[iii] Information and Control Systems for Energy Industry

Grid Edge Solution for Overcoming Challenges of Large-scale Renewable Energy Deployment

System Trial in the Republic of Slovenia

The shift toward renewable sources of electricity generation plays an important role in international action on decarbonization aimed at preventing global warming, as exemplified by the Paris Agreement. Unfortunately, connecting large amounts of renewable energy capacity to the grid raises a number of challenges. In the Republic of Slovenia, Hitachi supplies systems to overcome these problems and offers a cloud-based service that is available for shared use, including by smaller local users. While some trials still continue, the work done to date has demonstrated the effectiveness of the solution. This article presents an overview of this project, winner of the 6th ISGAN Award of Excellence (2020), an accolade that recognizes excellence in smart grid activities around the world.

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1. Introduction

1. 1 European Electricity Industry

Decarbonization policies are being pursued in Europe as a means of addressing the problem of climate change, with the European Union (EU) Clean Energy Package of 2019 containing a number of directives with numeric targets to be achieved by 2030 for the proportion of energy derived from renewable sources, energy efficiency, and greenhouse gas emission reductions. The package set a target of 32% renewable energy relative to total energy consumption and urged member nations to proactively adopt the new measures(1). To achieve this, and to ensure that variable supplies of renewable energy can be used efficiently and economically without compromising the stability and reliability of electricity supply, policies have been put in place for establishing systems and markets, encouraging the adoption of new technologies, and expanding the responsibilities of regulatory bodies and business.

1. 2 Slovenia's Electricity Industry and the Challenges it Faces

The Republic of Slovenia is a central European country of approximately two million people that became independent in 1991 from what was then Yugoslavia, joining the EU in 2004. In line with EU policies, Slovenia has pursued a target of obtaining 25% of its total energy consumption from renewable sources by 2020, with this target being raised in 2020 to 27% by 2030(2).

While the increase in grid-connection of distributed power generation from renewable sources requires distribution network operators (DNOs) to employ more sophisticated grid management techniques to deal with voltage fluctuations, power outages, overloads, and the provision of balancing and reserve capacity, they also face challenges from aging infrastructure and require solutions that can deliver a high quality of operation while keeping capital investment to a minimum.

Meanwhile, against a backdrop of market liberalization, the trends among electricity retailers and consumers are toward the use of more sophisticated energy management to secure reliable and economical supplies of electric power, improve resilience, and actively participate in electricity markets. With some consumers having installed batteries or other energy storage, a trend that looks set to accelerate, transmission and distribution companies see these consumers as playing a role in helping maintain grid stability.

Taking advantage of the agility that comes from being a small nation, Slovenia has actively pursued the development and trialing of new technologies, and in the electricity sector, it has a number of projects underway, cooperating with local and international stakeholders to address the challenges discussed above. The country has five DNOs that own distribution networks and a single distribution system operator (DSO), a state-owned business responsible for distribution network operation. The DSO leases and runs the distribution networks from the DNOs, outsourcing their actual operation back to the DNOs.

2. Background and Details of the Demonstration Project

To address the above challenges facing Slovenia, the demonstration project trialed the delivery of services to a number of DNOs using a cloud-based distribution management system (DMS)[3] and advanced energy management system (AEMS)[4] that reduce system development costs for customers.

2. 1 Cloud-based DMS

Table 1 lists the number of DNOs in various EU countries as well as in the neighboring country of Serbia (not an EU member). Even allowing for these countries' land areas and populations, the number of DNOs is an order of magnitude higher than in Japan where operation of the electricity grid is split between 10 main companies. The lack of consolidation is also the case in Slovenia, the site of this demonstration project, where five DNOs serve an area roughly the same size as the island of Shikoku in Japan, using DMSs supplied by different suppliers and with different levels of functionality. Some of the DNOs do not have a DMS at all. The financial situation and level of infrastructure management also varies between DNOs and there is a lack of data sharing and functional coordination. The demonstration project involved implementing and trialing a cloud-based DMS that could be used jointly by a number of DNOs. The aim was to improve the quality of electric power by offering a DMS with functions for advanced voltage regulation, fault recovery, and demand response (DR) that would also keep development and running costs low, even for small and medium-sized DNOs.

2. 2 Cloud-based AEMS

Following a major power outage caused by a vicious cold snap in 2014, Slovenia needs to better prepare itself for emergencies and to protect hospitals and other critical infrastructure. There is also a requirement for protection against instantaneous voltage drops caused by events such as heavy snow or lightning strikes because of the impact these have on factories and other major consumers that rely on high-quality electric power. Meanwhile, as a consequence

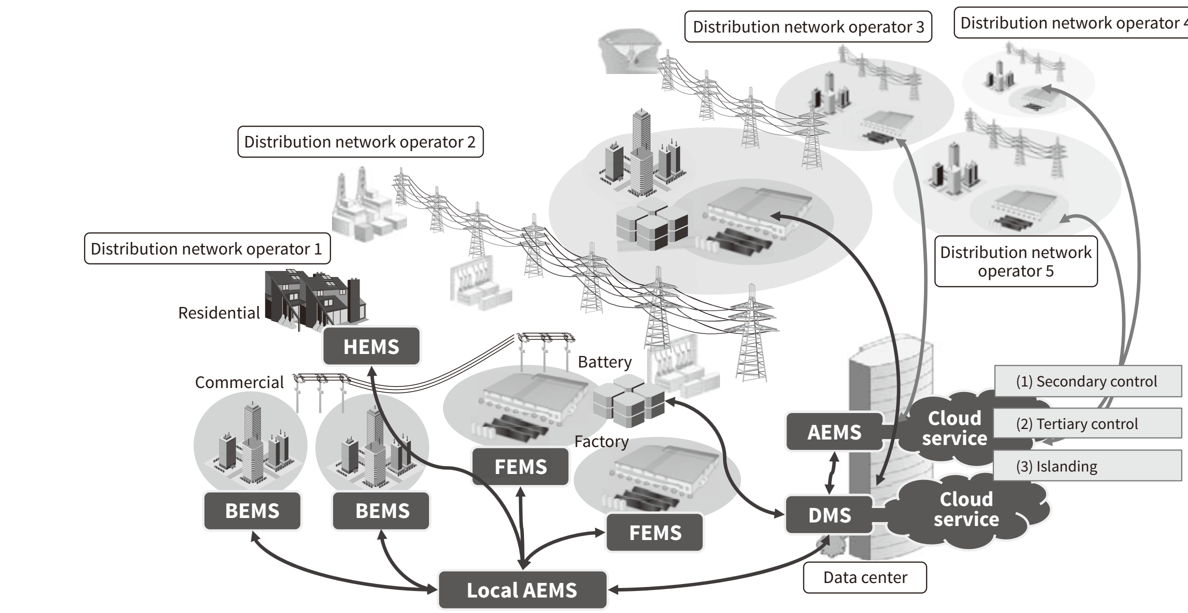
Table 1 — Number of Electricity Distribution Network Operators in EU and Adjacent Nations

The figures are based on data for FY2010 provided in Power Distribution in Europe Facts & Figures (published by Eurelectric), augmented by additional updates by Hitachi.

Nation	No. of distribution network operators			
	1997	2003	2010	2011
Germany	1,000	900	896	880
Spain	540	—	349	349
Poland	33	27	188	184
Serbia	230	190	170	173
France	—	—	158	158
Norway	200	157	150	155
Italy	200	195	135	144
Austria	137	137	138	138
Finland	115	93	85	85
Denmark	211	119	76	72
Estonia	—	—	36	36
Belgium	36	29	26	24
Portugal	4	1	13	13
Latvia	—	—	11	11

Figure 1 — Diagram of Demonstration Project System

The demonstration project system delivered a mix of services to electricity distribution network operators and consumers based around a cloud-based DMS and AEMS.



AEMS: advanced energy management system (for major consumers and electricity retailers) FEMS: factory EMS BEMS: building EMS HEMS: home EMS
DMS: distribution management system
*xEMS: x energy management system (general term for an energy management system intended for factories, buildings, or homes)

of lower levels of thermal power generation and the aging of power generators, the transmission system operator is having to deal with a lack of the reserve capacity needed for grid frequency regulation and so is looking to make use of batteries and other distributed power sources as a new source of supply. Prompted by these considerations, the demonstration project involved implementing and trialing a multi-function cloud-based AEMS that includes support for islanding (splitting off part of the grid during a fault) and ancillary services (the provision of balancing capacity to the transmission system operator).

2. 3 Configuration of Demonstration Project Systems

Figure 1 shows the system used in the demonstration project. By integrating the cloud-based AEMS and DMS (which run at a data center) with the battery capacity installed by consumers on the grid and the various energy management systems (xEMSs) used for factories or for commercial or residential property, the system can supply multiple consumers with ancillary services encompassing both secondary and tertiary control as well as other services such as islanding.

3. Cloud-based DMS

To deliver services to the DNOs, the demonstration project included the development of a cloud-based DMS with an architecture that features server consolidation and virtualization. The system is described below.

The DMS used for the project was implemented as a cloud service at a data center, with the only hardware installed at the DNOs being operation consoles. The benefits of this service delivery model include reducing up-front investment, minimizing discrepancies between operating rules and power quality management practices at the different DNOs, and cutting system maintenance and other running costs. In terms of the software, while only a single instance of the DMS application exists in the cloud system, logically separate databases and user interfaces are created for the individual DNOs. This maintains data security by preventing DNOs from accessing screens or data belonging to other DNOs and ensures that actions performed by one do not impact on the others (see **Figure 2**). Hitachi believes that this cloud-based approach represents a good solution for encouraging the adoption of DMSs in regions served by a large number of small DNOs.

4. Voltage Control for Distribution Networks

Phase 1 of the demonstration project covered a range of topics, including functions for advanced voltage regulation, fault recovery, and DR. The following focuses in particular on the control practices used to address the problem of voltage fluctuations associated with the connection of large amounts of renewable energy capacity.

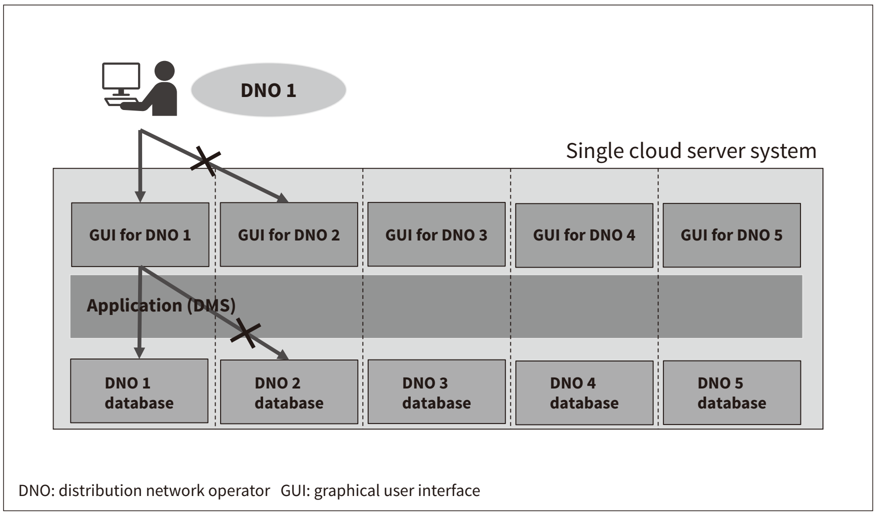


Figure 2 — Block Diagram of Cloud-based DMS

While only one instance of the application software exists in the cloud system, logically separate databases and user interfaces are created for the individual DNOs.

4. 1 Voltage Regulation

The three main voltage regulation techniques used on distribution networks are as follows.

(1) Standalone control

Control of voltage is achieved by changing tap settings based on measurements performed on the voltage control equipment itself, such as transformers equipped with on-load tap changers (OLTCs).

(2) Rule-based SCADA control

Rules are defined in advance specifying where to perform tap changes when the voltage at a particular measurement point goes outside its permitted range. The supervisory control and data acquisition (SCADA) system implements these rules, performing the tap changes accordingly.

(3) Distribution-model-based voltage control (VC)

The DMS determines the optimal combination of tap settings for multiple transformers based on both measurements from throughout the grid and the results of power flow calculations.

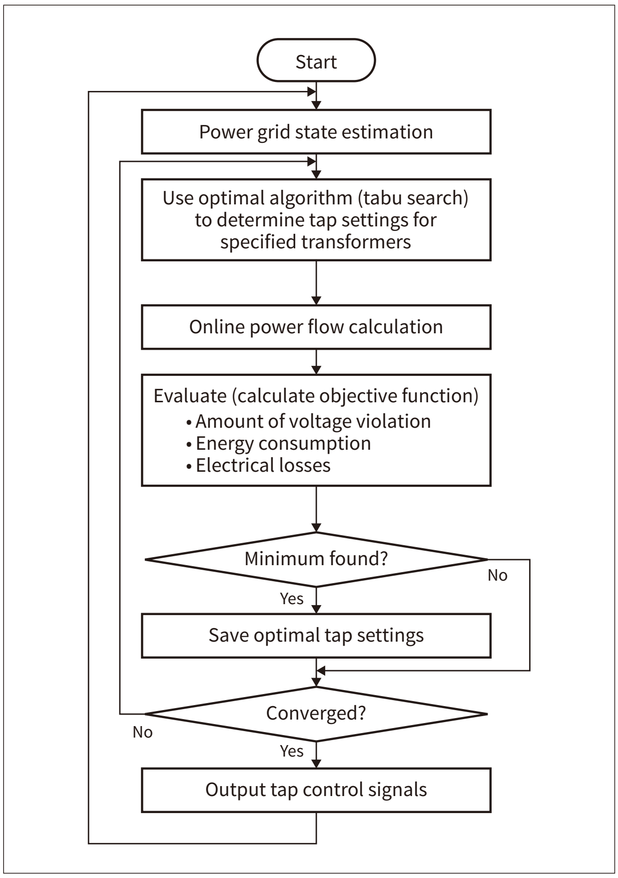
The demonstration project adopted the third of these methods and evaluated its performance on the actual grid in terms of the number of tap changes made and how well it eliminated instances voltage deviation from the target range(5).

4. 2 Algorithm

The problem of calculating optimal tap settings is a form of combinatorial optimization known as mixed-integer nonlinear programming (MINLP) and is characterized by the very large number of combinations that can occur. Just five transformers with 10 available tap settings each gives a total of 10^5 (100,000) possible combinations. This makes it impossible to search through all these possible settings for the optimal combination in a realistic amount of time. Accordingly, the project used the tabu search algorithm to calculate an optimal solution in a short time (see **Figure 3**).

Figure 3 — Voltage Regulation Algorithm

The tabu search optimization algorithm is used for high-speed calculation of the optimal combination of transformer tap settings.



4. 3 Performance Criterion

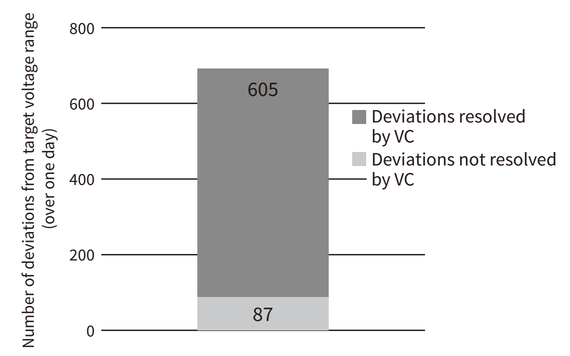
The project performed control using OLTCs both for high- and medium-voltage transformers and for medium- and low-voltage transformers. The DMS calculates and implements new tap settings when it detects a voltage violation, which occurs when voltages recorded by sensor measurements or obtained from power flow calculations deviate from the specified target range. The target voltage range was set in consultation with the DNOs and expressed as a percentage of the rated voltage, with an upper limit of 108% and a lower limit of 95%. This is a more stringent criterion than the ±10% stipulated in the EU standard (EN50160).

4. 4 Results

As shown in **Figure 4**, 605 (87.4%) of the 692 deviations from target voltage range that occurred over the course of one day were successfully dealt with by the VC technique used for the demonstration project. Among those deviations that were not eliminated were some where the problem lay with the capabilities of the infrastructure itself, which lacked the ability to overcome the deviation however the tap settings were changed. Nevertheless, no voltage violations occurred in terms of the EU standard EN50160 criterion.

Figure 4 — Reduction in Number of Deviations from Target Voltage Range

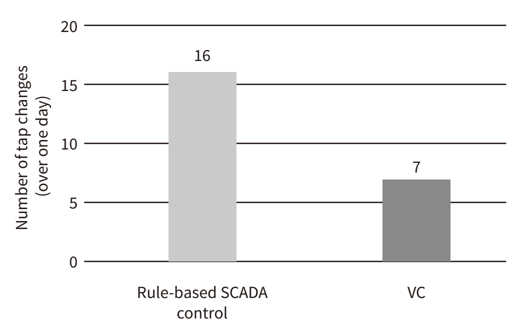
Of the 692 deviations from target voltage range that occurred over the course of one day, 605 (87.4%) were successfully dealt with by the VC technique used for the demonstration project.



VC: distribution-model-based voltage control

Figure 5 — Number of Tap Changes Required by Different Voltage Regulation Techniques

The graph shows the number of tap changes that occurred over the course of one day for the two different voltage regulation techniques used in the project: rule-based SCADA control and VC. VC required fewer tap changes to respond to voltage violations, requiring only seven compared to 16 for rule-based SCADA control.



SCADA: supervisory control and data acquisition

Furthermore, the comparison in **Figure 5** shows how VC required fewer tap changes to respond to voltage violations than the rule-based SCADA control technique used in the project by the Slovenian vendor, requiring only seven tap changes over the course of one day compared to 16 for rule-based SCADA control.

5. Supply of Reserve Capacity to Energy Market Using Consumer Plant

Phase 2 of the demonstration project covered ancillary services in which different areas and consumer equipment are used to supply reserve capacity to the energy market as well as plans to provide an islanding service as part of measures for improving resilience at a local level, as discussed later in this article. These are described below.

5. 1 Ancillary Services

The European Network of Transmission System Operators for Electricity (ENTSO-E) requires countries to maintain reserve capacity that can be used for balancing control to maintain power quality (frequency and voltage) in the form of: (1) frequency containment reserves (FCR), (2) frequency restoration reserves (FRR), and (3) replacement reserves (RR). These are based on the two criteria of how long it takes a power generator to reach the prescribed level of output and how long it can maintain that level of output(6).

In Slovenia, these three types of reserves are called primary control, secondary control, and tertiary control, respectively. As the country also suffers from a shortage of these balancing reserves as the aging of thermal and other power generators means fewer of these are available, and due to the EU-mandated increase in renewable forms of electricity generation such as wind and photovoltaics that have fluctuating output, it is looking to batteries and the reserve capacity available from prosumers as a means of making up the shortfall. In this project, the AEMS was used to deliver ancillary services for the provision of secondary and tertiary control capacity to balance supply and demand when this is needed.

5. 2 Secondary Control Using Batteries

Based on the monitoring of frequency and other grid parameters on its SCADA/EMS, Slovenia's single transmission system operator (TSO) obtains reserve capacity for secondary control by issuing requests for active power to its available resources, encompassing hydroelectric and thermal power plants and combined heat and power (CHP) systems. As existing infrastructure is unable to provide sufficient reserves, batteries have been installed to act as additional distributed power sources and the AEMS interconnected with the TSO's SCADA/EMS to enable integrated management of balancing capacity from different areas. This will be done by issuing active power requests to the batteries installed at the demonstration project sites at the Blagovno Trgovinski Center (BTC), a multi-purpose shopping complex in the capital Ljubljana, and in the Municipality of Idrija in the mountainous western part of Slovenia. This secondary control service for reserve capacity is scheduled to commence operation in July 2021.

The batteries at the Municipality of Idrija are a hybrid mix of high-capacity lead-acid batteries and low-capacity lithium-ion batteries (LiBs). Active power requests from the TSO are handled by allocating output across the different battery types in an optimal manner so as to combine rapid response (high output) with endurance (high capacity). This battery configuration is also designed to provide long battery life and to maintain a stable state of charge (SOC: the ratio of actual charge to full charge).

If operation of the different battery types was simply allocated in proportion to their capacity, for example, there is a high probability that the LiBs would quickly become unavailable as their SOC reached the maximum or minimum limit. Instead, the availability of the low-capacity LiBs is maintained by using a hybrid battery control technology that takes advantage of the respective characteristics of the two battery types, with the LiBs providing rapid response (high output) and the lead-acid batteries providing endurance (high capacity).

5. 3
Tertiary Control Using Prosumer Plant

While the TSO already had tertiary control measures in place to provide reserve capacity, this capacity was inadequate and therefore the project provided additional capacity through the use of load-shedding DR to reduce power use by loads at the BTC shopping complex and Municipality of Idrija.

A service providing capacity for tertiary control was scheduled to commence in May 2021. This involves interconnecting the AEMS with the TSO's SCADA/EMS to use equipment at the BTC and Municipality of Idrija for load-shedding DR and integrating its management with that of balancing reserves from other areas.

In response to load shedding requests from the TSO, the AEMS provides updates to the TSO about actual and predicted power use by the loads and how much load shedding is available so that the TSO can instruct thermal and other power generators by means of secondary and tertiary control requests. In this way, the AEMS will contribute indirectly to reductions in carbon dioxide (CO_2) emissions.

6. Improving Resilience at Local Level

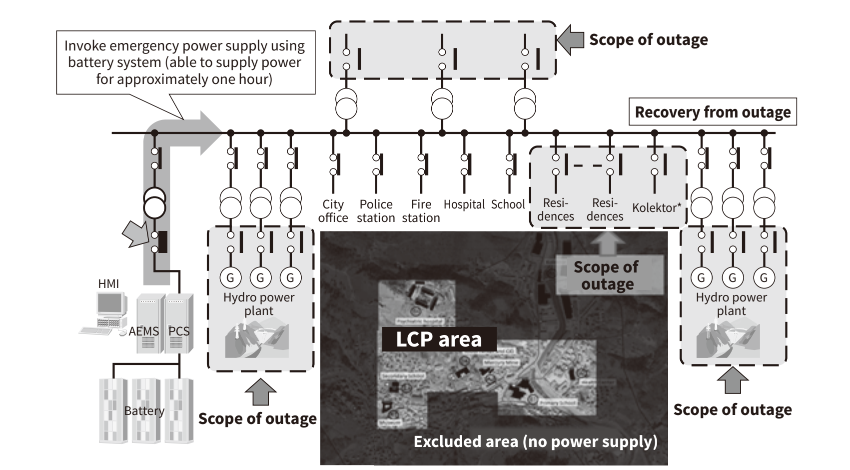
The demonstration project also plans to launch an islanding service for life continuity planning (LCP) areas that have critical equipment to which power must be maintained during emergencies. Scheduled to commence in July 2021, the service is intended for use when a disaster or other such event causes a long outage due to grid faults, supplying electric power from batteries to keep a section of the grid running in isolation from the rest of the power system.

6. 1
Islanding Service

The system used to deliver this service is split into three parts. The intention is to verify its utility by evaluating how long it can keep supplying power and how well it maintains power quality during islanding.

Figure 6 — Islanding Area

The area containing critical loads and designated as the island is that supplied by three medium- and high-voltage transformers installed at a substation in the Municipality of Idrija. These critical loads include a hospital, power company, police station, fire station, and school.



HMI: human machine interface PCS: power conditioning subsystem LCP: life continuity planning G: generator
*Large Slovenian company

The designated LCP area is the area supplied by three medium- and high-voltage transformers installed at a substation in the Municipality of Idrija. Idrija experienced a power outage lasting several days in 2014 that was caused by ice and snow damage. It is also part of Alpine Town with a concept like that of environmental protection programs for the European Alps. As shown in **Figure 6**, the LCP area contains critical infrastructure, including a hospital and a police station.

(1) AEMS

Provides the operator with the ability to start and stop islanding, monitoring of the supply area, and load prediction.

(2) DMS

Detects long-duration outages and operates switchgear and monitors the power system in accordance with islanding instructions from the AEMS.

(3) Battery energy storage system (BESS)

Supplies power to the supply area and maintains power quality (frequency and voltage) in accordance with islanding instructions from the AEMS. A power conditioning subsystem (PCS) operates as a protection relay to shut off the power in the event of a frequency or voltage irregularity.

7. Conclusions

The demonstration project described in this article was the winner of the 6th International Smart Grid Action Network (ISGAN) Award of Excellence (2020), an accolade that recognizes excellence in smart grid activities around the world. ISGAN operates under the umbrella of the International Energy Agency (IEA) and works internationally to encourage the development and deployment of smart grid technology.

Rather than resting on the laurels of this award, Hitachi intends to further expand its energy solution business by responding promptly and flexibly to developing global trends in the rapidly changing electricity and energy industries.

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