FUTURE ARCHITECTURES OF ELECTRICAL SUBSTATIONS

Paper No.EUR21_32

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Abstract -

For 40 years, most of the HV/MV & LV electrical substations have been build using copper cables wiring together protection relays, automation and measurement units and primary equipments such Power Transformer, Circuit Breakers, Switches and Voltage/Current Transformers and protection relays to control of the electricity. Beginning of the 21th century, the used of Ethernet based substation communication coupled with the generalization of digital technologies have started the step to digital substations.

The present paper presents the future evolutions for the HV & LV electrical substations based on the new technology evolutions and communication technologies with in detail the new Centralized Protection, Control, Automation & Measurement Systems for substation supported by IEEE and the expected evolution to the virtualization of all equipments taking benefits of the Merging Units (MU) generalization.

In conclusion, the impacts over substation engineering tools and security concepts are identified coupled with these new HV & LV architectures.

Index Terms — Substation Automation, Electrical Grid, Virtualization, Digitization, IEC61850, Centralized architecture, Merging Unit, Process Bus.

I. INTRODUCTION

One of the key challenge Industrial sites face is the need to optimize what is not in their core business and reduce all additional costs. Electricity is considered as a resource to be optimize in term of availability, dependability and cost. This is mainly achieved by integrating technology evolutions, adapted products and engineering tools and services able to reduce investments and managements costs in respect of site security, international applicable standards and interoperability between suppliers.

Introduction of digitization and possibilities of virtualization change the way the HV & LV industrial grid design will be done. We will see in the following chapters how this can be evaluated and what is today possible at reasonable risks and with potential benefits.

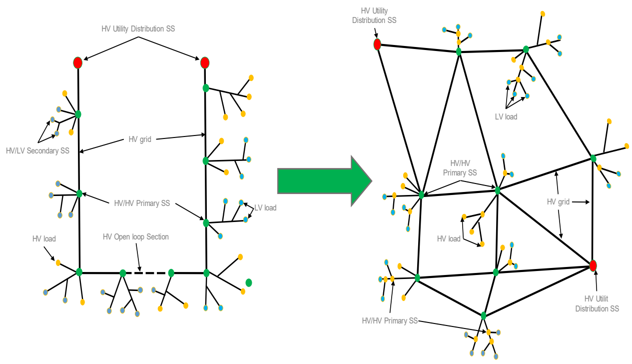
II. EXISTING ARCHITECTURES FOR HV & LV INDUSTRIAL GRIDS

Since the standardization of electricity use for industrial site process, the global structures of the site electrical grid have not changed but recent technological evolutions coupled with climate change regulations generate recent strong evolutions.

A. *HV & LV industrial grid architecture*

The HV & LV electrical grids of Industrial sites have been mostly designed since more than 50 years upon a traditional pyramidal architecture; The power is delivered by the Utility connection at the highest voltage level and then through various voltage transformers, substations and sub-grids distributed to the local applications connected on LV or HV. All elements are adapted to this top to down concern.

New availability of renewable and intermittent energy resources and storage capacities on site, industrial application consumption management with demand responses concepts create conditions for a complete redesign of the new grids from the historical pyramidal to a complete flexible mesh architecture.



Industrial Open-loop HV grid to HV architecture

B. *Protection, Control & Measurement systems*

Since the middle on the 80s, start to be applicable for HV & LV Electrical grid, Intelligent Electronic Devices (IED) based on the first hardened microprocessors and controllers taking advantage of analog grid measured quantities into digital signal. All these equipments were handling single function similar to what was possible with modular existing static devices. Technology evolutions make existing features smarter, faster and more integrated but without major changes in the architectures of the electrical substations and grids.

In the HV & LV substations, the various actuators (CB, SW,..) remains with their interposing relays and sensors (CT, VT, IOs); IEDs handle single function similar to what was possible with modular existing static devices, interconnection slowing move from the copper wirings to serial (IEC103, MODBUS, DNP3, ..) and Ethernet based protocols (OPC, IEC61850, IEC104, DNP3/IP, …), Local Display, SER (Sequence of Event Recorder) and RTU (Remote Terminal Unit) have been replaced by HMI (Human Machine Interface) and GTW (Gateway).

Traditional HV substation PCAS architecture

At Grid Level the technology migrations have push the replacement of the multiple cooper wiring cabinet by serial communications and by Ethernet or wireless support. Same evolutions for the Energy management System which features are now possibly embedded in the Process Management System (PMS) or the Building Management System (BMS).

II. Concepts of HV & LV Industrial grids virtualization

The publication of the IEC61850 fast and standardized Ethernet based standard have been the first formal step of the potential evolution of the HV and LV substation sand grid through mainly three directions:

- Communication structure for substation (61850-7.1)
- Time-critical and non-time-critical data exchange through local-area networks (61850-8.1)
- Publication of the sampled value Process bus (61850-9.2)

Other standards regarding Time synchronization (IEEE 1588), Ethernet redundancy (IEC 62439), Merging Units and Non-Conventional IT (IEC 61869) have been an enabler or the emergence of new substation PCAM solution architectures mainly based on the virtualization concept.

A. *Virtualization concepts*

Virtualization concept refers to the substitution of a virtual machine acting like the real one. Multiple physical machines may be virtualized in a single software with application running in parallel with different types of virtualization steps:

- Para-virtualization: Local applications are transferred in a dedicated hardware running in their own isolated domain with their own sensors. The different subparts are interconnected together in a real domain. It is usually a first step to virtualization allowing a smooth migration
- Full virtualization Complete simulation of the hardware to allow software environments, including a guest operating system and its apps, to run unmodified.

Virtualization help to reduce the physical infrastructure cost of electrical PCAM solution, ensure a shortest testing and restoration time and improve security and installation safety.

B. *Virtualized Industrial grid architectures*

Industrial electrical grid resource virtualization is the first concept to be considered and may be achieve using two ways:

- The Platform virtualization impacting mainly electric management applications.
- The Resource virtualization involves splitting or combining real IEDs into virtual groups.

Platform virtualization consider one physical equipment divided into multiple virtual environments. This approach provides positive elements:

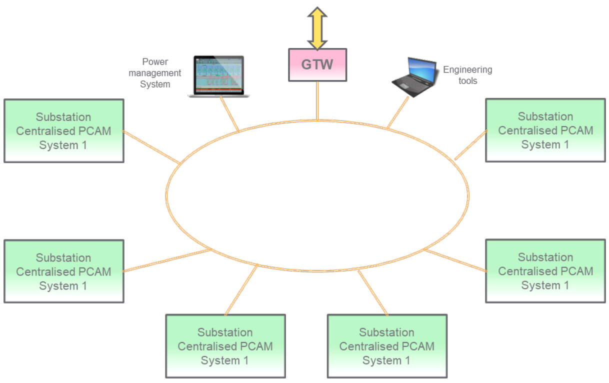
- Deployment/restoration time: Creating and installing a virtual machine is simple and request limited time (10 to 30 mn) compare to traditional methods (1 to 8 h)
- Cost reduction by the optimized used of equipments and energy resources
- Evolutions as most of tests are run using simulation machines similar to site elements

Resource virtualization mainly consider the communication network by the use of VPNs and VLANs making communication architecture simpler. A specific attention must be given by network administrator to performance and topology management to avoid complexity and security risk.

Storage and archiving virtualization are also very common and popular resource virtualization methods in Industrial applications by abstracting application data archiving from multiple physical storage unit to a virtual remote unit mostly known as "cloud storage".

Electrical Management virtualization can be deployed as:

- The entire industrial grid HV & LV elements (substations, feeders, generator, etc..) with all functional elements in a single or redundant central machine,
- HV and LV Substations as elementary bricks combine to run the industrial electrical grid application.



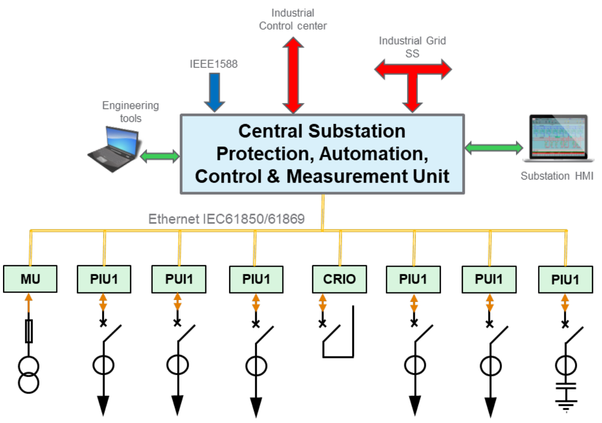
Industrial HV & LV grid architecture with virtualized PCAM System

Electric management virtualization simplifies the application installation and deployment as the application software are independent from the physical hardware and software environments. This makes possible running of simultaneous applications even they use the same data or used incompatible hardware or software.

Virtualization allows to mix over the same global application different virtualization concepts and architectures to full-fill application requirements and project delivery time constraints; Evolutions are also simplified and help to reduce maintenance costs.

III. Architecture of Virtualized Electrical Industrial Grids

Considering all virtualization concepts and availability of various applicable standards, the most suitable architecture for Industrial HV & LV site is the partial virtualization with HV & LV centralized substation PCAM systems connected on a redundant HSR/PRP Ethernet fiber optic network with Power Management system and interface to the Site Process management System.



HV Substation Centralized PCAM System architecture

A. *Substation elements*

In electric substations, the functional scope of the virtualization will mainly be:

- HV & LV Protection functions (OC, Dir OC, Diff Line, Diff Transformer, Generator, Busbar, etc..)
- HC & LV Control capability (Switchgear Control, Generator Start & Stop, OLTC control, …)
- HV & LV Automation schemes (earth control, Inter-tripping, Logic selectivity, Volt/Var regulation, …)
- HV & LV Measurements & Monitoring (Quality, Measure, CB monitoring, Oil monitoring
- HV & LV substation HMI and archiving
- HV & LV gateway (from associated equipments, to surrounding HV & LV substation, to Site Energy management system)
- Inter-equipment wirings (analog and logic) and associated interposing relays

In complement, virtualization concept will also integrate:

- HV & LV substation engineering tools for design, wiring, and configuration of the various IEDs
- Test procedures and methods of the single IEDs and the global HV & LV substation

Additional HV & LV substation parts are also impacted by the Digitization concept

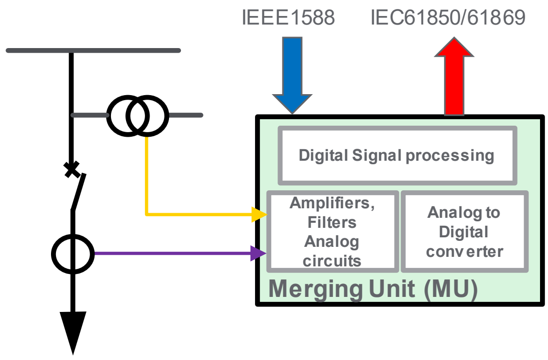
- Cabinets and cubicles hosting communication devices (switch, router, Gateway, ….)
- Auxiliary power supply including associated UPS
- Electric & communication cable trays
- Security & Cyber-security rules and procedures

B. *New Substation elements*

PCAM virtualized HV & LV substation architecture change strongly the hardware and software used.

Many IEDs are virtualized (protection relays, RTU, Measurement units, etc..) and some new elements mainly sensors interfacing electric process as defined by the IEEE/IEC WGs, Smart grid concepts and IEC61850 standards, are coming on field:

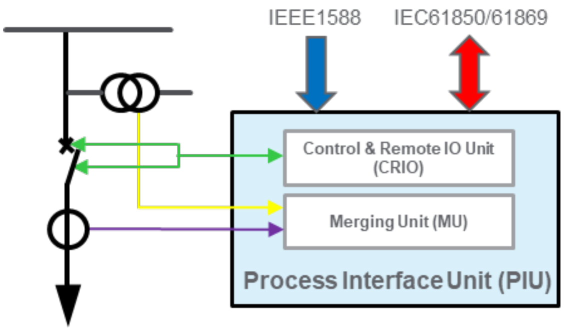
- Merging Unit (MU) IED converting analog signals (protection and measurement CT or VT mostly) into sampled values (IEC61869),
- Control & Remote IOs unit (CRIO) converts control and status information for primary equipment (SW, CB, Transformer, ...) to Process Bus GOOSE based mainly,
- Process Interface Unit (PIU) combines a MU and a CRIO unit into a single equipment. PIU can publish over IEC61850 analog values and equipment status and accept control commands for primary equipment operation.



Merging Unit typical architecture

Based on study done in IEEE PSRC WG, two physical model of PIU are considered:

- Class 1 PIU (PUI1) combines analog and logic bay equipment interface as per IEC 61850-9-2, IEC 61869-9/13
- Class 2 PIU (PIU 2) is a PUI with additional safety protection function able to run in a stand-alone mode



PIU typical architecture

All these new elements use Ethernet Fiber 1, 10 or 25 Gb/s with Standardized redundancy methods (Parallel Redundancy (PRP) and High-Availability Seamless Redundancy (HSR) and Time synchro IEEE 1588 based

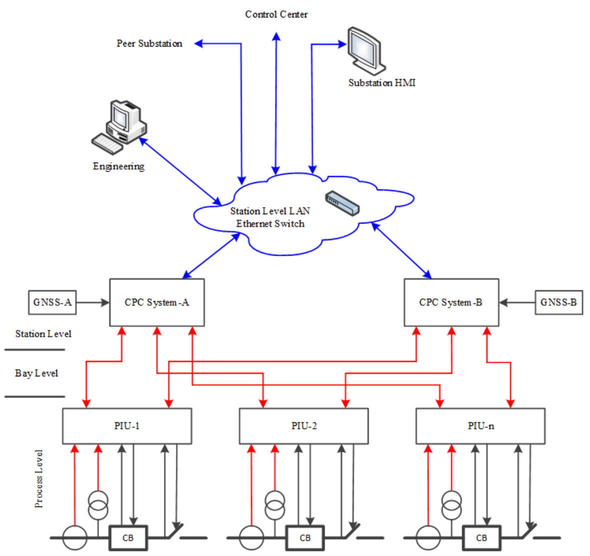
A central potentially redundant device embedded:

- Communication with the different PIUs, MU & CRIOs of the substation via IEC61850 Ethernet fiber interfaces
- Multiple functional bricks as define by IEC61850 and running all primary equipment, voltage level and substation functions (Protection, Automation, Control & Measurements) in a coherent and consistent manner based on data received from the PUIs, Mus and CRIOs
- Local Data storage and Archiving on a dedicated unit (optional)
- Display on a local Human Machine Interface (optional)
- Interfaces to the outside of the substation with two main directions:
  - the Site Energy management application,
  - Surrounding substations (HV & LV) for distributed protection and automation functions

C. *PCAM HV & LV substation solution architecture*

The PCAM HV & LV substation solution architecture is built around 3 main layers:

- The process/bay level interfacing the different primary equipments (logic and analog)
- The communication level based on Giga-Ethernet optical fiber (1, 10 or 25 Gb/s) with or without redundancy (IEC62439 HSR or PRP), Ethernet switch/router and IEEE 1588 time synchro clock
- The substation level with the central computer CPC (single or redundant), engineering tool, local HMI display, gateways to site Energy Management System and other site substations (HV & LV) and equipments (Generator, Storage units, ...)

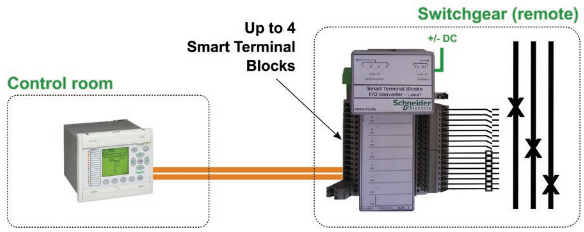


IEEE PSRC PCAM type 3 architecture

Note : for LV substation /equipment the attachment to a main HV substation allows to simplify the architecture by removing part of the CPC and associated equipments.

As define by IEEE PSRC WG, 6 typical PCAM architectures have been defined (type 1 to 6) with various integration level, redundancy and functional split. For Industrial site applications, type 3 and type 5 are the most usable. Both refer to similar organization while in type 3 PIUs are connected to CPC systems over Point-to-Point connection; In Type 5, PIUs are multicasting SV and GOOSE to CPC systems, and each PIU receives multicast GOOSE from CPC systems.

It is also key to note that these architectures allow the interoperability between the Virtualized environment and any legacy systems. This is a major challenge to support multiple suppliers and application domains in the same environment. Virtualization of legacy sub-systems is then easily and cheap.

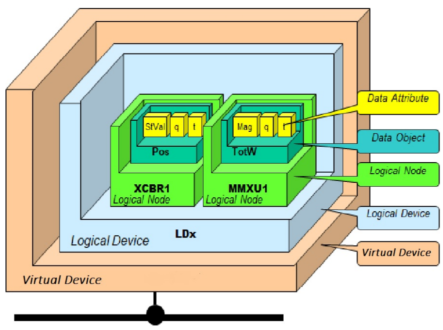


PUI (SE Smart Blocks) interfacing wired legacy equipment

D. *Engineering tools*

PCAM solution for industrial electrical HV & LV substation are configured based on IEC61850 concepts. The use of IEC61850 System Configuration Language (SCL) combine with the standardized data and function modeling (IEC61850-7) allows application engineering to be fully independent from the physical implementation and an easy migration from a traditional architecture to a full virtualized concept.

Applying IEC61850 concept, each standard bay (LV feeder, HV/LV transformer, HV busbar, ..) is associated a series of logical devices representing the bay functions housed in a virtual IED.

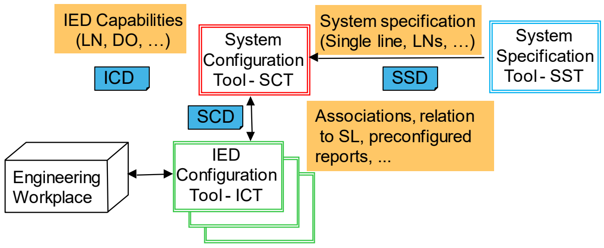


Virtual IED functional architecture

IEC61850 engineering are built mainly around three layers/tools:

- The System Specification Tool (SST) for the specifications of process signal, automation data exchange, communication and electric network topology. SST allows to associate IEC 61850 Logical Nodes to Industrial Power system resources

- The System Configuration Tool (SCT) integrate SST data and will generate application functions, communication network topology & characteristics.
- The IED Configuration Tool (ICT): in Digitization process, the ICT create the functional capabilities of a virtual IED including parameters.



IEC61850 configuration tools

Virtualization takes fully benefits of IEC61850 ed2 concepts and elements and provide all potentials to the designer and the user for a better and more efficient HV & LV electrical grid architecture and use.

E. *Tests of Virtualized CPAM*

The concept of CPAM testing is similar to what is done with traditional IEC61850 Substation Automation System (SAS) with a specific concern regarding Ethernet IEC61850 network and the various interfaces. Simulation testing tool help to cost reduction during Factory Acceptance Tests (FAT) and Site acceptance Tests (SAT) by minimizing all commissioning and outages time especially during the site installation phasing when part of the CPAMs have been validated and new ones are added to them (step by step installation);

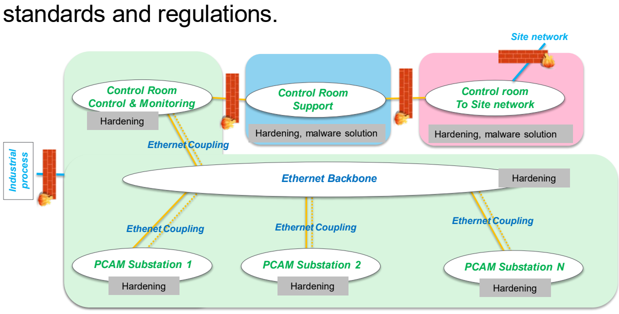
Simulation tools are also key for operator and maintenance team trainings. The simulation tools take benefits from the virtualization concepts by simulating at 100% the missing equipment, data or function

Same tools could be used to anticipated future evolutions of the site (new grid, increase of consumption, change in power delivery, etc.) These application software are also usable in the quasi-real-time simulation to provide options to the operator in their site management actions;

F. *Cyber-security for Virtualized CPAM architecture*

Cyber security management rules are applied to maintain application availability as a priority and then device integrity and data confidentially. Cybersecurity acts at 2 levels:

Network and Device. All are regulated by dedicated standards and regulations.



HV & LV secured Virtualized integrated architecture

The Cyber security design applied to Industrial Virtualized Electric grid must integrate the following items:

- In-depth Defense- concepts with firewall and DeMilitarized Zone (DMZ)
- Role-based Access Management
- Authentication, security and access management
- Remote communication Encryption
- Consistent patch management for all software and firmware components
- Intrusion detection systems

Use of NERC, NIST, IEC62351, ISO17065 rules and standards to analyze and prevent cyber threats is mandatory to protect industrial electrical grid from most of cyber threats of malicious intrusions.

IV. FUTURES OF HV & LV INDUSTRIAL VIRTUALIZED GRIDS

A. *New HV & LV grid industrial functions*

The capability to distributed over a common communication grid data (analog and logic) with a very precise time stamping allow to simplify existing installations and give new opportunities for protections and automation schemes with a clear objective to reduce Electrical costs and improve energy delivery.

The capability to have at the same moment LV and HV data will make motor management more efficient and reduce direct and indirect stress over involved electrical installation. Associated logic selectivity will be possible with a time refence of few milliseconds. Fast ATS becomes simple at HV and LV levels

Distribution of Voltage and frequency precise measurements make power generation more reactive and will reduce the associated costs and impact over the Industrial process

The imposed HV & LV electric grid mesh architecture change the rules of protection characteristics and impose the replacement of Overcurrent and Dir Overcurrent relay by more adapted Differential Current relay; The constraint of this type of protection relay is the need to have fact and precise measurement exchange between cable two ends; In the traditional approach this can only be achieve using dedicated communication path. Now with virtualization, this become possible easily and at near no cost with the capability to reduce fault elimination to less than 40 or 60 milliseconds.

B. *Globalization of the virtualized solutions*

The evident evolutions of the virtualization will be the transfer of all various PCAM central computers function to the Site Energy Management system central system physical hardware.

The second step will the virtualization of the Energy Management System it self on the site Process management System or on a local or remote cloud where all application dedicated to energy runs and exchange data with the rest of the site systems (Fluid, Process, Fire & safety, etc…).

C. *Primary equipment simplification and cost reduction*

The use of virtualized solution in HV & LV Electrical Industrial grid will directly impact the primary equipments in their actual design, manufacturing, testing and maintenance.

In a standard HV or LV Circuit breaker, there are mainly replicated information for the multiple display or use by various operators (position display on local and distance HMI, capability to open/close the CB, etc..). Virtualization will remove all these duplications at associated equipment with possible better availability and dependability, mostly by giving the capability to have real-time test (Ethernet communication vs cooper wiring) with efficient redundancy modes. Associated information are available at data level such as Time stamping, topological information, etc.…

Simplification in the primary equipment wirings and less interposing relays, will also reduce the execution time of any order or status change (typically an interposing relay introduces 3 to 5 ms time delay). With less devices at primary equipment level, global solution direct cost will be reduced and testing time either while possible space and weight reductions must be considered as direct benefits of Virtualization.

V. CONCLUSIONS

Virtualization of HV & LV Electrical grids for Industrial applications has created a significant interest as a new combination of technology and methodology that will potentially change the design, build, test and use of HV & LV electrical grids; This virtualization combines with the necessary changes in the use of energy and the need to comply with environmental requirements make new industrial installations acceptable from both a cost aspect and an ecological concern.

The use of standard and implication of international organizations and committees give a complete credibility to this approach and announces Digitization as a must have for the new HV & LV electrical grids in Industrial sites.

VI. ACKNOWLEDGEMENTS

The authors gratefully thanks IEEE PES PSRC C37 team's members, Alex Apostolov and Thomas Rudolph for their Digitization works, documents and studies and their advices for this paper.

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VIII. VITA

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