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The Power of
INFRASTRUCTURE MODERNIZATION

Envisioning an "Intelligent Edge" for Power Sector Digitalization

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UNLOCKING GRID EVOLUTION

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CENTRALIZATION AND VIRTUALIZATION ARE THE KEY

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1 INTRODUCTION

The evolving landscape of global energy production, distribution and consumption has accelerated the need for a smarter, more resilient and secure grid. Today's grid is becoming bidirectional as distributed energy resources (DER) are connected to the power grid. The shift from large centralized nuclear and fossil fuels to renewable energy resources and localized energy production holds great promise for a cleaner energy future, but also creates new challenges for grid operators. Adding to the challenge is an increased demand for electricity in homes, for transportation, and by data centers. Utility leaders are reimagining grid operations to meet the demands of a modern global energy paradigm.

In the 2020's, the industry has made the turn from imagining to investing. The market for substation modernization is growing as utilities replace legacy hardware and software with standardized infrastructure. A broad base of market participants including established equipment and technology suppliers, new technology pioneers, utilities, regulators, and energy users are finding ways to derive value for their businesses in the transformation to the resilient, cost-effective, and low-carbon energy system of the 21st century.

The vision of an "intelligent Edge" for the power sector developed from initial concept in 2016 to the launch of the Virtual Protection Automation and Control Alliance (vPAC Alliance) in 2023. vPAC Alliance is a coalition of technology leaders who are committed to modernizing global energy through standards-based, open, automated and secure solutions. The vPAC architecture combines standardized hardware with "software-defined" protection, automation and control (PAC) systems, replacing "fixed- function devices" currently in use. Intel, a member of vPAC, is collaborating with energy providers and customers across the energy ecosystem to consolidate OT and IT Applications onto scalable open platforms that meet future power needs.

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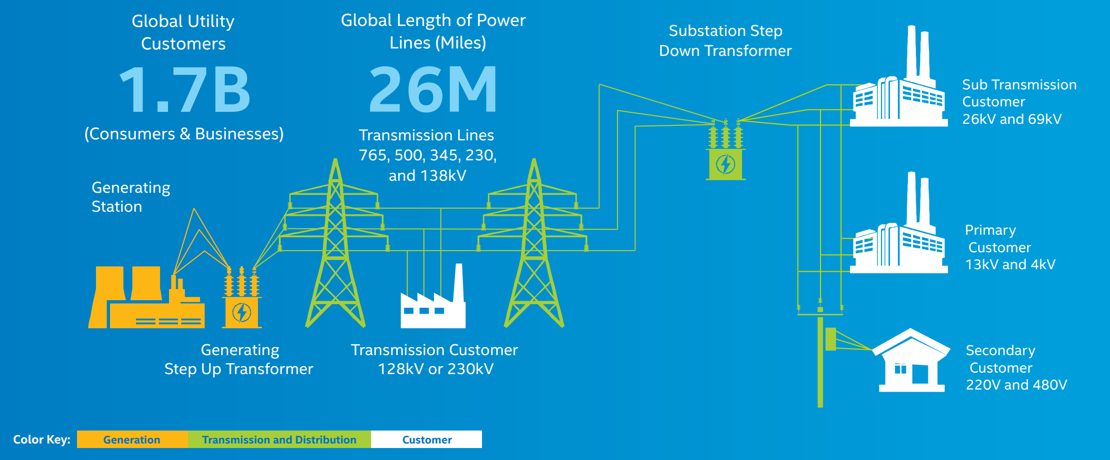
UNLOCKING GRID EVOLUTION

Future energy demands and increased reliance on renewable energy sources require a data-driven grid that is flexible, configurable, and can maximize energy resources at the transmission level. The modernized grid requirements include seamless integration of Distributed Energy Resources (DER) through an adaptive, automated system in the substations. The substation is the point of highest leverage in the evolution of modern grid architecture. The process starts with the widespread adoption of scalable open platforms for the substations' protection, automation, and control functions.

Modernizing the PAC infrastructure at substations is a massive undertaking, but the potential return on investment is significant. According to Anthony Sivesind, Senior Principal Engineer, Salt River Project, implementing software-defined automation and control will reduce the number of devices in a substation by 50% and result in a 76% reduction in operation and maintenance costs.

ELECTRIC POWER GRID ARCHITECTURE



Utility substations are now at the crossroads of a two-way flow of electricity and in the crosshairs of grid evolution. At the heart of the substation are the wires, transformers, and switch gear – elegant and durable yet expensive backbone infrastructure that will remain vital to maintain resilience and reliability even as so many changes are happening around them. Part of the story is that the capacity of this infrastructure requires expansion, and we will see capital investments in existing and new substation power infrastructure. But crucially, the technologies that monitor and protect this infrastructure while controlling the power flow through the substations – the protection, automation, and control systems (PAC systems), are not up to the challenge of the 21st-century grid. These legacy systems were designed to handle distribution from central power generation plants and are not equipped for the automation and data analytics required for building a power grid with distributed energy resources (DER).

> Tens of thousands of substations across North America currently rely on legacy systems to manage, maintain, and operate millions of devices that are part of an operational technology (OT) and information technology (IT) infrastructure of the power grid.

There are two related problems in the substation PAC systems deployed today. On one hand, there is simply a lot of older analog and analog-digital hybrid equipment that has been humming along for 40, 50, or even 60 years. On the other hand, even modern-day conventional PAC equipment (sensors, relays, controllers) use proprietary hardware and software that requires on-site intervention for maintenance and upgrades. In both cases, utilities are burdened with expensive system maintenance and security. Whenever there is a problem or the need for an upgrade, technicians must be sent into the field to handle installation, commissioning, configuration, provisioning, and testing.

By contrast, the utility gains operational efficiency and flexibility in a substation with standardized hardware and open PAC software. The hardware and infrastructure software are defined and documented so that utilities can choose which application software to run on that platform. Additionally, utilities will have expanded connections to the management interfaces of the system to secure it and supervise all aspects of the hardware and software through its lifecycle.

Scalable, open platform architecture for substations helps improve reliability, safety, and security.

Adopting this architecture will enable grid operators to exploit powerful computational capacity for advanced monitoring, diagnostics, and more security. Open platform systems unlock the promise of expanded automation and analytics. It makes it possible to aggregate and normalize data at the edge, which will help utilities understand the impact of renewables in real-time and unlock the value of data using machine learning advanced automation to ensure efficient, safe, and dependable energy distribution in the future.

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CENTRALIZATION AND VIRTUALIZATION ARE THE KEY

In the future, we envision a revolutionary change to the way PAC is implemented by adopting a standardized, scalable, open-platform architecture that enables the consolidation of many devices (of the same or different make, model, age, type, etc.) into a small cluster of resilient servers with redundancy "built-in" to the architecture. Further, this will yield the benefits of flexibility, scalability, and cost reduction, which will unblock the evolution of the grid at a time of tremendous external forces. But to understand the transformation, the key technology that allows for this consolidation of devices and functions, virtualization, must be examined. The term virtualization is used to refer to a quite specific technology, but also a class of techniques to achieve abstraction and portability of software, and finally, a general concept of being able to abstract (to virtualize) whole systems to another context or another place (i.e., a virtual copy or a twin in the cloud).

In the future grid, all these meanings and forms of virtualization will be utilized, but virtualization technology is the key for consolidating the PAC functions, as implemented in a software layer called a hypervisor. The hypervisor is loaded onto the server and allows a supplier of software to load their applications into the "virtualized server" in such a way that the software they load is allocated portions of all the resources of the server in a form called a virtual machine so that their software acts as if it has a server (albeit smaller capacity) all to itself. This technology has unlocked the change to how PAC systems will be designed and deployed in the future. The paradigm is taking root and is being tested and evaluated by grid operators for the centralization of all the functions of the substation in the virtualized server cluster.

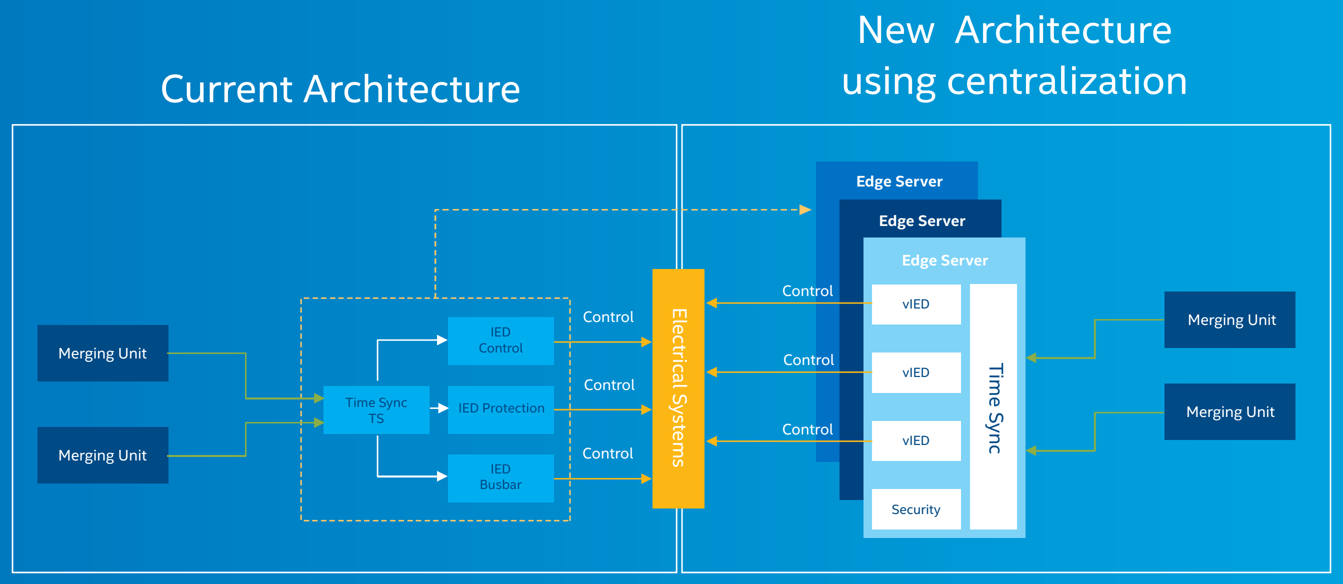
The substation is just one node of the grid, and as indicated above, there are 10s' of thousands of substations in North America today. Further, what happens in each substation and on the power lines between the substations can have a broad and nearly immediate impact across the grid because the PAC systems within the substation are in communication with a central management system (actually, a couple of tiers of the management system are in place). This information/communications connection from the substation to the central system must also evolve so that the grid can adapt to the changing environment.

The primary system that connects the substations to the central management center is SCADA (supervisory control and data acquisition), which utilizes standardized communications protocols to connect with one or more RTUs (remote terminal units) in the substation. The RTU has been a hub for the telemetry (for monitoring and remote control) of the substation to be exposed to the central system and the operator in the central operations facility. However, the RTUs and the SCADA protocols in widespread use are neither flexible nor scalable, so they do not easily or cost-effectively accommodate change. The RTU functionality will be virtualized and expanded, transparency to the hardware and software in the field will be expanded, and data from the substation will enable closed-loop automation using machine learning and artificial intelligence technologies.

- Migrating the PAC functions into virtualized server clusters will give utilities more secure systems that can be automated, upgraded, and monitored from the centralized control system. These system enhancements will eliminate the need to send maintenance crews into the field- helping reduce installation, commissioning, operation, and maintenance costs.

- Virtualization of PAC will facilitate self-diagnostics for optimum up-time, centralized maintenance and upgrades, flexibility, and enhanced security.

- Installing new hardware systems to deploy new applications will no longer be necessary. The software will be independent of hardware, reducing CapEx and OpEx costs. Security will be enhanced through device monitoring and onboard security features in each device.



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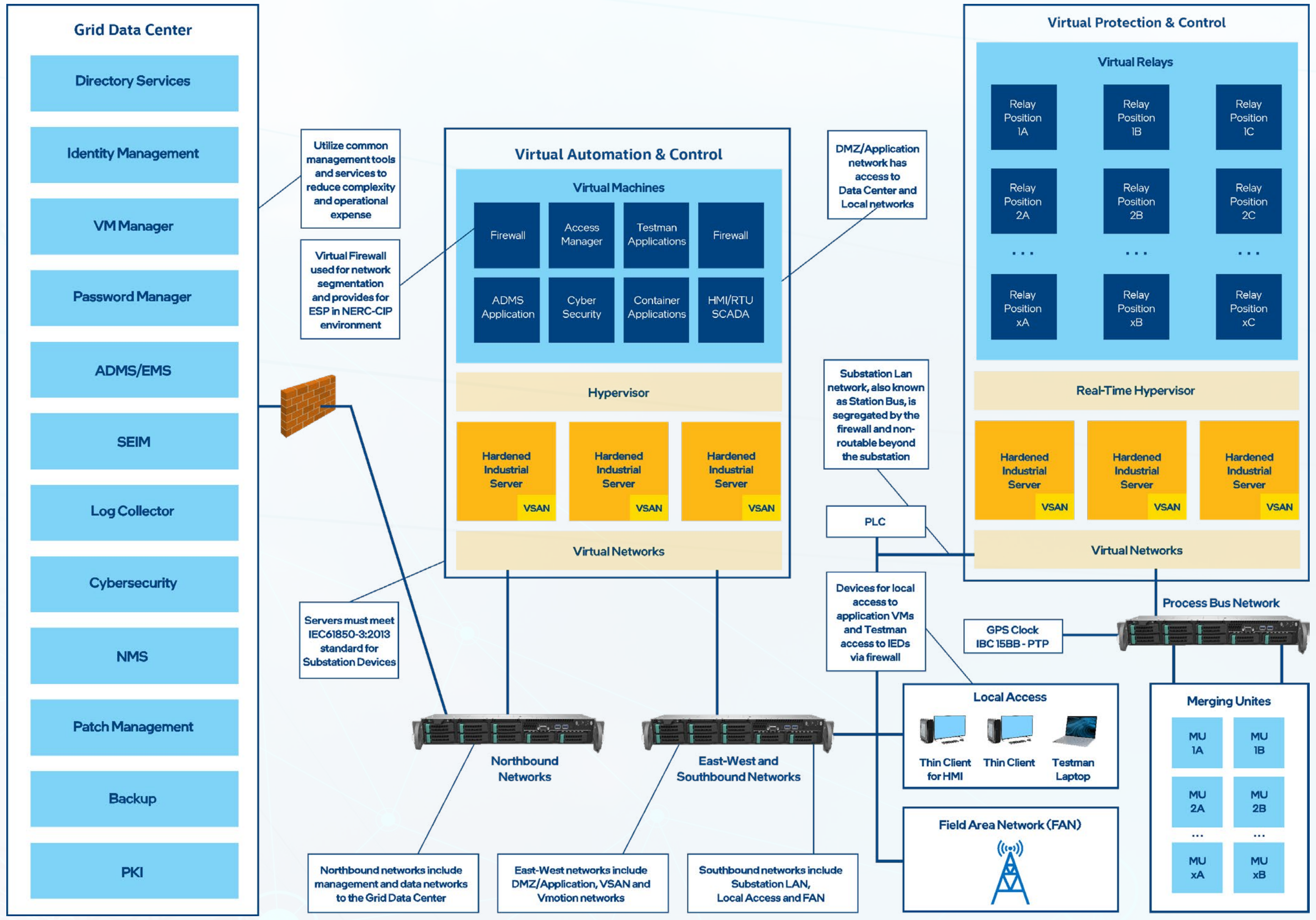
WORKLOAD CONSOLIDATION

The increased security and efficiency of virtualized grid operations opens the door to even greater optimization of grid management when advanced computing allows for consolidation of PAC and IT-centric functions. The substation control house (control room) is not the same environment as an office or data center. And substation control rooms are not all the same – many factors come into play: the local climate, the population density of the area, the size of the substation, the voltage levels at the transformers (e.g., 200kV or more, vs. 15kV or less have different requirements), the age of the substation, and the economic prosperity of the region. Over the past century, power system engineering standards have been created to give the suppliers, installers, and operators confidence that the PAC systems being deployed will survive and operate when called upon no matter the scenario or timing. The ability to operate reliably in the most challenging times sets the grid operations apart. Among these international standards is the suite of standards from the IEC, IEEE, and others, including the IEC 61850-3 standard. The server hardware used for the virtualized PAC systems in the substation is subject to the same environment and should meet these international standards. The terminology used to describe these servers is “hardened,” “ruggedized,” or “61850-compliant”. Several leading vendors offer 61850-complaint servers in the market today, and the VPAC Alliance Hardware Working Group is actively developing guidelines and additional requirements to facilitate the interoperability and interchangeability of these server products.

The standardization of the VPAC server goes beyond the environmental considerations. It includes technologies to effectively enable the convergence of PAC functions with more common IT-centric applications into the open scalable infrastructure discussed in the introduction. This level of consolidation means that everything from firewalls and routers, security and digital surveillance, user interfaces, computing system management, data archiving, data analysis, and the PAC power system applications can be run on the cluster of as few as two hyper-converged servers. This level of consolidation of different types of workloads is brought together in the field and adapted and changed as needed over time, often referred to as “software-defined infrastructure.”



Virtualization of Automation & Control And Protection & Control High Level Architecture

Software-defined infrastructure that can adapt and support the diverse workloads will be the edge intelligence hub that processes and analyzes data from multiple sources to make local decisions in real-time and will be used to optimize information flow and decision-making across the grid.

Enabled by virtualization technology, the ability to centralize PAC functions onto ruggedized standard hardware reduces the upfront cost of deployment, reduces operational costs over time, and reduces risks. From a business perspective, adding workload consolidation capability accelerates the rate of innovation at the edge.

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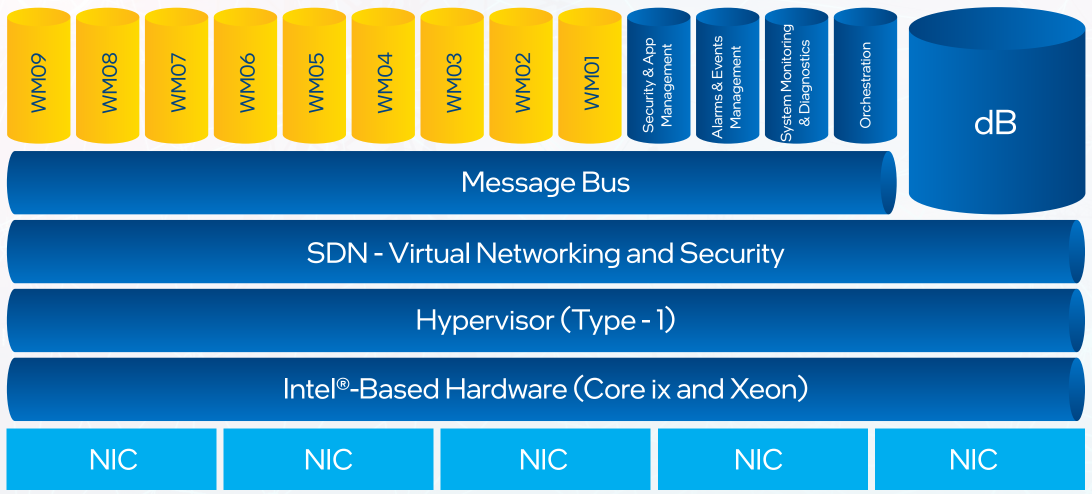
INTEGRATING DISTRIBUTED ENERGY RESOURCES INTO SECONDARY DISTRIBUTION

One of the trends in electric power generation has been the explosion of distributed energy resources at small (residential and small commercial) and medium-sized (campuses, communities, enterprises) customer premises. These were once almost exclusively grid-tie PV generation systems but now increasingly include PV plus or even pure battery storage systems. These systems most often couple to the grid at the lowest distribution voltages. At a high enough concentration, these resources create reliability problems, trigger capital expenditures for grid equipment upgrades, increase operational costs, and even raise safety concerns for the utility. Depending on the way the distribution grid is designed for the community in which the distributed energy resources are connected can impact how the utility can adapt.

Secondary Substation Digitalization using the Virtualization Technology



Utilities in Europe and the Asia Pacific distribution grid architecture includes a so-called “secondary substation” at the edge of the grid to distribute electricity to customers. Secondary substations deliver electricity to homes and businesses, ranging from a few hundred to a few thousand end users. It is estimated that more than 28 million secondary substations are in service worldwide. Most of these stations had no communications or computing technologies installed initially, but new secondary substations are built each year, and older stations are overhauled. In these updated secondary substations, several common technology functions have been introduced, including data concentrators for smart meters on the low-voltage feeders of the station, monitoring of the low-voltage feeder current and voltage levels, power quality monitoring, and others. However, it is the state of the market that each of these functions is implemented by installing a dedicated “fixed-function” device with its unique requirements. There can be five or more such devices in each secondary substation for some leading utilities. But, physical constraints in these substations mean limited real estate is available for adding new hardware for every application. Moreover, it is not economical to manually replace or upgrade every device. As the complexity of the distribution grid increases, the utilities are finding that new functions are needed in the secondary substations, which are expected to continue to evolve.

Looking to the same concepts mentioned in the introduction, including open hardware and open systems, virtualization, and workload consolidation, a consortium of utilities and their suppliers in Europe have formed the E4S Alliance to educate the market and to create an open specification document to guide the evolution of the secondary substation PAC systems. Intel is one of the founding members of the E4S Alliance and has led some of the key areas of developing an E4S Specification, including the Hardware section of the specification.

Intel has invested with Delta Electronics, Inc. to accelerate the market transformation, which has produced a modular, open, and ruggedized (61850-compliant) E4S system aligned closely to the E4S Hardware Draft Specification. The modular system includes slots for two compute modules (each with an Intel Core-i7 CPU), a power module, and a switch module. Multiple suppliers can customize up to four additional I/O modules for application-specific use. The system is brought together by a chassis with a standardized passive backplane that has connectivity for ethernet and PCIe communications between the modules.

Several E4S Alliance member companies have ported their infrastructure software and grid automation applications to the Delta Electronics E4S System for testing in the lab. Furthermore, the system has been demonstrated by Enedis, ABB, Broadcom, and Kalkitech at public tradeshows.

The Delta Electronics E4S solution is an example of a compact open platform with a multi-vendor modular format where analog-to-digital Grid interfacing connections can be brought into the chassis, computing, and networking. The system is designed to comply with IEEE-1613 and IEC 61850-3 standards to enable deployment in the harsh environments of secondary substations. Reducing the number of individual devices, achieving footprint savings, and enabling pre-configuration of modules before installation potentially reduce overall capital expenditures (CapEx), operational expenditures (OpEx), and utility integration costs.

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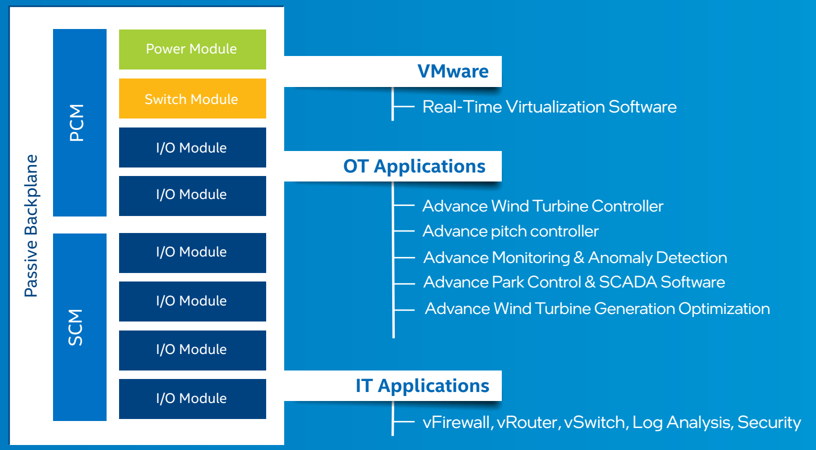
VIRTUALIZATION TECHNOLOGY IN WIND POWER GENERATION

The same workload consolidation and virtualization concepts applied in substations are being tested for use in the inner workings of wind turbines and interface power electronics. Virtualization of turbine control systems promises to improve operation and maintenance, efficiency, and security. Wind turbines have multiple control sub-systems for blade pitch control, rotor, power conversion, safety, and performance optimization, and SCADA RTU functions can be virtualized and hosted on a cluster of servers in much the same way as PAC functions are consolidated within a substation.

The number of wind turbines in operation worldwide is 743,000 as of January 2022[*], and many of the installed base of turbines will need to be refurbished or replaced in the coming decades. New turbine designs are also in development. Adoption of open standard systems with virtualization at the coupling point of the turbine to the grid will give wind turbine farm operators the ability to deploy whatever software they prefer to optimize the wind farm performance with analytics (improved efficiency, reduced maintenance costs, longer lifetime of components), regardless of which OEM supplied the turbines.

Wind Turbine Control Digitalization using the Virtualization Technology



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[*] Global Wind Energy Council (GWEC)

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RE-ARCHITECTING THE DISTRIBUTION GRID – MICROGRID TECHNOLOGIES

Microgrid is another term widely used but has a couple of different meanings depending on context and perspective. The US Department of Energy has provided a definition: “a microgrid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island mode.” This definition is broad enough to include a section of the distribution grid, for example, a distribution feeder owned and operated by the utility. This corporate or educational campus is owned and operated by a commercial entity and other institutions.

Microgrids enable consumers to utilize lower-cost and/or cleaner energy sources while retaining or improving supply resiliency. This potential for supporting mission-critical business operations using clean, sustainable energy is attracting so much interest. However, realizing the full potential of microgrids requires proper design to ensure the right mix and balance of distributed energy resources to achieve the owner’s reliability and cost objectives. In practice, the operation of the microgrid can become complex considering (a) that each of the DERs has its configuration parameters and APIs, (b) that the utilities are increasingly requesting direct access to the major DER assets (such as in Rule 21 of California), and (c) the orchestrated operation of the assets is technically challenging when it is required to ensure smooth transitions under all circumstances such as major disruptions to the DERs, loads, or the external grid. Using a standardized open automation and control platform, much like vPAC architecture, allows the microgrid owner to adopt the best-available applications and cost-effectively evolve the microgrid as new DERs are added, or new policies and requirements are given from the utility.

- The microgrid control and automation platform enables power resource management, grid connectivity, load shaping, and grid support services.
- Facilitate the ability to adjust based on real-time local and public data insights. Moreover, standardization will streamline control loops to enable seamless transitions between grid-connected and island modes.

8 MACHINE LEARNING FOR ADVANCED AUTOMATION

Machine Learning applications, including closed-loop automation, predictive and generative analytics, and Artificial Intelligence (AI) applications, will play a crucial role in enhancing the future power grid's efficiency, reliability, and overall performance. Real-time data analysis and predictions will help manage proactive maintenance, potential faults, and power flow optimization across transmission lines. The overall health of the grid will be enhanced, as automated closed-loop automation will allow operators to predict load based on historical and real-time data, facilitating improved stability and reliability.

Sophisticated algorithms can also optimize the charging and discharging cycles of energy storage systems, and automatically adjust the power output of generators in real-time to maintain the balance between generation and consumption. Automated control systems improve the reliability and adaptability of protection systems by continuously learning and adjusting protection settings based on the evolving characteristics of the power system. These data-driven algorithms and machine learning systems can be applied to solve optimal power flow problems, optimize power generation allocation, and manage system constraints while minimizing costs. Monitoring the data traffic patterns, flows, and even data content with real-time analysis by machine learning algorithms can increase the security of the power system by helping to identify cyberattacks as soon as they appear. This is crucial for safeguarding critical infrastructure.

Integrating predictive and generative analytics into automation and control systems for power grids is an ongoing process driven by the need for more resilient, flexible, and intelligent energy systems. Integrating algorithmic machine learning controls into the grid can support operators by providing real-time insights and recommendations, improving decision-making in complex situations. This human-machine collaboration enhances the overall efficiency of power system control. Data-driven closed-loop automation will become the cornerstone of the future grid, and many of the algorithms and machine learning models will be located at the substation.

9 CONCLUSION

Our energy sources are changing to meet the imperative for a sustainable economy. The changes are not completely compatible with the power grid architected and built in the 20th century. Renewable sources, distributed energy resources, and a shift from hydrocarbon fuels in transportation, manufacturing, heating, and cooking are all factors impacting the grid. As today's grid is becoming bidirectional, utility leaders are past the stage of reimagining and are moving to reinventing grid operations.

The technologies to unlock the next generation of grid operations have become available in the last 20 years, including advanced high-speed networking, high-performance efficient multi-core CPU's, machine learning hardware and software, and most importantly, virtualization. Bringing these technologies to focus for the industry requires broad participation and collaborative engagement between the grid operators and their ecosystem: suppliers of computing hardware, software, security, networking, integration services, testing services and products, standards bodies, and regulators. Intel has worked with leading utilities to form the VPAC Alliance and the E4S Alliance, which are effective organizations for creating this focus and accelerating the reinvention.