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Trends in Centralized Protection and Control in Digital Substations

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Abstract. In recent years, the trend of digitalization has sped up in all economic and industry sectors. In the electric power sector, new digital technologies will introduce deep changes in the architecture of protection and control systems of future electric substations to adapt to a new environment with increasing levels of inverter-based and distributed energy resources along with a large number of sensors, automation equipment and other control, protection and measurement devices.

This paper reviews the evolution of the traditional substation toward new protection and control architectures based on new computer and communication technologies. The main characteristics of virtualization technologies are also analyzed, as well as the benefits and main challenges in its application in substation protection and automation systems.

Key words. Digital substation, IEC 61850, process bus, centralized protection and control, virtualization.

1. Introduction

Energy transition requires the development of smart grids to efficiently manage an increasingly higher number of connected devices, to cope with the variability of high penetration levels of distributed renewable generation and to take advantage of the flexibility from electric mobility and energy storage.

Electric substations are the nodes of the power system and fundamental for grid operations. Substation modernization initiated with the implementation of the standard IEC 61850 in new installations and for retrofit of existent substations, but there are still many substations with old legacy systems that need updating.

In recent years, the trend of digitalization has sped up in all sectors. The application of new digital technologies in substations will help to meet the new requirements of the smart grid. In this sense, the application of virtualization has been proposed to achieve fully digitally enabled substations. As a result, the substation becomes less hardware dependent, opening up new possibilities for centralized protection, automation and control in contrast with traditional distributed architectures.

This paper reviews the main actual technological trends in substations. Firstly, in Section I, the evolution of actual conventional substation to become fully digital substations is presented. Next sections analyze the main technologies that will drive this transformation: Section 3 describes the main characteristics and architectures of substation centralized protection and control, and Section 4 introduces virtualization technology and its application in substations to obtain virtualized protection and control systems.

2. Evolution to future digital substations

Typical electric substations comprise primary equipment consisting of power transformers, busbars and switchgear connected according to a single-line diagram; and secondary equipment for the monitoring, control and protection of primary equipment. Earlier electromechanical protection relays have been replaced progressively by multi-function relays and modern IEDs (Intelligent Electronic Device) to constitute the Substation Automation System (SAS). They are fed by instrument transformers and are usually disposed close to switchyard, arranged in bays and connected with the substation HMI (Human Machine Interface) located in a shielded operation room. On this way, as shown in Figure (1), in a typical substation three different levels can be identified: process level, bay level and station level.

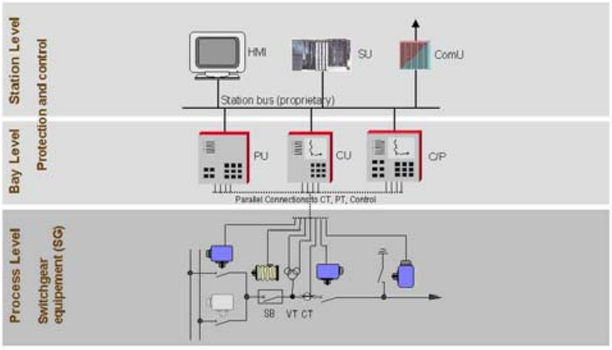

Fig. 1. Typical structure of automated substation [1]

The IEC 61850 standard "Communication networks and systems for power utility automation" introduced important changes in the communications within the substation. It allows for the digitalization of communications and is the basis for the evolution toward a digital substation. It defines the communication protocols and data models of an Ethernet based communication infrastructure structured in a station bus and a process bus (Figure 2). On this way, IEC 61850 eliminates copper wiring and the use of proprietary protocols in data exchange, facilitating interoperability between devices from different manufacturers.

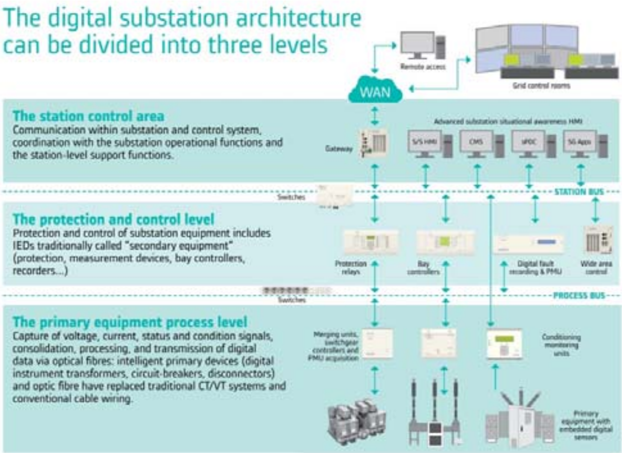

Fig. 2. Architecture of an IEC 61850 substation [2]

A further evolution of digital substations will lead to the introduction of the concept of substation edge device at the station level, consisting of a processing platform running multiple applications as software services using a container-based architecture. The substation edge device will facilitate a quick adaptation of the operation of the substation to the highly varying conditions of the power system, as it will make possible automatic and remote upgrading of substations with new smart applications for DER management, etc. In addition, the implementation of a real-time operation system will lead to a fully digitally enabled substation, centralizing protection, automation, monitoring and analytics, where protection and automation functions will run also as software services, avoiding the use of standalone devices for protection and automation (Figure 3).

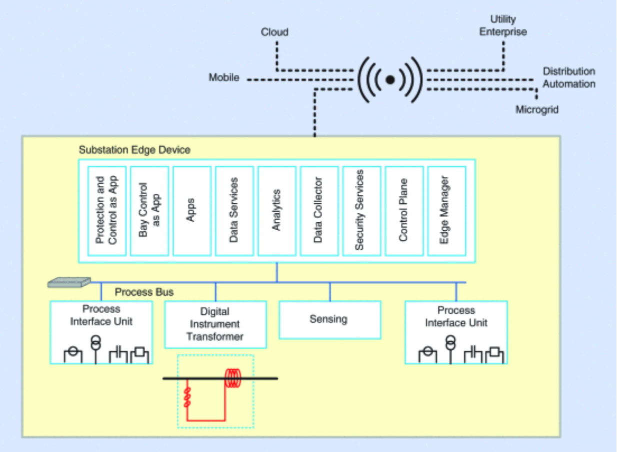

Fig. 3. Architecture of a fully digitally enabled substation [3]

3. Centralized protection and control

In contrast with conventional distributed protection and control systems, based on the use multiple bay-level IEDs, a Centralized Protection and Control (CPC) system consists of a central unit providing protection, control, monitoring, communication and asset management functions. The concept of CPC was firstly proposed in 1969, although implementation was limited by the technology then available. However, nowadays it is gaining more interest due to increasing digitalization of substation, as it allows a more efficient use of the processing power and a the use of a lower number of devices.

Advantages of CPC in comparison with the traditional protection and control approach are [4]:

- Lower number of devices to be identified, specified, configured, tested and maintained.
- Easier management and limited maintenance as result of the reduced count of devices.
- Security due to the limited number of access points which can be managed better.
- Improved interoperability.
- Master intelligent node for substation-to-substation communication.

A key technological enabler for the development of CPC is the implementation of the IEC 61850 process bus, as it enables sharing digital information between devices and shifting of protection and control functions between different relays and/or CPC units. Other enabling technologies are the advances in substation time synchronization and the development of intelligent merging units (IMUs) to interface primary equipment with the process bus, containing all functions to digitize measurement signals and able to receive trip, open or close signals to operate a circuit breaker [5].

The architecture of CPC systems differ from conventional SAS, although criteria based on backup and redundancy requirements still applies. In [4], five CPC possible general architectures, providing different reliability and availability levels, are discussed. Main differences between architectures are the combination of CPC with backup conventional relaying as well as the communication architecture, as described below:

- Architectures 1, 2 and 4 include IEDs at bay-level for primary protection and control and a CPC unit for partial or total backup. In Architecture 1, CPC are interfaced with bay level IEDs over station bus and IEDs are interfaced with primary equipment over traditional copper wire. In Architecture 2, both CPC and IEDs are interfaced with IMUs over a point-to-point connection, and in Architecture 4 over process bus.

- Architectures 3 and 5 include two CPC systems for both primary and backup protection and control functions. In Architecture 3, CPCs are interfaced with IMUs over a point-to-point connection, and in Architecture 5 over process bus.

The use of redundant equipment lead to architecture variations that enhance the reliability of the protection and control system (Figure 4). Also, IEC 62439-3 network level redundancy protocols (PRP, HSR) can be applied in the CPC communications architecture to achieve better performance and reliability (Figure 5). The basic concept behind PRP (Parallel Redundancy Protocol) is that a device is connected to two independent networks, while HSR (Highly-available Seamless Redundancy) involves that all devices are connected in a ring topology.

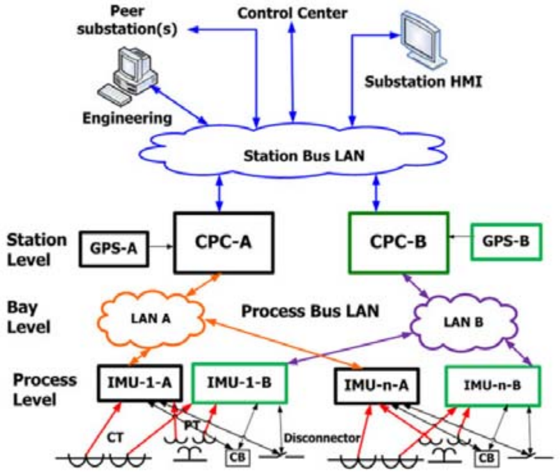

Fig. 4. Architecture 5 with redundant CPCs, IMUs and Process Bus LANs [4]

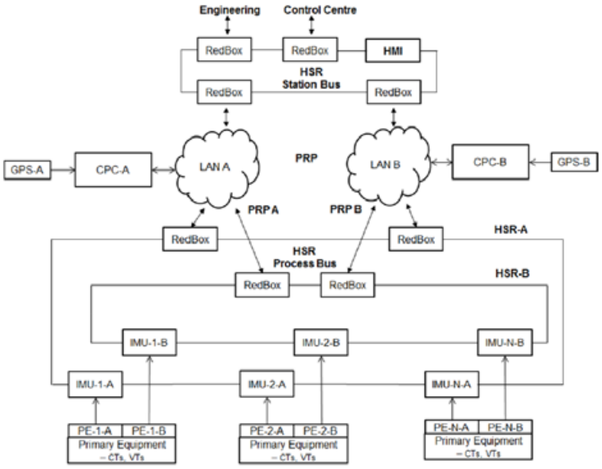

Fig. 5. Architecture 5 with mixed HSR/PRP networks with CPC connected to PRP (station bus) [4]

Further research is being carried out by the H45WG of the IEEE PES PSRC to develop standard PC37.300 “Guide for centralized protection and control (CPC) systems within a substation”, which will address CPC system architectures for typical substation configurations.

Evaluation of CPC has mainly focused on distribution substations. These substations are continuously upgraded and/or expanded to meet growing demand requirements, so there are more opportunities to apply CPC. In [5, 6] a fully CPC architecture with PRP based communication redundancy and a hybrid architecture combining CPC with numerical protection relays and no redundant communication, are proposed for a distribution substation. CPC architectures discussed in [7] take into account the size of the distribution substation (small: 4 to 6 feeders, large: more than 10 feeders), technology (air, metalclad) and topology (single bus, single bus with tie-breaker) of the substation. In this case, redundant CPC with process bus based on point-to-point architecture is proposed for small substations, and on PRP architecture for larger substations.

CPC can be implemented using a vendor-based specific solution where the manufacturer provides both the hardware and software. In [8] the performance of a pilot using a commercial centralized protection and control solution for distribution substations and installed at the Noormarkku 110kV/20kV substation to upgrade the automation functionality in the substation without large modifications to the existing protection and control relays, is described. Alternatively, the implementation of CPC based on the use existing transmission class protection relays has been proposed, utilizing the spare processing power in the relay and taking advantage of features already developed for transmission [9].

CPC systems can also be developed as a software-defined solution fully-hardware independent. An example is shown in [4], which describes a software-based SAS developed by LYSIS LLC and installed at the Olympic 110/10 kV substation. The solution was implemented using iSAS software to allocate function modules in four servers. Logical nodes distributed between a set of virtual IEDs, similar to physical IEDs and working asynchronously, perform complete protection and control functionality in the substation.

As stated in [10], software-based CPC is a promising technology. The commissioning process may be still complex but it is expected that advancements in configuration tools would significantly improve the process of system configuration. An issue can the shorter life of commercial servers in comparison to IEDs, which makes for sure the need of replacing the server by a new one in some years after commissioning.

4. Virtualization in substations

Virtualization is the foundation of cloud computing and its main characteristic is that it allows for a more efficient utilization of physical computer hardware. It has been applied with success in other sectors and its application in substations has recently started to be explored. The exploitation of the benefits of smart grid technologies will require modern substations with rugged computing platforms and the use of virtualization can provide an efficient cost-effective method of deploying these systems, so it is considered a key technology in the modernization of electric substations.

Virtualization uses software to create an abstraction layer over computer hardware that divides the hardware elements of a single computer (processors, memory, storage, etc.) into multiple virtual computers, or virtual machines (VMs), which run their own operating system (OS) and share the hardware resources of the computing platform. With virtualization, each application is executed on a separate guest virtual machine in the same computing platform, which makes possible a more efficient use of computing hardware. The hypervisor is the software layer that coordinates VMs and avoids them from interfering with each other. There are two types of hypervisors:

- Type 1 hypervisors run directly on the host hardware and manage multiple guest VM operating systems.
- Type 2 hypervisors run above a conventional operating system.

In Type 1 hypervisors there is no platform operating system that needs management, so are more adequate for application in substations. Recently, the containerization technology or "lightweight" virtualization has been developed. Containers consist on executable units of software in which application code is packaged, which are managed by a container engine, and unlike VMs do not include a guest OS. As a result, containers take up less space and are easier to scale. VMware ESXi, Microsoft Hyper-V and the open-source based KVM are examples of Type 1 hypervisors, while Docker and Kubernetes are open-source tools for packaging and running applications in containers and for container orchestration, respectively. Figure 6 shows the architecture of virtualization using either VMs with Type 1 hypervisors and containers.

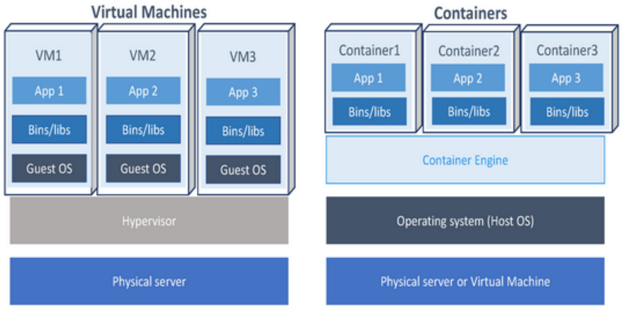

Fig. 6. Virtual machines and containers [11]

In substations, there are multiple applications with different requirements for operating systems or hardware resources, which are operated on individual computers, but virtualization allows running different substation applications autonomously on a set of VMs in the same computing platform. Other benefits derived from the application of virtualization in a modern substation automation system include [12]:

- improved operating efficiency
- reduced hardware dependencies
- reduced costs of procuring and maintaining hardware computing platforms
- redundancy by live migration
- creation of snapshots
- use of templates for rapid commissioning
- real-time backing up for disaster recovery applications

Relevant issues when applying virtualization technology in substations are mainly those related with the selection of the hypervisor [12, 13]:

- operating systems supported on guest VMs
- RAM memory allocation and cores assignment per OS
- memory management mechanisms available on the hypervisor
- live migration or similar capabilities
- networking support regarding VLAN (Virtual Local Area Network) and NIC (Network Interface Card) features
- scalability options

In addition, important issues to be taken into account in the design process are the redundancy requirements in the substation, sizing the hardware platform specifications, and the VLAN architecture planning for data separation and traffic priorizitation.

In 2021, the IEEE PSCCC approved the P21 Study Group "System Architectures Supporting the Virtualization of Substation Protection and Control Applications" to investigate about the creation of a guide, recommended practice, or standard to address system requirements and architecture for supporting the virtualization of substation protection and control applications. Topics being considered include: hardware specification, hypervisor specification, computing requirements, protection application requirements, system management and tools specification, user interface specification, and cyber security controls [14].

Figure 7 shows an example of a virtualized substation automation system with two redundant substation servers. Connection of servers via HSR/PRP redundant networking protocols provide full resilience in the event of the failure of a single server.

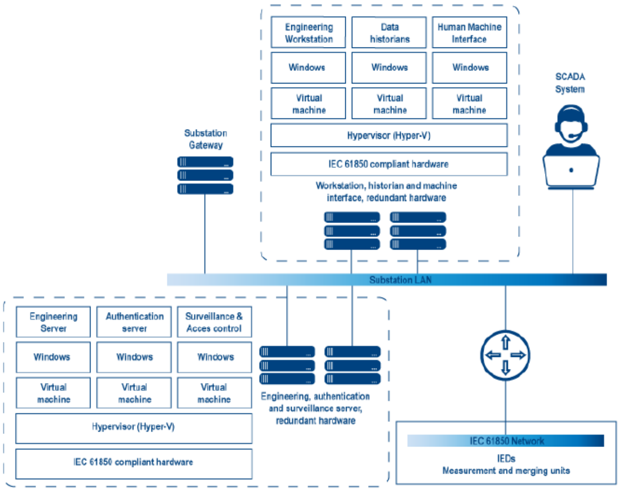

Fig. 7. Virtualized substation automation system [15]

Response time requirements of automation functions are less demanding, but protection and control functions require a fast response. As a result, virtualization of SAS require the use of servers with real-time operation capabilities, to support VMs for even the most critical substation protection and control functions, such as protective relaying.

The purpose of the project SEAPATH "Software Enabled Automation Platform and Artifacts (THerein)" of the Linux Foundation Energy is the development of an open source, real-time software platform that can run virtualized protection and automation applications from multiple vendors. Among the objectives of the project is the realization of a proof of concept consisting of testing on the platform the requirements of an automation and protection system [16].

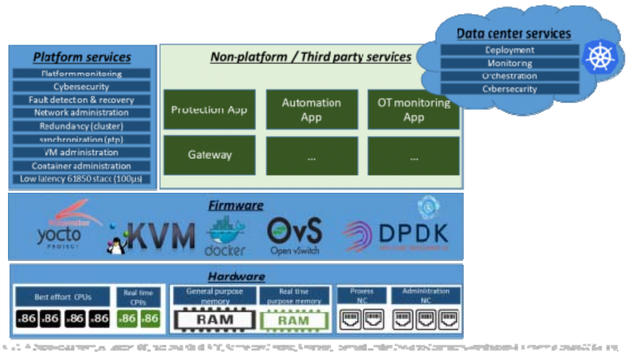

Fig. 8. SEAPATH project [16]

Virtualization of protection functionality involves integrating protection features from all separated protection devices in two or more reliable redundant servers, as in a centralized protection approach, where protection functions are deployed in VMs as software modules, or virtual protection relays (VPRs). The concept of virtual protection relay (VPR) is defined in [17] as an architecture where software-defined and virtualized platforms are deployed to host the critical circuit protection functions.

A relevant issue to take into account is how to develop the allocation of virtualized relays to VMs. An approach could be direct porting of discrete complete IEDs into different VMs, so every single IED would just be converted into an individual VM. In case of large number of protection IEDs, common functions can also be consolidated to a separate VM for greater efficiency when scaling. In addition, different containers would encapsulate individual protection function of IEDs (Figure 9) [17].

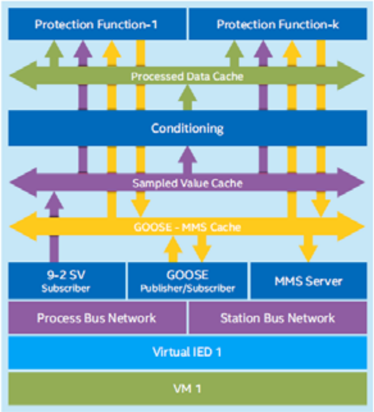

Fig. 9. Virtual protection relay [17]

A different approach is considered in [18], which proposes a stepwise approach to achieve a virtualized protection solution, where the migration from a traditional to a centralized protection approach would be the first step. A first substation pilot for virtualization of protection and automation, carried out during 2020 at the Noormarkku distribution substation in Finland, is also reported. A prototype system was deployed with CPC centralized protection, and was upgraded with CPC virtualized protection. Two virtual CPC instances (main, backup) were installed as VMs, each of them able to protect and control up to 30 bays.

According to [18], in comparison with CPC solutions, virtualized protection provide the same range of applications, however virtualized protection will allow to cover more bays and combine more protection functions under the same hardware.

In contrast, the use of individual and isolated VMs for every virtualized relay is not recommended, as dynamic allocation of hardware resources by the hypervisor to the different VMs could jeopardize real-time operation, introducing delays and queues in the process [18]. In a robust design, the behaviour of the protection functions should not depend significantly on the resource allocation to the VM over a wide range of configurations, so although some test results of the response time dependence of reference protection functions are included in [17], additional in-depth testing is needed to consider different hypervisor configuration settings.

5. Conclusions

The challenges associated with the energy transition and the development of the Smart Grid require the modernization of current substations and their transformation into digital substations in order to quickly adapt their operation to the new needs of the future electrical system.

Digitization of substation enable the application of centralized protection and control schemes, as an alternative to the conventional distributed one, which will allow to obtain more reliable and quicker deployment of protection and control systems.

In addition, virtualization technologies will make possible the development of SAS software-based solutions including centralized protection and control functionalities, which will provide ease of commissioning, maintenance and upgrading, as well as the flexibility required by future electric networks.

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