Taming the electric grid

Continuous improvement of wide-area monitoring for enhanced grid stability

Albert Leirbukt, Ernst Scholtz, Sergiu Paduraru

Several catastrophic power blackouts during the last decade have exposed a need for early warning systems in the transmission system control centers. Network Manager™, ABB's solution for Supervisory Control and Data Acquisition (SCADA) and Energy Management Systems (EMS) has, since 2008, offered wide-area monitoring and a new set of tools to get full control of the grid, even when it extends over thousands of kilometers.

Advances in computing and communication technologies have led to sophisticated monitoring and control systems with capabilities far superior to even the most experienced operator. For instance, major car manufacturers now offer models with electronic stability control systems that override operator inputs. In the airline industry, intelligent flight control systems are being developed that enable even inexperienced pilots to safely land a heavily damaged plane. In the power transmission industry, the wide-area monitoring system (WAMS) is an example of such advanced technology gaining industry acceptance. Nowadays, transmission system operators (TSOs) must handle more power transfers with fewer transmission facilities than before, fewer available staff for transmission planning and operation, as well as aging transmission infrastructure and workforce. WAMS forms an important building block in supporting TSOs in their complex task and the increased request for their use has led to a series of performance improvements and new functionalities.

The wide-area monitoring system provides the present status of the grid to the transmission system operator.

What WAMS technology can provide
In AC power systems, all voltage and current time signals are ideally sinusoidal as shown in **1a**. In a wide spread grid with dispersed generation and consumption units, the magnitude and the phase of voltage and current signals are dissimilar in different locations. Conventional remote terminal units (RTUs) measure the magnitude but do not record the corresponding phase angle.

This phase angle contains invaluable information about the state of the grid and WAMS collect these additional data alongside the simple voltage and current values.

A WAMS consists of geographically dispersed phasor measurement units (PMUs) – delivering time-tagged mea-

surements to phasor data concentrators (PDCs), where desired signal handling occurs. Backed up with data from historical archives, the WAMS provides the present status of the grid via a human machine interfaces (HMI) to the operator at the TSO **3**.

PMUs are highly sophisticated intelligent electronic devices (IEDs). In addition to measuring frequency, voltage and current values, GPS synchronization enables them to directly measure voltage phase-angles between substations equipped with PMUs, allowing a fast system-wide health assessment. PMUs transmit phasor measurements at rates of up to once per cycle of the network frequency (eg, 60 times per second in a 60 Hz system).

Although PMUs provide sampled values at the same time instant, unfortunately their arrival at the PDC is stochastic due to the nature of Ethernet communication. Therefore, the PDC sorts the incoming time-tagged phasor measurements before subsequent signal processing.

Signal processing is required to convert the huge amounts of PMU data into actionable information that can be presented to an operator directly or through the SCADA/EMS so that the operator can take appropriate action. Such signal processing methods are often referred to as WAMS applications. A general overview of WAMS applications is found in [1].

WAMS application results are displayed in an HMI providing operators with critical information and warnings in real-time, either as an integral part

of the SCADA/EMS system, or as a standalone WAMS.

WAMS archives provide invaluable information during post-fault analyses of an event. These data contain information that helps to illustrate the overall transmission system response to a disturbance, providing better understanding of the system's dynamical behavior and also assists in the calibration of computer models in the system.

ABB have the most complete WAMS solutions available that can be tailored to the customer's needs to include PMUs and standalone systems integrated with Network Manager SCADA/EMS.

A broad portfolio of WAMS
ABB, as a pioneer in WAMS technology, have the most complete solutions for WAMS available, and can tailor design systems to the customer's individual needs.

ABB's WAMS portfolio includes PMUs, standalone systems, systems integrated with Network Manager SCADA/EMS, and customized applications.

PMU technology
In 2003, with its RES521 product, ABB released the benchmark in terms of quantity and quality of the phasor signal acquisition, while the PMU industrial standard was still being developed. In 2007, the RES521 was updat-

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1 Vector representation of AC voltage waveform at two hypothetical locations. One location at 260 V (magenta line) and another at 240 V (blue line).
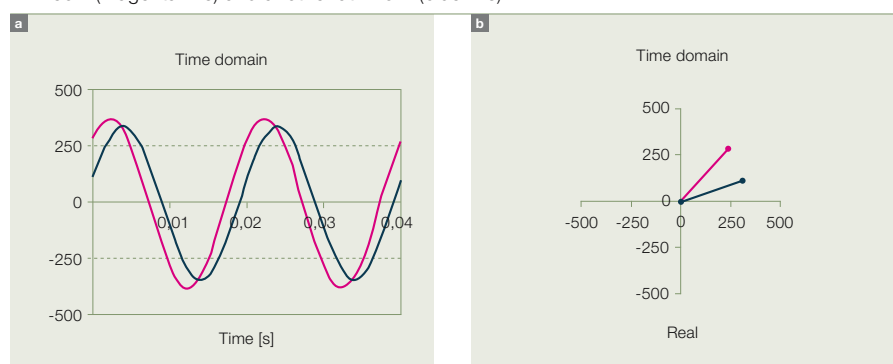
ed in order to comply with the finalized IEEE C37.118 communication protocol standard for synchro-phasors. Now the next generation ABB PMU is on its way. ABB is currently enhancing its new IED REx670 platform by adding PMU functionality, as well as accepting an increased number of analog and digital I/Os, flexibility in communications, including the IEC 61850 protocol, and more sophisticated WAMS functions, some of them presented herein.

Standalone WAMS
ABB's standalone product for WAMS, PSGuard, was the world's first product making use of PMU measurements. Based on the process control system 800xA, PSGuard provides HMI, PMU data acquisition, data storage and export functionality, alarming, WAMS applications, and connection to third-party SCADA systems. A communication gateway also enables real-time exchange of PMU data between TSOs. **2** shows the HMI for the installation in operation at Swissgrid, the TSO in Switzerland.

ABB's standalone product for WAMS, PSGuard, was the world's first product making use of PMU measurements.

Network Manager WAMS
ABB Network Manager SCADA/EMS offers a range of functions for energy systems operation: network control, SCADA systems with advanced applications for transmission, generation and distribution. These systems enable utilities to collect, store and analyze data from hundreds of thousands of data points in national and regional networks. ABB's Network Manager has also incorporated WAMS. Now, SCADA measurements can contain both conventional RTU and WAMS information, as well as WAMS related alarms and indicators included in the
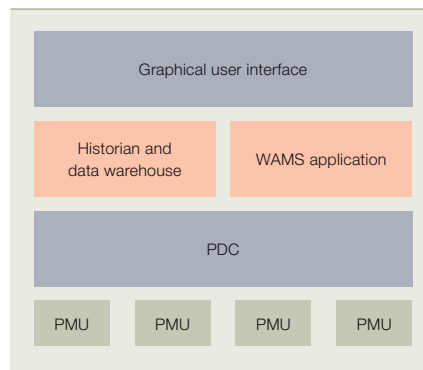
**2** Standalone WAMS installation for "Swissgrid"
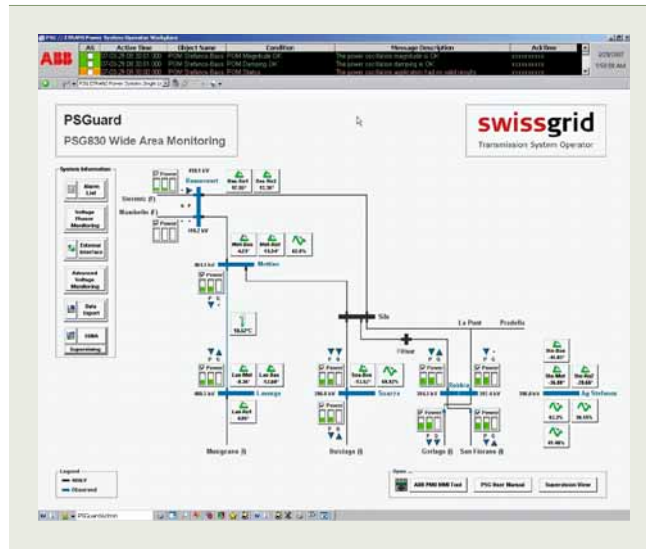
SCADA/EMS alarm list. Moreover, the EMS can be enhanced with the capacity to make use of WAMS in the state estimation process for improved accuracy.

The standard communication front-end system for Network Manager, PCU400, has been enhanced with PDC

3 Generic WAMS configuration

4 Network Manager with integral WAMS capability
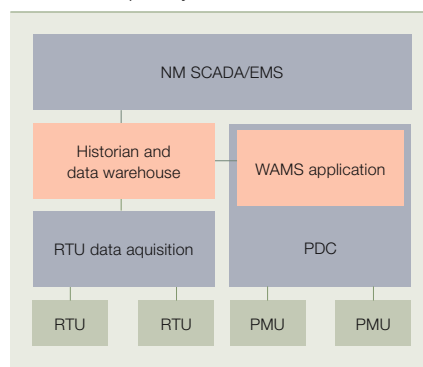
capability to receive and synchronize PMU measurements, and to execute WAMS applications. To enable future wide-area control applications, it can also communicate with ABB's MACH2™ control system used for controlling FACTS and HVDC systems **4**.

WAMS Applications
ABB's modular design of WAMS applications gives the customer the options to execute WAMS applications either within the PMU hardware, the PDC, or at the central control unit. This ensures an optimal design in terms of communication and CPU load. The list of currently available WAMS applications include:

- Phase Angle Monitoring (PAM) – disturbances can be detected by monitoring the phase-angle relations between strategically chosen substations, even if they occur outside the TSO's region.
- Line Thermal Monitoring (LTM) – estimates the average line conductor temperature based on phasor measurements from both ends of a transmission line. It is installed at Swissgrid in Switzerland and the electricity company Verbund-Austrian Power Grid AG (APG) in Austria, and is further described in [2].
- Voltage stability monitoring (VSM) – assesses the voltage stability of an important power transfer corridor in real-time using only phasor measurements from both ends of the corridor. It is installed at the electricity company Hrvatska Elektroprivreda (HEP) in Croatia.
- Event driven data archiving (EDDA) – detects system disturbances and records the system-wide WAMS responses for a certain period of time prior to, during and after the event.
- Power oscillation monitoring (POM) – alerts operators when power oscillations occur in their transmission grid.
- PMU assisted state estimator (PMUinSE) – network manager's state estimator can make use of PMU data for improved state estimate accuracy.

The two latter applications, POM and PMUinSE, are two of the most contemporary WAMS applications [3].

POM: identifying stability threats

Power oscillations are well known phenomena in power systems. They occur when individual generators, or clusters of generators, interact with each other through the transmission system.

Typically, several such interactions exist, and therefore power oscillations may exhibit several modes each having a distinct frequency. Systems characterized by long-radial lines with remote generation far from load centers are particularly vulnerable to oscillations. Power oscillations are not a concern if they are small and decay quickly. However, sustained or growing oscillations require prompt operator attention.

ABB's Network Manager SCADA/EMS offers a range of functions for energy systems operation: network control, SCADA systems with advanced applications for transmission, generation and distribution.

Existing SCADA systems lack the time resolution to reveal power oscillations in real-time, however with the high resolution measurements provided by WAMS, such oscillations can be exposed with proper signal processing.

The POM application is a patented approach that detects and identifies power oscillations. It can distinguish between individual dominating modes present in an oscillation and focus only on those representing a concern. As an illustration, consider the hypo-

5 Power oscillation comprising multiple modes. The red curve represents the measured power oscillations (left scale). m1, m2, and m3 show the oscillatory modes in the measured signal (right scale).
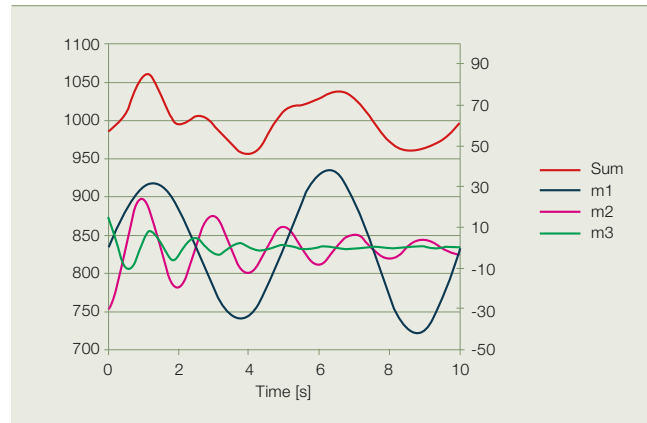
6 Improvements in state estimation with the number of PMU measurements. (Experiments conducted on a 39 bus system.)
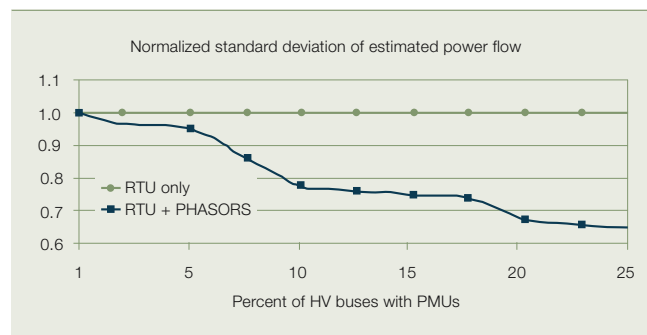
thetical power oscillation shown in 5 (red curve). With this information alone it is difficult to judge whether this situation represents a concern. However, the POM application can identify the individual modes present, revealing that in fact three oscillatory modes, m1, m2 and m3 are active. Moreover, mode m1 is increasing and requires prompt operator attention. The ability to provide such information in real-time is a breakthrough in stability monitoring. The POM application is a commercial product installed in several grids worldwide (eg, Electricity Generating Authority of Thailand (EGAT) in Thailand, the TSO Fingrid in Finland, the electricity company Hrvatska Elektroprivreda (HEP) in Croatia, TSO Swissgrid in Switzerland, and TSO Statnett in Norway). Further details on the methodology can be found in [4] [5].

PMU assisted State Estimator

SCADA measurements of voltage and current provide a system operator

with a static snapshot view of the status of a system. However, these measurements frequently exhibit errors (eg, measurement bias, telemetry errors), and state estimators (SEs) are used to find the best statistical fit of bus voltages to the SCADA measurements and the model of the network. The SE is the heart of the EMS and every improvement of SE will benefit all aspects of the EMS (such as contingency analysis, and power market operation). Integration of the accurate PMU measurements into Network Manager by augmenting the real-time database to accept voltage and current phasors, allows ABB to offer a more accurate SE. The technical details of this extension to a SE are discussed in [6].

6 illustrates that the accuracy of the SE improves as the level of PMU penetration into the network increases. The existing level of penetration in practical transmission networks is still fairly low, but in the next five to ten years we expect that this level will significantly increase as existing measurement IEDs are retrofitted with PMU capabilities, in conjunction with installation of new PMUs in the system. It is very likely that the integration of phasor measurements into state estimation will become the norm in the near future.

ABB WAMS references

ABB has a proven track record with PMUs and their use in applications, with more than 200 RES521 PMUs installed worldwide, and WAMS installations in Austria (APG), Croatia (HEP), Finland (Fingrid), Norway (Statnett), Switzerland (swissgrid) and Thailand (EGAT). The European installations also exchange selective PMU data in real-time via communication gateways 7. The data are used to monitor power oscillations and voltage phase-angle differences Europe-wide.

The first pilot for WAMS integrated with Network Manager has been run-

ning at the Norwegian TSO (Statnett) since 2007, where PMUs are installed at four different substations, as shown in ⑨. In addition, PMU measurements from Finland are collected via the communication gateway running at Fingrid. The PDC at Statnett applies POM analysis of the power flow on the lines emanating from the Hasle substation towards Sweden. Using National Instruments Labview software, Statnett have also developed their own analysis application to simultaneously access SCADA, WAMS and transient fault recorder data, providing a very powerful tool for post fault analyses. Further details on the Network Manager WAMS pilot at Statnett can be found in [7].
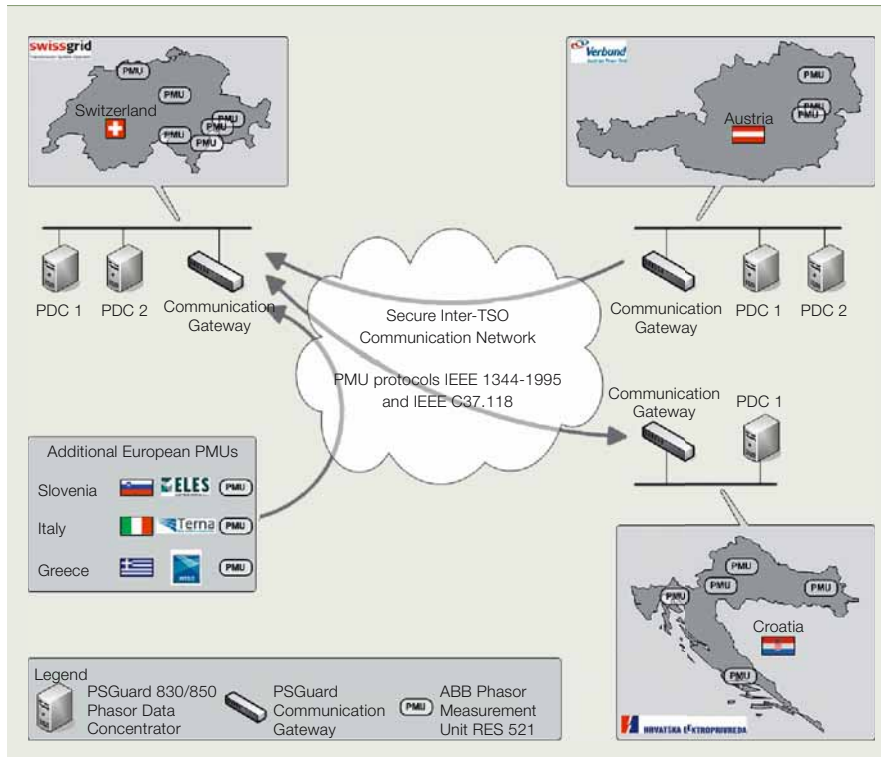
In Europe, the SmartGrids initiative is developing a road map to deploy the electricity networks of the future, and WAMS is one of the key technologies considered.

Oscillation incident
A very illustrative case of power oscillations was recorded by the WAMS in operation at Statnett on August 14, 2007. On this day, a combination of line outage and unfavorable generation dispatch led to sustained power oscillations in the Norwegian transmission system. The corresponding POM signals are shown in ⑧. ⑧a shows the measured power flow from Norway to Sweden. The frequency of the most significant oscillatory mode detected is shown in ⑧c. It shows that the 0.5 Hz mode, which is a well known characteristic mode for the Nordic power system, has been excited and is dominant in the signal. ⑧b shows the amplitude of this mode. The amplitude increases drastically, approximately 35 seconds into the sequence, when the oscillations appeared. The damping of this mode is shown in ⑧d, and drops from a satisfactory value to a negative value, then stays very low while the oscillations are present. The POM output signals can be combined in SCADA to generate simple operator signaling when oscillations appear.

It is also worth noting that even though the cause of the power oscillations was in a location approximately midway between the Fardal and Nedre Røssåga stations, ie, quite far away from the southern interface to Sweden, they are easily seen by the POM application. The stability of the entire grid can therefore be observed by strategic deployment of PMUs and POM applications monitoring key substations. A more detailed discussion of this event can be found in [8].

7 WAMS data exchange in Europe

8 POM responses to August 14, 2007 power oscillation event.
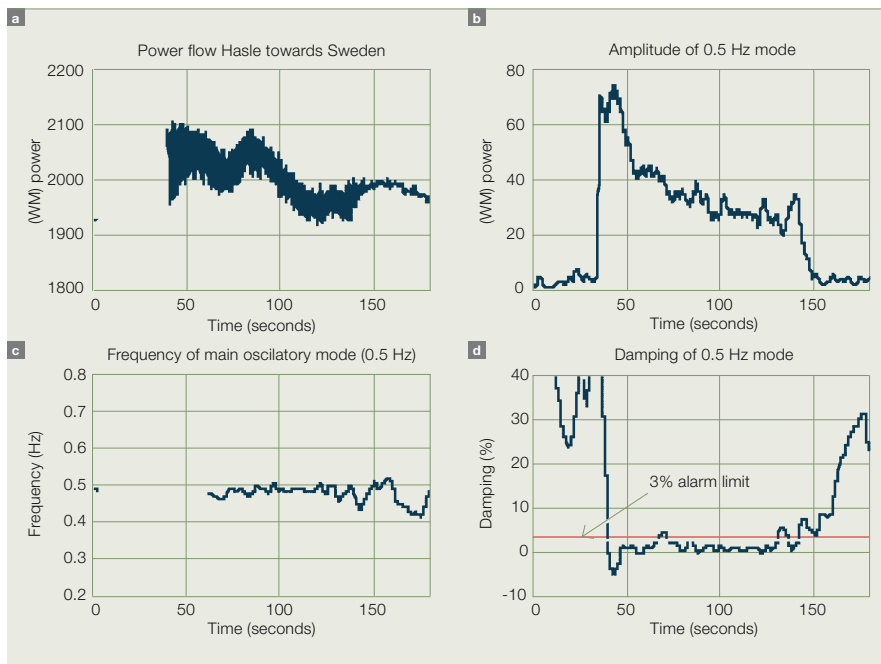
The way forward

The industry has started to realize the benefits and hence started to embrace WAMS technology. Thus, there is still tremendous development potential in the use of synchronized measurements in electric transmission system operation. Several ongoing broad initiatives will help to advance this technology. In Europe, the SmartGrids initiative is developing a roadmap to deploy the electricity networks of the future, and WAMS is one of the key technologies considered. In the U.S., the Electric Power Research Institute (EPRI) runs an initiative aiming to provide a technical foundation to enable massive deployment of such concepts (Intelligrid). The North American Synchro-phasor Initiative (NASPI) is another U.S. led initiative that aims to increase the deployment of WAMS and accelerate the development of new applications in order to improve operational reliability.

ABB's complete portfolio offers PMUs, PDCs, and WAMS both integrated with Network Manager SCADA, standalone systems or solutions integrated with third-party SCADA systems.

ABB have long been pioneers in the WAMS arena, and are committed through continued research and development to push the envelope of technologies, such as WAMS, that can facilitate enhanced monitoring and control of electric transmission systems. Due to this early and ongoing commitment, ABB offers the most complete portfolio, providing PMUs, PDCs and WAMS – all integrated with Network Manager SCADA – as well as standalone systems, and solutions integrated with third-party SCADA systems.

8 PMU substations
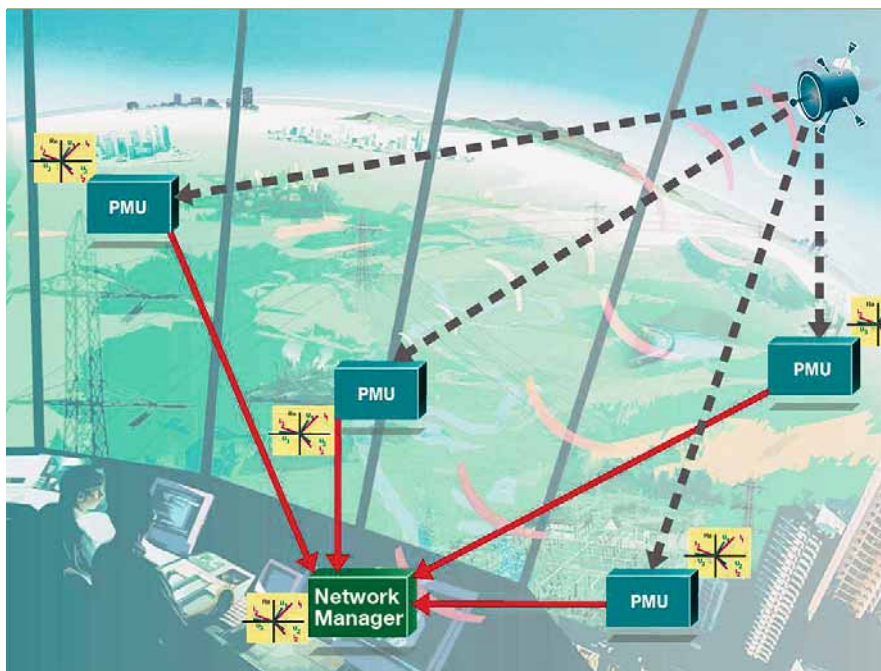
Albert Leirbukt
ABB Power Systems
Oslo, Norway
albert.leirbukt@no.abb.com

Ernst Scholtz
ABB Corporate Research
Raleigh, NC, USA
ernst.scholtz@us.abb.com

Sergiu Paduraru
ABB Power Systems
Västeras, Sweden
sergiu.paduraru@se.abb.com

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