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Unified Grid Control Platform Concept

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ABSTRACT

An emerging generation of technology reaches beyond the familiar configurations of protective relays and substation intelligent electronic devices. Contemporary topics in the technical literature may include Ethernet local and wide-area networking, functional elements and nodes in the IEC 61850 communications and modeling standard, virtualized functions, digital twins, and generic computing platforms. Another emerging topic is holistic grid-wide observation or protection functions based on measurements with microsecond- or nanosecond-precision time synchronization.

Each of these concepts may seem to serve a particular area of user need or to support the innovative value of a vendor’s particular new product. However, they also show how the equipment installed in substations is taking advantage of communications, computing, software, and tool technology evolution. These advances deliver new functionality or reduce the cost of increasingly capable products. These products provide new capabilities that aid to address various technical challenges the electric power industry faces. While many new topics appear disjointed, a broad view of them shows how the industry is evolving towards a cohesive new architecture for system protection and control. This architecture helps address grid operating challenges, including sustainability and security.

This paper assembles an array of these new concepts in a holistic architecture and functional solution. This solution addresses not only electrical protection and operations, but also business enterprise operations and management. Engineers and managers who understand and embrace this holistic roadmap are well positioned to specify new projects. In turn, these projects can broadly benefit the utility. They can help the utility maintain its infrastructure and organization on a sustainable path in times of rapid change. Individuals that grasp this vision are likely to support research, development, and new product advances to move towards this architecture and solution.

Keywords

IEC 61850
Power system automation
Power system control
Power system protection
Substations

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1 DRIVERS FOR A NEW UNIFIED GRID CONTROL INFRASTRUCTURE

Regulatory requirements to reduce greenhouse gas (GHG) emissions drive transform of the electric grid to renewable and carbon-free energy sources. Most of the new renewable energy production comprises large numbers of smaller installations distributed across transmission and distribution (T&D) grids, and at utility customer sites. In parallel, transportation and other industry sectors are gradually moving toward electrification. The number of new distributed energy resources (DER), along with new interfaces and facilities, is increasing system operation and protection complexities. The difficulty of dispatching DER reduces the controllability of energy flows and places difficult-to-predict demands on electric energy storage. Despite these uncertainties, consumers, regulators, and government agencies still demand higher service reliability, grid resiliency, and utility worker and public safety.

This drives the need to monitor and control the interaction of granular energy resources with the regional grid and new categories of loads and consumers. An evolution of protection, automation, and control (PAC) system architectures can make the power grid more adaptable, flexible, resilient, and sustainable. Conversely, existing fixed-function PAC systems are less likely to meet these needs.

In addition, the physical and electrical operating characteristics of DER differ from legacy generation. As a result, they call for new protection and control methods. Fossil-fueled turbine-generators provide rotational inertia. They can also provide robust short-circuit current during system faults to initiate protective relay tripping. By contrast, DER using power electronic inverters have no inertia; they can only deliver rated current during a disturbance or fault. Disturbances can trigger sudden excursions of voltage and current that can lead to loss of stability and blackouts. In some cases, recoverable grid disturbances have caused large arrays of DER inverters to shut down. This can lead to a sudden reduction in energy supply. Protecting a grid with high DER penetration calls for a transition from traditional indicators of stability like frequency to direct monitoring and holistic analysis. Voltages and currents need to be gathered at high speed across the impacted region, enabling rapid control to maintain stable operation.

Today's ubiquitous PAC infrastructure with its point-solution products are unlikely to adequately address these issues due to financial, asset management, and human resources constraints. Alternatively, the industry can conceive and build sustainable and affordable new PAC systems. To do this, the industry can adapt the rapidly advancing information technology (IT), computing, and analytic processing techniques that are transforming other major industries. Many of the latest utility grid functional concepts and solutions can be integrated with broad and fast-moving industrial and business automation and information technologies. This can help the industry reach a more sustainable and flexible, adaptable infrastructure using a unified grid control platform (UGCP) for PAC, monitoring, and management. UGCP is comprised of a decentralized, integrated, cloud-like array of redundant standardized data processing and storage elements. In UGCP, these elements are interconnected with highly reliable, cybersecure data communications. UGCP enables the utility enterprise to:

- Adapt functional behavior quickly and holistically across the grid for new operating requirements
- Operate a reliable, redundant, resilient, maintainable, and sustainable architecture of computing and communications
- Leverage emerging operational technology (OT) and IT networking solutions for scalable high-performance integration of digital substations over wide areas
- Simplify substation life-cycle maintenance with proven IT-based tools for centralized management of communications and computing environments
- Expand cybersecurity capabilities to counter evolving threats, with a single unified and manageable strategy
- Comply with current and emerging North American Electric Reliability Corporation (NERC) Critical Infrastructure Protection (CIP) requirements

This paper describes how UGCP concepts and elements under development today can fit into a comprehensive architecture of reliable computing and data communications that meets these needs.

2 EXISTING PAC ARCHITECTURE

Most of today's technical systems for transmission or distribution grid PAC have evolved from practices invented at the outset of the electric age. Panels and racks of dedicated single-function or single-purpose units like protective relays or local apparatus controllers are wired to power system apparatus. These arrangements consist of thousands of point connections between control building panels and the switchyard.

SCADA and EMS. Centralized supervisory control and data acquisition (SCADA) systems and energy management systems (EMS) help power system operators monitor and control entire grids. Remote terminal units (RTUs) in substations acquire the specialized data needed. Wide-area communications capacity limits the ability to gather information. Some utility operating organizations and their software suppliers are currently working on distributed energy resource management systems (DERMS). However, these systems act as a separate overlay with legacy grid operations.

Protective relaying systems. Custom-designed, individually set, redundant, fixed-function relaying systems handle fault protection and system stability protection. These systems' operating methods have been based on predictable power and fault current flows fed from large rotating machinery with high inertia and high fault current delivery. These relays are becoming more complex, and more difficult to configure and set. They are also limited in their ability to add new functions for evolving protection requirements. Updating functions or correcting programming errors has required on-site service and recommissioning. The unavailability at the substation level of a holistic live set of system measurements and states limits protection schemes.

Reliability and maintenance. Maintenance of PAC infrastructure has consisted of repair of failures or problems when observed. Some hidden failures are also discovered via time-based testing and inspection. Many failures are only discovered when a grid disturbance triggers a protection system misoperation or a customer outage. Overall configuration, maintenance, and reliability management has required costly dedicated human resources and tools. A limited group of utilities are only now considering monitoring and condition-based maintenance programs.

Asset management. Detailed information on the state of assets or operations has been difficult to gather or share across the enterprise. Some information gathering has required costly single-purpose add-on systems for observation or tracking. The industry is slowly progressing towards gathering of equipment and process data in efficient single streams. This data can then be shared among various enterprise and operational users.

Overall operational and business management. Enterprise management functions include asset management, event analysis, planning analysis, capital planning, maintenance management, and business management. Today, unique, costly software and hardware systems handle these functions. Each system is typically isolated from the others. As a result, each system requires hand-built linkages or human evaluation of the PAC and power system assets. Special-purpose systems independently monitor limited and isolated bodies of asset condition or site surveillance information.

3 UGCP SUBSTATION ARCHITECTURE

The new substation architecture, UGCP, is grid-wide, encompassing the following:

- Large facilities. UGCP supports large transmission substations and large generation plants.
- Small nodes. UGCP supports substations serving a specific facility, as well as distributed or small generation facilities tied to the transmission or distribution system.
- Customer sites. UGCP supports a substation at the point of interconnection to the grid, as well as substations within large industrial plants.

UGCP is best explained by initially focusing on its substation node level. Figure 1 shows the UGCP architecture for PAC infrastructure in a substation. UGCP shares key design concepts with those embodied in the latest editions of the IEC 61850 standards.

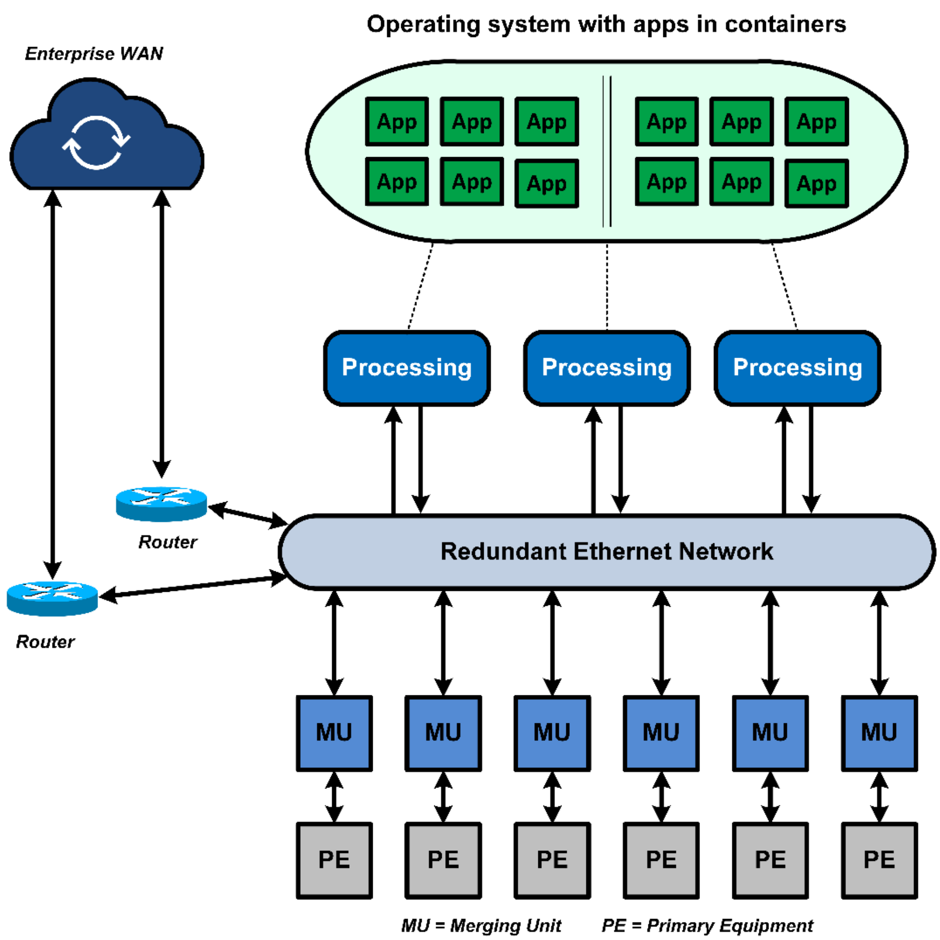

Figure 1. UGCP substation architecture

The primary equipment (PE) in substations includes current transformers, voltage transformers, circuit breaker and switch status and alarm contacts, trip-and-close control circuits, and other types of equipment. Most merging units (MUs) are installed in switchyard cabinets and wired to the PE. (In some cases, MUs are integrated into a circuit breaker or transformer, for example, at the factory to reduce field installation labor.) MUs are local electronic modules that gather and digitize measurements and point states at each switchyard location. The MUs then transmit this data on a single optical fiber from each of many apparatus locations through an Ethernet network to a processing array ("processing" in Figure 1). The communication is bidirectional, as shown by the double arrows and two-directional arrows. Standardized substation PAC functions (called "Apps" at the top of the diagram) can send tripping or control commands back through the Ethernet network and MUs to the PEs via return optical fibers. The apps include protective relaying functions for transmission lines, substation buses, transformers, and circuit breakers; metering; historical tracking of events; voltage or var control of load tap changer or power electronic volt/var compensators; local operator or remote-control center reporting and control via SCADA; and others.

The Ethernet network and processing arrays can be centralized in a control building or distributed in smaller replaceable structures or modules. Network reliability for this system is based on today's redundancy and security technologies, such as parallel redundancy protocol (PRP) dual Ethernet network links, looped redundancy, or software-defined networking (SDN). UGCP can also incorporate high-reliability networking technologies now arising in business and industrial applications.

The substation network on the right side of Figure 1 connects through the two redundant routers and two redundant communications paths to utility operational and enterprise wide-area networks ("enterprise WAN" on the left side of the diagram). Various host processing tasks are performed in the cloud. These are not shown in Figure 1, but are illustrated and described below in Figure 2.

In the UGCP architecture, there are no *fixed-function* relays or intelligent electronic devices (IEDs). The "processing" units in Figure 1 feature operating systems (OSs) that support virtual computing machines. Each virtual machine (VM) can run groups of apps as if each app had its own computing hardware. The apps can be isolated (placed in a separate container) so they can communicate with other apps only via network communications. This enables what is called "functional containerization" of the apps. The functional containers can be flexibly deployed across the "processing" units. This means, for example, that OS containers or apps can be placed to optimize reliability, processing workload, failure resilience, and practical maintenance and updating sequences. Combined with use of redundant hardware, this enables the commissioning of new or updated apps or hardware without disabling existing apps or hardware. Hardware elements—processors, networking equipment, and MUs—can be safely upgraded or replaced without outages of primary equipment or grid operating limitations. Upgradability is supported by a new physical installation design that enables practical, safe, and easy apps and equipment replacements without outages.

4 UGCP WIDE-AREA SYSTEM INTEGRATION ARCHITECTURE

While Figure 1 shows the UGCP architecture in a single substation, the bottom of Figure 2 shows an array of three substations. In practice, the number of substations connected in this way can be very large. The array of substations and grid nodes exchange information with a distributed and WAN-based processing infrastructure like that shown in the top of Figure 2. Note that this figure provides more detail on the same "Enterprise WAN" shown in Figure 1. Figure 2 includes key samples of various enterprise functions, which are described below.

The enterprise functions are distributed across the WAN, without the need to be concentrated at a specific physical location. The enterprise functions enable redundancy, maintainability, and flexible deployment of applications with little or no disturbance to operations or business and management processes. This is similar to the approach described earlier for substation systems. Resiliency is enhanced by configuring redundant data center and data communications facilities in the Enterprise WAN and enterprise functions.

The UGCP platform includes a redundant, high-reliability system for distribution of precise time (accurate to less than 1 microsecond) across the WAN. Emerging synchronized measurement and analysis functions need this precise time capability to eliminate dependence on vulnerable global network satellite system (GNSS) time references. The precision time can be synchronized to a GNSS external standard when available. However, the entire UGCP can operate coherently without that external standard.

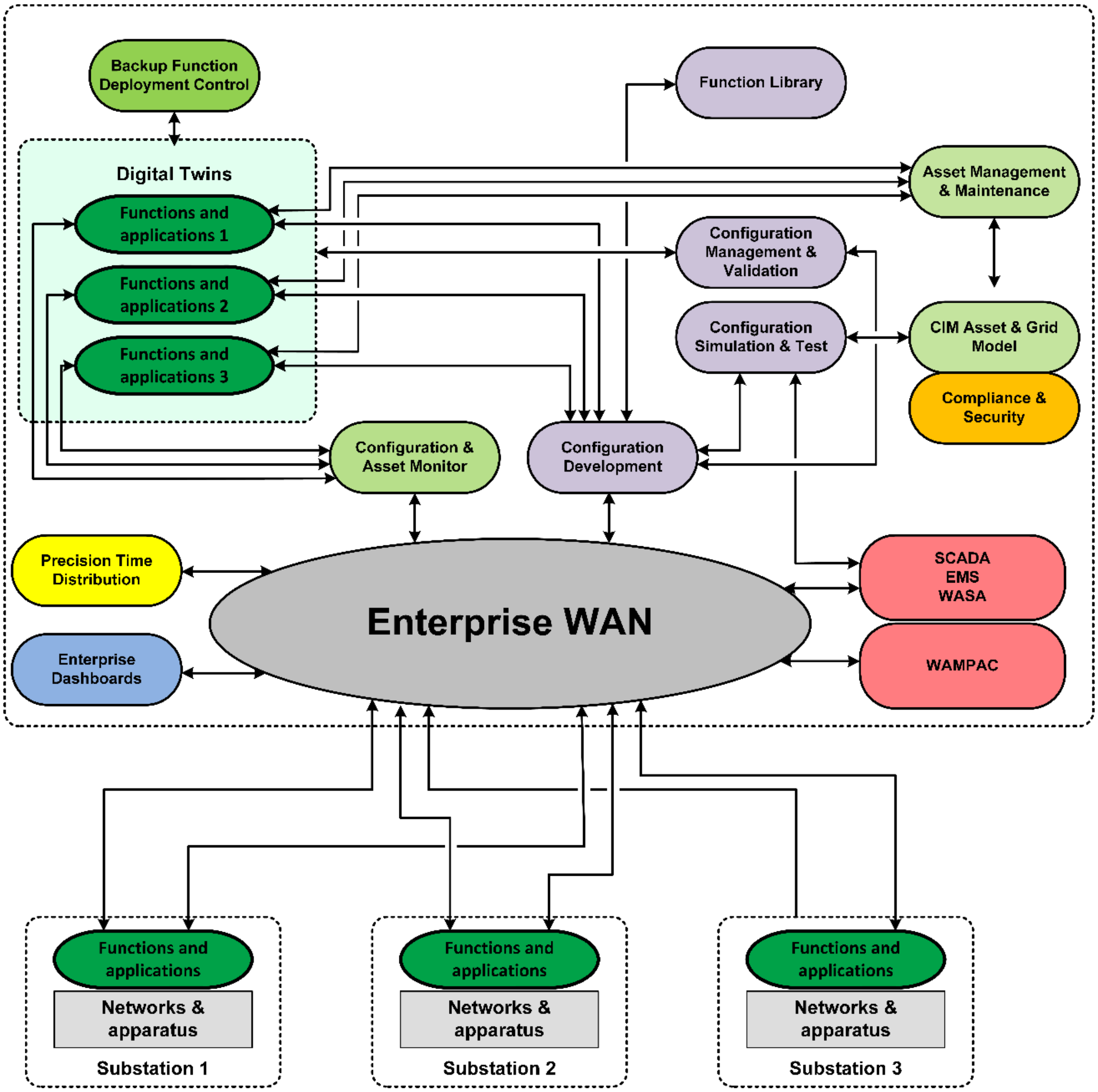

Figure 2. UGCP wide-area system configuration

5 UGCP ENTERPRISE FUNCTIONS

The key enterprise functions in Figure 2 are as follows:

- **The enterprise WAN** is a redundant, resilient operational and enterprise cloud communications infrastructure. It incorporates operational monitoring, management, and security functions. Mission-critical UGCP functions for PAC require multiple layers of redundant paths and equipment. In the enterprise WAN, network components like multiprotocol label switching (MPLS) or software-defined WAN (SD-WAN) routers support dispatching of many communications paths for multiple layers of failure or outage resilience. The network infrastructure in the enterprise WAN can also integrate or segregate operational versus enterprise business communications. This helps meet the needs of a utility plan for OT-IT integration, as opposed to segregation. The management security module in the enterprise WAN detects abnormal traffic patterns and defects. It can also define baseline traffic and define acceptable traffic as with SD-WAN.
- **A configuration and asset monitoring** process exchanges real-time information on the status of apps and PAC equipment with the substation. This process tracks elements in normal operation, as opposed to those in backup or workaround modes.
- **Digital twins** are a set of modular virtual models that serve as mirror images of the actual power system equipment elements and topology. The twin models include the PAC, monitoring, and management app configuration in each substation and across the grid.
- **Backup function deployment control** interacts with each grid node or wide-area PAC function and its digital twin status. It determines what preconfigured alternative or backup operating configurations are deployed, based on failures, malfunctions, operational decisions, and control center requests.
- **Configuration development facilities** are used by engineers and managers offline to assemble new app configurations. These personnel can also use these facilities to insert new or updated apps from a managed library in an operating substation or wide-area configuration. They can:
  - Test new configurations in a development environment
  - Validate operation of the new configuration using the digital twin grid models in a separate test environment
  - Download and start the production configuration in the substation system or wide-area configuration with a sequence that maintains real-time operation of all functions

  This process uses the inherent redundancy of the UGCP to update operating app configurations without outages or disruptions of grid operations.
- **The function library** supports the configuration development facilities with managed and version-controlled arrays of all available apps. This includes both in-service apps and newly introduced apps for functional updates.

- **Configuration simulation and test** is an offline environment for experimentation and validation of changes to app configuration. This includes real-time simulations of situations and events based on the digital twin grid model, its present or extreme operating states, and historical events.
- **Configuration management and validation** is a function that ties the operating configurations of substations, grid nodes, and wide-area functions to their digital twin representations, validation test configurations, and backup adaptations. This helps to track deployed and historical versions.
- **Asset management and maintenance** is a functional grouping that tracks all power system and UGCP infrastructure. The tracking is based on the history and on real-time condition or failure inputs processed through the digital twins function. This function can:
  - Dispatch reconfigurations
  - Trigger subject matter expert (SME) analysis or truck rolls to repair or replace failed items
  - Feed evolving-situation parameters to the master grid and asset model
- **Common Information Model (CIM) asset and grid model** is a function that maintains a database for the condition, history, and change plans for all grid and UGCP assets using the CIM (see below for more on the CIM). This information can be used for asset management, updating, and replacement. It contains the relationships and ratings of all elements to support validation of app configurations.
- **Compliance and security** is an element that monitors the relationships and limitations imposed by operational or regulatory restrictions. This supports development of app configurations and settings that comply with all requirements and limits. Contingency simulations and tests are needed to support some compliance checks. This module includes application-layer traffic monitoring and application-based anomaly detection of security intrusions. It then dispatches security actions to mitigate disruption events.
- **SCADA-EMS-WASA** are grid monitoring and control functions for the grid control center. UGCP supports redundancy and separation of these functions. The SCADA system comprises the first-tier observation of grid operating state and measurements. It also tracks control and mitigation actions in human-operator time frames. The EMS adds an application layer of analysis, dispatching, optimization, contingency study, operational planning, and support of separate energy market functions. Wide-area situational awareness (WASA) functions overlay the SCADA data with high-speed synchronized measurement-based displays and analyses. Parameters include voltage profile, real and reactive power flow dynamics, grid stability, and parameters that can evolve in faster than human-observation time frames.
- **WAMPAC** is wide-area monitoring, protection, and control. It includes holistic wide-area protective relaying schemes using synchronized measurements and high-speed wide-area control to accomplish the following:
  - Tripping for backup fault protection [1,2]

- Grid angular or voltage instability protection
- Closed-loop holistic voltage profile control or energy flow control
- Remedial action or system integrity protection schemes

These new protection concepts can help ensure fast and selective fault protection. This is needed to address dynamically changing generation mixes, including inverter-based resources (IBR), that characterize the emerging zero-carbon grid and challenge many of today's relaying methods.

- **Enterprise dashboards** are business applications and overall utility enterprise management functions. They can access all raw or processed information on states, events, and situations. They deliver flexible displays to help meet the needs of specific organizational stakeholders or leaders.
- **Precision time distribution** is a set of components that maintain, coordinate, deliver, and monitor reference time flow for the entire UGCP infrastructure with sub-microsecond precision. It uses the Ethernet network precision time protocol (PTP) and its future evolutions. Precision time data supports synchronized wide-area measurements that WASA and WAMPAC need. It also supports event analysis and grid management. Precision time service is a core requirement for emerging grid-wide IT-OT communications infrastructure. When utility IT departments do not implement this service, enterprise users need to use global positioning satellite (GPS) or GNSS satellite timing. However, redundant grid-relative timing independent of vulnerable outside sources is needed for emerging utility OT systems.

6 INTEGRATING TODAY'S ELECTRIC UTILITY TECHNOLOGIES INTO UGCP

Industry experts and supplier teams working today are developing advances that support UGCP. These can be grouped into the three categories of standards, infrastructure, and models and tools.

Standards

IEC 61850. The international standard IEC 61850 is entitled "Communication Networks and Systems for Power Utility Automation." The standard details the specifics for integration of PAC functions. It does this via standardized interface models of programmed functional nodes (that is, logical nodes) in generic processing environments. The standard also addresses the exchange of standard data objects via Ethernet messaging packets. The IEC 61850 structure supports flexible location of functions in a computing and data sharing platform like UGCP. It enables creation of cloud-based digital twins for the real-time functional array, as well as function-level configuration processes for complete PAC systems. These capabilities are required for practical integration of fine-grained DER and monitored loads such as transportation nodes. The alternative of manual configuration and maintenance of such large interconnected systems would require large amounts of unproductive work.

CIM. The IEC standard Common Information Model (CIM; IEC 61968, and related standard parts) is a platform for hierarchical and relational recording and management of the properties of all grid assets, including UGCP assets.

Infrastructure

Deployment of LAN and WAN infrastructure. Utilities have been increasingly using Ethernet local area network (LAN) and WAN technology, including the latest transport technologies like MPLS and SD-WAN. Collaboration is improving between IT experts and application domain experts for mission-critical grid monitoring, control, protection, and operations.

Synchronized measurements and applications. Utilities have been aggressively deploying phasor measurement units (PMUs) for precise synchronized measurements. This supports high-rate WASA presentation to operators, with selected WAMPAC functions deployed and others in development. In UGCP, the synchronized measurements are gathered from processing of synchronized MU measurements at low marginal cost, rather than from a stand-alone network of PMUs.

Models and Tools

Models and tools. Utilities already use various sophisticated tools to model the electrical behavior of the grid. These include operational modeling, three-phase fault analysis, dynamic performance modeling, and wideband transient behavior simulation. Industry initiative on unified modeling are working to integrate these into a single-source modeling toolset. However, progress is slow, and practical development is ongoing.

Real-time and HIL testing. The electric power industry has developed impressive capabilities for real-time transient modeling for hardware-in-the loop (HIL) testing of PAC hardware devices and their programmed functionality. This can be integrated within UGCP in the near term. Over time, functions will be implemented on standard platforms, rather than in specialized boxes. Ultimately, this will transition all testing into the modeling domain and reduce the need for routine operational HIL testing of equipment.

Emerging DER and grid control solutions. Various real-time functions are in ongoing development to help utilities meet the needs of increasing penetration of DER, loss of grid inertia as inverters replace rotating machines, or other new operating stresses. New DERMS are in development and demonstration.

Data management and analytic applications. Vendors are also developing new large-scale data management repositories, analytic and modeling tools, and operational applications. Many of these will be adapted as functional modules in new UGCP deployments.

7 INTEGRATING TODAY'S IT AND BUSINESS TECHNOLOGIES INTO UGCP

Developers of the overarching UGCP architecture can integrate and adapt elements from business operations. These elements can be grouped into two categories: cloud, standardization, and containerization; and network management.

Cloud, Standardization, and Containerization

- **Cloud services**. Today's business operations are based on a monitored and managed network of data centers and communications systems. These systems are dynamically and securely assigned to applications as needed. They systems include mission-critical high-speed financial and network operational services and military operations. The systems enable application experts to focus only on the functions of the applications themselves, rather than on computing or data transmission needs.
- **Containerization and isolation**. Cloud services are based on secure and managed partition of users and applications. This eliminates cross-impact or cross-access among users and functions. Individual apps can be managed and updated, while other mission-critical functions continue to operate.
- **Arrays of standard computers and operating systems**. Real-time OSs are evolving to support containerized applications. These consist of arrays of general-purpose processing hardware. Examples of these are flexibly configured racks of blade servers in data centers, serving other mission-critical industries.

Network Management

- **Network and computing redundancy**. Today's networks support configuration of application containers and infrastructure to avoid failures for any plausible set of contingencies. Today, robust configurations are implemented and managed in the cloud for mission-critical applications in other industries.
- **Distributed and remote network management and security tools**. Operation of the WAN is managed with sophisticated monitoring tools. These tools:
  - Track and report path or component performance
  - Monitor redundant services
  - Redeploy paths and functions to work around failures
  - Contain traffic abnormalities or security breaches
- **Big-data processing platforms, analytic tools, artificial intelligence (AI) tools, and dashboard tools**. A host of user-configurable processing tools support the functions of the technical operations center concept described in the next section.

8 FEATURES OF THE UGCP ARCHITECTURE

UGCP is built largely on IT world computing, communications, OS, containerization, and remote updating/management elements. Large-scale use of these across the industry brings flexibility and cost reductions, compared to custom-designed hardware packages with custom programming. This UGCP approach departs from the model of single-zone or single-function IEDs. Instead, it moves towards platforms with a standard array of sensors, communications paths, and user interfaces. In UGCP, new and interoperable apps tie these platform elements together in new and evolving ways to deliver functions not conceived when the platform was developed.

The UGCP can help utilities address impending grid and PAC challenges. At the same time, the platform can transform technical performance, reliability, resiliency, operating and capital expenses, and business operations efficiency. Following is a list of UGCP features:

- **Single-source principle**. A foundational principle of UGCP is that any data acquisition or processing is performed only once in the overall system for all candidate users. Processing at the substation or grid node level is performed as needed to deliver fast response. It provides this processing given of capacity demands on the communications path and the need to assure operation despite equipment or UGCP system failures. This single-source principle is augmented by redundant duplicate facilities. These facilities handle multiple layers of failure contingencies that extend beyond the single-point-of-failure criterion.
- **Limitless processing and sharing**. In UGCP, a hierarchical distributed computing and data management infrastructure eliminates the need for centralized physical locations of data sources. This removes limits on the processing and sharing of all primary data or processed information for any operational or business use. (The exception is intentionally implemented security boundaries.)
- **Digital twins**. The electric grid and its nodes, key UGCP elements, and application functions are modeled within UGCP as digital twins. This enables alignment and continuous comparison with real-world counterparts. This modeling is useful for performance monitoring, configuration management, and situational awareness.
- **Online testing and deployment**. The system is structured for online testing and deployment of new applications. UGCP eliminates outages when updating these apps.
- **Minimized manual configuration**. In UGCP, applications are built around unified electrical and asset hierarchy models of the grid infrastructure. This minimizes manual configuration of applications. System evolution is mapped into the models so that operating applications can adapt.
- **Integration of DER**. Substations and generating stations can remain as major nodes of the electric grid. These nodes are supplemented by many new, granular distributed-resource and user nodes. These nodes can be much more easily integrated in utility operations in the UGCP, compared to architectures used today.

- **Performance and functional monitoring**. The entire system is capable of continuous performance and functional monitoring, for both end-to-end and overlapping zone applications. Maintenance comprises remediation of diagnostic failure alarms and dashboard observations of performance bottlenecks. The system can combine its process data gathering and models of grid equipment. This facilitates monitoring and examining the histories of observable power system element performance, malfunctions, and measurement inconsistencies.

9 UGCP ENTERPRISE INTEGRATION: TECHNICAL OPERATIONS CENTER (TOC)

For efficient utility operations, the UGCP architecture of Figure 2 integrates databases with tools to provide the following capabilities:

- Tracking and management of grid and PAC assets
- Utility infrastructure support
- Component and system modeling and validation
- Event and operational analysis
- Maintenance and trouble dispatching
- Communications network and computing platform management
- Operational and business management dashboards
- Regulatory compliance
- Security management and monitoring
- Business enterprise process management

These operational functions can be conceived as a technical operations center (TOC). Rather than a physical center, the TOC is an integration suite with widespread access to real-time grid information and analysis results. The results drive actions or planning, with role-based enterprise-wide sharing.

Example TOC functions can be grouped in the categories of field monitoring and maintenance; tracking, visualization, and reporting; modeling and configuration management; and security and training.

Field Monitoring and Maintenance

- **Maintenance monitoring, performance and security management, and asset management** encompasses primary electric power equipment, the UGCP elements, and substation and grid communications networks. The latter include the operational WAN and mission-critical PAC communications.
- **Field crew dispatch** for repair and troubleshooting includes preparations driven by diagnostic analytics. This information prepares the field team for the mission.
- **Operational support** includes maintenance clearance and function/equipment tagging management for control centers and field crews.

Tracking, Visualization, and Reporting

- **Tracking of grid components and measurements** includes operation counts and timing, system-state validation, measurement and state comparisons, and alarming of data misalignments and failures.
- **Event data reporting** includes holistic analytics and situational awareness advice for operators, engineers, and regulators.
- **TOC management** includes key performance indicators (KPIs) and metrics based on service level agreements (SLAs) for all the TOC functions in this list.
- **Real-time management dashboard configuration** efficiently presents information for operators.

Modeling and Configuration Management

- **A unified modeling database** with electrical and physical twins of grid components reflect the full range of operational, configuration/settings, and asset management. Utilities today maintain an array of models for a range of uses. However, industry work is underway to align these models. The goal is a single reference representation of the system that connects and aligns all users.
- **Configuration management and change validation** provides updating of all UGCP apps and systems. This includes capabilities for secure remote updating, restarting, configuration validation, and error recovery.
- **Management and deployment of PAC system configuration** is based on IEC 61850-6 Substation Configuration Language (SCL), which automatically arranges functional data exchanges among substation relays and IEDs. This functional mapping across the WAN is to be supported by IEC 61850 Part 6 SCL and Part 8-1 Specific Communications Service Mapping (SCSM) capabilities. This will eliminate the need for engineers to map specific point lists across the grid or to maintain these lists point-by-point.

Security and Training

- **Site access and physical security monitoring** encompasses remote access control, monitoring, and historical trending.
- **Training tools** aid user training on all TOC functions.

10 CYBERSECURITY

IEC 61850 Routable GOOSE (R-GOOSE) and Routable Sampled Values (R-SV) services are examples of highly secure communications protocols among sites and among functions for protection and control. R-GOOSE conveys high-speed control and analog value messages on an as-needed basis. R-SV conveys steams of sampled waveform values from merging units to PAC computing systems. R-SV is also used for high-security synchrophasor transport across WANs on which UGCP is based. (R-SV originated as a synchrophasor transport service.)

Both R-GOOSE and R-SV feature authentication and encryption specifications that foil unauthorized decoding or spoofing. They utilize shared keys that are distributed with emerging high-reliability key distribution center (KDC) tools. The latter are designed with a protective relaying system philosophy: redundant keys, backup modes of operation, constant key rotation, and monitoring. This KDC capability can also serve other message exchange services that are not performing high-speed P&C functions (for example, file and configuration exchanges).

Cybersecurity, along with physical and operational security, will always be a central focus for UGCP because it employs distributed computing systems and communications. Security management is a function built into the substation and system monitoring. This function includes the following:

- Firewall configuration
- Traffic monitoring and analysis
- Role-based access security
- Incident handling
- Functional validation of application data integrity

UGCP will utilize ongoing advances in unified system-wide security management. In this way, UGCP will extend beyond today's role-based access approach. It will transition to multi-factor authentication, situational analysis, and resilient rotating key-based authentication and encryption of PAC message packets. Redundant systems can be isolated in two ways:

- Combinations of virtual and physical equipment barriers in installations
- Separate communication paths with hot standby capabilities

UGCP design will continue to evolve and remain resistant to new cyber threats as they arise. UGCP architecture retains safety-net protection functions at the substation level. This serves to isolate problems and avoid uncleared faults in the event of a wide-area communications failure. Managing security for all traffic and functions in a cohesive platform will become the only practical and affordable approach in UGCP. This is in contrast to the diverse array of specific-need security solutions that are applied in many situations today. These solutions are applied in the absence of unified communications and processing.

11 ROADMAP FOR UGCP ADVANCEMENT

The existence of platform components and tools today, as summarized above, provides utility R&D teams the opportunity to begin construction and demonstration of UGCP in stages and segments. A practical series of steps, grouped logically, is as follows:

1. **Perform initial testing**
   a. Develop specifications for specific components, platforms, communications, operating environments, and functions for a UGCP demonstration.
   b. Map specifications to a demonstration substation and WAN design.
   c. Assemble and integrate a digital substation test platform in a laboratory.
   d. Develop and test a demonstration set of substation functions on the general-purpose computing platforms, environments, and communications network.
2. **Demonstrate initial functions**
   a. Create additional substation or grid node platforms in diverse locations and interconnect them with realistic communications.
   b. Integrate one or two computing platforms or distributed environments for demonstration of enterprise functions.
   c. Develop in sequence, a set of demonstration wide area functions, including high speed PAC, data archiving, and TOC functions.
3. **Scale up**
   a. Create specifications for a practical industry UGCP architecture and environment based on development experience. Determine important points of specificity or standardization to limit design choices.
   b. Develop programs for education of utility organizations on UGCP and its integration of functions. Organizations need to be transformed to support the new design and business approach. New skillsets need to be added, and activities that UGCP renders obsolete need to be retired.
   c. Plan and support industry adoption and commercial development of a production UGCP based on specifications, standards, and demonstrated designs.

12 INITIAL TESTING OF VIRTUAL MACHINE COMMUNICATIONS

EPRI is currently performing basic tests to determine the feasibility of using the technology proposed for the UGCP platform. The initial testing focuses on determining the performance limits of networked interconnection and integration technology using a simple ping-pong exchange of IEC 61850 GOOSE messages [3,4].

The GOOSE ping-pong test is used to develop baseline metrics for ingress-to-egress GOOSE message exchange performance when used on a large scale. The test configures external GOOSE publisher(s) that publish at least one GOOSE message to a specified destination address. The test software receives and validates the published GOOSE message. If the GOOSE message is found to have a valid configuration, the test software updates the destination address and publishes the same content as a GOOSE message published back onto the network.

Initial test results have indicated that the virtualized test environment has sufficient processing capability to easily handle the largest substation data or control requirements. More testing is needed to understand how various real-time functions will perform, and to evaluate performance for other requirements such as failover, cybersecurity, and network maintenance.

13 SPECIFICATIONS FOR UGCP SYSTEMS AND DESIGNS

An EPRI report presents a thorough review and analysis of the layers of system component elements for a centralized protection and control (CPC) or UGCP array. The scope of the review spans:

- The physical networking and computing platforms
- The OSs
- The hypervisors[1] that containerize the utility PAC or operational applications
- The applications themselves [4]

The report examines choices in design and specifications for the purchase and integration for these elements, including a sample request for proposal (RFP) form. The following lists extract some of the key ideas to provide readers examples of requirements to consider in design. This does not approach a comprehensive listing.

- Containerized applications run on either Type 1 or Type 2 hypervisors. A Type 1 hypervisor is designed to run *directly* on the chosen computing hardware and support application module containers. A Type 2 hypervisor runs on top of a standard operating system like Windows or Linux versions.
- A condition-based maintenance (CBM) and protection system maintenance program (PSMP) for an Ethernet-based system monitors processors, computations, communications such as GOOSE and DNP3. With UGCP, the next step is to incorporate hypervisors, OSs, VMs or containers, and communication among these elements. Leading practices include monitoring performance, not just presence; and adding diagnostic filters for rapid remediation.
- The system should be designed with a combination of functional and physical switches that can isolate containers, functional groups, and hardware elements for failure, maintenance, and upgrading scenarios, while leaving one or more instances of critical functions in service. Time stamping and sequencing of inter-process traffic aids monitoring and diagnosis.
- Create strong configuration and settings management that includes VM deployment.
- Operate hardware (for example, processors, memory, and communications) at less than 50% of capacity. Passive cooling without fans and redundant power supplies are recommended. Redundant networking (for example, PRP) is recommended in addition to isolated redundant paths.

[1] In this context, a hypervisor is an operating system that virtualizes multiple computers so they can operate independently and communicate like legacy smaller hardware components on a network. This arrangement is more cost effective and flexible than traditional arrangements.

14 CONCLUSION

Controlling, monitoring, and protecting electric grids with assemblies of functional racks and special-purpose data processing devices is unlikely to continue to be a feasible approach as the industry addresses changes resulting from the emerging carbon-free grid. This approach is likely to lead to and unreliable and ultimately unmanageable array of point solutions. This means that the risk of maintaining legacy technology is probably higher than adapting to a UGCP architecture.

Key elements of the UGCP design are already available from other mission-critical industries, and from advanced development work in the electric utility industry. The recommended next step is to begin implementing UGCP designs, which is practical today. This paper describes example high-level steps by which trial UGCP substation platforms can be assembled and demonstrated in research projects. These platforms can then be integrated in wide-area UGCP demonstration arrays with sample functions. Readily available IT equipment, computing, application, and communications products can then support the evolution of a fully functional UGCP. A companion paper describes evaluation and testing approaches for basic elements in a prospective UGCP implementation [3].

Industry forums and standards committees need to coordinate a single design and deployment approach to maximize UGCP economic and functional benefits. Such activities would inform utility and industry participants on the emerging PAC design direction.

15 REFERENCES

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