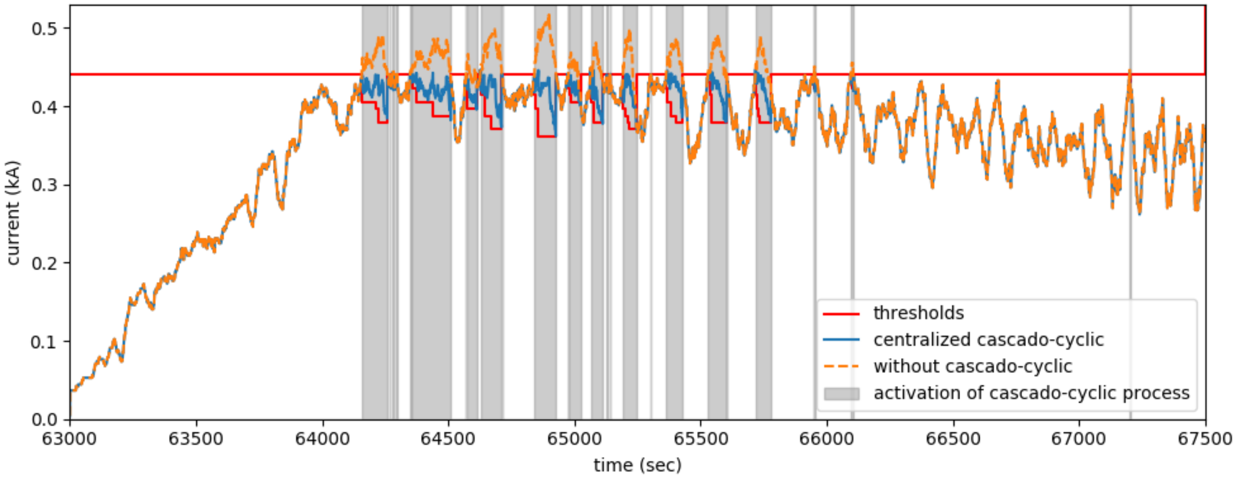

Fig. 2: Evolution of the current in Line1 over time with the centralized implementation with 30 sheddable households, an upper threshold of 440 A, a communication latency of 5ms and 1024 kb messages.

B. Influence of the upper current threshold

We can see from Figure 3 that both cascado-cyclic approaches significantly reduce overcurrent duration. Considering the default value of 440 A for the upper current threshold, the centralized (resp. decentralized) approach reduces overcurrent duration of about 94 % (resp. 89 %) compared to the baseline scenario without any shedding.

We can observe that the two approaches perform even better with lower thresholds when there are more overcurrent peaks to reduce. With a threshold of 410 A, the overcurrent duration is reduced by about 96 % (resp. 94 %) with the centralized (resp. decentralized) approach.

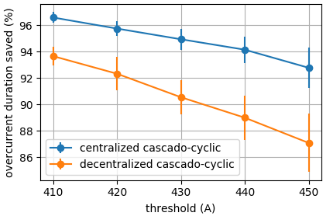

Fig. 3: Overcurrent reduction in comparison to the baseline scenario (without any shedding) when varying the current threshold.

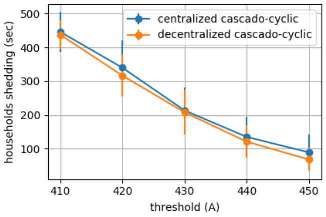

Fig. 4: Average cumulative shedding time per household versus current threshold.

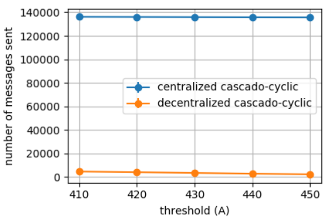

Fig. 5: Number of messages sent versus current threshold.

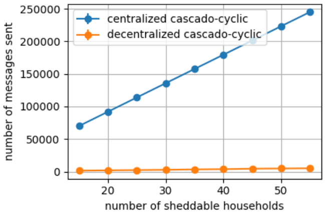

Fig. 6: Number of messages sent versus number of sheddable households.

The required reactivity of the approaches is more important with higher thresholds when the number and the duration of the overcurrent peaks decrease. This explains why the centralized approach outperforms the decentralized one, in particular in this case. Indeed, the decentralized approach is less reactive because the shedding commands may have to be forwarded several times from household to household before being applied. At the opposite, the centralized implementation sends the shedding commands directly to the sheddable households. Nonetheless, even in this context, with a threshold of 450 A, the two approaches significantly reduces overcurrent duration of about 93 % (resp. 87 %) for the centralized (resp. decentralized) approach.

We can observe from Figure 4 that both approaches achieve such a performance with a similar amount of shedding for every considered threshold. As expected, the duration of the shedding decreases when there is less overcurrent peaks –i.e. with higher thresholds. Even in the worst considered case with a threshold of 410 A, the shedding remains significantly low with an average cumulative shedding duration per household of about 7 minutes during the considered period. With our threshold default value of 440 A, the shedding becomes negligible for the end-users with an average cumulative shedding time per household of about 2 minutes only.

As shown on Figure 5 and as expected, the upper threshold does not have a significant impact on the number of messages sent by the two approaches. We observe that, because of its power probes, the centralized approach sends about 27 times more messages through the telecommunication network than the decentralized one, no matter the upper threshold value. This may strongly limit the performance with wireless telecommunication technologies (e.g. Wi-Fi).

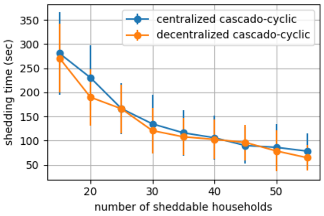

Fig. 7: Average cumulative shedding time per household versus number of sheddable households.

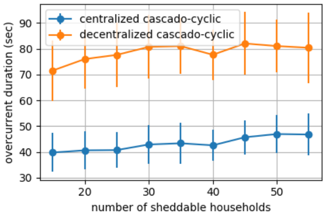

Fig. 8: Cumulative overcurrent duration versus number of sheddable households.

C. *Influence of the number of sheddable households*

Figure 6 shows that the gap between the number of sent messages increases linearly with the number of sheddable households (and therefore with the number of power probes in the centralized approach). With 55 households, the centralized approach sends about 50 times more messages than the decentralized one. This may limit the scalability of the centralized approach, which would be even more limited in a wireless context.

Figure 7 shows the decreasing standard deviation for the average per-household shedding duration when the number of sheddable households increases. It means that, in this case, both approaches efficiently share the shedding effort between the available households. As expected, the average shedding time per household decreases as the number of sheddable households increases: it goes from about 4.5 minutes with 15 households to about 1 minute with 55 households.

Figure 8 shows that the number of households does not impact significantly the cumulative overcurrent duration. This means that both approaches scale up in our context and do not require a high number of sheddable households for a reasonable upper current threshold. As expected, since the centralized approach is more reactive and takes advantage of more information, it achieves a lower overcurrent duration (about 40% lower) than the decentralized approach.

These results indicate that the telecommunication network size, which represents here the number of sheddable – and thus communicating – households, slightly impacts the cumulative overcurrent duration for both approaches. Yet, the better performance of the centralized approach comes with a strong increase in the required number of messages: 55.5 messages per second on average for 55 households, against 1.1 messages per second for the decentralized approach. Here also, relying on a wired network with a reliable transport protocol makes the scenario feasible for demand-side management.

D. *Influence of the communication latency and message size*

Figure 9 shows that the two approaches are not significantly impacted by the size of the messages. Although the centralized approach outperforms the decentralized approach in terms of overcurrent duration (45 seconds on average against 80 seconds), both equally distribute the shedding duration among the households and present a similar average shedding duration per household.

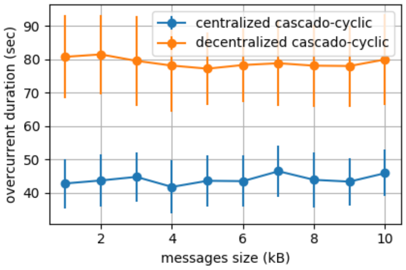

Fig. 9: Cumulative overcurrent duration versus messages size.

Concerning the number of sent messages, the decentralized approach largely outperforms the centralized one as observed in Figures 5 and 6. The negligible impact of message size is mainly due to the scenario conditions: packet losses are not considered in this scenario because the wired telecommunication network does not experience congestion, and the transport protocol is reliable (i.e. TCP). This behavior would significantly change in the context of power line communications or Wi-Fi networks.

Similarly, the telecommunication network latency does not significantly impact the number of sent messages for both approaches (results are similar to Figure 5). However, we observe from Figure 10 that the telecommunication latency has a non negligible impact on the approaches' performance. If we consider an unrealistic 0 ms latency (instantaneous data transfers and reactions), like many studies of the literature, the centralized approach decreases the cumulative overcurrent duration of about 75 % compared to the decentralized one. However, if we consider a 1 ms latency, the centralized approach reduces the overcurrent duration of only about 40 % compared to the decentralized one. With a 20 ms latency, the overcurrent duration is getting even closer in both approaches especially when taking into account the standard deviation. In addition, we observe on Figure 11 that the centralized approach also largely outperforms the decentralized one in terms of average overcurrent duration when considering a 0 ms latency, but this gap is tighter for latencies above 0 ms. We also note that results' variability grows faster in the decentralized management as the latency increases. Consequently, the centralized approach significantly outperforms the decentralized one only with low communication latencies, and the difference diminishes for larger latencies.

According to Figure 12, when considering low latencies, the average cumulative shedding time per household is comparable between both the decentralized and the centralized approaches. However, the gap between them increases with latency because it impacts the propagation delay of the shedding commands in the decentralized approach, which is then outperformed by the centralized one. Hence, with a 20 ms latency, the average shedding per household is about 140 s (resp. 250 s) in the centralized (resp. decentralized) approach. In this case, the

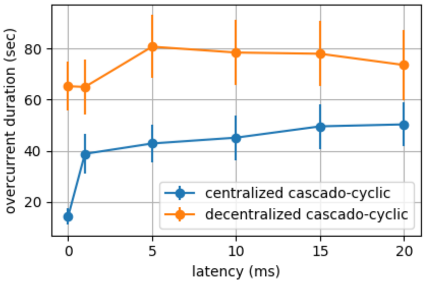

Fig. 10: Cumulative overcurrent duration versus telecommunication latency.

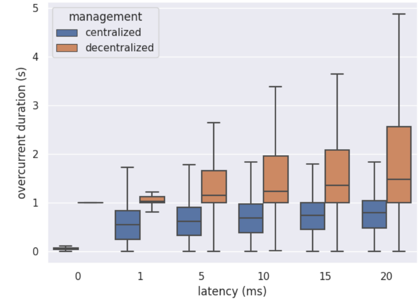

Fig. 11: Average overcurrent duration versus telecommunication latency.

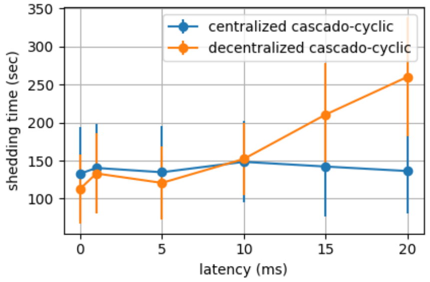

Fig. 12: Average cumulative shedding time per household versus latency.

decentralized approach overreacts and performs more shedding than required.

E. Discussion

The two proposed approaches greatly reduce the overcurrent peak duration (from about 96 % to 87 %) without a significant impact on the end-users: the average cumulative shedding per households ranges from about 7 to 1 minutes, corresponding respectively to 9% and 1% of the simulated time.

When disregarding the telecommunication network parameters, one may consider that the centralized approach is always better than the decentralized one because it decreases the overcurrent peak duration more with a similar impact for the end-users (i.e. (cumulative) shedding duration per household). However, the centralized approach requires a high number of messages to achieve this level of performance, even on a small-size network (up to 55 households). Since it significantly increases the traffic on the telecommunication network (up to more than 50 times), the centralized approach may not scale up well with the expected large number of households to be deployed on the smart grid (e.g. with the Wi-Fi technology). In addition, as the network latency increases, the overcurrent reductions achieved by the centralized approach get closer and even similar to ones obtained with the decentralized one. However, at higher latencies, the decentralized approach has significantly more impact on the end-users as it increases the cumulative shedding duration per household. It means that, although decentralized approaches should better scale with larger networks than centralized ones, they may be less accepted by electrical grid users since their performance in terms of shedding time per household is more impacted by latency. Thus, the approaches should be carefully chosen according to the telecommunication network features and the size of the considered power system. In this work, for both centralized and decentralized cases, we evaluated simple algorithms not requiring significant computation power in order to highlight the network latency influence on the performance of a smart grid. In the case of more complex algorithms, the computation duration adds time to the latency, and can consequently impact the shedding performance as well.

VI. CONCLUSION

Residential reactive demand-side management becomes feasible in the context of smart grids and Energy Internet. In this paper, we explore the cascado-cyclic shedding strategy with electrical heaters to avoid electrical network congestion. We compare the centralized and decentralized management versions of this strategy and study the impact of wired telecommunication network latency on the performance perceived by the power system manager and by the electricity consumers.

The evaluation exploits a realistic scenario of 55 households based on traces from a real electrical grid and numerical co-simulations, combining SimGrid, ns-3 and pandapower simulators, to faithfully reproduce the co-evolution of the power system and of its wired telecommunication network. We made available the open source co-simulation tools used in this paper.

Our results show that not considering any telecommunication network latency, as often assumed in literature, implies a strong overestimation of the performance achieved by the centralized approach from the power system operator's perspective. We also show that, for the power system operator, larger telecommunication network latency penalizes the centralized approach and favors the decentralized approach, although for the studied latency range, the centralized approach always performs better. As for the electricity consumer's point of view, larger telecommunication network latency has a strong negative impact for the decentralized approach, while it is negligible for the centralized one. Thus, for the decentralized approach, the latency affects negatively and heavily consumers. Considering the studied scenario and from the consumer point of view, the centralized approach is preferable for latencies above 10 ms.

Future work will consider larger scale, unbalanced smart grids, and exploring other telecommunication technologies, such as wireless networks.

ACKNOWLEDGMENT

This project is funded through RennesGrid project from the "Programme des Investissements d'Avenir" operated by the French Environment and Energy Management Agency (ADEME) and by the CNRS Momentum project RI/RE.

REFERENCES

[1] ADEME, "Les avis de l'ademe, modes de chauffage dans l'habitat individuel," ADEME, Tech. Rep., 2014.

[2] Ardiansyah, Y. Choi, M. R. K. Aziz, and D. Choi, "Latency Minimization for Energy Internet Communications with SDN Virtualization Infrastructure," in *IEEE SmartGridComm*, 2019.

[3] B. Camus, A. Blavette, A.-C. Orgerie, and J.-B. Rouchossé, "Co-simulation of an electrical distribution network and its supervision communication network," in *IEEE Consumer Comm. & Net. Conf.*, 2020.

[4] H. Casanova, A. Giersch, A. Legrand, M. Quinson, and F. Suter, "Versatile, Scalable, and Accurate Simulation of Distributed Applications and Platforms," *J. of Par. and Dist. Comp.*, vol. 74, no. 10, pp. 2899–2917, 2014.

[5] C. Deng, F. Yang, X. Liu, H. Zhang, J. Ye, C. Pan, and J. Song, "CSMA-and-NOMA-based Random Massive Access in Power Line Communication for Smart Gird Applications," in *IEEE SmartGridComm*, 2019.

[6] DIgSILENT, "Official website," https://www.digsilent.de/en/powerfactory.htm, Accessed March, 9 2020.

[7] M. Ghorbanian, S. H. Dolatabadi, M. Masjedi, and P. Siano, "Communication in Smart Grids: A Comprehensive Review on the Existing and Future Communication and Information Infrastructures," *IEEE Systems Journal*, vol. 13, no. 4, pp. 4001–4014, 2019.

[8] Grid'5000, "Official website," https://www.grid5000.fr/w/Grid5000:Home, Accessed March, 9 2020.

[9] J. Guo, G. Hug, and O. Tonguz, "Impact of Communication Delay on Asynchronous Distributed Optimal Power Flow Using ADMM," in *IEEE SmartGridComm*, 2017.

[10] H. T. Haider, O. H. See, and W. Elmenreich, "A review of residential demand response of smart grid," *Renewable and Sustainable Energy Reviews*, vol. 59, pp. 166 – 178, 2016.

[11] T. R. Henderson, S. Roy, S. Floyd, and G. F. Riley, "NS-3 project goals," in *Proceeding of WNS2*. ACM, 2006.

[12] IEEE PES AMPS DSAS Test Feeder Working Group, "European low voltage test feeder," http://sites.ieee.org/pes-testfeeders/resources/, Accessed March, 9 2020.

[13] S. P. Meyn, P. Barooah, A. Bušić, Y. Chen, and J. Ehren, "Ancillary service to the grid using intelligent deferrable loads," *IEEE Transactions on Automatic Control*, vol. 60, no. 11, pp. 2847–2862, 2015.

[14] N. Nimalsiri *et al.*, "A Survey of Algorithms for Distributed Charging Control of Electric Vehicles in Smart Grids," *IEEE Trans. on Intelligent Transportation Systems*, 2019.

[15] OFGEM, "Insights paper on households with electric and other non-gas heating," EU, 2015.

[16] pandapower, "Official website," http://www.pandapower.org/, Accessed December, 18 2019.

[17] M. H. Rehmani, M. Reisslein, A. Rachedi, M. Erol-Kantarci, and M. Radenkovic, "Integrating Renewable Energy Resources Into the Smart Grid: Recent Developments in Information and Communication Technologies," *IEEE Trans. on Indus. Informatics*, vol. 14, no. 7, pp. 2814–2825, 2018.

[18] RTE, "Outlines of RTE's R&D programmefor 2017-2020," RTE, Tech. Rep., 2017.

[19] RTE, "French national daily load curves," http://clients.rte-france.com/lang/fr/visiteurs/vie/vie_histo_courbes.jspp, Accessed March, 9 2020.

[20] A. Safdarian, M. Fotuhi-Firuzabad, and M. Lehtonen, "Optimal Residential Load Management in Smart Grids: A Decentralized Framework," *IEEE Transactions on Smart Grid*, vol. 7, no. 4, pp. 1836–1845, 2016.

[21] P. Schneider *et al.*, "Analytic Considerations and Design Basis for the IEEE Distribution Test Feeder," *IEEE Transactions on Power Systems*, vol. 33, no. 3, pp. 3181–3188, 2018.

[22] A. Shrestha *et al.*, "Peer-to-Peer Energy Trading in Micro/Mini-Grids for Local Energy Communities: A Review and Case Study of Nepal," *IEEE Access*, vol. 7, pp. 131 911–131 928, 2019.

[23] S. Singh, A. Namboodiri, and M. P. Selvan, "Simplified Algorithm for Dynamic Demand Response in Smart Homes Under Smart Grid Environment," in *IEEE PES GTD Asia*, 2019, pp. 259–264.

[24] A. Varga and R. Hornig, "An overview of the OMNeT++ simulation environment," in *Proceedings of ICST*, 2008, p. 60.

[25] J. Vaubourg *et al.*, "Multi-agent multi-model simulation of smart grids in the MS4SG project," in *Advances in Practical Applications of Agents, Multi-Agent Systems, and Sustainability (PAAMS)*, 2015.

[26] R. Verzijlbergh, L. D. Vries, and S. Lukszo, "Renewable Energy Sources and Responsive Demand. Do We Need Congestion Management in the Distribution Grid?" *IEEE Transactions on Power Systems*, 2014.

[27] B. Vinot *et al.*, "Congestion Avoidance in Low-Voltage Networks by using the Advanced Metering Infrastructure," in *ACM e-Energy*, 2018.

[28] K. Wang, X. Hu, H. Li, P. Li, D. Zeng, and S. Guo, "A Survey on Energy Internet Communications for Sustainability," *IEEE Transactions on Sustainable Computing*, vol. 2, no. 3, pp. 231–254, 2017.

[29] Y. Zhang, W. Wu, Q. Lu, S. Liu, and Y. Zhu, "Security-Based Load Shedding Strategy Considering the Load Frequency Dependency in Island Distribution System," in *IEEE Conference on Energy Internet and Energy System Integration (EI2)*, 2018.