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Virtualization in substations. Technologies and applications

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Abstract. The application of digital technologies in electric substations will be a key driver to develop the green transition and leverage the benefits from a smarter power grid. One of those technologies is virtualization, widely used in IT. Substation virtualization will allow the development of more flexible and agile substations and will contribute to a more resilient grid. However, its application in substations poses several issues, as they are critical facilities with real time and high reliability operation requirements. This paper reviews main virtualization concepts and technologies, and their application in electric substations, taking into account the role and functionalities of distribution primary and secondary substations, with special focus on control and protection functionalities.

Key words. virtualization, virtual machine, containerization, distribution substation.

1. Introduction

Substations play an essential role in power systems that consists on voltage transformation for transmission and distribution of electricity in power systems. Relevance of substations increases with the voltage level, being higher for substations at transmission voltage levels, and lower for distribution substations. In addition, distribution substations are classified according to their voltage levels in primary and secondary distribution substations, which interconnect high and medium voltage levels, and medium and low voltage levels, respectively.

In the traditional power system, power flows unidirectionally, from power plants to final users, through the transmission and distribution networks, so distribution networks have typically played rather a passive role with low automation capabilities. However, challenges of the green transition and the development of the smart grid will require distribution grids to play a more active role and be able of managing bidirectional power flows due to the presence of distributed energy resources (DERs). To accomplish this, substations will have to evolve to facilitate the integration of a high number of distributed energy resources and the management of highly varying operation conditions. The application of virtualization technologies in substations will allow obtaining digitally enabled substations, running multiple applications as software services to meet the changing needs of the grid [1].

In this paper, the application of virtualization in substations is reviewed. In Section 2, main virtualization concepts and technologies are introduced, and in Section 3 main issues regarding to the application of virtualization in electric substations. Finally, Sections 4 and 5 review the characteristics of some of the virtualization solutions proposed so far for primary and secondary distribution substations.

2. Virtualization technologies

Virtualization allows decoupling software from underlying hardware, improving scalability and flexibility of systems. There are two main virtualization technologies: hardware level virtualization and operating system (OS) level virtualization [2].

Hardware virtualization uses virtual machines (VMs), each running its own OS and applications. A VM is a copy of a physical machine in terms of behavior and functionality, providing an abstracted version of the entire hardware of a physical machine. The hypervisor allows one host computer to support multiple guest VMs by virtually sharing its resources, such as memory and computing power. It can be a Type 1 (bare metal) hypervisor, which runs directly on the host physical hardware, or a Type 2 (hosted) hypervisor, which runs as a software layer on top of the host operating system. Bare metal hypervisors are more secure and efficient than hosted hypervisors, as they are isolated from the attack-prone operating system and have direct access to physical hardware. Examples of bare metal hypervisors are VMWare ESXi, Microsoft Hyper-V and Xen. Examples of host hypervisors include VMWare Workstation and Oracle VirtualBox.

In contrast, in operating system-level virtualization, applications and their dependencies are encapsulated as processes of the operating system. Containers constitute portable instances of software with its dependencies that run on a physical or virtual machine. They share the host kernel and are orchestrated by a container engine or orchestrator. Popular OS virtualization tools are Docker for building, running and distribution of containers and Kubernetes for container orchestration.

Virtual machines are typically more resource-intensive than containers but provide a higher level of isolation, whereas containers are more lightweight but enable more rapid scaling and deployment of virtualized applications. Figure 1 compares virtualization architecture of virtual machines with Type 1 hypervisor and containers.

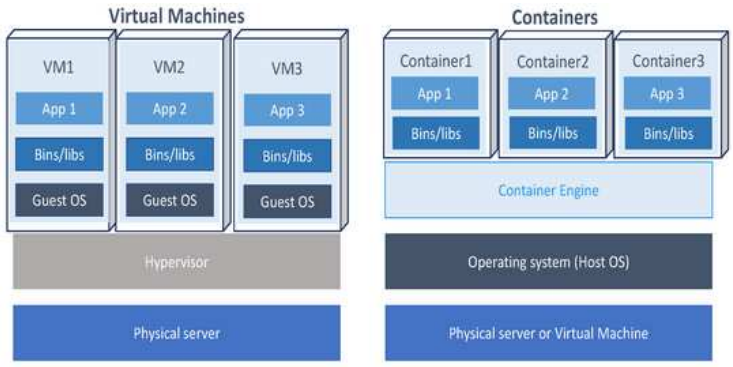

Fig. 1. Virtual machines (Type 1 hypervisor) and containers [3]

3. Application of virtualization in substations

Virtualization has proven to be very advantageous in the information technology (IT) sector and recently, has been also proposed to be applied in electric substations [4, 5]. It will allow to virtualize current substation automation systems to develop fully-digital or software-defined substations.

A substation automation system provides protection, control, automation, monitoring, and communication capabilities as a part of a comprehensive substation control and monitoring solution, commonly termed as Protection, Control and Automation (PAC) system, which is currently designed according to IEC 61850. The IEC standard data model divides functionalities in logical nodes, providing a high modularity that paves the way to the development of software-defined PAC systems by means of the application virtualization technologies.

Expected benefits from the application of virtualization in substations include improved operating efficiency and reduced hardware dependencies. In addition, the reduction in the number of devices will enable more agile commissioning, simplified asset management and increased interoperability.

However, the application of virtualization in substations poses new and different challenges from those in the IT sector, so virtualization solutions for IT may not be directly applicable in substations. Performance characteristics of virtualized functions depend on the virtualization approach, so it should be carefully evaluated in order to ensure that specific substation related requirements are met and that is readily scalable.

A first difference with IT sector is that hardware resources in a substation are comparatively lower than in cloud environments, so adequately sizing and specifying the correct computing platform becomes essential. For example, relevant hypervisor characteristics to take into account are: operating systems supported on guest VMs, RAM memory and number of cores to be allocated per guest OS, resource assignment mechanism used by the hypervisor, maximum number of guest OS supported by the hypervisor, live migration capabilities, networking characteristics and scalability options [6].

Environment conditions are also much more severe in substations than in data centers, so rugged IEC 61850-3 and IEEE 1613 certified servers should be used in substations to withstand the harsher environment.

A further difference is that some substation equipment, such as protection and control IEDs, have real-time performance and high-reliability requirements. As a result, a virtualized approach should guarantee a deterministic behaviour of protection and control IEDs with low latency and zero packet loss, and support high-accuracy time synchronization.

Virtualization is an emerging and promising technology that is still being evaluated by electric utilities and manufacturers through the development of pilot projects corresponding to different use cases. Relevant utilities and industry partners have joined in two international consortiums, Edge for Smart Secondary Substation Alliance (E4S) and Virtual Protection Automation and Control Alliance (vPAC), whose purpose is to accelerate the creation of standard-based, open, interoperable, and secure architectures of future smart digital secondary distribution substations, and of virtualized protection, automation, and control solutions for power system substations, respectively.

There is no standard architecture either for vPAC or, in general terms, for digital substation. However, the CIGRE WG B6.60 considers in [7] the topic of protection, automation and control architectures with I/O (Input/Output), processing hardware and functionality independent of hardware, and proposes five reference architectures for digital substations, with different functional integration level. One of them (Architecture 5) consists of redundant centralized protection and control (CPC) systems developing all PAC functions, where functional integration could be achieved by means of virtualization.

The virtualization technology more appropriate may depend on the use case. A virtualization solution based on the use of virtual machines provide the higher isolation. Type 1 real-time hypervisors provide predictable performance to VMs, and so for virtualization of critical workloads such as power system protection, whereas the host OS layer between the hardware and the hypervisor in Type 2 hypervisors can introduce unexpected and unpredictable delays to the hosted hypervisor and then to the VMs [8].

In contrast, containerization would provide a more flexible and agile framework for deploying and executing new smart functionalities in secondary distribution substations [9]. In this case, container orchestration becomes essential for the automation of functions such as resource allocation, monitoring and managing of individual containers.

4. Virtualization in primary distribution substations

PAC systems comprise hardware and software components for the monitoring, control and protection of the electric system. Conventional PAC systems are currently costly and need to evolve to integrate new functions to support the needs of future grids.

Virtualization will enable the development of more flexible and rapid scalable primary distribution substations, with virtualized centralized control and protection systems. By means of virtualization, traditional PAC hardware components can be converted into software applications and consolidated onto a single platform. So, the main components considered in virtualized PAC are: rugged high-powered computing hardware, software-defined protection, automation, and control applications, and a virtualization environment with real-time capabilities.

The vPAC digital substation high-level architecture is shown in Figure 2, where traditional PAC is replaced by two high-computing servers, thus simplifying PAC architecture [10]. Benefits from vPAC are lower cost and complexity, more simple maintenance, increased reliability, as well as easiest development of multi-vendor solutions, as multiple virtual IEDs from different vendors can coexist, in the same computing platform.

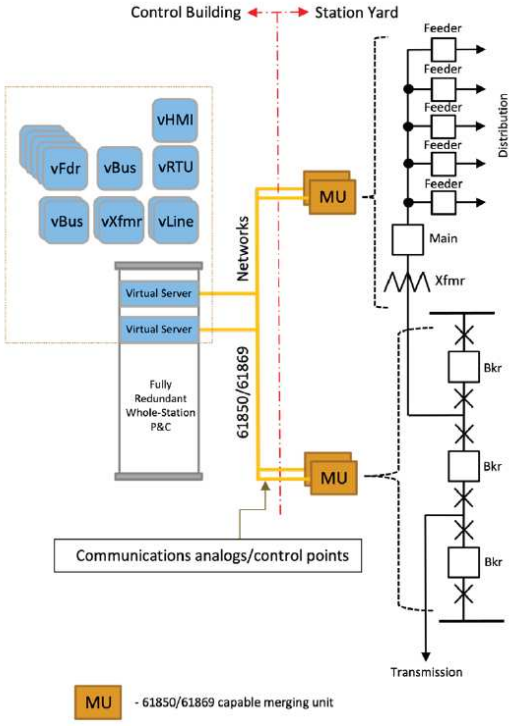

Fig. 2. High level architecture of virtualized PAC digital substation [10]

In addition, vPAC enables real-time and and non-real-time workloads to run adjacent to, yet isolated from, each other on the same host (Figure 3). Benefits from sharing hosts are further consolidation of functionalities, simpler networking, easier methods of sharing data, and a reduction in management tasks [11].

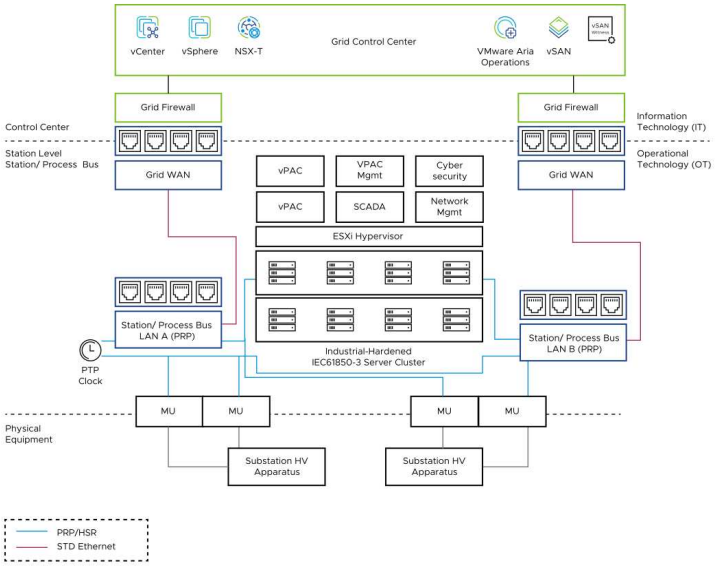

Fig. 3. vPAC with shared process/station bus [11]

The virtual protection relay (VPR) concept is described in [12] by Intel and Kalkitech and a VPR reference application with a set of reference protection applications (21, 87T, 51, 51N, 50, 50N 50BF) is presented, which provides basic infrastructure for implementing virtual protection relays based on IEC 61850. In [12], different approaches are identified for the development of virtual protection relays (VPR). In comparison to a straight-forward approach consisting on directly porting discrete IEDs into different VMs on the host, a shared responsibility based approach can be used, which consolidates common modules (e.g. MMS server on the station bus) to a separate virtual machine, provides higher efficiency when scaling to a larger number of protection functions. In addition, encapsulation of individual protection functions of IEDs in containers improves scaling and portability characteristics (Figure 4).

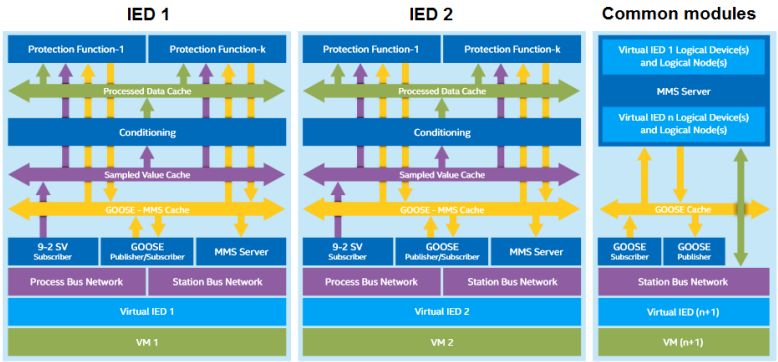

Fig. 4. Virtual Protection Relaying (VPR) [12]

Virtualization requirements should be carefully evaluated in order to ensure that virtualized protection solutions can be readily scalable without loss of reliability. In [13], real-time performance of a virtualized protection and control software for primary substation using different virtualization technologies is examined. Also, the influence of communication between containers is analyzed in [14] and some results regarding the effect of the allocation of hardware resources are presented in [12].

Utilities and manufacturers are also developing pilot and research projects to test the performance of vPAC and develop real-time platforms for testing virtual IEDs. For example, in [15], a pilot project of a vPAC solution tested in a 110kV/20kV substation in Finland, is reported. Two instances of a Centralized Protection and Control (CPC) commercial solution encapsulated in Docker containers were running in one shared industrial server host, together with other non-real-time applications. On the other hand, the SEAPATH project (Software Enabled Automation Platform and Artifacts Therein) [16] is intended to develop a reference design and industrial grade open source real-time platform that can run virtualized automation and protection applications, hosting multi-provider applications using open source tools (Figure 5).

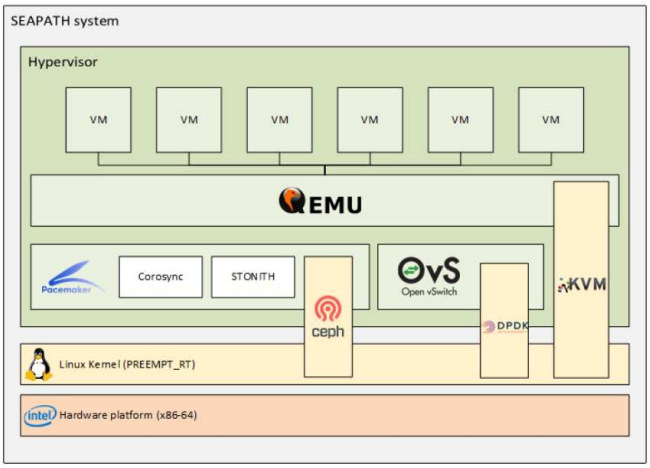

Fig. 5. SEAPATH architecture [16]

5. Virtualization in secondary distribution substations

Edge computing is an emerging paradigm, which brings storage and processing capabilities to the network's edge close to data sources, reducing latency and increasing the system response speed [17]. In secondary distribution substations, virtualization will allow obtaining edge nodes, which will have new and smart functionalities and increased computing capabilities leveraging data from smart-meters and other distributed energy resources. The high-level system architecture envisioned by the E4S Alliance in [17] for future secondary substations is shown in Figure 6.

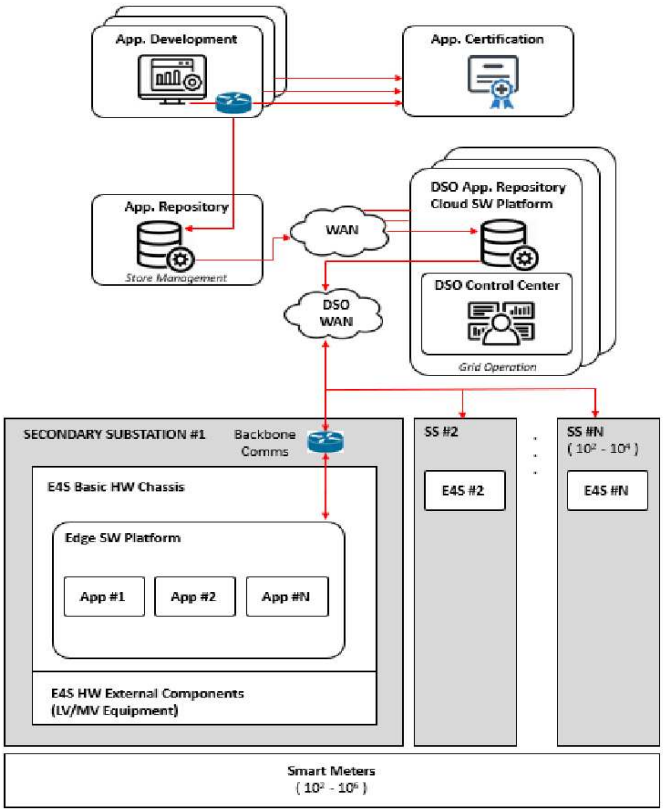

Fig. 6. High level architecture of smart secondary substation [17]

The architecture proposed has two levels: an edge node deployed in the secondary substation, executing containerized applications and managing edge devices (e.g. smart-meters, etc.), and a central system (cloud or on-premise) for deploying, managing and monitoring thousands of edge nodes deployed across the distribution network. The components of the edge node (Figure 7) include a layer of core services that provides security, networking, storage, backup and snapshot, service monitoring and resource monitoring.

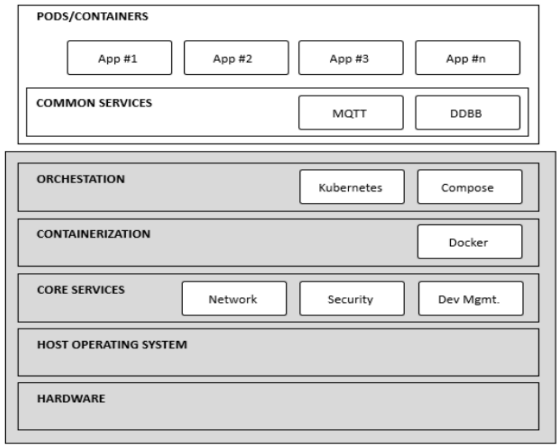

Fig. 7. Edge node distributed components [17]

Possible applications of an edge computing based solution developed for secondary distribution substations may be classified into the following groups [18]: grid knowledge and analysis (e.g. phase connectivity, fraud detection, calculation of losses), grid monitoring (e.g. fault location, state estimation), asset management (e.g. predictive maintenance) and flexibility related and innovative functionalities (e.g. DER monitoring and control, demand response).

However, the high number of secondary substations of a medium sized distribution company, which can be easily of several thousands, their scattered location across a wide geographical area, and their variable size, which depends on the number of customers supplied, requires a scalable and tailored deployment of intelligence in secondary substations. As a result, some of the requirements of the application encapsulation in edge nodes deployed in secondary substations should be, according to [9]:

- Use of open source tools to avoid dependency from proprietary platforms that could prevent competence and increase costs.
- Use of a containerized microservice-based architecture for faster application development and testing, instead of a monolithic architecture combining various functionalities.
- The access to hardware resources and opening communication ports should not be managed directly by applications to avoid dependency from hardware, as well as cybersecurity threats.
- Applications should include a configuration file to facilitate the deployment in secondary substations, taking into account their particular characteristics.
- Applications should include mechanisms to enable their remote monitoring and management.

Utilities are developing different pilot projects and proofs of concept (PoC) to evaluate the application of edge-computing solutions based on virtualization technologies in secondary substations. An example is the PoC of the Spanish utility Iberdrola to implement the following smart functionalities as containerized applications in a secondary substation: aggregation of smart meter data, calculation of energy unbalance, voltage regulation, transformer monitoring and DLMs connector (Figure 8) [9]. The solution is based on the Edge Workload Consolidation Architecture (eWLCA) defined by Intel and Minsait for the distribution and scaling of IoT/Edge technologies, which uses different open source technologies (Docker, Kubernetes, etc.). The analysis in [18] of the technologies (and their alternatives) used in the eWLCA concluded that they were appropriate for its implementation in an edge-computing solution at secondary substations, but the deployment process tested was found to be complex and should improve on user-friendliness.

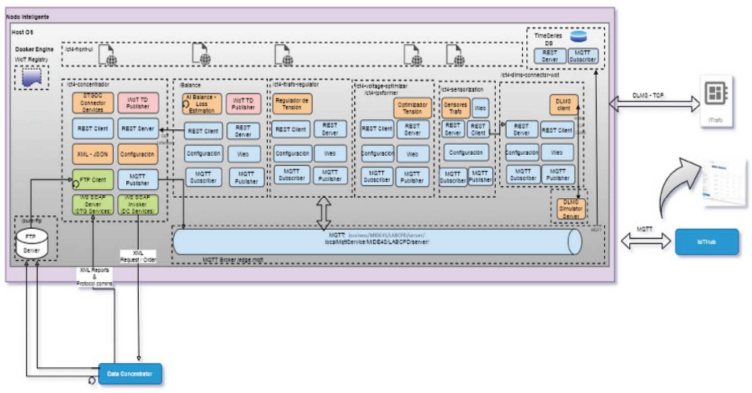

Fig. 8. Logical scheme of edge node architecture [9]

6. Conclusion

Virtualization is an IT mature digital technology, which is nowadays being assessed for substation digitalization, as a tool to develop a smarter and more resilient power grid.

It will mean a paradigm shift in the design and operation of electric substations and will require the development of standardized solutions that meet the real time and high reliability performance requirements of these facilities.

The analysis of the main issues and proposals for the application of virtualization in substations has allowed to identify two differentiated substation virtualization approaches, which take into account the different role and functionalities of distribution primary and secondary substations, mainly based on virtual machines and containers, respectively.

Acknowledgement

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