WHITE PAPER

Real-life pilot of virtualized protection and control – Experiences and performance analysis

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Virtualized protection and control (VPC) is seen as a promising evolution for the centralized protection and control (CPC) concept. The centralization of protection functions consolidates the functions of multiple conventional relays into one device. This consolidation reduces the complexity of the communications network and offers effective ways to manage the protection applications of the substation. Making CPC available as a VPC software image, instead of a dedicated device, brings yet another degree of freedom. The solution becomes hardware-independent, which leads to increased flexibility and scalability.

Together, ABB and Finnish Distribution System Operator (DSO) Caruna, wanted to explore these possibilities in a real-life substation pilot.

In this white paper, we explore the piloted VPC environment and the results from the piloting period. The results show that virtualization technology is suitable for time critical protection and control applications, with real-time performance comparable to that of existing non-virtualized solutions.

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Introduction

The electrical power system is going through major changes, as the requirements to de-carbonize our society is pushing for many things to happen in parallel. There is a rapid increase of distributed energy resources (DER) in the electricity network bringing volatility to the energy production. In addition, new flexible and controllable consumption concepts are taken into use, and different kinds of energy storage mechanisms. All these aspects make the distribution system more active and dynamic than before.

At the same time bigger parts of the whole energy system is moving to electrical energy, since it is one of the most flexible forms of energy that is possible to produce and distribute with a low carbon footprint. The importance of a continuous supply of electrical energy will grow even more, increasing reliability requirements further. This creates a challenging situation to the protection, automation, and control (PAC) systems used in electricity distribution. PAC systems in the future need to be more flexible than today, as a result of the increasing reliability requirements. To address these challenges, new digital technologies need to be taken into use.

Concepts of centralized and virtualized protection and control

The main target of centralized protection and control (CPC) is to move the protection and control functionality from multiple bay level devices to a single centralized device within a substation [1]. With this approach, only dedicated process interface units, merging units (MU), remain at the bay level. The overall concept is illustrated in Fig. 1.

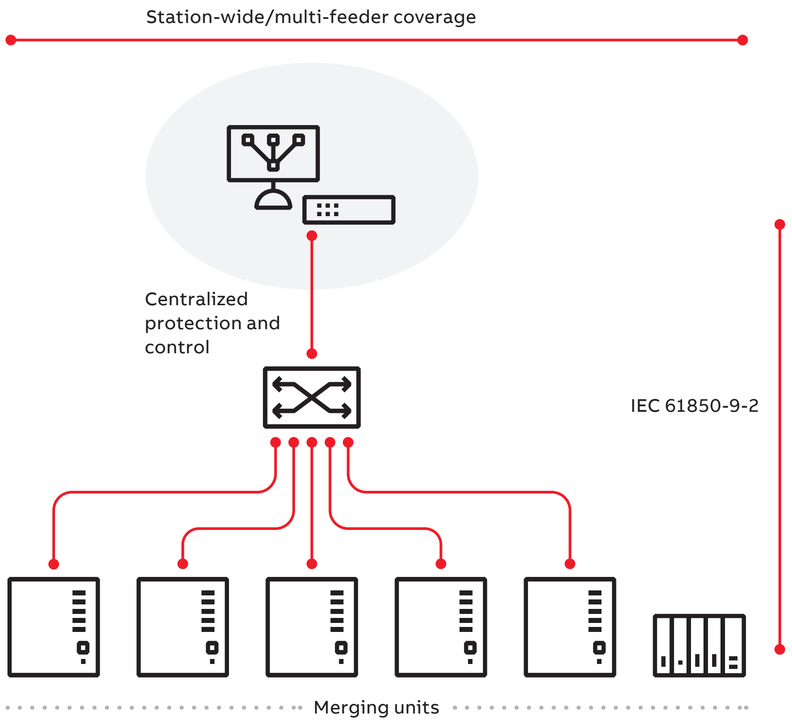


Fig. 1. Centralized protection and control concept

The targeted benefits with CPC are related to improved functionality and reduced overall lifecycle costs [2]. There are commercial products available on the market that are entirely based on digital standards such as IEC 61850. Performance and reliability results from CPC-based substation solutions can be further explored in papers [3] and [4] in the Reference list.

An evolutionary step in CPC concept development is Virtualized Protection and Control (VPC). The term virtualization broadly describes the separation of a resource or request for a service from the underlying physical delivery of that service [5]. Virtualization, as applied to protection and control (P&C), is the use of software for the creation of an abstract image of a traditional P&C solution inside a physical host that is a ruggedized computing hardware (HW). This means that the protection application is not anymore tied to a particular centralized device, but it is a software image that can be freely deployed to versatile industrial server architectures in different environments.

Virtualization as a technology is not new, and it is used widely in the domain of information technology (IT) in non-real time applications. Recent results show that the necessary real time performance for PAC solutions can also be achieved with various virtualization technologies, containing both Virtual Machines (VM) and containers [6].

Description of the virtualized protection and control pilot

Together, ABB and Finnish DSO Caruna, wanted to explore these possibilities in a real-life substation pilot. The pilot setup was arranged so that it had three different systems for protection and control. (1) A standard bay level relay protection solution was used as backup. The protection relays were equipped with MU (merging unit) functionality, which means they could also publish substation measurements via the IEC 61850-9-2LE process bus.
(2) A commercial CPC solution was running in the substation as the main protection system. In addition to these two active protection systems, (3) a separate VPC solution was used in standby mode – executing identical protection functions as the CPC device, but without the possibility to send trip commands to the protection relays.

Pilot substation

The pilot setup was realized in a 110kV/20kV substation in western Finland. The substation was equipped with a double busbar and one power transformer. In total, the substation had 13 measurement points, and 13 protection and control relays equipped with IEC 61850-9-2LE process bus. There was one incomer bay with two relays, one on the 110 kV side before the power transformer and one in 20 kV side.
In addition, there was one bus-coupler bay, two bays for the substation self-supply from both busbars, one bay for the capacitor bank, and seven outgoing feeders. The single line diagram (SLD) of the substation is shown in Fig. 2. Detailed information about the pilot is provided in [3].

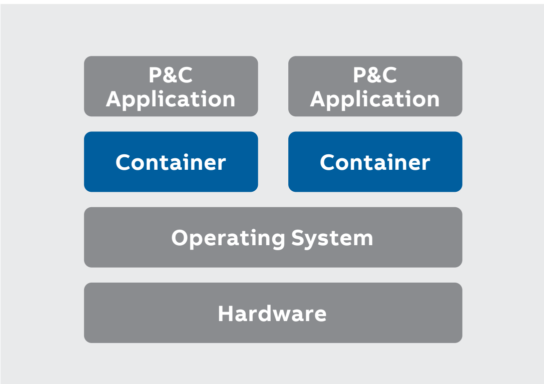
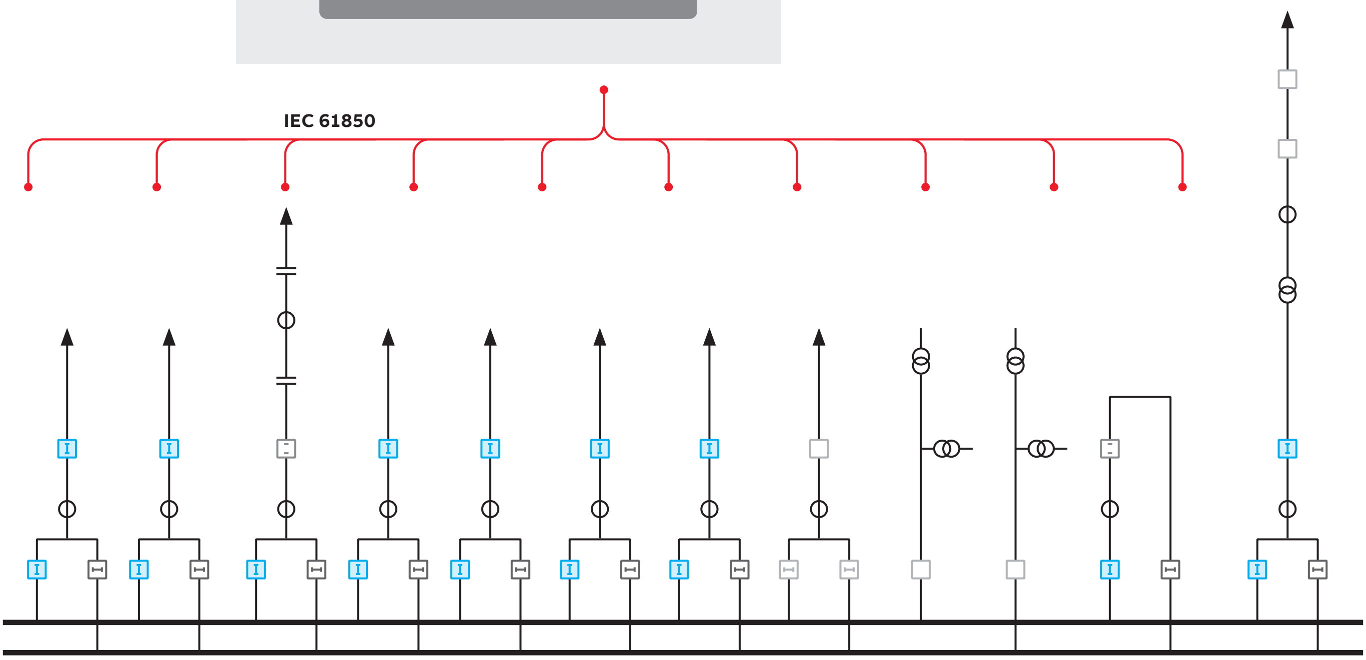


Fig. 2. Pilot substation of VPC



Piloted software architecture

To demonstrate how VPC can work in real-life, a prototype solution was built, which virtualized ABB's hardware-based CPC solution, SSC600, by wrapping it into a Docker container. Containerization is a lightweight virtualization technology that allows us to easily deploy a program as software images and run them in isolation from each other. Containers directly share the operating system kernel, thus avoiding one layer of indirection. This reduces the virtualization overhead, which allows us to reach near bare metal performance. This is critical for applications with stringent real-time requirements, such as CPC. More specifically, in the pilot we used Docker v19.03.13 to provision containers on top of Linux kernel v5.10.56 with the PREEMPT-RT patch applied to enhance the operating system's real-time capabilities. While the PREEMPT-RT patch is not suitable for real-time applications in the microsecond range, it is enough to satisfy the millisecond latencies needed for substation automation applications.

To test the prototype, the software was deployed on top of an IEC 61850-certified server. Using careful resource partitioning, this server can run two fully configured VPC instances in parallel. From the outside, these VPC instances appear and act the same way as a standalone CPC solution. The substation was controlled by a physical CPC device, ABB’s SSC600, which was used as reference to test the VPCs. Both VPC instances had the same application configuration as the SSC600 and received the same IEC 61850 9-2LE digitized voltage and current measurements from the protection relays, but without the possibility of sending control commands to the protection relay which would operate the breakers. Moreover, both instances were synchronized via PTP (Precision Time Protocol) to the same time domain as the physical CPC and the protection relays.

Monitoring system of the pilot setup

Each VPC was connected to two separate monitoring systems to record the performance and behaviors and compare it to the SSC600 device. The two VPCs, as well as the SSC600, connected to ABB’s cloud-based monitoring system ADAM, which recorded their state, reported on the host and the network, including active configurations and substation events. With the web-based monitoring solution ADAM, operators can conveniently monitor a fleet of CPC devices and VPC images deployed at multiple substations, providing a global view.

In addition, a second monitoring system was deployed directly on the same server as the two VPC instances recording relevant VPC metrics at a finer time scale. The aims of the second monitoring system were twofold: (1) provide deeper insights on the performance of the VPCs for debugging purposes; and (2) demonstrate the capability of running mixed criticality applications on the same server. This second system used two additional containers: an instance of InfluxDB, an open-source time-series database, to record the data, and an instance of Grafana, a multi-platform open-source analytics and visualization tool, to provide a web user interface (UI) to the data. The collected information can be exported for further analysis. The piloted software (SW) environment with the monitoring system is described in Fig. 3.

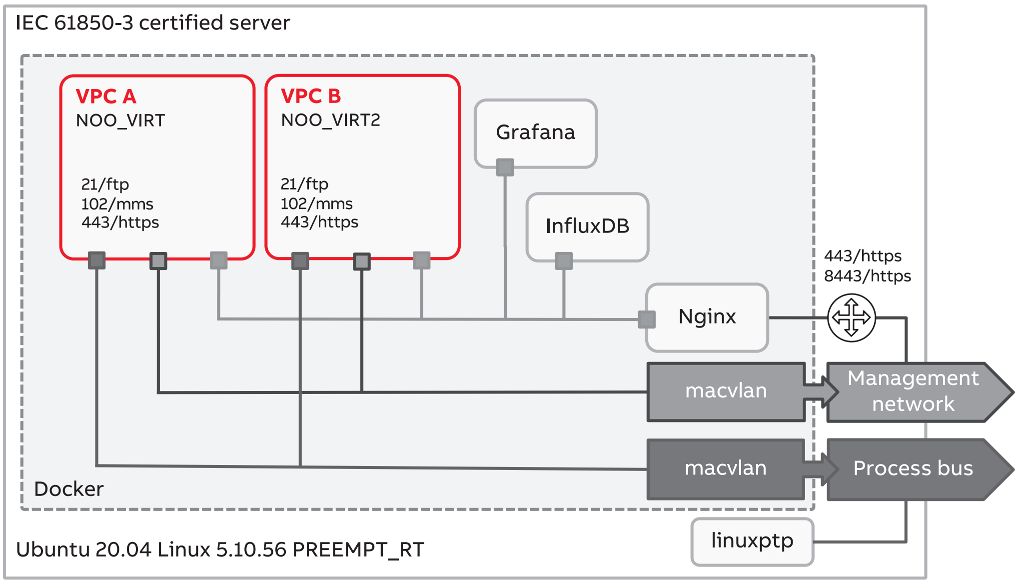


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Fig. 3. Overview of the piloted SW environment

Fig. 3 summarizes the deployed system configuration. It comprised of an IEC 61850-3 certified industrial server running two instances of the VPC docker image pushing the KPI (Key Performance Indicator) data to an InfluxDB and Grafana instance running on the same server. It used two physical network interfaces: (1) one for management, providing remote access to ADAM, and (2) one to receive the IEC 61850-9-2 streams connected to the process bus via an Ethernet switch.

The management network provided access to the two VPC instances, named VPC_A (NOO_VIRT) and VPC_B (NOO_VIRT2), via engineering tools, as well as to the host Linux system and Grafana monitoring web UI. The process bus interface was also used for the PTP time synchronization. Virtual switches were used to route the traffic to and between the container instances as well as the host operating system (OS). The configuration of virtual networks can be seen in Fig. 3.

For details on the evaluation of virtual networking options for containers in the context of real-time software, please refer to [7]. A more technical description of the virtualization setup can be found in [6].

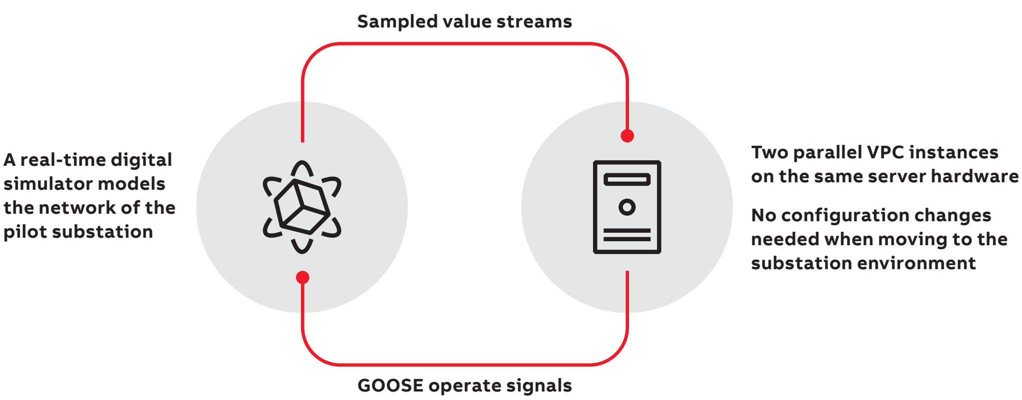
Results from the pilot

Pilot deployment process and pre-deployment testing

The deployment process in the substation was straightforward, as the protection relays used in the substation already supported IEC 61850-9-2LE process bus and PTP time synchronization. The substation also already contained an existing physical CPC device, SSC600, for the active protection and a GPS (Global Positioning System) master clock. This setup was installed already earlier, when the current physical CPC system was taken into use [3]. Also, a dedicated 'research zone' was built in the substation environment, behind a configured Ethernet switch. The switch was configured so that it allowed all substation measurements to be transferred to the research zone, but it blocked all traffic from the research equipment to the protection relays. This additional benefit of a digital substation allows for testing research systems with real-life data, without any risk to the active protection system.

Before the physical deployment was initiated, the VPC environment was first tested in ABB laboratories within an RTDS (Real Time Digital Simulator) test environment. This is illustrated in Fig. 4. A simulation model of the pilot substation network was built in the RTDS and the VPC setup was tested with different scenarios. The utilized RTDS system was able to provide all the measurement data as sampled value streams to the VPC, similar to what merging units would do in a real substation environment. This meant that it was possible to execute all the tests without utilizing additional devices (MUs or relays). After all the RTDS tests had been successfully passed, the VPC setup was moved to the substation environment for the real-life pilot. This approach resulted in an extremely quick and easy deployment on site, requiring only minor adjustments – to set up the management IP addresses as well as minor modifications of the PTP settings.

Fig. 4. RTDS test environment for VPC



Piloting period

The two VPC containers were running in the pilot substation for over a year. The results reported below show that during the whole period from November 1, 2021 to January 5, 2023 both VPCs were able to match the behavior of the SSC600 device flawlessly.

VPC timings

Fig. 5 shows the internal timings of the two VPCs: VPC A (green) and VPC B (yellow). The red line marks the upper bound, i.e., the limit which is never to be exceeded to meet the real-time requirements of the substation protection and control application. This is one of the toughest requirements on CPC. Each point records the maximum cycle time measured over the sampling period. Here we can see that both VPCs have stable timings at around 500us, which is quite far from the cycle time limit. It is also noteworthy that not even one sample exceeds the threshold during the whole year. During the piloting period all real-time requirements of the PAC solution were met, despite the additional overhead from virtualization as well as contention from concurrent workloads.

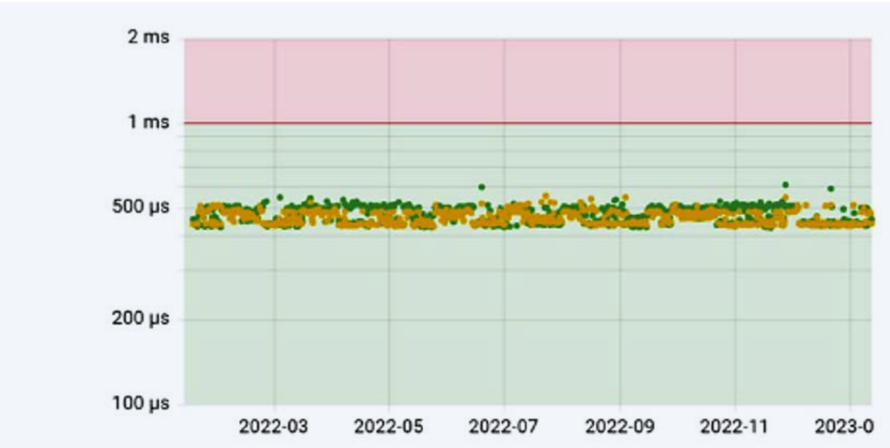


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Fig. 5. Maximal application timing of VPC A (green) and VPC B (yellow) during the past year.

Resource utilization of the VPC

In addition to the timings, also resource utilization both in terms of CPU (Central Processing Unit) and memory was monitored, see Fig. 6. Overall, the peak utilizations were stable across time, and well below the core capacity, yet with the highest utilization recorded by the cores running the protection and control logic. The memory utilization of the VPC instances was constant at 2 GB (gigabyte).

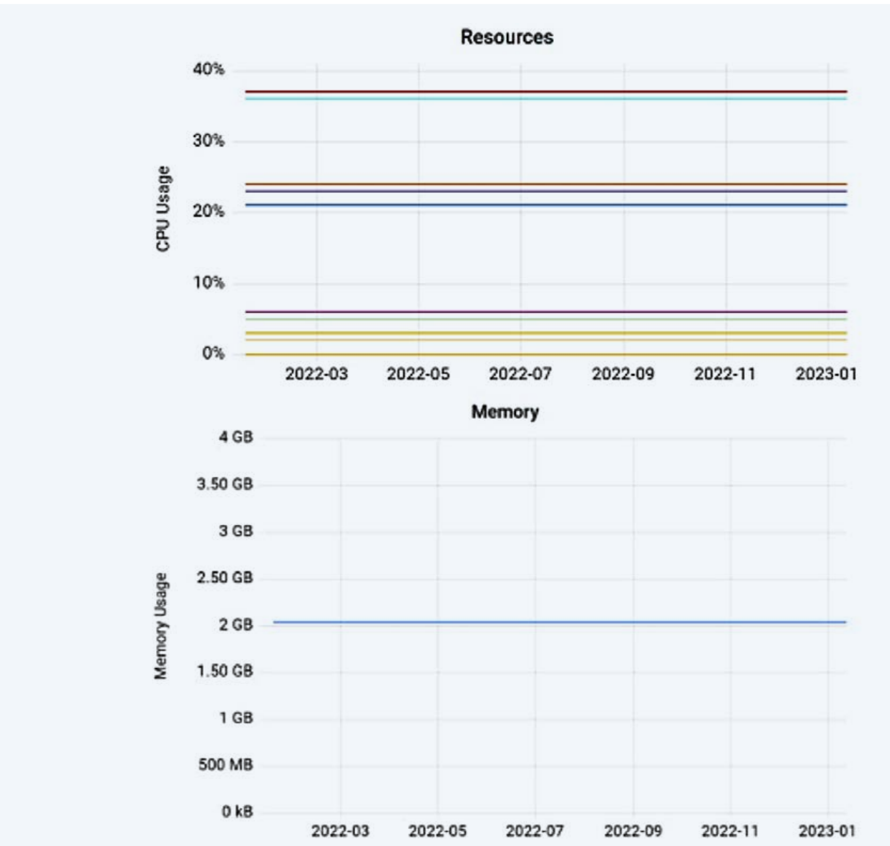

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Fig. 6. Resource utilizations of VPC A and VPC B: CPU usage of all utilized cores in different colors (top graph) and memory usage of the VPC application (bottom graph).

Protection application performance

To compare the performance of the two VPCs with that of the locally installed physical CPC device, all event logs – from all three – were collected via ADAM, the cloud-based monitoring tool. The event logs recorded a broad set of events relevant to the substation's PAC operation. These events range from login attempts to time synchronization state changes to protection function starts and breaker operations. Event logs from the virtual instances were compared to the ones obtained from the physical SSC600 device with particular focus on the observed substation faults, to verify that the behavior of the VPC images matched the SSC600 device. During the piloting period of November 1, 2021 to 5 January, 2023 a total of 11 real faults were observed and clustered on 4 different days: 4 short circuits and 7 earth faults. The distribution of faults across the different bays is presented in Table 1.

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Table 1. Summary of analysed faults

Bay	Short circuits	Earth faults	Total
Bay J08	2	3	5
Bay J11	2	4	6
Total	**4**	**7**	**11**

Based on the event logs, we made the following analysis:

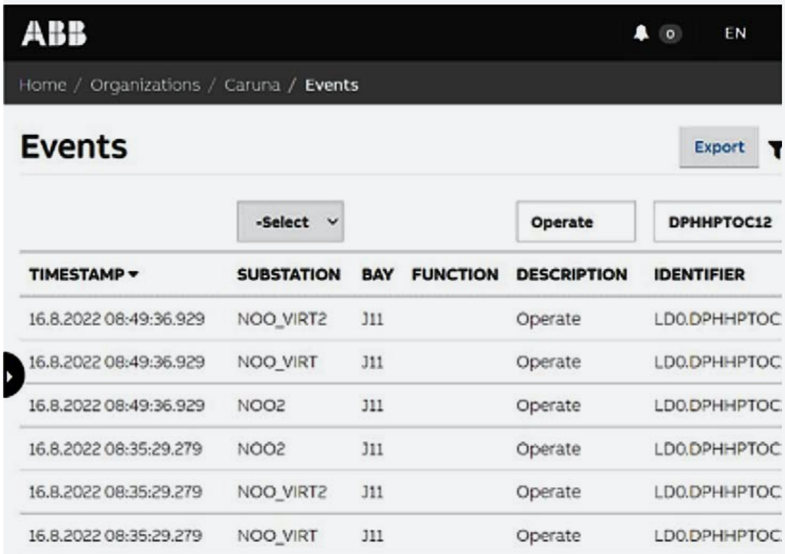

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Fig. 7. Event log comparison on August 16, 2022.

Reaction to fault: during the piloting period real faults occurred at the substation on 25. Nov. 2021 (2), 8.Dec.2021 (3), 16.Aug.2022 (2) and 21. Dec.2022 (4). These triggered the three-phase directional overcurrent protection (DPHHPDOC) as well as the multi-frequency admittance-based earth-fault protection (MFADPSDE).

In all fault situations both VPCs reacted correctly: the detected faults and operating protection functions were identical for all 11 faults between the physical SSC600 device and the two virtual instances – both in occurrence and timing. Fig. 7 shows a screenshot of the event logs on 16. Aug. 2022 of both VPCs and the SSC600 device. The events of the protection instances of VPC A (NOO_VIRT), VPC B(NOO_VIRT2) and the SSC600 device (NOO2) corresponded with each other to the millisecond.

Event timing of the VPCs: The protection function events in both VPC images carried the same timestamps in the event log, measured down to the millisecond. Handling the faults did not interrupt the required real-time performance in any way.

Summary

ABB and Finnish DSO Caruna have piloted and tested a virtualized protection and control solution in a real-life substation in Finland. In the pilot, two Docker VPC containers were running in one shared IEC 61850-3 certified industrial server host, together with other non-real-time applications.

The pilot period ran from November 1, 2021 - January 5, 2023. The target was to compare the protection operations between active commercially available protection systems and two VPC container instances. In addition, the overall stability of the VPC environment was monitored via dedicated logging. The results show that a virtualized protection and control solution can have the performance and reliability equal to that of a commercially available CPC device or relay-based solution.

Another key result from this pilot is the validated benefits of a fully digital substation solution (CPC or VPC). When all functionality resides in one SW-oriented solution, it is possible to complete testing beforehand in a digital simulation environment. As shown in this pilot, with comprehensive RTDS simulations it is possible to conduct all the required tests without any copper wiring, merging units or protection and control relays.

ABB’s virtualized protection and control solution

In January 2023, ABB launched the first virtualized protection and control solution with Smart Substation Control and Protection SSC600 SW. The virtualized product enables customers to use the hardware of their choice and gain access to the same proven protection and control functionality as with ABB’s turnkey solution, SSC600.

To create a robust power system protection and control solution that provides the flexibility and enhanced resiliency necessary to face increasingly complex grids, SSC600 SW supports Linux KVM and the VMware Edge Compute Stack platform as virtualization environments and runs on Intel® Xeon® scalable processors to ensure real-time performance. [8]

References

[1] R. Das et al., 2015, “Centralized Substation Protection and Control”, IEEE Power System Relaying Committee Working Group K15 Report

[2] J. Valtari, 2013 “Centralized Architecture of the Electricity Distribution Substation Automation – Benefits and Possibilities”, Ph.D. Thesis, Tampere University of Technology, Finland

[3] J. Valtari, H. Niveri and J. Reikko, 2019, “Performance analysis of centralized protection and control solution for a distribution substation”, Proceedings PAC World Conference

[4] B. Sousa, J. Starck and J. Valtari, 2017, “Viability assessment for centralized protection and control system architectures in medium voltage (MV) substations”, Proceedings CIRED conference

[5] VMWare, 2022, “Virtualization Overview”, White Paper, [ONLINE]. Available: https://www.vmware.com/pdf/virtualization.pdf

[6] S. Schönborn, R. Birke, D. Kozhaya and T. Sivanthi, 2023 "Real-Time Performance of Virtualized Protection and Control Software ", Proceedings CIRED conference

[7] G. Albanese, R. Birke, G. Giannopoulou, S. Schönborn, and T. Sivanthi, 2021, "Evaluation of Networking Options for Containerized Deployment of Real-Time Applications." Proceedings 26th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA).

[8] ABB, 2023, “ABB launches world’s first virtualized protection and control solution”, Press Release, [ONLINE] Available: https://new.abb.com/news/detail/98682/abb-launches-the-worlds-first-virtualized-protection-and-control-solution

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List of abbreviations

CPC	Centralized protection and control
CPU	Central processing unit
DER	Distributed energy resources
DPHHPDOC	Three-phase directional overcurrent protection
DSO	Distribution System Operator
GB	Gigabyte
GOOSE	Generic object-oriented substation event
GPS	Global positioning system
HW	Hardware
IT	Information technology
KPI	Key performance indicator
MFADPSDE	Multi-frequency admittance-based earth-fault protection
MU	Merging unit

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For more information, please contact your local ABB representative
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solutions.abb/centralizedprotection

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