A Methodology to implement a Virtual and Augmented Reality Solution to Engineering, Maintenance and Control phases of HVDC System

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ABSTRACT

High-voltage direct current (HVDC) transmission systems are becoming more and more important in an energy landscape that is characterized by increasing digitalization, decarbonization, and distributed generation. HVDC technology offers the most efficient means of transmitting large amounts of power over long distances, helping connect green power to the grid, and stabilizing three-phase grids. The fourth industrial revolution, also known as Industry 4.0, is challenging companies to change the way they do business. Indeed, the focus of this revolution is on improving the efficiency and productivity of processes, based on logistics and information readiness. It is not just about the simple advancement of technology, but mainly due to the paradigm of integration and connectivity emerging from the Internet of Things, Cloud Computing, and, more recently, the arrival of 5G for mobile devices. In the same way, Virtual and Augmented Reality applications have proven high-efficiency results in maintenance and operational procedures special for remote assistance and integration between remote central operations with the field that uses the new generation of smart glasses. However, the use of such techniques in the context of an HVDC has not yet been observed in the scale of application of this public notice. Therefore, research questions on how to adapt these technologies in the context of an HVDC, in order to make its engineering, maintenance, and system control processes more integrated and efficient, remain unanswered. In this scenario, Virtual and Augmented Reality can offer disruptive tools capable of mitigating some challenges present in the sector. This work presents digital twin results of an R&D project for *Eletronorte* located in Brazil that integrate a real-time database with a set of 3D parametric BIM elements in a cloud solution that provide some stage Electrical tests of preventive maintenance, Simulation of technical maintenance instructions and Simulations of planned maintenance procedures.

Keywords: Virtual Reality, Augmented Reality, HVDC, BIM, Immersive application, Digital Twin, Cloud Solution

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I) Introduction

The fourth industrial revolution, also known as Industry 4.0, is challenging companies to change the way they conduct their activities. Indeed, the focus of this revolution is on improving the efficiency and productivity of processes, based on logistics and information readiness. It is not just about the simple advancement of technology, but mainly because of the paradigm of integration and connectivity that emerged from the Internet of Things, Cloud Computing and, more recently, the arrival of 5G technology for mobile devices in Brazil. HVDC technology has been used for several purposes, including interconnecting the country's fragmented electrical power systems, transmitting power from hydropower plants in the northern regions to the highly populated southeast region, and for exporting power to neighboring countries. Some notable HVDC projects in Brazil include the Rio Madeira HVDC transmission system, the Itaipu Binational HVDC system, and the Belo Monte HVDC system. These projects have helped to improve the reliability and efficiency of Brazil's electrical power system and have played a significant role in supporting the country's economic growth. *Eletronorte* is a private electric utility company in Brazil and operates the Rio Madeira HVDC transmission system, which is one of the largest HVDC systems in the world. The system was commissioned in 2014 and runs over 2,000 kilometers (1,243 miles) between the hydropower plants in the northern region of Brazil to the populated southeast region. The Rio Madeira HVDC system helps to meet the increasing demand for electricity in the southeast region and helps to reduce transmission losses, thereby improving the efficiency and reliability of Brazil's electrical power system. The quality of an organization's management is what determines its success or failure. In a competitive environment, where vanguard organizations are introducing industry 4.0 technologies into their operations, extracting the maximum value from investment in assets cannot be neglected.
To maximize the value of an asset, it is necessary to preserve records (in appropriate software) of its performance throughout its useful life. This performance comprises operating activities and related costs, accompanying the return on investment. Thus, it can be ensured that the value generated is aligned with the strategic and operational objectives of the organization. Among the benefits of good management of the lifecycle of industrial assets are:

- Extend the useful life of machines and equipment;
- Increase the reliability of the operation;
- Increase productivity;
- Keep maintenance costs at an optimal level;
- Improve health and safety for employees;
- Generate greater energy efficiency;
- Contribute to the profitability of the business.

Another area that has been gaining ground in the electricity sector, with the use of Augmented Reality, is training and remote assistance. Through asset identification techniques in the field (QR Code, fiducial markers, etc.), the operator can receive instructions, videos, images and others from the Operation Center, which, in turn, are projected onto the asset, while they can make use of hands free to perform the operation.
Finally, it is important to point out that, while the power generation industry works with high levels of safety, process and logistics optimization are still essential to reduce expenses. When a problem occurs in a station/power plant/transmission network, it is necessary to send an experienced team to correct it immediately. However, such experienced staff is not always easy to find, but is also expensive to hire.
In this scenario, Virtual Reality and Augmented Reality technologies can offer disruptive tools capable of mitigating some challenges present in the sector. According to works published by Azuma (1997); Gavish et al. (2015); Kim et al. (2018) and van Krevelen et al. (2010), these technologies are especially useful with regard to design review (Dunston et al., 2011), training (Alaraj et al., 2011), monitoring the operation of equipment (Cheng et al., 2013), inspection and maintenance (Henderson et al., 2009).Additionally, in recent years, VR and AR equipment has become much cheaper, more comfortable and more accurate (LaViola et al., 2017). Among these devices are wearable displays, systems for tracking people or objects, and systems for interpreting gestures.Although the evolution of technologies has expanded the application options for end users and researchers, the energy industry has not yet adopted many of the existing resources. And, in fact, combined with 3D modeling using CAD (Computer Aided Design) tools, VR/AR systems can offer an attractive option from a technical and economic point of view.
Given this context, it is understood that this work brings to light the latest trends in research and innovation observed in the electricity sector. The investigation of the possibilities of using Virtual and Augmented Reality for not only training and remote assistance, but also for management, control and operation of the electrical system is notorious.
However, the use of such techniques in the context of an HVDC has not yet been observed in the scale of application of this notice. Therefore, research questions on how to adapt these technologies to the context of an HVDC, in order to make its

engineering, maintenance and control processes more integrated and efficient, remain unanswered. This work presents an ongoing R&D project in development applied to *Eletronorte* Company and the first results presented.
The main objective of this Research project is to investigate and propose software solutions and adaptation of specific hardware, based on Virtual Reality and Augmented Reality interfaces, for Engineering, Operation, Control and Maintenance of Direct Current Transmission Systems (HVDC), with Training and Real Time Assistance components.
Specific objectives:
• Design and develop a Virtual Reality System (integrating hardware and software available on the market and within *Eletronorte's* domain) that is capable of supporting the visualization, navigation and interaction with the arrangements and components of the substations of the HVDC system, as well as the rooms of valves (also referred to as Back-to-Back valve room) of the *Araraquara* and *Porto Velho* HVDC system (extendable to similar standards of HVDC installations): RV-HVDC;
• Ensure that this system meets the requirements of a VR environment, namely: navigation, immersion and interaction in real time;
• Certify that the developed VR system adheres to: (a) training, learning, control and maintenance (intervention) requirements to: (b) implementation of planned maintenance procedures and technical maintenance instructions and (c) evaluation of magnitudes measurements and predictive conditions of *Eletronorte's* supervisory system, providing conditions for users to: monitoring the operational status of components; the visualization of structures and arrangements, and, consequently, improvement of asset management, regardless of their location or the availability of equipment;-exploitation of existing constructions, their components, their interoperability, without compromising user safety; local training of substation operators, involving the simulation of commands and operations of substation elements, valve rooms and the like; virtual training of operation engineering teams, involving the simulation of commands, operations of substation assets, valve rooms and related areas; simulations of exercises carried out within the Company, with equivalent exposure to risk situations.
• Design and develop an Augmented Reality System to support the Engineering and Maintenance of the HVDC System: RA-HVDC, with support for training and remote assistance at different levels: Operator-Maintainer, Site Maintenance Specialists, Operation Center Operators Porto Velho and Corporate Maintenance Specialists and from other locations, who support:
-inspection conditions, in an accelerated way, with damage assessment together with remotely separated specialists, in less time and cost.
-Integration with computer networks and systems such as ERP (Enterprise Resource Planning) or SCADA to access asset data, such as the in-touch system (ABB) and SAGE (*Eletronorte*).
local training of substation maintainers, involving the simulation of maintenance execution and electrical tests of substation assets, valve rooms and related areas;
virtual training of operation and maintenance engineering teams, involving the simulation of commands, operations, maintenance and electrical tests of assets in substations, valve rooms and related areas;
the detailing of processes, tools and information, superimposed on the real environment with the use of wearable devices, to support interventions, in the field, using such techniques.
• Investigate, design and develop geometric, physical and behavioral modeling techniques for a better and more faithful representation of the components of an HVDC (Thyristors, DC Busbars, HVDC Transformers and others), in order to promote an intuitive and natural interface in Virtual Reality for *Eletronorte* employees, when operating the system;
• Updates to Preventive Maintenance Procedures for HVDC system assets;
• Integrate the RV-HVDC with *Eletronorte's* distance learning system, through the development of Open Educational Resources – OER, methodology and training of instructors (in person or at a distance);
• Carry out in the simulation environment recovery tests for disconnected networks, similar to those of the "Drill" concept, with real-time integrations;
• Create an HVDC system monitoring environment through a Virtual and Augmented Reality room in *Brasilia*, for the integration of real and virtual systems, where engineering teams can interact with field teams.

II) Development the 3D models Library of virtual objects

In this stage, the models of the components that will compose the virtual environments will be developed, with the corresponding geometric, physical and behavioral modeling of each component, with the directives:
a) Identify the appropriate pattern of development of the virtual models of the different real components and structures of the substations, installations and components of the HVDC system, enabling the adequate identification of these by users. At this stage, it is intended to obtain a standard representation of such structures and components that allows the rapid reuse of components developed within the scope of this project;
b) Design component library (virtual objects) substations, installations and HVDC system components, with their respective 3D models.

c) Elaborate strategies that allow the allocation of such virtual models in a library of components (similar to the real components of the substations), using information from the CAD plan, photos, textures, etc.;

A field survey to model 3D involves collecting data and measurements of objects, structures or landscapes in real-world locations. This data is then processed and used to create a three-dimensional representation of the environment as shown at Figure 1. This process often involves using specialized equipment such as drones, photogrammetry cameras or total station instruments to measure distance, angles and other parameters. The collected data is then processed using computer software to generate 3D models that were used for a variety of purposes such as architecture, construction, engineering, or virtual reality.

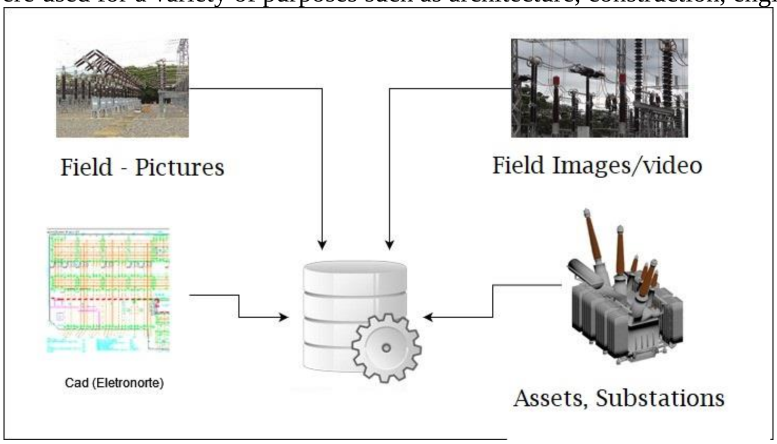

Figure 1- Method to Survey and collect data to 3D Model

A 3D model library applied to AR (Augmented Reality) and VR (Virtual Reality) solutions refers to a collection of pre-made 3D models that was composed to be utilized in AR and VR application. The library contains all types of 3D models such as objects, characters, environments, of the HVDC substation. These models are used to enhance the user experience in AR and VR by providing a more realistic and immersive environment. The library is integrated into AR and VR applications through APIs, SDKs, or software plugins

The use of a 3D model library in AR and VR solutions were concepted to save time and effort in creating custom 3D models, and it can also help ensure consistency and quality across different AR and VR experiences. The 3D models were customized and animated to fit the specific needs of each AR or VR application and bring effectivity form an engineering application. Additionally, having a centralized library of 3D models can make it easier for developers to find and utilize relevant models in the company projects.

In the engineering phase (Figure 2) of HVDC systems, VR and AR technologies were used to simulate the design and performance of HVDC, develop geometric, physical and behavioral modeling techniques for a better and more faithful representation of the components of an HVDC (Thyristors, DC Busbars, HVDC Transformers and others), in order to promote an intuitive and natural interface in Virtual Reality for *Eletronorte* employees, when operating the system;

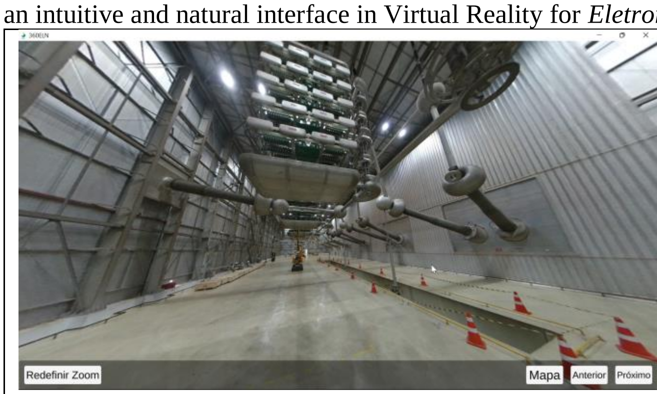

Figure 2 – HVDC Thyristor valve shed (Eletronorte – Araraquara – SP / Brasil)

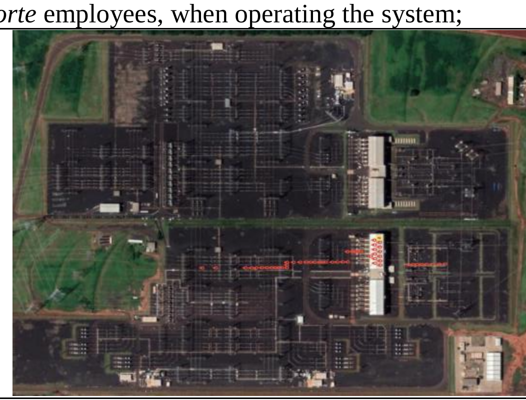

Figure 3- General View of HVDC Substation (ELN360)

VR simulations will be used to provide an immersive and interactive environment for engineers to visualize and test different design configurations, while AR simulations can be used to overlay virtual components on real-world objects, allowing engineers to visualize the system in real-world conditions.This can help to reduce the time and cost associated with traditional testing methods and improve the accuracy of design decisions. The field logistic were assisted by a set of 360° spherical images as shown at figure 4 by red points, starting in the ACt substation area from left to right with valve shed to DC substation area. Each assets 3D modeling is created observing the use of visual tools, modeling conventions and validations through checklists. Preferably, this step consumes data from the components, through images, videos and datasheets for the constitution of models through modeling tools, such as 3DSMax, Inventor, Blender, etc. (Figure 5). The strategy is not focused on capturing large files using point clouds (drone), since this process generates very large files and is difficult to adapt to the phases of using such models in virtual and/or augmented environments. In addition, the point cloud model makes it difficult to separate the electrical components, as well as their parameterization. The ability to have the electrical component in 3D and still parameterized is very important for training and remote assistance – treating asset details separately.

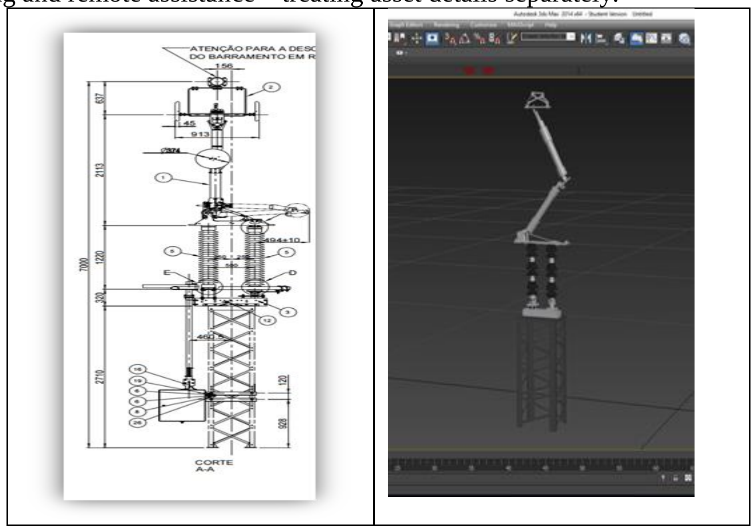

Figure 5 – Generation process of a virtual object (the author)

i. Adequacy of Floor and Template of Virtual Environments: The Virtual Environments are prepared to receive their respective 3D models. The floor and template are built using a game engine tool, such as Unity 3D, according to inputs received and CAD validation;

ii. Semi-Automatic Generation of the Virtual Environment: The models are inserted into the environment through scripts, and their respective animations and behaviors are also created. Scene validation is performed according to the project template, generating the first version of the substation's Virtual Environment;

iii. Cable Generation: Cables are automatically generated and inserted according to the connection topology. This process significantly reduces the substation generation time. The final environment, then, is composed (Figure 6);

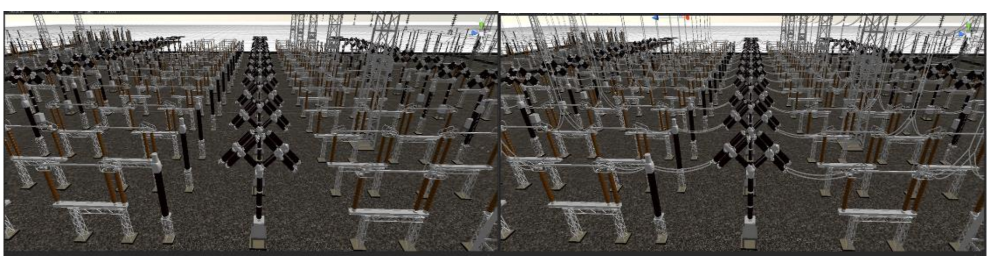

Figure 6 – Cable Generation (the Author)

iii. Integration with field databases: Integration with the supervision system and equipment status update;
iv. Tests: The Virtual Environment is finalized and test cases, validations and final adjustments are applied.
The final system will then be forwarded to *Eletronorte* for review and possible request for adjustments.

III) Maintenance phase:

In the maintenance phase, VR and AR technologies will be used to train technicians and engineers in performing maintenance tasks. VR simulations will provide a safe and controlled environment for training, while AR simulations can be used to provide real-time guidance to technicians in the field. This can help to improve the safety and efficiency of maintenance operations, as well as reducing downtime and maintenance costs. Figure 5 proposes a training of maintenance routine to support to deal with a wide variety of situations quickly and effectively. Therefore, at times when the complexity of the equipment increases, it is necessary to rely on the support of specialists, who normally do not work directly in the field and need to travel to the location to carry out the repair, and this has an impact on time and cost. With an augmented reality application, the operator can use the camera to transmit his vision in real time to the specialists, who will be able to pass on the data they need to operate or inspect remotely. AR also facilitates the processes of maintenance technicians in the field, as it allows the management platforms to be supplied with important information through the IIoT (Industrial Internet of Things), for capturing and processing data with more speed at the same time. use connected equipment. Thus, the professional will have much more agile and effective access to the machinery manuals, for example, reducing errors and providing less maintenance time. This technology can be made available through tablets and cell phones, but it is much more effective if used by headsets, or Smart Glasses as they are also known, because in this way, professionals can absorb the immersive use of augmented reality with their hands free. It is important to highlight some features of the proposed Solution and the RV-HVDC System, whose schematic is presented at Figure 7.

1. Navigation, through different modes (first-person view, third-person view, etc.), allowing component identification and visualization of its status, in real time, through integration with the Concessionaire's supervisory system.
2. Integration of the RV System in the valve room with the ABB Hitachi In-touch system, currently in operation, so that its data is presented in the virtual environment of the valve room (providing conditions for its use in Augmented Reality).
3. Integration with SAPIU, SAGE, InfoPR and DIANE System, reproducing textual or parametric information defined as strategic for the information visualization process in the supervisory and maintenance context in an augmented environment.
4. Implementation of the “Zoom GO TO” functionality (Location of alarmed active elements) allowing a guided tour in 3D in the virtual environment to the element that is in an alarmed status in the ABB In-touch supervisory system, facilitating the location of faults and decision-making based on visualizing the virtual environment and the highlighted alarmed element.

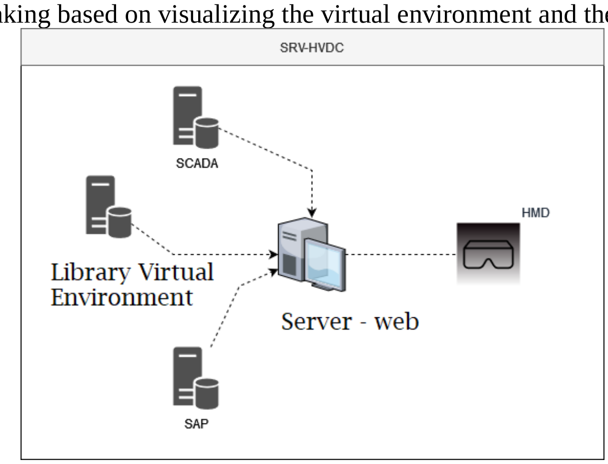

Figure 7 – RV HVDC Schema – (The Author)

The process of maintenance and operational technical support will take place through virtual environments and objects, in the field and an “Operational Support” platform, with a desktop solution. In these cases, the operating environment will include the different virtual objects created by the support team and will allow, through the updating of information, maintenance in the field by the technician, either using Helmets (HMD) or Tablets. Figure 8 highlights some components of the Solution, using Augmented Reality.

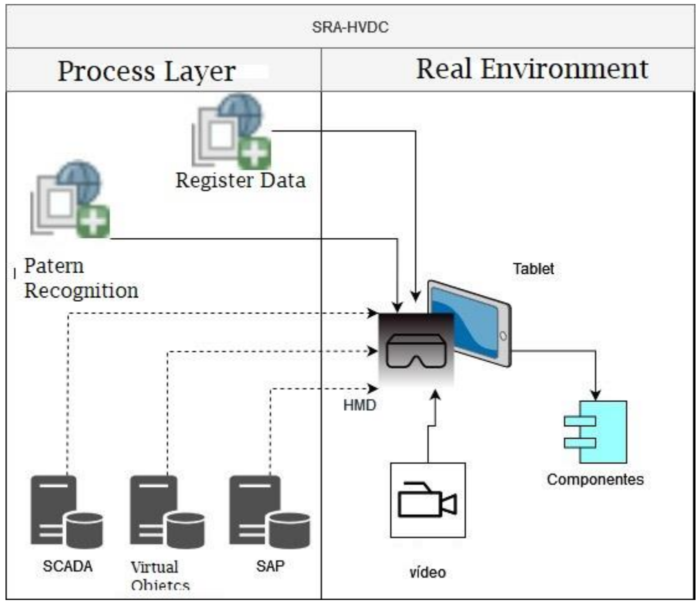

Figure 8 – Augmented Reality System components (The Author)

It is important to highlight some features of the Maintenance Solution and the RA-HVDC:
i. Integration of the Augmented Reality System with the real environment of the valve room, so that data from current systems, such as ABB Hitachi's In-touch are presented in the real environment of the valve room;
ii. Integration with SAP displaying information in real time through Augmented Reality;
iii. Application of Augmented Reality compatible with strategies like:
The. Optical See-Through: wearing an HMD helmet, elements of the Real Environment are captured, with subsequent position processing and recognition. Once such information has been processed, a virtual object is presented through the Optical Combiner, such as the Microsoft Hololens, in the solution development environment. The user can visualize a virtual object over the real field.
In this context, project teams must identify and develop a communication process between operation control systems and the virtual environments related to substations, installations and components of the HVDC system, so that changes in the first imply corresponding changes in the second and vice versa. -versa. System user interactions with virtual environments must conform to those available in systems that appropriate information in real time;
Results and products of the phase:
i. Integration of the Virtual Reality System with management of the HVDC Operation;
ii. Methodology for using the Virtual Reality System in valve rooms and HVDC system substations for operator training purposes;
iii. Methodology for using the Virtual Reality System in valve rooms and substations of the HVDC system for use in pre and post operation.
iv. Methodology for using the Augmented Reality System for remote assistance in the field;

IV)Training and remote assistance

In the control phase, AR technologies can be used to provide real-time information to operators, helping them to make informed decisions and respond quickly to changes in system conditions. AR-enabled control systems can provide visual representations of system performance and provide alerts in the event of any issues. This can help to improve the reliability and efficiency of HVDC systems, as well as reducing the time and costs associated with system maintenance. Following similar concepts, Figure 9 presents the schematic related to the Augmented Reality system (RA-HVDC), to support Training and, mainly, Remote Assistance (Intervention Planning).

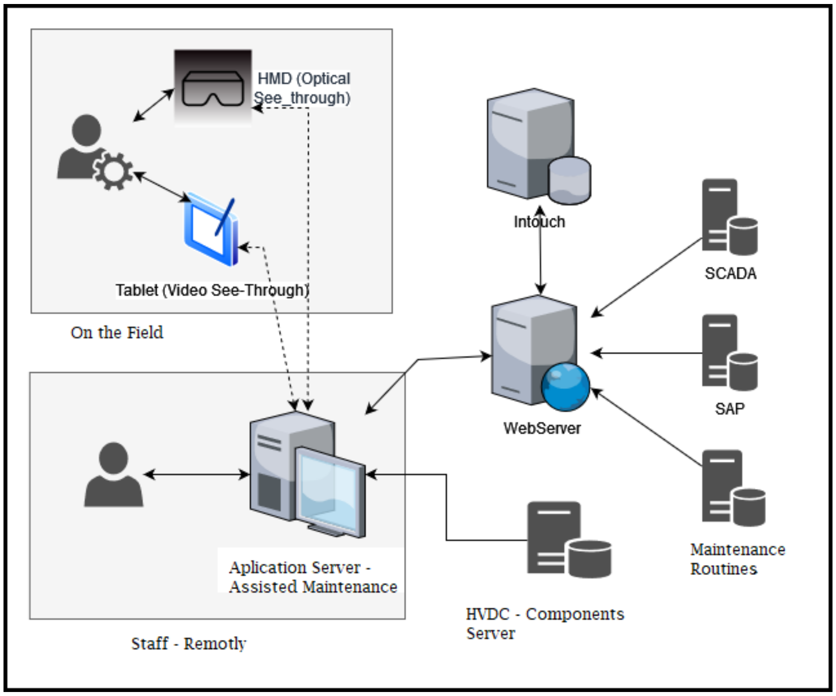

Figure 9 - RA-HVDC schematic for the maintenance and remote assistance process –(Author)

In this stage, a strategy for using the RA-HVDC for asset maintenance training will be studied and implemented, as well as for planning real interventions in remote assistance processes. Results and products:
-Training methodology for maintenance engineering teams in AR;
-Methodology for using the Virtual Reality System of valve rooms and substations of the HVDC system for maintenance training purposes;
-System for planning interventions in the field, in real time, through the RA-HVDC;
-Analysis system of maintenance execution, in real time, through RA-HVDC;
-Planned maintenance program for HVDC Substations in RV;
-Maintenance execution support system, through the RA-HVDC;

II) Cloud Experimental Architecture

The high-level architecture presented in the previous diagrams depict a prototype implementation of the proposed system leveraging in-lab resources to support the design, engineering, simulation, and proof-of-concept of the design. However, HVDC systems are critical infrastructure for any country, and when its operational procedures start relying in VR and AR systems, these latter ones also become part of that critical infrastructure, requiring appropriate design to satisfy the requirements of stability, reliability, and security. While in the past implementing such requirements would demand large investments in computing infrastructure, people, and processes to implement high-availability and disaster-recovery capabilities, not mentioning the added complexity for implementing and testing the system compliance with those requirements, nowadays this challenge has been largely remediated with the advent of Cloud Computing. Through a Cloud Computing provider one can have immediate access to APIs that allows designing, configuring and programming distributed, automated, scalable, global, interconnected, reliable, and secure computing infrastructure. When deciding on how to port the proof-of-concept architecture to the Cloud, we can select virtual servers (virtual machines, VMs) through the IaaS (Infrastructure-as-a-Service) model, or ready-to-use services in a PaaS (Platform-as-a-Service) model, or even to opt for a SaaS (Software-as-a-Service) model. Our goal is to reduce the complexity and TCO (total cost of ownership) of the system while improving the mentioned non-functional requirements. In an initial approach to port it to the Cloud, this team has selected AWS (Amazon Web Services) as the provider, due its maturity, diversity of services, global coverage, and leadership as indicated in multiple Gartner ‘s Magic Quadrant reports. The initial architecture, at this moment in validation stage, is shown at figure 10.

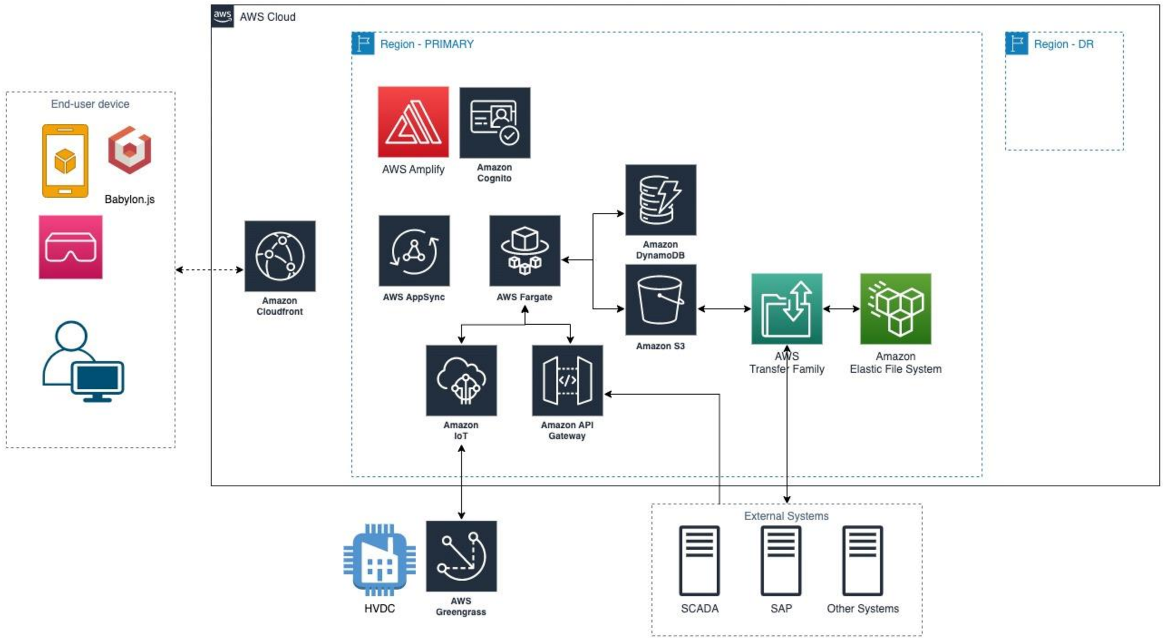

Figure 10 – Cloud Experimental Architecture – Font (Author)

The proposed architecture leverages mostly regional, serverless services. Regional services are available in a region, which is composed by two or more groups of physical data centers denominated “availability zones” (AZ). These AZs are far enough to isolate them from local issues – like energy and climate disruptions – but closer enough to allow synchronous replication between relational databases and storage services. “Serverless services” are PaaS services that do not require the installation and configuration of virtual servers, so the team could focus on the system’s needs. The diagram shows a primary region, where the systems will be running in business-as-usual mode, and a second region shown will be activated only in case of failure of the primary region. As Serverless services will not be running in costs while not in use, so this selection reduces the operational costs of maintaining a disaster-recovery environment. The architecture relies on a Content Distribution Network (CDN) represented by the CloudFront service, that reduces the latency for the end-user’s accesses, and connects them with the internal services. These services are properly isolated from the internet, and implement RBAC (role-based access control) to provide fine-grained access to the systems’ functions exposed through APIs. The applications run on containers managed by the AWS Fargate platform, and the data is stored on distributed databases and storage. For the case of on-site sensor data acquisition, we are leveraging Amazon IoT and AWS Greengrass, and the integration with the companies if designed case by case, based on the compliance and operational requirements, and may include business-to-business API integrations, secure file-transfer-protocol (sFTP), or other means. This pilot implementation allows a monthly uptime not lower than 99.99% with optimal TCO, and there is room for improvement.

V) Results / Conclusion:

• Investigate and propose the best interaction metaphors in the AR system interface: arrows, videos, texts, voice commands and others, in order to support the planning of interventions, with verification of difficulties, alternatives and solutions with lower cost and time related to step-by-step activities. To do so, there must be details of processes, tools and information, superimposed on the real environment with the use of wearable devices;

• Updates to Preventive Maintenance Procedures for HVDC system assets;

• Integrate the RV-HVDC with *Eletronorte's* distance learning system, through the development of Open Educational Resources – OER, methodology and training of instructors (in person or at a distance);

• Carry out in the simulation environment recovery tests for disconnected networks, similar to those of the “Drill” concept, with real-time integrations;

• Create an HVDC system monitoring environment through a Virtual and Augmented Reality room in *Brasilia*, for the integration of real and virtual systems, where engineering teams can interact with field teams.

Additionally, it should be noted that one of the constant objectives in the maintenance of the Electric Energy sector is to maximize the operational safety of equipment at a minimum cost. In this context, Augmented Reality is a technology that, by increasing the user's (sensory) perception and providing conditions for interaction with the real environment (Nee et al., 2012), has shown great potential to support such demands. Indeed, Roy et al. (2016) highlight some of the main challenges faced for the implementation of AR in the daily lives of companies and industries: i. a wide variety of tasks, from diagnostics to repair; ii. varying complexity of maintenance requirements due to diversity of models, access to components, frequency of maintenance, etc.; iii. long equipment life causing varying levels of quality, standards and depth in documentation; iv. a large number of types of equipment to maintain, with different profiles, useful lives and construction and operational details. In conclusion, VR and AR technologies have the potential to greatly enhance the engineering, maintenance, and control phases of HVDC systems. By providing a safe and interactive environment for design and testing, providing effective training for technicians and engineers, and providing real-time information to operators, these technologies can help to improve the efficiency and reliability of HVDC systems and reduce associated costs. As VR and AR technologies continue to evolve, it is likely that they will play an increasingly important role in ensuring the optimal performance of HVDC systems in the future. Finally, several VR and AR applications in maintenance and training have been studied in the context of the electricity sector. However, the work remains in an exploratory phase, mainly in the context of HVDC substations, providing an adequate environment for the development of applied research.

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