Using Smart Breakers for Demand Side Management in Smart Grids

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***Abstract*—The electrical energy system is handled as the largest machine humankind built, which is very understandable if one imagines the changes currently happening. It is rapidly leaving behind its centralized roots with "the" power plants generating energy for all loads connected to it via copper wires. Year after year, new records are reported of integrating more percentages of sustainable renewable generation at every conceivable decentralized point. This rise of uncontrollable, fluctuating production, combined with the increase of loads, is taking away flexibilities needed to keep the power grid stable at every point in time. This paper describes a mechanism called demand response, which is an aspect of demand-side management, to increase this fleeting flexibility again on the load side, by using newly developed smart actuator components. Field tested results show domain specific gains of annual consumption reduction from six to 33 percent.**

I. Introduction

The ongoing transformation from our traditional energy distribution grid to a Smart Grid provides new opportunities to connect prosumers to energy providers and distribution system operators (DSO). The work at hand presents a prototypical implementation that takes advantage of these new cross-domain communication capabilities by connecting a local Customer Energy Management Systems (CEMS) to the centralized Supervisory Control and Data Acquisition system (SCADA) of a hypothetical DSO, using an end-to-end encrypted tunnel as communication medium. The resulting system can combine the automation capabilities of traditional home automation approaches with a local intelligence that is capable of reacting autonomously to the status of the energy grid, actively attempting to help stabilizing the grid during strain periods, while otherwise trying to reduce consumption by following open and closed loop control patterns and prioritizing self consumption for consumers that have their own energy source, e.g. PV systems. We validated the prototype by using it to implement four different use cases in a realistic field test setup. In the next section, we will introduce related works that touch on topics relevant to this publication, followed by a very brief summation of further papers that provide more in-depth information on related issues that would go beyond the scope of this work. After this state-of-the-art section, we will present our methodology by giving a brief overview of the usage scenarios that provide the fundamental requirements for the work at hand, and an introduction of the concepts and components developed to fulfill these requirements. The field test section will then outline concrete use cases that have been implemented on a realistic field testing site and present the results produced during the testing period. These results will include an overview of the successfully tested functionalities, especially concerning the usage scenarios introduced at the beginning of the paper. Afterwards, we discuss the quantitative changes in energy consumption provided by the new system. The final section of this work will present our conclusions based on these results and provide a quick outlook on possible follow up work.

II. State of the Art

The following subsections will introduce some general concepts that are relevant to the work at hand. After this, we will give an overview of previous iniGrid related publications that contain more detailed information on the various aspects of the project.

A. Related Works

Central aspects of this work relate to the concept of a Customer Energy Management System (CEMS). According to [1] such a system is characterized by providing a homogeneous communication platform for sensors and devices used by an energy consumer, as well as providing services from energy distributors or providers in a format that motivates energy consumers to participate in said services. The CEMS used in the setup discussed in this paper extends these concepts by offering services from the consumer to the energy providers and distributors, only with the consumer's permission of course. The central aspect here is the possibility for users to offer consumption adjustments, based on the providers or distributors need, most likely in exchange for some monetary compensation. In order to illustrate this functionality, we developed a Supervisory Control and Data Acquisition system (SCADA). According to [2], a SCADA system can be categorized as an integration of various sensors and actuators with a data processing unit, using communication infrastructure. The authors, therefore, identify three main components in a SCADA system: (1) the control network, containing all physical equipment, (2) the process network, containing the user interface and processing servers and (3) the communication infrastructure, that connects the various components of the system. There are open source SCADA solutions available, for example at [3], but since our system requires a subset of a full SCADA's function range, we decided to develop a customized Java-based solution, in which we have complete control and knowledge over the possible data flows and connections for security reasons. Providing limited interactions with a centralized SCADA system is one functionality of the CEMS in our prototype setup. Another important functionality we explored within the work at hand is demand side management, in particular, the local consumption optimization using a simple local intelligence. This aspect of demand side management can be referred to as physical demand response. For additional information on demand side management, including a portfolio of other measures typical in this domain and the categorization characteristics for physical demand response, see [4].

B. The iniGrid Project

The results presented in this paper are based on components and concepts developed in the iniGrid project. Exploring all parts of the project in detail would go beyond the scope of this publication. For additional information on the project components, we recommend the following publications: an overview on the basic concepts and methodologies used to produce the system we used in this field test is available in [5], including a short overview of alternative communication frameworks considered during early development stages. Additional information on the security concepts used for the communication between SCADA and CEMS is available in [6]. Information on the systems communication infrastructure and the local intelligence is available in [7].

III. Methodology

Project iniGrid defined a series of application scenarios on how improved integration of customer side management with energy providers and distributors could benefit all involved parties. For the work discussed in this paper only two of the total of five scenarios are relevant, and therefore only these two will be introduced in the following subsection. After this, we will present the software and hardware components developed to implement these scenarios.

A. Usage Scenarios

The first scenario, illustrated in Figure 1, is a typical local optimization scenario, where the measurement data from local Smart Breakers, dedicated Smart Meters or both, is utilized by a local intelligence to optimize consumption towards some user-defined goal. For the purpose of the field test, the goal is reducing the measured energy consumption without considering energy costs or self consumption of local distributed energy source, i.e. no PV integration.

The second scenario, illustrated in Figure 2 was initially formulated to introduce a new approach to active grid stabilization by connecting various sensors and transformation equipment from the energy distribution network to many CEMS, preferably for households having their own distributed local energy sources, like PV equipment. By providing communication channels between CEMS and distribution network, we

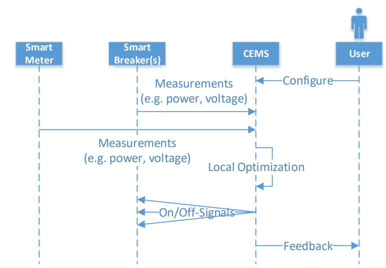

Fig. 1. Scenario A - Local Consumption Optimization

allow the secondary substations in the grid to mediate between local consumers/producers and the distribution network. Given proper control, either by a human operator or an adequate algorithm, such a substation could counter voltage or power fluctuations within the grid by initializing many small changes on the consumer side, like temporarily disconnecting non-essential equipment, or changing the characteristics of the distributed energy providers via their Q(U) or P(U) function, that, in sum, would have significant impact on the grid.

B. System Components

Various partners provided hard- and software to implement and test the scenarios described in the previous subsection. Central to these components are the hybrid Smart Breaker and the Customer Energy Management System (CEMS). Figure 3 shows the various components and their connections. The thick Grey lines in Figure 3, connecting CEMS, SCADA and ECI, represent network connections, the green lines represent wireless access and the black lines are power lines.

a) The new hybrid Smart Breakers: combine the capabilities of a Smart Meter and a remotely controlled switch with the protective capabilities of a circuit breaker. The resulting device offers wireless access, for easy deployment within industrial environments and makes energy consumption, voltage, temperature, and current breaker status available to its control unit, while being able to disconnect it's associated power line upon signal or fault. The wireless communication is routed through an Ethernet Communication Interface (ECI) that is accessed via a proprietary protocol. The CEMS is the central communication nexus that connects the local Smart Breakers and other sensor equipment (e.g. dedicated Smart Meters, air quality, and movement sensors) to the internal control logic. It

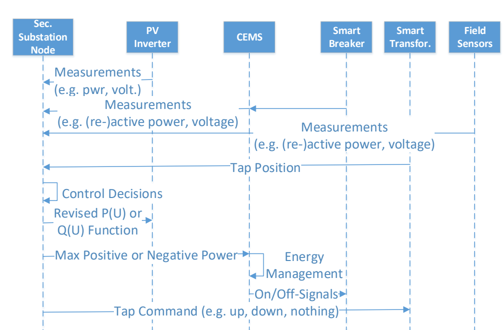

Fig. 2. Scenario B - Grid Stability

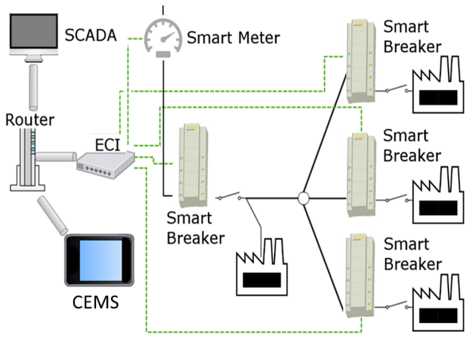

Fig. 3. CEMS as mediator between Smart Breakers and SCADA

also provides the connection between the control logic and the centralized control systems of the distribution network, i.e. the secondary substation mentioned in the second scenario above. This connection to the distribution grid or energy provider allows the CEMS to react autonomously to changes in the grid status.

To demonstrate this functionality, we developed a Supervisory Control and Data Acquisition System (SCADA) that uses traffic light based grid status signals, as proposed by the German Association of Energy and Water Industries (BDEW), to indicate the grid state efficiently. In this system the Green traffic light represents a healthy grid state, the Yellow traffic light suggests an approaching violation of the grid characteristics and the Red traffic light indicates a borderline grid state. The CEMS uses these states to prioritize local and grid demands. The CEMS requires a reliable communication infrastructure, with the ability to connect various systems via a multitude of drivers. Because of this, we decided to use the OpenMUC framework [8], developed at the Fraunhofer Institute of Solar Energy Systems, for our communication. OpenMUC is a lightweight, Java-based, communication framework and available under General Public License (GPL) at [9]. We used this framework to combine our various drivers and provide logging and debugging capabilities during development. The internal control logic of the CEMS provides the following functionalities:

- **Fail safety**: the system should be able to mitigate problems autonomously
- **Priority lists**: the system should provide means to prioritize the connected sub-systems
- **Self consumption optimization**: the system should optimize local consumption
- **Switch patterns**: many systems together should be able to form switch patterns for emergencies

b) Fail safety: is provided two folds, first by broadcasting the current bandwidth limits for the Yellow and Red traffic light states at regular intervals, even if the grid status is still unimpaired. This way, in case of communication loss, the system can react defensively and switch into a yellow traffic light state and follow the most recent bandwidth limits. We implemented the second fail safety aspect by making the inputs to the CEMS interchangeable via the OpenMUC system. This way we can compensate for equipment losses. For example: if the CEMS loses contact to the buildings Smart Meter it will replace these sensor measurements with results from an algorithm that determines total consumption by aggregating the individual measurements from the local Smart Breakers. The process is described in more detail in [7].

c) Priority lists: are created for a specific deployment and specify the importance of connected power circuits from a consumers perspective. The CEMS will use this information during yellow and red traffic light states, to determine in which order to shed the loads. A priority list is also crucial in deciding the shutdown and startup sequence in cases where specific circuits need to be started ahead of others.

d) Self consumption optimization: is implemented by having the local intelligence mediate between the demands of all the involved parties, trying to optimize local consumption by utilizing locally distributed generators, like PV system and optimizing local storage by loading batteries before providing power back to the grid. In a novel approach in cooperation with FH Wels in Upper Austria, we also developed interfaces for integration of third-party consumption optimization algorithms. These alternative algorithms can be deployed on powerful machines at remote locations while acting and reacting on and to local signals. This option, however, was not taken advantage of in the field test setup due to a lack of existing third-party solutions for the given task.

e) Switch patterns: This functionality is intended for emergency situations where the DSO or TSO has to shed part of the grid to keep the rest functional. For security reasons, the CEMS are only able to receive information from DSOs and TSOs, but cannot send information to them, their SCADAs or other CEMS. Therefore, we based this functionality on the even distribution of random numbers. As a result, the SCADA system only distributes the percentage of CEMS that should disconnect themselves from the grid, and each CEMS then determines randomly if it is effected. Given a sufficient number of participants and regular re-calculation, fair switching patterns will emerge.

IV. Field Test

The following subsection will present the concrete use cases we developed for evaluating our approach in a field test environment.

A. Use Cases

We performed field testing at an Austrian museum, located in a temperate climate region, having approximately 30000 visitors a year and being open from 8 am to 6 pm for six days a week, with one additional activity hour per day for cleaning and maintenance. The museum is closed during the winter season, but all related measurements were taken outside of this season. Considering options and demands of our field testing site, we divided the local control tasks, based on Scenario A above, into three use cases:

a) Use Case 1 - Multimedia: Multimedia equipment, consisting of mini-PCs connected to screens of various sizes, is used to present relevant information to visitors of the exhibition. The exhibition is divided into different zones, showing different aspects of the current exhibition. All zones are equipped with one or more movement sensors that can be utilized by the CEMS to determine and possibly predict visitor movement. We restricted this use case to the multimedia equipment in a single zone. The controlled area borders on three other zones resulting in three possible routes a visitor might take to reach the equipment. The goal of this use case is minimizing the local energy consumption, without diminishing the visitors multimedia experience, by cutting power supply to equipment that is currently not observed by any visitors.

b) Use Case 2 - Ventilation: The exhibition halls are equipped with a powerful ventilation system that is capable of providing sufficient fresh air to the exhibition to maintain a comfortable environment. The Goal in this use case is minimizing local consumption, by replacing the baseline policy of ventilating at full capacity during the opening hours of the location, with a demand-based ventilation strategy. The technical implementation of the ventilation system prevents the CEMS from throttling the ventilation to lower volume throughput. Therefore the only control actions available to the CEMS are enabling or disabling of the power supply to the whole ventilation system via a Smart Breaker.

c) Use Case 3 - Lights: The exhibition halls are equipped with various light sources, both diffuse light for room illumination and spotlights for highlighting specific exhibits. The goal of this use case is to minimize local consumption by cutting the power supply to the parts of the exhibition that are currently not frequented by any visitors. It is important to note that this requirement is not linked to the opening hours of the exhibition, but instead light must be available around the clock, if needed, as it is possible that people need to enter the exhibition halls during the night for purposes other then a museum visit, e.g. the night watchman or fireman in case of an emergency.
The use cases above cover only the local optimization scenario. In order to have a first implementation of the distributed control requirements from Scenario B, we introduced an additional use case that impacts the system behaviour in the three uses cases above, depending on signals from our exemplary SCADA system.

d) Use Case 4 - Grid Control: As we can not directly impact the actual power supply grid of the field test region we replaced the secondary substation of Scenario B with a self-developed, securely connected SCADA system that we use to send status information to the CEMS. We set up the SCADA system at two control sites, one in Vienna and one in Linz. The use case defines two types of loads on the field test site: essential and non-essential loads. We categorized the ventilation system as a non-essential load since the effects of disabling the ventilation are not immediate due to the size of the exhibition area and can be further mitigated by opening the windows. The other two aspects of the above use cases, multimedia and lights, were deemed essential and should only be disconnected in absolute emergencies where it becomes necessary to shed whole facilities to keep at least parts of the grid functional.

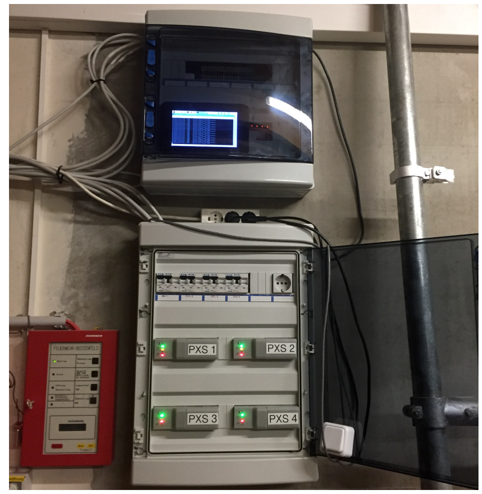

Fig. 4. Field Test installation

We would like to note that the presented use cases do not cover the entire range of requirements that could be conclude from Scenarios A and B, especially some aspects of Scenario B are omitted for the field test, since it was out of scope to secure a field testing setup that included access to an actual secondary substation and a smart transformer, but the omitted parts were separately tested at the AIT SmartEST Laboratory in a controlled setting. We still consider the given use cases sufficient to show the basic concept behind active grid stabilization by incorporating local CEMS with a centralized SCADA system.

B. Field Test Setup

The field test is implemented using the hard- and software components introduced in subsection III-B System Components. We installed three Smart Breakers, controlling the power lines to the equipment mentioned in the use case descriptions. The breakers are located centrally in a switch cabinet at the testing location as can be seen in 4. This deployment proved surprisingly beneficial as we could avoid having to install and maintain multiple remote controlled switches throughout the location, but instead, we could access most of the equipment at a central place. We run the CEMS on a Raspberry Pi 3 that communicates with the breakers via an Ethernet Communication Interface (ECI).

The Raspberry Pi was chosen because it qualifies as an affordable, off-the-shelf (OTS), low-cost solution with low consumption and is easy to deploy. The SCADA system required to fulfill use case 4, is running on a computer approximately 116 kilometres away from the testing location. The communication between SCADA and CEMS is secured in accordance to VHPready using IEC 62351 with IEC 61850, i.e. routing the data through an end-to-end encrypted tunnel. In addition to the described components, we deployed an additional laptop at the testing site, that can be accessed remotely

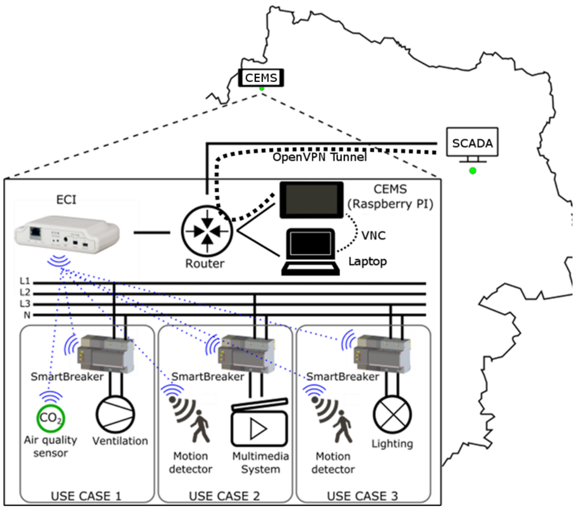

Fig. 5. Field Test Setup, modified from [10]

to allow enhanced debugging and deployment facilities.
To allow quantification of the changes introduced by the new Smart Breakers and the local control system, our partners also deployed dedicated measurement equipment at the testing site to monitor the consumption of various parts of the museum. The measurement equipment was installed one month prior to the actual field test, to provide a consumption baseline for the site.

V. Results

This section summarizes the results gathered from the field test described in the previous chapters. We consider results in two different value domains. First, we have the proof of concept provided by implementing the communication between our SCADA system, acting as a replacement for the energy distributor, while adhering to the security demands and other requirements set forth by use case 4. As a second value domain, we have the quantifiable results of consumption reduction, with respect to the baseline measurements performed before the field test, for use cases 1 – 3.

A. Extended Functionality - Use Case 4

We successfully implemented a CEMS that is capable of reacting to grid status information provided by a SCADA system at a remote location. The communication between SCADA and CEMS uses end-to-end encryption and can be considered safe as it meets current security standards. We further improved the security in addition to meeting data privacy considerations, by disabling any communication from the CEMS to the SCADA directly in the communication layer of the system. The local intelligence in the CEMS was able to envelop the control algorithms needed for use cases 1 – 3 into the logic required for reacting to the grid state. The test contained manual switching of the grid state identifier, represented by a traffic light based system from green to yellow and finally to red. The CEMS maintained the full use case specific functionalities during green and yellow state, and successfully disabled the ventilation system during the red state, as specified for use case 4. After switching back to the yellow state, the ventilation system re-engaged as required. The two central lesson we take away from this result is that using the Smart Breaker devices in a fashion similar to more traditional building automation equipment is feasible and can provide significant consumption improvements, as outlines bellow and that integration of the decentralized CEMS with a central grid information system is possible using existing technologies and cost-effective OTS equipment.

B. Quantitative Savings

In the following paragraphs, we will summarize the quantifiable results, i.e. the consumption reductions, achieved during the field test. We give a comparison of the averaged daily consumption during baseline measurements and field test period in Figure 6.

a) Use Case 1 – Multimedia:: Regarding consumption reduction, the multimedia use case provided the second-best results. Fig. 6 shows that the projected annual change in consumption for this use case is approximately 25 %. We did expect this position to provide a good reduction in energy consumption, since the a-priori strategy, running all multimedia devices continuously during the operation hours of the museum, showed obvious drawbacks. The implementation of the use case provided an unexpected, additional challenge since the controlled equipment required considerable startup time, in some cases up to 60 s. We handled this constraint by extending the trigger for enabling the multimedia equipment from movement sensors in zones containing the actual multimedia equipment to movement sensors in neighbouring zones. From the viewpoint of distributed control, this use case covered the integration of a non-optional consumer. As long as the exhibition is running, the multimedia equipment needs to operate whenever a guest enters the respective zone.

b) Use Case 2 – Ventilation: Best results were achieved by the ventilation use case reducing consumption. As shown in Fig. 6, the projected annual change in consumption for this use case is approximately 33 %. The primary challenge was the slightly higher complexity of the control algorithm and the fact that the ventilation system was considered an optional consumer, that should be disconnected in situations where the energy distributor or provider alerts the CEMS about an unstable grid status. If enough of these optional loads exist in a network segment, disconnecting them could be enough to stabilize the segment, or at least delay a grid collapse until appropriate measures can be taken in other parts of the distribution chain. The consumption reduction in this use case, as shown in Fig. 6, is based on the successful combination of data from a single air quality sensor, with a simple timing algorithm making sure, that the ventilation is never disengaged for more than 60 minutes. The ventilation is also disabled entirely outside of exhibition hours but this behaviour was already present when establishing the consumption baseline and therefore did not contribute to the reduction.

c) Use Case 3 – Lights: This use case was not expected to provide significant consumption reduction since the lighting system was already connected to a commercial building automation system during baseline measurements. Our field test, therefore, reproduced the existing operation mode, using different equipment, but fully integrated with the CEMS that controls the two other use cases. This successful integration of traditional building automation equipment and logic, with new Smart Breakers and a CEMS that can react to external information, is the main contribution we provide with this use case. During implementation, this use case proved surprisingly challenging, since the electric circuitry was not compatible with our approach. A single power line supplied the lights and motion sensors. Installing a Smart Breaker on that line would have disabled the motion sensors, together with the lights. In an attempt to still prove the integrability of this use case with the rest of the field test, we used commercial remote switches as replacements for the Smart Breaker and controlled the lights individually, instead of disconnecting the entire power line. The minor consumption reduction, visible in Fig. 6, is based on the slightly tighter scheduling of the follow up-times used for the motion sensors in the respective zone.

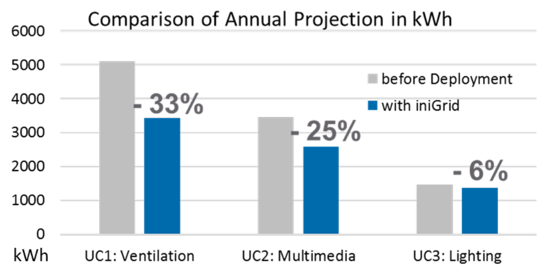

Fig. 6. Consumption comparison with and without Smart Breakers

VI. Conclusion and Outlook

This work summarizes and discusses the results obtained by using a new variant of a Customer Energy Management System, that is specifically tailored for industrial applications, in collaboration with a new generation of hybrid Smart Breakers, in a field test setup. Based on the results detailed in section V, we conclude that the integration of a simple local intelligence with a centralized guidance system, in our case a system providing information on the grid stability, is possible and can be implemented using existing and affordable hard- and software. The equipment and methods we used, were sufficient to maintain a high level of security on the communication level. The consumption reductions presented in this work show that our system can apply our methods successfully and improve energy consumption measurably. The implementation of Use Case 3, using classical remote switches shows, that integration of a traditional home automation system and potent new Smart Breakers into a CEMS that can react to information from energy providers and DSOs, is, in fact, possible, and can be achieved with affordable OTS hardware and openly available software.

The physical capabilities of the next-generation hybrid-Smart Breakers used in our tests, which are discussed in greater details in [5], give strong evidence that our solution is applicable for industrial usage scenarios, even though the tests themselves were not yet performed in an industrial environment. The Smart Breakers ability to switch entire line segments proved beneficial in regards to the development of the local control software, as well as for the physical system setup since we could install most of our equipment at the central junction box, with exception of remote switches used in Use Case 3.

We consider the field test described within these pages as a point of departure and our next goal will be the integration of multiple CEMS from different locations and research on how distributed control techniques can be utilized to improve the local intelligence and autonomy of participating systems further. The long-term goal for these next steps is the development of a self-organizing and secure system of distributed CEMS, working towards the common goal of lowering energy consumption and possibly even autonomously stabilizing the energy distribution grid using simple mechanics like shedding of optional loads and controlling distributed energy providers, e.g. PV systems. Another promising follow-up track, with similar long-term goals, will be the research into extending the communication possibilities between consumers and energy providers or distributors.

VII. Acknowledgements

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