APPLICATION OF THE IEC 61850-7-420 STANDARD IN THE MODELING OF DISTRIBUTED ENERGY RESOURCES IN A PHOTOVOLTAIC MICROGRID

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Abstract

This paper presents the modeling of Distributed Energy Resources (DERs) in a photovoltaic microgrid according to the IEC 61850-7-420 standard, with the aim of standardizing communication and improving interoperability between devices. The microgrid under study, called MG GREI, belongs to Grupo de Redes Elétricas Inteligentes (GREI) at the Department of Electrical Engineering at Federal University of Ceará and has photovoltaic generation, battery storage, and controllable loads. The methodology involved mapping the logical devices and logical nodes corresponding to each DER, according to the object-oriented structure of the standard. Single-line diagrams and UML diagrams were developed representing the functional hierarchy and data flows. The results demonstrated the possibility of integrating existing systems, previously based on Modbus, into standardized and interoperable architecture. The study lays the foundation for a robust supervisory system, expanding the automation and control of the MG. It is concluded that the adoption of the IEC 61850-7-420 standard modernizes the management and communication of DERs, promoting interoperability, efficiency, reliability, and integration with smart grids.

Keywords: Microgrids, IEC 61850-7-420, Logical Nodes, Distributed Energy Resources, Interoperability

1. Introduction

Microgrids (MGs) are small-scale electrical energy systems that operate independently (island mode) or connected to the main electrical grid (connected mode). MGs integrate renewable sources (solar, wind), energy storage systems, and conventional generation, using advanced control to optimize energy flow and ensure system stability (Hatziargyriou, 2014). They represent a significant evolution in electrical power distribution systems, offering greater flexibility, resilience, and sustainability.

The integration of Distributed Generation (DG) and MGs into electricity distribution networks brings with it a number of needs and challenges that require attention to ensure system stability, security, and efficiency. The variation in the penetration levels of these MGs in the system and the difficulty of maintaining interoperability, together with inadequate power flow control, trigger several problems that are difficult for the system to resolve, causing impacts on the local distribution network. Aspects such as bidirectional power flow management, adaptive protection systems, robust communication infrastructure, and advanced simulation and analysis tools are essential for assessing the impact of DGs and MGs on the grid and for optimizing system planning and operation (Ustun; Ozansoy; Zayegh, 2011).

Given this diversity of factors, to ensure the efficient operation of the microgrid, power generation, load sharing, control, and protection strategies must be adjusted in real time, following variations in the grid (Hatziargyriou, 2014). This practice is important to ensure good resource management, since MGs can contribute to increasing the reliability and stability of the electrical system, provided that their installation and operation are appropriate to local conditions (Ustun; Ozansoy; Zayegh, 2011).

In this context, the IEC 61850 standard is a model developed to unify and standardize protection, automation, and control systems for electrical power systems. Its development brings together researchers

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and manufacturers in a joint effort, considering the problems related to maintaining interoperability between devices and equipment from different manufacturers, given the diversity of protocols (FREITAS, 2023). MGs often use manufacturer or industrial communication protocols such as Modbus and DNP3, and specific data models, which makes integration difficult. Thus, the implementation of the IEC 61850-7-420 module in microgrids drives the modernization of the electrical sector, offering several benefits such as: standardization of communication, improvement in supervision and control, support for digitization and automation, and integration with smart grids and advanced features.

The objective of this work is to model and implement the modeling standards of IEC 61850-7-420 in a real photovoltaic microgrid to improve the management, control, and interoperability of its DERs. The main contribution of this work is the modernization of the communication and control strategy of a real photovoltaic microgrid, which currently operates with the Modbus communication protocol.

This modernization is possible through the implementation of the IEC 61850-7-420 standard. The expansion proposed by this module of the IEC 61850 standard constitutes an innovative and broad platform for DER management and communication resources. However, these resources have not yet been widely applied. The present development is the initial step to enable this evolution in the MG GREI, located in the Department of Electrical Engineering at the Federal University of Ceará.

This paper is divided into five sections: Section 1 presents an introduction to the main concepts that permeate the work, comprising its motivation and justification; Section 2 presents the theoretical basis; Section 3 approaches Methodology and Development; Section 4 presents the results of the study; and Section 5 explains and discusses the conclusions.

2. Theoretical Basis

The IEC 61850 standard presents a standardized data model in an object-oriented architecture instantiated in the configuration of logical nodes. In addition, the standard proposes some communication protocol standards that seek to ensure the interoperability of electrical systems in general, based on the supervision and monitoring of system data and the proper performance of the protection and control functions implemented in Intelligent Electronic Devices (IEDs) (IEC, 2013). For a better understanding of the standard, it is necessary to be familiar with some concepts present in the object-oriented modeling proposal. Figure 1 shows the hierarchical structure of the IEC 61850 data model.

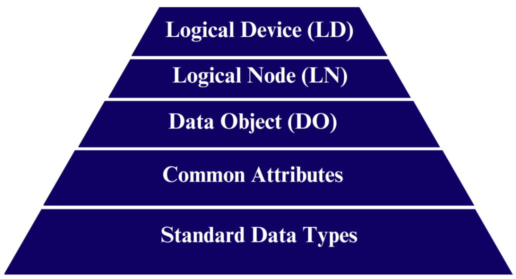

Figure 1: Hierarchical structure of the IEC 61850 data model

- Physical Device: This is the data communication and processing unit and represents the hardware of a real device in an automation system, for example, an IED. It may contain one or more Logical Devices;
- Logical Device: Brings together a group of logical nodes that characterize an instance of a device, i.e. it is contained within the operating logic in a Physical Device;
- Logical Node: Represents a functional unit of protection, automation, and control through a set of Data Objects. The essential protection, control, and automation Logical Nodes are listed in IEC 61850-5, and the specific Logical Nodes for DER modeling are listed in IEC 61850-7-420;
- Data Object: Instance of the Logical Node that indicates a functionality, such as measurement or status identification. Within a Logical Node, there are Data Objects defined as optional and others defined as mandatory to ensure proper function;

- Data: This is the information contained in a Data Object; it does not configure a hierarchical instance in the model organization;
- Data Attribute: Refers to the type of information stored, such that several Data Attributes can compose the same Data Object. Attribute groups can be of six types according to the function they perform: status information (ST), measurements (MX), control (CO), configuration (CF), description (DC), and extended definition (EX);
- Common Data Class (CDC): Set of attributes that can be used in common by different Data Objects. The divisions and definitions of CDCs are presented in IEC 61850-7-3.

The example in Figure 2 shows the standard configuration for sending data in a logical measurement node.

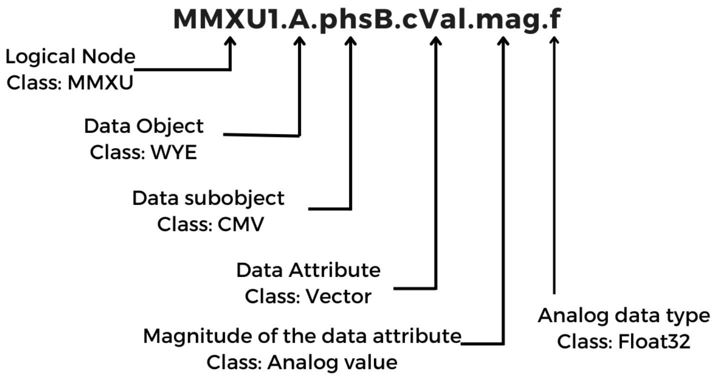

Figure 2: MMXU measurement logical node sending structure (Adapted from IEC, 2020)

The module IEC 61850-7-420:2021 recognizes the importance of expanding distributed generation for a region's electrical infrastructure and, considering the related issues and impacts on the electrical power system, presents a new model for Distributed Energy Resources (DERs). Thus, DERs are defined as localized energy resources, classified by the following functions: generation, storage, or load. DERs can include protection, control, and monitoring, and each DER can aggregate multiple units. In addition, the standard allows for a recursive model for DERs, where an MR is seen as a single common point of connection to the electrical grid. However, the recursive model makes it possible to analyze the MR in detail, exploring the diversity of DERs aggregated in generation, storage, and load (Guise et al., 2021).

In addition, for the purposes of implementing a robust communication system, IEC 61850-7-420:2021 presents specific logical nodes for the most diverse DERs available, within the scope of generation, storage, and load, including fuel cells, microturbines, photovoltaic energy, motors, batteries, and monitoring sensors (Aviles Sanchez et al., 2018) (IEC, 2020). The set of these logical nodes constitutes an object-oriented data model that is sufficient and complete for supervising and controlling the operation of a microgrid, since communication for plants containing DERs must include communication between DERs and between DERs and operators or aggregators who will manage the system (Salazar-Zuluaga et al., 2017) (Guise et al., 2021). Figure 3 shows an overview of all logical nodes proposed for DERs and where they are allocated within the set of devices and equipment available in a distributed generation plant (IEC, 2020).

Based on this overview, it is possible to develop a model that considers only the typical DERs of a photovoltaic generation plant, as is the case of the MR analyzed in this study. Table 1 presents the logical devices specified in Figure 3 and their respective associated logical nodes, with which it is possible to model any DER of a photovoltaic microgrid plant.

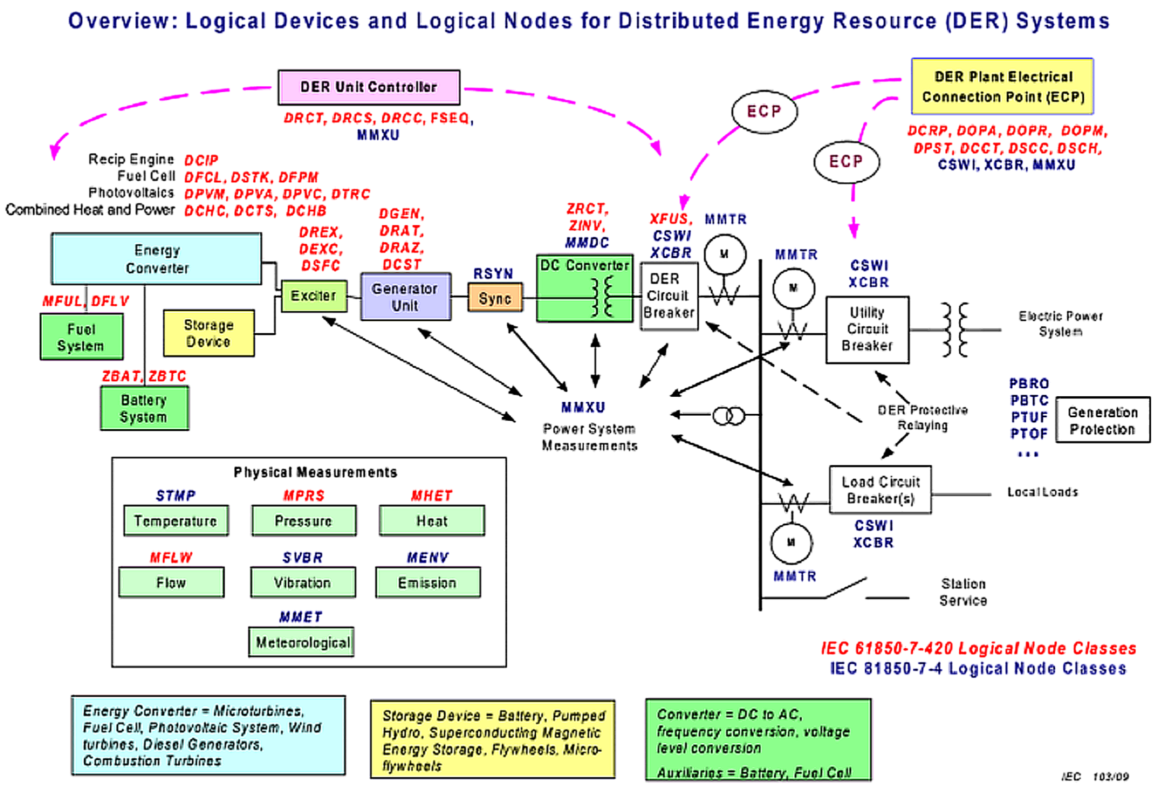

Figura 3: Overview: Logical Devices and Logical Nodes for DER Systems (IEC, 2020)

Table 1: Specific logical devices for photovoltaic microgrids and their associated logical nodes.

Logical Device	Logical Node	Function
Control Unit	DRCT	Defines the characteristics and control capabilities of a DER unit
	DRCS	DER status controller
	DRCC	Defines the control actions for a DER unit
	FSEQ	Provides information on sequences of actions during the start-up or shutdown of a DER unit
Photovoltaic array	DPVM	Describes nominal operating characteristics of a photovoltaic module
	DPVA	Describes the configuration and layout of the installation and arrangement of the modules
	DPVC	Photovoltaic array controller
	DTRC	Defines array or device guidelines even if no active tracking is included
Batteries	ZBAT	Nominal operating characteristics of the battery array
	ZBTC	Battery charger
Inverter	ZINV	Inverter characteristics
	ZRCT	Rectifier features
Circuit Breaker	CSWI	Circuit breaker drive controller
	XCBR	Circuit breaker status

Energy meter	MMXU	Electrical measurements
	MMTR	Electrical measurements
Temperature sensor	STMP	Temperature measurement
Heat sensor	MHET	Heat measurement
Meteorological Sensor	MMET	Meteorological measurements

3. Methodology and Development

The object of study in this paper is the MR GREI, which was implemented in the Electrical Engineering Department at the Federal University of Ceará by the Smart Grids Group. The topology of the MR GREI is shown in the single-line diagram in Figure 4.

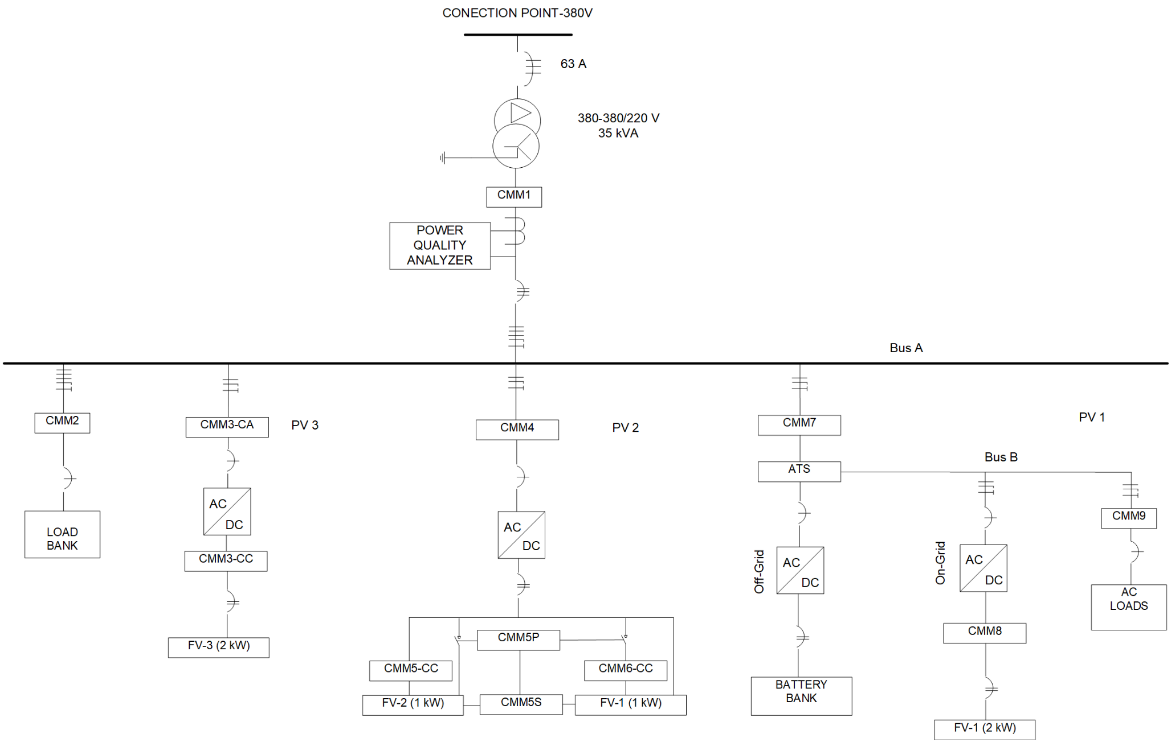

Figure 4: Single line diagram of MG GREI.

As can be seen in Figure 4, the MR GREI consists of a 35 kVA isolating transformer with a primary winding connected in a Y-grounded configuration, 380-220 V connected to the microgrid busbar, and a secondary winding connected in a delta configuration, 380 V connected to the three-phase low-voltage network of the Pici Campus of the Federal University of Ceará. The secondary side of the isolating transformer has a main circuit breaker and a power quality meter. Connected to the microgrid busbar are two controllable load banks, one single-phase and the other three-phase, and a photovoltaic generation system composed of 30 modules, generating a power of 7.8 kWp.

Given the object-oriented structure of the standard, the analysis enables the creation of an adapted single-line diagram and UML class diagrams for each subdivision of the MR. These are structured according to the energy function of each DER, with emphasis on the logical nodes contained in each logical device of the MR GREI, with the aim of providing a clear and organized representation of the system. An initial analysis of the current MR GREI scenario allows us to identify opportunities for improving the system, communication, and interoperability, with a view to enabling the evolution towards the application of the IEC 61850 standard protocols. To this end, it is first necessary to survey the available DERs and associate each one of them with their respective logical nodes, which ensure the proper supervision and control of the MG's operation.

4. Results

Based on the modeling of the MR GREI according to the IEC 61850-7-420 data standard, the following are developed: the mapping of the energy function and the respective logical nodes; the adapted single-line diagram; and the UML diagrams, which detail the functional structure of each device and subsystem. Figure 5 presents a UML diagram showing the classification of MR DERs according to their respective control, generation, storage, or load functions.

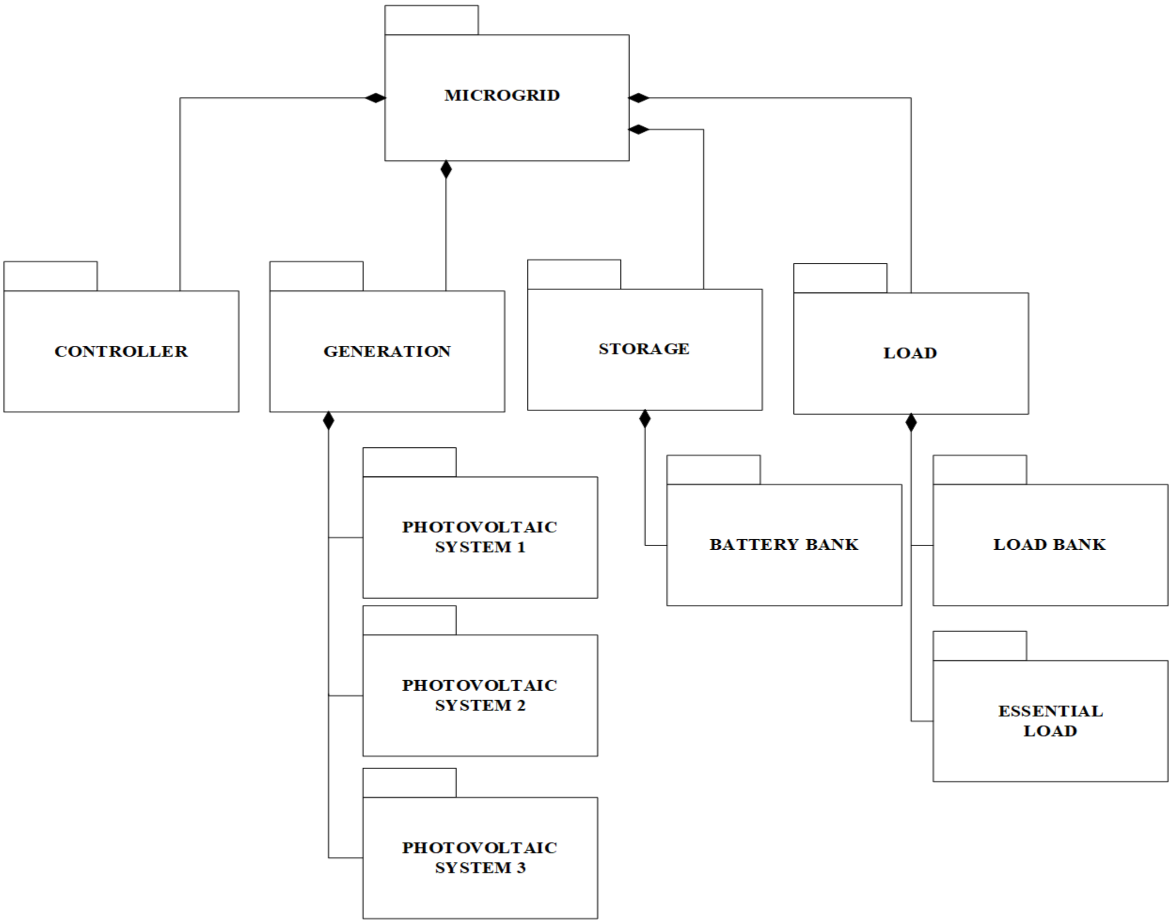

Figure 5: Single-line diagram of the MR LabREI with IEC 61850-7-420 standard logical nodes

Complementing the analysis of DERs, Table 2 presents the mapping of logical nodes for each logical device of the GREI MR according to IEC 61850-7-420:2021. From this survey, it is possible to identify the data objects, their respective data attributes, and the mandatory Common Data Classes (CDCs).

Table 2: Energy function of MR GREI DERs

Logical Device	Logical Nodes	Logical Device	Logical Nodes
Controller	DRCT | DRCS | DRCC	**Photovoltaic System 2**	
Common Connection Point		AC Circuit Breaker	XCBR | CSWI
Three-Phase Circuit Breaker	XCBR | CSWI	Inverter	ZRCT | ZINV
Power Quality Analyzer	MMXU | MMTR	DC circuit breakers	XCBR | CSWI
Single-Phase and Three-Phase Load Bank		Photovoltaic Array	DPVM | DPVA | DPVC | DTRC
Single-phase circuit breaker	XCBR | CSWI	**Photovoltaic System 3**	

Three-phase circuit breaker	XCBR | CSWI	AC Circuit Breaker	XCBR | CSWI
Photovoltaic System 1		Inverter	XCBR | CSWI
Off-grid Inverter	ZRCT | ZINV	DC circuit breakers	ZRCT | ZINV
DC circuit breakers	XCBR | CSWI	Photovoltaic Array	DPVM | DPVA | DPVC | DTRC
Battery bank	ZBAT | ZBTC	**Essential loads**	
Ongrid inverter	ZRCT | ZINV	Single-phase circuit breaker	XCBR | CSWI
AC circuit breaker	XCBR | CSWI	**Auxiliary measurements**	STMP | MMET
Photovoltaic Array	DPVM | DPVA | DPVC | DTRC		

Based on the above, it is possible to draw up the adapted single-line diagram with the mapping of the logical nodes that will be responsible for the operation and control of the MR, shown in Figure 6.

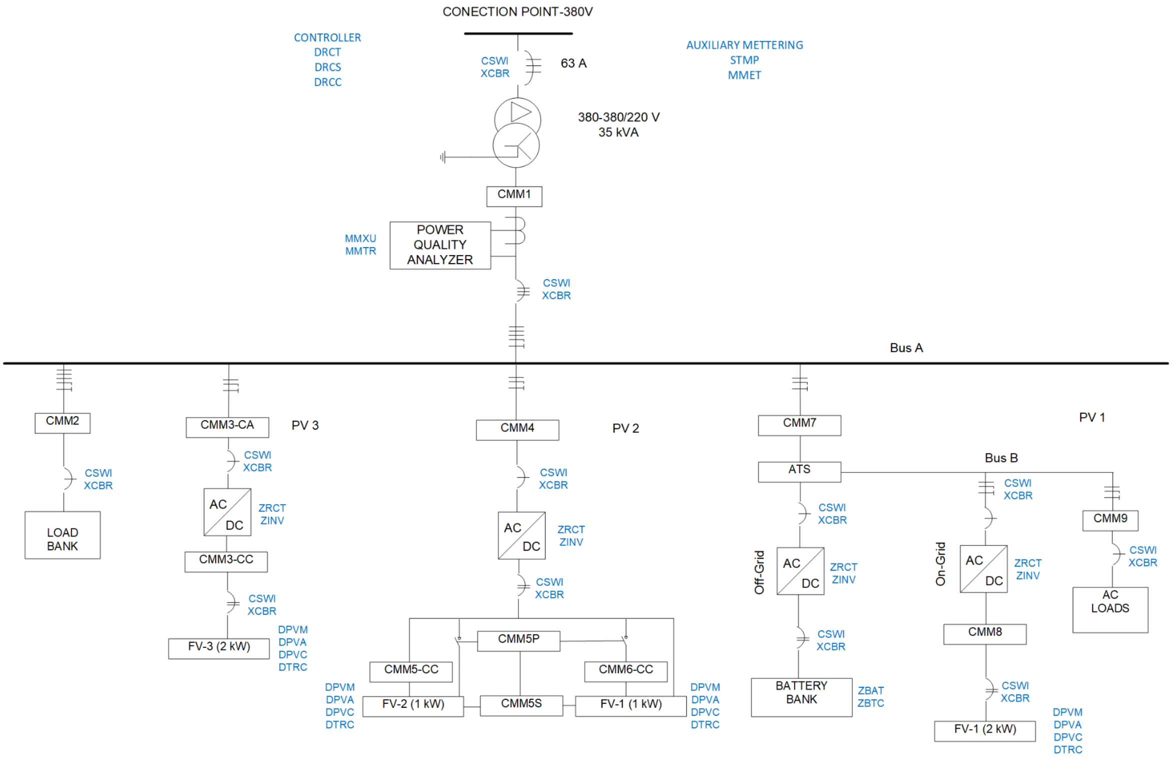

Figure 6: Single-line diagram of the MG GREI with standard IEC 61850-7-420 logical nodes

The UML diagrams for each logical device containing the logical nodes and their respective data objects and mandatory CDCs in accordance with the normative specifications are shown below. Figure 7 shows the UML diagram for the connection point to the university distribution network, for the DER controller, and for auxiliary measurements:

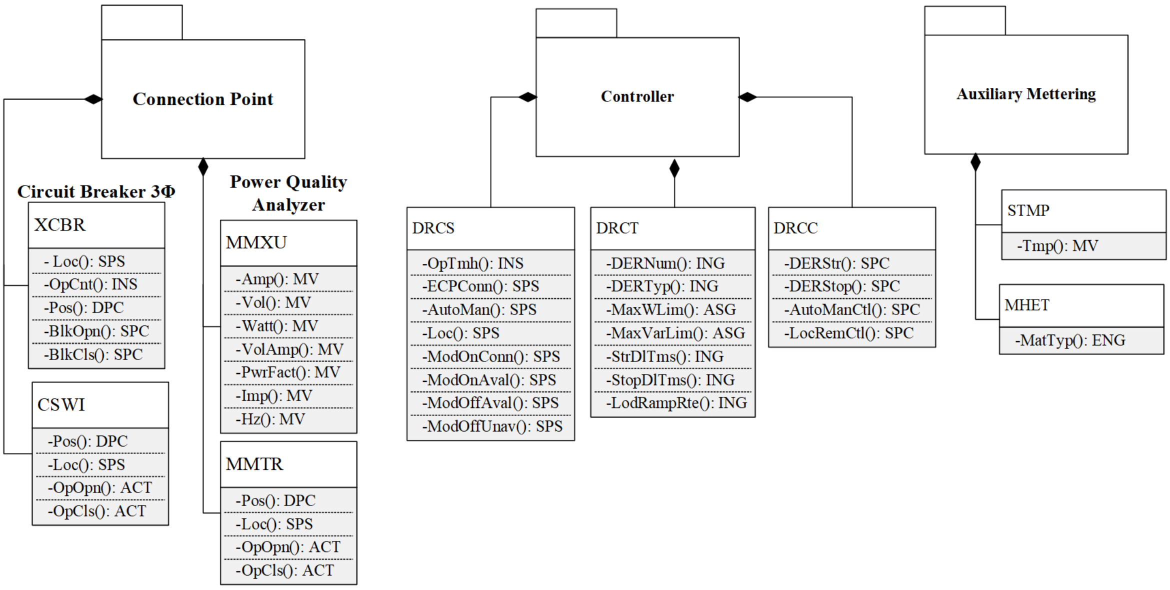

Figure 7: UML diagrams for the connection point to the university network, for the controller, and for auxiliary measurements

Figure 8 shows the UML diagram for load banks for essential loads:

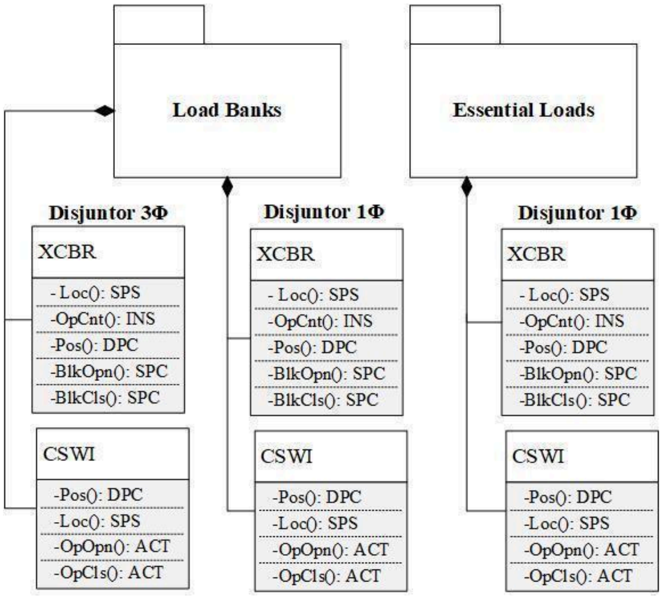

Figure 8: UML diagrams for single-phase and three-phase load banks and essential loads

Figure 9 shows the UML diagram for the SFV-1:

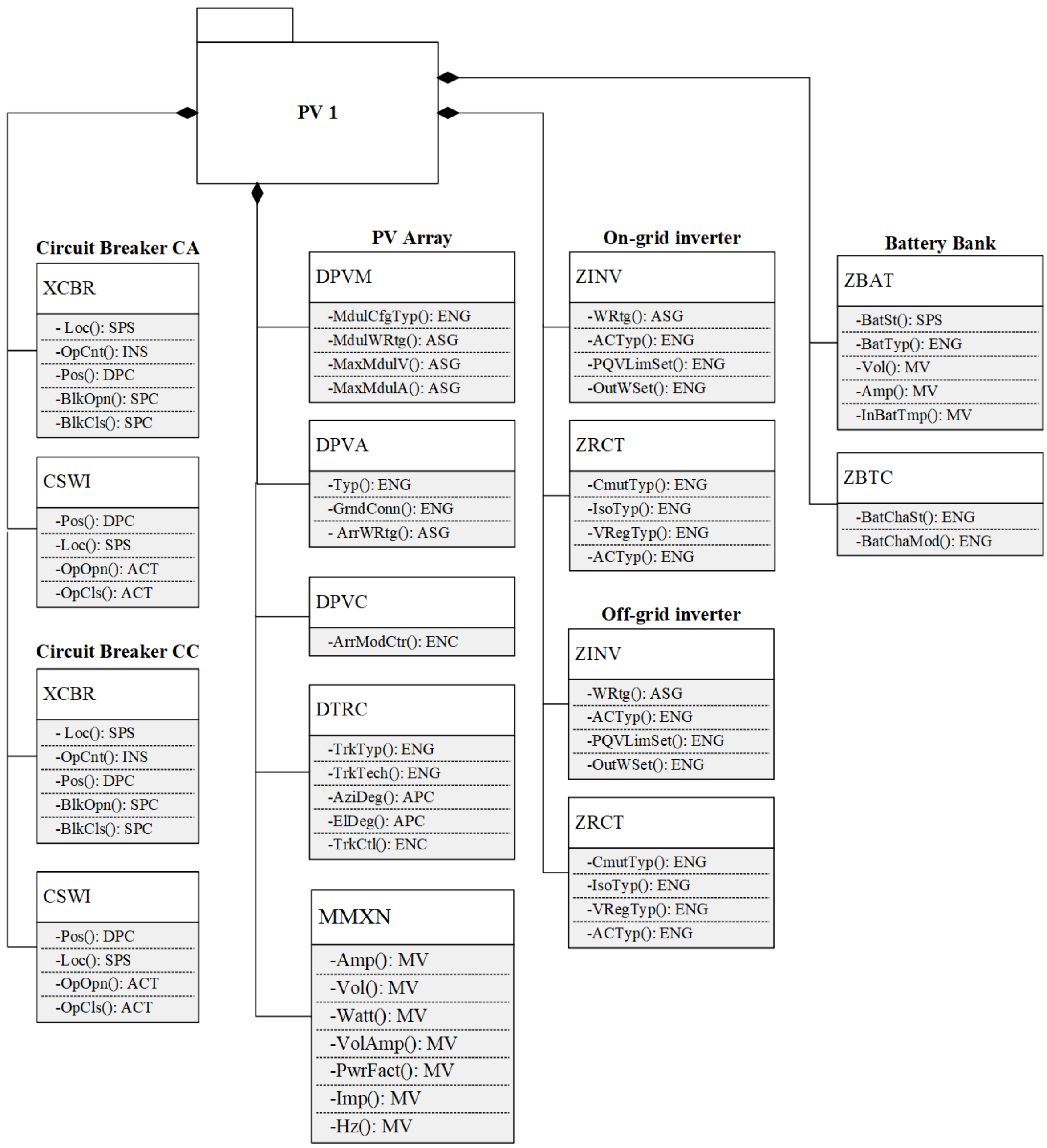

Figure 9: UML diagram for photovoltaic subsystem 1

Figure 10 shows the UML diagram for SFV-2:

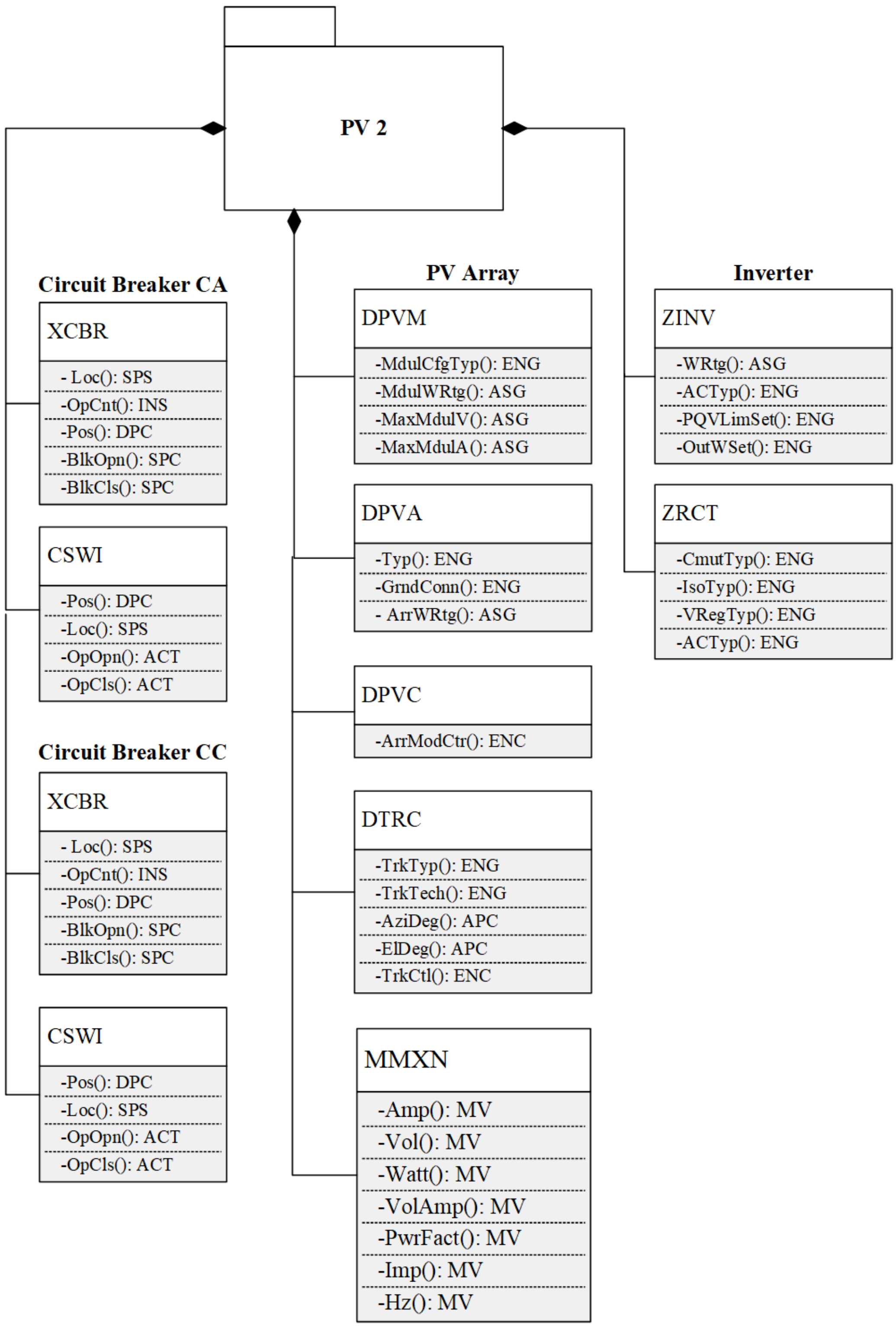

Figure 10: UML diagram for photovoltaic subsystem 2

Figure 11 shows the UML diagram for SFV-3:

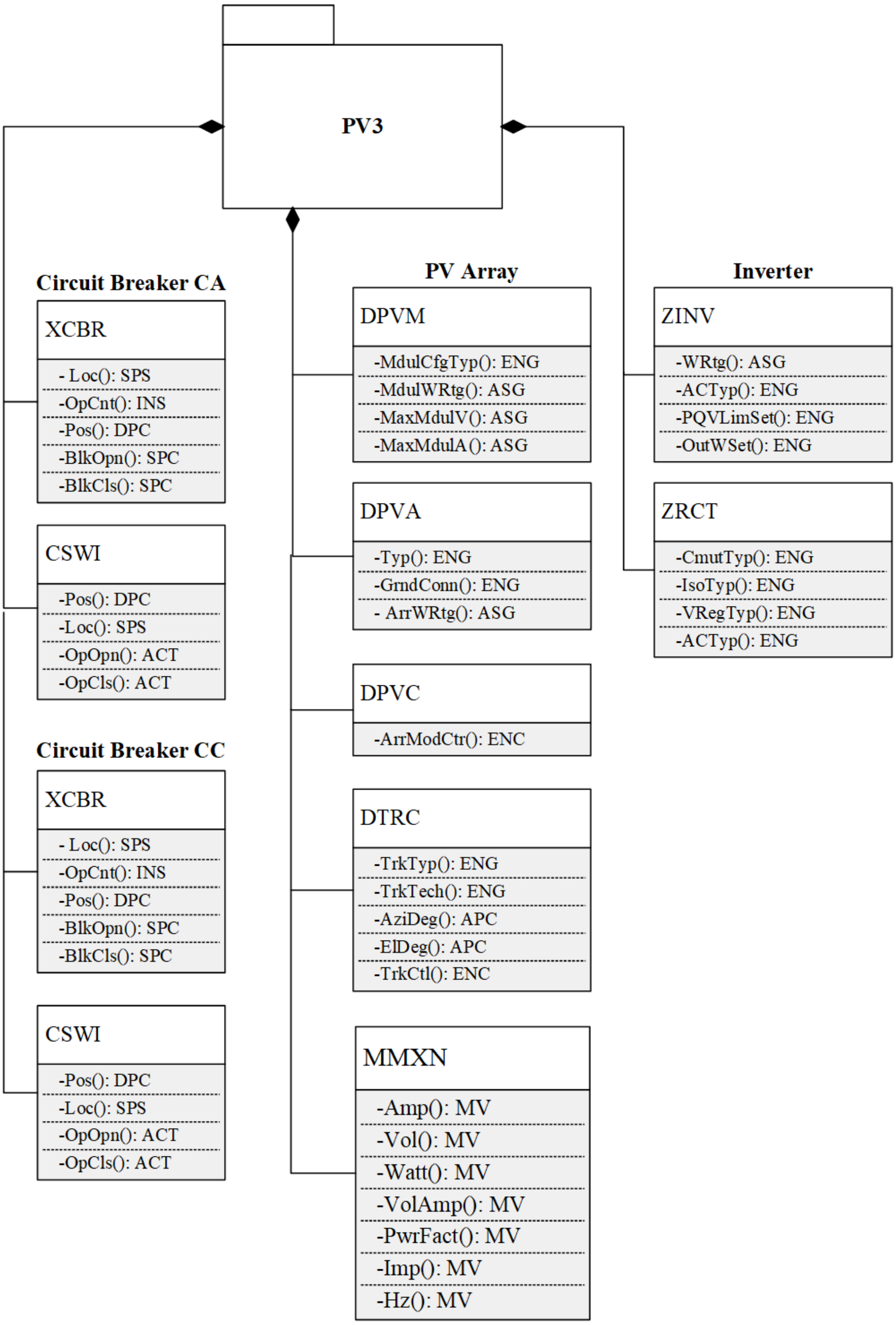

Figure 11: UML diagram for photovoltaic subsystem 3

5. Conclusion

Given the results presented, it is possible to understand the operation and energy function that each DER performs within the MR GREI. The standardized data model and UML diagrams presented are developed in accordance with IEC 61850-7-420, with the aim of implementing the most current regulatory requirements. The results also establish the basis for the creation of a more robust, comprehensive, and interoperable supervisory system capable of supervising and controlling MR GREI based on a range of information made available and monitored through the use of these logical nodes and their respective data and attributes.

Therefore, this work constitutes the basis for the modernization of MR GREI communication and automation and ratifies the adoption of the IEC 61850 standard as an efficient alternative for the management and interoperability of existing DERs. Thus, the modeling and validation of the proposed processes constitute an evolution of protection, automation, and control strategies, aligning with the demands of the growing insertion of DG in the distribution network and contributing to the development of Smart Grids.

The implementation of IEC 61850-7-420 in microgrids, especially in scenarios of solar and wind energy expansion, such as in Fortaleza, Ceará, Brazil, offers a differential factor in interoperability, efficient communication, and advanced DER management. This standardization results in smarter, more efficient, and more reliable operation, facilitating the integration of renewable sources and the development of control systems essential for the distributed energy future.

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