Pathways to Digital Substations: a Comparative Case Study

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***Abstract*—Electrical substations must keep their critical task of providing the power grid safe, reliable, protected, and manageable electricity flow within the context of increased digitalization in the power sector. On one hand, digital substation automation systems enable novel capabilities and functions, but on the other hand utilities must effectively manage such transformation while keeping their assets in operation. This paper presents an overview of how substations of different epochs are designed, operated and maintained in a practice-centered context of a Brazilian transmission utility. Drawing from a comparative case study based on a theoretical classification model, three high-voltage substations with different degrees of digitalization are analyzed regarding their automation system's design, features, lifetime upgrades, and future implications. The study shows that real-world conditions present challenges to operators and utilities retrofit existing substations in modernization efforts. There is a strong tendency to digitalize substation automation systems based on the IEC 61850, but the implementation of a process bus is still not widespread. Contrasting the cases with the academic literature reveals there are still areas that require further development to be competitively implemented by utilities, such as the usage of low-power instrument transformers, and that utilities must actively prepare to leverage the long-term benefits of those installations. Particularly in Brazil, extensive upcoming investment in such facilities is expected. As such, this study contributes to the understanding and discussion of the role of digital technologies in substations and their relationship to the professional practice of transmission utilities.**

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***Index Terms*—Digitalization, digital substations, substation technologies, substation automation systems.**

I. Introduction

THE mounting investment in research, development and innovation towards smart grids is part of a low-carbon economy context, with intense digitalization and electrification of the energy mix [1]. A great proportion of smart grid projects tackle topics such as demand-side management, distributed energy resources integration, and energy storage, studied in several countries [1], [2]. However, the digital transformation has also been reaching power substations, with the improvement of their automation, protection and control systems, connecting devices with enhanced functionality [3]–[7].

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While new technologies promise operational improvements, the modernization of the power grid must also be economically justified. Energy supply quality and reliability must be guaranteed; while equipment nearing their end-of-life can result in decreased quality and increased operating costs [8], new technologies enable more advanced applications, promising benefits in optimizing maintenance, ultimately reducing costs, not only benefiting the power system operators, but also reflecting in a potentially better, cheaper service for consumers. Regulatory practices, combined with the long operational lifespans of assets, inherently lead to the coexistence of multiple technology generations within the power grid. Thus, integrating different technologies within substations is also a challenge. For example, [9] describes an intermediary system to integrate legacy equipment to a more advanced smart grid. In that sense, solutions should also consider such integration in existing facilities, besides being economically viable - be it for an expansion need, maintaining power quality, or the expiration of the asset's lifetime, to cite a few examples.

The Brazilian energy sector presents significant opportunities for modernizing power grid equipment, particularly in substations. According to the Ten-Year Energy Plan (PDE) developed by the Energy Research Office (Empresa de Pesquisa Energética, EPE), investments totaling R$40.3 billion (aproximately 7.2 billion, using mid-2025's exchange rate) are projected for substations between 2025 and 2034. Additionally, approximately R$39 billion (USD 7 billion) in substation assets are expected to reach the end of their regulatory lifetimes before 2034 [10]. Although the regulatory life - used as a key criterion in sector planning - typically underestimates the actual operational life of assets, it remains a critical benchmark for modernization initiatives and system expansion. Current evidence underscores the need for a substantial investment cycle in Brazilian transmission substations to address these challenges. Expanding transmission capacity is critical for the integration of clean energy, with investment plans in multiple countries [11], including in power substations. However, there is still no clear consensus on which technologies would be the most cost-effective to implement to the modernization of substations.

Understanding the technologies and benefits of digitalization is essential for informed investment decision-making by transmission system operators (TSOs) [12]. Digital transformation [13] has already brought significant advantages to multiple industries However, evidence suggests that digital transformation in the power sector has progressed at a comparatively slower pace [14]. Possible rationales for this slow adoption is the sector's careful approach to innovation, as well as the high reliability requirements in a highly regulated and low-margin sector. Nonetheless, the benefits of digitalization can be considerable, enabling smart grids, incrementally improving functions such as asset management and maintenance policy. TSOs must be aware of their asset's condition, especially within substations, to better plan, operate, maintain, improve, or replace those assets. This need is also felt by policy makers, for the system's capacity is one of the fundamental inputs for planning the power grid's expansion.

This paper analyses substation digitalization, considering different technological generations. This was accomplished by a comparative case study of three Brazilian transmission substations drawn from the theoretical classification model based on Ref. [15]. The study presented here is based on qualitatively identifying and comparing characteristics between three operational substations, that serve as prototype-examples of different digitalization degrees, with data collected using a mixed-methods approach.

This study contributes to the ongoing discussion on substation digitalization in academic and professional engineering. Firstly, it presents an application of a theoretical substation classification model [15], demonstrating its utility in characterizing substations across different technological generations. Second, it presents a case-based, professional comparison of three operational high-voltage substations, examining their technologies and historical evolution. Third, the findings are used to discuss contextual factors that underscore the relevance of substation digitalization in the Brazilian power sector. The discussion is further extended to include implications for the broader Latin American and European energy markets.

The remainder of the paper is structured as follows: Section II presents the theoretical background and the relevant academic literature on the topic. Section III describes the methods followed for collecting and analyzing data. Section IV presents the results of the comparative case study, and discusses those results in light of the Brazilian power sector and its implications to theory and practice. Finally, conclusions and final considerations are presented by Section V.

II. Theoretical Background

A. Digital Transformation

Digital transformation, according to the working definition by [13] is "a process that aims to improve an entity by triggering significant changes to its properties through combinations of information, computing, communication, and connectivity technologies". Thus, it can have profound impacts to people, organizations, industries, and society. This concept is relevant not only for academics [16], but also for practitioners across industries [17]. More research is still needed to understand digital transformation's practical and ethical implications, its relationship to dynamic capabilities [13], as well as its relationship to performance, namely to which degree digitally transformed companies can have improved performance, and even how should those gains be measured and assessed [18].

The electric power sector has also been impacted by digital transformation, part of the "3D's": digitalization, decentralization and decarbonization [19]. Implementing this agenda has been a great challenge for utilities, and part of this effort consists on developing smart grids, seeking greater flexibility, efficiency, and sustainability [20], [21]. The increased integration of renewable generation [22], distributed energy resources [2], and smart metering are also among the key technologies for implementing a smarter power grid [23]. Among the challenges brought by digital technologies (including but not limited to power grid applications) is also the need for resilience and cybersecurity [24], [25].

B. Digital Substations

A significant part of the power sector's digitalization occurs in electrical substations. Substations are key components of the power grid, facilities which enable voltage-level conversion, operational switching, and the grid's protection and control system [26]. Digitalization is mostly present in the substation's automation, protection and control systems. While conventionally those systems were built around electromechanical relays, since the 1980s they were increasingly replaced by numeric and electronic devices, until the development of so-called Intelligent Electronic Devices (IEDs). Since early 2000s the trend towards digital substation automation intensified, with the development and widespread adoption of an international standard for IED communications, the standard IEC 61850 [27], [28]. Nowadays, substation evolution culminated in smart substations [4], [6], [15], in which multi-functional and interoperable IEDs [29], [30] are connected by optic-fiber networks in a process bus [31], [32].

Current discussion in substation automation also encompass the development and real-world deployment of Virtualized Protection, Control and Automation (VPAC) systems [7]. By virtually emulating physical substation infrastructure, especially in communication and networks, new features can be added, tested, and validated [33]. Such systems may also include software-defined networking (SDN), which can enhance the cybersecurity of the critical automation systems [25], [34].

The development and deployment of digital substations have become a global focus. These initiatives range from pilot projects in early-stage R&D programs to large-scale installations [35]–[37]. The literature highlights various system-specific studies, such as interoperability tests [38] and tackling cybersecurity challenges [39], which are extremely critical in the context of virtualized and digitalized systems [25]. However, comprehensive assessment methodologies to understand, evaluate, and manage the digitalization of substations have been comparatively less studied [12]. Some of the benefits promised by digitalized substations include improved operations and maintenance, improved reliability, reduced footprints and commissioning times [40], as well as reduced operational costs [41]. A framework to systematize and assess those benefits is presented by [12].

C. The Standard IEC 61850

One critical enabler of substation digitalization was the standard IEC 61850. The standard was initially published in the early 2000s, with subsequent improvements published to date. It provides an abstract data model and standardizes the communication between substation automation system equipment, such as merging units and IEDs. It has been widely regarded as a cornerstone and a well-accepted technology in the backbone of smart substations' automation systems. Since its publication and initial application reports [27] it has been continuously implemented in solutions by substation equipment manufacturers and transmission utilities, becoming an open standard widely used in digital substations projects worldwide [35]–[37]. As such, IEC 61850 has been instrumental in the standardization of architecture and communication for digital substations [42], whose final realization might culminate in a greater degree of virtualized systems [7].

D. Contextualizing Brazil's Electric Power Sector

The Brazilian electric power sector features specific characteristics that underpin the importance of researching digital substations. Electricity planning forecasts significant investments not only in grid expansion but also in asset renewal. Many facilities commissioned in the 1970s and 1980s are approaching their regulatory end-of-life. According to the Energy Research Office, responsible for integrated national-level energy planning, approximately USD 7 billion in substation assets are expected to reach their regulatory end-of-life by 2034, with an additional USD 7.2 billion projected for grid expansion investments [10]. A significant proportion of those substations predates digital technologies, so that their end-of-life is a valuable opportunity for transmission utilities to implement new technologies with improved performance, for example with greater efficiency and asset observability. This context underpins the importance of understanding substation technologies and the different pathways to their digitalization.

III. Methods

This research followed a case-study method. This type of study enables the deep investigation of one or multiple cases, validating, consolidating or developing theory from cases [43]. Academic research in power systems typically uses practical studies or experiments to develop or validate techniques, models, methods or equipment. Combining a theoretical proposition with the practical experience of a transmission utility is a great opportunity for developing research and discussing implications for the power sector.

A. Theoretical Framework: Substation Classification Model

In this paper, we take the theoretical framework derived from the literature review of [15] in order to devise the substation classes for analysis. This framework classifies substations into four categories: conventional substations, early-stage digital substations, state-of-the-art digital substations, and future smart substations. Such a model has the potential to assess substation projects more effectively. The framework is presented in Table I, used with the original authors permission.

Conventional substations are characterized by fully analog data collection, processing, and control systems. Their architecture is typically based on point-to-point wiring and lacks digital communication protocols. Early-stage digital substations introduce digital elements at the station level, while maintaining analog data and hardwired connections at the process level, using vendor-specific communication protocols. Current state-of-the-art digital substations feature digital process buses using fiber optic communication and rely on IEC 61850 for standardized interoperability. Analog signals from conventional instrument transformers are typically digitized via merging units, which interface with the digital process bus. Finally, future smart substations aim for full automation digitalization, including the use of low-power instrument transformers and centralized or virtualized protection and control schemes. The implementation of VPACs also emerges as a future trend for smart substation design [7], alongside new open communication and validation protocols [33]. Communication protocols, data stream processing hardware, data acquisition and analysis, are becomingly increasingly integral components of the communication system and its architecture. Advanced functionalities such as real-time analytics and predictive maintenance are also enabled in such substations, thanks to the combination of multiple data sources.

B. Case Selection and Sampling

In this study we compare three digital substations operated by a transmission utility in Brazil, in the state of São Paulo. Some basic requirements for consideration were: different technologies implemented in their design, operational facilities of the country's high-voltage network (Sistema Interligado Nacional, or SIN, which consists of the over-230 kV power grid), and also access to conduct the strategic research.

C. Data Collection and Analysis Procedures

Multiple data sources were integrated to cross-check information and minimize potential biases. Semi-structured, in-depth interviews were conducted with professionals involved in the engineering, operation, and maintenance of the substations. Four engineers participated in the study, referred to as Interviewees A, B, C, and D. Interviewee A was the lead engineer responsible for commissioning a recently developed fully digital substation. Interviewee B, a senior specialist in protection, control, and automation, oversees an early-2000s substation and has over 35 years of professional experience. Interviewee C was the project manager for the exploratory R&D project on the smart substation case. Interviewee D has had over 30 years of experience in commissioning and managing substation protection and control systems, and is responsible for the area where one of the substations is located. The interviews aimed to characterize the substations, facilitating a comparative assessment of their technologies and upgrade policies. Each interview lasted approximately 40 minutes, was recorded and then analyzed. The interview questions are provided in Appendix A.

Furthermore, a guided technical visit was conducted in the substations, seeking to collect more data and make *in loco* observations. Data collection was complemented by the document analysis of technical documents and press releases regarding the facilities.

Data was gathered, synthesized and analyzed with multiple tools. Interviews were transcribed, and the main points were

TABLE I
THEORETICAL FRAMEWORK FOR CLASSIFICATION OF ELECTRICAL SUBSTATIONS

	Conventional substation	**Early-stage digital substation**	**Digital substation - state of the art**	**Smart substation - future prospects**
Communication protocol	Non-existent (analog signals)	Proprietary (vendor-specific) and early standards	IEC 61850	IEC 61850
Hardware for process data flow	Copper cables, hardwired	Copper cables, hardwired	Copper and optical fiber cables	Optical fiber cables, wireless
Protection, control and automation devices	Electromechanical relays / solid state	Numeric relays and 1st gen IEDs	Intelligent electronic devices (IEDs)	Centralized Protection and Control (CPC)
Instrument transformers	Conventional	Conventional	Conventional, occasionally with merging units	Fully digital/electronic (LPITs)
Data acquisition methods	Manual (e.g. checklists, paper notes) assisted by non-integrated devices	Manual and digital, SCADA	Digital with some integration	Fully integrated digital and autonomous
Data analysis	Non-existent, only in case of fault	Not in real time, non-integrated software (e.g. spreadsheets) and SCADA systems	Software-based in near-real-time	Big data analytics and advanced AI algorithms
Maintenance policy	Scheduled and corrective	Scheduled and corrective	Scheduled, corrective and predictive (condition-based)	Predictive (condition-based), corrective and scheduled
Technical competences	Electromechanical	Electromechanical + electronics	Electronics + Networks + Electrical	Networks + Data + Electronics + Electrical

Source: [15]

TABLE II
BASIC DATA OF THE THREE CASE STUDIES

	Unit	SE ANH	SE LOR	SE JAN
Voltage level	kV	345 / 230 / 88	500 / 230	138 / 11.5
Transformation capacity	VA	1300	1200 (3x400)	NA
Insulation type		GIS (SF6)	AIS (Air)	AIS (Air)
Bay count		28	14	1
Inauguration year		2007	2021	1980s/2022

coded in synthetic tables, which enabled the comparison between the cases. Once the comparative analysis was concluded, results were discussed in light of the extant literature. Other works reporting practical experiences in substation digitalization, in the Brazilian or international context, were also analyzed, in order to identify common or contrasting information and reported procedures, and ground the discussion presented in this paper.

IV. RESULTS AND DISCUSSION

This section presents the results and discusses the cases comparatively. Table II presents the basic data on the three substations, including voltage level, transformation capacity, isolation type, bay number and inauguration year.

A. General Classification of Substations

Two substations are part of the Basic Network of the Integrated National System (SIN). Substation ANH operates in three sectors, with voltage levels 345 kV, 230 kV and 88 kV, acting as one important node in the electricity supply for the city of São Paulo. Substation LOR operates in voltage levels 500 / 230 kV, in the electricity supply of the region of the Vale do Paraíba, about 200 km distant from the city of São Paulo. Substation JAN is a distribution substation providing transformation from 138 kV to 11.5 kV that feeds the distribution grid of a midsize city, some 140km distant from São Paulo. JAN recently became a testbed facility with new technologies implemented as part of an R&D project on smart substations [44]; the R&D project explored the concept of Centralized Protection and Control (CPC), which was implemented in parallel with a traditional digital protection scheme. CPC was initially implemented passively as a testbed, therefore not being the primary protection actuator in the substation. A summary of the key information on the substations is provided by Table II.

There is a notable difference in the insulation media between the substations: ANH's 230 kV and 88 kV sectors are gas-insulated, whereas LOR's and JAN's bays are air-insulated. Despite the differences in high-voltage equipment, insulation types, and substation configurations, the automation systems of the two larger substations are comparable; regardless of the high-voltage bay insulation media (air or gas), bays should be monitored and protected by automation system consisting of instrumentation, relays, switches and circuit breakers. Since the automation system is the focus of the present study, the comparison between facilities can still provide useful insight. Including the smaller JAN substation was also considered useful, for it explored some novel digital technologies as a testbed facility, and therefore could be a prototype for such advanced applications. JAN also features a protection, control and automation system, compatible with its smaller scale.

Following the theoretical substation classification framework presented in Section III [15], it was possible to classify Substation ANH as an early-stage digital substation; Substation LOR as a state-of-the-art digital substation; and Substation JAN as a prototype or testbed facility towards the future smart substation, partially implementing the characteristics of this type of substation.

B. Substation Automation Systems

The technologies employed in the automation systems generally reflect the prevailing paradigms at the time of their design. This observation was confirmed through analysis of the substations examined in this study, which are detailed for each of the three cases in this section.

SE ANH, an early-stage digital substation, has implemented aspects of the IEC 61850 standard in its station bus and, according Interviewee B, was the first IEC 61850-based substation in Brazil's Basic Network. However, IEC 61850 was applied only at the station level and did not extend to the process bus. As a result, the substation relies heavily on conventional hardwired signals, leading to substantial material usage and a high volume of copper cabling routed between switchyard and control room. Fig. 1 illustrates part of the cabling entering the control room, routed through overhead ceiling cable trenches before reaching the panels. This architecture makes extensive use of copper cables, with hundreds of connections carrying electrical signals between the switch-yard and the control panels. In substations utilizing a process bus, such extensive cabling is largely replaced by fiber-optic connections, possibly offering significant material and operational efficiencies [12].

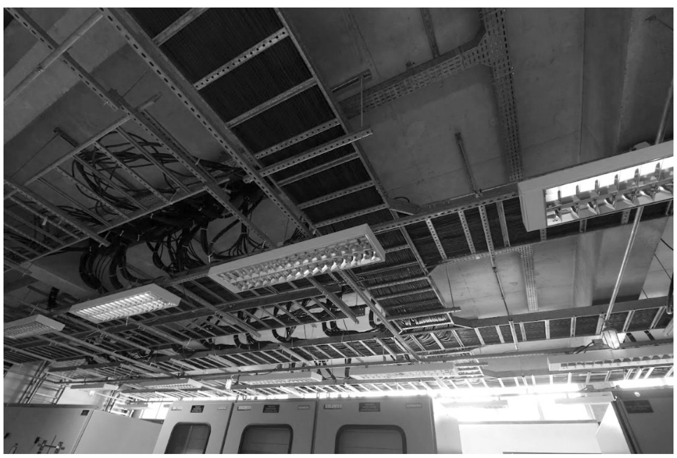

Fig. 1. View of part of the ceiling cable trenches in the control room of Substation ANH.

In SE LOR, the architecture incorporates merging units to digitize analog signals from instrument transformers installed in the field. These digitalized signals, in the form of Sampled Value (SV) messages, travel along fiber-optic cables to the control room. The implementation of both process bus and station bus at SE LOR allows for the transmission of SV messages, as well as protection and equipment status signals (GOOSE and MMS messages), over fiber-optic networks. The use of copper cables is minimized, being limited to connections between the instrument transformers and the merging units located in the yard, an approach followed by other IEC 61850-based digital substations [37].

Despite being a legacy substation, SE JAN's retrofitting efforts in early 2020s tried to incorporate some novel technologies towards the concept of a smart substation. Instrument transformer data was digitalized with Merging Units in a fashion similar to SE LOR, but the control system experimented with a CPC architecture. According to data collected for this research, CPC was being tested in the facility, but was not yet widespread across all substations. As such, CPC was deployed in parallel with the standard control system based on IEDs, keeping flexibility and maintaining reliabiltiy requirements.

It should be noted that, despite being highlighted as one of the great advantages of the IEC 61850 standard and a key technological driver for digital substations [12], interoperability between manufacturers was not verified in the substations we analyzed. The solutions presented were developed using equipment from one major manufacturer for each substation: General Electric (GE) in substation LOR, Siemens in substation ANH, and Hitachi ABB in substation JAN. This preference may be attributed to economies of scale and the convenience of managing a single supplier contract. Additionally, practical challenges in operating equipment from different manufacturers have been reported [38], despite other projects specifically testing interoperability between vendors [35]. Future system updates could explore applications involving multi-manufacturer interoperability.

C. *Technological Upgrades in the Substations*

ANH and JAN have undergone upgrades since they started operations. Most of the assets of ANH are original from commissioning, but its communication systems were replaced based on the regulatory mechanism that enables updates and upgrades. Substation JAN's automation systems were recently modernized and digitalized, replacing its original 1980s equipment as part of an R&D project aimed at exploring the concept of the future substation [6], [44]. In contrast, substation LOR, having only recently begun operations, has not required any updates to date.

According to Interviewee B, developing a fully digital substation (LOR) was only possible due to past experiences in R&D projects within the company, for instance, with the use of IEDs and IEC 61850. The experience of using IEC 61850 in substations such as ANH paved the way for later developments, highlighting a gradual technological evolution and adoption. Some installations that implemented innovative technologies, especially in early stages, did so by the means of the R&D Program regulated by Brazil's Electricity Regulatory Agency (ANEEL). Similarly, Substation JAN also explored CPC towards the future smart substations as part of an R&D project. This highlights the potential of ANEEL's R&D program for the development of new technologies and applications for the power sector in Brazil.

Furthermore, Interviewees C and D mentioned an ongoing R&D project to develop an asset monitoring center, to become instrumental towards better maintenance policies with continuous asset health data gathering. Such a shift towards condition-based maintenance has been highlighted for the future prospects of smart substations, including the classification model [15], and is also subject to many research papers. Data analytics are enabled by digital technologies, and such techniques should be instrumental in developing more advanced applications in substations.

D. *Future of the Substations*

It is also worth noting that the digitization of existing substations takes place as an ongoing process. Interviewee B highlighted the challenge of doing this while keeping the substation in operational condition, especially due to the necessary coordination with the system operator and customers/distributor. Modernization is typically performed incrementally, on a bay-by-bay basis, without fully de-energizing the substation. Thus, the development of new green-field projects can have faster lead times and reduced organizational complexity when compared to conventional substations. This has been appointed as a positive outcome of the commissioning of LOR by Interviewee A, a benefit which has also been previously identified by extant literature [12].

One significant challenge identified in the literature is the use of environmental and equipment sensor and instrument data to support condition-based asset management and enable predictive maintenance, especially in smart substations [15]. This indicates that combining multiple data sources could become a future pathway for enhanced substation operation. The analysis of large volumes of data *(big data analytics)* with condition monitoring applications can improve the operation and maintenance routines of systems, for instance with improved forecasting [45]. Although the three substation cases studied by this research show some awareness and effort towards improving maintenance policies through technology, the implementation of predictive maintenance has not been fully verified. Operational data is collected and transmitted to the system operator, but it is usually analyzed especially in the event of a failure.

Substation remuneration policies are typically done in the basis of operation and maintenance. This encourages maximizing the operation of substation and the extension of their useful lifespan [46], which have also been appointed as benefits of smart substations [12], but must also be supported by regulation and company guidelines which support more advanced maintenance policies. According to the interviewees, while predictive maintenance was not yet a reality, even in modern substations, plans were underway to use collected data more effectively to enhance the company's asset management practices in a connected and integrated manner. An ongoing R&D project at the time sought to develop such practices in the company. It is worth noting that by itself, infrastructure, such as sensors and information systems, is insufficient for effectively implementing improved maintenance practices. Successful adoption requires organizational support, including internal policies and personnel with the necessary technical expertise in data analytics [15]. The extent to which digital technologies may affect substation maintenance and remuneration is still underexplored, and also depends on the regulatory framework.

E. Contextual Discussion

It is worth to consider the impact of substation deployment in the broader Latin American context, as well as comparing it to other markets. Infrastructure in the power sector has been estimated to account for a high proportion of investments, across multiple evaluation scenarios in the following decades [47]. Evidence points that advanced economies have been replacing and modernizing aging assets to ensure reliability, more effectively integrate renewable sources, and enable digital solutions [11]. Latin American countries, however, feature very heterogeneous conditions, including different capacity for investment, digitalization, and new renewable integration [48]. The country-specific regulatory framework has been found to play an important role in the development of effective asset management policies [49]. For example, Peru's regulatory framework incentivizes the implementation of smart grids and posits the modernization and digitalization of distribution, which includes investments in smart substations as a strategic goal in its power grid vision for 2030 [50]. Furthermore, regulatory policies in the countries are challenging, historically focused on simpler approaches, but which may need improvements to better balance the costs and benefits of new technologies [51]. Considering that substation and power grid investment typically draws from national electricity planning, and that the management of these assets is critical for their long-term sustainable operations, the sectoral discussion about the suitability or potential evolution of regulatory frameworks is also encouraged.

Different energy market conditions also influence the degree and feasibility of digitalization. Digital and smart substations, have been found to have generally higher investment costs (CAPEX) but could have operational gains (lower OPEX) than conventional substations [41]. However, the life-cycle costs and reliability-based study of [40] concluded that, considering the Colombian market conditions at the time, an IEC 61850-based solution was not yet economically viable. This could reflect insufficient incentives to offset digitalization costs, despite its potential benefits.

Personnel and staffing are also sectoral challenges. A study in Colombia [40] suggests that expanding professional training for digital substations could reduce technical personnel costs, and, thus help with the modernization efforts of substations. The shift in professional competencies has also been highlighted by the classification model [15], and was a topic discussed by interviewees for the cases discussed by this paper. Adequate training is necessary to effectively deploy and operate substations.

V. Conclusion

This paper compared three operational substations with different degrees of digitalization. The comparison applied a theoretical classification model [15], demonstrating its usefulness in understanding different substation generations. With the analysis of the three cases, it was also possible to better understand how substation technologies evolved. When compared to earlier-stages digital substations, more modern implementations were found to feature significant reduction in copper cabling, physical space reduction and faster commissioning. Proof-of-concept technological development through regulated R&D projects has been found to be important to the utility for the exploration of novel technologies. There are still opportunities to explore in future substations, especially with non-conventional instrument transformers, data collection and analysis for better asset management and predictive condition-based maintenance, as well as workforce training.

The Brazilian power sector is in an important moment for the replacement of dated infrastructure. Many assets, including substations, are close to their regulatory lifetime expiration [10], underpinning an opportunity to invest and improve the power system. Expansion of transmission capacity to accommodate demand, integrate renewable sources, and make better use of existing infrastructure through digital technologies has also been seen in other countries [11]. In this context, understanding the benefits of digitalizing substation enables more informed decisions by the stakeholders involved in the sector's planning and operations [12].

This research has limitations on sampling and methodology. The qualitative comparison of substations of a single TSO constrains broad generalization, especially for unique projects such as power substations. Operational standards set by the TSO may also impact the practical realization of digitalization benefits. Nonetheless, the findings can still help shed light into the practical aspects of substation digitalization.

Future research can expand the number of analyzed cases, potentially exploring different TSO's practices, as well as complement the research with quantitative data. Modern approaches to substation automation, such as VPACs, warrant deeper analysis and comparison with earlier-stage projects, along with solutions to address cybersecurity challenges. A wide-scale characterization survey on the state of Brazilian or Latin American power substation's assets is also an opportunity, alongside the economic and market evaluation of the cost-benefit of such digitalization in this context , as well as comparisons to other markets.

Appendix
Interview script

This section presents the questions used to guide the semi-structured interviews.

- Could you briefly tell your previous experience with power substations, both conventional and digital ones? How long have you been working with substations?
- What was your role in the development, design, commissioning and/or operation of this substation?
- When the substation started operations?
- Was the substation designed with digitalization in mind?
- Which aspects of IEC 61850 were implemented?
- Does the substation feature a process bus? What about optic fibres? If so, which devices are connected?
- Is there some sort of continuous data collection within the substation? How and what for are these data collected, processed and analyzed?
- How many people are involved in the operations and maintenance of the substation? Are teams dedicated to this substation, or regional shared teams?
- Were previous upgrades performed, or does the substation feature the original equipment it started operations with? Did the substation undergo upgrades, and if so, how was the experience?
- Is there a plan to upgrade sections or the full substations in the future or in the companies roadmap?
- What is the order of magnitude of the substation's RAP?
- Was the substation part of an R&D project? If so, how, and what were the project's results?

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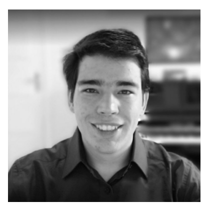

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