Vulnerable Operation of Brazilian Northeastern System Under Hydric Crisis and Large Amount of Renewables

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***Abstract*—This paper discusses the impact of the new electricity matrix on the behavior of the electrical system in the Brazilian Northeastern region, showing the challenges faced by a new configuration in which hydroelectric plants operate proportionally with few machines and there is great penetration of wind and photovoltaic power plants, reducing the mechanical inertia present in the grid in addition to reducing control resources associated with hydroelectric plants. Suggests alternatives to compensate for these losses, which should be stimulated by regulatory agents.**

Keywords-ancillary services; frequency control; inertia; regulatory agents

I. INTRODUCTION

Since the 1950s, hydroelectric energy generated in the falls of the São Francisco River has started to reach Brazil's Northeast big cities. With a flow between 2000 and 4000 m3/s, used in six large power plants, totaling 11,000 MW of power, the load in this region (17% of Brazilian load) was supplied by this source in recent decades, even exporting energy after the electrical interconnection with the North of the country. In recent years, the increase in drought, possibly aggravated by climate changes and numerous human impacts that lead to the destruction of the river, has forced regulatory organizations to drastically reduce the use of water, often limiting plants to operate with less than 20% of the capacity.

The need for more energy has increased the use of thermoelectric plants and renewable sources, especially wind. In this new configuration of the Brazilian energy matrix, some weaknesses were evidenced in the shutdown of March 2018, when the installed wind capacity was 14000 MW, given a major disturbance originating in the North of the country, in which the Northeast lost 3600 MW from other regions [1]. Power system protection removed many loads to keep the islanded system in operation. With this scenario of low mechanical inertia, frequency and voltage fluctuations, the Northeast was not able to remain in operation, with the entire load being disconnected. The intermittence of renewable sources has intensified the implementation of thermal plants, even more stimulated by the large volume of gas currently available in Brazil.

This work discusses the impact of the new energy matrix on the behavior of the electric system in Northeast region, showing the challenges faced by a new configuration in which hydroelectric plants operate with few machines and there is great penetration of wind and photovoltaic (PV) plants, reducing the mechanical inertia present in the grid, and suggests alternatives to compensate for this loss, which should be stimulated by regulatory agents.

Adequate remuneration for ancillary services can enable the storage of energy in synchronous compensators, flywheels and conveniently located batteries. Large generators could have activated the operation as synchronous compensators, quickly reversible to generators, augmented with intelligent control features that would offer highly beneficial behavior in large disturbances.

In addition to the related event, Brazilian electrical system experienced another important events related in an analysis done by [2] of the main blackouts suffered by the Brazilian electrical system from 1984 to 2002, it has revealed the following facts:

1) The traditional planning criterion used for expansion in Brazil is the widely known single contingency criterion (N-l). However, it is apparent from most cases studied that the Brazilian blackouts were caused by multiple contingencies or single contingencies with multiple shutdowns not foreseen in the normal planning procedures.

2) Special protection systems are acknowledged as the best way to improve performance of electric systems during disturbances. This makes it necessary to use improved computational tools when conducting dynamic studies and to enhance the communication media presently available for protection purposes.

3) It remains a difficult and laborious task to identify the root causes of large blackouts.

4) The processes of supervision and control of electric systems should be given absolute priority by the industry itself and the government.

5) Training programs for system operators must be given high priority.

6) Simulations of disturbances conducted on digital computers are a good way to assure understanding of the blackout phenomenon, enhanced using mathematical models used as a complementary tool.

7) Clearly it is very important to have access to automatic control of the voltage profile during the dynamic period. The protection settings against circuit over-voltage, the automatic insertion of reactors/disconnection of shunt capacitors and the opening of circuits are all crucial elements in this process, not only to minimize problems but to increase the speed of the restoration of the post-blackout system.

This analysis was showed to exemplify que kind of problems faced by system operators. Some of these facts were solved with the advancement of technologies and modernization of the electric sector.

II. Impact of the new energy matrix on the behavior of the Northeast system

Contribution of power generation from renewable energy sources (RES) increase permanently. RES high penetration in Brazilian northeastern region increases faster as well.

An analysis is made to demonstrate this growth in the last five years by calculating the penetration level based on the concept of energy penetration proposed by [3]. Energy penetration is the ratio of the amount of energy obtained from the generation to the total energy consumed in the power system, normally on an annual basis. It can be calculated according to (1) [3] with data extracted from Brazilian Transmission System Operator (TSO) [4]. Tables I-IV present the data used to calculate penetration levels:

$$Energy\ penetration = \frac{Total\ energy\ produced\ (GWh)}{Total\ energy\ consumption\ (GWh)} x100\% \quad (1)$$

Data from the year 2016:

$$Energy\ penetration(wind) = \frac{26.074}{87.469} x100\% = 29,8\% \quad (2)$$

$$Energy\ penetration(PV) = \frac{24}{87.469} x100\% = 0,027\% \quad (3)$$

$$Energy\ penetration(hydro) = \frac{22.099}{87.469} x100\% = 25,3\% \quad (4)$$

TABLE I. WIND, PV AND HYDRAULIC GENERATION AND ENERGY LOAD IN THE NORTHEAST REGION (2016) [4].

Month/2016	Wind energy (GWh)	PV energy (GWh)	Hydro energy (GWh)	Energy consumption (GWh)
Jan	892	2	2.157	7.147
Feb	1.490	2	1.913	6.935
Mar	1.565	2	1.954	7.740
Apr	1.856	2	1.746	7.292
May	1.903	2	1.840	7.500
Jun	2.215	2	1.741	7.080
Jul	2.684	2	1.803	7.112
Aug	2.822	2	1.809	7.207
Sep	2.879	2	1.766	7.125
Oct	2.783	2	1.842	7.509
Nov	2.667	2	1.776	7.334
Dec	2.318	2	1.752	7.488
Total	**26.074**	**24**	**22.099**	**87.469**

TABLE II. WIND, PV AND HYDRAULIC GENERATION AND ENERGY LOAD IN THE NORTHEAST REGION (2021) [4].

Month/2021	Wind energy (GWh)	PV energy (GWh)	Hydro energy (GWh)	Energy consumption (GWh)
Jan	4.960	344	2.400	8.751
Feb	3.141	278	1.971	7.876
Mar	3.547	374	2.110	8.484
Apr	3.968	375	2.477	8.056
May	4.839	412	2.473	8.116
Jun	5.244	438	2.172	7.866
Jul	6.647	435	2.035	8.135
Aug	7.543	446	2.142	8.283
Sep	7.087	619	2.974	8.541
Oct	6.524	603	2.389	8.983
Nov	5.173	578	2.469	8.586
Dec	5.304	542	2.355	8.368
Total	**63.977**	**5.444**	**27.697**	**100.045**

Data from the year 2021:

$$Energy\ penetration(wind) = \frac{63.977}{100.045} x100\% = 63,9\% \quad (5)$$

$$Energy\ penetration(PV) = \frac{5.444}{100.045} x100\% = 5,44\% \quad (6)$$

$$Energy\ penetration(hydro) = \frac{27.697}{100.045} x100\% = 27,7\% \quad (7)$$

TABLE III. SUMMARY OF ENERGY PENETRATION.

Year	Wind (%)	PV (%)	Hydroelectric (%)
2016	29,8	0,02	25,3
2021	63,9	5,44	27,7

When the scenarios are compared with a difference of only five years, a drastic change can be seen in relation to the amount of energy generated from wind and solar sources. It is noted that consumption remained with a natural increase over time and hydraulic generation had a slight increase. It is noteworthy that the data presented are exclusively from the northeast region of the country.

TABLE IV. THERMOELECTRIC GENERATION AND ENERGY LOAD IN THE NORTHEAST REGION [4].

Month	Thermoelectric energy (GWh) 2016	Energy consumption (GWh) 2016	Thermoelectric energy (GWh) 2021	Energy consumption (GWh) 2021
Jan	2.602	7.147	2.609	8.751
Feb	2.062	6.935	1.496	7.876
Mar	2.124	7.740	407	8.484
Apr	2.397	7.292	550	8.056
May	1.613	7.500	962	8.116
Jun	1.749	7.080	2.441	7.866
Jul	1.523	7.112	3.053	8.135
Aug	1.666	7.207	3.565	8.283
Sep	1.926	7.125	3.567	8.541
Oct	2.233	7.509	3.548	8.983
Nov	2.025	7.334	3.039	8.586
Dec	1.881	7.488	1.951	8.368
Total	**23.801**	**87.469**	**27.188**	**100.045**

$$Energy\ penetration(thermoelectric - 2016) = (23.801)/(87.469)\ x100\% = 27{,}2\% \tag{8}$$

$$Energy\ penetration(thermoelectric - 2021) = (27.188)/(100.045)\ x100\% = 27{,}2\% \tag{9}$$

With this brief comparison of scenarios, it is possible to understand the challenges that the electrical system faces. In proportion to what is generated, there are fewer machines operating in hydroelectric plants and with this there is a reduction in mechanical inertia in the electrical system and possibilities of control as well. The presence of thermoelectric plants is relevant in the Brazilian electrical system, especially those that depend on fossil fuels. Even so, the energy matrix of the northeast has a predominance of generation by wind source (41,73%) while thermoelectric participates with 24,89% and hydraulic with 25,70% [4].

In Fig. 1 part of Brazilian map, specifically northeast region, is presented. Some characteristics deserve to be highlighted, such as the fact that wind generation is concentrated both on the coast and inland. Large solar plants are concentrated inland, as are hydroelectric plants. Thermoelectric generation plants are concentrated where the greatest loads are found. One of the main reasons for this is that this type of generation does not need large areas to be built.

1) *Flexibility of operation*

With the high level of penetration of variable renewable energy (VRE) comes concerns about flexibility of operation. Flexibility of operation is the ability of a power system to respond to change in demand and supply, is a characteristic of all power systems. Flexibility is especially prized in twenty-first century power systems, with higher levels of grid connected VRE, primarily, wind and solar [5].

According to the generation level, discussed before, the flexibility of the system changes and needs different

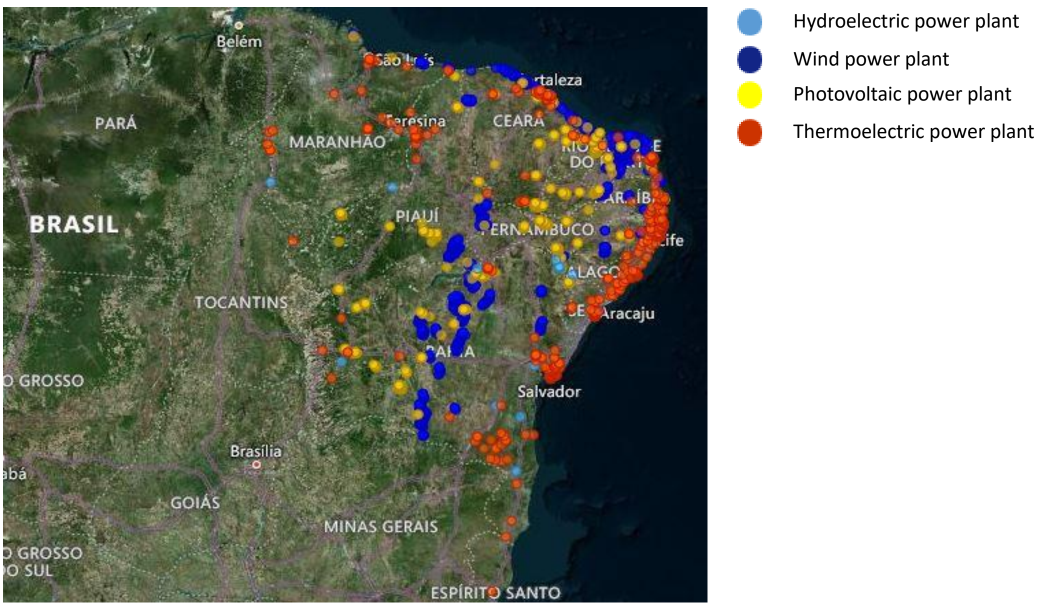

Figure 1. Power plants location in the Northeast region.

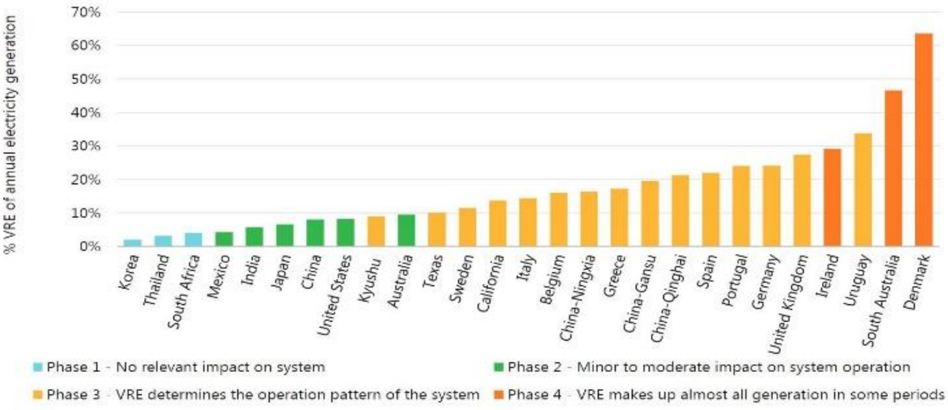

Figure 2. Annual VRE share and corresponding system integration phase in selected country/region in 2018 [6].

approaches as presented in Fig. 2.

Comparing data presented in Fig. 2 with northeastern generation data, northeast would be on phase 4 (VRE makes up almost all generation in some periods). Around July to October the northeastern generation is exported to other regions for a few minutes due to the great wind scenario this time of the year.

Electrical systems need to be managed not just for productivity, reliability, quality, or stability, they also need to be managed for resilience (or flexibility). The large use of renewables in the northeast region requires additional system studies to test the grid's ability to recover from major disturbances. As many of these new sources are generally based on inverters, in which time-distorted variations, frequency and voltage variations can alter system dynamics under severe disturbances.

From what was stated, it is possible to highlight some vulnerabilities of the system:

- Hydroelectric plants operating under hydric crisis and proportionally with few machines.
- Use of fossil fuel powered thermoelectric plants.
- Reduction of mechanical inertia in the electrical system (presence of RES).
- Problems arising from low inertia in the electrical system.

Based on the last two points related to inertia in the electrical system, some considerations will be made to present issues related to low inertia and what this entails in the system, as well as suggestions of appropriate technologies to enrich inertia and regulatory aspects related to the subject.

III. Inertia and Grid Frequency Stability

Frequency stability is the ability of a power system to maintain steady frequency following an imbalance between supply and demand [7].

Grid frequency and inertia are closely related. Grid frequency, which is a measure of the balance of supply of electricity and demand, can drop if a large power plant or transmission line fails. Inertia resists this drop in frequency, giving the grid time to rebalance supply and demand.

In [8] some points on the subject are highlighted:

- Inertia is only one of several grid services that help maintain power system reliability. Understanding the role of inertia requires understanding the interplay of inertia and these other services, particularly primary frequency response, which is largely derived from relatively slow-responding mechanical systems.
- The importance of inertia to a power system depends on many factors, including the size of the grid and how quickly generators in the grid can detect and respond to imbalances. A grid with slower generators needs more inertia to maintain reliability than a grid that can respond quickly.

In the event of a sudden failure in the system or connection of a large load, the system frequency starts dropping (Fig. 3). For the occasions that the frequency drops greater than the defined limits, generation plants are required to provide additional frequency response duties [9]. These responses are called primary and secondary reserves.

Primary reserve is intended to be the additional capacity of the grid that can be automatically and locally activated by

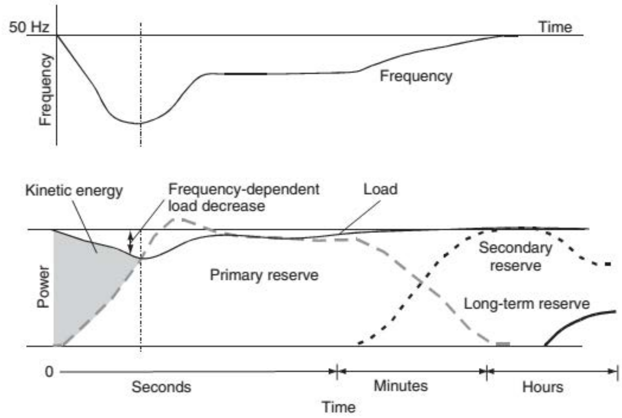

Figure 3. Power system frequency and power reserve activation facing a grid event [10].

the generator's governor after a few seconds at most of an imbalance between demand and supply of electricity in the grid [11]. The aim of primary reserve is to quickly balance the consumed and generated power in the system and thus stabilize frequency at a certain level.

Secondary reserves are activated to restore the rated frequency of the system, releasing primary reserves, and to restore active power interchanges between control areas to their set points [11]. They are activated by the TSOs by modifying the according active power set points of the generating units within each respective control area.

Even though the power output of wind turbines depends on the unreliable and difficult-to-predict wind speed and the generator set does not provide an instantaneous power reserve, there are methods for wind power plants to provide power reserves and thus to participate in grid frequency control. Such abilities will be crucial for the successful integration of wind power plants into the grid [12]. To meet the requirements of operators, wind turbine manufacturers have developed new functionalities in their control systems in recent years, especially regarding the control of active power of wind power plant.

IV. Alternatives to Compensate for Inertia Losses

According to [8], using power electronics, inverter-based resources including wind, PV, and storage can quickly detect frequency deviations and respond to system imbalances. Electronic-based resources for this fast frequency response can enable response rates many times faster than traditional mechanical response from conventional generators, thereby reducing the need for inertia. Replacing conventional generators with inverter-based resources, including wind, PV, and certain types of energy storage, has two counterbalancing effects. First, these resources decrease the amount of inertia available. But second, these resources can reduce the amount of inertia needed - and thus address the first effect. In combination, this represents a paradigm shift in how we think about providing frequency response.

In [13], appropriate technologies for enhancing inertia in a more comprehensive way are related. It summarizes technologies that can be used in a power system to increase the inertia and avoid a high rate of change of frequency (ROCOF) in the power system. Alternative technologies such as synchronous condensers, pumped hydroelectric energy storage, compressed air energy storage, flywheels and batteries, and ultra-capacitors can provide the required fast response to balance the power.

A brief explanation of each technology based on [13] is showed next.

Synchronous condensers consist of a freely spinning synchronous machine connected to a high-voltage network. The reactive power and voltage are controlled by changing the field current of the synchronous condenser. Usually, it regulates the voltage by supplying or absorbing reactive power when needed. It is a rotating machine, and thus inertia is an implicit attribute. An unloaded synchronous machine can be referred to as a synchronous condenser, and the real power output is zero. The kinetic energy stored in the synchronous condensers rotating mass will help in the frequency regulation when a power imbalance occurs.

Pumped hydroelectric energy storage (PHES) is a type of hydroelectric energy storage used to balance a load. PHES reserves electric power by moving water between a lower and upper reservoir. If excess energy is available, the water is pumped to an upper reservoir. Otherwise, water is released to meet the demand. PHES offers inertia to the grid in both pumping and generating modes. When the PHES is not using for the pumping and generating modes, the pump can be detached from the turbine to act as a synchronous condenser to deliver inertia and reactive power support.

Compressed air energy storage (CAES) is another type of energy storage and mainly depends on the potential energy in pressurized air. CAES supports the large-scale integration of RES into the grid. It is a promising technology, owing to its high efficiency and long life. Basically, compresses air when there is excess power in the grid, and decompresses the air to inject power when needed.

Flywheel is a mechanical element that stores energy in the form of kinetic energy. The rotor is accelerated/decelerated by a motor/generator to absorb or inject the power. They are connected to the grid to offer inertia. Flywheels can provide ancillary services like inertia and frequency regulation, do not have any geographical constraints, and can be installed easily. Typically, are connected to the grid through a power electronic device.

Batteries and ultra-capacitors are electrical energy storage elements and operate at direct current. Hence, power electronic converters and inertia emulation algorithms are needed to offer inertia from batteries. A proper control algorithm with a battery enhances the frequency stability of a power system. However, the type of battery plays a key role in frequency stability.

Also, literature review shows diverse techniques for inertia and frequency control form wind and PV power plants [14]:

Wind power plant

- Inertial response: droop control, fast power reserve and hidden inertia emulation.
- De-loading technique: over speed control and pitch

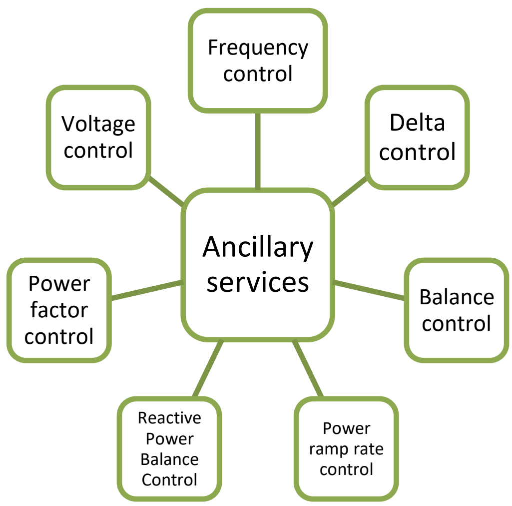

Figure 4. Basic ancillary services provided by power system generation.

angle control.

- Using energy storage system (ESS)

PV power plant

- De-loading technique
- Using energy storage system (ESS)

V. Ancillary services

In many conventional power plants the synchronous generators are equipped with power system stabilizers that dampen rotor speed oscillations [15]. If wind power plants, for example, are to replace a considerable amount of conventional power generation in the future, they will have to assist in the damping of power system oscillations such as grid frequency oscillations and inter-area oscillations. This can be achieved by a variation in output power of the wind power plant [16].

With the increasing exploitation of RES, the requirements of system operators have also increased in relation to the behavior of this power source. Some points of interest that have arisen with the high penetration of wind power in the systems are the reserve power and frequency control [17].

In accordance with TSO grid codes around the world, the frequency delivered to the consumer must not vary from the declared value by more than an average of 1%. This is to guarantee the quality of energy delivered to the consumer.

Frequency control takes a very important role in the so-called Ancillary Services, these services are required from the power generation units to provide. Fig. 4 shows some ancillary services examples.

Definitions for ancillary services can differ significantly based on who is using it. While some definitions emphasize the importance of ancillary services for system security and reliability, others mention the use of ancillary services to support electricity transfers from generation to load and to maintain power quality. In short, ancillary services are services provided to the system (transmission network) for the purpose of transporting the energy sold under conditions of quality, reliability, and safety. Some TSOs are including more specific types of ancillary services than others because:

- Differences in the definitions.
- Some of the required properties of the generation plants are embedded in conventional power plants using directly grid connected synchronous generators.
- New ancillary service products seem to pop up in power systems with large scale penetration of renewables.

In several countries where there is wind generation, grid codes have long provided for the behavior of wind power plants in some way and not just their shutdown, when there is an event in the electrical system. We can mention some examples according to [18]:

Germany: wind power plants are required to reduce their production of available power when the grid frequency is higher than normal values. Generation plants whose rated capacity is less than 100 MW can provide primary response through agreement with the TSO.

Canada: the code establishes that wind power plants with a rated power greater than 10 MW must have a frequency control system that helps to reduce frequency deviations of wide variation (>0.5 Hz) and short duration (< 10s) in the system.

Denmark: It is required that the power output of each generator be controlled individually using an automatic frequency regulation controller. The TSO should require a primary response of 47 to 50 Hz and a high frequency response of 50 to 53 Hz.

Great Britain: the grid code states that wind power plants must provide balancing services that are originally supported by conventional generation plants. All wind farms must be able to meet both primary and secondary frequency response requirements.

A. *Brazilian ancillary services*

Local TSO grid codes and normative resolution establish the following ancillary services. Some discussions about them will be made on next topic.

Self-recovery: capacity of a generator to go from a total stop condition to an operating condition, contributing to the restoration of the electrical system.

Frequency control: speed control of generating units to maintain or restore the system frequency when there is an imbalance between load and generation.

Reactive Support: supply or absorption of reactive by generating units. Used for system voltage control.

Special Protection System: comprises systems that, from the detection of risk to the electrical network, perform automatic actions to preserve the integrity of the national interconnected system.

Maintenance of operating power reserve: thermoelectric dispatch to maintain water in the hydroelectric reservoir that provides frequency control.

VI. Brazilian Ancillary services under review

As mentioned earlier, Brazilian electrical matrix has undergone transformations marked by the reduction in the regularization of hydroelectric power plant reservoirs and strong penetration of renewable sources with intermittent generation concentrated in specific geoelectrical regions, especially in the Northeast region. This movement leads to the need to provide ancillary services to the electrical system that will compensate for variations in electrical quantities, whose standards are not met by the programmed energy production. The provision of ancillary services naturally imposes costs on systems related to the implementation of additional equipment, operation and maintenance, fuel consumption and opportunity costs.

For the national interconnected system to be provided with ancillary services suited to the reality of the national electricity matrix, the spatial and temporal distribution of energy resources and load and the existing and planned transmission system, sectoral planning actions are needed to indicate such needs. of the system, in the dimensioning of the requirements, in the location of ancillary services equipment and in the long-term contracting of these services in favor of cost reduction.

The operator is dependent on the system (electrical matrix, distribution of energy resources and load and transmission system) available to him for operation. It seeks to optimize energy resources, with the required electrical safety, to meet the load, using the resources made available to the system by sectoral planning.

The actions of the regulator, responsible for regulating the operator, are limited to the resources made available to the system and the characteristics of the expansion of the system. In any case, it is up to the regulator, given the equipment made available by sectoral planning and the ancillary service requirements identified both by planning and by the operator, to encourage quality provision, identify costs, and allocate them efficiently. These actions provide feedback to sectoral planning, regarding the characteristics of system expansion and its costs; as well as the operator, regarding the costs of optimizing electrical energy resources [19].

The National Electric System Operator (ONS) promoted discussions to evaluate ways to increase the incentive to provide quality ancillary services, to identify the costs of delivery and to allocate costs efficiently. Discussions are about modifying existing ancillary services, cited before, and proposing new services. They are briefly shown below [19].

A. Self-recovery: increase the incentive to avoid failures in real situations.

1) Determination of test failures could affect the determination of the plant's physical guarantee.

Advantage: it can increase the incentive to avoid failures in real situations.

Disadvantage: possible conceptual failure, as the calculation of the original physical guarantee does not include provision of ancillary services.

2) Carry out revisions and readjustments to the amounts to be paid on a four-yearly basis, using an economic regulation technique.

Advantage: It can increase the incentive to avoid failures in real situations.

Disadvantage: may impose operational complexity and adaptation of economic regulation tools to the provision of ancillary services.

B. Reactive support as a Synchronous Compensator

1) Maintain payment for the ancillary services fee.

Advantage: the method is already established.

Disadvantage: may not cover the costs of converting the generating unit to synchronous compensator.

2) Change the remuneration methodology to consider the availability of the service (annual fixed amount with reduction for unavailability) and a variable remuneration for operating time (instead of remuneration by Mvarh).

Advantage: it can increase the incentive for quality in the provision of the service.

Disadvantage: it can increase the complexity in determining the provision of the ancillary service.

C. Other services for Reactive Support: creation of new services

1) Remuneration for Photovoltaic plants to provide reactive support in periods with little or no light.
2) Reactive support in Wind Power Plants when they are turned off.
3) Remuneration for time in operation outside the allowed range in generating units.
4) Reactive support in the distribution network.

Advantage: the method of applying the tariff for ancillary services is already established

Disadvantage: may not cover the costs of technological adaptation, if necessary.

5) Payment for service availability.

Advantage: it can increase the incentive for quality in the provision of the service.

Disadvantage: it can increase the complexity in determining the provision of the ancillary service.

D. Secondary frequency control: change the remuneration methodology to encourage greater service availability

1) Make payment to hydroelectric plants for equipment deterioration.

Advantage: it can increase the incentive for quality in the provision of the service.

Disadvantage: complexity in identifying the cause x effect relationship on equipment deterioration.

2) Fixed payment plus variable installment according to use.
3) Pay for frequency of use.
4) Pay per opportunity.

Advantage (for the three points above): it can increase the incentive for quality in the provision of the service.

Disadvantage (for the three points above): it can increase the complexity in determining the provision of the ancillary service and in identifying the valuation method for the provision of the ancillary service.

E. Inertia as ancillary service

1) Implementation of equipment for the provision of inertia to the system.

Advantage: it can reduce the need to activate thermoelectric plants for this purpose.

Disadvantage: can increase system losses.

2) Use of thermoelectric plants out of order of merit to increase inertia.

Advantage: it can reduce the need to implement equipment intended to provide inertia to the system.

Disadvantage: It can increase the cost of operating the system.

VII. Conclusions

Moving towards the expansion of renewable energy sources in the electrical matrix in addition to the existing and predominant hydraulic source, solar and wind sources have already been consolidated with accelerated expansion in recent years. Northeastern region stands out for having the most favorable conditions for these two sources in the country. The amount of wind energy penetration was analyzed, and it is similar to many countries with high level of wind energy penetration, leading to the system export energy in some periods of the year. Linked to the numerous advantages related to RES, there are the questions associated with low mechanical inertia due to sources connected to the grid by inverter-based technologies. A sort of alternatives and technologies were presented as suggestions to compensate for inertia losses. Flexible operation in hydroelectric plants, intensified by the penetration of variable and noncontrollable generation sources can accelerate the deterioration of equipment, with impacts on energy production. Ancillary services can be an important source of revenue to enable new enterprises and to facilitate RES integration. These services are under review to precisely meet the demands of this new scenario, following the trend of encouraging the participation of all sources in the various controls of the network.

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