Real-life pilot of virtual protection and control - experiences and performance analysis

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REAL-LIFE PILOT OF VIRTUAL PROTECTION AND CONTROL – EXPERIENCES AND PERFORMANCE ANALYSIS

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ABSTRACT

Virtualized protection and control (VPC) is seen as a promising evolution for the centralized protection and control (CPC) concept. Centralization of protection functions consolidates the functions of multiple traditional relays into one device. This consolidation reduces communications network complexity and offers effective ways to manage protection applications of the substation. Making the CPC available as a VPC software image instead of a dedicated device creates yet another degree of freedom. The solution becomes hardware independent, bringing more flexibility and scalability to the solution. ABB and Caruna together wanted to explore these possibilities in a real-life substation pilot. This paper describes 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 existing non-virtualized solutions.

INTRODUCTION

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, that brings 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 part 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 low carbon footprint. The importance of continuous supply of electrical energy will grow even more, increasing the reliability requirements. 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, with 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 in the concept of CPC is to move the protection and control functionality from multiple bay level devices to a single centralized device within a substation [1]. In this concept only dedicated process interface units, merging units (MU), are remaining in the bay level. The overall concept is illustrated in Fig. 1.

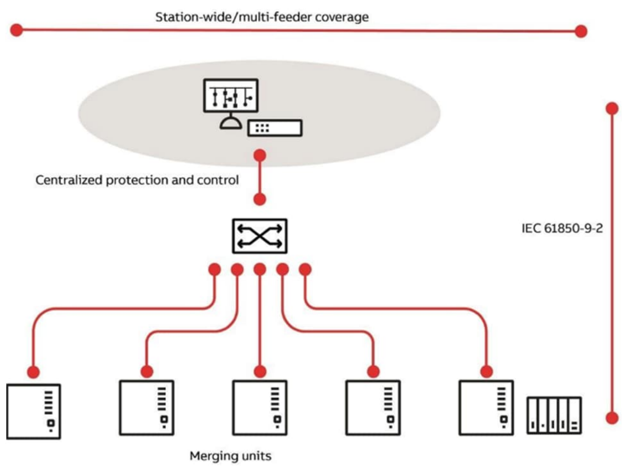


Fig. 1. Centralized Protection and Control concept

The targeted benefits in the CPC concept are related to improved functionality and reduced overall lifecycle costs [2]. There are commercial products on the market, that are entirely based on digital standards such as IEC 61850, and performance and reliability results from CPC based substation solutions are available in [3] and [4].

An evolutionary step in the CPC concept 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 & control is the use of software for creation of an abstract image of a traditional protection & control solution inside a physical host that is a ruggedized computing hardware. This

Authors' preprint of J. Valtari, A. Kulmala, S. Schönborn, D. Kozhaya, R. Birke and J. Reikko, "Real-life pilot of virtual protection and control - experiences and performance analysis," 27th International Conference on Electricity Distribution (CIRED 2023), Rome, Italy, 2023, pp. 2268-2272, doi: 10.1049/icp.2023.1219.

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, but it is used widely in information technology (IT) domain in non-real-time applications. Recent results show that 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

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

Pilot substation

The pilot setup was realized in a 110kV/20kV substation in Western Finland. The substation had 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, one bus-coupler bay, bays for substation self-supply, one bay for capacitor bank and seven outgoing feeders. The single line diagram of the substation is shown in Fig. 2 and detailed information about the pilot is provided in [3].

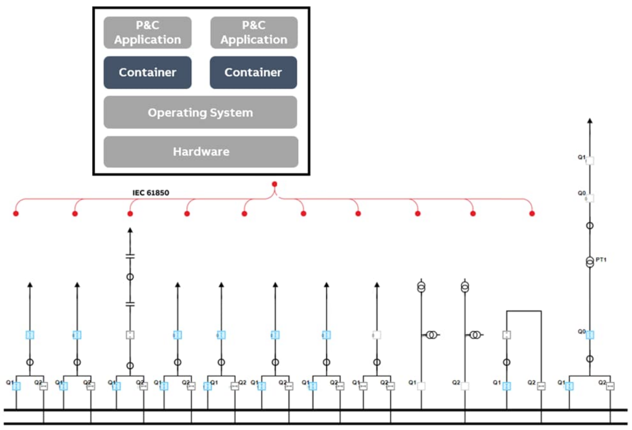


Fig. 2. Pilot substation of VPC

Piloted SW Architecture

To demonstrate how VPC can work in real-life, a prototype solution was built, which virtualized ABB's HW-based CPC solution by wrapping it into a Docker container. Containerization is a lightweight virtualization technology which allows to easily deploy a program as software images and run them in isolation from each other. Containers directly share the operating system kernel avoiding one layer of indirection. This reduces the virtualization overhead allowing to reach near bare metal performance. This is critical for applications with stringent real-time requirements such as the CPC. More specifically, for 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 its 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 outside the VPC instances appear and act the same as a standalone CPC. The substation was controlled by physical CPC which was used as reference to test the VPCs. Both VPC instances had the same application configuration as the physical CPC 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 breakers. Moreover, both instances synchronized via PTP to the same time domain as the physical CPC and the relays.

Monitoring system of the pilot setup

Each VPC was connected to two separate monitoring systems to record the performance and behaviours and compare it to the CPC. The two VPCs as well as the CPC connected to an ABB cloud-based monitoring system that recorded their state, reported on the host and network including active configurations and substation events. It was a web-based monitoring solution allowing to conveniently monitor fleets of CPC deployed at multiple substations providing a global view to operators.

In addition, a second monitoring system was deployed directly on the same server as the two VPCs instances recording relevant VPC metrics at a finer time scale. The aims of the second monitoring system were twofold: i) provide deeper insights on the performance of the VPCs for debugging purposes; and ii) 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 multiplatform open-source analytics and visualization tool, to provide a web UI to the data. The collected information can be exported for further analysis. The piloted SW environment with the monitoring system is described in Fig. 3.

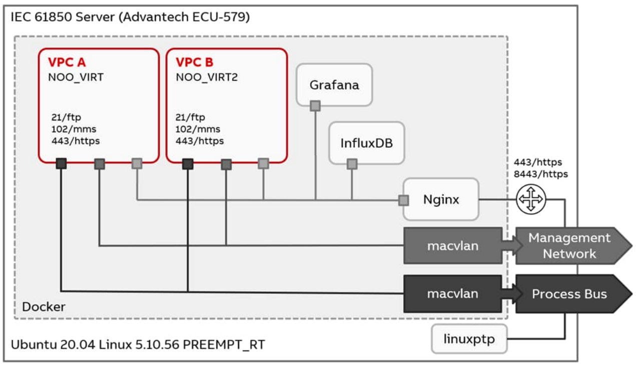


Fig. 3. Overview of the piloted SW environment

Fig. 3 summarizes the deployed system configuration. It comprised an IEC 61850-3 certified industrial server running two instances of the VPC docker image pushing the KPI data to an InfluxDB and Grafana instance running on the same server. It used two physical network interfaces: one for management providing remote access to the cloud monitoring system and 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 VPCs 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 IEEE 1588v2 time synchronization. Virtual switches were used to route the traffic to and between the container instances as well as the host OS. The configuration of virtual networks can be found in Fig. 3. For details on evaluation of virtual networking options for containers in the context of real-time software refer to [7]. A more technical description of the virtualization setup can be found in [6].

RESULTS FROM THE PILOTING

Pilot deployment process and pre-deployment testing

Deployment process in the substation was straightforward, since the relays used in the substation already supported IEC 61850-9-2LE process bus and IEEE 1588v2 time synchronization. The substation also contained already an existing physical CPC device for the active protection and a GPS master clock. This setup was built already earlier, when the current physical CPC system was taken into use [3].

Also, a dedicated 'research zone' was built to 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 blocked all traffic from research equipment to the protective 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 made, the VPC environment was first tested in ABB laboratories with an RTDS test environment, illustrated in Fig. 4. A simulation model of the pilot substation network was built to RTDS and the VPC setup was tested with different scenarios. The utilized RTDS system was able to provide all measurement data as sampled value streams to the VPC similarly as merging units in the real substation environment. Therefore, all tests were possible to execute without additional devices (MU or relays). After all RTDS tests were passed, VPC was moved to the substation environment. This allowed to have an extremely quick and easy deployment on site with only setup of the management IP addresses and minor modifications of the PTP settings.

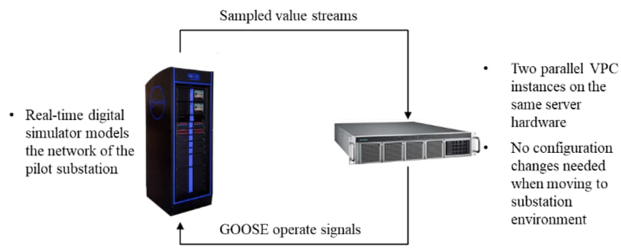


Fig. 4. RTDS test environment for VPC.

Piloting period

The two VPC containers were running in the pilot substation for over a year. The results reported below show that in the whole period from 1.11.2021 to 05.01.2023 both VPCs were able to match the behaviour of the physical CPC flawlessly. More details are provided in the following.

VPC timings

Fig. 5 plots the internal timings of the two VPCs: VPC A (green) and VPC B (yellow). The red line marks the upper bound to be never exceeded to meet the real-time requirements of the substation control and protection application. This is one of the hardest requirements on a CPC. Each point records the maximum cycle time measured over the sampling period. One can see that both VPCs have stable timings around 500us, quite far from the cycle time limit, and without even one sample exceeding 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 and contention from concurrent workloads.

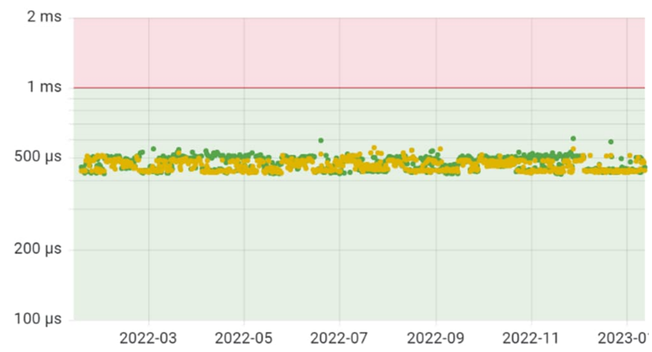


Fig. 5. Maximal application timing of VPC A (green) and VPC B (yellow) during the past year.

Resource utilization of the VPC

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

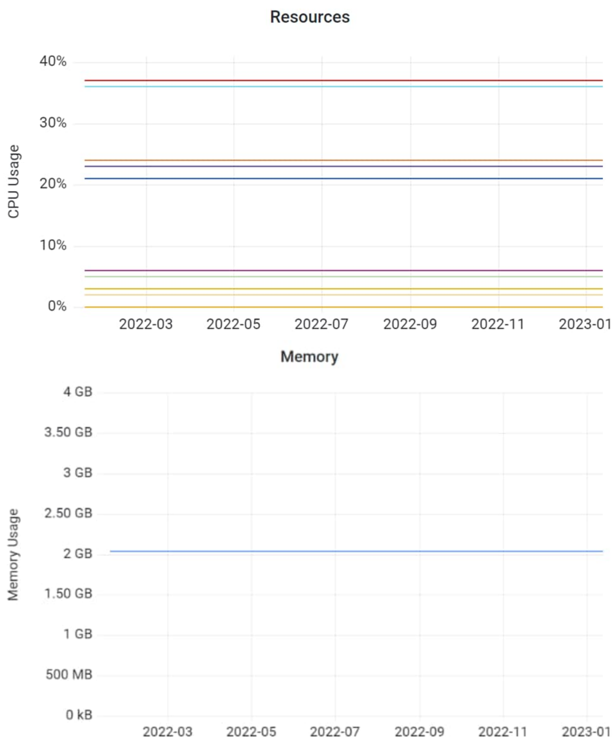


Fig. 6. Resource utilizations of VPC A and VPC B: CPU usage of all utilized cores in different colours (top graph) and memory usage of the VPC application (bottom graph).

Protection application performance

To compare the performance of the two VPCs with that of the locally installed physical CPC, all event logs from all three were collected via the cloud monitoring tool. The event logs record a broad set of events relevant to the substation PAC operation. These range from login attempts to time synchronization state changes, passing by the protection function starts and breaker operations. Event logs from virtual instances were compared to the ones obtained from the physical device with particular care on observed substation faults, to verify that the behaviour of the VPC images matched the physical CPC. During the piloting period of 1.11.2021-5.1.2023 in total 11 real faults were observed clustered on 4 different days: 4 short circuits and 7 earth faults. The distribution of faults across the different bays is presented in Table I.

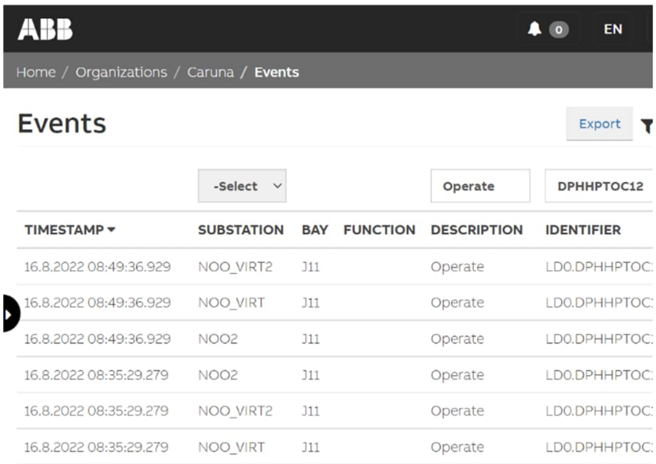
Table I. Summary of analysed faults

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 the following analysis was made.

Reaction to Fault: during the piloting period real faults occurred at the substation on 25.11.2021 (2), 8.12.2021 (3), 16.8.2022 (2) and 21.12.2022 (4). These triggered the three-phase directional overcurrent protection (DPHHPDOC) as well as the multi-frequency admittance-based earth-fault protection (MFADPSDE). In all cases both VPCs reacted properly: the detected faults and operating protection functions were identical for all 11 faults between the physical and two virtual instances both in occurrence and timing. Fig. 7 shows a screenshot of the event logs for 16.8.2022 of both VPCs and the physical reference CPC. The events of VPC A (NOO_VIRT), VPC B(NOO_VIRT2) and physical CPC (NOO2) protection instances 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.



TIMESTAMP	SUBSTATION	BAY	FUNCTION	DESCRIPTION	IDENTIFIER
16.8.2022 08:49:36.929	NOO_VIRT2	J11		Operate	LD0.DPHHPTOC
16.8.2022 08:49:36.929	NOO_VIRT	J11		Operate	LD0.DPHHPTOC
16.8.2022 08:49:36.929	NOO2	J11		Operate	LD0.DPHHPTOC
16.8.2022 08:35:29.279	NOO2	J11		Operate	LD0.DPHHPTOC
16.8.2022 08:35:29.279	NOO_VIRT2	J11		Operate	LD0.DPHHPTOC
16.8.2022 08:35:29.279	NOO_VIRT	J11		Operate	LD0.DPHHPTOC

Fig. 7. Event Log Comparison for the 16.8.2022

SUMMARY

Virtualized Protection and Control solution was piloted and tested in a real-life substation, in cooperation with ABB and Caruna. Two Docker VPC containers were running in one shared IEC 61850-3 certified industrial server host, together with other non-real-time applications.

During the piloting period of 1.11.2021-5.1.2023 the purpose was to compare the protection operations between the active commercial protection systems and the 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 a commercial CPC or relay-based solution.

One of the results of this pilot is also a demonstration of the benefits of a fully digital substation solution (CPC of VPC). When all functionality resides in one SW oriented solution, complete testing is possible to do beforehand in a digital simulation environment. With comprehensive RTDS simulations it was possible to conduct all required tests without any copper wiring and without any Merging Units or protection and control relays.

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 centralised 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)*.