Technical Note

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Beyond the potential: technical challenges of renewable energy integration

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List of Abbreviations and Acronyms

Acronym	**Meaning**
LAC	Latin America and the Caribbean
CO_2	Carbon dioxide
AC	Alternating current
DC	Direct current
HVDC	*High-Voltage Direct Current*
STATCOM	*Static Synchronous Compensators*
AVR	Automatic Voltage Regulator
EMT	*Electromagnetic Transients*
NCRE	Non-Conventional Renewable Energy Sources
FENOGE	Non-Conventional Energy and Efficient Energy Management Fund
PINES	Projects of National and Strategic Interest
CREG	Energy and Gas Regulatory Commission
UPME	Mining and Energy Planning Unit
ERNC	Non-Conventional Renewable Energy

Beyond the potential: technical challenges of renewable energy integration

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Abstract

Wind and solar photovoltaic energy have grown rapidly in Latin America and the Caribbean (LAC), emerging as the great promise for confronting the climate crisis, reducing dependence on fossil fuels, and reaching isolated areas where conventional generation cannot reach. Our region is committed to reducing CO2 emissions, despite having a relatively clean electricity mix. However, as non-conventional renewable energy sources increase their share in power grids, new challenges also emerge for the planning, operation, and control of power systems, topics that are rarely discussed outside specialized circles. How can grid stability be maintained in scenarios of high generation variability? What strategies make it possible to take advantage of surplus solar generation during periods of low demand? To what extent can existing grids absorb renewable energy without profound transformations to their infrastructure? This article seeks to answer these questions from a clear and accessible perspective. Our objective is to analyze the main technical aspects associated with the growing integration of renewable energy into power systems and how engineering, innovation, and planning seek to address them. Understanding these technical challenges not only makes it possible to better appreciate the progress achieved, but also to understand the transformations necessary to build a sustainable energy future.

KEYWORDS: *inverter-dominated systems, power electronics, wind, solar photovoltaic, FACTs, transmission constraints, frequency control, voltage control, regulatory framework.*

Resumen

Las energías eólica y solar fotovoltaica han crecido aceleradamente en América Latina y el Caribe (ALC), presentándose como la gran promesa para enfrentar la crisis climática, reducir la dependencia de los combustibles fósiles y llegar a zonas aisladas donde la generación convencional no logra llegar. Nuestra región apuesta por reducir las emisiones de CO2, a pesar de contar con una matriz eléctrica relativamente limpia. Sin embargo, a medida que las fuentes de energía renovable no convencionales aumentan su participación en las redes eléctricas, también emergen nuevos desafíos para la planificación, la operación y el control de los sistemas eléctricos, temas que pocas veces se discuten fuera del ámbito especializado. ¿Cómo mantener la estabilidad de la red en escenarios de alta variabilidad de la generación? ¿Qué estrategias permiten aprovechar los excedentes de generación solar durante períodos de baja demanda? ¿Hasta qué punto pueden las redes actuales absorber energía renovable sin transformaciones profundas en su infraestructura? Este artículo busca responder estas preguntas desde una perspectiva clara y accesible. Nuestro objetivo es analizar los principales aspectos técnicos asociados a la creciente integración de las energías renovables en los sistemas eléctricos y cómo la ingeniería, la innovación y la planificación buscan abordarlos. Comprender estos desafíos técnicos no solo permite

valorar mejor los avances alcanzados, sino también entender las transformaciones necesarias para construir un futuro energético sostenible.

PALABRAS CLAVE: *sistemas dominados por inversores, electrónica de potencia, eólica, solar fotovoltaica, FACTs, restricciones de transmisión, control de frecuencia, control de voltaje, marco regulatorio.*

From the conventional system to the modern system

The so-called "war of the currents," which unfolded at the end of the nineteenth century between Thomas Alva Edison and George Westinghouse, marked one of the most important milestones in the evolution of modern power systems. The former defended his direct-current (DC) transmission systems, while the latter, backed by Nikola Tesla's patents, promoted alternating-current (AC) transmission. Time demonstrated the technical superiority of the latter, establishing AC systems as the global standard for electricity transmission. The triumph of alternating current was not accidental, but rather the direct consequence of two fundamental devices: the synchronous machine and the transformer.

The synchronous machine is one of the most efficient ways of generating electrical energy from mechanical rotation. Both hydroelectric and thermoelectric power plants use large-scale synchronous machines. Synchronous operation means that all machines operate at the same frequency: 50 Hz in countries such as Chile, Paraguay, and Argentina, or 60 Hz in Colombia, Ecuador, and Mexico.

On the other hand, efficient transmission of electrical energy requires minimizing losses in the lines. Since electrical losses are proportional to the square of the current, it is desirable to operate at low currents. This is achieved by increasing the voltage level. The transformer—the second fundamental element—is the only practical device that makes it possible to efficiently increase or decrease voltage levels, thereby enabling the transmission of electrical energy over long distances.

Thanks to the combination of generation produced by the synchronous machine and voltage transformation, alternating-current systems became established as one of the greatest engineering achievements of the twentieth century. Nevertheless, modern power grids increasingly incorporate components inherently associated with direct current, such as photovoltaic panels, battery storage systems, and high-voltage direct-current transmission links (HVDC, *high-voltage direct current*). Likewise, power-electronics devices used for reactive-power control and voltage support, such as STATCOMs (*Static Synchronous Compensators*), use internal direct-current links for their operation. Wind turbines also require intermediate DC conversion stages to adapt their rotational speed to wind speed and thereby achieve maximum power transfer. Thus, we could say that the modern system is a tie between Edison and Westinghouse, since it uses both AC and DC components [1].

As a consequence of this technological evolution, a new fundamental component emerges: **the power inverter**, which is responsible for interconnecting DC sources and devices with the AC grid. Due to the massive penetration of these devices, contemporary power systems can be characterized as inverter-dominated systems. Moving from a system dominated by synchronous machines to one dominated by inverters represents a paradigm shift in operation and control. The coordinated operation of a system of this magnitude represents a considerable technological challenge that requires new planning, operation, and control strategies. Unlike other engineering systems, the electrical system must maintain an almost instantaneous balance between generation and demand under changing conditions and in the face of unavoidable disturbances, such as equipment failures, abrupt load variations, or line disconnections. Figure 1 shows an Ishikawa diagram associated with the massive integration of wind and solar photovoltaic generation sources. The following sections explain each of the branches of the diagram.

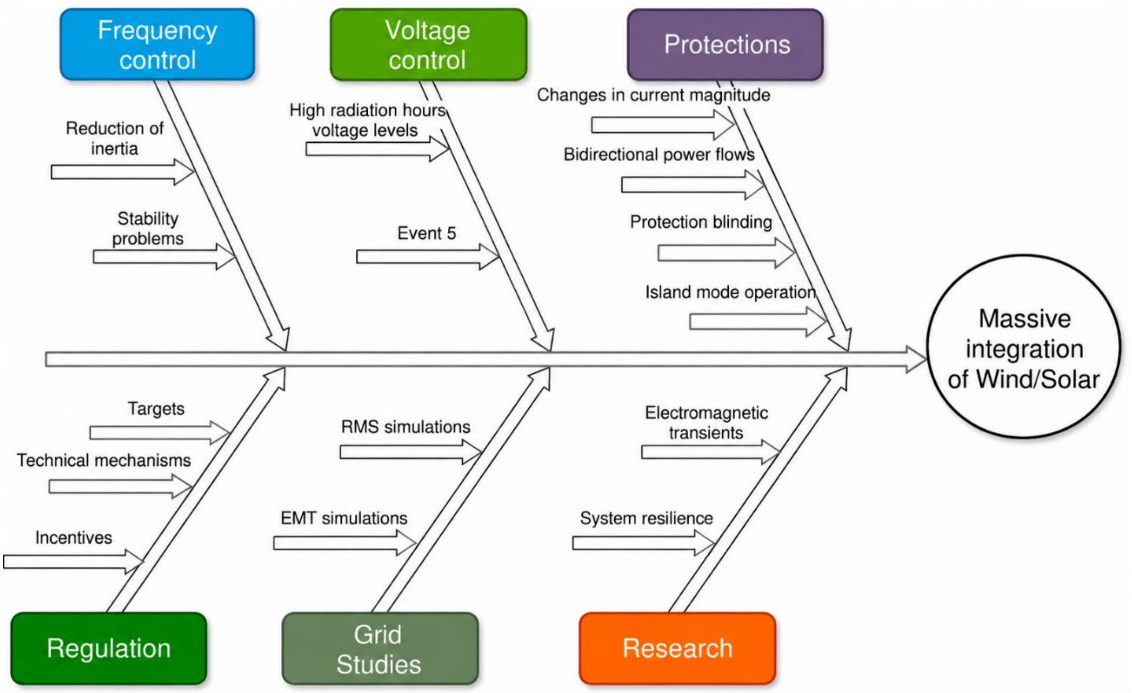

Figure 1. Ishikawa diagram associated with the massive integration of wind and solar photovoltaic generation.

Frequency control in inverter-dominated systems

In conventional power systems, frequency control falls mainly on synchronous machines. In this context, **inertia** plays a fundamental role in maintaining stability. Let us break it down: stability in power systems is the ability to maintain synchronism (basically, to operate at appropriate frequency levels) and to return to an acceptable operating condition after a disturbance. Thus, a system is stable when its variables remain bounded within acceptable operating limits. A constant frequency of 50 or 60 Hz—depending on the country—is an indicator of stable system operation. On the other hand, inertia corresponds to the kinetic energy stored in the rotating masses of synchronous generators. This energy constitutes the system's first line of defense against disturbances by limiting the rate of change of frequency. In the event of a disturbance, such as a short circuit or a sudden loss of generation, grid frequency tends to deviate. However, in high-inertia systems, these variations occur more gradually, providing time to take corrective actions.

By contrast, the power inverter is an electronic device that has no inertia of its own. Consequently, modern power systems characterized by high inverter penetration may present low levels of inertia, making it necessary to incorporate new control strategies and support services to maintain adequate dynamic system performance. Nevertheless, despite their lack of inertia, inverters have two key characteristics that can be leveraged: on the one hand, they are highly flexible devices, which allows them to operate under different control schemes. On the other hand, because they are electronic devices, they have a much faster dynamic response than electromechanical devices such as synchronous machines. This makes it possible, first, to emulate the dynamic behavior of synchronous machines through a control scheme called a **virtual synchronous machine [2]**. Under this control scheme, the converter behaves like a synchronous machine, emulating inertia virtually. Likewise, the inverter can virtually emulate impedance behavior in order to adapt to system conditions and achieve stable operation. The inverter's fast response can include damping effects that would not be possible in a conventional synchronous machine.

Not all inverters can operate as a virtual synchronous machine. For this, specialized control and certain additional physical conditions are required. Although the machine can emulate dynamic behavior virtually, energy is a real physical property that must come from an energy storage element, such as a battery. Another alternative is to operate the system below its rated capacity to allow partial control of the power injected into the grid. This means that inertia emulation may affect the cost of the project and, therefore, must be considered even at the design and planning stage.

In addition to virtual synchronous machines, it is necessary to develop wide-area controls that make use of synchrophasor measurements, which are increasingly common in power systems. In this way, low-inertia problems can be counteracted through the inherently fast response of power inverters and the ability to send and receive remote information to identify the best action to execute. This is a concrete example of the application of the smart-grid concept. At this point, it is important to highlight the relevance of technological sovereignty in this control layer, which constitutes the brain of the operation of inverter-dominated systems.

Voltage control in inverter-dominated systems

In conventional power systems, local voltage (V) control has been associated with control of the reactive power (Q) supplied by synchronous machines. This control is achieved through the generator excitation system, governed by the automatic voltage regulator (AVR), which is responsible for adjusting the rotor field current on time scales on the order of hundreds of milliseconds. Adjusting the excitation not only makes it possible to regulate the voltage at the generator terminals, but also determines the exchange of reactive power with the grid. The influence of active power on voltage is secondary under the assumption of electrically strong grids, characterized by X>>R ratios, which justifies a direct V-Q relationship.

Voltage control at the system level is also supported by other elements such as compensation systems (reactors, SVC / STATCOM, capacitor banks) and transformers with on-load tap changers (OLTC). In conventional systems, the SCR short-circuit capacity is considered high, which means that voltage varies little in response to changes in load or generation, and that small disturbances in P or Q produce minimal changes in V.
In contrast to systems with high penetration of converter-based resources, system voltage is highly sensitive to variations in both active and reactive power. This sensitivity is accentuated by the reduction in SCR levels, a typical characteristic of these systems.

In addition, the temporal variability of the primary resource associated with wind and solar photovoltaic generation, together with the growing incorporation of converter-based resources, requires more advanced control and coordination strategies to maintain appropriate voltage profiles in the system.

Among the specific problems that may arise in such systems are overvoltages during periods of high irradiance and low energy demand, for example around midday; undervoltages under low-generation conditions (afternoon hours); and rapid voltage oscillations. Some grid operators are already experiencing these problems in Latin America, and these challenges will become increasingly important as the incorporation of new technologies such as solar photovoltaic generation and electric vehicles continues.

These challenges can be addressed through control and power electronics. Power inverters can modify their reactive power to adjust voltage levels [3]. Even during nighttime hours, inverters can operate under a scheme called Q-at-night, controlling voltage in a manner similar to a STATCOM. Nevertheless, adequate coordination between grid operators and generators is required, as well as a grid code that promotes flexibility, coordinated control, and stability. The existence of the technology alone is not enough; a policy that promotes its implementation is required.

Protection systems in inverter-dominated systems

One of the most important, and least visible, principles of the electrical system is that it protects itself. When a fault occurs, such as a short circuit on a line or damaged equipment, a series of protection devices act automatically to isolate the affected part within milliseconds. As a result, the rest of the system continues to operate normally and the problem is prevented from spreading.

In conventional distribution systems, this process is relatively straightforward because protection systems are based on a very clear physical principle: electrical faults produce very high currents. Relays detect this increase in current and order the corresponding circuit breaker to open. This scheme has worked for decades because grids were supplied mainly by synchronous machines capable of providing very high short-circuit currents.

As power grids incorporate a greater share of distributed energy resources connected through inverters, traditional protection principles must evolve to respond to new operating conditions. [4].

As mentioned above, an electronic inverter is not designed to deliver large short-circuit currents. In fact, its internal protection systems typically limit current to values only slightly above the equipment rated current (for example, between 1.1 and 1.2 times its rated value). This means that, in the event of a fault, the current flowing may be too small for traditional protection systems to recognize it. In other words: the current may be insufficient for conventional protection schemes to detect it properly

This phenomenon reduces protection sensitivity. A relay that previously detected a fault easily may now take longer to react or, in the worst case, may not react at all.

The problem is not limited to the magnitude of the current. In grids with distributed generation, energy no longer flows in only one direction (from the substation toward users), but in multiple directions. This means that, during a fault, current may flow in directions opposite to those anticipated in the original protection design.

This affects the selectivity of the protection system, that is, its ability to isolate only the faulted zone. As a result, unnecessary circuit-breaker openings may occur in healthy areas of the grid, leaving users who were not involved in the fault without service.

In some cases, an even more counterintuitive effect occurs, a phenomenon known in the technical literature as 'protection blinding.' When a distributed generator contributes to the fault from a nearby point, part of the short-circuit current no longer passes through the relay that should detect it. From the relay's perspective, the current may even decrease compared with the condition without distributed generation. In other words, the growing incorporation of distributed generation changes the operating conditions for which many conventional protection schemes were conceived, making it necessary to adapt their detection and coordination criteria to maintain adequate performance during faults.

Many distribution grids in Latin America use fuses and automatic reclosing schemes, which are designed under the assumption of high fault currents. In the presence of inverters, these devices may require adjustments to their coordination criteria. A fuse may not melt because the current is low; an automatic recloser may re-energize an area that still presents an abnormal condition. This creates conflicts between the classical protection philosophy and the new operating conditions of active distribution grids and microgrids.

The situation becomes additionally complex when a microgrid disconnects from the main grid and operates in island mode. In this scenario, the large short-circuit current contribution from the main power system disappears. Faults are now supplied only by current-limited inverters.

Under these conditions, many of the protection settings that operate correctly when the microgrid is connected to the main grid are no longer suitable in island mode.

The response to these challenges does not lie in a single device, but rather in a change of approach in the protection philosophy. The following are among the changes that must be made:

- ✓ Use of directional protection instead of simple overcurrent relays.
- ✓ Incorporation of additional variables such as voltage drops, frequency variations, and their rate of change to detect faults.
- ✓ Implementation of adaptive protection systems, whose settings change dynamically according to the quantity and type of resources connected to the grid.
- ✓ Coordination among the protection systems of the feeder, the microgrid, and the distributed energy resources themselves.
- ✓
- ✓ In some cases, even the incorporation of devices capable of supplying artificial short-circuit currents (such as flywheels and supercapacitors) entails additional investments that must be considered during system planning.

The evolution of protection systems has historically accompanied the development of power systems. The growing incorporation of inverter-based resources represents a new stage in that technological evolution and requires adapting traditional protection criteria to the new operating characteristics of the grids.

Importance of EMT studies and quasi-dynamic models

Power flow and phasor or RMS models are two of the most widely used tools for analyzing the integration of new components into electric power systems. Nevertheless, these tools are insufficient in the face of the widespread adoption of power-electronics-based devices. The fast dynamics of these devices, as well as the variability of primary resources, make it essential to use quasi-static power flows with time series—also called quasi-dynamic—in place of conventional power flow, and electromagnetic transient simulations, or EMT for its acronym in English *(Electromagnetic Transients),* as a complement to RMS simulations.

While conventional power flow makes it possible to analyze system voltages, currents, and losses at a single operating point, quasi-dynamic power flow evaluates the same variables over a time range of at least one day, with different levels of discretization. This is particularly important in distribution systems with high penetration of solar photovoltaic generation, where, as mentioned above, different proportions of generation and demand occur throughout the day, which can induce overvoltage at some times and undervoltage at others. Maintaining a constant power factor throughout the day for each distributed resource is not a viable option under these highly variable conditions. Figure 2 shows the result of a quasi-dynamic power flow taken from [5]. Recent research demonstrates that very low computation times can be achieved despite the complexity of the problem and the number of scenarios. In this case, the algorithm was implemented in the Julia programming language on a desktop computer with an Intel(R) Core(TM) i7-8700 CPU at 3.20 GHz.

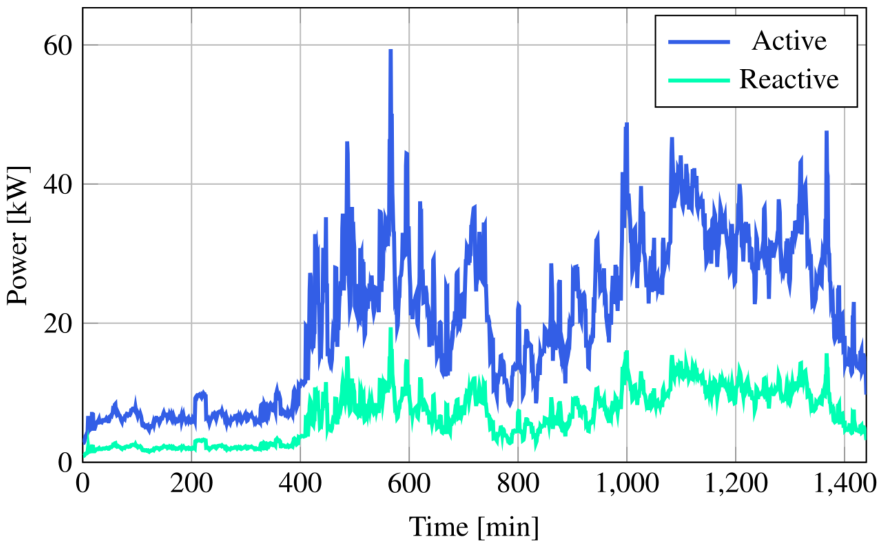

Figure 2: Example of a quasi-static power flow with time series considering 1440 generation and demand scenarios for a three-phase, unbalanced 900-node distribution system. The total computation time was only 17 seconds on a desktop computer. Taken from [5]

On the other hand, the fast dynamics of the controls associated with power inverters, as well as their possible interaction with other controls, make it necessary to use simulations that include a greater level of detail. This is where EMT-type simulations come into play. Programs such as PSCAD complement conventional studies by showing these dynamics. Unlike RMS models, EMT studies model the system by considering the fast dynamics of each of the system inductances and capacitances, as well as the switching of the IGBTs in the inverters and the associated controls. This entails longer computation time and significant effort in building the model. Some manufacturers provide models of their devices, but in other cases it is necessary to build them from scratch. Figure 3 shows a comparison between an RMS simulation and an EMT simulation of the same system.

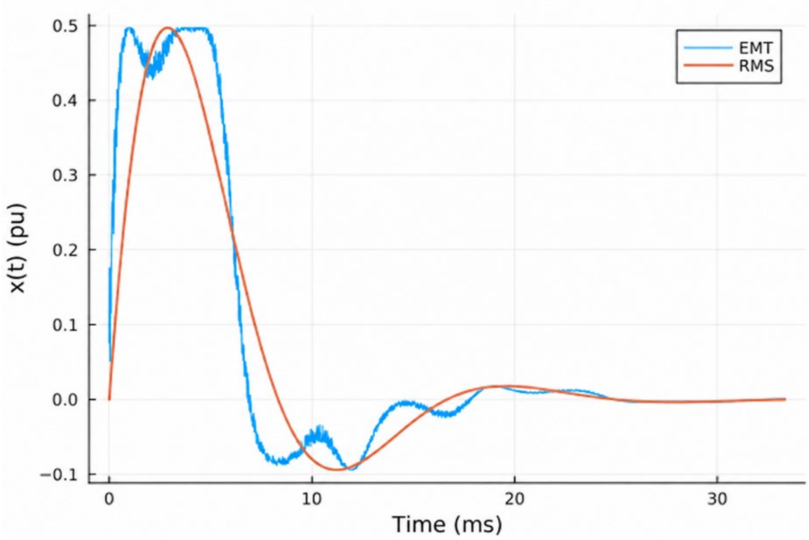

Figure 3: Comparison between an RMS simulation and an EMT simulation. Both models show the system dynamics. However, the EMT simulation provides a greater level of detail.

Nevertheless, it is important to emphasize that these models are a complement, not a replacement for existing methods and models. The two can be viewed as bifocal lenses: while RMS simulations make it possible to see far away, that is, the system as a whole, EMT simulations make it possible to see up close, that is, with a higher level of detail, but only in the area where the new device will be located.

Regulatory enablers for the integration of renewable energy into transmission systems

In Latin America and the Caribbean, the abundance of solar, wind, hydroelectric, and other resources that are part of Non-Conventional Renewable Energy Sources (FNCER) has generated growing interest in integrating the electrical energy produced by these sources into traditional power grids dominated by fossil fuels. Regulation plays a key role by creating clear legal frameworks, attracting investment, defining renewable-source participation targets, and facilitating the technical and economic integration of these sources into power systems. Each country in the region has been adjusting its laws to advance toward an energy-transition model that complies with the environmental commitments established in different agreements. To this end, it has been necessary to establish regulatory enablers, ranging from the way connection points are awarded to project developers to adjustments in auction processes and updates to technical regulations [6].

The Colombian case is particularly interesting for the region, as in recent years it has experienced significant growth in the incorporation of solar energy into the electricity mix. Beginning with Law 1715 of 2014, which introduced tax incentives for projects investing in clean energy and created the Fund for Non-Conventional Energy and Efficient Energy Management (FENOGE), followed by Law 2099 of 2021, which introduced the category of Projects of National and Strategic Interest (PINES) to streamline permits and incentives, and CONPES 4075 of 2022, which establishes strategic measures aimed at increasing the country’s energy security; in addition, Law 2294 of 2023 incorporates the energy transition into the National Development Plan and confirms the concept of energy communities, the latter developed in greater detail by the Energy and Gas Regulatory Commission (CREG) in Resolution 101 072 of 2025. This new regulation has also been coordinated with the expansion of the transmission grid, which is essential for the entry into operation of new generation projects. The Mining and Energy Planning Unit (UPME) has promoted the slogan “Without transmission there is no transition,” and this is evident in megaprojects such as “Colectora,” which will interconnect La Guajira’s renewable electricity generation potential with the rest of the country, and in the progress on the terms of reference for the call for Colombia’s first HVDC line [7].

Taken together, these measures reflect a regulatory evolution aimed at supporting the expansion of renewable energy by strengthening transmission infrastructure and incorporating new tools for system planning.

The Chilean case is also of great interest to the region; the country has charted its path toward decarbonization through a strong regulatory and strategic framework. This path began with the 2008 Renewable Energy Law (Law 20.257), which established a mandatory minimum quota of 10% generation from Non-Conventional Renewable Energy (ERNC) sources by 2020, a target that was increased in 2013 to 20% by 2025. Subsequently, the 2050 Energy Policy, published in 2015 and updated in 2022, established long-term targets for a sustainable energy mix. Added to this is the 2022 Framework Law on Climate Change, which establishes carbon neutrality by 2050 as a legal obligation. All of these policies have made it possible for hydroelectric and solar energy to account for 28% and 24%, respectively, of the country’s electricity mix by 2025 [8]. Wind energy also contributes significantly, at around 13%. As for fossil fuels, they generate almost 30% of electricity, with coal and gas contributing similarly, at around 14% each, and oil representing a minimal fraction, only slightly more than 1%. Chile has also made important advances in electricity transmission infrastructure, and it is important to highlight its first HVDC line, the Kimal-Lo Aguirre project, which is expected to enter operation in 2029 and spans 1350 kilometers between Antofagasta and Santiago.

As noted above, the growing share of resources with variable availability creates new requirements for power-system operation, which has driven the development and incorporation of technologies that strengthen its stability and flexibility. One of the technologies that helps address these new operating requirements is synchronous compensators, which make it possible to integrate renewable sources reliably into the power grid. These devices regulate voltage and stabilize the power grid, helping to strengthen a reliable electricity supply. They contribute to improving system stability and strengthening the reliability of the electricity supply." [9]. In Chile, Brazil, and Colombia, procurement processes for this type of device are already moving forward through public calls.

Finally, it is worth mentioning some of the progress Brazil has made in the region's renewable-energy regulatory framework. In 2025, Offshore Energy Law No. 15097 was enacted, regulating the supply and concession of areas for the exploration of offshore electricity-generation projects, so the development of offshore wind farms appears to be getting ever closer. In 2024, Laws 14.948 and 14.990 were enacted, establishing the legal framework for low-carbon hydrogen.

Advances in renewable-energy research in LAC are evident, and they must be coordinated with updates to the regulatory and legal framework to ensure that the Energy Transition becomes a reality and that the path toward carbon neutrality becomes increasingly clear.

Regional overview

The introduction of inverter-based resources is growing in LAC and has accelerated in recent years. We highlight the cases of Colombia, Peru, Chile, Brazil, and Uruguay as highly representative of the region: in Colombia, the Bacata STATCOMs and the introduction of more than a dozen series-compensation *SmartValve* devices stand out. With regard to solar photovoltaic generation, more than 2 GW of solar generation are installed, along with a potential of more than 30 GW of wind generation. Many plants are smaller than 10 MW, in part because of the challenges associated with environmental licensing and prior consultations for larger-scale projects. This means that most inverters are grid-following. However, the system is moving toward greater penetration of resources integrated with grid-forming capability. Recently, a connection-testing scheme for grid-forming converters has been proposed [10]. On the other hand, Peru aims to double its solar photovoltaic capacity, which would reach 2.4 GW, while wind would remain at 1.02 GW [11]. This demonstrates the growing penetration of these technologies.

Unlike Colombia, large-scale projects stand out in Peru, especially in the case of wind power. Chile is one of the regional benchmarks in the integration of inverter-based resources and battery storage systems. This is due to the enormous potential for solar photovoltaic generation, especially in the north of the country. One of the region's first battery storage systems was developed precisely in Chile more than 15 years ago [12]. Brazil has also experienced rapid growth in inverter-based resources, mainly due to the expansion of wind and solar generation in its power system. Brazil already has experience with HVDC transmission systems and an adequate technological infrastructure for the introduction of new generation sources. Finally, Uruguay stands out for its high penetration of renewable energy, especially wind, which has led to a growing presence of inverter-based resources in its power system. This transformation has enabled a cleaner and more diversified energy mix, although it has also required the incorporation of new operation and control strategies characteristic of systems with a high share of renewable resources.

Taken together, these experiences reflect the diversity of approaches adopted by the countries of Latin America and the Caribbean to integrate inverter-based resources, as well as the growing incorporation of new technologies, operating tools, and regulatory frameworks accompanying this transformation.

Final comments

International experience demonstrates that the growing share of inverter-based resources constitutes one of the most important technological transformations experienced by power systems in recent decades. Various countries already operate with high levels of renewable generation while maintaining adequate safety and reliability standards, thanks to the incorporation of new technologies, regulatory frameworks, and planning and operating strategies. In this context, the aspects addressed in this Technical Note should be understood as part of the natural evolution of modern power systems and of the capabilities they require to accompany this transformation.

The growing incorporation of inverter-based resources, devices responsible for converting DC systems into AC, is one of the distinctive features of the recent evolution of power systems. This transformation modifies the dynamics of power systems and makes it necessary to incorporate new control, operation, and planning strategies to maintain system stability and reliability. Addressing this challenge requires structural changes in the way the system is controlled and operated. Inertia can be emulated in an inverter, but the energy required to emulate that inertia must come from an energy storage element (batteries) or from derating the converter. In any case, these capabilities must be considered from the project planning and economic evaluation stages. Likewise, it is necessary to include wide-area coordinated control stages to respond more quickly to dynamic changes. These new capabilities also require additional investments that must be considered during system planning.

On the other hand, the electrical system has always protected itself according to the laws of physics. In systems with a high share of power electronics, those laws no longer manifest themselves in the same way. Therefore, protection systems must become more intelligent, more coordinated, and more adaptive. Thus, the massive integration of renewable energy requires not only new frequency and voltage controls, but also the adaptation of protection schemes to detect and isolate faults under the system’s new operating conditions. This is one of the least visible, but most critical, technical challenges in the transition toward modern and sustainable power grids.

In LAC, the technical challenges associated with the energy transition—such as low inertia resulting from the high penetration of power-electronics-based generation, the need for adaptive protection schemes, the performance of electromagnetic transient (EMT) studies, and the modernization of regulatory frameworks—do not arise in the abstract, but rather in power systems with structural characteristics specific to the region: extensive radial grids covering large territories with low load density, a marked dependence on hydropower, and historical limitations in transmission infrastructure that restrict the efficient integration of new renewable sources.

Finally, it is important to emphasize that there is a clear difference between understanding and applying knowledge. Our society may have access to knowledge that has already been discovered and still fail to grow if it does not understand that knowledge sufficiently to adapt it to our reality, combine it, and improve it. Implementing without understanding often leads to rigid copies, low adaptability, and, above all, technological dependence. Therefore, it is essential to develop research programs that result in analytical tools adapted to the needs of LAC—from mathematical models to software tools and even power-electronics tools. As already mentioned, the three key components of a modern power system are the synchronous machine, the transformer, and the power inverter. We could add a fourth and fifth component if we include coordinated control and protection systems. LAC already has a solid business ecosystem for the design, construction, and commissioning of transformers and generators. However, the region is called upon to advance in the development of a regional industry focused on power electronics and wide-area control and protection. This is key not only to achieving some degree of technological sovereignty, but also to strengthening regional technological capabilities, promoting technical cooperation among countries, and improving the competitiveness of companies for a safer and more sustainable energy transition.

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