Unified Grid Control Platform Concept

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Introduction

Technical literature presented to protection, automation, and control (PAC) engineers in literature and at conferences increasingly presents an emerging generation of technology that reaches far beyond the familiar generations and configurations of protective relays and substation intelligent electronic devices. Contemporary topics may include Ethernet local and wide-area networking, functional elements and nodes in the IEC 61850 communications and modeling standard, virtualized functions, digital twins, generic computing platforms, and 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, but they also show how the equipment we install in substations is taking advantage of communications, computing, software, and tool technology evolution to bring new functions or to reduce the cost of increasingly capable products. These new capabilities come as the industry faces historic technical challenges these products aim to solve. While many new topics appear disjointed, a broad view of them shows how our industry is evolving towards a cohesive new architecture for system protection and control that addresses grid operating challenges as it brings sustainability and security which won't be possible without this evolution.

This paper brings together an array of these new concepts in a holistic architecture and functional solution that addresses not only electrical protection and operations, but also business enterprise operations and management. Engineers and managers who understand and embrace such a holistic roadmap are well positioned to specify new projects that broadly benefit the utility and keep its infrastructure and organization on a sustainable path in times of rapid change. Individuals with grasp of this vision are likely to be supportive of research, development, and new-product advances that support movement towards this architecture and solution.

Drivers for a new unified grid control infrastructure

Our industry faces the imperative of transforming the electric grid to renewable and carbon-free energy sources, driven by stringent regulatory requirements and consumer demands to eliminate carbon dioxide and other greenhouse gases. In contrast with the still-operating legacy of large fossil-fueled dispatchable central generating plants, most of the new renewable energy production comprises massive numbers of smaller installations scattered across the transmission and distribution grids, and at utility customer sites. In parallel, transportation and other industry sectors are driving electrification and supporting growth of T&D infrastructure. The number of new distributed energy resources (DER), along with new interfaces and facilities, are expanding system operation and protection complexities exponentially. Inability to dispatch DER production reduces controllability of energy flows and places difficult-to-predict demands on storage. In the face of this energy supply and control uncertainty - consumers, regulators, and government agencies still demand higher service reliability, grid resiliency, and accommodation of constantly changing weather and environmental conditions, along with public safety.

This drives massive need for advanced new infrastructure to monitor and control the interaction of granular energy resources with the regional grid and with new categories of loads and consumers. The grid requires evolution of protection, automation, and control (PAC) systems to architectures that are functionally adaptable, flexible, resilient, and sustainable. Fixed-function PAC systems designed for the predictable grid will struggle to adapt to these needs.

In addition, the physical and electrical operating characteristics of DER are profoundly different from legacy generation and demand new protection and control methods. Fossil-fueled turbine-generators have massive rotating inertia and can provide robust short-circuit current during system faults to initiate protective relay tripping. By contrast, DER using power electronic inverters have no inertia, and can only deliver close to rated current in the face of a disturbance or fault. Disturbances may trigger sudden excursions of voltage and current that can lead to loss of stability and blackout. Already, on multiple occasions, recoverable grid disturbances have caused large arrays of DER inverters to block or shut down completely, leading to a sudden reduction in energy supply and risking blackout. Protecting a grid with high penetration of DER calls for a transition from traditional indicators of stability like frequency to direct monitoring and holistic analysis of voltages and currents gathered at high speed from across the impacted region, with rapid control to maintain stable operation.

The utility industry cannot realistically expand today's ubiquitous PAC infrastructure with its point-solution products to address these issues. This will load financial, asset management, and human resources beyond the breaking point while not bringing sustainable solutions. Instead, the industry can conceive and build sustainable and affordable new PAC systems by adapting the rapidly advancing 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 to reach the sustainable, flexible, adaptable infrastructure for 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 interconnected with high-reliability and 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 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.
- Continuously expand cybersecurity capabilities to counter constantly evolving threats, while complying with current and emerging NERC CIP requirements, with a single unified and manageable strategy.

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

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 with thousands of point connections between control building panels and the switchyard.

- **SCADA and Energy Management Systems (EMS)** - Monitoring and control of the entire grids has been handled by centralized SCADA and EMS with specialized data acquisition by remote terminal units (RTUs) in substations. Information gathering is limited by wide-area communications capacity. Utility operating organizations and their software suppliers are currently working on distributed energy resource management systems (DERMS); but only as a separate overlay to integrate those resources with legacy grid operations.
- **Protective relaying systems** - Fault protection and system stability protection have been handled by custom-designed, individually set, redundant, fixed-function relaying systems whose 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, difficult to configure and set, and are 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. Protection schemes are limited by the unavailability at the substation level of a holistic live set of system measurements and states.
- **Reliability and maintenance** - Maintenance of PAC infrastructure has consisted of repair of failures or problems when observed, plus discovery of some hidden failures by 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. Monitoring and condition-based maintenance programs are just now being considered by a limited group of utilities.
- **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. There is only slow progress towards gathering of equipment and process data in efficient single streams for sharing among various enterprise and operational users.
- **Overall operational and business management** - Enterprise management functions including asset management, event analysis, planning analysis, capital planning, maintenance management, and business management are all handled in unique, costly software and hardware systems isolated from one another and requiring 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.

UGCP Substation Architecture

UGCP is a grid-wide architecture, but we begin at the substation node level. Figure 1 shows the UGCP architecture for PAC infrastructure in a substation. The same architecture is scaled to serve large facilities or small nodes and customer sites. It shares key design concepts with those embodied in the latest editions of IEC 61850 standards.

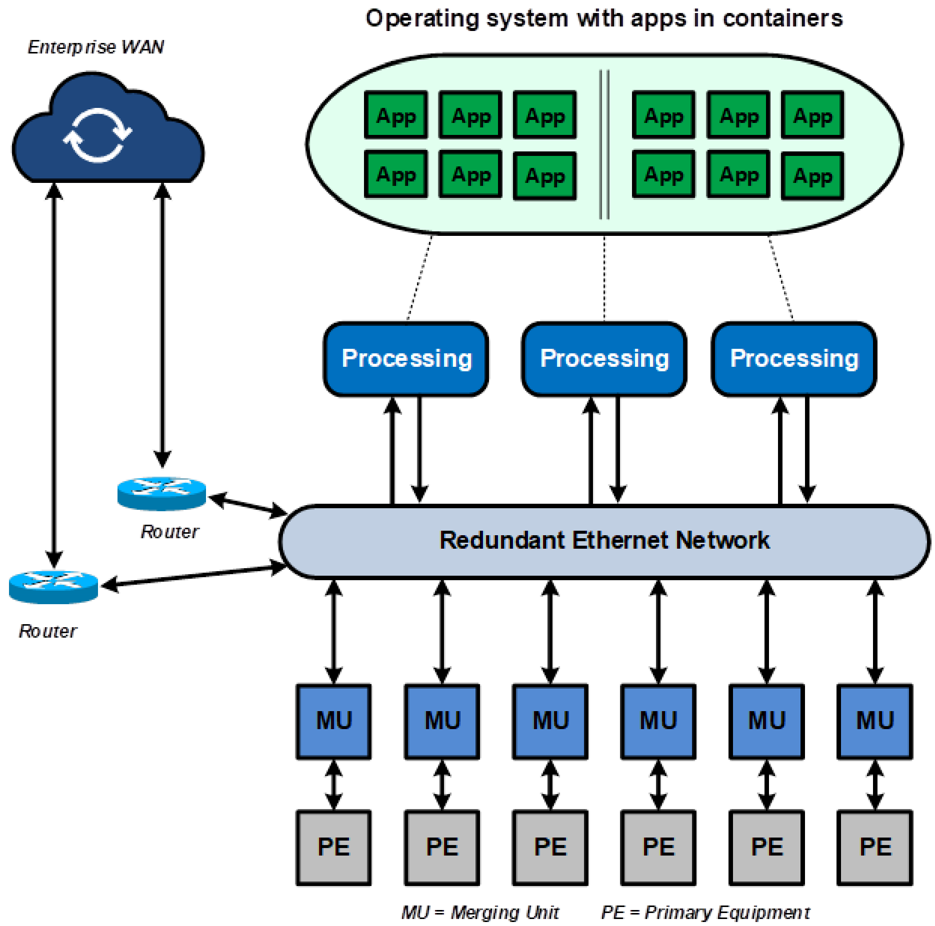

Figure 1 – UGCP Substation Architecture

The primary power apparatus includes integrated or wired merging units (MUs) – local electronic modules which gather and digitize measurements and point states at each switchyard location and combine them for transmission on a single optical fiber from each of many apparatus locations to a processing array attached to a redundant substation Ethernet network. Substation PAC functions can send tripping or control commands back to the apparatus via return optical fibers to the MUs.

The network infrastructure comprises a redundant, resilient, secure Ethernet interconnection of MUs and redundant computer arrays hosting standardized substation PAC functions. Networking and processing arrays can be centralized in a control building or distributed in smaller replaceable structures or modules. Network reliability is based on today's redundancy and security technologies such as parallel redundancy protocol (PRP) dual links, looped redundancy, or software-defined networking

(SDN). UGCP can absorb high-reliability networking technologies now arising in the larger business and industrial IT worlds going forward. The substation network connects through redundant routers and communications paths to redundant utility operational and enterprise wide-area networks and host processing systems.

In the target architecture, there are no fixed-function relays or IEDs. The processing units feature operating systems with real-time capability and with functional containerization of power system application programs (apps). The standardized function containers are flexibly deployed across the processing units - operating-system containers or apps can be placed to optimize reliability, processing workload, failure resilience, and practical maintenance and updating sequences. The ability to commission new or updated apps without disabling components or functions, in combination with redundant functions, leads to a completely sustainable installation. 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 sustainable physical installation design that makes practical no-outage replacements safe and easy for maintenance crews.

UGCP Wide-Area System Integration Architecture

The array of substations and grid nodes exchange information with a distributed and WAN-based processing infrastructure like that shown in Figure 2. The figure includes key samples of enterprise functions and applications we explain below.

The enterprise processing functions are distributed across the WAN, not needing to be concentrated at a specific physical location. The distributed processing and networking array yields redundancy, maintainability, sustainability, and flexible deployment of applications with little or no disturbance to operations or to business and management processes – as we described for substation systems. Resiliency is enhanced by configuring redundant data center and data communications facilities with WAN and processing array management functions.

The UGCP platform includes a redundant, high-reliability system for network-based precision time distribution required by emerging synchronized measurement and analysis functions, to eliminate dependence on vulnerable GNSS satellite system time references. The WAN-consistent precision distributed time reference sources can be synchronized to GNSS external standard when available, but the entire UGCP can operate coherently without that external standard.

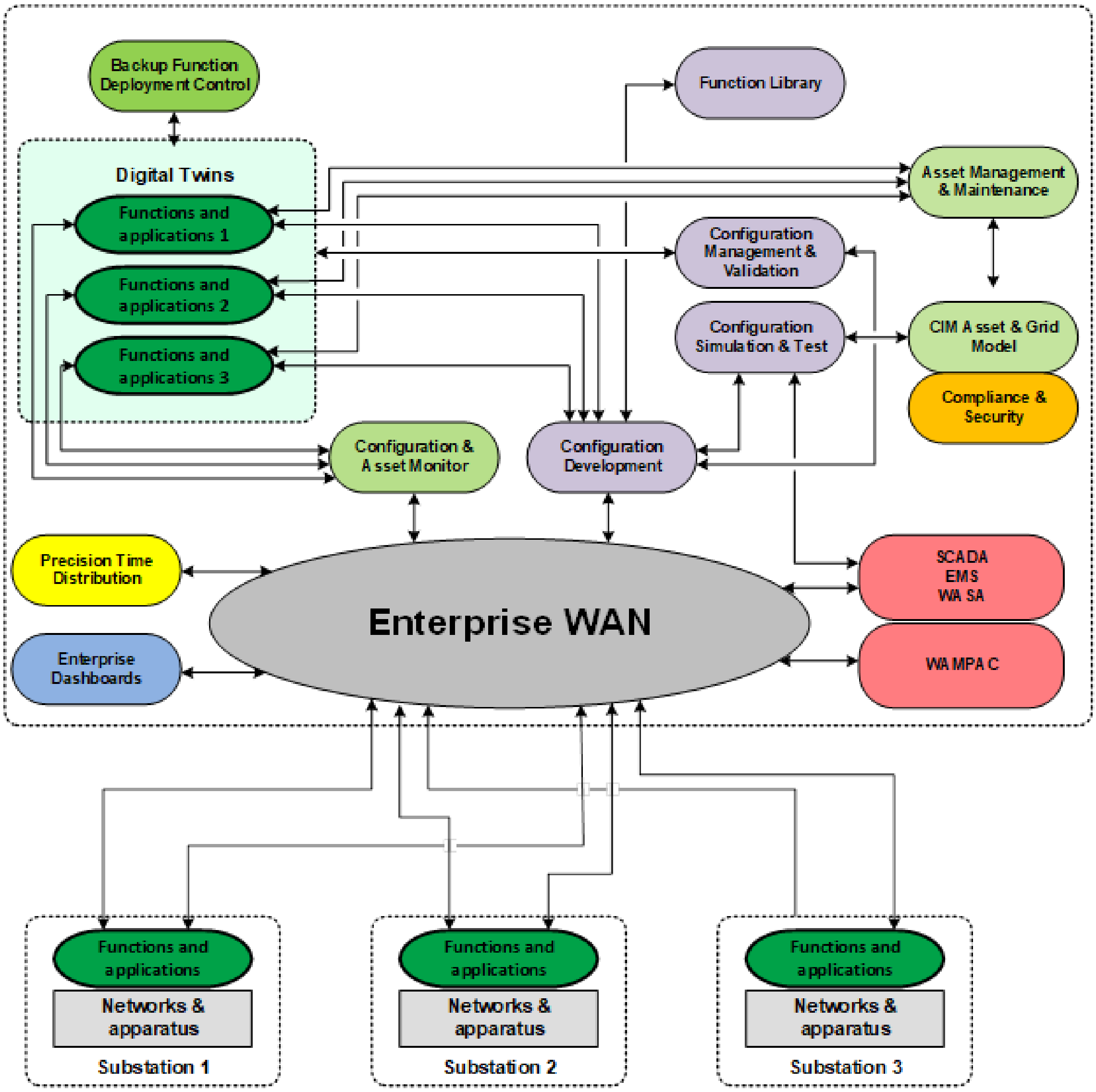

Figure 2 – UGCP Wide-Area System Configuration

UGCP Enterprise Functions

The key functional elements in the Figure 2 enterprise container are as follows:

1. ***Config & Asset Monitoring -*** process that exchanges live information on status of apps and PAC equipment with the substation – tracking elements in normal operation, versus those in backup or workaround modes.

2. ***Digital Twins*** – set of modular virtual application function models serving as mirror images of the actual existing power system equipment elements and topology with the PAC, monitoring, and management app configuration in each substation and across the grid mirrored exactly in the twin models.

3. ***Backup Function Deployment Control*** – function that interacts with each grid node or wide-area PAC function and its digital twin status to determine what preconfigured alternative or backup operating configurations are to be deployed, based on failures or malfunctions, or on operational decisions and control center requests.

4. **Configuration Development Facilities** - used by engineers and managers offline to assemble new app configurations or 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 the operation of the new configuration using the digital twin grid models in a separate test environment, and can then finally download and start the production configuration in the substation system or wide-area configuration with a sequence that maintains live operation of all functions. This configuration development and deployment process uses the inherent redundancy of the UGCP to update operating app configurations without outages or disruptions of grid operations.

5. **Function Library** - supports the configuration development facilities with managed and version-controlled arrays of all available apps, both in-service and newly introduced for functional updates.

6. **Configuration Simulation & Test** - an offline environment for experimentation and validation of changes to app configuration, including real-time simulations of situations and events based on the digital twin grid model, its present or extreme operating states, and historized events.

7. **Configuration Management & Validation** - function that ties the operating configurations of substations, grid nodes, and wide-area functions to their digital twin representations, validation test configurations, backup adaptations, to track deployed and historical versions.

8. **Asset Management & Maintenance** - functional grouping that tracks all power system and UGCP infrastructure based on history and on live condition or failure inputs processed through the Digital Twins function. It can dispatch reconfigurations as well as triggering SME analysis or truck rolls to repair or replace failed items, and feeds evolving-situation parameters to the master grid and asset model.

9. **CIM Asset & Grid Model** – function that maintains the database for the condition, history, and change plans for all grid and UGCP assets, to be used for management, updating sustainment, and replacement. It contains the relationships and ratings of all elements to support the validation of deployed app configurations.

10. **Compliance & Security** - element that monitors the relationships and limitations imposed by operational or regulatory restrictions, to support 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, and dispatches security actions to mitigate disruption events.

11. **SCADA-EMS-WASA** – grid monitoring and control functions associated with the grid control center, although UGCP supports redundancy and separation of these functions. Supervisory Control and Data Acquisition (SCADA) comprises the first-tier observation of grid operating state and measurements, with control and mitigation actions in human-operator time frames. The Energy Management System (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 SCADA data with high-speed synchronized measurement-based displays and analyses of voltage profile, real and reactive power flow dynamics, grid stability, and parameters that can evolve in faster than human-observation time frames.

12. **WAMPAC** - wide-area protection, automation, and control. It includes holistic wide-area protective relaying schemes using synchronized measurements and high-speed wide-area control for tripping for backup fault protection [1, 2], grid angular or voltage instability protection, closed loop holistic voltage profile control or energy flow control, and remedial action or system integrity protection schemes. These new protection concepts can assure fast and selective fault protection in the face of dynamically changing mixes of machine and IBR generation that characterize the emerging zero-carbon grid and challenge many of today's relaying methods.

13. **Enterprise Dashboards** - business applications and overall utility enterprise management functions which can access all raw or processed information on states, events, and situations to deliver flexible displays aimed at the needs of specific organizational stakeholders or leaders.

14. **Precision Time Distribution** - components to maintain, coordinate, deliver, and monitor reference time flow for the entire UGCP infrastructure with sub-microsecond precision, using Ethernet network precision time protocol (PTP) and its future evolutions. Precision time data supports synchronized wide-area measurements critical to WASA and WAMPAC, along with event analysis and grid management. Precision time service is a core requirement for emerging grid-wide IT-OT communications infrastructure. Many utility IT departments have resisted tackling the delivery of this service to date, forcing enterprise users to GPS or GNSS satellite timing; redundant grid-relative timing independent of vulnerable outside sources is a requirement for utility OT systems going forward.

15. **Enterprise WAN** - redundant and resilient operational and enterprise cloud communications infrastructure including operational monitoring, management, and security functions. Mission-critical UGCP functions for PAC include multiple layers of redundancy of paths and equipment. Network components like MPLS or SD-WAN routers support dispatching of many communications paths for multiple layers of failure or outage resilience exceeding any plausible chance of loss of communications. The network infrastructure can also integrate or segregate operational versus enterprise business communications to meet the needs of a utility plan for OT-IT integration

versus segregation. The management security module detects abnormal traffic patterns and defects or can create traffic baseline definition and acceptable-traffic listing as with SD-WAN.

Integrating Today's Electric Utility Technologies into UGCP

Industry experts and supplier teams working today are developing advances that support UGCP:

- **IEC 61850** - The international standard IEC 61850, Communication Networks and Systems for Power Utility Automation, details the specifics for integration of PAC functions by standardized interface models of programmed functional nodes (logical nodes or LNs) in generic processing environments and exchanging standard data objects via Ethernet messaging packets. IEC 61850 structure supports flexible location of functions in a computing and data sharing platform like UGCP. It enables creation of cloud digital twins for the live 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 like transportation nodes. Manual configuration and maintenance of such large interconnected systems will prove to be massive unproductive work that must be automated.

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

- **Models and tools** - Utilities already operate with a range of sophisticated modeling tools for electrical behavior of the grid – operational modeling, three-phase fault analysis, dynamic performance modeling, and wideband transient behavior simulation. Unified modeling initiatives are working to integrate these into a single-source modeling toolset, although progress is slow and practical development will continue for years.

- **Real-time and HIL testing** - The industry has developed impressive capability 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, the implementation of functions on standard platforms rather than in special boxes will move all testing into the modeling domain and reduce the need for routine operational HIL testing of equipment.

- **Deployment of LAN and WAN infrastructure** - Utilities have been increasing their use of Ethernet 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.

- **Emerging DER and grid control solutions -** A range of new real-time functions are in constant development to handle requirements of utilities with increasing levels of DER, loss of grid inertia as inverters replace rotating machines, or other new operating stresses. New DERMS are in development and demonstration.

- **Synchronized measurements and applications** - Utilities have been aggressively deploying phasor measurement units (PMUs) for precise synchronized measurements to support 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.

- **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.

Integrating Today's IT and Business Technologies into UGCP

Developers of the overarching UGCP architecture can integrate and adapt elements from the general business operations world:

- **Cloud services** – Today's business operations, including even mission-critical high-speed financial and network operational services and military operations, are based on a monitored and managed network of data centers and communications systems which are dynamically and securely assigned to applications as needed. The application experts can focus only on the functions of the applications themselves and not on the computing or data transmission needs.

- **Containerization and isolation** – Cloud services are based on secure and managed partition of users and applications so that there is no 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 operating systems are evolving to support containerized applications in arrays of general-purpose processing hardware – such as flexibly configured racks of blade servers in data centers serving other mission-critical industries.

- **Network and computing redundancy** – today's networks support configuration of application containers and infrastructure to avoid failures for any plausible set of contingencies. Robust configurations are implemented and managed for mission-critical applications of other industries in the cloud today.

- **Distributed and remote network management and security tools** – operation of the redundant robust wide-area network is managed with sophisticated monitoring tools that track and report path or component performance, monitor redundant services, redeploy paths and functions to work around failures, and 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.

Features and Benefits of the UGCP Architecture

UGCP is built largely on IT-world computing, communications, operating system, containerization, and remote updating/management elements whose large-scale usage across industry brings sustainability and cost reductions compared to custom-designed hardware packages with custom programming. This departs from the model of redundant single-zone or single-function IEDs to move towards a smartphone model - platforms with a standard array of sensors, communications paths, and user interfaces. New and interoperable apps tie these platform elements together in new and evolving ways to deliver functions not even conceived when the platform was developed.

The unified grid control platform can deal with the impending grid and PAC challenges while transforming technical performance, reliability, resiliency, operating and capital expenses, and business operations efficiency.

- A foundational principle 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 for fast response, limitation of communications path capacity demands, and need to assure operation in the face of foreseen equipment or UGCP system failures. This single-source principle is augmented by redundant duplicate facilities specifically to handle multiple layers of failure contingencies which go beyond the single-point-of-failure criterion.

- Hierarchical distributed computing and data management infrastructure overarches the specific physical locations and specific data sources, removing limits on ability to process and share all primary data or processed information for any operational or business use (except for intentionally implemented security boundaries).

- The electric grid and its nodes, key UGCP elements, and application functions are modeled within UGCP as digital twins, where they are aligned with and continuously compared to real-world counterparts for performance monitoring, configuration management, and alarming of problems.

- The system is structured for in-flight testing and deployment of new applications for monitoring, control, protection, operations, and management. UGCP eliminates outages for updating these apps.

- Applications are built around unified electrical and asset hierarchy models of the grid infrastructure to minimize manual configuration of applications. System evolution is mapped into the models so that operating applications can adapt.

- Substations and generating stations can remain as major nodes of the electric grid, supplemented by many new and finely grained distributed-resource and user nodes which can be much more easily integrated in utility operations than is true today.

- The entire system is capable of continuous performance and functional monitoring, both end-to-end and in overlapping zones, so that maintenance and sustainment comprise remediation of diagnostic failure alarms and dashboard observations of performance bottlenecks. The system can combine its process data gathering and models of grid apparatus to monitor and historize observable power system element performance, malfunctions, and measurement inconsistencies.

UGCP Enterprise Integration - Technical Operations Center (TOC)

For efficient utility operations, the UGCP architecture of Figure 2 integrates databases with tools for tracking and management of grid and PAC assets, utility infrastructure sustainment, 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 and security management and monitoring, and business enterprise process management.

We conceive these operational functions as a *Technical Operations Center (TOC)*, which is not a physical center, but rather an integration suite with widespread access to real-time grid information and analysis results that drive actions or planning, with role-based enterprise-wide sharing.

Example TOC functions include:

- **Maintenance monitoring, performance and security management, and asset management** of primary electric power apparatus, the UGCP elements, and substation and grid communications networks including the operational WAN and mission-critical PAC communications.
- **Tracking of grid components and measurements** for operation counts, operation timing, system-state validation, measurement and state comparisons, and alarming of data misalignments and failures.
- **Event data reporting** with holistic analytics and situational awareness advice for operators, engineers, and regulators.
- **Unified modeling database** with electrical and physical twins of grid components for the full range of operational, configuration/settings and asset management. Utilities today maintain an array of models for a range of uses, but many work at aligning these models in a drive towards a single reference representation of the system that connects and aligns all users.
- **Configuration management and change validation** for 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** based on IEC 61850-6 Substation Configuration Language (SCL), which automatically arranges functional data exchanges among substation relays and IEDs. SCL eliminates substation control-building point-to-point wiring functionally maps information exchange among logical node (LN) functions. 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 to eliminate the need for engineers to map specific point lists across the grid or to maintain those lists point-by-point.

- **Field crew dispatch** for repair and troubleshooting, with preparations driven by diagnostic analytics that focus and prepare the dispatch team for the mission.
- **Site access and physical security monitoring** with remote access control, monitoring, and historizing.
- **Operational support** including maintenance clearance and function/equipment tagging management for control centers and field crews.
- **Real-time management dashboard configuration** of presentations
- **Tools for training** of users for all TOC functions.
- **TOC management** with key performance indicators (KPIs) & metrics based on service level agreements (SLAs) for all the TOC functions in this list.

Cybersecurity

Cybersecurity, along with physical and operational security, will always be a central focus for UGCP as it employs distributed computing systems and communications. Security management is a function built into the substation and system monitoring including firewall configuration, traffic monitoring and analysis, role-based access security, incident handling, and functional validation of application data integrity. UGCP will utilize ongoing advances in unified system-wide security management, advancing beyond today's role-based access to systems to multi-factor authentication, situational analysis, and resilient rotating key-based authentication and encryption of PAC message packets. Redundant systems can be isolated with combinations of virtual and physical equipment barriers in installations and separated communications paths with hot standby capabilities.

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

Roadmap for UGCP Advancement

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

1. Develop specifications for specific components, platforms, communications, operating environments, and functions for a UGCP demonstration.
2. Map specifications to a demonstration substation and wide-area network design.

3. Assemble and integrate a digital substation test platform in a laboratory as shown for a Test Area in Figure 3 below.
4. Develop and test a demonstration set of substation functions on the general-purpose computing platforms, environments, and communications network.
5. Create additional substation or grid node platforms in diverse locations and interconnect with realistic communications.
6. Integrate one or two computing platforms or distributed environments for demonstration of enterprise functions.
7. Develop in sequence, a set of demonstration wide area functions including high speed PAC, data archiving, and Technical Operations Center functions.
8. Create specifications for a practical industry UGCP architecture and environment based on development experience. Determining critical points of specificity or standardization to limit design choices is critical to success and industry absorption.
9. Develop programs for education of utility organizations on UGCP and its integration of functions. Organizations themselves must be transformed to support the new design and business approach, with addition of new skillsets and retirement of activities made obsolete by UGCP.
10. Plan and support industry adoption and commercial development of a production UGCP based on specifications, standards, and demonstrated designs.

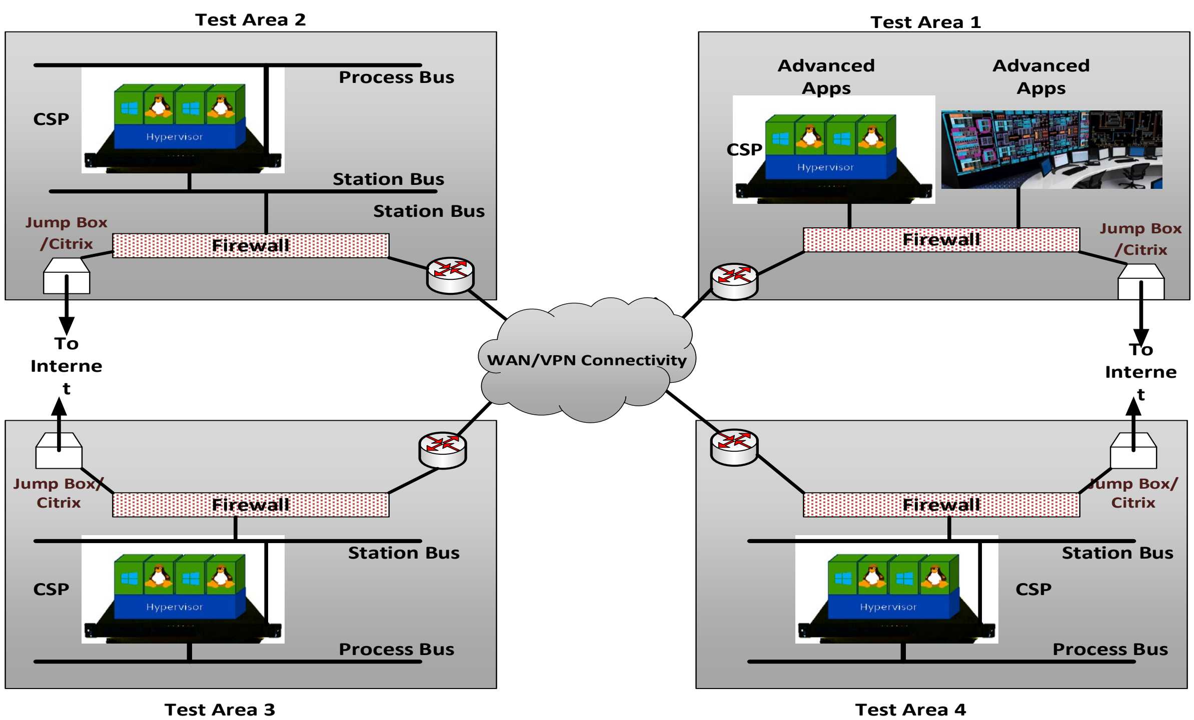

Figure 3 – UGCP Demonstration Array

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 is focused on determining the performance limits of networked interconnection and integration technology using a simple ping-pong exchange of IEC 61850 GOOSE messages.

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 valid configuration, the test software updates the destination address and publishes the exact same content as a GOOSE message published back onto the network.

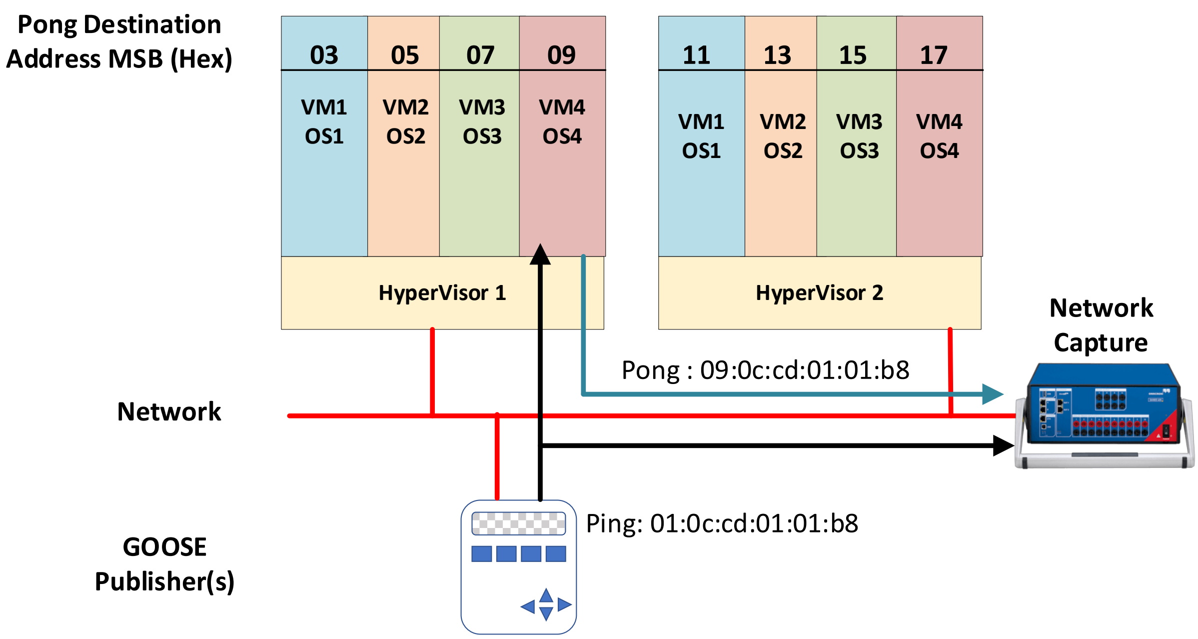

Figure 4 - Test Architecture

Figure 4 depicts the laboratory setup for the GOOSE ping-pong test. The test environment consists of two identical servers from the same vendor. Each server is provisioned with different hypervisors or virtual computing machine simulations. The hypervisors are Type 1 (operating directly on the host computing platform) from multiple vendors. Each of these virtual environments has four different virtual machines with different guest operating systems (e.g., various versions of Linux or MS Windows). The goal of this testing is to determine the hypervisor I/O rate capability using repeated GOOSE ping-pongs as described above, and then to add features and loading to determine performance metrics.

The test software, hosted in the guest operating system of each virtual machine, is designed to take incoming GOOSE ping messages and retransmit them as pong GOOSE messages by replacing the first octet based upon configuration. Figure 5 shows an example capture of a pong of 09-0C-C-01-01-B8 in response to a ping of 01-0C-C-01-01-B8. Both the ping and pong GOOSE messages are recorded by a network traffic capture device that times observation of ping and pong frames with nanosecond resolution.

```
36 2.195841984  b4:b1:5a:10:8e:07  01:0c:cd:01:01:b8    IECGOOSE
37 2.195882304  b4:b1:5a:10:8e:07  09:0c:cd:01:01:b8    IECGOOSE
```

Figure 5 - Example Network Capture in PCAP File Format

Figure 6 depicts the processing of the network capture results over time and their analysis.

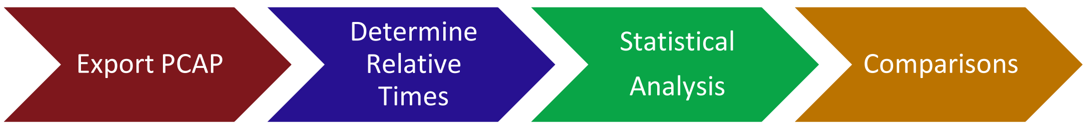

Figure 6 - Process for Processing of the Network Capture

The process of analyzing the network capture consists of:

- Exporting the network capture in PCAP file format.
- Determining the relative times between ping and pong GOOSE pairs based upon the destination address, GOOSE state number, GOOSE sequence number, and other identifying GOOSE fields. The output is then subjected to a statistical analysis.
- The statistical analysis determines the min, max, mean, and standard deviations of the relative times. It produces a text file as in Figure 7 and plots the information by creating accumulating relative time bins as in Figure 8.

The presentation tool provides additional capability to visually compare results from different test runs, system loading, or operating system and hypervisor pairs as shown in Figure 9.

Thus far the initial test results have indicated that virtualized test environment has more than enough processing capability to handle the largest substation data or control requirements with ease. More testing is to be done to understand how various real-time functions will perform, and to evaluate performance for other requirements such as failover, cybersecurity, and network maintenance.

```
PCAP file name: HyperVisor 1- VM4 - 2023-02-02-17-07-24.pcap
Total Number of records: 6948
Number of unmatched Pong Packets: 0
Number of unpublished/matched - No Pong Found: 0
--- Range Analyzed -
First Pong Detected at Record: 18
Last Pong Detected at Record: 6918
Minimum Ping-Pong time (sec) : 3.399999695830047E-05
Maximum Ping-Pong time (sec): 0.000122999990070819467
```

Figure 7 – Example Text Output of Analysis Processor Tool

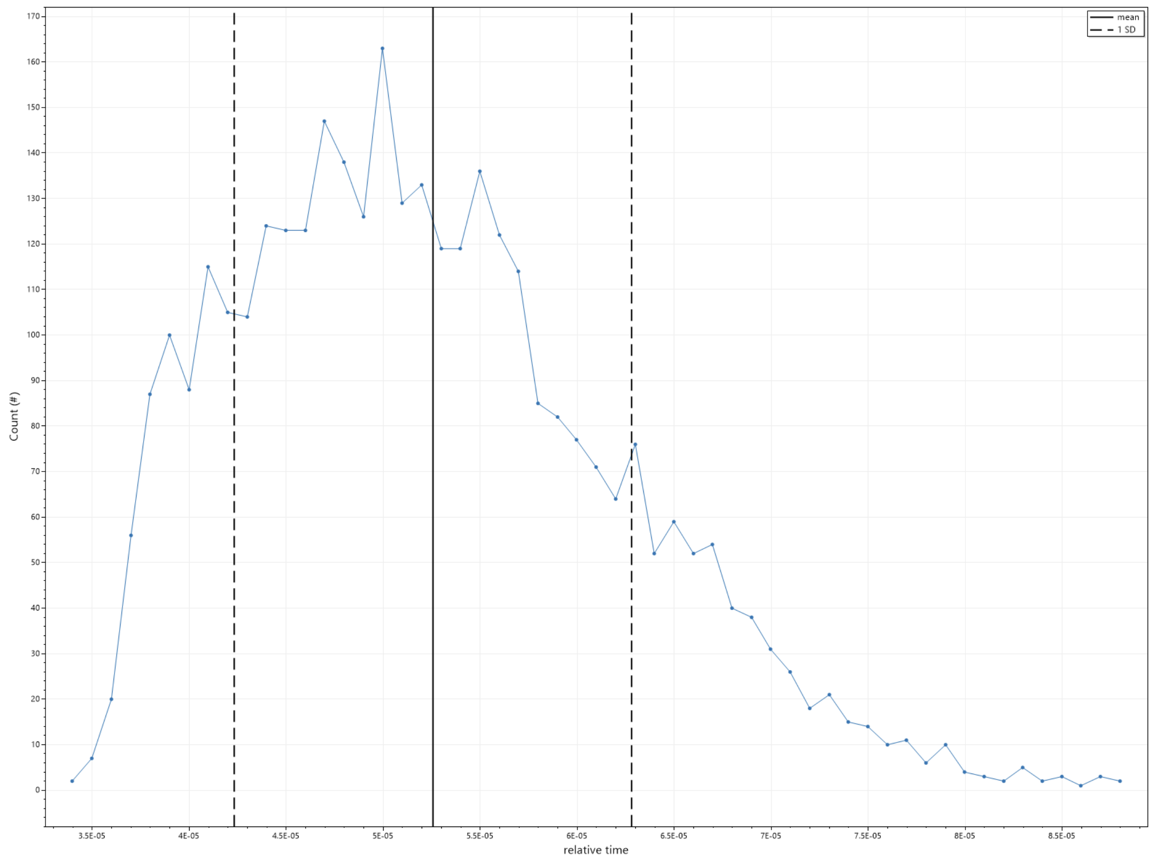

Figure 8 – Ping-Pong Time Distributions and Bins

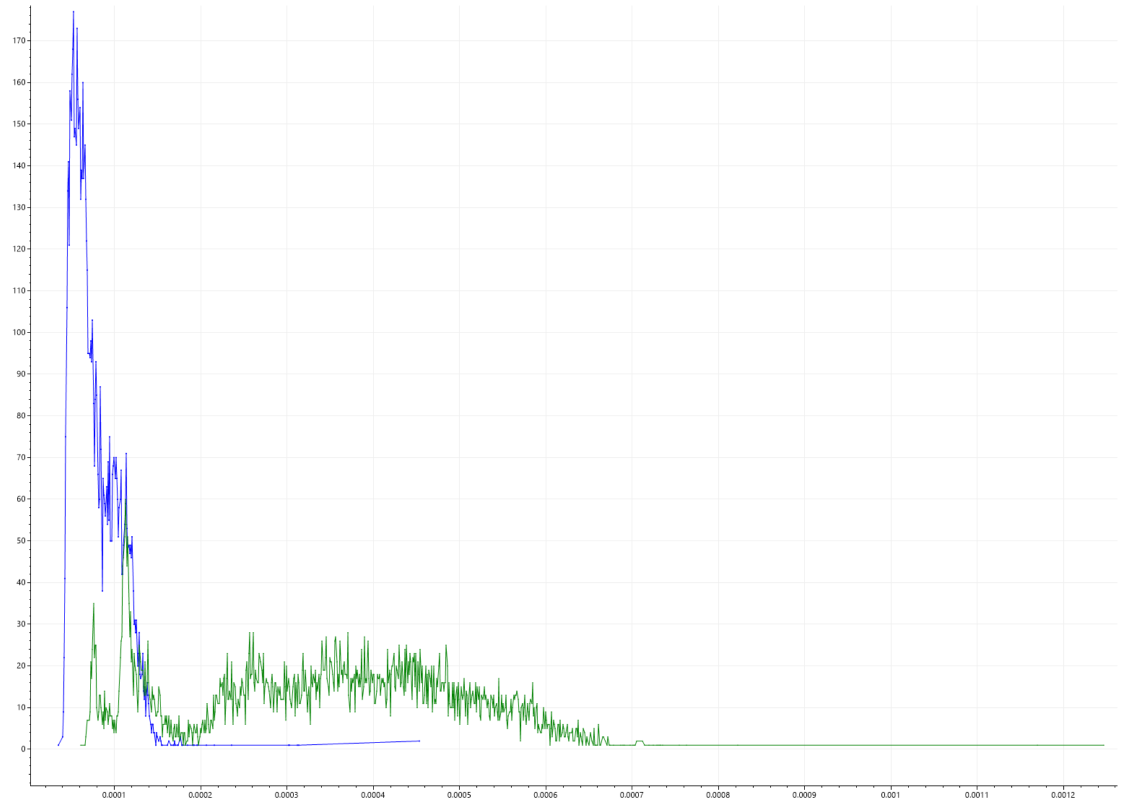

Figure 9 – Superimposed results from timing runs for two different test cases

Conclusion

Controlling, monitoring, and protecting electric grids with assemblies of functional racks and special-purpose data processing devices will not be a sustainable approach as we face the changes resulting from the emerging carbon-free grid. Utilities will accumulate a massive, unreliable, and ultimately unmanageable array of point solutions whose functions were needed at the time of installation. There is therefore more risk in keeping up the old technology than adapting to UGCP architecture as described here.

Key elements of UGCP design are already available from other mission-critical industries, as well as from advanced development work on components already taking place in the electric utility industry. The next step is to start implementing UGCP designs, and this is fully practical today. We have described 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. Companion paper [3] describes evaluation and testing approaches for basic elements in a prospective UGCP implementation.

Industry forums and standards committees must coordinate a single design and deployment approach to maximize the economic and functional benefits, as they inform utility and industry participants on the emerging new PAC design direction.

References

[1] Udren, E., "Principles for Practical Wide-Area Backup Protection with Synchrophasor Communications", Paper B5-112, CIGRÉ 2014 General Session, Paris, France.

[2] Udren, E., Rahman, T., "WASA and the Roadmap to WAMPAC at SDG&E", PACworld Magazine, September 2019, Volume 49.

[3] Myrda, P., Falk, H. "Performance Testing of the Unified Grid Control Platform", CIGRÉ Grid of the Future Symposium, November 7-10, 2022, Chicago, IL, USA.

Biographies

Paul Myrda is the Grid Operations and Planning Senior Program Manager with the Electric Power Research Institute working in the Power Delivery and Utilization Sector. Paul has been with EPRI for 14 years. Previously Paul led the Information and Communications Technology for Transmission program as manager. Paul is an active member of Technical Committee 57 - Working Group 10 that supports the development of the IEC 61850 standard. He is also active in the IEEE Power System Relaying Committee. Paul has over 40 years of experience leading technology implementations. His diverse background includes planning, engineering, information systems and project management. He has an MBA from Kellogg Graduate School of Management and MSEE and BSEE from Illinois Institute of Technology. He is a licensed professional engineer in Illinois, member of CIGRE and Senior Member of the IEEE.

Rich Hunt is Executive Advisor in the Protection, Control & Automation team of Quanta Technology, and serves as the lead expert for digital substation development and IEC 61850. Rich has over 30 years of experience in the electric power industry, emphasizing protective relaying. Over the last 15 years, his focus has been on all aspects of specifying and designing digital substations, including IEC 61850, process bus, non-conventional instrument transformers, networking, and time synchronization. Rich earned his BSEE and MSEE from Virginia Tech, is a Senior Member of IEEE, a member of the IEEE Power System Relaying & Control Committee and is a registered Professional Engineer.

Eric A. Udren has a distinguished 53-year career in design and application of protective relaying systems, substation control, IEC 61850, wide-area monitoring and control systems, PMU applications, and communications systems. He works with major utilities to develop new substation protection, control, communications, and remedial action scheme designs based on Ethernet, IEC 61850 integration, and synchrophasor techniques. Since 2008 he has served as Executive Advisor with Quanta Technology. Eric is Life Fellow of IEEE, and twice served as Chair of the Relaying Communications Subcommittee of the IEEE Power System Relaying and Control Committee (PSRC). He is Technical Advisor to the US National Committee of IEC for TC 95 relay standards; and is SME member of NERC System Protection and Control Working Group (SPCWG). He has written and presented over 100 technical papers and book chapters and holds 12 patents. Eric appeared as PACworld Magazine Industry Guru in September 2016. In 2019 Eric was elected to the US National Academy of Engineering 'for leadership in advancing protection technologies for electric power grids.'