International Research Journal of Advanced Engineering and Science
ISSN (Online): 2455-9024

Overview of Photovoltaic Solar Plants and their Regulations in Colombia

Cristian Rosas, Juliet Avendaño, Cesar Hernandez
Facultad Tecnológica, Universidad Distrital Francisco José de Caldas, Bogotá D.C., Colombia
Email address: cfrosasa@udistrital.edu.co, jaavendañop@udistrital.edu.co, cahernandezs@udistrital.edu.co

Abstract— *For the development of this research work, the regulations established in Colombia by the CREG (Commission for the Regulation of Energy and Gas) were considered. Within its legislative powers, this body determines the different factors of mandatory compliance that the generators of photovoltaic and wind plants must have to participate in the national energy system. It also grants powers to the CNO (National Operation Council), whose primary function is to agree on the technical aspects to ensure that the SIN (National Interconnected System) operation is safe, economical, and environmentally sustainable. From the above, the UPME (Mining and Energy Planning Unit) has established strategies and projects to improve electrical systems at the national level; within these projects and plans are photovoltaic solar plants that, in addition to being a renewable energy source, can support the different susceptible variations in the electricity system, guaranteeing stability*.

Keywords—*Solar plants, CREG, SIN, STN, Active power*.

I. Introduction

Renewable energies and energy efficiency have become the most critical issues given a transition in the implementation of new technologies that are more sustainable and, at the same time, reliable in the integration into the interconnected electricity system. The ones that have stood out the most in recent years are photovoltaic and wind generation, as well as their usefulness in controlling the different electrical variables within the connection point to the electricity system.

Law 1715 of 2014 defined Non-Conventional Renewable Energy Sources (NSFs) as those renewable energy resources available globally that are environmentally sustainable [1]. In particular, this paper will focus on the limits of operation and control variables in photovoltaic solar plants that generate energy from the radiation coming from the sun.

Due to the importance of implementing renewable energy projects in the country, regulations have been promulgated that define the operational requirements and services necessary to supervise and control photovoltaic and wind generation systems concerning the connection point with the National Interconnected System (SIN). These control services are detailed in the regulations established by the Energy and Gas Regulatory Commission (CREG).

The general technical operation of photovoltaic plants is to capture solar energy through photovoltaic panels, which convert solar irradiation into electrical energy that is later transformed into alternating current with the same characteristics of the AC power grid. To achieve this purpose, a system consisting of a set of photovoltaic panels that form the generator, a DC/DC converter used when an adaptation of the DC signal to the generator output is required, a capacitor, a power inverter, a filter, and/or a transformer connected to the grid and a control system. [2]

A simplified diagram of this system is shown in Fig. 1. The point at which the photovoltaic system is connected to the grid is called the common coupling point or connection point.

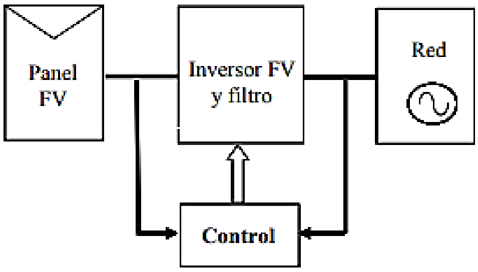

Fig. 1. Grid-connected photovoltaic system.

This article presents an overview of the global and national landscape of photovoltaic systems, as well as research of the requirements according to the Colombian regulatory framework.

II. Overview of Photovoltaic Solar Plants

Due to climate change and the large-scale pollution that the planet is facing, many countries have shown their concern about finding energy sources that are efficient and that do not generate an impact on nature. This is why using renewable energy resources is the most favorable option to generate clean electricity.

Harnessing the sun's rays significantly reduces the use of fossil fuels, eliminates greenhouse gas emissions, and provides energy self-sufficiency. Photovoltaic solar energy has proven to be highly efficient and environmentally friendly; its resistant components, high durability, power generation capacity, and storage of its surpluses make it extremely reliable and attractive, and it is one of the most abundant resources on the planet.

Commercial, residential, and industrial solar panels are used as a backup system to ensure the availability and reliability of the service, allowing the electricity supply to be maintained in different sectors when there are failures in the grid.

A. *Global Overview*

The growth of renewable energies in recent years has been quite considerable; the ease of use, government policies, investments, the fall in costs throughout the manufacturing line,

Cristian Rosas, Juliet Avendaño, and Cesar Hernandez, "Overview of Photovoltaic Solar Plants and their Regulations in Colombia," *International Research Journal of Advanced Engineering and Science*, Volume 9, Issue 1, pp. 128-137, 2024.

International Research Journal of Advanced Engineering and Science
ISSN (Online): 2455-9024

and their generation capacity make them the best alternatives for electricity worldwide, especially concerning solar photovoltaic which has become the pillar of the growth of clean energies.

In the 2022 report of the IEA (International Energy Agency), an autonomous body within the Organisation for Economic Co-operation and Development (OECD) and in charge of meeting the objectives related to energy security, economic development, and environmental sustainability pointed out that, in the coming years, renewable energies will expand electricity.

According to Review Energy, which is the most influential news portal and provides information on the most relevant data about renewable energies, it reported that the manufacturing capacity of each of the solar photovoltaic energy production segments is expected to double to reach 1,000 GW by 2024, as it is expected to be led by China and the growing diversification of supply in the United States. India and Europe. By 2030, global solar PV manufacturing is projected to comfortably meet the level of annual demand projected in the IEA's 2050 net-zero emissions scenario.

That is why China, with an installed capacity of about 393.1 GW at the end of 2022, positioned itself as the world's leading country in solar photovoltaic energy. The United States and Japan ranked second and third, respectively. It should be noted that Spain also managed to sneak into the 15 largest markets for this type of renewable energy, having an installed capacity of nearly 21 GW in the year in question. [3]

One of the leading manufacturers of photovoltaic components is the company Yingli and Trina, located in China and Taiwan, responsible for 70% of global production; the other 15% is due to other Asian countries, the main one being Japan. Europe contributes a meager 3% and North America another 4%, even though one of the world's largest manufacturers, First Solar (USA), is located there, as shown in Fig. 2.

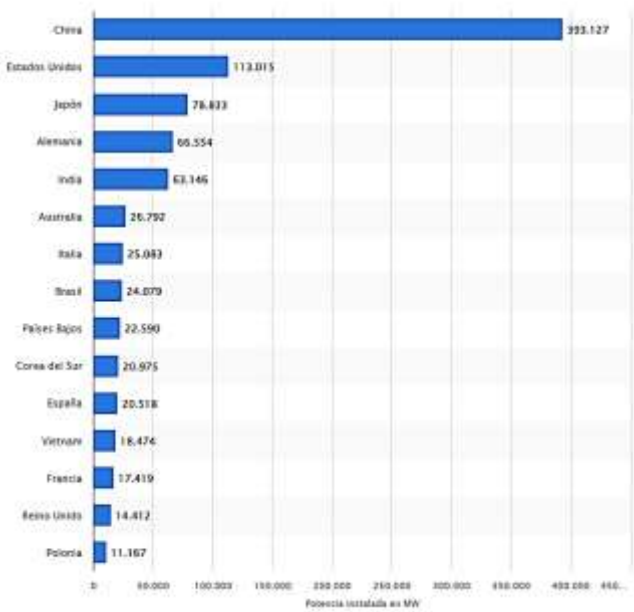

Fig. 2. Countries with the highest installed solar PV capacity in 2022. [4]

According to Review Energy, renewable capacity in Europe had an increase of approximately 40%; several countries in the wake of the problem between Russia and Ukraine felt the need to use solar energy to decrease dependence on Russian natural gas, in addition to high electricity prices, this growth has also been influenced by political support in the main European markets, such as Germany, Italy, and the Netherlands.

The June report published by the IEA estimates that the rise of alternative energies, especially photovoltaic and wind energy, has saved consumers about 100,000 million euros from 2021 to 2023. The growth in installed renewable electricity capacity will continue, and the world's total renewable electricity capacity will be approximately 4,500 gigawatts (G.W.), equivalent to the total output of China and the United States combined.

The IEA also reports that global renewable capacity additions will soar by 107 GW, the most significant absolute increase in history, to exceed 440 GW in 2023. This dynamic expansion is taking place in the world's major markets. Renewables are at the forefront of Europe's response to the energy crisis, accelerating its global growth. The new policy measures are also helping to drive significant increases in the U.S. and India over the next two years. Meanwhile, China is consolidating its leadership position and is projected to account for nearly 55% of global renewable energy capacity additions in 2023 and 2024. "The global energy crisis has shown that renewables are critical to achieving not only a cleaner but also a more secure and affordable energy supply, and governments are responding with efforts to deploy them more quickly. But to achieve higher growth, policies need to adapt to changing market conditions, and we need to improve and expand power. Grids to ensure we can take full advantage of the vast potential of solar and wind," Birol explained. [5]

Similarly, it is also presumed that the increase in manufacturing of all segments that are involved in the production of photovoltaic solar energy, the estimated figure is 1000 GW in 2024, led by China and followed by the United States, India, and Europe, if the outlook continues in this way in 2030 the world will have enough solar energy manufacturing capacity to meet the annual demand in the IEA's 2050 net-zero emissions scenario.

On the other hand, in the IEA's most recent report, published on September 19, 2023, the renewable sector calls for tripling clean energy capacity to 11,000 GW by 2030.

Several international organizations, producers, supply chain agents, buyers, and environmental groups, among others, who are aware of the activity of the renewable energy market worldwide and with a view to COP28 to be held later this year, requested through a letter to meet the goal of tripling renewable energy capacity to 11,000 GW by 2030 to decarbonize the economy to ensure that the earth is still habitable.

According to the International Renewable Energy Agency's 2023 WETO (World Energy Transitions Outlook) report, an immediate change of course is needed this decade to limit global warming to 1.5ºC. This requires tripling global renewable energy capacity by 2030 to at least 11,000 GW and doubling energy efficiency improvement rates. Some $4 trillion of annual investment in transition technologies would be needed to rapidly deploy wind, solar, hydropower, geothermal, and other forms of renewable energy, laying the groundwork for technologies such as green hydrogen and long-duration energy storage to scale up beyond 2030. [6]

B. Panorama in Colombia

Title Colombia has one of the cleanest production matrices because electricity generation comes mostly from renewable sources such as hydropower. The potential of non-conventional renewable energy sources such as solar and wind energy has been evaluated in recent years. However, their participation in the SIN (National Interconnected System) is still minimal compared to hydro and thermal, despite the gradual adoption of these two energies.

According to data from the Mining-Energy Planning Unit (UPME), between 2022 and 2027, it is estimated that 16 G.W. of installed capacity will enter clean energy. This represents almost double the current matrix. (which is just over 17 GW) and the vast majority corresponds to renewable energies. Of these, 62% of the total allocated corresponds to solar energy, 17% to hydro, and another 17% to wind. [7]

The Colombian government announced that, for the next few years, the goal is to reach 30% of the capacity for non-conventional renewable energy by 2030, which would support Colombia to reduce CO_2 emissions by 67 million tons by that year. For renewable energy in Colombia to achieve its goal, it will require a private and public investment of 6 trillion pesos.

For this, there are several solar and wind energy projects in Colombia under the figure Power Purchase Agreement (PPA), which refers to a financial agreement in which a developer or developer (EPC) is responsible for the design, permitting, financing and installation of a solar photovoltaic energy system on a client's property without initial investment from the client. The developer or one of the solar energy companies in Colombia sells the generated energy to the primary customer at a fixed price, lower than the retail rate of the local electricity trading company. This lower electricity price compensates against the grid customer's purchase of electricity. At the same time, the developer receives future revenue streams from these electricity sales, tax credits, and other tax and tariff incentives generated. [8]

The country's operational installed capacity in solar energy in 2022 was 290 MW, representing 1.5% of electricity capacity.

Incentives and policies: The Colombian government has implemented incentives and procedures, such as tax breaks and subsidies, to encourage investment in solar energy. These measures aim to promote the diversification of the energy matrix and reduce dependence on fossil fuels.

An example of this is President Gustavo Petro's project that has emphasized the concept of "energy communities" through a new solar program, which he has called *Solar Energy Burst*, which is currently under development. The four projects being executed consist of individual solar photovoltaic systems that will provide solutions for the expansion of the coverage of the energy service in Riohacha and Maicao, where the Colectora electric power transmission project is being developed.

Of the 70 billion pesos allocated by the national government for the execution of 'Works for Taxes', 14,000 million pesos were approved for this department, key in the country's energy transition due to the wind and solar farms being built there.

Through the construction of four projects for the provision and installation of individual photovoltaic solar solutions that will benefit about 17,862 people in vulnerable rural communities in La Guajira with energy and Transmission, Grupo Energía Bogotá (GEB) will execute the highest investment of resources in the energy sector through the 'Works for taxes' mechanism for a department in the country. About 14,000 million pesos will be invested in the implementation of these systems in educational institutions and a similar number in Community Care Units (UCA) located in non-interconnected areas of Maicao and Riohacha, in which Transmission influences the construction of the Colectora electric power transmission project. [9]

Solar energy projects: Solar projects have been developed in different regions of Colombia, taking advantage of the solar radiation available in a large part of the territory. Some of these projects are large-scale and contribute to the generation of clean energy.

The most relevant solar energy projects due to their installed capacity and for marking the beginning of solar energy in the country are:

- In 2018 Parque Solar Castilla was built by AES Colombia and Ecopetrol. This project has an installed capacity of 21 MW. This park will prevent the emission of 154,000 tons of CO_2 into the atmosphere, which is equivalent to planting 16,200 trees thanks to the 54,500 solar panels installed on 18 hectares.
- In 2019, the El Paso solar plant in the northern Colombian department of Cesar was the largest centralized dispatch solar plant (with daily commitments to deliver energy to the grid) built so far in the country, with 86.2 MW representing 80% of the total installed solar capacity. This plant has the potential to produce around 176 GWh per year, covering the annual energy needs of approximately 102,000 Colombian homes, equivalent to about 400,000 people, avoiding the annual emission of around 100,000 tons of CO_2 into the atmosphere.
- In December 2020, the Celsia Solar plant was inaugurated. It is located in Espinal in the Tolima department. This solar energy project has 37,876 solar panels installed on 17 hectares. Celsia Solar has an installed capacity of 9.9 MW that can supply 6,000.
- In March 2021, construction work began on La Loma. A photovoltaic solar park owned by Enel Green Power Colombia located in the Colombian department of Cesar, which has an installed capacity of 187 (MWdc), generating 420 GWh of renewable energy per year, thanks to the more than 400 thousand panels that will be installed on the 437-hectare site.
- The San Fernando Solar Park was inaugurated in 2021. It has an installed capacity of 61 MW to supply Ecopetrol and Cenit operations in the Eastern Plains and is located in Castilla La Nueva in Meta. It has 57 hectares where some 115,000 bionic solar panels that capture radiation on both have been installed.

International Research Journal of Advanced Engineering and Science
ISSN (Online): 2455-9024

- In July 2022, in the department of Atlántico, precisely in the municipalities of Ponedera and Sabana Larga, Enel Green Power began construction work on Guayepo I and II, which has been called the largest solar park in Colombia and South America and has a size similar to that of 2,000 football fields. Once construction is completed, the solar energy park is expected to generate an estimated energy production capacity of 1,030 GW, supplying the electricity needs of approximately 770,000 Colombians. [10]
- In 2022, the company China Three Gorges also arrived in the municipality of Baranoa, which will make the first of three new solar parks they plan to build.
- In a meeting with representatives of the Asian company, it was learned that the construction of the first solar park will soon begin, which seeks to generate 20 megawatts of renewable energy with an investment of about 20 million dollars and, during construction, 300 jobs will be generated; Between 15 and 20 people will be employed during the period of operation. This project will be connected to the national energy grid and contribute to the country's energy exchange. [11]

For this first quarter of 2023, according to XM's latest statement, 18 new projects have entered the SIN (National Interconnected System), seven of them are generation projects and eleven are to reinforce energy transmission networks, which can be seen in TABLE I.

TABLE I. Generation project. [12]

Guy	Check-in date	Name	SIN Power Delivery Capability
Solar	January 30	Lancers	9.1MW
Solar	January 30	San Felipe	9.1 MW
Generator distributed	March 24	GD 1 Solar El Salvador	12.7 MW
Generator distributed	March 24	GD 2 Solar El Salvador	3.7 MW
Solar	March 27	Yuma	9.1 MW
Solar	March 27	Dulima	19.9 MW
Solar	March 27	Flanders	19.9 MW
PC Hydroelectric	March 31	Caracolí	3.75* MW (antes 2.6 MW)

As for the transmission projects that entered the SIN in this first quarter, they were distributed as follows: 1 in the STN, 6 in the STR network and 4 connections between SDL and STR.

Of these projects, the following stand out*:*

STN (National Transmission System):

- On February 6, ISA INTERCOLOMBIA declared in operation the 500/220/34.5 kV transformer and its associated bays at the Bolívar power electrical substation, related to the UPME 07 – 2017 call "LT Sabanalarga - Bolívar 500 kV and second transformer Bolívar 450 MVA 500/220 kV".

STR (Regional Transmission System):

- On January 29, EPM declared in operation the D-FACTS SSSC series devices in the Envigado and Guayabal 110 kV substations, improving with this equipment the operational flexibility in EPM's networks; and on March 31, it declared the new 110 kV Nueva Colonia substation in Urabá Antioquia in operation, which strengthens the reliability of meeting demand in this region.
- For its part, Celsia Colombia declared in operation a line bay at the San Marcos substation to Codazzi 115 kV on February 5 and on February 22 declared the second Brisas – Mirolindo 115 kV circuit and its associated bays in operation.
- On March 30, Enerca declared the Santa Rosalía 115 kV Substation in operation, which completed the Casanare-Vichada interconnection project, which integrates a Non-Interconnected Zone of the country into the National Interconnected System.

STR-SDL (Regional Transmission System – Local Distribution System):

- Celsia Colombia installed additional elements in the departments of Tolima and Valle del Cauca to distribute the energy between the STR and the SDL, thus increasing the power injection capacity, as follows:
  - In Tolima: On February 2, a 60 MVA 115/34.5 kV transformer entered the Flandes substation and on February 17 a 20 MVA 115/34.5 kV transformer entered the Nueva Cajamarca substation.
  - In Valle del Cauca: On February 16, a fourth 25 MVA 115/34.5 kV transformer entered the El Pailón substation and on March 10, a 25 MVA 115/13.2 kV transformer began operating at the Alférez II substation. [12]

Challenges: Despite the growth, there are challenges facing solar energy in Colombia, such as the variability of solar radiation and the need to invest in energy storage technologies to ensure a steady supply.

Environmental impact: Solar energy is a clean and renewable energy source, reducing greenhouse gas emissions and dependence on fossil fuels, which is very important in the fight against climate change.

With the implementation of the new projects in what the government defined as the *Solar Energy Explosion* in the department of La Guajira, environmental costs will be reduced, such as the generation of CO2 by the burning of fossil fuels, as well as the expenses of families who compare diesel, candles, batteries and other elements for the generation of electricity. These types of projects also improve the population's conditions and quality of life by providing more daylight hours.

III. Legal Framework in Colombia

Colombia's energy policy is defined by the National Energy Plan (PEN) 2020-2050, which includes solar and wind energy in its different scenarios, both for grid-connected and non-grid-connected areas. Electricity planning is defined by the 15-year expansion, generation and transmission plans that are updated annually.

The public institutions that participate in the renewable energy sector in Colombia are the Ministry of Mines and Energy (MME), the Mining-Energy Planning Unit (UPME), the Energy and Gas Regulation Commission (CREG), and the Transmission System Operator (XM). The corresponding environmental licensing authorities are also crucial: the

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National Authority (ANLA) for projects larger than 100 MW and the Regional Autonomous Corporations (CARs) for projects smaller than 100 MW. The technical entity in charge of supporting the formulation and implementation of policies in the mining-energy sectors is the UPME, as indicated in several planning documents, such as the National Energy Plan, the Generation and Transmission Expansion Plan, and the Indicative Plan for the Expansion of Electricity Coverage. [13]

To understand the requirements related to operating limits and control variables in the national legal framework, we will describe the most important resolutions, agreements, and articles related to the subject.

A. Regulations established by the CREG (Energy and Gas Regulatory Commission)

According to the regulatory powers of Law 142 of 1994 to the CREG on electricity services, it aims to supply the electricity demand of the community under economic criteria and financial viability, ensuring its coverage within a framework of rational and efficient use of the country's energy resources, ensuring an efficient, safe and reliable operation in the activities of the sector and maintaining the established levels of quality and safety. [14]

To achieve the above objective, Article 23 of Law 143 of 1994 assigned to the Energy and Gas Regulatory Commission, among others, the functions of defining and drawing up the technical criteria for the quality, reliability, and safety of the energy service and establishing the operating regulations to carry out the planning and coordination of the operation of the National Interconnected System. I am considering the concept of the CNO (National Operation Council).

In resolution 060 of 2019 and by article 5, in which modifications and transitory additions are made to the operating regulations to allow the connection and operation of photovoltaic and wind-solar plants in the SIN, among other provisions, the services that photovoltaic plants must provide are determined, which are:

1. Active power and frequency control.
2. Voltage control and reactive power.
3. Power stabilization.
4. Frequency regulation by means of an active power/frequency control.
5. Fast reactive current response.
6. Adjustment of parameters that define these functionalities.

For a correct interpretation of this resolution, it is essential to take into account the following definitions, which are fundamental to understanding the control variables that will be discussed in the next chapter:

- *Frequency statism:* It is a technical characteristic of a plant and/or generation unit that determines the percentage variation of the frequency for each unit of percentage variation of the load.
- *Voltage statism:* It is a technical characteristic of a plant and/or generation unit that determines the percentage variation of voltage for each percentage variation of reactive power throughout the voltage regulation range.
- *Deadband:* This is the frequency range within which generation units do not automatically vary their power.
- *Voltage ride throuhg:* This is the area of operation whose upper limit is the High Voltage Ride Through curve (HVRT) and the lower limit is the Low Voltage Ride Through curve (LVRT).
- *Consignment:* It is an order issued directly or indirectly by the CND that tends to modify the mode or condition of operation of an installation.

Each article in this document refers to the most relevant aspects of integrating photovoltaic solar plants into the National Interconnected System – SIN. Resolution CREG 060 of 2019 also applies to wind farms, but in this document, emphasis will be placed on what corresponds to photovoltaic solar plants.

Main reference articles:

Article 11 of resolution CREG 060 of 2019 and according to the CND, mentions the adjustments of the frequency relays of the generation units of the SIN; for the specific case of this document, the ranges between which the photovoltaic solar plants connected to the STR (National Transmission System) and STR (Regional Transmission System) must operate, states that they must work usually for a frequency range between 57.5 HZ and 63 Hz.

Article 12, corresponding to the modification of article 4 of CREG 023 of 2001, defines that all centrally dispatched plants and/or generation units must provide the primary frequency regulation service, equivalent to 3% of their scheduled hourly age so that the plants must be enabled to increase or decrease their generation, Exceptions to the decrease when the plants operate at their technical minimum. For adequate frequency quality, generating units shall have a headband with a frequency change response of less than or equal to 120mHz.

Solar PV plants connected to the STN and STR must have active power/frequency control that includes a dead band and adjustable permanent statism.

The active power/frequency control of solar photovoltaic plants connected to the STN and STR must comply with the following requirements:

- *Be stable:* Control output signals must be dampened against step input signals for all operating modes and conditions.
- *Statism*: Must be configurable in a range between 2% and 6%,
- *Deadband*: Must be configurable in a range between 0 and 120mHz. Initially, you should have a Dead Band of response to frequency changes less than or equal to 30mHz.
- *Adjustment of the frequency control function for under-frequency and over-frequency events* must be reported to the CND by the agent representing the plant prior to testing for start-up. If this control function presents risks to the safety of the SIN, it should be readjusted.
- *The gain parameters and time constants* must be able to be modified to meet the stability and response speed criteria of the SIN, in the same way the CND will define these parameters through study, analysis and postoperative monitoring to comply with what is requested in the SIN.
- *Compliance with the following parameters*:
    - Initial response time (Tr) of 2 seconds.
    - Maximum set time (Te) of 15 seconds.

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The CND will define the value of statism and Dead Band within the ranges established according to the needs of the SIN. Paragraph 1: Solar photovoltaic plants connected to the STN and STR must be able to provide primary regulation service for over- and under-frequency events.
Paragraph 2: Temporarily, photovoltaic solar plants connected to the STN and STR are excluded from the obligation to provide the primary response service for sub-frequency events, only when the CREG decides to do so, it must provide that service.

Article 14, specifically in numeral 5.7, indicates voltage control for photovoltaic solar plants connected to the STN and the STR and specifies that they must comply with the following:

a) Have the ability to control the voltage continuously in the normal operating range of connection, through the delivery or absorption of reactive power according to its load curve and according to the instructions declared by the CND, in addition to this it must meet the following requirements:
   - The voltage regulator shall have the following control modes: *voltage, reactive power and power factor.*
   - The voltage regulator must have a configurable statism.
   - The reactive power/voltage control must be adjusted in such a way that it is stable to any change in the voltage setpoint, reactive power or power factor. The reactive power of the plant will have an initial response time of less than 2 seconds and establishment time of less than 10 seconds. The control must receive at least one local or remote reactive power, voltage, or power factor setpoint.

b) For voltages within the normal operating range at the connection point, it should operate within the limits of the following curve (see Fig. 3).

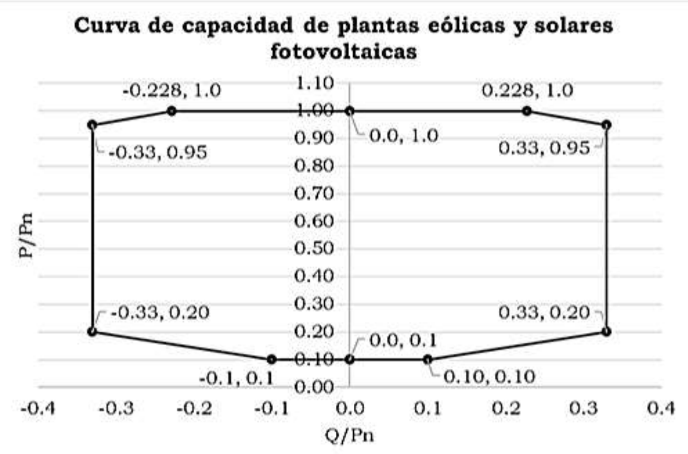

Fig. 3. Capacity curve of wind and solar photovoltaic plants. [15]

Where: Q/P_n
P: Active Power
Q: Reactive power
P_n: Nominal power

When a photovoltaic solar generation plant connected to the STN and STR operates with power values less than 10% of the nominal active power, the delivery or absorption of reactive power will not be required for voltage control; in that condition, the plant must not exceed 5% in reactive power input or absorption concerning the nominal active power capacity of the plant (5% Q/).P_n

c) Symmetrical or asymmetric faults must operate within the limits of the behavior curves of voltage depressions (LVRT) and overvoltages (HVRT).

The voltage depression and surge characteristic for solar PV plants connected to the STN and STR that does not include the 500kV grid described in Fig. 4.

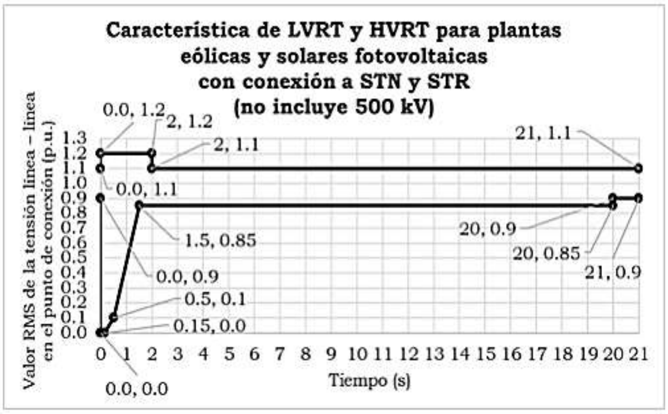

Fig. 4. Features of LVRT and HVRT for wind and solar PV plants with connection to STN and STR (Does not include 500kV). [16]

The Voltage Depressions and Surges Characteristic for non-synchronous sources connected to the grid at the 500 kV voltage level is shown in Fig. 5.

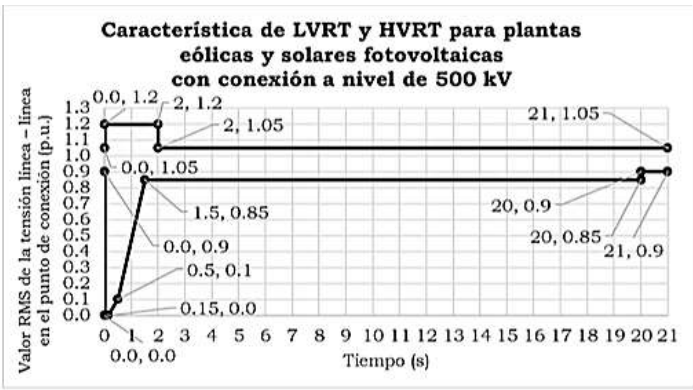

Fig. 5. Features of LVRT and HVRT for wind and solar PV plants with connection to STN and STR with 500kV connection. [16]

Photovoltaic solar plants must withstand successive depressions separated by 30s between pits; the voltage depression is considered overcome when the line-to-line voltage is more significant than 0.85p.u. When the voltage depression is exceeded, the generation source must recover 90% of the active power it supplied in a time not exceeding 1 second. As in all cases, the CND will monitor compliance with this requirement before the SIN.

Article 15, specifically in numeral 5.8, corresponds to the operational ramp for start and stop, where the photovoltaic solar plants connected to the STN and STR must have an adjustable

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ramp and a maximum ramp of 14% of the nominal power of the plant in MW/min is defined that can be evaluated by the CND. To this end:

- The start-stop requirement applies as long as the primary generation resource is available.
- The agent must report the maximum ramp of the plant.
- According to the system conditions, the parameter should be adjustable according to the system, considering the maximum ramp reported.

The CND will define and publish on its website the ramp value to be used, taking into account certain criteria such as the degree of penetration of these plants in the SDL, and will also be able to evaluate the values and operating conditions of the SIN.

Article 18. Before declaring themselves in commercial operation, the photovoltaic solar plants connected to the STN and STR must carry out and submit the results of the tests to the CND according to the terms and deadlines established by the CNO Agreement, these tests are:

- Capacity curve testing.
- Testing of the characteristics of the active power/frequency control.
- Operational on- and off-ramp testing.
- Testing of the characteristics of the reactive power/voltage control.
- Fast frequency response performance testing.
- Testing of operating characteristics against voltage depressions and overvoltages for wind and solar photovoltaic plants.
- Testing of prioritization requirements in rapid reactive current injection.

Article 20. In the case of the CND's supervision of photovoltaic solar plants, according to these regulations, it must be carried out through:

- RTUs (Remote Terminal Units).
- Using communication protocols between control centers.
- Using communication protocols over the public internet data network that are supported by the CND.

Article 23 establishes the requirements for measuring and reporting meteorological variables for photovoltaic solar plants connected to the STN and STR.

Photovoltaic solar plants connected to the STN and STR must have monitoring systems for meteorological variables at the plant site, with the capacity to store this data and report it to the CND.

The measurements and the reporting to the CND of meteorological variables must have a ten-minute or higher frequency frequency, i.e., five-minute, two-minute, or a few seconds, in accordance with the CNO's protocol of quality verification and reliability.

The minimum meteorological variables that must be monitored in photovoltaic solar plants are those described in TABLE II.

To conclude the summary of the most relevant articles of this regulation, Annex *CC.6* of resolution CREG 025 of 1995, numeral 3.3.1.1, establishes the measurements and information of the photovoltaic solar plants connected to the STN and STR, which must comply with the transmission of their data to the CND. The information they must provide every four seconds or less is as follows:

- Value of the active and reactive power of the generating plants.

TABLE II. Minimum meteorological variables for monitoring in photovoltaic plants.

Variable	**Unit**
Irradiation on the plane of the photovoltaic panel	Watts per square meter [W/m2]
After-temperature of the photovoltaic panel	Degrees Celsius [°C]
Horizontal global irradiation	Watts per square meter [W/m2]
Ambient Temperature	Degrees Celsius [°C]

- Line-to-line voltage and phase current.
- Status of the frequency control function.
- Voltage control setpoint value (if applicable in accordance with the CNO Agreement by voltage level).
- Power factor setpoint value (if applicable in accordance with the CNO Agreement by voltage level).
- Value of reactive power (if applicable in accordance with the CNO Agreement for voltage).
- Voltage control mode.
- Frequency control mode.

As mentioned above, it is mandatory to transmit data to the CND every five minutes or less of the maximum possible instantaneous capacity (MW). This must take into account the percentage of the plant available for generation, the number of turbines, arrays of photovoltaic solar panels or inverters that are in operation.

B. Agreements established by the CNO (National Operating Council)

The National Operation Council of the electricity sector is a body whose primary function is to agree on the technical aspects to ensure that the operation of the National Interconnected System (SIN) is safe, reliable, and economical, in addition to being the executor of the Operation Regulations. This article will specify the agreements applicable to solar photovoltaic and wind plants in the SDL with net adequate capacity or maximum power greater than or equal to 5MW. Still, in this document, emphasis will be placed on solar photovoltaic plants.

CNO 1525 Agreement

The CNO 1525 agreement dictates the requirements for the supervision of the electrical variables of solar photovoltaic plants in the SDL with net adequate capacity or maximum power greater than or equal to 5MW.

This agreement deals with the functions of the National Dispatch Center CND and the OR network operators to directly supervise, coordinate, and control the operation variables of the assets of the STRs and/or SDLs that, at their discretion, are required, in addition to having the following additional functions, to those established in Resolution CREG 080 of 1999:

- The ROs must supervise the operation of the photovoltaic solar plants covered by this resolution.

- The ROs and the CND must coordinate and will be able to control the voltage regulation of the photovoltaic solar plants that are the subject of this resolution.
- The CND shall coordinate the operation of the photovoltaic solar plants covered by this resolution. The supervision, coordination and control of this article will be carried out in accordance with numeral 11.3.1 of Chapter 11 of the General Annex of Resolution CREG 070 of 1998.

As mentioned above in Annex *CC.6* of Resolution CREG 025 of 1995, which defines remote operation monitoring for solar photovoltaic plants connected to the STN and STR, this agreement specifies that such plants must also send a connection status signal:

Attached to the grid and operating or not connected to the grid.

For the above signals, the following should be taken into accoun:

- When the plant is dispatched centrally and in the event that the CND does not have them, the above measurements must be sent to the Control Center of the network operator and this must send them to the CND discriminated by generator. If requested by the CND, the above states and electrical variables must also be sent for plants not dispatched centrally.
- Real-time telemetered data must be sent to the Network Operator's Control Center, with a frequency of less than or equal to 4 seconds and with the units and decimal places defined by the CNO. The agent must ensure the correct synchronization of the time stamp of the signals sent to the Network Operator's Control Center; The maximum permissible error may not exceed +/- 200 ms.

The CNO shall define by Agreement and taking into account Resolution CREG 038 of 2014 the following:

- The methodology for calculating the quality, reliability and availability for the measurements of analog and digital variables according to international standards. The Agreement must consider that the analogous variables are: Active Power, Reactive Power, Current and Voltage, the analog and digital variables will be monitored by the CND.
- Decimal units and decimal places for real-time telemetered data.

Supervision of solar plants will be done by the provisions of CREG Resolution 148 of 2021. It will be carried out through the exchange of information between the CND and the Control Centers of the network operators through links between the Control Centers.

CNO 1529 Agreement

This agreement establishes the requirements for obtaining and validating the parameters of the generation units and plants and the control system models associated with the photovoltaic solar units and generation plants connected to the SDL with net adequate capacity or maximum declared power equal to or greater than 5 MW and defines the guidelines for the testing and readjustment of the associated controls.

Important definitions covered in this agreement:

- *Net Effective Capacity*: This is the maximum net power capacity (expressed in MW) that can be supplied by a plant and/or generation unit under normal operating conditions, measured at the trade border. It is calculated as the Nominal Capacity minus the Own Consumption of the plant and/or generation unit.
- *Generation* Control: May refer to Active Frequency/Power Control, Reactive Voltage/Power Control, and the limiters associated with these controls.
- *Stability*: This is the response characteristic of the system in which it is verified that the output signals of the validated models are dampened over time against stable input signals, for the modes and operating conditions analyzed.
- *Equivalent Unit Model:* A model that represents the dynamics of a set of generating units in a power plant.
- *Stable Model:* This is the model in which it is verified that the output signals are dampened in time against input signals dampened in time, for all the modes and operating conditions analyzed.
- *Validated* model: It is the mathematical model in which the ability to reproduce within the margins defined in this Agreement, the behavior of the active power/frequency control and voltage/reactive power control of a generation plant and its equivalent units, has been verified by contrasting the field tests defined in this Agreement and real events. and the simulation of equivalent conditions. Validated models must be decrypted and parameterized. Industry players can use validated models for their electrical analyses.

Required Parameters of the Generation Plant

The generating agents representing the plants must determine the parameters of the generation plant model that best define the dynamics of the model, considering elements such as transmission lines, compensators, transformers, inverters, generators, or any other physical or electrical parameter that affect the static or dynamic behavior of the generation plant. At least the following information must be provided (as long as it applies to the plant):

1. Connection Type (3PH, 3PH-E, etc.)
2. Primary source of generation (photovoltaic)
3. Number of generating units in the plant.
4. Number of solar panels (photovoltaic solar plants).
5. Maximum forward current supported by each inverter (if applicable).
6. Nominal power of the power plant.
7. Nominal capacity of each generating unit in the plant.
8. Characteristics of reagent compensation systems (capacity, nominal voltage, reactance).
9. Characteristics of the connecting transformers and that of each equivalent unit (type of connection, capacity, reactance, number of tap positions, voltage delta associated with each tap, etc.).
10. Parameters of the lines that connect the plant to the connection point (ballast, length, nominal capacity, etc.). These lines include those associated with each equivalent unit and the entire generation plant.
11. Auxiliary systems.
12. Equivalent impedances between the medium-voltage side of the generation transformers and the medium-voltage side of the connecting transformer.
13. Grounding zigzag transformer, depending on your location.

Cristian Rosas, Juliet Avendaño, and Cesar Hernandez, "Overview of Photovoltaic Solar Plants and their Regulations in Colombia," *International Research Journal of Advanced Engineering and Science*, Volume 9, Issue 1, pp. 128-137, 2024.

14. Number of equivalent units.

To define the validity of the model of the generation plant and its parameters, the reproduction of the different tests carried out by the agent must use the dynamic simulation tool used by the CND and the template defined in Annex 5 of this Agreement, the results obtained from the simulations will be compared with the results of the field tests and event records. The evaluation indices set out in Annex 3 to this Agreement shall be applied to verify the validity of the models.

Delivery of the results of the validation tests of the models of the generation controls and parameters of the generation plant.

For the validation of the models and the corresponding parameters, the generating agents must send the following information to the CND and the corresponding RO, by means of official communication:

1. Report of results to the CND and the RO describing: the methodology used, the tests carried out and the results obtained in the validation process of the control models and the parameters of the generation plant.
2. Models of the generation plant and its associated controls implemented in the simulation tool used by the CND.
3. The template defined in Annex 5 to this Agreement duly completed in accordance with the help tab.
4. Data required to reproduce test logs and simulations in text format (.txt) taking into account the format set out in Annex 5. Test records must have the corresponding test name as indicated in the template.

Model Tracking

The CND and the RO will monitor the quality of the models. To this end, the quality of the active power/frequency control and reactive power/voltage control models will be evaluated in the following variables:

- Active power/frequency control: Active power at the connection point, active power measured in the equivalent units (as long as these are monitored in real time).
- Reactive power/voltage control: Connection point voltage, reactive power at connection point and reactive power of the equivalent units (as long as they are monitored in real time).

Records of voltage disturbances and frequency events defined as:

- Voltage disturbance: variations greater than 5% of the voltage at the connection point.
- Frequency Event: Frequency variations outside the range of 59.8 Hz to 60.2 Hz. When the plant is providing AGC service or has a period change command that modifies the reference power of the plant, the comparison will be made until the moment in which the setpoint change is applied.

To compare the curves, it shall be verified that the simulated signal starts at a value whose difference with the measurement does not exceed 10% of the actual measurement error.

IV. CONCLUSIONS

Concerning the Colombian regulatory framework, there are still some gaps related to the type of behavior that is desired in the modes of operation of frequency and voltage control since, although the operating ranges are limited in both cases, there is no clarity on how the behavior of statism should be within the regime.

Photovoltaic solar parks must take into account the different variables that can generate losses of energy supplied to the point of coupling or connection since these losses could represent that the actual generation capacity is lower than the installed capacity, which becomes essential when the power is supplied must be declared to the control and monitoring bodies.

Solar parks must have measuring equipment capable of recording and monitoring the different electrical variables with high precision and a fast sampling time, as this will determine the performance of the control and supervision system.

As is generally known, the drawback of photovoltaic systems is that they cannot guarantee a fixed value of irradiance due to climatic conditions; this would be achieved with the use of a backup system such as a Battery Energy Storage System (BESS) to guarantee the generation capacity of the system in an extended time slot.

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