Advancements in Synchronizing Systems for Microgrids and Grid Restoration

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Abstract

Synchronizing systems have traditionally been used for bringing a generator online. Today, synchronizing systems are required to reconnect islanded power systems together. These generation/load islands can be intentional in the case of microgrids or unintentional in the case of grid restoration after a blackout or a system separation event. Another advanced synchronizing application includes independent power producers that locate generation remote from the transmission network interconnection point. This paper describes a number of proposed and real-world synchronizing systems that have been implemented using advanced technology. The paper is a reference to provide guidance to transmission system operators and protection and control engineers on how to overcome the technical limitations imposed by traditional synchronism-check and automatic synchronizing equipment.

1 Introduction

Synchronizing systems have traditionally been used for bringing a generator online. Today, synchronizing systems are required for many more diverse applications, including the following:

- Microgrids (synchronize back to the grid).
- Reliability islanding systems (separate, survive, resynchronize).
- Grid restoration after system breakup (tie islands back together).
- Independent power producer resources separated from grid interconnections (remote synchronizing).

Modern technology allows synchronizing systems never before possible. This paper describes the advancements made possible by modern synchronizing systems and provides examples of proposed and real-world systems that have been implemented using this technology. The paper is a reference to provide guidance to transmission system operators and protection and control engineers on how to overcome the technical limitations imposed by traditional synchronism-check and automatic synchronizing equipment.

2 Synchronizing systems

Designing systems for synchronizing a generator to the power system is a well understood and mature engineering exercise. Automatic and/or manual systems are used to match the generator frequency and voltage to the bus prior to initiating the close of the synchronizing circuit breaker as close to zero degrees phase angle coincidence as possible. By reducing voltage difference, slip, and angle difference to minimum levels, excessive transient shaft torques and damaging winding current levels can be avoided—reducing the stress on the valuable and complex electro-mechanical system that makes up the generator and prime mover, as well as minimizing power and voltage transients on the connected power system [1].

2.1 Generator synchronizing

In most applications, the controls for the governor for adjusting the frequency and the exciter for adjusting the voltage and for the synchronizing breaker to initiate close are in close proximity to the synchronizing panel used to visualize the three parameters that have to be matched. This close proximity facilitates the use of simple hardwired conventional technology for manual (human operator in the loop) and automatic synchronizing systems.

2.2 Generation/load island synchronizing

Traditional synchronizing technology is often not well suited to the challenges and constraints imposed by synchronizing generation/load islands including microgrids to each other or to the main grid. The design constraints are often quite different from traditional synchronizing applications.

In many cases, the synchronizing point may be remote from the generator controls, preventing direct hardwired designs. The synchronizing point may be at an unplanned, ad hoc location where synchronizing equipment is not available. The generation/load island may consist of a mix of generation sources instead of simply one machine that has to be controlled, requiring complex control strategies to match frequency and voltage between the islands to be synchronized [2] [3] [4].

On the other hand, synchronizing islands may allow greater tolerance for less than perfect synchronizing. The mechanical and electrical energy transients caused by synchronizing at larger slip rates and/or at poorer angle matching can be absorbed by the combined generator and load rotating inertia in the island. Further, there will often be greater transfer impedance between the asynchronous island and the grid that can reduce the magnitude of transients as well. In other words, there is often more “rubber” in the system when synchronizing an island than when synchronizing a generator.

2.3 Advanced synchronizing technology

The challenges discussed in Section 2.2 often can be solved by using advanced technology that can overcome the limitations of traditional synchronizing systems.

2.3.1 Advanced automatic synchronizers

Advanced automatic synchronizers (A25A) located at the synchronizing point can be used to verify slip and voltage difference and close the breaker at the slip compensated advanced angle without the necessity of a synchronizing panel with a synchroscope and meters to allow a human operator to visualize conditions and initiate the close. More importantly, an A25A can eliminate the need for operators to travel to a remote location to perform the synchronizing process at all—reducing costs and speeding the process of reconfiguring or restoring the power system.

A25A devices can provide frequency and voltage matching functions to bring frequency and voltage difference within synchronizing acceptance limits in multiple ways. For example, they can telemeter the slip and voltage difference parameters to a control center to allow for manual adjustment of frequency and voltage in the island to be synchronized. They can provide direct LED and/or LCD indication of the synchronizing acceptance criteria to operators who can communicate with a remote location for manual adjustment. Or, they can use fiber-optic communications to send correction pulses to a remote governor and exciter to automatically adjust frequency and voltage.

The heart of an automatic synchronizer is the slip-compensated advanced angle feature. The automatic synchronizer compensates for the breaker mechanism close delay by calculating the advanced angle per (1), using the measured slip.

$$\text{ADVANG}^\circ = \left(\frac{(\text{SLIP})\,\text{cyc}}{\text{sec}}\right)\left(\frac{\text{sec}}{60\ \text{cyc}}\right)\left(\frac{360^\circ}{\text{cyc}}\right)\big((\text{TCLS})\,\text{cyc}\big) \quad (1)$$

where:

ADVANG is the advanced close angle.
TCLS is the circuit breaker close mechanism delay.

At the angle calculated using (1), the breaker close coil is energized and the breaker main contacts will close at exactly zero degrees if the breaker mechanism delay is known with certainty and the breaker timing is consistent. The main advantage of an automatic synchronizer over an operator is that the device can more consistently close the breaker at the precise moment—reducing power system and torque transients.

2.3.2 Advanced synchronism-check relays

Advanced synchronism-check relays have capabilities that make them much better suited for synchronizing applications over traditional synchronism-check relays and digital relays that do no more than emulate traditional synchronism-check relays. Traditional synchronism-check relays are not optimal for supervising the close command in the situation where two asynchronous power systems must be tied together [5]. Traditional relays check that the angle is inside a ± angle window and stays there for a time delay. The angle window and time delay are a surrogate for measuring slip. The time criteria of such a relay would be set using (2).

$$25_{\text{TD}}\ \text{sec} = \left(25_{\text{ANG}}{}^\circ - \text{ADVANG}_{\text{MAX}}{}^\circ\right)\left(\frac{\text{cyc}}{360^\circ}\right)\left(\frac{\text{sec}}{\text{SLIP}_{\text{MAX}}\text{cyc}}\right) \quad (2)$$

where:

25TD is the synchronism-check time-delay setting.
25ANG is the synchronism-check angle setting.
$\text{ADVANG}_{\text{MAX}}$ is the ADVANG at SLIP_{MAX}.
SLIP_{MAX} is the allowable slip in Hz.

The $\text{ADVANG}_{\text{MAX}}$ is calculated per (1). For such a synchronism-check relay, the time-delay setting must accommodate the advanced angle. For example, using a 10-degree angle window, a 0.100 Hz (36 degrees per second) SLIP_{MAX}, and a mechanism delay of 5 cycles, the $\text{ADVANG}_{\text{MAX}}$ would be 3.0 degrees. The setting 25TD would be less than 0.19 seconds to allow the synchronism-check relay to close its contacts before 3.0 degrees in advance of 0 degrees at SLIP_{MAX}. If the actual slip is less than SLIP_{MAX}, the synchronism-check relay will close its permissive contact in advance of the close command from the operator or automatic synchronizer.

This type of synchronism-check relay can cause a late close [5]. For example, if the delay is set to 0.19 seconds per the previous example and the operator has misjudged and initiated the close with slip at a slightly fast 0.125 Hz (45 degrees per second), the close coil would be energized at 8.55 degrees past 0 degrees (because the operator’s hand is still on the control switch). The breaker main contacts would make at 12.3 degrees past 0 degrees because the asynchronous systems would advance 3.75 degrees relative to each other during the 5-cycle mechanism delay at 0.125 Hz. Similarly, if the operator is counting on the synchronism-check relay to ensure a good close and simply holds the control switch in the close position, if the slip is less than SLIP_{MAX}, the relay would cause an early close. It should be understood that traditional synchronism-check relays are used to prevent bad closes—not cause good closes.

Modern microprocessor-based synchronism-check elements directly measure slip and provide a permissive with no time delay if the slip is within the allowed setting. Advanced synchronism-check elements additionally provide slip-compensated advanced angle close timing similar to an automatic synchronizer to assert the permissive at the precise time to close at near zero degrees angle difference. In the following application examples, applications are described that take advantage of this capability of advanced synchronism-check relays for synchronizing islands and microgrids.

3 Applications

This section describes several proposed and real-world examples of synchronizing systems using advanced technology to solve problems.

3.1 Microgrids

The use of distributed energy resources, energy storage, backup generation, and co-generation to support critical loads and perform economic demand management in either parallel with the grid or islanded operation is not new. However, the term microgrid has come into common usage to describe these localized grids that can disconnect from the traditional grid to operate autonomously. The U.S. Department of Energy's official definition of a microgrid is "a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid (and can) ***connect*** [emphasis added] and disconnect from the grid to enable it to operate in both grid-connected or island-mode" [6]. The Department of Energy looks to microgrids as a means of strengthening grid resilience and improving efficiency [7]. As the definition states, one important requirement for a microgrid control system is the ability to synchronize the microgrid back to the main grid.

A major subset of microgrids used in industrial facilities with important processes that must be kept operational, even during grid disturbances and blackouts, has a long history of application. These systems are sometimes called, "reliability islanding systems" or "three S systems that separate, survive, and resynchronize." When a grid disturbance, loss of local generation, or loss of import tie lines is detected, the system will separate and respond with high-speed contingency-based load shedding of non-critical loads to survive. Once the grid has recovered from the disturbance, the critical load island must be resynchronized with the grid or main generation systems without perturbing the energy supply to the critical loads.

Another important distinction of a microgrid is that it must be a controllable entity with clearly defined electrical boundaries. That implies a microgrid controller is required that can control the mix of generation and storage resources as well as loads to maintain frequency and voltage within acceptable limits during islanded operation. For such systems, when synchronizing back to the grid, the automatic synchronizer will typically not provide frequency and voltage correction pulses directly to the generator controls. In these systems, the A25A telemeters the slip and voltage difference measurements at the synchronizing point to the microgrid controller. The microgrid controller adjusts the generation to minimize these control error signals until the synchronizing acceptance criteria is satisfied and the A25A can close the breaker.

3.1.1 Large industrial

Reference [2] describes the synchronizing system for a reliability islanding application at an alumina processing facility. Due to the nature of and the complexity involved in the many possible islanded microgrids, the refinery project included the requirement that no manual synchronization is allowed. For this reason, the automatic synchronizing system had to be fully redundant to allow operations to continue in the event that the primary system failed.

This industrial power system, shown in Fig. 1, supports loads on multiple buses—many with no generation. Each of the six generators can support loads independently on different islands, making it possible for six islands to occur simultaneously. These generators also supply power to the gas-insulated substation (GIS) bus for loads throughout the refinery. The refinery power system can be connected in various topologies, requiring the automatic synchronizing system to be flexible and adapt to all refinery electrical grid topologies.

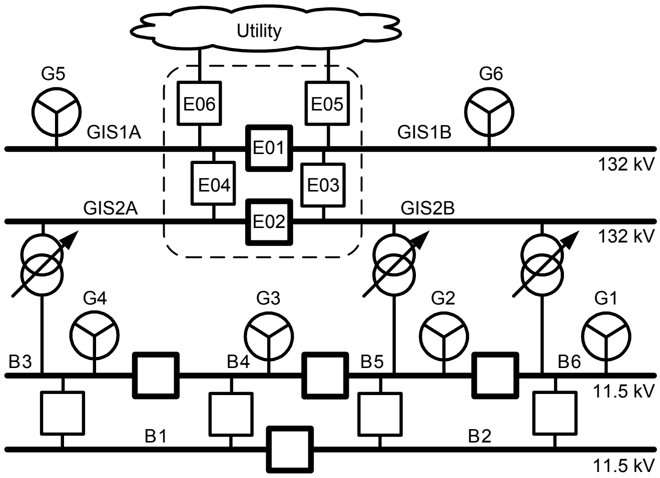

Fig. 1. Simplified one-line diagram of refinery power system [2].

The redundant A25A devices can synchronize the many possible islands via the six breakers in the 132 kV GIS that are inside the dashed line. All voltage transformer (VT) signals and binary I/O control signals are hardwired to the A25A devices and selected internally depending on the requirements of the selected synchronizing scenario, resulting in very simple and reliable control circuitry. Unreliable auxiliary relays and switches for switching circuits are completely eliminated from the design. The microgrid controller includes a generator control system for load sharing and overall frequency and voltage control of the power system. The generator control system receives slip and voltage difference signals from the A25A and brings these parameters into band by adjusting the generation in a particular island to allow the A25A to synchronize.

3.1.2 Offshore oil platform

Reference [5] describes the synchronizing systems for two offshore oil platforms. The power generation and distribution systems for this application have to be extremely flexible, robust, and fault-tolerant to meet the requirements of economy, compliance with regulations, and safety for personnel and the environment.

Primary electrical power is generated by multiple dual fuel combustion turbine generator sets. Each platform also has two diesel generators. The emergency generator is sized to run all U.S. Coast Guard and American Bureau of Shipping mandated systems and critical life support, control, utility electrical loads, and platform essential loads when the primary generators are offline. The black-start/hurricane generator, is used to furnish electrical power for startup and for the critical habitable loads when the primary generators are offline.

In this application, each diesel generator has its own A25A installed. For this reason, slip and voltage difference matching controls are relatively simple given that only one generator has to be controlled by each synchronizing system. Simple raise and lower output contacts are used to adjust the governor and voltage regulator on the generator during synchronizing.

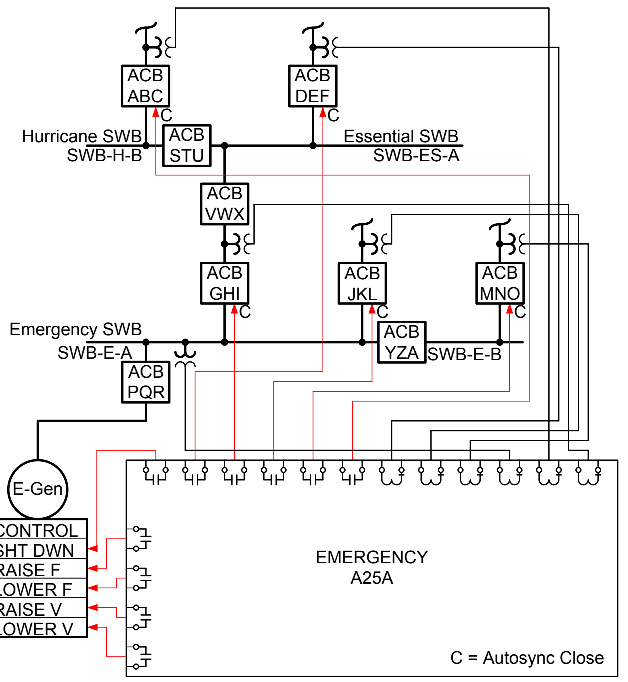

Fig. 2. Emergency generator A25A [5].

Fig. 2 shows the complex distribution system that the emergency generator must be able to support and synchronize back to the main generation after a disturbance. Each of the five possible synchronizing breakers is marked with a C in the figure. In this system, all VT signals and binary I/O control signals are hardwired to the A25A devices and selected internally depending on the requirements of the selected synchronizing scenario, resulting in very simple and reliable control circuitry.

3.1.3 Municipal microgrid

Fig. 3 shows a municipal microgrid application. The municipal electric utility operates their own generation as well as receiving wholesale power via a tie line to the transmission grid. The power plant is located near the center of town where the original municipal power distribution system started. As the grid expanded and became interconnected many years ago, a tie substation was constructed at the edge of town.

The municipal entity operates its generation for both economic and reliability reasons. When wholesale rates are high, they reduce demand by running local generation in parallel with the grid. And, during an outage of the transmission tie line, they run their generation in isosynchronous mode to maintain continuity of service.

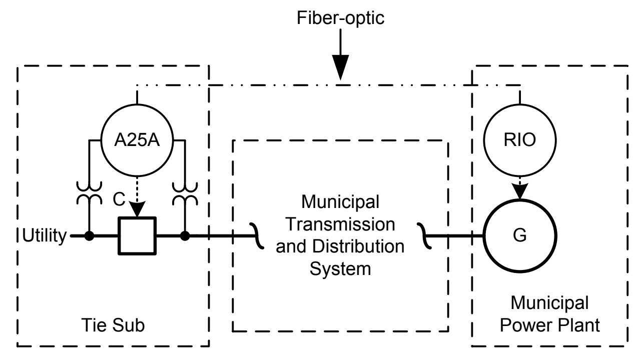

Fig. 3. Municipal microgrid with remote synchronizing.

To be able to easily synchronize back to the grid, an A25A that is capable of sending the proportional control pulses over a fiber-optic link is installed at the synchronizing breaker. A remote I/O (RIO) module is installed at the power plant and directly connected to the generator controls. The A25A can be initiated and the synchronizing process monitored from the operator control room via a DNP supervisory control and data acquisition (SCADA) link. The use of an A25A system greatly simplifies the process and improves the accuracy and time to synchronize as opposed to having an operator at the tie station talking over radio to the power plant control room to adjust frequency and voltage before the breaker can be closed.

3.2 Grid restoration

Major system blackouts happen from time to time due to unplanned abnormal system stress or natural disasters such as hurricanes and ice storms. When these events occur, load shedding systems are used to help match local load to local generation to allow formation of islands to arrest the cascade of the blackout and limit the affected area.

Regional transmission system operators and utilities are then faced with the complex task of restoring the grid. To prepare for such high-impact but low-frequency events, many are preparing disaster recovery plans. One of the challenges of planning for grid restoration is that it is impossible to predict with any accuracy where the system separation points may be for all possible events. Because the interconnected grid has been so reliable, in many cases, transmission substations do not include synchronizing panels that might allow synchronizing two asynchronous islands at an ad hoc location. Modern synchronism-check and advanced automatic synchronizers can be used to solve this problem.

3.2.1 Portable synchronizer

A novel disaster recovery plan is to equip each utility operations and service center with a portable automatic synchronizer. The equipment is so compact that it can be carried easily and installed quickly in the field at an ad hoc synchronizing location. Fig. 4 shows a portable automatic synchronizer. Fig. 5 shows the front panel LED indications and controls.

Fig. 4. Portable synchronizer.

The crew can take this assembly to the substation and connect it to the breaker's synchronizing VTs. The remaining connections are simple. Connect a 52A contact from the breaker to be controlled to the status input (simply connect across the red lamp if necessary). Connect the close command output to the close circuit.

Verifying the VT phasing and I/O connections is equally simple. The procedure to verify the connections and then synchronize is as follows:

1. Open the remote breaker to create a dead line.
2. Verify that BKR OPEN and DEAD VOLTAGE DETECTED LEDs are asserted.
3. Enable DEAD LINE CLOSE by pressing the pushbutton.
4. Close the breaker by pressing the INI 25A button and verify that the BKR CLOSED LED asserts. Now the bus- and line-side VTs are energized from the same system.
5. Press the PHASE TEST pushbutton to verify that the ANGLE IN WINDOW LED asserts.
6. Open the synchronizing breaker to de-energize the line.
7. Close the remote breaker to energize the line.
8. Initiate the autosynchronizing process by pressing the INI 25A button. The ACTIVE LED will blink.
9. Report INCOMING FREQUENCY HIGH, INCOMING FREQUENCY LOW, INCOMING VOLTAGE HIGH, and INCOMING VOLTAGE LOW indications to the control center.
10. Monitor the LCD display for slip and voltage difference magnitude.
11. Monitor any alarms. If necessary, abort the process by pressing the INI 25A button a second time.

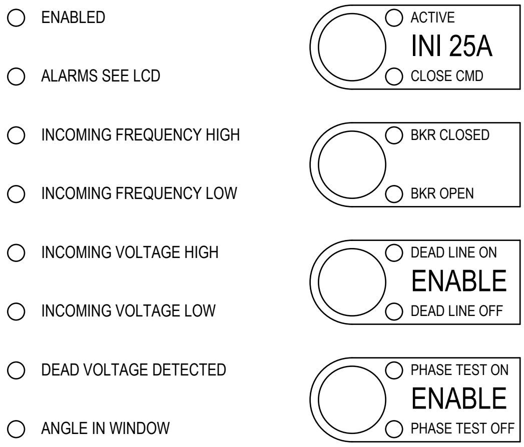

Fig. 5. Portable synchronizer controls and indications.

3.2.2 Drift synchronizer

Section 2.3.2 covered the fact that not all modern synchronism-check relays are created equal. If the standard line or breaker relays being installed include advanced synchronism-check functions, any breaker can be a potential point for synchronizing islands during grid restoration—even those without a synchroscope. The disaster recovery plan can identify which breakers on the transmission system include synchronism-check relays with direct slip measurement and slip compensated advanced angle close features. All that is necessary is to enable the slip function if it is not already enabled. Those without advanced synchronism-check relays can be targeted for upgrade at strategic locations.

In many cases, it may be difficult or impossible to control frequency and voltage on the power systems being restored. In these cases, the strategy may include so-called "drift synchronization." In this case, the objective is to wait until the slip and voltage difference between the two asynchronous power systems are at reasonably acceptable levels and close the breaker at zero degrees angle coincidence as the two systems drift together. This strategy is reasonable in situations where there is a lot of "rubber" in the system.

3.3 Remote synchronizing

With the separation of generation and transmission services providers, power plants and their associated transmission interconnection substations often now have separate owners. In many cases, independent power producers may locate the generation some distance from the transmission substation. To maximize the isolation between what were once integrated facilities, it is desirable to reduce the amount of interconnections running between the power plant and the substation yard.

Advanced automatic synchronizers that use a fiber-optic link are often a good solution. The A25A system shown in Fig. 3 has been applied in these cases. The generator can be synchronized by initiating the A25A located in the substation from the generator control room via the fiber-optic link.

This scheme eliminates the need for long runs of VT circuits between facilities, and concerns about ground potential differences and isolation between the dc battery systems of the two facilities are eliminated. In fact, these attributes make this system design attractive for any generator synchronizing application.

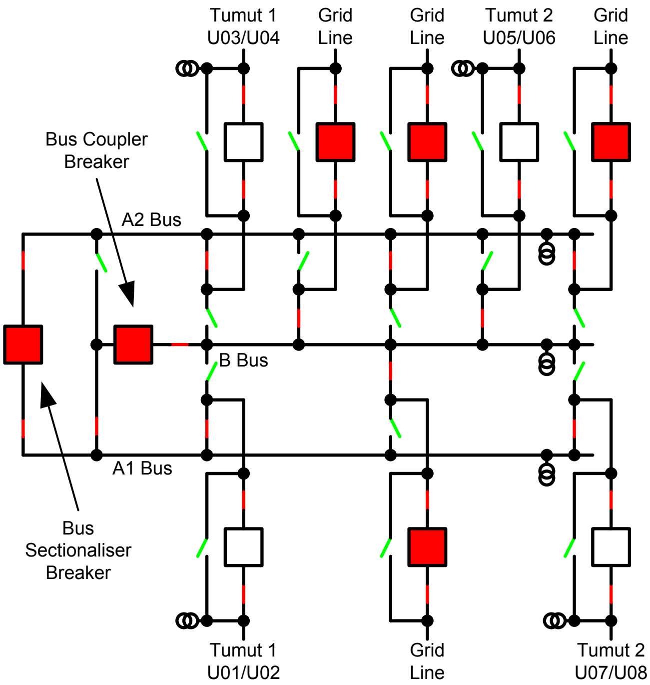

Fig. 6. Synchronizing with a complex switchable bus [8].

Reference [8] describes an application with a complex switchable bus arrangement and the requirement for remote synchronization. The substation connects the generators at two hydroelectric dams to the transmission grid. The system is shown in Fig. 6. The system specifications require that every generator be able to be synchronized via its line breaker, or bypassed to either the A bus or the B bus and synchronized via the bus sectionalizer breaker or the bus coupler breaker, respectively.

The system includes one A25A for each incoming generator line. Logic processors monitor the topology of the substation and provide this information to the A25A devices. Each A25A automatically determines which VTs to monitor and which breaker to close when the operators select a breaker for synchronizing.

4 Conclusion

Conventional synchronizing technology used for generator applications is not well-suited to the special requirements of microgrid synchronizing applications. Advanced synchronizing systems can easily solve the unique problems associated with microgrid applications and improve the reliability, costs, and even feasibility of difficult synchronizing challenges.

In many cases, if the user has selected relays with advanced synchronism-check features that include direct slip measurement and the slip compensated advanced angle close function, they may already have the capability of doing rudimentary synchronizing such as the discussed drift synchronizing system at ad hoc locations during disaster recovery.

The systems described in this paper have a well-established history of successful implementations and use proven, readily available equipment in novel ways.

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