Software-Defined Protection, Automation, and Control in Power Systems

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Power systems' Protection, Automation, and Control (PAC) functionalities are often deployed in different constrained devices (Intelligent Electronic Devices) following a coupled hardware/software design. With the increase in distributed energy resources, more customized controllers will be required. These devices have high operational and deployment costs with long development, testing, and complex upgrade cycles. Addressing these challenges requires that a 'revolution' in power system PAC design takes place. Decoupling from hardware-dependent implementations by virtualizing the functionalities facilitates the transition from a traditional power grid into a software-defined smart grid.

PAC systems | IT/OT convergence | software-defined/virtualized PAC | virtualization technology | interoperability | IEC 61850 | smart grids

1. Introduction

Today, power systems face rising challenges that motivate their development into smart grids. The numerous challenges include: reaching carbon neutrality goals, electrification of end-uses, and the energy transition into renewables [1]. The integration of Distributed Energy Resources (DERs) at both Medium Voltage (MV) and Low Voltage (LV) levels is actively transforming the traditional centralized design of power systems; from a mostly static, uni-directional grid into a grid supporting bidirectional flows of energy and information between different energy actors with much faster operating dynamics and limited predictability [2][3]. Therefore, maintaining the supply–demand balance and avoiding grid congestion becomes an increasingly complex task with significant uncertainties [4].

As the power system evolves, introducing novel improved Protection, Automation, and Control (PAC) systems supporting its operation becomes a necessity [5]. Researchers formally define PAC systems as a cohesive set of power system functionalities that allow to protect, automate, and control the electrical grid, spanning the field, process, and operational zones. Examples include substation voltage controller, under/overvoltage protections, differential protection, Supervisory Control And Data Acquisition (SCADA) systems, wind farm controllers, etc.

PAC systems are based on three main components spread across the power grid [6]: (i) Protection functions located as close as possible to the monitored structures (e.g., line or a transformer); (ii) Control for coordinated actions by local automation/control software (e.g., in an electrical substation or DER plants); (iii) Optimization by the grid operator's control center (e.g., set of monitoring software, management systems) requiring a global macroscopic system view.

However, the possibility of massive DER integration was rarely considered during conventional PAC design schemes with limited coordination between PAC systems' three-layer hierarchy. This could lead to several cascading events triggered by faults in the High Voltage (HV) level and unwanted tripping of DER protections. For example, a recent event around London in 2019 resulted in the disconnection of approximately 1.1 million customers, where many DER generators disconnected due to underperforming protection settings and mechanisms (e.g., low voltage ride-through) [7].

1.1. Motivation

Following the energy transition paradigm, the digital transformation of the power industry is thought to 'revolutionize' its management, reliability, and efficiency [3]. As a result, more and more energy stakeholders are getting interested in implementing adaptive systems such as those offered by the Information Technology (IT) field (e.g., Virtualization Technology, Cloud/Edge Computing), with the reliability and security required for Operational Technology (OT) power assets [8]. In the particular case of PAC systems, this concerns field deployments of the numerous hardware devices (otherwise known as Intelligent Electronic Devices IEDs) embedding the functional logic and the associated information systems monitoring and operating them.

Conventional PAC systems' hardware infrastructure is currently costly to evolve (e.g., to integrate new advanced functions), maintain (e.g., during hardware failure events), and operate in face of long-term system specification uncertainties and reliability concerns [9][10]. Furthermore, deployments require significant manual and inconsistent efforts that are highly error-prone when not automatically validated.

In light of the problems facing PAC implementations, the concept of software-defined PAC systems recently gained popularity; it is the result of the convergence efforts between IT and power system communities. The idea, which was first mentioned by Lo et al. [11], can be formally defined based on [12], as *"an approach to decouple PAC software from their dedicated hardware using efficiently managed architectures supporting heterogeneous, time-deterministic protection, automation (e.g., SCADA), and control (e.g., closed- or open-loop) applications*".

1.2. Related Work: Trends and Evolutions of Protection, Automation, and Control Systems for Smart Grids

Recent growth in communication, information, and networking technologies has led to a shift in PAC design and supported architectures. This tendency has also been observed in several previous research works reviewed in the following paragraphs. Bo et al. [13] performed a survey on protection and control evolutions in power systems covering the impacts of advancements in communication, information, and networking technologies (as presented in **Figure 1**). The survey addressed hybrid, wide area (regional), and local (substation-level) protection and control architectures that can be coordinated to enhance system performance. The work presented in [13] also discusses the implementation of this concept on a distributed real-time computing platform they name `power cloud'. Despite suggesting the importance of interoperability (Defined by the International Electrotechnical Commission (IEC) as: *"The capability to communicate, execute programs, or transfer data among various functional units in a manner that requires the user to have little or no knowledge of the unique characteristics of those units"* [14]) and openness of the platform, Bo et al. [13] do not discuss the integration of such platform and architectures with existing protection and control standards.

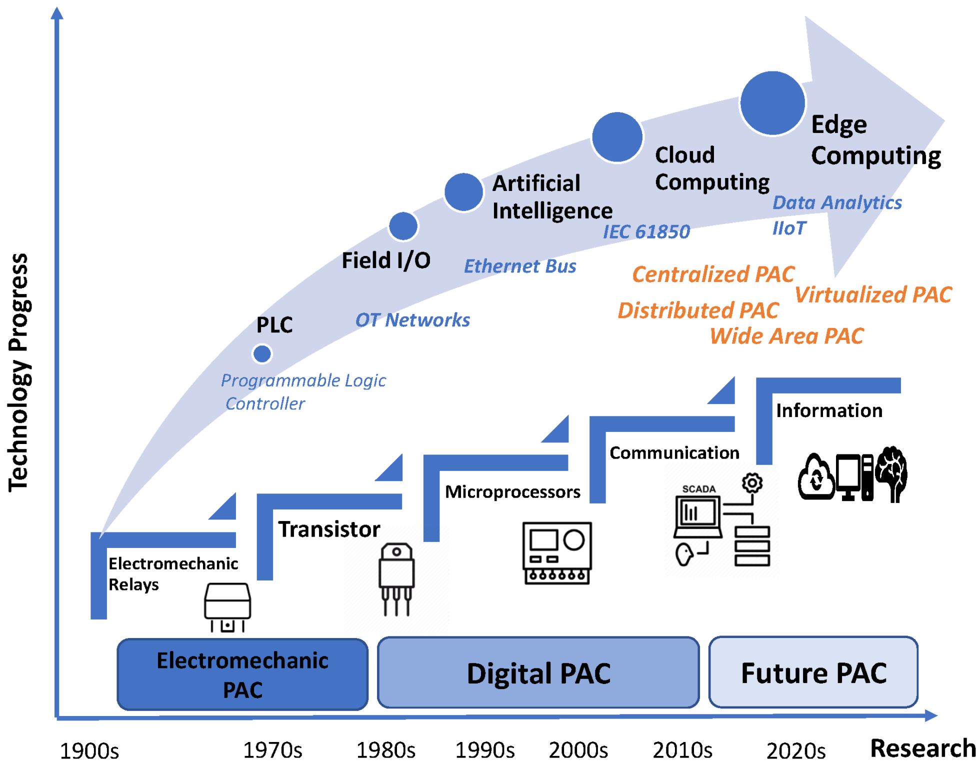

Figure 1. Evolution of PAC systems based on [13].

Phadke et al. [15] presented some opportunities and motivations related to the recent development of Wide Area PAC systems including: monitoring the suitability of relay characteristics, supervision of backup zones, adaptive protections, managing wide area disturbance. Similarly, the IEEE Power System Relaying Committee [16] reviewed recent advances in centralized protection and control architectures. The authors summarize the main results comparing traditional (distributed) and different centralized architectures in terms of qualitative metrics (security, interoperability) and quantitative metrics (availability, reliability, cost) with experience from a test trial.

Regarding the concept of distributed intelligence in power systems, Strasser et al. [17] surveyed the needs of future smart grids (e.g., hardware/controller levels, local/coordinated optimizations). The survey also covered the application of software technologies for power system automation and control. However, trends towards decentralization with specific implementation technology were outside the scope of [16][17].

Furthermore, Birman et al. [18] discussed the cloud computing model's suitability for smart grid applications. The topics addressed included scalability, real-time operation, consistency, fault tolerance, privacy, and security. All these aspects remain highly relevant despite the research dating back to 2011. Authors in [18] declared that a dedicated data center or private dedicated internet for power systems is not cost-beneficial enough and thus analyzed an integrated cross-sectoral solution. The concept of 'grid function virtualization' was detailed by Kruger et al. in [19] based on similar concepts developed by the telecommunication industry. However, the authors focus on examples of flexible distribution automation (e.g., state estimation) without covering trends towards protection and control in digital substations or mentioning practical feedback from the telecommunication industry's virtualization experience.

2. Challenges Related to the Deployment of PAC Systems in Intelligent Electronic Devices

2.1. IED Design Requirements

PAC systems are currently deployed by numerous IEDs (defined in IEC 61850-5 ED 2.0 [20] as: *"a device incorporating one or more processors with the capability to execute application functions, store data locally in a memory, and exchange data with other IEDs over a digital link"*). Examples include: protection relays, automation controllers, and data gateways spread across substations, power plants, and DERs. These communicating devices result from technological advancements in communication and processing power from originally electro-mechanical, electronic static/solid-state relays to today's digital era of microprocessor-based devices (seen in **Figure 1**). According to [21][22], an IED should respect the requirements characterized by its governing PAC system including:

- **Reliability**: Reliability can be decomposed into (1) dependability, which is defined as the degree of assurance that a PAC system will work correctly when required; (2) security, refers to the assurance that a PAC system will operate correctly during failure for which it is not responsible.
- **Speed**: The time delay to receive, treat, and issue a response for a data stream from physical assets. The response time should be respected in order to minimize damage caused by equipment and system failures.
- **Selectivity**: In the specific case of protection functions, the ability to determine and disconnect the minimum possible parts of the network necessary for fault elimination and disconnect the minimum number of customers.
- **Redundancy**: Required at both hardware and communication network levels.
- **Interoperability**: Allows to support multi-vendor deployments.
- **Cost**: Keeping the implementation and operating costs low while achieving the PAC system goals. This is tightly related to the 'interoperability' feature.
- **Simplicity**: Keeping operations as straightforward as possible to recover rapidly during emergency events. This is also tightly related to the 'interoperability' feature.

2.2. Current IED Design Requirements Limitations

A missing, yet vital, characteristic that has yet to be considered so far is flexibility. Flexibility in engineering scope can be described as: *"the ability of a system to respond to internal or external changes affecting its service, in a timely and cost-effective manner"* [23]. In the context of IEDs, research tackling this topic is limited to [24][25][26][27]. The primary use cases include: (i) reducing initial manual deployments efforts; (ii) capability to modify or add new functionalities; (iii) system recoveries in case of hardware failures or maintenance.

Moreover, the number of IEDs currently present in electricity grids is rather significant (could reach hundreds in a HV substation) with a mixture of both outdated and novel digital devices [9] (seen in **Figure 2**). Each IED is usually based on proprietary vendor hardware, coupled with different operating systems and firmware that require managing vendor-specific hardware configuration and maintenance tools.

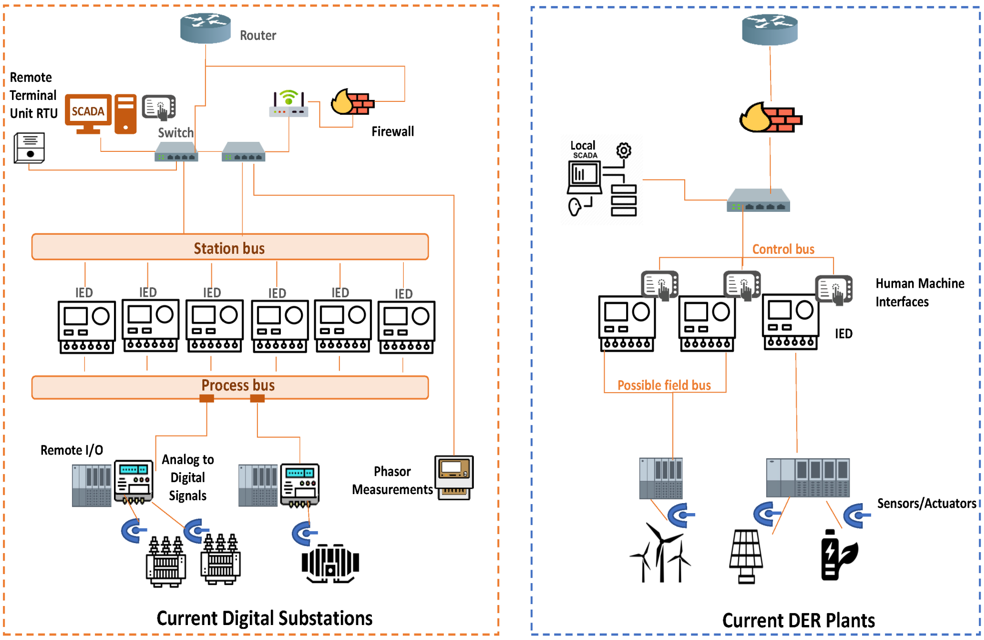

Figure 2. Current Digital Substation and DER Plant architectures based on [28][29].

This number is projected to increase further as more innovative digital solutions are developed. Active research exists on optimal placement of control devices that enhance grid reliability and reduce investment costs in the electrical infrastructure itself, as studied in [30][31]. Such complexity burdens utilities and grid operators with expensive CAPEX and OPEX for the ICT infrastructure. In some cases, this might even push them into establishing a functional dependency on a single vendor solution (hoping to reduce operational costs).

3. Communication Needs for Future PAC Systems

PAC systems process numerous data for applications that can be critical to power system operation and require ubiquitous, reliable, and real-time communication. PAC systems' communication architecture is hierarchical, governing two extremities: a central-slow level and a local-fast level.

- **Local level**: ensuring simple, safe functions based on local information acting on very fast timescales
- **Central level**: allowing coordinated actions at the scale of the whole system, with complex algorithms, slower action times, and the need to collect information from dispersed network components

The downsides of such hierarchy were studied extensively by an IEEE Smart Grid Research group [5] with a recommendation to move part of the ‘intelligent control’ from the central-regional level to an intermediate-zonal level as a future vision by 2030. This new control architecture defines stringent communication requirements to ensure robust coordination of heterogeneous smart grid components.

Assuring real-time exchange of information from different electrical grid components will permit power system actors to monitor, control, and manage grid operations more efficiently, reliably, and flexibly [32]. Wide Area Networks (WAN), Neighborhood/Field Area Network (NAN/FAN) and Local Area Networks (LAN) are basic communication categories in smart grids. The three categories are interconnected hierarchically as illustrated in **Figure 3**. The content of this section is summarized in **Table 1**, which illustrates communication requirements of various PAC applications. Many research studies have detailed the wired and wireless communication technologies cited in **Table 1**, including [33][34][35][36].

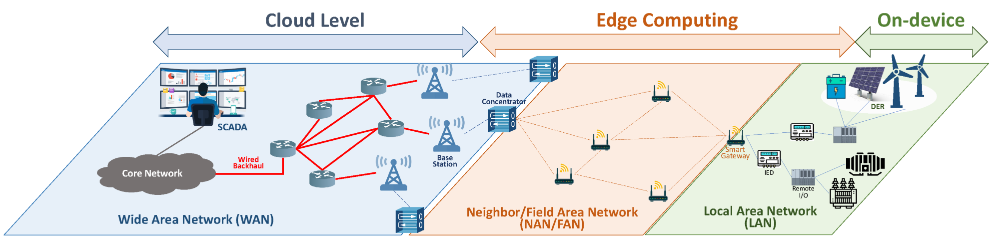

Figure 3. Communication categories interconnection [34][35][37].

Table 1. PAC application communication requirements [20][35][38][39][40][41].

Category	Communication Link		Application	Throughput	E2E Delay	Reliability
	Wired	Wireless				
LAN	Coaxial Cable, Ethernet	Bluetooth, ZigBee, Wifi, Z-wave	Transfer tripping	<10 kbps	3–10 ms	>99.99%
			GOOSE	-	4 ms	>99.99%
			Sample Value SV	80, 256 samples per 20 ms	-	>99.99%
			IED to IED interlocking	9.6–64 kbps	<10 ms	>99.99%

Category	Communication Link		Application	Throughput	E2E Delay	Reliability
	Wired	Wireless				
			IED to IED, reverse blocking	9.6–64 kbps	<10 ms	>99.99%
NAN FAN	Coaxial Cable, Ethernet, DSL, Fiber optic,	ZigBee Pro, WiFi, Cellular, LPWAN, Satellite	Meter reads	10 kbps	2–10 s	>98%
			Distribution system monitoring and maintenance	10–30 kbps	<5 s	>99.5%
			Volt/VAR control	10–30 kbps	< 5 s	>99.5%
			DSDR	10–30 kbps	<4 s	>99.5%
			Distribution grid FLISR	10–30 kbps	few 100 ms	>99.9%
			Optimization for distribution grids	2–5 Mbps	25–100 ms	>98%
			Protection for microgrids	-	0.1–10 s	>99%
WAN	Coaxial Cable, DSL, Fiber optic	Cellular, LPWAN, Satellite	Distribution Management System	9.6–100 kbps	0.1–2 s	>99%
			Wide-Area Situational Awareness (WASA)	600–1500 kbps	15–200 ms	>99.9%
			Outage management	56 kbps	2 s	>99.9%
			Wide-Area Monitoring PAC	10–100 kbps	<10 ms	>99.99%
			Adaptive islanding	-	<100 ms	>99.9%
			Cascading failure control	-	<5 s	>99.9%
			Wide-area voltage stability control	-	<5 s	>99.9%
			SCADA	1–10 kbps	<100 ms	>99.99%
			Phasor Measurement Unit-based state estimation	<1 Mbps	10–200 ms	>99.9%
			Dynamic state estimation	-	100 ms	>99.9%

ems enable data exchange between IEDs and a controller close to the power grid (for example, in the substation). A LAN can be connected to other smart grid stakeholders, such as an electric utility or third-party energy service provider, through a gateway. Since all data exchange occurs close to the power grid, the communication requirements for LAN applications of PAC systems are low latency, high reliability, low perform

Category	Communication Link		Application	Throughput	E2E Delay	Reliability
	Wired	Wireless				
			Fault location	<10 kbps	10 ms	>99.99%

3.2. Neighborhood/Field Area Network

NAN and FAN are networks in the distribution domain, supporting the flow of information between WAN and LAN using either wireless or wired communications. They allow data collection from various components on the distribution grid for transmission to a central processing point or, in the reverse direction, to transmit commands from the central processing point to distribution grid components. NANs/FANs capacities (i.e., data rates in the range of 100 kbps–10 Mbps and a coverage up to 10 Km) enable the implementation of various services on the distribution grid [42][43] such us: smart metering, fault management, distribution grid control and automation, Fault Location, Isolation, and Service Recovery (FLISR) for distribution grids, distribution system demand response (DSDR), etc.

3.3. Wide Area Network

The Wide Area Network (WAN) offers communication resources for intelligent backbone networks, and spans long-haul distances from the control center to NAN/FAN. This supports applications such as wide-area PAC and high-frequency data transmission from many measurement points. As a result, an efficiently coordinated control is allowed, improving the stability of the power system. Moreover, managing various IEDs can enable various application, such as dynamic state estimation, distribution management system, and cascading failure control.

Wide-area PAC applications leverage information on the overall state of the system and locally collected data to limit the spread of significant disturbances [44]. These applications, compared to conventional SCADA and Energy Management (EMS) systems, reduce response time and provide higher data resolution. Real-time measurements are taken across the entire electrical network by IEDs and transmitted to control centers. Conversely, orders and commands are transmitted from control centers to IEDs [43].

WAN applications collect a large amount of data at high data rates (10 Mbps–1 Gbps) while covering a wide perimeter of the electrical network (10–100 km). Various communication means can meet the requirements of WAN applications:

- Optical fiber network: Often used due to its high capacity, security, and low latency.
- Cellular Network: Used for its wide coverage range and high data rate.
- Satellite Network: Provide backup communications through redundant communications at critical nodes of the power grid (i.e., transmission/distribution substations).

4. Interoperability Needs for Future PAC Systems

Integrating Information and Communication Technologies (ICT) in the power system promises to ensure an automated, self-healing smart grid model preventing unnecessary blackouts caused by human errors [17]. However, correctly describing and configuring the necessary data (e.g., primary asset data, IEDs) by different interoperable ICT tools becomes a tedious task. Traditional practices involve highly complex documentation to interpret grid data (mainly saved on memory registers), thus lacking inherent interoperability properties.

In order to simplify access to grid data, the IEC published the main standards semantically defined for power systems: (1) IEC 61850 for power automation; (2) power system operation and planning standards bundled in Common Information Model (CIM) (parts IEC 61970, IEC 61968, IEC 62325) [45]; (3) IEC 62056 for metering [46]. The standards aim to provide a more efficient, and reliable electrical grid where large scale information can be shared without lock-ins from proprietary vendor definitions [47].

The standardized information can then be transmitted over multiple IEDs or hosts over the communication channels with no additional mapping of essential meta-data (e.g., value, unit, scale). Protocols (communication rules), Semantics (data meaning), and Syntax (data format) interoperability are all indispensable for future PAC systems operations. Researchers particularly focus on IEC 61850 standard as they generally (but not fully) limit the scope of the PAC applications considered in this research to those that can be embedded and formally modeled within IEDs (especially in digital substations and distribution grid control systems).

Fundamental Components of IEC 61850

IEC 61850 is an international, well-established standard for specifying communication networks and systems in power utility automation. Its primary goals are to ensure interoperability between multiple vendor IEDs and the data exchange between physically separated subsystems performing different functionality [28]. Interoperability as per IEC 61850 is often a pre-condition to interchangeability and portability but does not automatically imply them [48]. Interchangeability includes behavioral and performance characteristics in contrast to portability which solely concerns hardware and platform level modifications [28].

Most importantly, IEC 61850 is not just a communication protocol; it also does not describe the “behavior” of IEDs. For example, how each piece of equipment should operate and be implemented to perform its expected function(s) is outside the standard’s scopes [28].

IEC 61850 consists of three main elements:

- **Data Model**: Partitioning each IED into modular object-oriented components (using Logical Devices (LD), Logical Nodes (LN), Data Objects (DO), and Data Attributes (DA)) which allows performing independent replacements [49]. The standard defines the common ‘Classes’ to specify different semantic data objects. This permits modeling and describing several electrical network information (including electrical protections, electro-technical equipment, power quality equipment, DER, etc.) homogeneously.

- **Communication**: Describing Abstract Communication Service Interfaces (ACSI) (IEC 61850-7-2 [50]), based on the functional requirements in IEC 61850-5 [20], facilitates the information exchange between IEDs, and towards external remote information systems. The standard specifies the procedures to map the abstract stack to the final communication protocol stack, including Sample Value (SV), Manufacturing Messaging Specification (MMS), and Generic Object-Oriented Substation Event (GOOSE) protocols (IEC 61850-8-1 [51]/IEC 61850-9-2 [52]).

- **Engineering and Testing**: The standard specifies engineering tools for the specification, configuration, and testing of IEDs (IEC 61850-6 [53]). The files exchanged with the vendors are in standardized digital eXtensible markup language (XML) format.

In recent years, the idea of ’Cloud IEC 61850’ based on the cloud computing model emerged. Ferreira et al. [11] were the first to demonstrate the migration concept of the original (physical) IEC 61850 structure into a (virtual) infrastructure. The study proposes a mapping from the ’logical’ IEC 61850 specification (LD, LNs) to a portable virtual machine environment connected to process interfaces benefiting as much as possible from traditional IEC 61850 engineering design. The study also proved the important contribution of IEC 61850 when transitioning into software-defined PAC systems.

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