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Development of Virtualized Centralized Protection and WAMPAC Systems: A Review

Meysam Pashaei, *Senior Member*, *IEEE*, Kimmo Kauhaniemi, *Member*, *IEEE*, Hannu Laaksonen, *Member*, *IEEE* and Nikos Hatziargyriou, *Life Fellow, IEEE*

***Abstract*—Power system protection has evolved significantly due to the ongoing energy transition and digitalization. The development and standardization of information and communication technologies (ICTs) used for power system protection, monitoring, and control have led to the digitalization of substations and the introduction of new protection and control schemes. These include virtualized centralized protection and control for intra-substation applications, as well as advanced wide-area monitoring, protection, and control (WAMPAC) for inter-substation applications. This paper reviews the development of virtualized centralized protection, with a focus on key practical advancements, emerging technologies, and state-of-the-art studies in centralized protection and control (CPC) and WAMPAC systems. It also identifies directions for future research.**

***Index Terms*—Centralized protection and control, cloud and edge computing, digitalization, 5G, IEC 61850, machine learning, virtualization, WAMPAC.**

I. INTRODUCTION

Power grids are undergoing radical changes in the age of renewables to accommodate ever-increasing energy demands and to mitigate global environmental issues [1]. The high integration of green energies, however, may pose several challenges to the power system. Inverter-based resources (IBRs) can affect the short circuit power of networks, which in turn may lead to stability issues at the high-voltage (HV) level. These challenges also include protection-related issues in medium voltage (MV) and low voltage (LV) levels [2], necessitating a shift from aging substations designed for one-directional power flow to digital ones capable of adapting to the dynamic integration of renewables [3].

Grid operators are seeking comprehensive digital solutions for sustainable power generation to fulfill the growing demand for renewable energy sources and achieve decarbonization objectives while ensuring grid stability [3], [4]. These requirements dictate trends in digitalization at the substation and enterprise levels, leading to increased operational technology (OT) and information technology (IT) system complexity, especially at the station level. This involves several functions and devices including human-machine interfaces (HMIs), gateways, fault recording, cybersecurity components, such as intrusion detection, secure remote access, and many more described in [5]. Physical security components such as access control, drones, fire alarms, and other systems required at the enterprise level further contribute to growing complexities. As a result, challenges emerge in managing the rise in digital assets, the need for more space in substations, and networking and cybersecurity issues. This is where virtualization and centralization can offer advantages in future modernized grids [5]. The protection, automation, and control (PAC) systems in such smart grids require ultra-reliable low-latency communication [6] and high -speed computers previously unavailable in power systems of the past. However, commercially available off-the-shelf software and hardware can now facilitate the shift to smarter grids using CPC schemes, such as the Constellation Project, which achieves annual savings of 19 million tons CO_2 and helps meet the UK net-zero target by 2025 [3].

The core concept of CPC is to consolidate the multiple bay-level protection and control functionalities into a centralized device within a substation, with main benefits including enhanced functionalities and reduced lifecycle costs [7]. The definition of CPC is one of the key elements in this paper. However, CPC schemes can be interpreted differently depending on the perspective. For example, a protection scheme might be considered centralized when viewed from the location of a secondary substation but distributed from that of a main substation. The IEEE Power System Relaying Committee's Centralized Substation Protection and Control

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Working Group K15 defines CPC as "a system comprised of a high-performance computing platform capable of providing protection, control, monitoring, communication and asset management functions by collecting the data required for these functions using high-speed, time- synchronized measurements within a substation" [8]. The CPC concept dates back to 1969, when research explored fault protection using digital computers [9]. This research predicted the use of digital computers for centralized protection and control devices that are now commercially available [1]. These efforts led to investigations into the Prodar 70 computer system [10], with test results presented in 1971 [11]. This system offered faster breaker tripping, greater dependability, and economic viability. It was readily adaptable to digital transducers, but required significant programming, input requirements, computer speed and security [9]. After these studies, extensive research was conducted between 1969 and 2025. The research focused on computer relaying, centralized protection, integrated protection, wide-area monitoring, protection, and control. The market introduction of smart substation control and protection devices, such as ABB's SSC600 in 2018, followed by its virtual version (SSC600SW) in 2023, has further advanced CPC, which can adopt different architectures. Five of these architectures are defined by Working Group K15 [8]. Assessment of viability, considering reliability and cost for different Details on CPC structures, and the first real-world experience of such schemes can be found in [12], [13], respectively. These analyses showed higher availability compared to traditional systems due to functionality redundancy. To implement these five architectures, various technologies are required to overcome barriers in CPC deployment. One evolutionary step in CPC is making protection and control software-driven, resulting in virtualized CPC, commonly known as virtual protection and control (VPC) [14]. The integration and consolidation of various workloads into a shared hardware platform is one of the fundamental tenets of the Industry 4.0 movement, which includes applications like digital substations [15]. Therefore, this paper reviews the evolution of virtualized centralized protection from both technological and application perspectives from 1969 to 2025, with a focus on recent years. The key enablers, including IEC 61850, cloud and edge computing, virtualization technologies, digital twins of relays, test devices and power systems, 5G, time synchronization, redundancies, and artificial intelligence (AI), as shown in Fig. 1, will first be reviewed in Section II. These main components of CPC and VPC will then be applied to various uses in modern power grids in Section III. Finally, we discuss future research needs and conclude the paper.

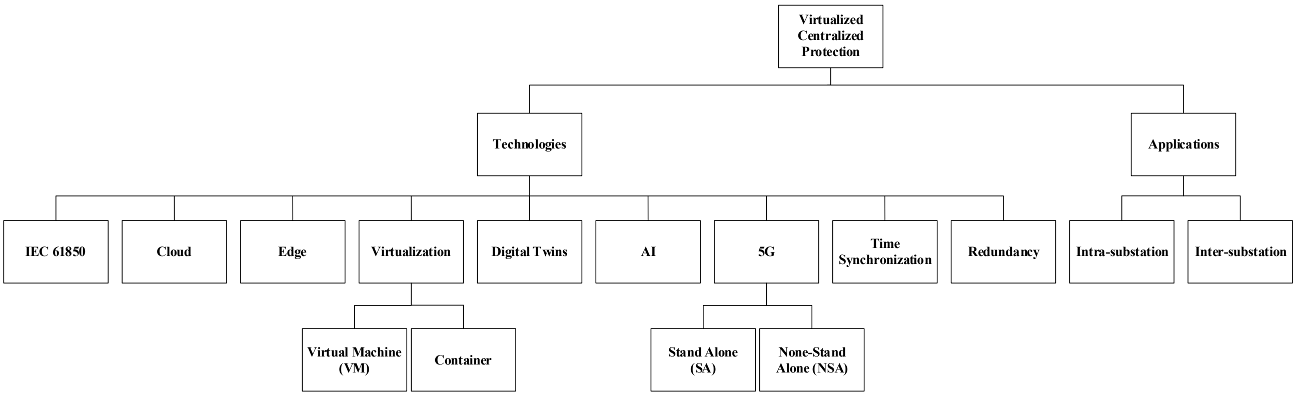

Fig. 1. The main focus areas of this review paper.

II. TECHNOLOGIES FACILITATING CPC AND VPC IMPLEMENTATION

The general overview of CPC is illustrated in Fig. 2 [16], [17], where all measurements within a substation are sent via high-speed communication to CPC devices to protect the whole substation. This section describes different levels of modern CPC and VPC based on key technologies. By studying these components, as shown in Fig. 1, facilitates a better understanding of the merits and demerits of centralized schemes. A modern virtualized centralized protection architecture can then be formed by combining these key enablers.

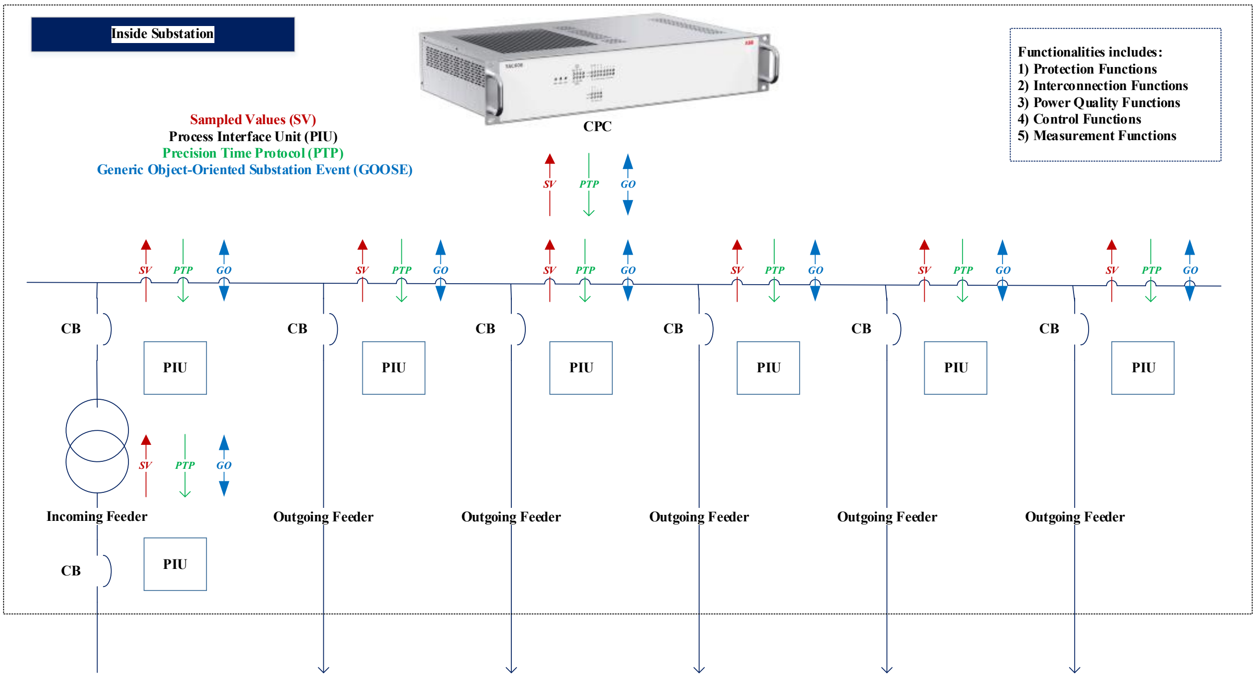

Fig. 2. A general overview of CPC schemes [16], [17].

A. IEC 61850 Standard

IEC 61850, a fast standardized Ethernet-based communication protocol, is one of the key enablers for the implementation of CPC [7]. This standard divides the scheme into three main levels, namely process, bay, and station, as shown in Fig. 3. Process interface units (PIUs) or merging units (MUs) reside at the process level. They communicate digitized measurements and input/output (I/O) signals, such as status of circuit breakers (CBs), to the bay level, where traditional intelligent electronic devices (IEDs) are placed and can act as intelligent MUs. In CPC and VPC, these IEDs are removed with a single physical or software defined protection and control system that can be installed in a substation as indicated in Fig. 3. Therefore, the process and station levels are the most important aspects of centralized schemes.

1) Process Level

This level includes low voltage circuits of primary equipment, CBs, disconnector switches (DS), and the secondary circuits of current and voltage transformers (CTs/VTs) [18]. The use of MUs in this level allows for the complete separation of centralized protection devices from measurements, including those from new sensors or conventional CTs and VTs. This separation in turn provides flexibility for arranging centralized devices optimally and for changing algorithms dynamically without changes to physical wiring since all measurements are accessible to any computers running CPC [19]. The process bus solution is critical in the implementation of CPC for existing distribution systems. It is defined in IEC 61850-9-2 (LE), which facilitates the sharing of sampled values (SVs) from instrument transformers or sensors with CPC or relays [7].

References [20], [21] present three possible schemes for designing CPC. The first one uses copper connections between primary devices and CPC, while the second and third schemes employ point-to-point (P2P) and IEC 61850-based process bus [21]. P2P connects MUs or PIUs directly to the CPC using fiber-optic cable. In P2P schemes bandwidth is not an issue, as a Sampled Values (IEC 61850-9-2LE SV) stream consumes approximately 6Mb of a typical 100Mb link [17]. However, IEC 61850-based process buses require switches, external clocks, and additional fiber-optic cables to connect MUs to relays. This solution eliminates some devices, including fuses, lockouts, and test switches [21]. Ethernet network-based time synchronization protocols, such as precision time protocol (PTP), dedicated connections, such as IRIG-B, or a combination of both, ensure that all relays and MUs are time-synchronized [21]. This type of process bus offers the benefit of interoperability with devices from different vendors and the possibility of sharing data from one MU or relay with other protection and control devices, irrespective of the number of available communication ports. Studies indicate that the process bus solution is more expensive than traditional approaches when considering only the costs of protection and control (P&C) devices and secondary systems, which can be attributed to the addition of merging units and a new generation of relays. However, according to [22], 75 % of traditional P&C system installation costs in North America are related to labor, which demonstrates that process bus solutions can dramatically reduce time and cost expected due to reductions in space requirements, labor costs, and system maintenance. Table I compares different CPC structures based on the connection of PIUs to CPC devices. The higher unavailability shown for IEC 61850 can be improved by selecting high-quality components with high meantime between failures (MTBF) values, by designing simpler systems, or by adding redundancies. Redundancy improves reliability but increases complexity [21].

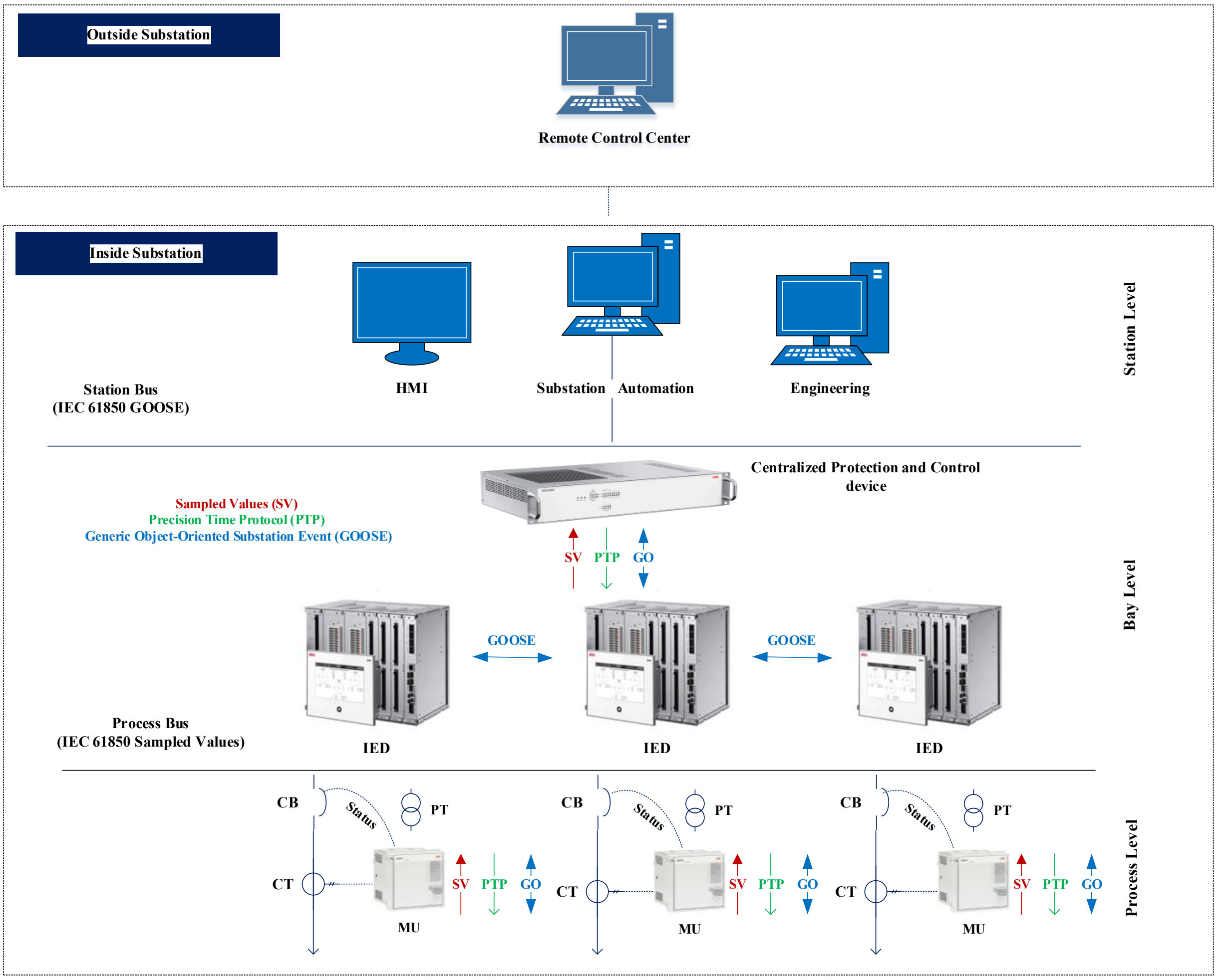

Fig. 3. Different levels of IEC 61850 in CPC schemes.

TABLE I
DIFFERENT CPC STRUCTURES BASED ON THE CONNECTION OF PIUS TO CPC DEVICES [20], [21]

CPC Type	Advantage	Disadvantage	Reliability	Availability	Speed
Hardwired	Using internal clock of relay Eliminating Ethernet switches Simple engineering Higher reliability at lower cost	Limited number of CPC ports Not applicable for large substations	High	Highest	Fastest
P2P	Using internal clock of relay Eliminating Ethernet switches Simple engineering	Limited number of CPC ports Not applicable for large substations	Medium	Moderate	Moderate
IEC 61850	High interoperability Sharing data with IEDs	Needing switches and external clocks	Lowest	Lowest	Lowest

One of the considerations at the process bus level in CPC is a well-defined PIU, including MUs with 80 and 256 samples per cycle, remote input/output (RIO) units with high-speed high-break (HSHB) contact outputs, which compensate for generic object-oriented substation event (GOOSE) message delays [23]. A review of process bus, including IEC 61850-9-2 and IEC 61869-9, is presented in [24]. IEC 61850-9-2 is primarily concerned with the communication of sampled values in a substation automation system, whereas IEC 61869-9 offers a thorough standard for digital instrument transformers that covers their functionality, compliance with IEC 61850-9-2, testing, and technical specifications. Improved safety arises from reduced exposure to high voltage components is an additional advantage of the process bus [24]. Data from the process bus fed into Internet of Things (IoT) and data analytics tools can support asset management and preventive maintenance [24]. IEC 61850-9-2 LE supports sampling rates of 80 samples per cycle for protection applications and 256 samples per cycle for measurements, revenue metering, digital fault recorders, and power quality analysis. It has lower bandwidth requirements than the original standard, making it suitable for cost-sensitive applications and digital systems with less-demanding requirements [24], [23]. The sampling rate defined in IEC 61869-9 (4800 Hz-14400 Hz) is independent of power system frequency, whereas in the LE, the sampling rate varies with the power system frequency. Unlike the lightweight edition with fixed dataset of four currents and four voltages, IEC 61869-9 offers flexibility in configurations and allows various combinations up to 32 channels, providing adaptability in network bandwidth. The paper also discusses network load based on sampling rate [24]. Overall, if process bus solutions are well engineered and implemented, they can reduce terminations and connections, enable remote operations that reduce site attendance and improve personnel safety, and lower substation construction time and costs [20]. Moreover, CPC and process bus solutions should not be considered only from installation and commissioning perspectives but also from those of operation and maintenance. For instance, philosophy and testing of protection require revisions in the absence of lockout relays and test switches in process bus solutions compared to traditional systems [21].

2) Station Level

The station bus, as defined by IEC 61850-8-1, provides horizontal relay-to-relay communication, thus reducing copper connections and wiring between relays [7], [25]. Station-level protection and control systems are primarily composed of HMI and substation automation systems (SAS) [18]. SAS gathers, centralizes, and processes data from multiple sources, including remote control centers, MUs, and bay-level IEDs. HMIs are used by operators to monitor and manage substations locally [18]. Most of the solutions presented in subsection D of Section II (Virtualization Technologies) and Section III (Applications) primarily discuss this level. The engineering process of CPC, according to substation configuration description language (SCL) in IEC 61850-6, is presented in [26], including system specification, system configuration, and device configuration. In this process, different files such as system specification description (SSD), substation configuration description (SCD), IED capability description (ICD), instantiated IED description (IID), and configured IED description (CID) are used. These files are vendor- and device-independent and outlast devices' lifetimes.

B. Cloud Computing

According to the CPC definition presented by Centralized Substation Protection and Control Working Group K15, monitoring and asset management are important functions, as well as protection and control. Data aggregated in the cloud and at the edge can play a significant role in these areas. Cloud computing is a well-established paradigm in the IT industry that provides on-demand access to computer system resources, particularly data storage and computational power, without requiring direct active management [27]. Large clouds often have functions distributed across several locations, each serving as a data center. Cloud computing is positioned at the highest level in Fig. 3, where applications handling large amounts of data from different locations can operate. However, it is not commonly used in substation automation primarily due to the real-time requirements of protection applications [28]. Privacy and security can also pose challenges. To address these, several solutions tailored to specific applications have been proposed. For instance, federated learning based on blockchain has been suggested to shift the training process from the cloud to edge devices in centralized machine learning-based applications [29]. Cloud computing is categorized as public, private, and hybrid, offering data management, scalable and flexible resource allocation, disaster recovery, backups, remote access to real-time data, monitoring, device control, cost-effective solutions and better collaboration [27]. Edge computing, however, enables faster responses locally and preprocesses data for the cloud. This makes edge computing suitable for protection applications. Therefore, we primarily focus on this computing platform in this paper.

C. Edge Computing

Edge computing is a distributed computing platform that eliminates the need for a centralized cloud-based system by bringing computation and data storage closer to the data source [30]. This approach aims to provide better decision-making with low latency, enabling real-time applications, improved response times, bandwidth optimization, data privacy and scalability [30]. The increasing number of sensors and generation of vast amounts of data have prompted utilities to modernize their substations and incorporate more intelligence at the edge [4]. This solution enables continuous real-time data analysis with minimal latency and higher processing power at the edge (substation), necessitating the use of IEC-61850-3-compliant commercial-off-the-shelf server hardware in substations and software-defined PAC systems [4]. The environmental requirements imposed by IEC 61850-3 and IEEE 1613 for substation computers are stricter than those of data centers [31], [32]. Cloud-edge computing with 5G for power system applications has been proposed in the literature [33]-[35]. Examples include fault location, adaptive differential and distance protection, trip conditioning, fast edge-to-edge inter-trip between two edge devices, switch controllers, and interlocking applications. The use of edge technology and 5G standalone (SA) for smart grids, including a comparative analysis of quality of service (QoS) measurements with 5G non-standalone (NSA), which requires both LTE (eNB) and 5G (gNB) base stations, is studied in [33]. 5G NSA relies on the 4G cell structure and core network. However, 5G SA, which has been prioritized in urban areas, can perform 5G functions faster [33]. More than one million private networks are anticipated in Europe by 2030, offering industries the opportunity of parametrizing networks and leveraging their full performance [2]. Researchers in [35] explored the use of edge computing to improve communication links in isolated microgrids, which are primarily in rural areas. However, in such areas, edge-computing might not be cost-effective [33].

Function allocation is also crucial in the design of CPC. Table II outlines recommended functions for edge and cloud deployment in CPC schemes as general guidelines. Based on IEC 60834-1, communication can enhance functionalities for some applications. This can also affect function allocation. Permissive and blocking distance are among the enhanced functionalities while inter-trip and differential communication are applications requiring communication [33]. Therefore, the latter are the best candidates for allocation to the edge. Apart from protection functionalities, control and monitoring functionalities with less strict communication requirements can be allocated to the edge, with the benefits of accessing data from various points in the system, thus enabling advanced functions for better decision-making [33]. Fault detection of underground distribution cables is shifted from the main station to the edge due to limited communication bandwidth, computational burden and slow responses of the main station in [36]. Another role of the edge can be data preprocessing before transmitting data to the cloud for applications such as predictive maintenance and fault forecasting [33]. Edge computing for digital substations for up to ten feeders, using virtualized centralized system with Docker containers for distance and differential protection functions was studied in [37]. Various other functions such as faulted-phase selection algorithms have also been implemented in this software-defined centralized platform [38], [39]. The implementation of phasor measurement units (PMU) using IEC 61850 sampled values in this platform demonstrates the capability of CPC in digital substations for deploying Wide-Area Monitoring, Protection, and Control (WAMPAC) systems [40].

TABLE II
FUNCTION ALLOCATION TO EDGE AND CLOUD [2], [33]

Function location	Time requirements	Features of candidate functions
Cloud	> 1 sec	Back up functions
Edge	5 ms – 1 sec	Inherently needing telecommunication, back up functions
Site	< 5 ms	Main functions

D. Virtualization Technologies

Virtualization, which decouples software from underlying hardware to accommodate functionalities from different vendors and allows for efficient hardware utilization with more functions, has become a standard practice in IT [5], [41]. In some cases, devices in traditional systems are vendor specific, meaning that modifications require specialized skill sets, incurring additional costs compared to virtualized systems with limited hardware. Moreover, these devices require power supplies, cooling, maintenance, and ventilation. Using proprietary hardware for various purposes may lead to higher maintenance, training, and logistical costs. Another disadvantage of hardware heterogeneity is that it can hinder vendor compatibility [42]. Reductions in hardware footprint are also noted in [4], [42] as a key benefit of software-defined protection and control schemes. A virtual substation requires less physical space, fewer connections and has lower environmental impacts [4]. Virtualization alleviates these issues by consolidating multiple tasks from various computing devices into a single platform, encompassing both IT software, like engineering tools, and OT software, like protection and control [41]. It also enables remote operation in real-time globally, further contributing to time and cost savings. Furthermore, system-wide monitoring for utilities is now more important than in the past to inform better decisions regarding power quality, asset management, renewable integration and related areas [41]. Testing using digital twins and remote upgrades of substations are the other benefits of software-defined substations [43]. This approach opens the door for those with less expertise in hardware. These are reasons why virtualized protection and control has become a focal point in power system protection. Software-defined technology is mainly used in the communication field and data centers. It employs virtualization of physical devices and software to mimic hardware-level functionalities [43]. One challenge posed by virtualization is at the organizational level, where mutual collaboration among different fields is required. This may also alter the structure of organizations [5]. Modernization of substations will likely change the status quo of separating IT and OT teams [31].

Virtualization technologies are discussed in two main categories: hypervisor-based and container-based [44], [45], as shown in Fig. 4. The hypervisor partitions the host hardware and allocates computing, storage, and networking resources among the isolated partitions. The main difference between hypervisor-based and container-based virtualization is that the latter shares the host's kernel and operating system, offering less isolation.

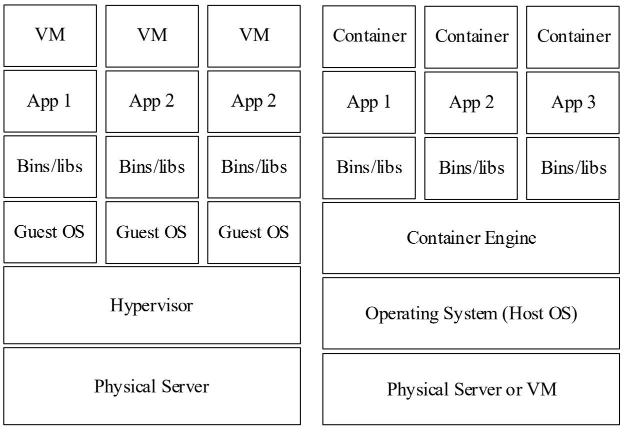

Fig. 4. Virtualization Technologies: VM and Container [43], [46].

Hardware-level virtualization, such as KVM, which is widely utilized in cloud environments, is not well-suited for edge computing. This limitation stems from the fact that edge computing is designed to provide low-latency, bandwidth-efficient, and resilient services for IoT applications while operating on resource-constrained edge devices. Thus, virtualization infrastructure must be scaled down to the OS level, using technologies such as Docker and LXC [47]. Virtualization is increasingly a prominent topic in power systems for substation automation, enabling changes in functionalities without hardware changes. Virtualization technologies enable mission-critical applications such as live migration, clustering, and replication [5]. This involves moving virtual machines (VMs) between hypervisors of different servers, facilitating automatic or manual workload balancing during testing or maintenance without service interruption. Clustering provides the capability for servers to work together to increase availability and transfer active VMs in the event of failures or boot times. Automated replications of VMs and storage ensure the availability of the latest backups. However, ensuring interoperability and conformance in multi-vendor environments for migration and clustering presents a challenge.

The use of these virtualizations approaches for non-real-time applications is a mature field studied in cloud infrastructure, while for time-critical applications it remains immature requiring numerous considerations. For instance, low-latency networks [48] for transmitting measured values, accessible computing hardware, accurate time synchronization using PTP and redundancies of schemes must be considered [44]. These requirements are detailed in IEC 61850. For example, messages are classified as fast speed (Type 1), medium speed (Type 2), low speed (Type 3), raw data (Type 4), file transfer functions (Type 5), command messages and file transfers with access control (Type 6) per IEC 61850-5. A summary of the delay requirements is presented in Table III [48].

TABLE III
DELAY REQUIREMENTS FOR DIFFERENT MESSAGE TYPES

Message	Applications	Performance class	Transfer time
Type 1	Protection	P1 P2 P3	≤3 ≤10 ≤20
Type 2	Automatics	P4	≤100
Type 3	Operator	P5-P6	≤500, ≤1000
Type 4	Samples	P7-P8	≤3, ≤10
Type 5	File Transfer	P9	≤1000
Type 6	Command	P10-P12	≤500, ≤500, ≤10000

In general, transfer time delays must be sufficiently low so that they do not impact the performance of related functions with fault clearance time of up to 40 ms [48]. Communication requirements for fault location (61850-9-2LE SV) and inter-trip (R-GOOSE) applications including signal intervals, latency, jitter, and availability are also discussed in [33]. A summary of different virtualization solutions is presented in Fig. 5, while details regarding hardware virtualization or operating system (OS) level virtualization including file systems, networking, and security are beyond the scope of this review. Examples include, Hyper-V [49], Proxmox [50], vSphere [51] as commercially available solutions. Other platforms in early stage of development use the Linux Foundation [52].

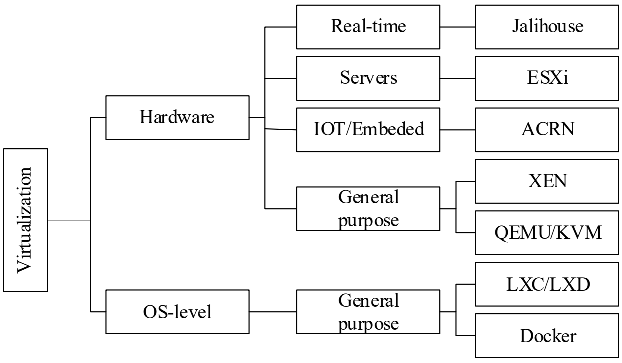

Fig. 5. Examples of vitalization solutions [28].

The high real-time performance requirements of substation automation protection and control have been a key factor limiting the adoption of virtualization technologies for protection applications [28]. However, the reference presents promising findings on the performance of containers and VMs under various workloads, using a maximum task execution threshold of 1 ms for evaluation. Latency measurements for LXC/LXD, Docker, and native values on the OS of the same system, as shown in Table IV, indicate that both LXC and Docker exhibit stable and well-bounded performance. Containers achieve near-native performance, with maximum jitter values that remain within acceptable limits for protection and control applications.

TABLE IV

JITTER FOR DIFFERENT VIRTUALIZATION TECHNOLOGIES [28]

System	Jitter on different systems max (avg) µs Xeon Silver 4208 5.6.19-rt12	 Xeon Gold 6248R 5.15.65-rt49
Native	37 (3)	16 (2)
Docker	38 (3)	17 (2)
LXD	43 (5)	25 (2)

To improve flexibility and isolation, the study also examines the transition from container-based virtualization to hypervisors. The results show that both KVM and VMware ESXi maintain a maximum application timing of approximately 600 µs, remaining below the 1 ms threshold, with VMware ESXi demonstrating slightly lower latency than KVM [28]. A similar setup in [45] reports stable timing around 500 µs, while also providing memory and CPU usage data for two Docker VPC containers.

Both non-optimized and optimized VMs, containers, and bare-metal solutions are assessed, considering key factors such as latency, security, and resource utilization [53]. Additionally, a numerical comparison of hypervisor and container technologies is presented in [54], covering various benchmarks, including CPU, memory, storage, and network performance, as shown in Table V.

TABLE V

COMPARISON OF PERFORMANCE AVAILABILITY WITH AND WITHOUT VIRTUALIZATION [54]

Benchmark	Bare metal	Container	VM
CPU	100%	28% - 86%	28% - 108%
Memory	100%	61% - 91%	51% - 139%
Storage	100%	64% - 118%	93% - 197%
Network	100%	95% - 112%	90% - 103%

The study also presents performance metrics across bare-metal, container, and VM environments. The findings indicate that selecting the appropriate virtualization technology can significantly reduce performance losses, with containers showing a minimal loss of 5% and VMs around 10%. However, selecting unsuitable technology can lead to performance losses of up to 72%, depending on the workload. Therefore, a comprehensive evaluation of workload requirements is essential before selecting a virtualization approach [54].

A study in [55] compares the performance overhead between virtualized and non-virtualized systems for network and disk-intensive benchmarks. The results indicate that hypervisors incur higher overhead compared to containers, leading to increased latency for KVM relative to Docker. The study found that, compared to a bare-metal (non-virtualized) system, KVM exhibits the highest performance degradation, with a 42% reduction in CPU-intensive tasks, 14.98% in memory-intensive tasks, and 48.29% in network and disk-intensive benchmarks. The percentage of performance overhead for virtualization technologies in network and disk-intensive benchmarks is shown in Fig. 6. This high overhead limits the suitability of hypervisor-based virtualization for high-performance computing (HPC) environments. Consequently, next-generation cloud data centers are shifting from hypervisors to containerization [55].

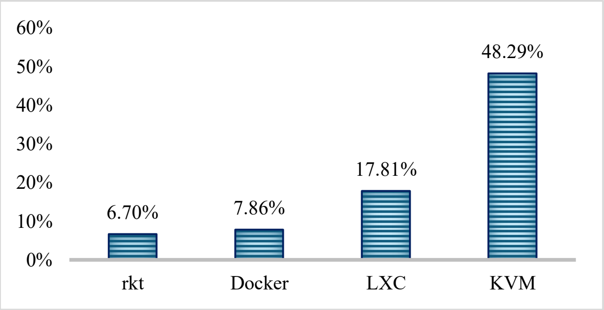

Fig. 6. Percentage of performance overhead for virtualization technologies in network and disk-intensive benchmarks [55].

A comparative analysis in [56] evaluates the performance, resource consumption, and power consumption overheads of various virtualization technologies in cloud environments. The study assesses CPU, memory, disk, and network utilization, using throughput and latency as key performance metrics. While VMs offer better isolation and fault tolerance, making them preferable when reliability is a priority, containers provide greater scalability, flexibility, and lower overhead, making them more suitable for real-time processing [56]. However, container-based virtualization, which relies on sharing the host OS, presents two major challenges. First, if one application excessively consumes OS resources, other applications may be deprived of the minimum resources required for proper operation [47]. Second, if an attacker gains control of the host OS, they can access all applications running on the system [47], making containers more vulnerable regarding security. Thus, containers trade security for performance [47]. Additional characteristics of hypervisor-based and container-based virtualization are shown in Fig. 7. Specifically, a smaller image size requires fewer resources for hosting and reduces migration time, while a shorter instantiation time leads to lower latency.

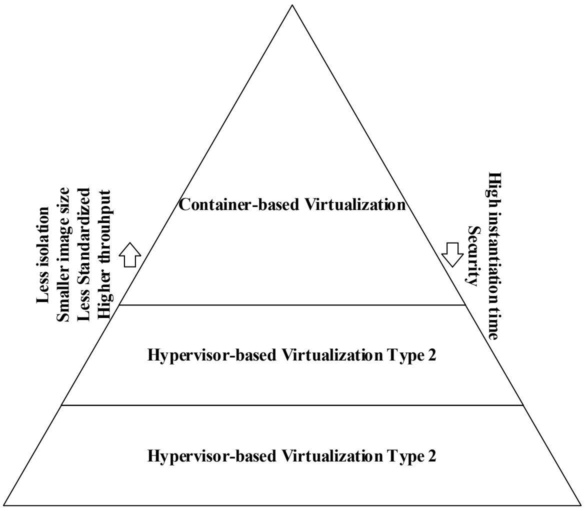

Fig. 7. Characteristics of virtualization technologies [47].

An open-source cost-benefit analysis of virtualized protection, automation, and control (vPAC), considering capital expenditures (CAPEX) and operational expenditures (OPEX), was presented in [4]. The model was assessed for a 30-year simulation period and concluded that the CAPEX and update cost of vPAC compared to those of traditional IED-based substations experienced a dramatic reduction of 20% and 60%, respectively. The study examined many factors such as the effects of corrective maintenance (CM), predictive maintenance (PM), failures of IEDs and vIEDs, costs of updates, power consumption of IEDs, personnel training and time needed for learning new technologies, replacement costs of IEDs, societal assessments as well as reductions in system downtime and carbon footprint. It also noted factors like software licensing as hindrances to overall cost savings [4]. However, the study did not explicitly consider the impact of cybersecurity.

Therefore, virtualization can serve as one key enabler in centralized schemes. This is important because the number of decentralized power system solutions like DER applications outside the control centers has been increasing, requiring more computing devices and scalability in substations. Centralized virtualized protection schemes eliminate the need for installing new hardware for new functions [46], making centralized schemes cost-effective over their life cycle. Virtualization is not a new technology, but it is widely used for non-real-time applications in the IT [28], [45]. However, recently, it has become a focus for both industry and research for real-time applications, employing different virtualization technologies [28], [45]. A real-life pilot of a virtualized centralized protection and control scheme, including lessons learned, can be found in [45]. In this study, VPC is used in standby mode, providing the same functionalities in parallel with a physical centralized protection and control device. Such advancements have led to the market introduction of the first virtualized protection and control solution, ABB's SSC600 SW, a standalone software that can be installed on the hardware of choice [41]. The physical version of this centralized solution was introduced in 2018, with each physical device covering up to 30 feeders. Spare part management is also an expensive aspect of power system protection [26]. This can be alleviated by reducing station-level and bay-level hardware [5].

Many other new solutions can be implemented in virtualized environments. For example, developing an analog processing module based on IEC 61850 sampled values via software, without vendor-specific software or hardware, in a containerized edge computing-based project is one such approach [39]. The module is used to extract essential information for CPC. This includes reconstruction of SVs, resampling, frequency measurement, phasor, harmonics and symmetrical components calculations. Reference [57] presents a framework for engineering virtualized IEDs to pave the way for standardization, where interoperability and portability remain issues. [31] tested the operation of relays from different generations, with the virtual protection relay being the fastest in general. One important consideration in testing virtualized protection schemes is that the protection system can be represented by precompiled function blocks. This means the protections in the system are provided as precompiled function blocks with a detailed model of the system for testing purposes, without the need to understand or access the proprietary details of the vendors [19]. Recent literature on software-defined PAC systems, eight industrial projects demonstrating the concept, and eight standardizations are reviewed in [46].

E. Digital Twin for Efficient Testing of CPC

A digital twin (DT), as a virtualization product, is a virtual replica of physical systems and assets [58], [59], and brings many advantages in centralized virtualized protection. These include but are not limited to Factory Acceptance Tests (FAT), Site Acceptance Tests (SAT), fault analysis, design, operation, validation, training and education, technical support, maintenance and service, COMTRADE replay, and remote training [58]-[60]. When it comes to remote testing of CPC, a DT is essential for configuration validation of modernized substations at an early engineering stage to reduce time, cost and on-site errors. The use of DTs is even more critical because of the increasing frequency of new firmware releases for protective devices [58]. A virtual testing environment is demonstrated in [59] for virtualizing bay-level IEDs to test line differential and distance protection functions. Virtualization of IEDs, switching elements, and wiring demonstrates the future of test environments. Benefits include reduced execution time and costs of projects, reduced OPEX due to pre-testing, automatic testing, mitigating human errors, 24/7 availability at the cloud, and reductions in manual field tasks.

Characteristics and challenges of mirror operation of protective relays based on DTs were studied in [61]. These include consistency, transparency, interactivity, and sharing. Challenges include real-time data interaction, interface standardization, protection logic transparency, and human-computer interaction. Power systems can benefit from virtualization technology by creating a fully virtualized FAT platform that is nearly identical to real conditions. This eliminates costly constraints associated with physical equivalents, such as the purchase, wiring, assembly, and power supplies of equipment. Virtual platforms are also used to model protective relays, bay control units (BCUs), and primary equipment [18]. IEDs, wiring, the DIGSI 5 configuration tool, the communication protocol, injected voltage, injected current, CT, VT, CB, DS, and other station-level components are all virtualized in the SIPROTEC 5 Digital Twin presented in [18]. A maximum delay of 2.1 ms for SV packets was achieved, which was improved to 1.6 ms using a dedicated physical core for VMs [62]. Availability of servers with up to 64 cores can reduce these values.

F. Artificial Intelligence and Machine Learning

This section briefly discusses why artificial intelligence (AI) and machine learning (ML) are important enablers in CPC and VPC schemes. Traditional bay-level IEDs are limited in handling system-wide applications, which can be facilitated by the valuable data concentrated in one location. This is where AI and ML techniques prove useful. This approach was adopted in [63] to develop an ML model using PMU data for transmission system fault analysis, addressing shortcomings of SCADA-based and purely PMU-based fault detection. The system-wide fault detection and classification can detect faults that local IEDs cannot identify. Substation-based remedial action schemes (RAS) are also evolving into centralized remedial action schemes (CRAS) [64]-[66], which are prone to cyber-security threats. An ML-based algorithm was used in [64] for cyber-physical anomaly detection in CRAS.

G. 5G Communication

The need to communicate high-speed, time-synchronized measurements within a substation is a key feature of CPC. The fifth generation of mobile network offers ultra-reliable low-latency communications (URLLC) with a latency of 1 ms, reliability of 99.999%, and high security [67], [68], enabling faster CPC schemes. These features make 5G an option for facilitating cost-effective installation and retrofitting to replace fixed connections [68]. SV and GOOSE are both Layer 2 protocols designed for intra-substation. This limitation in data transfer outside the substation is addressed by IEC 61850-90-5, which defines improved SV and GOOSE (R-SVs & R-GOOSE) over the IP protocol with multicast UDP addressing to transfer data, including synchrophasor information.

The results of [68] showed that, in most cases, 4G fulfills the minimum requirements for latency, but reliability and variability of latency are major issues. The application of IEC 61850 in substation local area network (LAN) is widely studied. Currently, power systems can leverage emerging high-speed wireless communication, such as 5G. The feasibility of using 5G and 4G communication in smart grid applications is assessed in [33]. However, the authors recommend wireless communications for non-protection applications. It is also noted that ultra-reliable low-latency communication cannot be fully supported by 3G/4G or with optical fiber. However, 5G wireless cellular networks can facilitate wide range of applications and synchronization services required for PAC [6]. Field test results for PAC applications showed that 5G slicing is a promising solution to meet performance requirements in smart grids; even when a public slice is congested, smart grid slices meet the minimum requirements [6]. The use of 5G for line differential protection with R-SVs and inter-trip with R-GOOSE over user datagram protocol (UDP), based on IEC 61850-90-5, was studied in [68]. Finnish distribution system operators (DSOs) have studied a comparative analysis of public 4G and private 5G SA for anti-islanding protection in an MV network in [69], with an average latency of 28.2 ms and 45 ms for 5G and 4G, respectively. 5G for protection-related functionalities, such as Permissive Underreach Transfer Trip (PUTT), using an NS-3 network simulator, was also researched in [67]. One issue of wireless communication is the latency and reliability of LTE and NSA 5G [33]. 5G new radio (NR) technology offers enhanced mobile broadband (eMBB) to increase data rates, massive machine type communications (mMTC) for communication between up to one million devices, and URLLC with 1-5 ms [33]. These features are only supported by 5G SA. 5G NSA only enables eMBB. In addition to all the benefits associated with 5G at the edge, there is potential to reduce communication media, as shown in Figure 3 in [33], thereby reducing latency and increasing reliability due to the reduced devices.

Cybersecurity threats associated with communication protocols have been investigated in the Technical Committee 57 of IEC since 1998. The committee has identified issues requiring attention and offered recommendations [70]. These threats include unauthorized control, spoofing, replay, modification, and eavesdropping, which are addressed for securing IEC 61850. Most of these issues are countered in IEC 62351. Cyber-attacks may occur at different levels, such as the time synchronization level by spoofing GPS signals, as addressed in [71]. Often, solutions to cyber-attacks can be implemented during the initial phases of project development, particularly during substation design. For instance, one notable consideration is the choice between stand-alone and integrated MUs, with integrated MUs maintaining synchronism of voltage and current [71]. This, in turn, positively impacts the performance of directional overcurrent and distance protection systems [71]. The study examines effects of timing attacks on protective relays. When it comes to using public telecom networks in IEC 61850-based substations, cybersecurity must be addressed [72]. For instance, IEC 61850-8-1 MMS lacks encryption, and has a limited authentication mechanism, although it supports password authentication (though not defined in IEC 61850). Therefore, using a virtual private network (VPN) tunnel, for example, between SCADA and CPC is recommended [72]. MMS can also be secured based on IEC 62351 by defining transport layer security (TLS) and application layer security, both of which can include authentication and encryption with separate certificates [72]. [25] discusses firewalls, intrusion detection and prevention, VPN, verified malware prevention, and whitelisting as valuable tools to protect against cyber threats. While many projects use relays with internal time synchronization, cybersecurity issues in schemes dependent on centralized time synchronization can arise from false measurements with wrong timestamps, potentially resulting in maloperations of relays and cascading failures in transmission systems [71]. Researchers have sometimes turned to decentralization, for instance multi-agent-based methods, to tackle security threats in centralized protection [73]. However, the final decision is made by consensus of interconnected agents. The study highlights improved flexibility and resiliency of such methods relative to centralized ones against malicious attacks.

H. Time Synchronization

The simple network time protocol (SNTP) is a popular method for small networks and local substations, but it may cause latency issues and may not be ideal for system-wide solutions [25]. This can be addressed by methods outlined in IEEE 1588v2 and IEC 61850-9-3, achieving 1μs time synchronization accuracy needed for IEC 61850-9-2 process bus [25]. Highly available, precise, and low-cost time synchronization is required for IEC 61850-based modern substations [74]. The PTP Ethernet protocol, as detailed in IEEE 1588 and IEC 61588 Edition 2 [17], [75], is preferred, using either the IEC 61850-9-3 utility profile [76] or the IEEE C37.238 power profile [77], both offering high accuracy time synchronization of 1μs [74]. When it comes to virtualization, host-level synchronization (e.g., not for each container) is required, benefiting from clocks on physical network cards or hardware timestamps [28]. This can be achieved using linuxptp. If CPC can act as an accurate time synchronization master to the process bus and PIUs, then it can eliminate the need for a separate grandmaster clock [17]. Many substations still use relays with internal clocks, while centralized time synchronization may become the future. This can be accomplished by obtaining common time references using a global positioning system (GPS) and, subsequently using different methods, e.g., hardwired-based protocol such as IRIG-B or packet-based ones like PTP [71].

I. Redundancy

Redundancy in distribution substations is not a common practice due to increased costs, low risk of device failures, and backups in alternative relays and devices [17]. However, availability and reliability are one of the main concerns in implementation of digital CPC (or VPC)-based substations [25], [78]. Especially the backup zones located in a centralized unit, making redundant CPC essential. This redundant CPC has identical configurations except for GOOSE messages [17]. This redundant unit also provides benefits for testing one of the units in (hot standby) test mode, allowing protection of the system with the redundant unit [17]. IEC 61850-5 [75] specifies acceptable communication recovery times, ranging from 400 ms for SCADA to zero for sampled values. IEC 62439-3 recommends high-availability seamless redundancy (HSR) in Clause 4 and parallel redundancy protocol (PRP) in Clause 5, both with zero recovery time and no packets lost [25]. In PRP CPC receives the first frame and discards the second. In Section II, we discussed P2P and IEC 61850-based process bus. To eliminate the hardware limitations of P2P, a star-connected redundant CPC is recommended [17]. The drawback of PRP relative to P2P is the additional capital expenses associated with switches that require maintenance [17]. Additionally, in larger substations where P2P is not applicable, PRP takes priority over redundant star networks. In HSR all devices are in a ring without Ethernet switches, making it suitable for small networks where all IEDs can be taken out of service concurrently. The number of devices, delays, and bandwidth are limiting factors in this redundant ring scheme considering that commercialized PIUs focus on 100Mb/s Ethernet ports for cost reasons, limiting HSR to 12 SV streams, and thus fewer PIUs [17]. Another challenge in HSR involves maintenance and permits to work [17]. Centralized protection, monitoring, and control units should also be redundant to mitigate the risk and provide benefits for maintenance, testing, and updates. During tests, maintenance and updates, redundant units can operate while the main unit is temporarily offline [25]. For example, CPC redundancy is essential for frequent firmware updates due to cybersecurity concerns. Redundancy in PIUs (MUs) is neither cost-effective nor recommended in CPC implementations, and changing a failed PIU is a simple task in a digital substation [17].

A summary of these technologies is presented in Table VI. It is worth noting that the table shows the primary focus and discussions of technologies in each reference, although in all CPC-based solutions most of the technologies and standards such as time sysnchronizationor IEC 61850 are required. "Digital Twin" can also refer to the digital twin of a power system, where a real power grid is modeled, or to digital twins of relays or test devices.

TABLE VI
SUMMARY OF TECHNOLOGIES ENABLING APPLICATIONS OF CENTRALIZED VIRTUALIZED PROTECTION SCHEMES

Technologies Enabling CPC												CPC Applications	
Reference	IEC 61850	Cloud	Edge	Virtualization	Digital Twin	AI	5G	Time Synchronization	Redundancy	Intra-substation	Inter-substation	Description	Year
[1]	*				*	*		*	*	*		Implementation of Centralized Adaptive Protection	2024
[2]		*	*				*			*		Centralized Fault Location, Isolation, and Recovery	2024
[3]				*								General Description of Virtualization	2023
[4]				*						*		Cost-benefit Assesment of Virtualized Protection	2024
[5]				*					*	*		Virtualization in Protection of Digital Substation	2022
[6]				*			*	*		*		5G network Slicing for Protection of Smart Grid	2020
[7]										*		Centralized Current-based Condition Monitoring	2021
[8]										*		Review of Centralized Protection and Control	2015
[9]										*		Use of "Computer Relaying" as Starting Point of CPC	1996
[10]										*		Computer Relaying Including Non-relaying Functions	1972
[11]										*		The Results for First Use of Computer Relaying	1972
[12]	*									*		Viability Assesment of Centralized Protection Scheme	2017
[13]	*									*		Performance Analysis of Centralized Protection	2020
[14]	*			*					*	*		Function Testing of Centralized Virtualized Protection	2023
[15]	*	*	*	*	*			*	*	*	*	Virtualized Protection Automation & Control (vPAC)	2023
[16]	*				*			*	*	*		Implementation of Centralized Protection Scheme	2024
[17]	*							*	*	*		Centralized Protection Architectures in Small Substations	2022
[18]	*			*	*					*		vPAC using Digital Twin	2019
[19]	*			*				*	*	*		vPAC for Substations with IBRs	2022
[20]	*							*		*		Different Centralized Protection Schemes	2024
[21]	*							*	*	*		Different Process Bus Solutions	2022
[22]	*											Practical Approch on Process Buss	2009
[23]	*							*	*	*	*	Centralized Protection Using Transmission Level Relay	2020
[24]	*							*	*	*		Process Bus Solution (IEC 61850-9-2LE & IEC 61869-9)	2024
[25]	*			*				*	*	*		Describing Centralized Virtualized Protection Schemes	2023
[26]	*									*		Engineering Process of CPC using SCL (IEC 61850-6)	2015
[27]		*										General descriptions of cloud computing	2021
[28]	*			*				*		*		Performance Analysis Centralized Virtualized Protection	2023
[29]		*	*			*						Blockchain-Based Federated Learning at the Edge	2024
[30]										*		Centralized Model-based Transformer Protection	2024
[31]	*			*				*	*	*		Feasibility and Testing of Virtalized Protection	2024
[33]	*	*	*	*		*	*	*		*		5G and Edge-based Centralized Protection Scheme	2023
[34]	*	*	*	*			*		*	*	*	Virtualized 5G Edge-based Protection for Smart Grids	2019
[35]	*		*			*		*		*		Edge-based Protection for Isolated Microgrids	2021
[36]			*							*		Edge-based Underground Cables Fault Detection	2022
[37]	*		*	*				*		*		Virtualized Centralized Distance & Differential Function	2023
[38]			*							*		Centralized Fault Phase Detection to Run in EPICS [37]	2023

[39]	*		*	*				*		*		Software-defined Analog Processing at the Edge	2024
[40]	*		*	*				*		*		Centralized Software-defined PMU at the Edge Using SV	2024
[41]				*						*		General Description of Virtualization	2021
[42]	*	*	*	*	*			*	*	*	*	Virtualized Protection Automation & Control (vPAC)	2023
[43]	*			*				*	*	*		Lesson Learned from Centralized Virtualized Protection	2023
[44]	*			*			*	*	*	*	*	Centralized Virtualized DERs Loss-of-mains Protection	2023
[45]	*			*				*		*		Real-life Centralized Virtualized Protection Performance	2023
[46]	*	*	*	*				*	*	*		A review of Software-defined PAC System	2022
[47]		*	*	*								Comprehensive Review of Edge Computing	2021
[49]				*								Hyper-V Virtualization Solution	2025
[50]				*								Proxmox Virtualization Solution	-
[51]				*								vSphere Virtualization Solution	-
[52]				*								Linux Foundation Virtualization Solution	-
[53]		*	*	*								Performance Evaluation of Virtualization Technologies	2024
[54]		*	*	*								Performance of Bare Metal vs Virtualization Technologies	2023
[55]		*	*	*								Review of Virtualization Technologies	2021
[56]		*	*	*								Comparing Virtualization Technologies	2018
[57]	*			*						*		An Engineering Process for vPAC	2023
[58]	*				*					*		Digital Twin Testing from a Device to the Substations	2022
[59]	*				*					*		Benefits of Digital Twin for Testing vPAC	2020
[60]					*							Digital Twin for Training and Education Purpose	2024
[61]					*							Characteristic and Overview of Digital Twin of Relays	2023
[62]	*	*	*	*	*	*	*	*	*	*	*	Implementation and Test of Virtualized Protection	2022
[63]						*					*	Machine Learning and PMU-based Fault Analysis	2022
[64]	*					*					*	ML-based Anomaly Detection in Centralized RAS	2021
[65]	*								*		*	Centralized Remedial Action Scheme (CRAS)	2014
[66]	*								*		*	IEC 61850-based CRAS	2014
[67]	*						*	*			*	Communication Over 5G for Protection Schemes	2022
[68]	*						*				*	5G-based Communication for Line Differential Protection	2019
[69]							*			*		5G-based Communication for Anti-islanding Protection	2023
[71]	*							*		*		Centralized Time Synchronization Attacks	2017
[72]	*								*		*	Use of IEC 61850-based CPC as communication gateway	2021
[73]						*				*		Multi-agent-based Solution to address attack in CPC	2020
[74]	*							*	*	*		System-wide Disturbance Recording Using CPC	2023
[79]	*			*							*	5G-based Wide Area Protection for LOM Improvement	2023
[80]	*							*	*	*		Different Aspects of Centralized Protection	2023
[81]	*							*	*	*		Real-life Implementation of Centralized Protection	2022
[82]	*							*		*		Testing of IEC-based Centralized PAC Systems	2007
[83]	*									*		Virtual Isolation for Testing IEC 61850-based Substation	2014
[84]	*									*		Centralized Protection for Hidden Failure Detection	2016
[85]	*								*	*		Centralized Protection for Hidden Failure Detection	2018
[86]								*			*	Communication for Wide-area PMU-based CPC	2011
[87]										*		Centralized Phasor-based Fault Detection and Control	2018
[88]							*					Use of 5G for Centrally Fault Current Limiter Switching	2021
[89]										*		Centralized Voltage Control to Bring it to Tighter Limit	2018
[90]	*									*		Centralized Protection of Wind Farm	2010
[91]												IEEE 802.16 WiMAX centralized scheduling protection	2018
[92]	*							*		*		Centralized High Impedance Fault Detection	2013
[93]										*		Inter-area Oscillation Solutions: Centralized& Distributed	2024
[94]	*							*	*	*		Centralized Protection to be Used in Oil and Gas Industry	2022
[95]	*									*		Idea of Centralized Adaptive Protection Schemes	2022
[96]	*									*		Centralized Protection Modeling Using IEC 61850-7-420	2012
[97]								*				Centralized Wide Area Protection	2019
[98]										*		Guide for Centralized Protection and Control Systems	2024
[99]										*		Centralized MVDC Microgrid Protection	2019
[100]										*		Centralized MVDC Microgrid Protection	2017
[101]							*					Effect of Slicing on 5G Communication	2025
[102]							*					Economic Assessment of 5G Planning in Power Networks	2024
[103]							*					Network Slicing in 5G Communication	2022
[104]	*				*					*		IEC 61850 MMS for Virtualized Centralized Schemes	2024
[105]	*											New IEC 61850 Edition (Ed. 2.1)	2020
[106]			*				*	*				Real-Time Edge AI Model in 5G Environment	2023
[107]			*				*					Edge-AI Model in Smart Microgrids	2022
[110]	*		*	*				*		*		Lesson Learned from Virtualized Protection and Control	2010
[111]	*			*						*		Implementation of MMS Interface for CPC and VPC	2024

VIII. Applications of CPC and VPC

The advancements in technology and international standards discussed in previous sections have enabled the implementation of CPC. These technologies can be integrated to play a crucial role in the protection of power networks like the one depicted in Fig. 8. This section reviews some practical applications of CPC, ranging from monitoring and control to protection, which are summarized in Table VI.

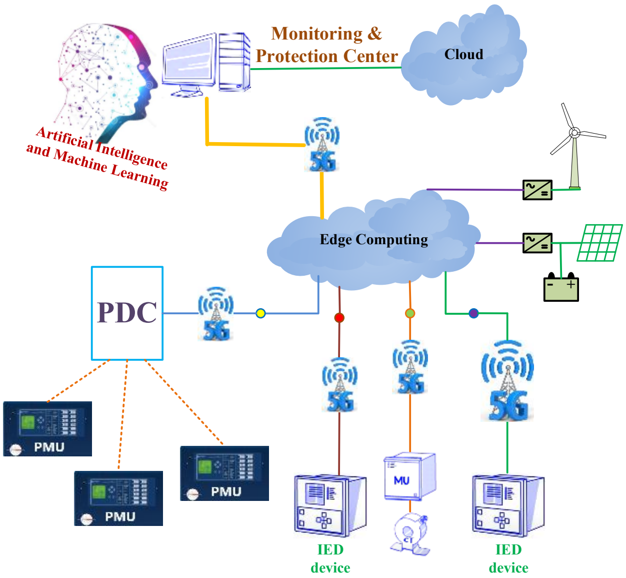

Fig. 8. Integrating enabling technologies for CPC and VPC.

A. 5G Communication-based Wide Area Protection for Loss of Mains Improvement

As the share of distributed energy resources (DERs) increase in power systems, it contributes more significantly to the voltage and frequency stability issues of power systems more than that in the past [79], [44]. The cascading unwanted tripping of distributed generators (DGs) on November 4, 2006, resulting from disturbances and sensitive frequency setting can be an example of such events in Europe [15]. Therefore, DER participation in power system stability, through low-voltage ride-through (LVRT), voltage control, virtual inertia and frequency control is required in many grid codes. In [12] centralized loss-of-mains (LOM) protection is studied, using wireless R-GOOSE inter-trip functionality combined with wide-area disturbance detection to reduce the risk of unintentional islanding. The benefits of such proposed schemes include improving the security aspect by blocking local LOM protection when system-wide disturbances occur in the upstream substation as shown in Fig. 9. Although islanding detection using remote methods might have high cost [79], it is worth investigating new schemes based on virtualized centralized protection.

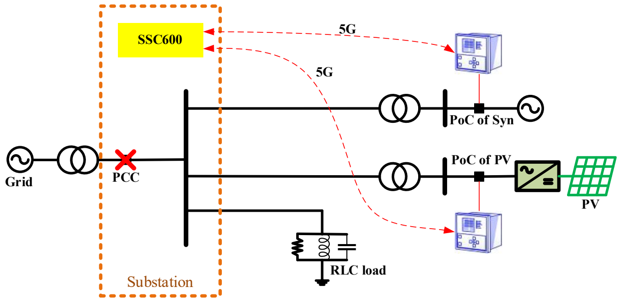

Fig. 9. System-wide LOM protection combined with local one to increase the security of protection systems.

B. Adaptive Centralized Protection Scheme Using Setting Groups

Power system protection in its ideal form must isolate the faulted region immediately. However, the unavailability of reviewed technologies in the past has postponed real-world implementation of CPC. References [1], [12] have also taken advantage of these cutting-edge technologies to implement CPC. These studies conducted extensive tests using hardware-in-the-loop setup to examine different functionalities for up to 30 feeders, as shown in Fig. 10.

The scheme benefits from accurate time synchronization and PRP to cover communication or single point failures. The scheme continuously monitors the status of the power system modeled in real-time simulator and, if needed, activates new predefined settings via GOOSE (IEC 61850-8 -1). To achive this, MUs at each bay receive measurements from current and voltage transformers and transform them into SVs (IEC 61850-9-2LE) with the sampling rate of 4 kHz, as stated in IEC 61850-9-2LE and IEC 61869-9 [25], followed by sending the digitized data to the centralized protection and control unit via Ethernet switches. Trip signals issued by the centralized protection and control device are communicated back to CBs using MUs. The MUs are also responsible for communicating the status of CBs to centralized devices. A wealth of experiences and practical tips regarding the same centralized protection and control device that we studied can be found in white papers presented by ABB. The CPC concept, component, system design considerations, the reasons why it is now the right time for CPC implementations, and how CPC improves different aspects of protection systems such as reliability, availability, operational cost-efficiency of digital substations, and flexibility are discussed in [80]. Other benefits of CPC, namely substation-wide disturbance, event and fault recording, are presented in [71]. More details regarding the use of functions in PCM600, CPC relay settings, signal matrix, application configuration, and IEC 61850 engineering for both process bus and GOOSE can be found in [81].

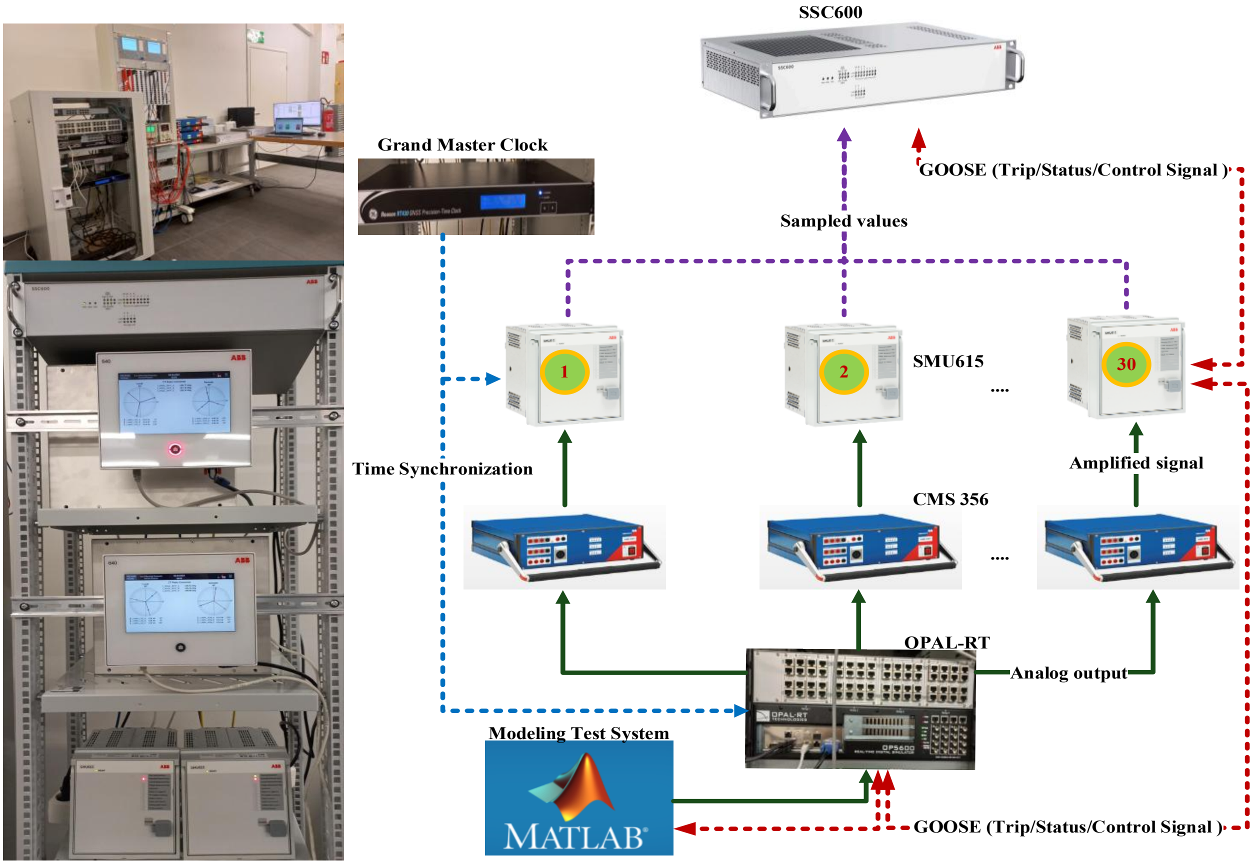

Fig. 10. Laboratory implementation of CPC [1], [12].

C. Advanced Current Measurement Condition Monitoring

A substation-level Six Sigma-based current circuit supervision approach using CPC which gathers real data from a substation pilot installation over two years, is presented in [7]. This new application does not require new installations, but it is enabled by software modules of CPC, which bring all the measurements together into one place. The method uses three standard deviations to calculate lower and upper limits, with any current outside the limit being considered saturated in one of the CTs or indicative of a failure in the current circuit.

D. Virtualized Centralized Protection Schemes

Virtualized centralized protection for DER islanding protection is studied in [44] using VMware ESXi and KVM virtual machines and Docker containers, all of which meet real-time requirements. The authors developed information exchange between the distribution substation and DER site using routable-GOOSE (R-GOOSE) over a 5G network to develop system-wide islanding protection, which blocks the local one in case of wide disturbances and disconnects the islanded DG with transfer trip functionality. The results indicate similar responses in both the virtualized centralized scheme and centralized protection scheme with dedicated hardware. Containerization and virtualized solutions were used in a real-life pilot to compare physical and virtual CPC, which were operated in parallel [45], [28]. Cloud-based monitoring was applied to both schemes to monitor the events and performance of the systems. The results from two containerized VPCs and a physical CPC running for over a year show that all real-time requirements were met, without even one sample exceeding the threshold. Finally, both the physical CPC and containerized VPC with an IEC 61850-3 certified server had the same response to the 11 faults that occurred at the substation during the piloting period. It is also worth noting that when virtualized solutions are adopted, it is possible to perform all tests before real-life implementation, for example, using an RTDS platform or DT one explained in previous sections. Reference [28] offers a Docker container-based OS-level virtualization solution to demonstrate real-time protection and control application and compares different virtualization technologies. Isolation of applications and virtual network delay can be the root cause of VPC failure and play a key role for real-time applications, which was better in VMs, with greater deployment flexibility compared to the container-based approach [28].

E. Substation-wide Disturbance, Fault and Event Recording for Distribution Network

Using traditional relays for disturbance recording has many drawbacks [25], [74], including distributed bay-level records, limited-to-local zone recording, a labor-intensive process for combing different types of disturbances, differences in the sampling rate, triggering method, record length, and method of time synchronization between old numerical relays with serial protocols and the modern ones with Simple Network Time Protocol (SNTP) and Precision Time Protocol (PTP). It is also a major challenge for protection engineers to perform manual downloads and compile the entire disturbance record to obtain substation-level disturbances. This, however, might be possible with remote communication-based data upload, but it can negatively impact available network bandwidth for other traffic, such as Manufacturing Message Specification (MMS), GOOSE, SV, and time synchronization traffic in modern IEC 61850-based substations [74]. To take corrective measures to minimize disturbances in today's complex power systems, all modern protection and control devices, such as the one used in Fig. 9, have their own fault, event, and disturbance recording to ensure that all events are recorded [74]. In traditional bay-level relays, all the local disturbances and binary signals need to be collected to generate station-wide information, which is still reliant on other software and makes the investigations time-consuming. CPC provides access to all substation measurements and events simultaneously, which can be post-analyzed to improve the reliability of the system [74]. CPC also offers the possibility of using other substation-wide functions, like low-impedance-based busbar differential, without the need for separate wiring, hardware, or instrument transformers [74].

F. New Method for Testing IEC 61850-based Centralized Virtualized Protection Schemes

New methods of testing are one of the benefits that IEC 61850-based CPCs and VPCs bring about. According to this standard, depending on the mode of IEDs, including On, Test, Test/Block, *and* Off, protection engineers can take advantage of running part of the application and testing the other part. In future evolving power systems, scalability is one important aspect. CPC and VPC offer this by facilitating the addition, adaptation, and testing of new functionalities, while keeping the other part in its normal operation [14]. According to [108], incorrect setting, logic, and design errors account for 40% of the mis-operations caused, which can be improved by system-wide testing in the engineering phase. However, this is not a common practice because of the efforts needed to establish a lab with a high level of fidelity. Ethernet communication and combined functionalities in CPC facilitate the system-wide design-phase testing [45]. A comprehensive testing procedure is one key challenge regarding CPC. Another issue is that IEC 61850 defines only one LPHD.Sim flag for each IED, meaning that the possibility of testing some newly added functions due to an extension in the network, while keeping the older functions in operations, is not feasible. This can be further researched. To address this limitation, a VPC with multiple functionally segregated IED instances on one physical server is theoretically proposed in [14]. Alexander Apostolov scrutinized functional testing of IEC 61850-based systems in several publications [82], [83]. In these works, virtual isolation is contrasted against traditional physical isolation of the test object based on test switches to open a circuit for a testing. These tests depend heavily on the type of testing, such as Device Acceptance Test, Device Interoperability Test, Integration Test, FAT, Commissioning Test, SAT, or Maintenance Test. The main use case for virtual isolation is Maintenance Testing, since it occurs in an energized substation [83]. The engineering of digital substations using System Configuration Language (SCL), the introduction of virtual IED (vIED) containing logical devices for protection, automation, measurement, monitoring, and recording with single or multiple layers of hierarchy, allows for testing individual logical node [82]. This is called "white-box testing", which is not just concerned with the proper operation of objects under testing (as black-box testing is) but also with the internal behavior of the object. This monitoring of the signal exchange and internal behaviors of the object in CPC is useful in case of test failure. This isolation and testing of a virtual device in CPC is enabled by the possibilities in IEC 61850 Edition 2, such as putting logical node or logical device in test mode, sending GOOSE for test purposes, flagging any value in the quality attribute for testing purposes, different modes such as ON, TEST-BLOCKED, simulation of a message, and mirroring control information. For instance, the Test-blocked mode and mirroring of control signals pave the way for testing a device while it is connected to the system. If a command with Test=False (a control or GOOSE command with the test flag set to False) is initiated, it will be executed only when the LN or LD is ON. In the second case, with Test= True (a control or GOOSE command with the test flag set to True) and the IED (LD or LN) in Test Mode, the wired output to, for instance, CBs will be generated, and in the case of testing a device connected to the process, the IED Mod must be set to TEST-BLOCKED to only have a processed command without activation of wired output to the CBs. In this case as soon as receiving the control command, the device activates the opRcvd data attribute. The command then will be processed to issue OpOk and tOpOk, which will not produce wired output in the case of the TEST-BLOCKED Mode. To summarize, during a test, the relay will receive sampled values with the simulation flag set to True. The data object sim in LN LPHD of the relay under test is set to True, and the logical device will be set to TEST. The logical node interface of relay to CB, XCBR, will be set to TEST-BLOCKED in order not to produce wired output, while issuing opRcvd, XCBR.Pos.opOk, and XCBR.Pos.tOpOk [83]. In-service testing for CPC is only needed after a change in settings or critical changes or configuration changes. Redundancy will facilitate such testing [21]. The use of a single CPC requires putting logical devices in test mode, which is a sophisticated method with some associated risk.

G. Centralized Remedial Action Scheme (CRAS)

Previous studies on CPC have predominantly focused on IEC 61850-based implementations at the distribution substation level; however, this scheme can be extended to transmission level. At this level, numerous studies have been conducted on wide-area monitoring, protection and control (WAMPAC) using various standards such as IEEE C37.118. These studies have been comprehensively reviewed in prior literature. Remedial action schemes (RAS), also known as special protection systems (SPS) or wide-area protection schemes (WAPS) [64], represent one such area of research. The objective is to develop an automated protection system that mitigates issues related to dynamic stability, thermal overloads and post-transient voltage violations, while implementing corrective actions such as load shedding to maintain system reliability [65]. However, in some cases overlapping, typically load over shedding, occurs while ensuring adequate protection [66]. To address such issues, Southern California Edison (SCE) improved its existing RAS/SPS limited to isolated substations to centralized RAS (CRAS) encompassing over 100 substations, being the first CRAS of its kind to apply IEC 61850 and benefiting from fast timings of 50 ms and 20-22.5 ms for GOOSE message transport over 660 miles, enabling complete action within less than 16 cycles [66]. Therefore, application of IEC 61850 can be extended beyond CPC implementation within a single substation. This extension is also studied in [72], which utilizes the same Substation Configuration Language (SCL) for SCADA communications, typically handled via remote terminal units (RTU) that convert hardwired signals and substation protocols into telemetry protocols, including IEC 60870-5-104, DNP3, and Modbus. In the Gateway data model, all signals and legacy protocols are translated into the IEC 61850 data model, allowing SCADA to view all data as a single Logical Device (LD). In contrast, the Proxy model makes LDs visible to SCADA, requiring that all devices in Proxy data model be IEC 61850-based [72]. Consequently, CPC serves as a substation communication gateway over public networks toward SCADA, reducing investment costs by eliminating RTUs and streamlining the engineering process. The use of IEC 61850 as a remote communication protocol is detailed in “IEC TR 61850-90-2:2016, Communication networks and systems for power utility automation - Part 90-2: Using IEC 61850 for communication between substations and control centers.” This technical report describes Proxy and Gateway data models for substation and control center communication.

H. Centralized Hidden Failure Detection

Hidden failures are classified by the North American Electric Reliability Corporation (NERC) as one of the main reliability concerns, as they remain unnoticed until an abnormal condition arises and may provide incorrect inputs to relays [84]. This phenomenon can lead to a second contingency and a catastrophic scenario such as a total blackout. These failures might occur in any part of the power system protection such as CT saturation or reverse polarity, failures in the CT cables, blown fuses in VTs, failures in relays due to settings or I/O issues, failures in the communication systems or CBs [84]. To address this issue, a dynamic state estimation-based CPC approach is utilized in [84], [85] to handle instrumentation channel failures (including CTs, VTs, and their associated secondary cables), relay misoperation, and miscoordination. The dynamic state estimation-based relay for each zone, known as a setting-less relay, which consistently monitors the physical laws in the zone mathematically is executed every two samples. There is no need for coordination of these relays with other zones, and fault detection occurs in less than a second. Once hidden failures are detected, the scheme locates the fault and corrects the bad data.

I. Other Studies

Another potential application of CPC is the implementation of centralized arc flash protection, which can be achieved using current measurements or light sensor technology [25]. These measurements are collected by MUs and transmitted to a centralized device. Trip signals from the centralized device are communicated back to the MUs, whose high-speed output contacts then trip CBs. A limitation of these inputs can be challenging; for example, SMU 615 has only 3 light sensing inputs [25]. This integrated arc flash protection eliminates the need for separate arc flash units, additional CTs, and extra wiring [25]. A wide-area centralized PMU-based schemes aimed at improving applications that were not possible with supervisory control and data acquisition (SCADA) systems due to their low sampling rates or lack of precise time synchronization are presented in [86]. These applications include oscillation detection, frequency and voltage instability assessment, and line temperature monitoring. Numerous studies propose ideas that can be implemented in CPC schemes, including a centralized PMU-based coordinated protection and control strategy. This strategy employs centralized fault detection and secondary control algorithms in collaboration with relays and local controllers of islanded DGs to calculate active and reactive power disturbances and facilitate voltage/frequency stability after fault detection [87]. A model-based power transformer protection algorithm, in which multiple linear models operate in parallel as part of a CPC system, can be found in [30]. Centralized line protection for networks with high penetration of renewables considering DG type, location, and capacity as well as the network topology and theoretical analysis is proposed in [109].

Furthermore, in regions with increasing short-circuit levels exceeding the breaking capacity of CBs, a fault current limiter (FCL) is one mitigating solution. A centralized 5G-based FCL switching approach considering voltage sags is proposed in [88], optimizing the number of FCLs installed and reducing the number of switched FCLs and associated costs in the grid. We primarily focus on protection applications rather than monitoring and control ones. However, centralized protection, monitoring and control will form a complete package in future schemes. For instance, applications like voltage control are discussed in [89], aiming to maintain voltages within tighter limits in combination with the local controllers of DG units to provide a reactive power correction factor from each unit. A central relaying unit (CRU) presented in [90] for the protection of large wind farms uses point-to-point fiber communication and merging units suitable for outdoor applications. IEEE 802.16 WiMAX centralized scheduling for protection of complicated configurations in smart grids is proposed in [91] to identify the faulty zone based on centralized shared information. A centralized IEC 61850-based high-resistance earth fault detection and location scheme using COM600 as a centralized station is studied in [92], covering the faults in the range of 100-200 kΩ. While the centralization of protection functions is generally a beneficial practice, depending on the application it can also have drawbacks. For instance, in inter-area oscillation analyses using the integration of virtual synchronous generator control-based IBRs (VSG-IBRs), it was found that the distributed substitution of SGs with VSG-IERs has a more positive damping effect in improving stability than the centralized approach [93].

The deployment of centralized virtualized protection for substations with IBRs, such as HVDC and STATCOM, (commissioned around 25 years ago) is an interesting application [19], and it can combine both DC and AC protection and control [110]. This fully integrated protection and control solution was installed and tested by Vattenfall and GEAB utilities for 70kV/10kV and 130kV/40kV substation in Sweden. In this project, maintenance of such new systems was allocated to those involved in the testing process, since it was quite new for the maintenance staff. Additionally, more than one hundred AC substations connected to STATCOM and HVDC converters in countries such as Norway, Denmark, Italy, Australia, and the US are using centralized protection that includes protection for components such as AC filters, shunt reactors, breaker failure, transformers, and bus differential protection [19]. The advantages of centralized hybrid protection and control (CHPC) systems for the MV/LV networks, as well as the simplicity of maintenance and operation of industrial facilities and their viability for implementation in the oil and gas sectors, are discussed in [94]. Many adaptive protection systems that use setting groups, such as [95], or those that the authors studied in [1], suggest CPC methods; however, only a small number of them, like [1], actually detail how the schemes are implemented. IEC 61850-7-420 is used for centralized microgrid protection modeling, which models several DG types to communicate their status, rated current, and type to the microgrid central protection unit [96]. A real-world implementation of a CPC scheme using transmission level relays, as an alternative to industrial computer-based centralized schemes that offers benefits of IEC 61850-90-5 PMU & R-GOOSE, built-in IEEE 1588 master clock, teleprotection, and conventional communication protocols is demonstrated in [23]. All details regarding why a transmission class relay can prove CPC schemes are provided in this study. A centralized wide-area protection approach combining current differential and phase comparison schemes in a transmission network using synchro phasor data is also proposed to protect large scale systems in approximately 5 ms [97]. The recently approved 'Draft Guide for Centralized Protection and Control (CPC) Systems within a Substation' (IEEE PC37.300/D6.5) provides complementary insights into the development and implementation of CPC systems [98]. Today’s technologies and mature standards have paved the way for fully IEC 61850-based digital substations. For instance, regarding time synchronization and redundancy, IEEE 1588 v2 (PTP), PRP (for large substations) and HSR (for smaller substations) are mature enough to be used in a CPC structure. However, in addition to the challenges mentioned in this paper, there is always room for improvement, especially in a virtualized environment. Redundancy at the network card level [104], redundant systems with a multivendor approach for certain voltage level [104], time synchronization in a virtualized environment, especially between multiple edges, and the IEC 62351-4 security standard for MMS to standardize external communication and data exchange [111] are topics needing standardization. Virtualized centralized protection schemes offer greater scalability than bay-level IED-based schemes. However, scalability in the context of 5G faces challenges under extreme conditions, such as high-interference environments, remote areas, and regions with limited infrastructure. Limited coverage, delays, and infrastructure constraints can make CPC implementation in these conditions either non-cost-effective or unfeasible. Several approaches can help mitigate other scalability challenges in 5G networks. Network slicing improves coverage, serviceability, and resource availability by allowing operators to tailor network slices to specific distribution network requirements [101], as well as reducing infrastructure costs [102]. Integrating network slicing with massive MIMO and beamforming enables scalability, supporting a higher number of devices while ensuring reliable communication [101]-[103].

The scalability and limitations of virtualized centralized protection, monitoring, and control schemes can indeed be analyzed from multiple perspectives. When scaling a centralized protection system that includes key enablers, namely IEC 61850, cloud and edge computing, virtualization technologies, digital twin, AI, 5G, time synchronization, and redundancy, several limitations may arise. These include scalability limitations for each component. For instance, centralized protection, monitoring, and control devices can cover a limited number of sampled values streams. As an example, the SSC600/SSC600SW from ABB can manage protection, monitoring, and control for up to 30 feeders, which is typically sufficient for most distribution substations. For larger substations, multiple centralized devices can be employed. A scalability test for the SIPROTEC 5 virtualized centralized approach, considering a 1Gbit/s network interface with 60% and 80% network bandwidth utilization in [104], shows that the maximum number of MUs supported is sufficient for typical substations. The maximum number of MUs ranges from 42 to 181, depending on the sampling rate, the number of Application Service Data Units (ASDUs) per frame, varying load conditions, and the assumption of one stream per MU. Limitations in the scalability of IEC 61850 can include interoperability issues, especially when integrating older legacy systems from different manufacturers, GOOSE and sampled values configuration issues, and bandwidth limitations resulting in communication delays. However, with the introduction of IEC 61850 Edition 2.1, Ed. 1, Ed. 2, and Ed. 2.1 IEDs can be integrated into the same project [105]. For virtualization technologies and edge computing, limitations in dedicated resources may cause issues when integrating more devices in the future. Container-based virtualizations technologies offer better scalability of applications. Latency variations and time synchronization across various edges can be problematic. For digital twins, maintaining an updated, accurate model is a challenge as the system scales. Accurate and balanced training data and high computational load can pose scalability issues in edge AI technologies. Regarding time synchronization, clock drift in synchronizing substations, and GPS dependency can be issues when scaling. Cost overhead, complexity, and added latency, especially in HSR, are the scalability issues in redundancy. Given the nature of the schemes reviewed in this paper, the primary focus has been on virtualization and communication-related challenges. However, Section III examines how virtualization, communication, and state-of-the-art technologies contribute to addressing protection-related issues that communication-less and traditional schemes have been unable to resolve. References [112]-[114] provide valuable insights into protection-related challenges in AC/DC microgrids, grid code requirements, various functionalities, and stability issues. The CPC concept is not limited to AC systems, but it has also been studied for DC systems, mostly with differential functions backed up by local ones such as overcurrent [99], [100]. However, protection of the former systems is backed by mature standards and a wealth of experience. On the other hand, protection of DC microgrids is more challenging due mainly to a lack of experience and standards, the high rate of current rise, and the withstanding capability of power electronic devices [99].

IV. CONCLUSION

This paper examines how advancements in the centralization and virtualization of protection systems can facilitate the transition from aging substations to digital ones, playing a crucial role in the green transition. Key enablers, namely IEC 61850, cloud and edge computing, virtualization technologies, digital twins of relays, test devices, and power systems, 5G, time synchronization, redundancies, and AI along with the challenges they may pose on protection systems are discussed. The paper also explores the role of the new generation of centralized/virtualized protection, monitoring, and control devices in implementing PAC and vPAC systems from both technical and non-technical perspectives, ranging from new functionalities required for networks with high penetration of IBRs to consolidating numerous workloads from different vendors into limited hardware. Finally, it is shown how these technologies can be integrated to form various centralized/virtualized applications. These IEC 61850-based station-wide schemes, unlike traditional bay-level IEDs, provide better situational awareness, asset management, faster and safer deployment, remote operations with reduced costs and increased safety through reduced site attendance, reduced lifecycle cost, less physical space, remote upgrades of substations, scalability, facilitated FAT and SAT, and device-independent SCL files that outlast devices lifetimes, while also having some challenges related to cybersecurity, frequent firmware updates, and single point failures, for which some solutions were proposed. In summary, virtualized centralized protection, monitoring, and control may represent the future of most power systems. To realize this future, substantial changes are required, including enhancing the skills of current protection engineers to master new technologies and standards such as IEC 61850, as well as communication and networking knowledge. Additionally, company structures must be adapted to support these advancements. Key considerations for future research and industry applications include:

- As with the adoption of other technologies in power system protection, virtualization and centralization may face resistance. However, this study demonstrates that the reviewed commercial off-the-shelf technologies and standards have paved the way for this transformation. The reviewed applications represent a significant advance in achieving centralized virtualized protection systems, requiring further investigation and more standards and guidelines regarding software-defined PAC systems.

- In schemes with bay-level IEDs in different feeders, implementing system-wide applications might be difficult. In CPC & VPC schemes, where multiple functionalities are available in a single device, further research can explore new logics to prevent maloperations of relays and enhance protection schemes security. Additionally, the use of real time-synchronized data using disturbance recordings of centralized devices for the whole substation can be investigated for various purposes such as asset management, predictive maintenance, and ML-based solutions for future power systems.

- Considerable research focused on improving the speed of protection schemes using optimization algorithms such as metaheuristic ones to improve operation time and the dependability of protection systems. Greater focus is needed on system-wide approaches to further enhance the security aspect of reliability such as a 5G-based wide area protection for loss-of-mains (LOM) improvement that blocks local rate-of-change-of-frequency (ROCOF) functionality at the DER site during system-wide disturbances. This is particularly important in modern networks with tighter voltage, stability, and thermal limits. Moreover, the impact of IEC 61850-based schemes on relay setting coordination time interval (CTI) of 0.2 or 0.3 needs to be reconsidered for backup relays' operation. Technological advancements over these years may enable lower CTI values due to reduced device errors and high-speed sampled values and GOOSE communications.

- The IEC 61850-7-420 standard defines logical nodes (LNs) for modeling and control of DER. Further work could develop IEC 61850-based extension standards such as IEC 61850-7-420 extension for CPC in future grids. This would improve communication and interoperability of DERs, propose advanced control and energy management systems, and facilitate DERs integration into the smart grids.

- Industry 4.0 applications, such as the protection of modern substations, require high accuracy and low latency [106]. The integration of 5G networks and edge AI facilitates the deployment of AI algorithms at network edges, closer to end devices, improving the reliability and responsiveness of intelligent services [106]. A study in [107] presents an edge AI-based forecasting approach to balancing power supply and demand while enhancing the efficiency of smart microgrids. Further research on real-time optimization of edge AI models within 5G environments could enhance the latency and accuracy of protection-related functions, including fault detection and prediction.

- The virtualized centralized protection, monitoring, and control schemes examined in this paper can also serve as a digital twin of power systems, if a comprehensive grid model is available. This allows for using sampled values and optimization-based integration and hosting capacity analysis. It includes applying optimization methods to determine the optimal location and capacity for renewable energy integration. The results can be fed into the digital twin, which incorporates various functionalities such as voltage regulation, thermal overload management, power quality assessment, and protection functions within a centralized device (e.g., ABB SSC600/SSC600SW). Based on these functionalities, the interconnection of renewable energy sources can be validated. Alternatively, if any alarms are issued by these functions, this information can be fed back into the optimization tool to refine the capacity and location of DERs that the grid can accommodate.

- The use of CPC as a substation communication gateway over public networks for SCADA could be further explored to reduce investment costs by eliminating remote terminal units (RTUs) and simplifying the engineering process.

- In centralized protection schemes, measurements from several locations are available. Thus, new functionalities such as multi-point differential protection warrant further study. The same applies for new low-inertia power system stability support functions at the distribution network level by detecting low-frequency oscillation and protection of 100% inverter-dominated grids with grid-forming inverters.

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AUTHORS' CONTRIBUTIONS

Meysam Pashaei: conceptualization, literature search, investigation, methodology, visualization, writing – original draft, writing – review & editing, funding acquisition, project administration. Kimmo Kauhaniemi: conceptualization, writing – review & editing, supervision, funding acquisition. Hannu Laaksonen: writing – review & editing, supervision. Nikos Hatziargyriou: writing – review & editing. All authors read and approved the final manuscript.

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AVAILABILITY OF DATA AND MATERIALS

Not applicable.

DECLARATIONS

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