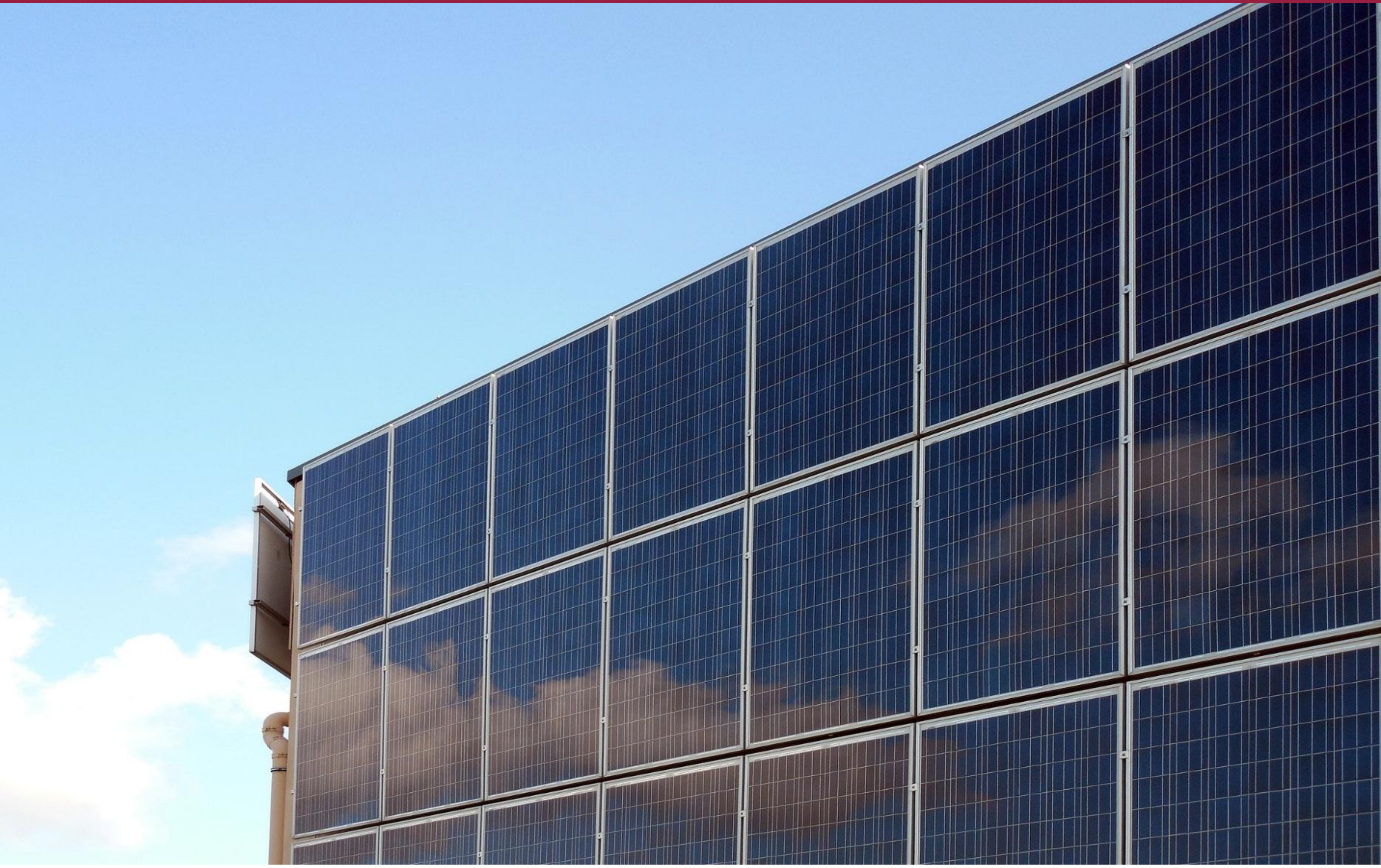
5.2. Use of storage technologies for ancillary services provision and its potential for climate change mitigation

October, 2020



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SECRETARÍA DE MEDIO AMBIENTE Y RECURSOS NATURALES

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Mitigation Potential of Utility-scale Electricity Storage in Mexico

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Executive Summary

This study analyses the introduction of storage into the electricity network operation, both by providing balance services on a large scale, as has been done until now or by using it as a tool for improving the quality of service (resolving network contingencies). It provides the system with anciliary services (inertial response, primary reserves, "spinning" reserve). Numerous applications are identified in electrical networks, grouped into five categories according to the system in which they perform their function (generation, transmission, distribution, demand or auxiliary services). This study refers only to the latter.

This study estimates the size of ancillary services and the CO2 mitigation potential of utility-scale storage in Mexico through the two fundamental actions that are taken into account to offer a quality electric service: (i) frequency regulation; and (ii) voltage regulation. It presents results and an assessment of such actions in the Mexican interconnected system (SIN), composed of 158 generators, 2,022 buses , and 3,025 lines as well as in the isolated system of Baja California Sur.

Studies are carried out to assess the frequency behavior, in the different control areas of the Mexican interconnected system (SIN), under sudden load increments. Likewise, the possible reactive power compensations in areas of paramount interest for the system are quantified to solve low voltage profile problems, which were detected in previous studies carried out by national authorities. This is done to assess its behavior and propose the embedding elements to help improve it.

Based on reserve values required by the National Energy Control Centre (CENACE) , it is proposed to provide them through energy storage technologies. The reduction in CO2 and polluting emissions is quantified, assuming that the generation technologies that are displaced are conventional technologies that are out of operation.

From the generators viewpoint, the spinning reserve is a problem for several reasons, among them the fact that it forces the generators to work in non-optimal points or under deviation from the nominal operation. The use of storage allows generators to operate at full power, thus, in case of an increase in power, storage supplies that services. In this way, storage systems and their associated converters can take over the spinning reserve, allowing conventional machines to work at their nominal or maximum power. Thus, the operation of the transmission and distribution network also benefits from storage facilities. Various forms of energy storage contribution to the maintenance of the system frequency have been described in the document. The high speed of response, characteristic in batteries, allows them to collaborate effectively in primary frequency control.

This study shows in the first and second sections an understandable review of ancillary services especially frequency and voltage control. In sections three and four, the context of these services within the concept of flexibility for the integration of Variable Renewable Energies (VRE) in electrical systems and Energy Storage Systems (ESS) are also presented. In section five, the study system is described as well as the results of the frequency and voltage studies. Section six and seven explain the role of power electronics in the VRE integration and an approach on how to estimate the mitigation potential of ESS. Sections 8 and 9 show the results of an analysis to determine the location of ESS based on the reactive compensation degree of single buses and the size of ESS requirements, based on ancillary services and backup needs. Finally, in section 10 some conclusions are outlined as well as a comparison of the possible emissions mitigation potential comparing the approach presented in section seven with the IPCC 2006 guidelines and the estimation based on the national inventory emissions factors.

The results show for the different control areas in the Mexican Interconnected System that ESS could be employed to provide ancillary services. In these cases, ESS allows deviations in frequency and voltage signals within technically acceptable limits. The speed of response of such ESS technologies is critical to the success of the support they provide, especially concerning frequency. ESS could support the integration of VRE on those regions with ancillary services and backup requirements. Yet ESS makes sense only if regulations are in place to ensure ESS will be used with clean or exclusively renewal energy.

For 2018 the capacity requirement for Fast Frequency Control (FCC) was estimated on approximately 37 MW, these data represent a minimum installation to help improve the operation of the network, this requirement could be supplied with storage technologies. By 2033 these capacity requirements for FFC are estimated to be 121 MW

This contribution of ESS for frequency control is significant in small systems (for instance, the Baja California Sur system), where asynchronous technologies may displace a considerable part of the synchronous machine-based generation. In more extensive networks, storage technologies used in the appropriate locations may achieve significant results for frequency and voltage control. The high speed of response, characteristic of batteries, allows them to collaborate effectively in primary frequency control. But at the present high-speed frequency control is not a recognised ancillary service and will not remunerated.

Flexibility is another relevant factor at the stage of grid planning before the integration of renewables and storage technologies. The use of storage technologies allows providing flexibility services to the system and contributing to improving the quality of the service provided by the utility within the process of VRE integration.

Regarding the location of ESS, it seems results show a distribution along with the network, associated with the generation facilities near areas of high consumption since it would mean that the storage devices are close to the points that require a higher input of reactive power. Some geographical regions become exceptional cases, such as the areas around León, Querétaro, Chihuahua, Riviera Maya, Saltillo, the isolated BCS system. There, due to low voltage levels, it would be convenient to use reactive resources to help support them. The potential mitigation of ESS for ancillary services could lie between 2.2 and 2.5 kt CO2, under the assumptions made in this study, if we only consider only carbon dioxide, The mitigation potential profoundly depends on the energy mix used to load an ESS.

1. Ancillary services

Ancillary services are defined by the US Federal Energy Regulatory Commission (FERC) as those services required to support the electric power transmission from sources to loads and needed to sustain transmission system reliable operations *(US FERC, 1996)*. Essential, ancillary services are those necessary services in power system operation other than the provision of real power *(Wu, F. F., 1998)*.

Ancillary services are derived from the unbundling of the generation and transmission functions in the power system. FERC separated the ancillary services into two categories. **The first category** includes ancillary services that must be provided by the transmission provider. **The second category** comprises ancillary services that can be offered by the transmission provider. Still, the customers are free to accept from the transmission provider, a third party, or self-provide.

Scheduling, System Control, and Dispatch: This service is used for programming, confirming and implementing an interchange schedule with other control areas, including intermediary control areas providing transmission service, and ensuring operational security during the interchange transactions. This service is often associated with the functions of the control operator.

Reactive Supply and Voltage Control from Generating Sources: This service provides reactive supply through changes to reactive generator output to maintain transmission line voltage and facilitate electricity transfers. This service is also known as voltage/var support.

Black start: By combining an electronic converter in Voltage-Source Converters (VSC) configuration with a battery, a three-phase system of tensions may be attained. In addition to the Direct Current (DC) side of the converter, the use of batteries allows feeding the auxiliary elements of the system (voltage meters, current and power; the control systems; and the cooling system). Then the converter operation can be started even if there are no other generating machines supplying a three-phase system. The tensions synthesised on the inverter alternating current supply can be used to power loads and also the auxiliary systems of other conventional generators.

The remaining ancillary services in the second category are defined as follows *(US FERC, 1996)*, *(Glossary of Term Task Force, 1996)*:

Energy Imbalance: This service provides energy correction for any hourly mismatch between a transmission customer's energy supply and demand.

Operating Reserve-Spinning Reserve: This service offers additional capacity from online electricity generators, loaded to less than their maximum output, and available to serve customer demand immediately should a contingency occur.

Operating Reserve-Supplemental Reserve: This service provides additional capacity from electricity generators that can be used to respond to a contingency within a short period, usually ten minutes.

The purpose of ancillary services is to ensure the reliable delivery of electricity. As such, FERC definitions for ancillary services are guidelines for all entities to maintain reliability.

2. Frequency, Voltage, and Black start

2.1 Frequency

The electric power system is unique in that it must match aggregate production and consumption instantaneously and continuously. Power systems always require a balance between production and use of electricity to maintain the frequency within a particular interval ($f_{nominal}$ ± 0.1 Hz). More significant frequency deviations can cause blackouts or damage equipment connected to the grid. Thus, frequency and regulation are based on the dynamics of the generating units concerning the system load. The scheduled frequency is a function of the balance between load and generation *(Anderson, P. M., Fouad, A. A., 2008), (Elgerd, O.I., 1982), (Kundur, P., 1994), (Cohn N,1967), (Akhil, A. A., et al., 2015)*.

Operating reserves (controllable reserves) hinge on a percentage of the system demand. They are used to maintain system reliability in case of a generation failure, or unanticipated increment in system load. **Operating reserves that are synchronised with power system** are referred to as **spinning reserves**. Spinning reserves are available within a ten-minute timeframe. This timeframe is arbitrary and can be defined differently by a control area.

The calculation of the Regulation Reserve requirement is made on an hourly basis, considering the components that have a very short-term effect on the load-generation balance of the system. These components are the following,

a. The demand of the National Interconnected System (SIN), by its initials in Spanish.
b. Net exchange scheduled.
c. Industrial load.
d. Wind/PV generation (Intermittent or variable generation).

Several types of controllable reserves are maintained to help the system operator achieve this required generation/load balance. The continuous random minute-to-minute fluctuations in load and uncontrolled generation are compensated for with **regulating reserves** (day-ahead market) (third column of the daily file published by CENACE[1] in the requirements of ancillary services). Frequency deviations are compensated for with frequency-responsive reserves and generator dispatch. Additionally, CENACE[3] publishes the 30-minute supplementary booking requirements (sixth column of the file).

In México, sudden failures of generation and transmission are compensated for with two additional reserves: 10-minute spinning reserve, 10-minute non-synchronized reserve (fourth and fifth columns, respectively, of the daily file published by CENACE in the requirements of ancillary services).

Thus, in Mexico for the SIN, the reserve requirements are specified for each hour of the day. For instance, the regulation reserve amounts to approximately one unit of 350 MW, with variations depending on the value of demand at that hour. The spinning and unsynchronised 10-minute

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[1] https://www.cenace.gob.mx/SIM/VISTA/REPORTES/ServConexosSisMEM.aspx

reserves are, respectively, 2 and 3 times the value of the regulation reserve. The so-called supplementary reserve is the sum of the two previous ones.

Table 2.1. Example of kinds and amounts of reserves in the SIN in one hour. Source: Own elaboration with data from CENACE.

Hour	Regulating reserves (MW)	10-minute spinning reserve (MW)	10-minute non-synchronized reserve (MW)	Supplementary reserve (MW)
1	343	687	1031	1717

Appendix A describes the frequency method for analysing two control areas, the methodology followed in this study for the Mexican electricity grid.

Appendix B summarises how different utilities estimate the various reserves schemes.

2.2 Voltage regulation

Traditionally, Voltage and reactive support affect power system stability. Robust power system stability requires that the electric buses and system voltages be maintained at a specific voltage; in México, 0.95 to 1.05 per unit. The voltage support is a function of the reactive power in the system. Generators, shunt capacitors or reactors (under no-load conditions), static var compensators, and synchronous condensers are reactive power sources. However, unlike real power, reactive power is difficult to transmit over long transmission due to line charge current. There is a localising effect for voltage/var support.

Initially, only reactive power support from generation sources is considered as an ancillary service and is eligible for financial compensation.

The capability of its prime mover usually limits the real power output from a synchronous generator. Figure 2.1 illustrates a synchronous generator capability curve. The importance of the curve lies in the fact that it determines the operating limits of the machine. It is important to emphasise that the temperature determines these limits in the generator windings (field and armature), *(Kundur, P., 1994).*

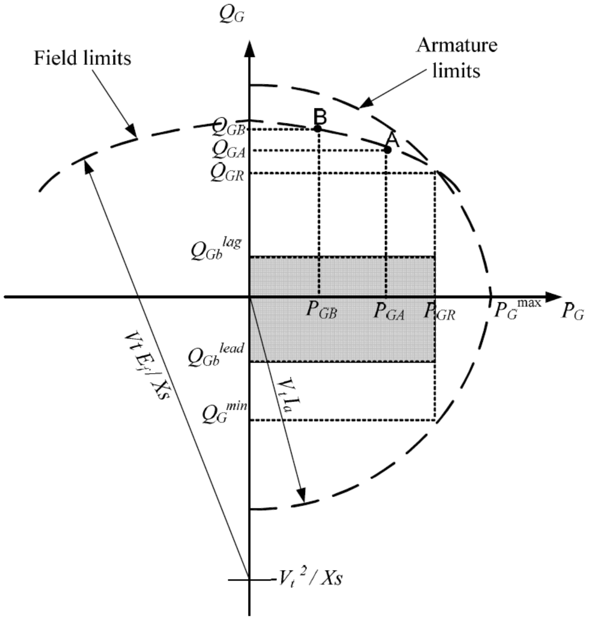

Figure 2.1. Synchronous generator capability curve. (Kundur, P., 1994).

All electrical equipment for power system applications is specified in MVA (Mega-Volt-Ampere), and this includes its active power capacity (MW) and its reactive power capacity (Mvar) ($MVA = \sqrt{MW^2 + MVAR^2}$). The generator's MVA rating is the point of intersection of the two curves, and therefore its corresponding real power rating is given by P_{GR}. At an operating point A, with real power output P_{GA} such that $P_{GA} < P_{GR}$, the limit on reactive power Q_G[2] is imposed by the generator's field winding heating limit, whereas, when $P_{GA} > P_{GR}$, the limit on Q_G is set by the generator's armature winding heating limit.

There is a mandatory amount of reactive power that each generator has to provide (the shaded area in Fig. 2.1). If the generator is called upon by the ISO (independent system operator) for additional reactive power provision beyond this area, it is then eligible for payment to compensate for the increased costs associated with losses in the windings. Such mandatory and ancillary classifications of reactive power capability are in line with what most system operators currently have in place for reactive power management.

According to the capability curve in Fig. 2.1, the generator can provide reactive power until it reaches its heating limits (point A in Fig. 2.1); any further increase in reactive power provision from the generator will be at the expense of a reduction in its real power generation.

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[2] In electrical grid systems, reactive power is the power that flows back from a destination toward the grid in an alternating current scenario. In alternating current, there are different phases having to do with elements of the system like capacitors and inductors. Reactive power gets energy moving back into the grid during the passive phases. Another way to explain this is that reactive power is the resultant power in watts of an AC circuit when the current waveform is out of phase with the waveform of the voltage, usually by 90 degrees if the load is purely reactive, and is the result of either capacitive or inductive loads. Actual work is done only when current is in phase with voltage, such as in resistive loads. An example is powering an incandescent light bulb; in a reactive load energy flows toward the load half the time, whereas in the other half power flows from it, which gives the illusion that the load is not dissipating or consuming power

Hence, the generator is expected to receive an opportunity cost payment for providing reactive power beyond Q_{GA}, which accounts for the lost opportunity to sell its real power in the energy market and the associated revenue loss.

2.3 Black start

If there is a blackout or complete power failure, then there must be generating units capable of restoring the system load. Black start support is limited to those generating units that can provide electrical power after an adverse power system condition. Complete power failure or blackout is a very low probability event if there are adequate load shedding schemes in the power system.

2.4 Ancilliary services in México

Table 2.1 summarises the primary ancillary services required by the Mexican electricity company *(CENACE, 2017), (Secretaría de Energía MÉXICO, 2019)*. The CENACE (National Energy Control Center) shall acquire the following Ancillary Services as necessary for the National Electric System Reliability in terms of the Grid Code and its operational provisions issued by the Energy Regulatory Commission (CRE for its acronym in Spanish), *(CRE, 2016).*

The current regulation remunerates three services through tariffs:

i. Reactive reserve.

ii. Reactive power.

iii. Grid re-energization.

Table 2.2. Classification of ancillary services in the Mexican market according to current market rules. Source: own elaboration.

Market-based services	Regulated services
a. Frequency regulation	a. Black start (associated with *iii above*)
b. Spinning reserve (10 minutes)	b. Emergency operation (associated with *iii above*)
c. Non-spinning reserve 10 minutes)	c. Islanding operation (associated with *iii above*)
d. Spinning supplemental reserve (30 minutes)	d.Voltage regulation & reactive power (associated with *i and ii above*)
e. Non-spinning supplemental reserve (30minutes)	

3. Flexibility

The evolution of the power system has a significant impact on the operation and planning of the future power system. Three major global trends influencing the development of the power system are (*ISGAN and the Swedish Smart Grid Forum, 2018)*:

Decarbonisation	Decrement of the carbon footprint from electric power production.
Decentralisation	Transition from few and large, centralised, power plants to many smaller, decentralised, power production units.
Integration	Increasingly integrated electricity markets, the greater interconnection of previously independent grids, and more integrated energy systems.

Flexibility has technical and commercial viewpoints, where the technological capabilities may be utilised to support the network and the system under the business capabilities of the markets and their regulations. However, the concept does not have an accepted global definition. Several suggested descriptions are available. The broad range of meanings of the proposed definitions leads to the general statement that:

Flexibility is associated with managing changes in power systems

The power system flexibility is seen as a key to coping with some of the challenges of their future. Quite relevant are solutions providing advances in flexibility, making this an increasingly important topic to consider for operation, planning, and policymakers *(IEA, 2018).*

Some studies present an analysis of the flexibility contribution that could be provided by storage participating in the energy markets and through the trans-national coupling of balancing markets *(Calisti, R. et al., 2016).*

The examples of flexibility solutions presented in Fig. 3.1 includes an overview that provides for different aspects of electric service, from the local level through the distribution and transmission system levels, to the system-wide level. Notice that resources can be used as flexible solutions for more than one of the categories.

Flexibility for power

Characterisation: the short-term equilibrium between the power supply and power demand, a system-wide requirement for maintaining frequency stability.

Rationale: High penetration of stochastic power supply.

Timescale activation: Fractions of a second up to an hour.

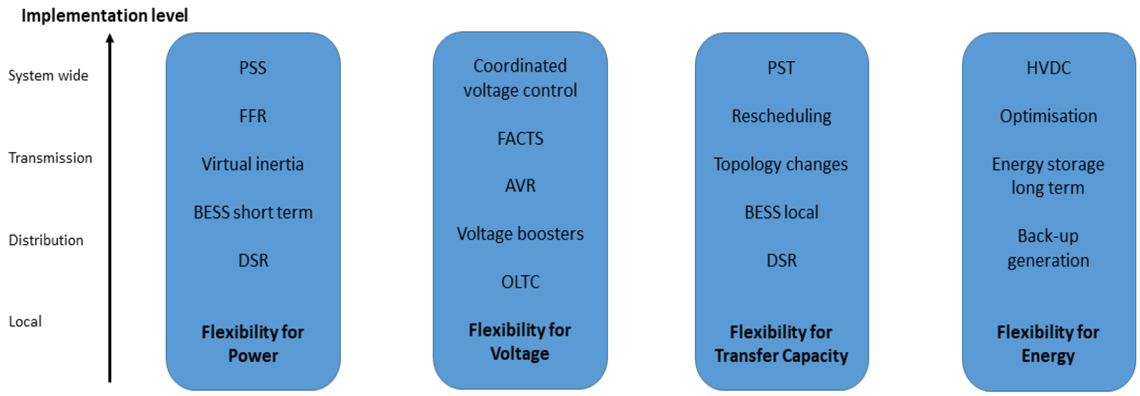

Figure 3.1. Examples of flexible solutions for each type with implementation levels from local to system-wide. (*Hillberg, E., 2019*)

Acronyms:

AVR: Automatic Voltage Regulator; BESS: Battery Energy Storage System; DSR: Demand Side Response; FACTS: Flexible AC Transmission System; FFR: Fast Frequency Response; HVDC: High Voltage Direct Current OLTC: On-Load Tap-Changer; PSS: Power System Stabiliser; PST: Phase-Shifting Transformer

Flexibility for energy

Characterisation: Energy supply and energy demand equilibrium for medium - long term, a system-wide requirement for demand scenarios over time.

Rationale: Decrement in fuel storage-based energy supply.

Timescale activation: Hours to several years.

Flexibility for transfer capacity

Characterisation: Transfer power between supply and demand, where local or regional limitations may cause bottlenecks resulting in congestion costs.

Rationale: Rising utilisation levels, with raised peak demands and increased peak supply.

Timescale activation: Minutes to several hours.

Flexibility for Voltage

Characterisation: Short term ability to keep the bus voltages within predefined limits, a local and regional requirement.

Rationale: Increment of distributed power generation in the distribution systems, resulting in bi-directional power flows and increased variance of operating scenarios.

Activation timescale: Seconds to tens of minutes.

Wind generators and photovoltaics (PVs) exhibit intermittent and stochastic nature because of weather conditions. Both have three main characteristic features: *variability, uncertainty, and location dependency*. Therefore, power system reliability may be threatened by the expansion of variable energy resources (VERs), thus arising the requirement for flexibility that reinforces the system with the capability of compensating for real-time generation and consumption mismatches. **The generation reserve capacity of thermal and hydropower plants is considered the system flexibility** *(Akrami, A., 2019)*.

Hence, high penetration of renewable resources and their variability, intermittency, and uncertainty have enlarged the prominent role of flexibility in modern power systems. Then, either forecast or unforecast deviations in demand need flexible services to deal with.

4. Energy storage technologies

Nowadays, transmission and distribution systems have embedded energy storage systems, that provide power system reliability benefits. Generation and load must be balanced to satisfy reliability and power quality. Strategically placing energy storage resources may raise safety and efficiency for balancing demand and supply. They may provide all possible ancillary services, such as frequency regulation, voltage regulation, peak shaving, black start, spinning, non-spinning and supplementary reserves.

The energy storage systems come with many technologies and in different forms and also differ in terms of the life cycle, system life, efficiency, size and other characteristics.

The classification of storage technologies can be made taking into account various point of views, for example, speed of response or operation cycles. Thus, batteries and flywheels are capable of responding in the order of milliseconds, making them ideal for frequency control applications. On the other hand, hydraulic pumping does not have that speed of response. Still, very high amounts of stored energy can be achieved for use over extended periods, and this is useful for other applications, such as peak shaving.

Extensive analyses have been carried out on the different energy storage technologies, the description, primary data and conclusions about selected technologies are presented in the deliverable D2 (Technology Catalogue for Electricity Storage) by this Institute as part of the study. Then, the use of storage technologies is broad and is one of the reasons why this report evaluates their eventual incorporation into the Mexican electricity system.

5. Study system

Dynamic models for the National Interconnected System (SIN, by its acronym in Spanish) and for the Baja California Sur system (BCS) are adopted to assess the frequency and voltage deviations at different buses to determine its electrical robustness.

System studies in this research hinge on a dynamic model of the SIN, which represents parts of the bulk 400, 230, 138 and 115 kV transmission network, Fig. 5.1. For the operating condition studied in this report, the network consists of 158 generators and 2022 transmission buses, encompassing the interconnected operation of seven regional systems. The base working condition is based on the 2018 base case *(Secretaría de Energía MÉXICO, 2018)*. The information used does not include some new plants, for which no technical information is available due to confidentiality issues.

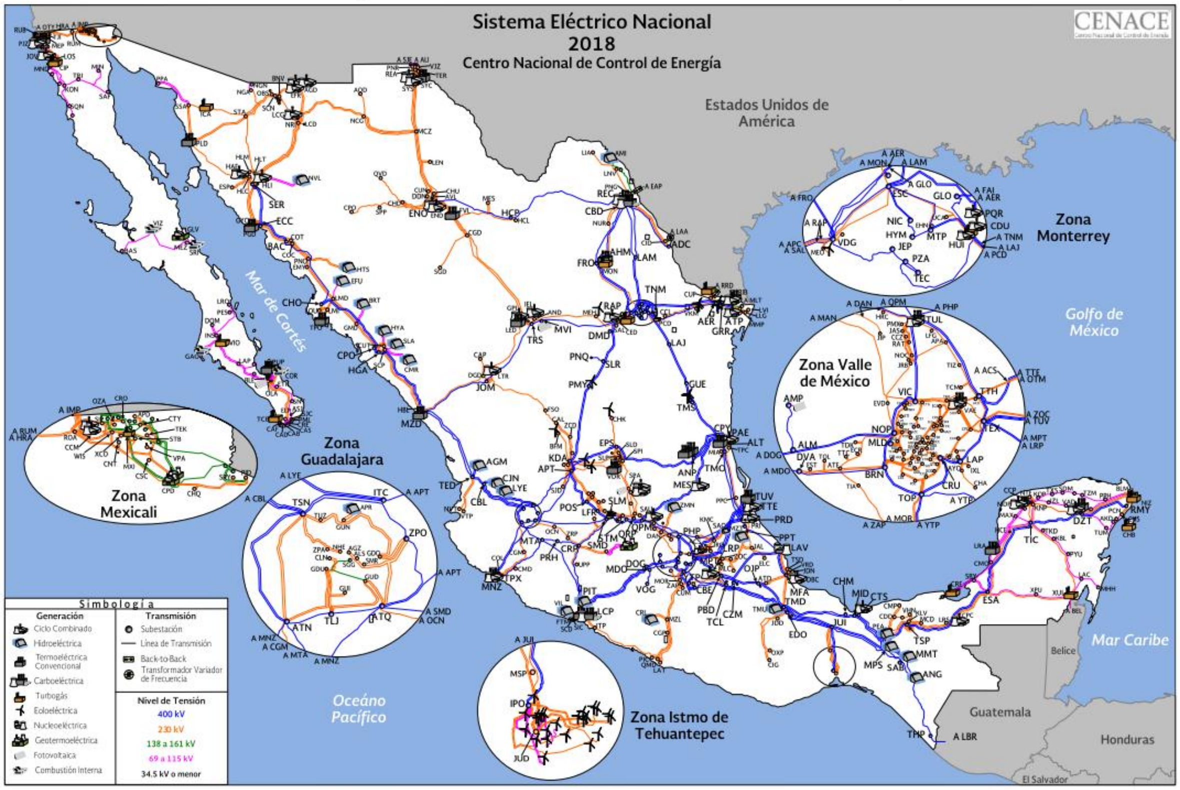

Figure 5.1. General structure of the National Electrical System (SEN by its acronym in Spanish). Source: (PRODESEN, 2019).

The SIN extends from the border with Central America to the border with the USA. It comprises the interconnected operation of seven regional systems here designated as north-western (NW), northern (N), northeastern (NE), western (W), central (C), south-eastern (SE) and peninsular (P) systems. The SIN is characterised by sparse long transmission paths, scattered generation and variable patterns of operation. As a consequence, dynamic security is often dictated by voltage control considerations and first contingency stability *(Anderson, P. M., Fouad, A. A., 2008), (O. I. Elgerd, 1982), (Kundur, P., 1994)*. Such a one-line diagram is used in the following to assess the frequency and voltage deviations under sudden load changes. Table 5.1 presents the capacities (MW) installed in each control area of the SIN *(Secretaría de Energía MÉXICO, 2019, Tables 6.1 and 6.5).*

Table 5.1. Installed capacity per control area and demand (2018). Source: (SENER, 2019)

Control area	Max (MW)	Demand (MW)
Central	8,401	6,997
Eastern	6,949	5,740
Western	10,137	7,775
Northwestern	4,248	2,818
North	4,524	3,082

Control area	Max (MW)	Demand (MW)
Northeast	9,043	6,442
Peninsular	1,866	1,483

The capacity margin is the difference between the supply and maximum demand of the system. This margin indicates the excess capacity that a system has when faced with a given level of demand.

An exceptional emphasis must be put on the Primary Regulation response of the Power Plant Units, so the requirements to guarantee the reliability are *(IRENA, 2017)*:

a. The regulation characteristic (R) expressed in percentage, must be within the following range: 3 ≤ R ≤ 7.5, see **Appendix A**;

b. The minimum frequency deviation necessary to activate the primary regulation must be between 0 and ±20 mHz, considering the insensitivity of the controllers and the precision of the frequency measurement. In total there must be an unintentional Deadband not exceeding ±20 mHz;

c. The primary regulation action should start immediately when a frequency deviation is detected. **For frequency deviations greater than 200 mHz, 50% of the total primary regulation reserve (spinning reserve) must be used within 20 seconds, and 100% of the trip must be reached within 30 seconds;**

d. All power plant units must operate without blocking their speed governors; i.e. in free mode;

e. The primary regulation reserve must be physically distributed among the different power plant units.

In the studies carried out in this report, the values of R = 5% are assumed for the frequency regulation of each control area, which is under the conventional values used in many countries, including Mexico (value of parameter R_i utilized in Fig. 5.4).

Likewise, compliance with paragraphs (d) – (e) has been mainly observed, by assuming that each control area has generators available to perform frequency regulation that contributes to regulating it for the benefit of the interconnected system.

5.1 Isolated system: Baja California Sur

In Mexico, there are several isolated electrical systems (Baja California, Mulege y Baja California Sur). In this report, we focus on that of Baja California Sur because it is a peculiar system in its structure (longitudinal) and the generation technologies employed (a mix of conventional and clean), Fig. 5.2. Besides, Table 5.2 indicates the installed capacity and demand for such a system.

Table 5.2. Installed capacity in Baja California Sur (2018). (PRODESEN, 2019, Table 6.5)

Region	Max (MW)	Demand (MW)
BCS	500	457.2

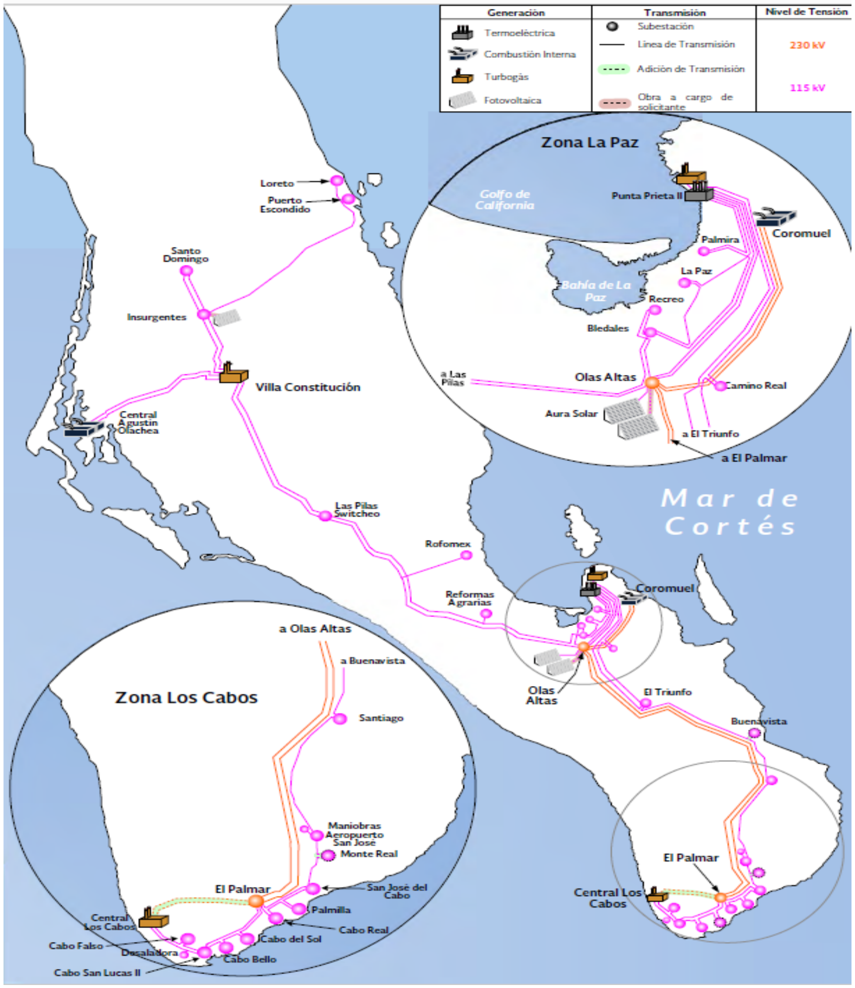

Figure 5.2. Electrical system diagram of Baja California Sur. Source: (CENACE, 2018).

Note that the distance from Cabo San Lucas to Loreto is 380 km. The entirely longitudinal structure of this electrical system is noteworthy, which in advance indicates a low profile in voltage magnitudes. The transmission voltage levels are 115 kV, except for a few small sections at 230 kV. Therefore, it is a system that requires attention to reactive power management.

On the other hand, two of the power plants taken into account are photovoltaic: Insurgentes (27 MW) and Olas Altas (Aura Solar I with 39 MW); therefore, lacking inertia. This results in weakness for frequency regulation. The voltage and frequency results for such a system are summarised below. Thus, the installed capacity in the region is made up of single-cycle gas turbine (TG) plants, internal combustion engine (IC) plants, and photovoltaic plants (PV).

5.2 Frequency studies

In the SIN study, to analyse the behaviour of the frequency throughout the system, a disturbance equivalent to 1.5%, 1,0%, and 0.5% of the area coincident total demand in each control area was applied, Fig. 5.3 and Table 5.3 (Appendix A).

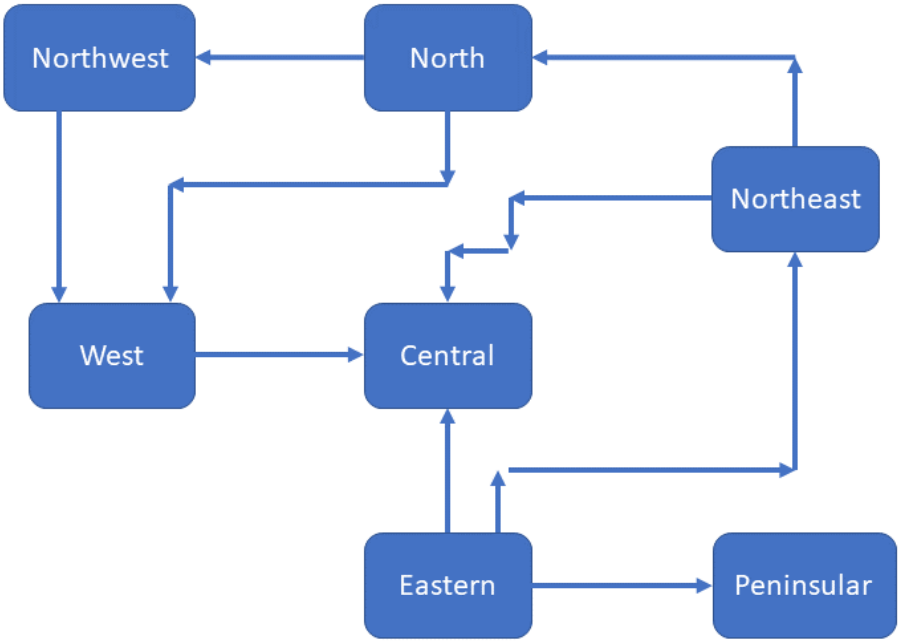

Figure 5.3. The interconnection structure of the seven control areas of the SIN. Source: Own elaboration.

For the frequency analysis of the seven control areas, Fig. 5.3, the strategy of interconnection by regions is followed, Fig. 5.4. The nominal demands are summarised in Tables 5.2 and 5.3.

Table 5.3. Coincident demand capacity and load change. Source: own elaboration.

Control area	Coincident demand (MW)	0.50%	1.00%	1.50%
		Load change (MW)		
Central	6,997	35.0	70.0	105.0
Eastern	5,740	28.7	57.4	86.1
Western	7,775	38.9	77.8	116.6
Northwestern	2,818	14.1	28.2	42.3
North	3,082	15.4	30.8	46.2
Northeast	6,442	32.2	64.4	96.6
Peninsular	1,483	7.4	14.8	22.2
BCS	315	1.6	3.2	4.7

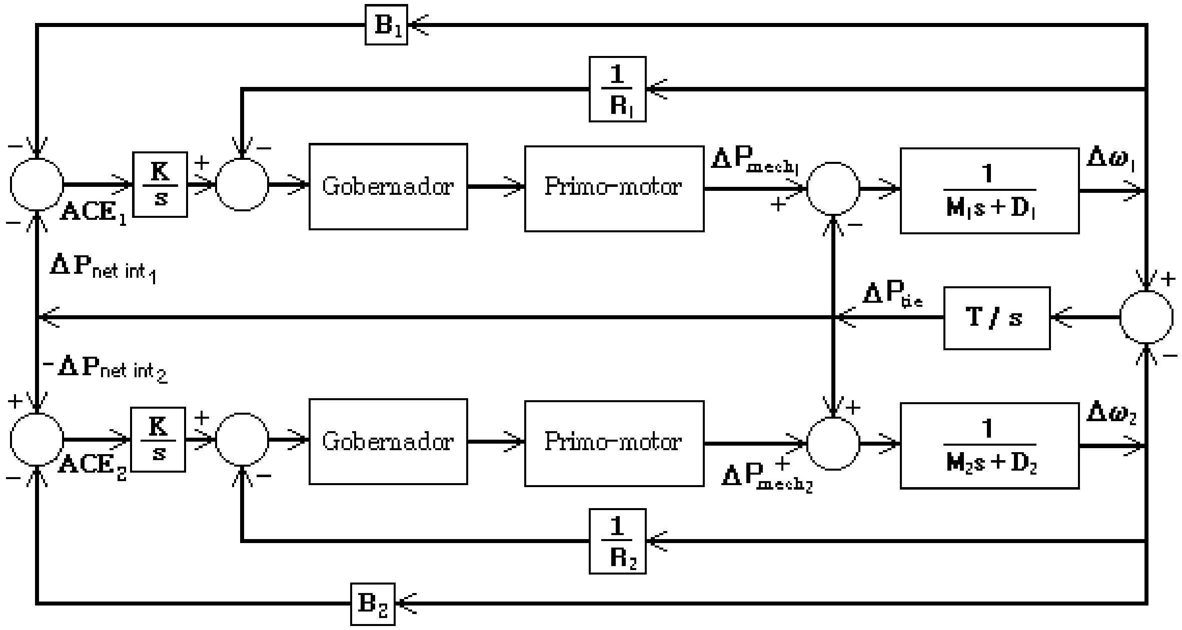

Figure 5.4. Two-area control system. In this study, it was extended to seven areas (not shown for simplicity). (Elgerd O.I., 1982).

The data for the simulations are attached in the following Matlab files.

Main program[3]: " StateSpace_ModelFreq_Sieteareas_JMRA_Mar2020.m";

data: "siete.mat", “parametros.mat”, and " area7_conBESS.mat".

Figure 5.5 represents typical results under a load change in the Northeast area. The graph describes the frequency evolution in the seven regions under such events. The progression is as expected for this type of disturbance; it may take several minutes before the signals reach their nominal condition.

The line in red represents the frequency behaviour assuming stored energy (for instance, batteries) available in the region to be injected five cycles after the change in demand (0.083s, sufficient time and commonly spent on electrical protection). The case corresponds to the amount of 1% of the demand of the control area. Note that the frequency stabilises in a few seconds. This demonstrates the benefit that storage technologies could have in frequency regulation, thus freeing conventional generators (mainly gas-based and combined cycle) from such tasks. It is crucial to note that in none of the analysed cases does the frequency deviate more than 0.04 Hz (point called *nadir*), which ratifies the advantage of operating the network in an inter-connected manner.

For the BCS isolated system, Fig. 5.6 displays the frequency behaviour at a step of demand of 1.5%, 1%, and 0.5% of the total demand. It is noticeable that after one min, the frequency does not tend to stabilise, even with the insertion of stored energy. This is an indication of the weakness of frequency regulation that this system exhibits. An important reason for the initial frequency

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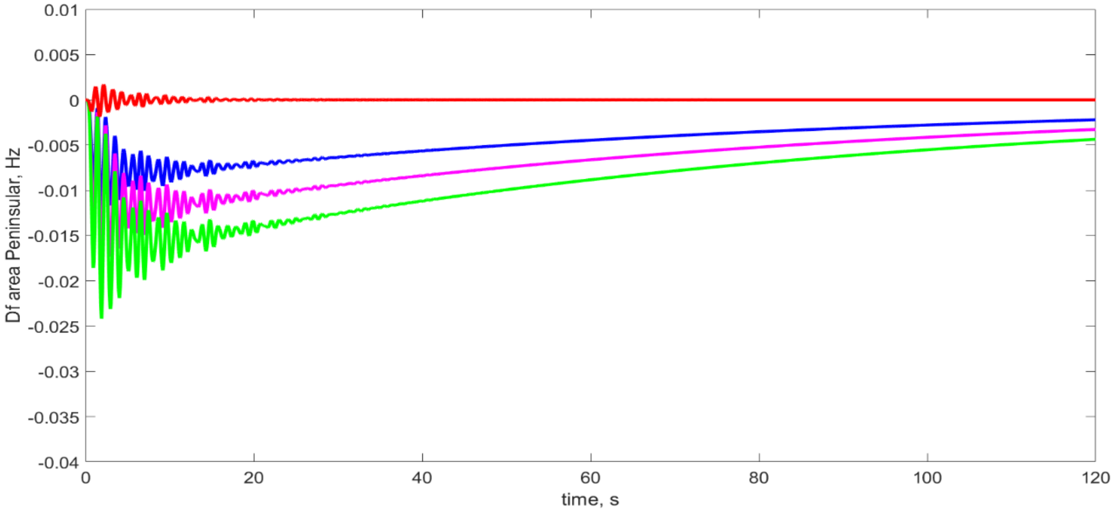
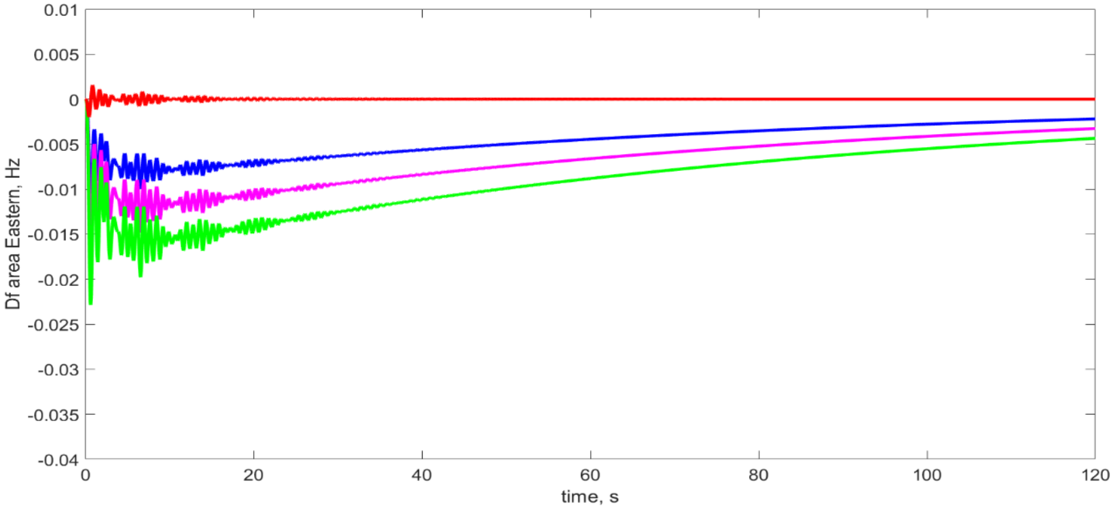
[3] These programs can be run with the free software Octave

excursion is the lack of inertia because of the installed generators are a set of small machines (single-cycle gas turbines, diesel engines). A more detailed analysis indicates that it is a system that tends towards instability. Being a longitudinal system, the output of a transmission line creates two isolated subsystems. Again, the lack of power sources and inertia becomes notorious.

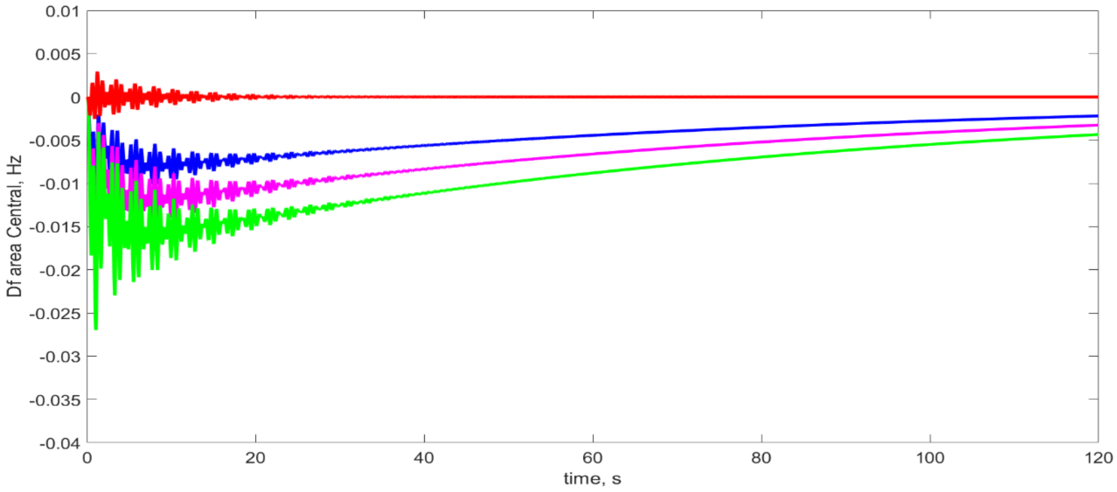
Then, as far as frequency is concerned, the fact that the SIN works synchronised saves them from manifesting more significant problems (the **Baja California Sur** system does not, because of its lack of inertia).



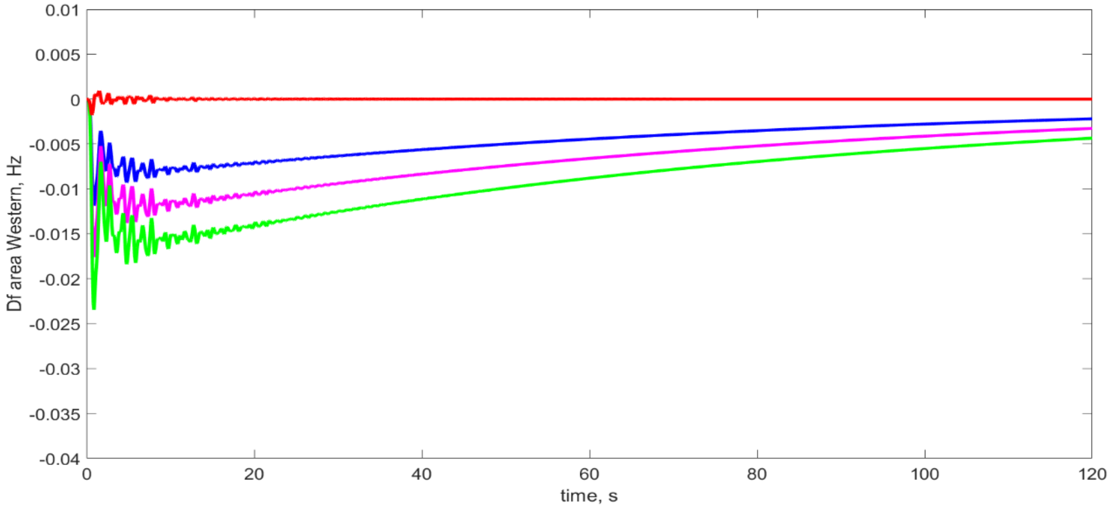
(a) Peninsular



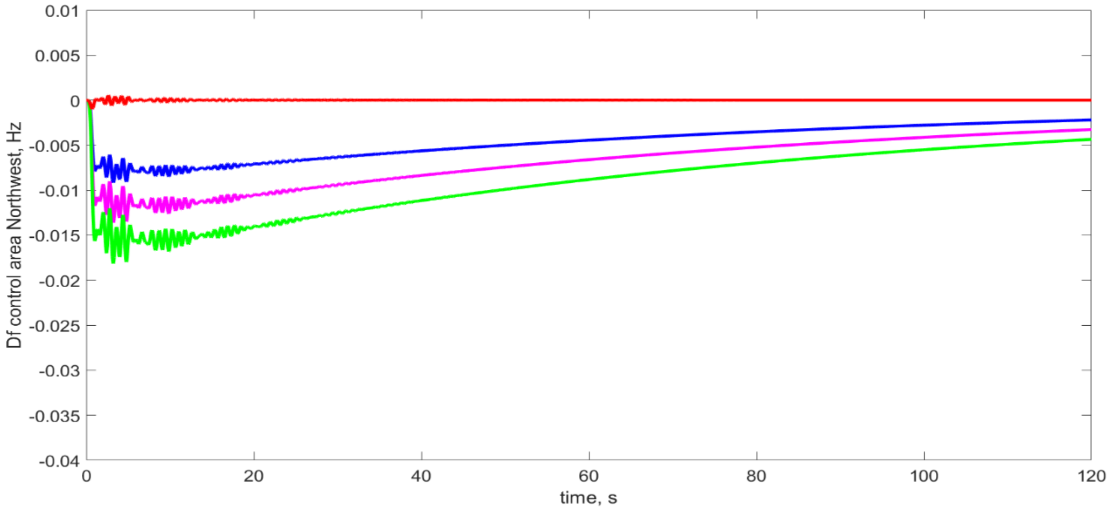
(b) Eastern



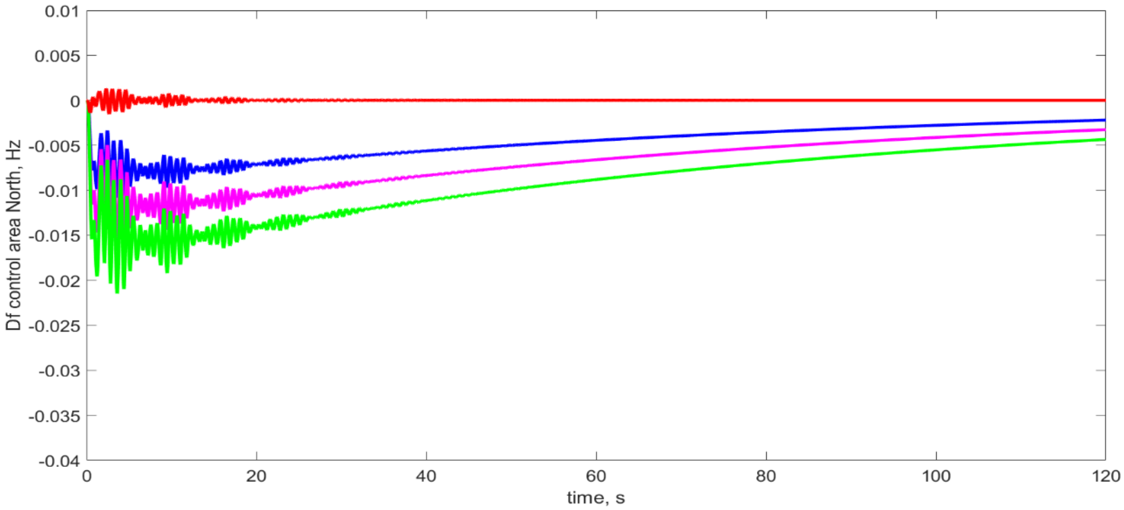
(c) Central



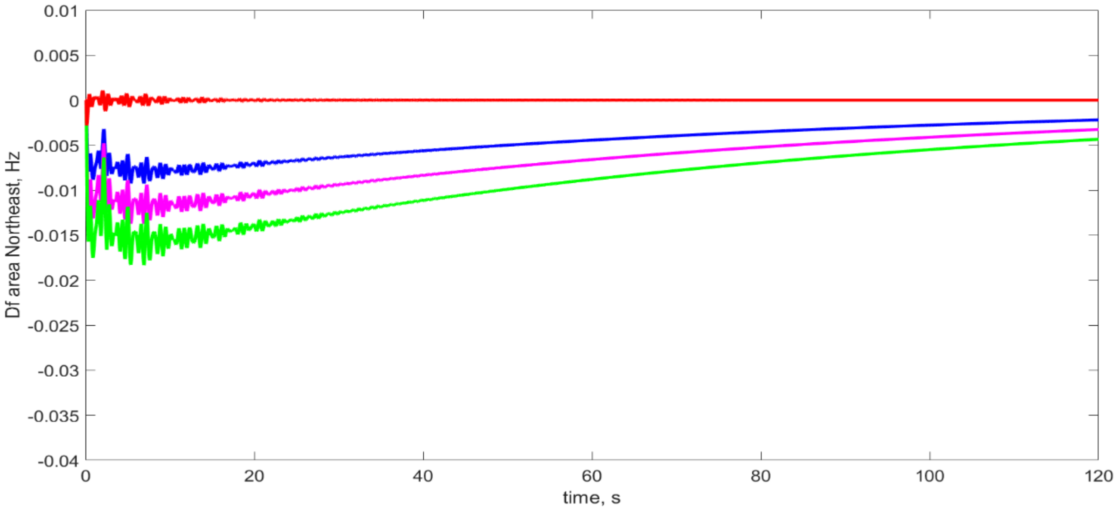
(d) Western



(e) Northwest



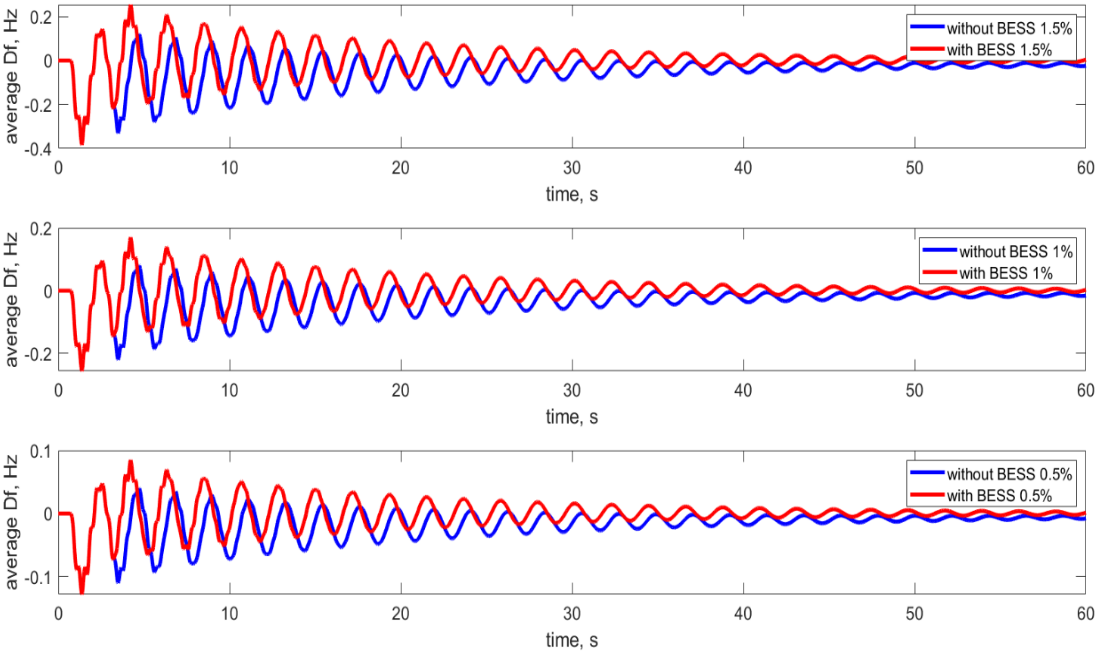
(f) North



(g) Northeast

Acronyms: BESS: battery energy storage system; Df: frequency deviation (Δf)

Figure 5.5. The behaviour of the frequency under a sudden load change the different control areas of the SIN (1.5%-green line, 1.0%-pink line, 0.5%-blue line of the control area total demand); BESS included (red line). Source: Own elaboration.



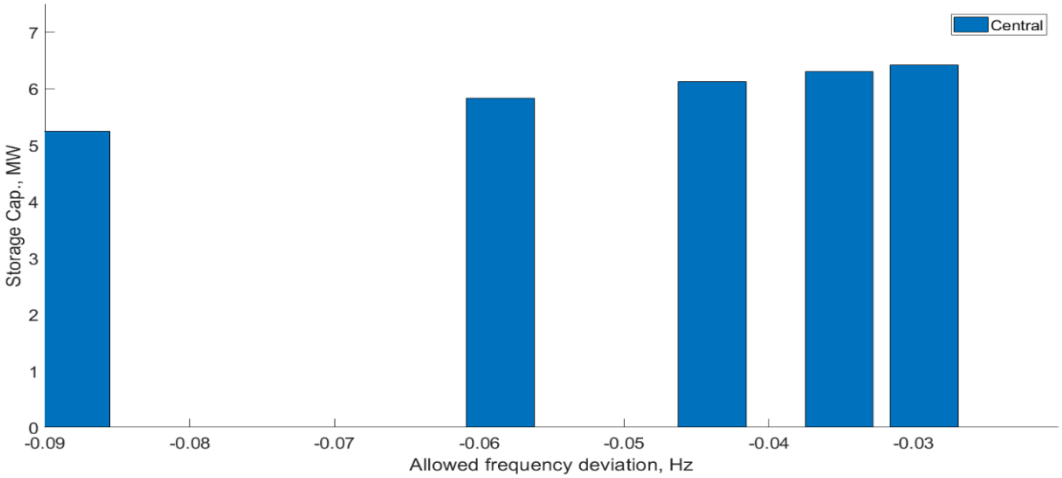
Acronyms: **BESS:** battery energy storage system; Df: frequency deviation (Δf)

Figure 5.6. The behaviour of the frequency in the event of a step-change in the BCS system (0.5%, 1.0%, and 1.5% of the total demand). Source: Own elaboration.

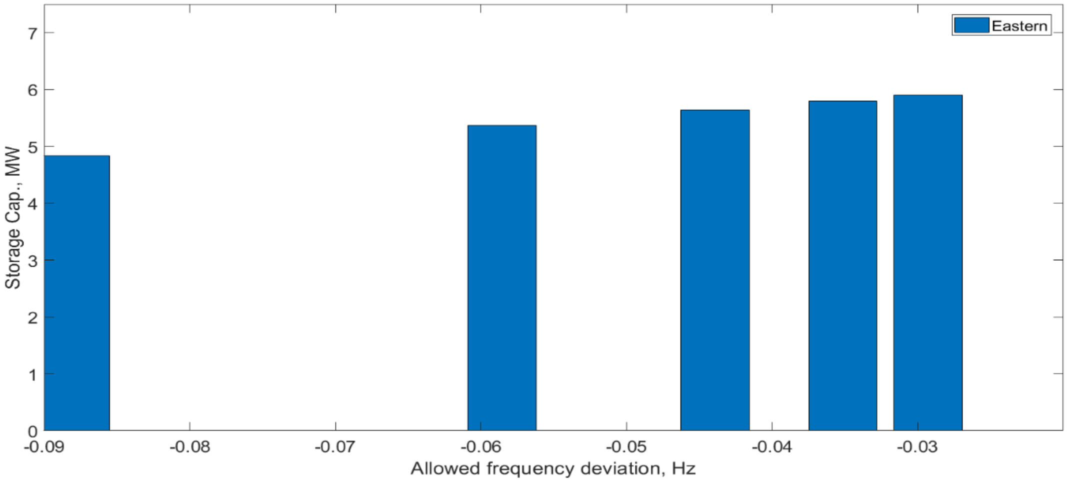
5.2.1 Calculation of the required storage capacity, taking into account frequency deviations

The calculation is summarised in Appendixes A and D. After a step-change in the area demand, the frequency deviations experienced in the different control areas are described. To calculate the level of storage necessary for frequency regulation, a sweep of demand injections was made, detecting the levels of frequency deviation that these cause. The purpose is to reach a trade-off between the degree of allowable deviation and the necessary level of storage. Such permissible variations are chosen hinged on previous studies (Figs. 5.5 and 5.6), which showed that an average frequency deviation in the range [0.3, 0.4] Hz in the seven areas of the SIN is a good trade-off.

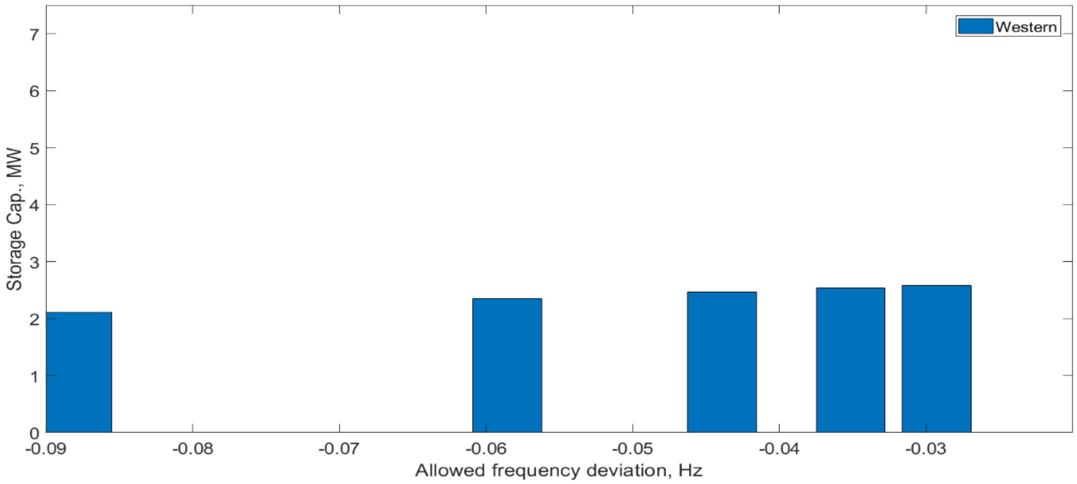
It is clear that if frequency deviations are to be minimised under the same type of demand change, more storage capacity will be required, although as shown in the Figures 9-10, this tends to reach a maximum. In short, the smaller the frequency deviation allowed, the more storage is required. Table 5.4 provides a good deal for storage capacity for each region.



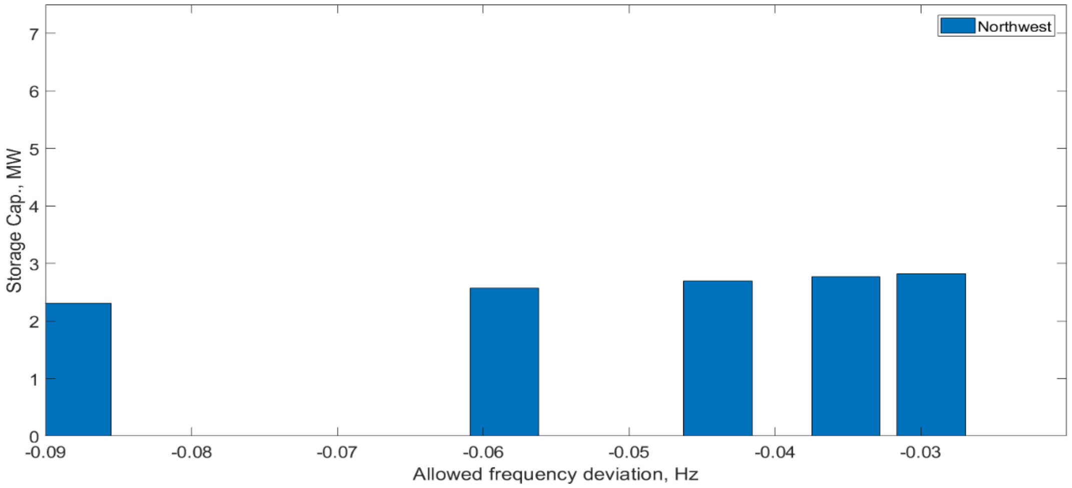
(a) Central



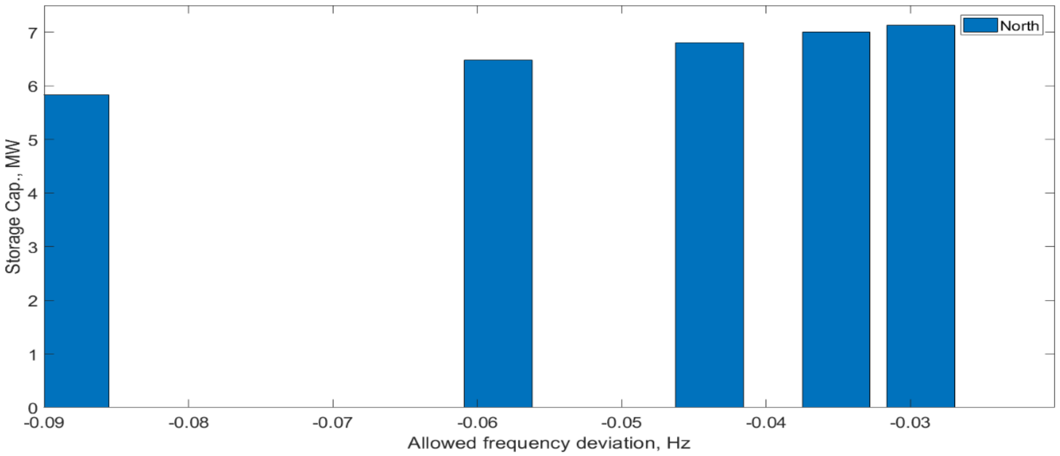
(b) Eastern



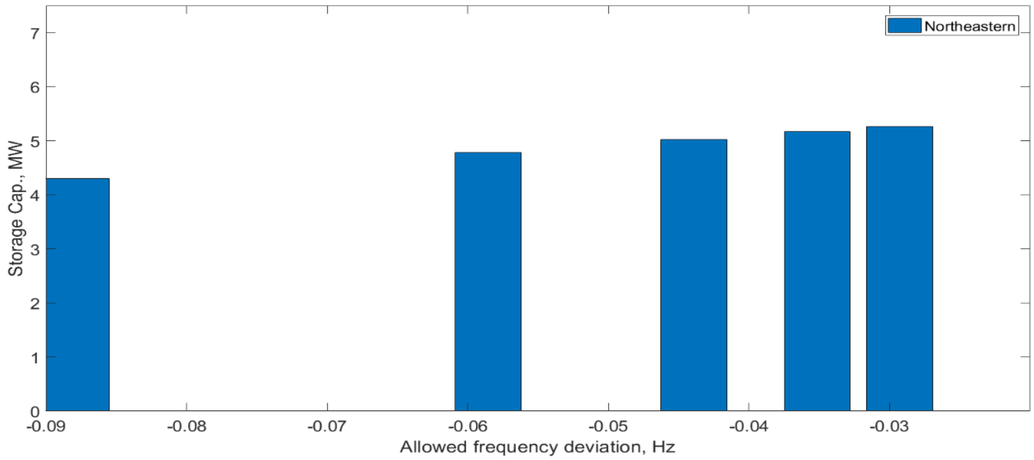
(c) Western



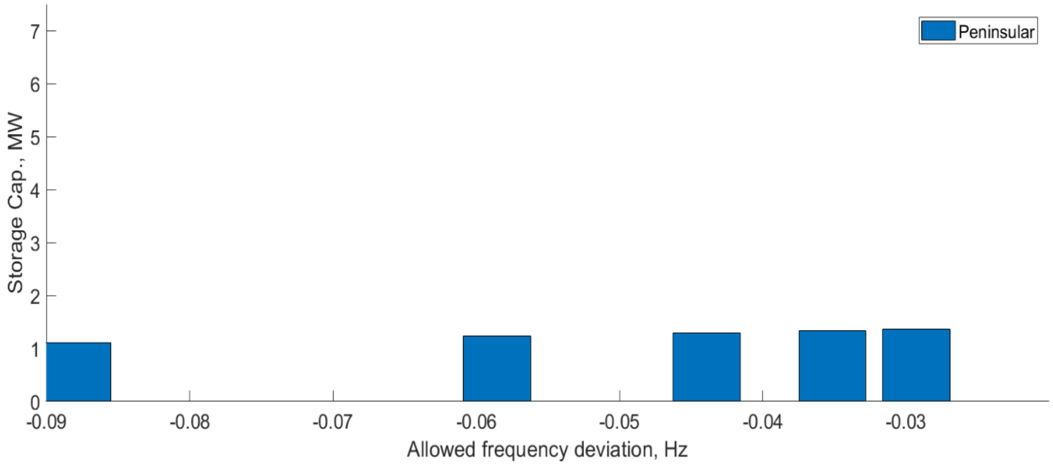
(d) Northwest



(e) North



(f) Northeastern



(g) Peninsular

Figure 5.7. Storage capacity allowing an average frequency deviation from 0.09- 0.03 Hz per control area. Source: Own elaboration.

Table 5.4. Amount of storage required to avoid deviation of frequency (min. ES) beyond a threshold in the SIN in 2018. Source: Own elaboration.

Control area	min ES <= 0.03 Hz (MW)	min ES <= 0.04 Hz (MW)
North	6.99	6.8
Central	6.29	6.12
BCS	6.03	6.01
Eastern	5.79	5.63
Northeast	5.16	5.02
Northwestern	2.77	2.69
Western	2.53	2.46

Peninsular	1.33	1.29
Total	**36.89**	**36.02**

Table 5.5. BCS: Storage capacity to limit frequency excursion. Source: Own elaboration.

Region	min. ES < 0.04 (MW)	min. ES < 0.05 (MW)
BCS	6.03	6.01

In the case of BCS, Fig. 5.8 illustrates the behaviour of the degree of storage capacity, as the frequency deviation is limited to the range [0.04, 0.05] (Fig. 5.8). Note that when the storage capacity is chosen by frequency regulation, there is a tendency to a maximum limit.

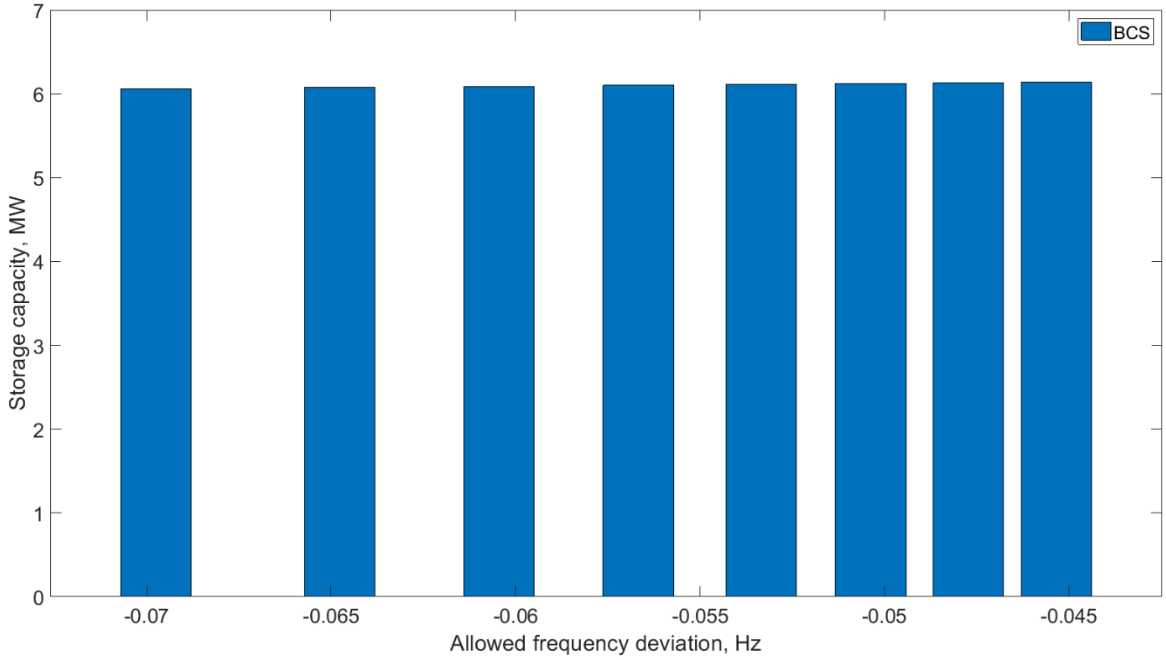


Figure 5.8. Isolated BCS system: storage capacity to limit frequency excursion in the event of a swept of step-changes in load. Source: Own elaboration.

To identified the among of capacity needed for Frecuency control under the planning forecast of PRODESEN (PIIRCE) 2019-2033, the main assumptions to do so were: (a) generation will increase (as expected in PIIRCE until 2033) in the same proportion as demand, except that conventional generation will be aprox. 70% and 30% renewable in that year, (b) Auxiliary services increase in proportion to the increase in demand (approx 3,400 MW + 121 MW storage). With these assumptions,frecuency control capacity needs for 2033 was stimated and afterwards the CO_2 reductions and generation displacement were estimated, according to the Kindle strategy and INGyCEI (see section 10).

Table 5.6. Amount of storage required to avoid deviation of frequency beyond a threshold in 2024-2033. Source: Own elaboration.

Control area	min ES (MW) <= 0.03 Hz
Eastern	26.94
Northeast	24.47
Western	18.25
BCS	13.91
North	12.67
Northwest	12.33
Central	10.51
Peninsular	2.56
Total	121.634

5.2.2 Reserve required at 9 pm (includes the spinning reserve)

The CENACE publishes daily the active power reserve requirements for the next 24 hours. This publication has been followed and does not present substantive changes day by day. The *ReqServiciosConexos SIN MDA Dia 2020-02-02 v2020 02 01_14 50 27.xls*[4] file is an example of the requirements at SIN level. Based on these, the following calculations were made, which indicate the percentage of fuel consumption savings that would be made if some storage technology were available.

In the SIN, reserve roughly equals to 1700 MW at 21 hrs. That represents a maximum MW range reserved to correct frequency deviations and Area Control Error for that hour. We know that MWh is what drives emissions production.

Let us assume three scenarios: replace 10%, 25% and 50% of the base case conventional generation capacity (MW) assigned for reserve by energy storage. For the 1700 MW frequency regulation reserve margin for that hour, it means that the 10% scenario replaces 170 MW of fossil generation with storage; the 25% scenario replaces 425 MW, and the 50% scenario replaces 850 MW. For such an hour, that represented a maximum output reduction from fossil units of (170 MW/45167 MW*100% =) 0.377%, 0.941% and 1.882%, respectively. Note that the calculations were made assuming a maximum coincident demand of 45.167 GW *(SECRETARIA DE ENERGIA, 2019, Table 6.5)*. Taking into account a similar proportion to that Table *(SECRETARIA DE ENERGIA, 2019, Table 6.5)*, Table 5.6 displays the percentages per control area.

Table 5.7. Percentage reserve reduction per control area at 21:00 hrs (SIN). Source: Own elaboration.

Control area	Scenario 1 (%)	Scenario 2 (%)	Scenario 3 (%)
Central	0.05	0.12	0.24
Eastern	0.10	0.25	0.49

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[4] https://www.cenace.gob.mx/SIM/VISTA/REPORTES/ServConexosSisMEM.aspx

Control area	Scenario 1 (%)	Scenario 2 (%)	Scenario 3 (%)
Western	0.06	0.16	0.32
Northwest	0.03	0.07	0.14
North	0.03	0.08	0.16
Northeast	0.09	0.23	0.47
Peninsular	0.01	0.03	0.07

In the case of Baja California Sur, the reserve requirements are the same for 24 hours a day: 60 MW. Let us assume three scenarios: replace 10%, 25% and 50% of the base case conventional generation capacity (MW) assigned for reserve by energy storage. For the 60 MW frequency regulation reserve margin for that hour, it means that the 10% scenario replaces 6 MW of fossil generation with storage; the 25% scenario supersedes 15 MW, and the 50% scenario replaces 30 MW. For such an hour, that represented a maximum MWh output reduction from fossil units of (6 MW/457.2MW*100% =) 1.31%, 3.280% and 6.561%. Note that the calculations were made assuming a peak demand of 457.2 MW *(SECRETARIA DE ENERGIA, 2019, Table 6.5)*.

In the case of a smaller system, such as that of Baja California Sur, the possible contribution of storage technologies to displace plants operating with fossil fuels is promising.

Likewise, notice that conventional fossil-fueled resources have a limited range of operation for frequency regulation service. Most fossil-fueled resources cannot provide frequency regulation service through their entire operating range and thus are limited to 10% to 20% of their capacity for any given hour. The mix of conventional resources providing frequency regulation favours combined cycles, rather than coal or combustion turbines.

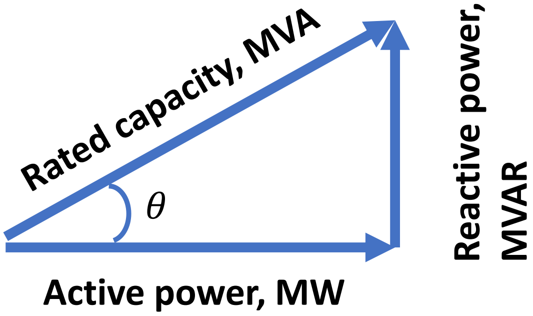
5.3 Guarding against voltage collapse

Given its impact on the operation and lifespan of electrical facilities, the maintenance of the voltage level within limited ranges of variation is a vital criterion in the quality assessment of the electrical energy supply.

Because the transmission and distribution grids are mainly inductive, voltage drops in high voltage networks are mostly due to the circulation of reactive power. Therefore, it is via the control of this quantity that voltage control is carried out on the transmission system.

The electrical equipment capacity (generator, transformer, breakers, etc.) is specified in MVA, Fig. 5.9. Active power (MW) can be converted into useful work; reactive power does not. However, for example on a transmission line, to transmit a specific amount of active power, a certain amount of reactive power is required to supply the electric and magnetic fields on the line, without which transmission between two points could not be achieved. If a transmission line is not operated correctly, it can become a *reactive sink*, wasting a lot of power that could be turned into useful work.

In the case of a synchronous generator, it can be used to provide only reactive power (an operation called *synchronous capacitor*), with a minimum of active power. This operation is used when the operator admits that the power system requires reactive support to operate correctly, especially from the voltage point of view, since there is a close relationship between reactive power and Voltage. Thus, especially in electrically remote nodes, it is convenient to provide (*compensate*) reactive power locally (through reactive sources, such as capacitors), instead of carrying the reactive power through the transmission line, which causes losses.



$$\cos(\theta) \coloneqq power\ factor$$

Figure 5.9. Power triangle. (Elgerd O.I., 1982).

The relationship between the active power P and the magnitude of the voltage V is of great interest in studies on voltage stability, and the analysis of their interaction has been reflected in the construction of the curves called power-voltage (P-V), see Appendix C.

On P-V curves, as the load increases, the voltage magnitude decreases and gradually approaches the point of operation marked as maximum power Pmax (voltage collapse point). If the system is operating near this critical value, the main issue is that a slight increment in load produces a drastic drop in voltage magnitude; which can lead to an inoperable condition, named a *voltage collapse*.

Thus, the P-V curves may be used as a metric of how close a bus is from a voltage collapse and the inoperability of the system (Appendix C).

As mentioned above, the voltage profile study is local, as opposed to the study of the frequency, which can be more regional and even system level. Thus, in what follows, some important nodes for different relevant projects are analysed, to evaluate the reactive/voltage requirements, and propose the reactive compensation value that allows improving the voltage profile within the area of interest, Fig. 5.10, and keep it within the nominal values ($V_{nominal}$ ± 5%).

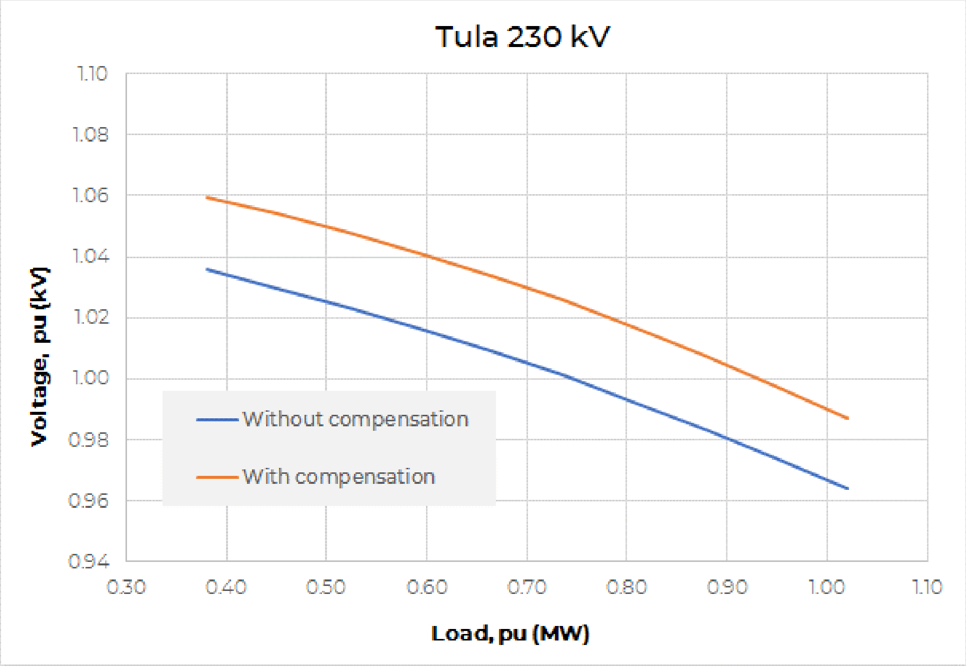
Figure 5.10 illustrates the demand and voltage behaviour on buses in different regions of the SIN, For instance, MOCTEZUMA in Chihuahua, SALTILLO in Saltillo, ZIMAPAN in Hidalgo, TULA in Hidalgo, VALLADOLID, and CANCUN in Yucatán. Table 5.8 presents the sampled nodes and their location. The nodes have been chosen for their importance within current projects of concern to SIN *(CENACE, Dic. 2017)*.

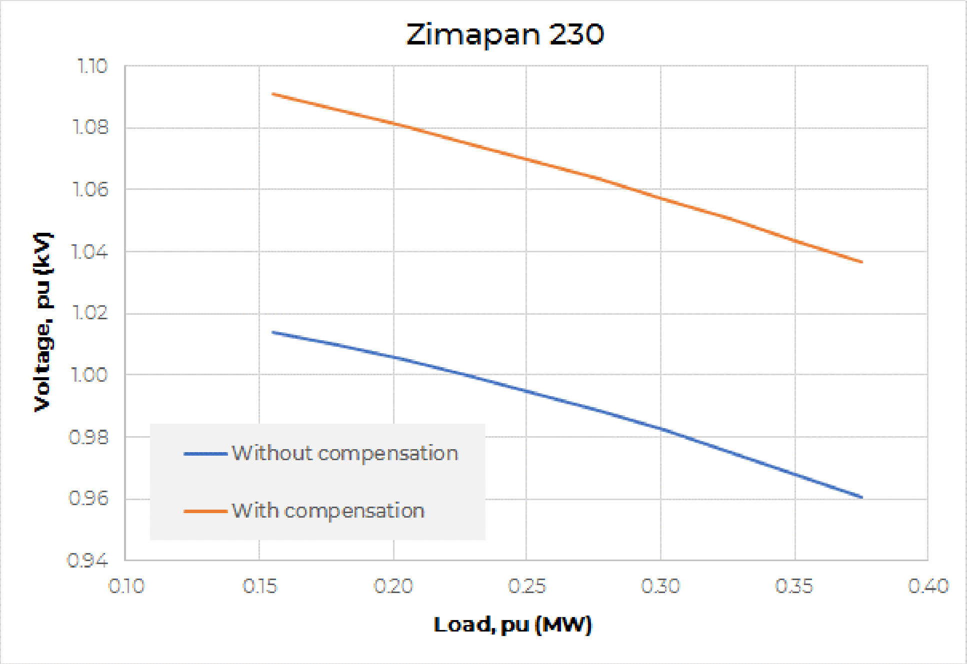
Table 5.8. List of some nodes of current interest for the SIN. Source: own elaboration.

Control area	Buses to be tested
Central	SIN:ZIMAPAN and TULA in Hidalgo;

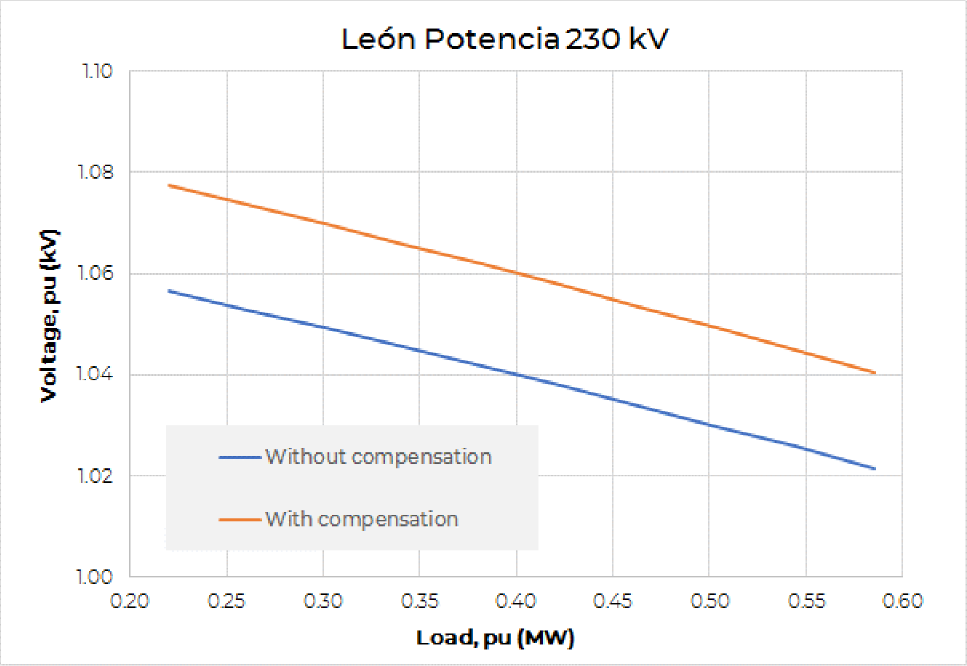
Control area	Buses to be tested
Western	SIN: LEON in Guanajuato, QUERETARO in Querétaro, SILAO and SAN LUIS DE LA PAZ in Guanajuato;
Peninsular	SIN: VALLADOLID, CANCUN, and RIVIERA MAYA in Yucatán
Northeast	SIN: SALTILLO, RAMOS ARIZPE, CEDROS in Saltillo
North	SIN: MOCTEZUMA 230, CAMARGO, in Chihuahua
BCS	LORETO, EL PALMAR, VILLA CONSTITUCION, OLAS ALTAS, PUERTO ESCONDIDO, and SANTO DOMINGO

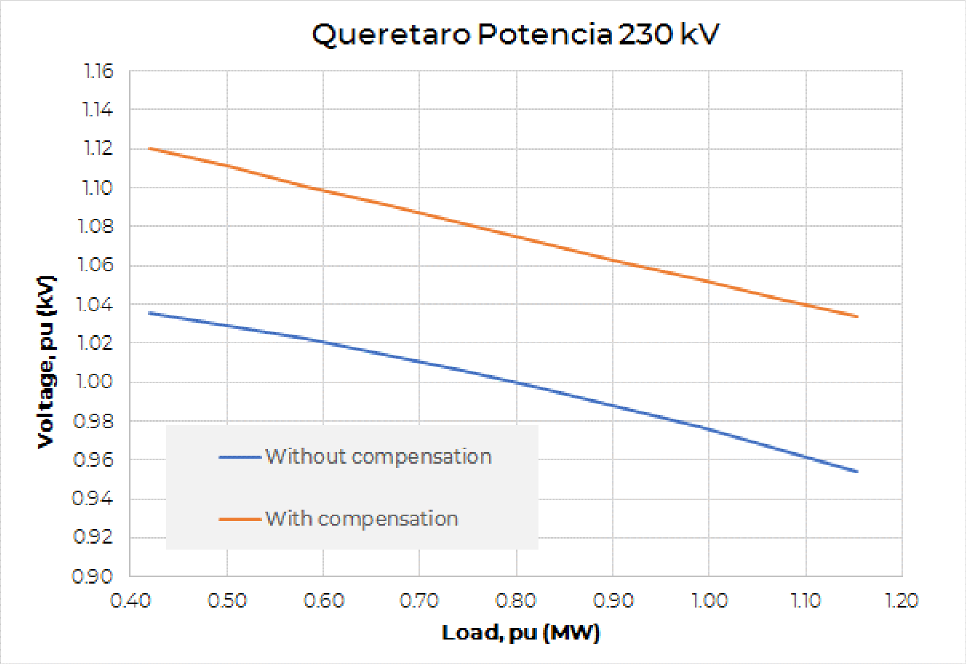
It is noteworthy that as the load increases, the voltages decrease. Particularly in regions where there is a lack of reactive power, either because they are located far from generation sources or because of increased demand. There, low Voltage is notorious, even without substantial increases in load. The red lines indicate that reactive compensation has been inserted (with the compensation value shown in Table 5.8) to improve the performance of the bus and allow more powerful load management. In general, the improvement is noticeable. It is relevant to indicate that the compensation of reagents represents a way to reinforce the transmission ability of a corridor because it implies voltage support under demand variations. Compensations may be made through batteries.



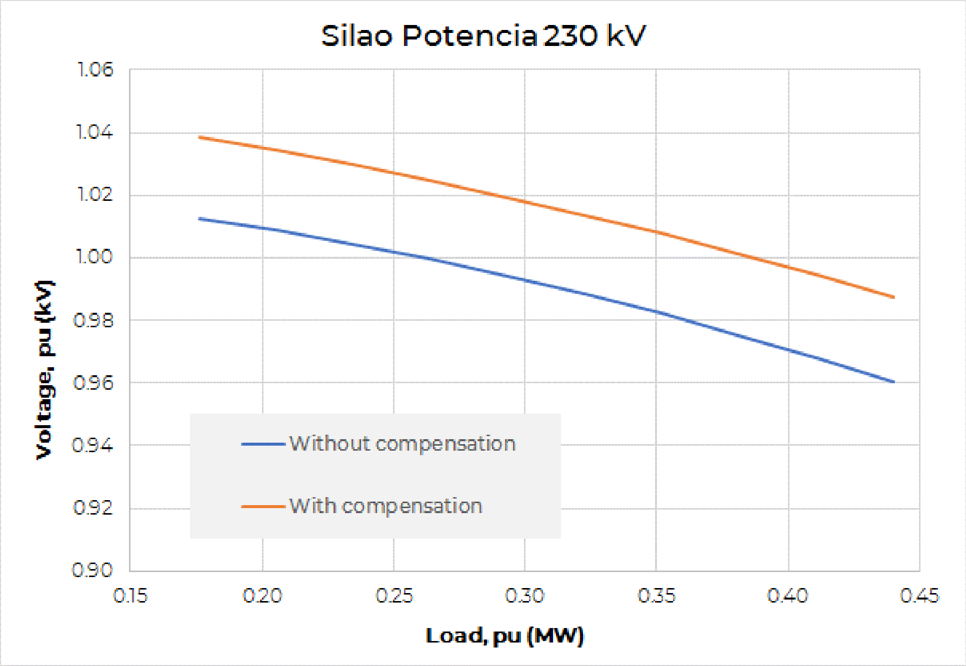

Zimapan 230
Voltage, pu (kV)
1.10
1.08
1.06
1.04
1.02
1.00
0.98
0.96
0.94
0.10
0.15
0.20
0.25
0.30
0.35
0.40
Load, pu (MW)
Without compensation
With compensation

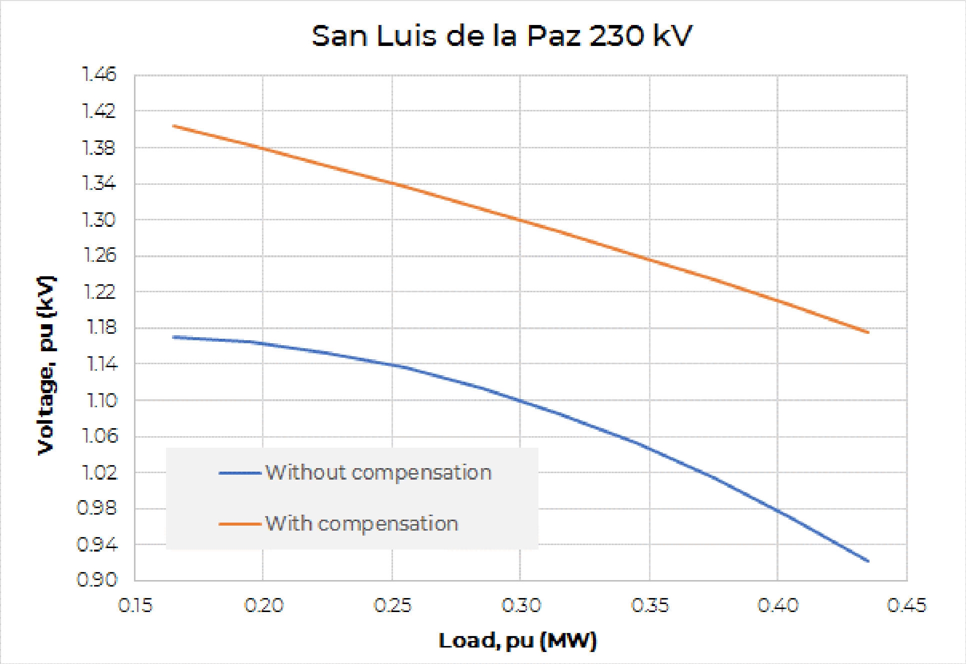
(a) Western 1


León Potencia 230 kV
Voltage, pu (kV)
1.10
1.08
1.06
1.04
1.02
1.00
0.20
0.25
0.30
0.35
0.40
0.45
0.50
0.55
0.60
Load, pu (MW)
Without compensation
With compensation

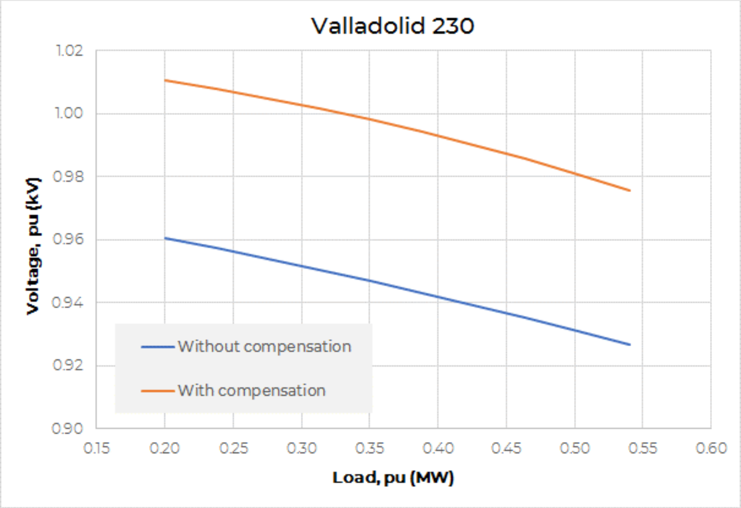

Queretaro Potencia 230 kV
Voltage, pu (kV)
1.16
1.14
1.12
1.10
1.08
1.06
1.04
1.02
1.00
0.98
0.96
0.94
0.92
0.90
0.40
0.50
0.60
0.70
0.80
0.90
1.00
1.10
1.20
Load, pu (MW)
Without compensation
With compensation

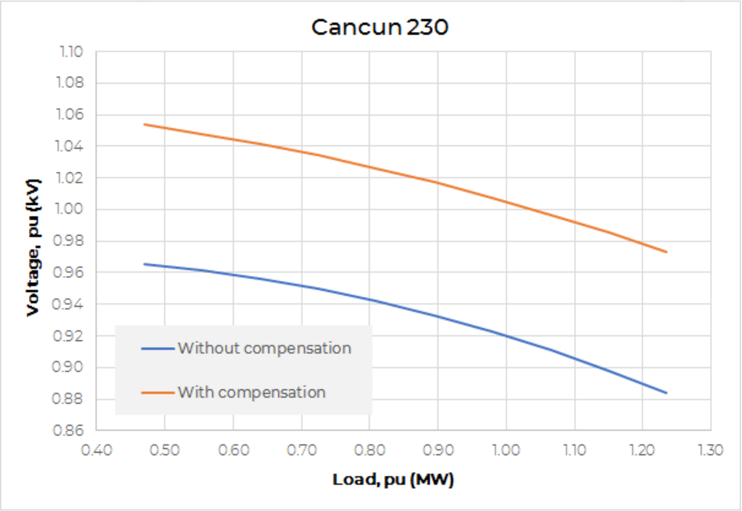
(b) Western 2

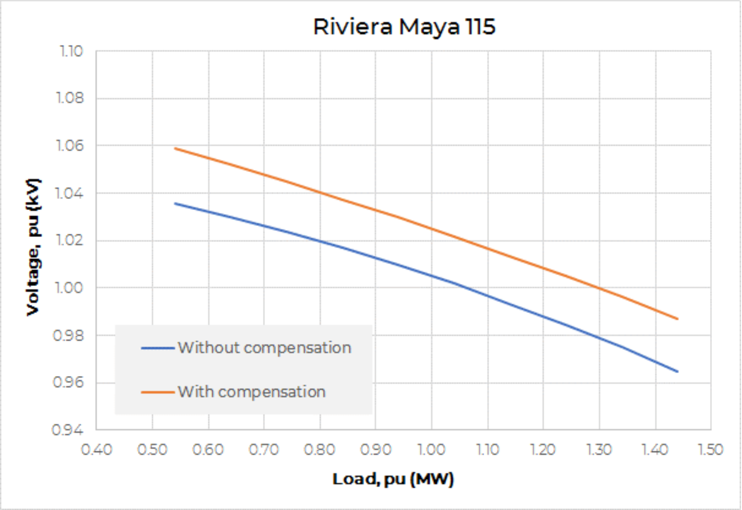

Silao Potencia 230 kV
Voltage, pu (kV)
1.06
1.04
1.02
1.00
0.98
0.96
0.94
0.92
0.90
0.15
0.20
0.25
0.30
0.35
0.40
0.45
Load, pu (MW)
Without compensation
With compensation


San Luis de la Paz 230 kV
Voltage, pu (kV)
1.46
1.42
1.38
1.34
1.30
1.26
1.22
1.18
1.14
1.10
1.06
1.02
0.98
0.94
0.90
0.15
0.20
0.25
0.30
0.35
0.40
0.45
Load, pu (MW)
Without compensation
With compensation

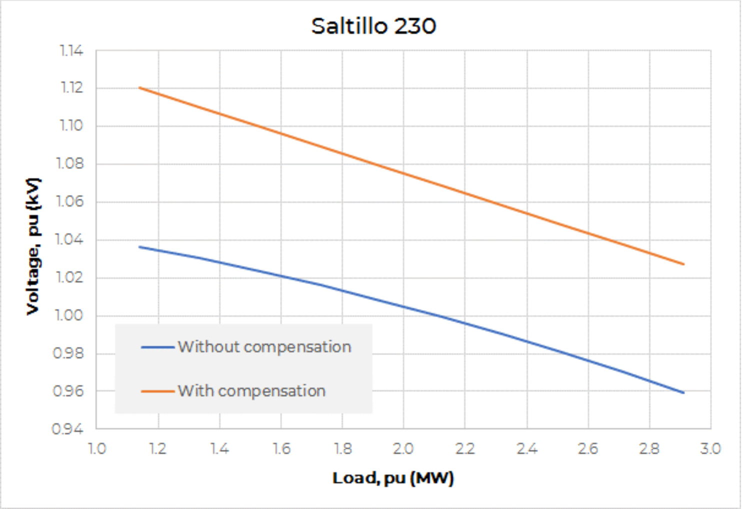
(c) Western 3

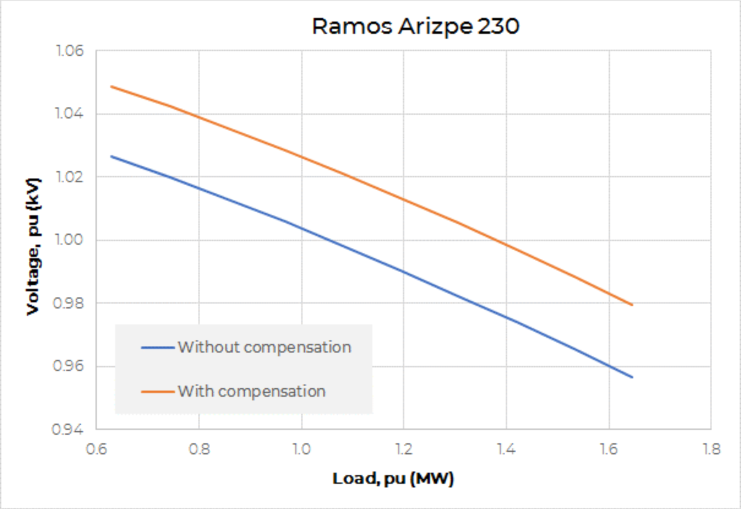

Valladolid 230
Voltage, pu (kV)
1.02
1.00
0.98
0.96
0.94
0.92
0.90
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
0.55
0.60
Load, pu (MW)
Without compensation
With compensation

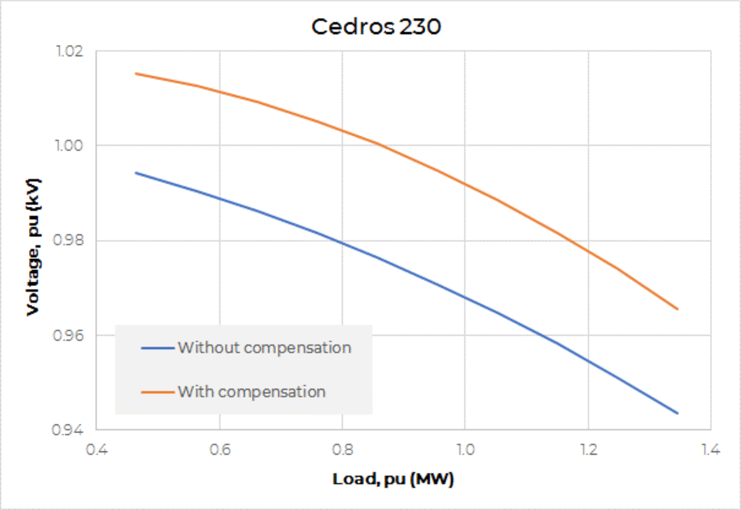




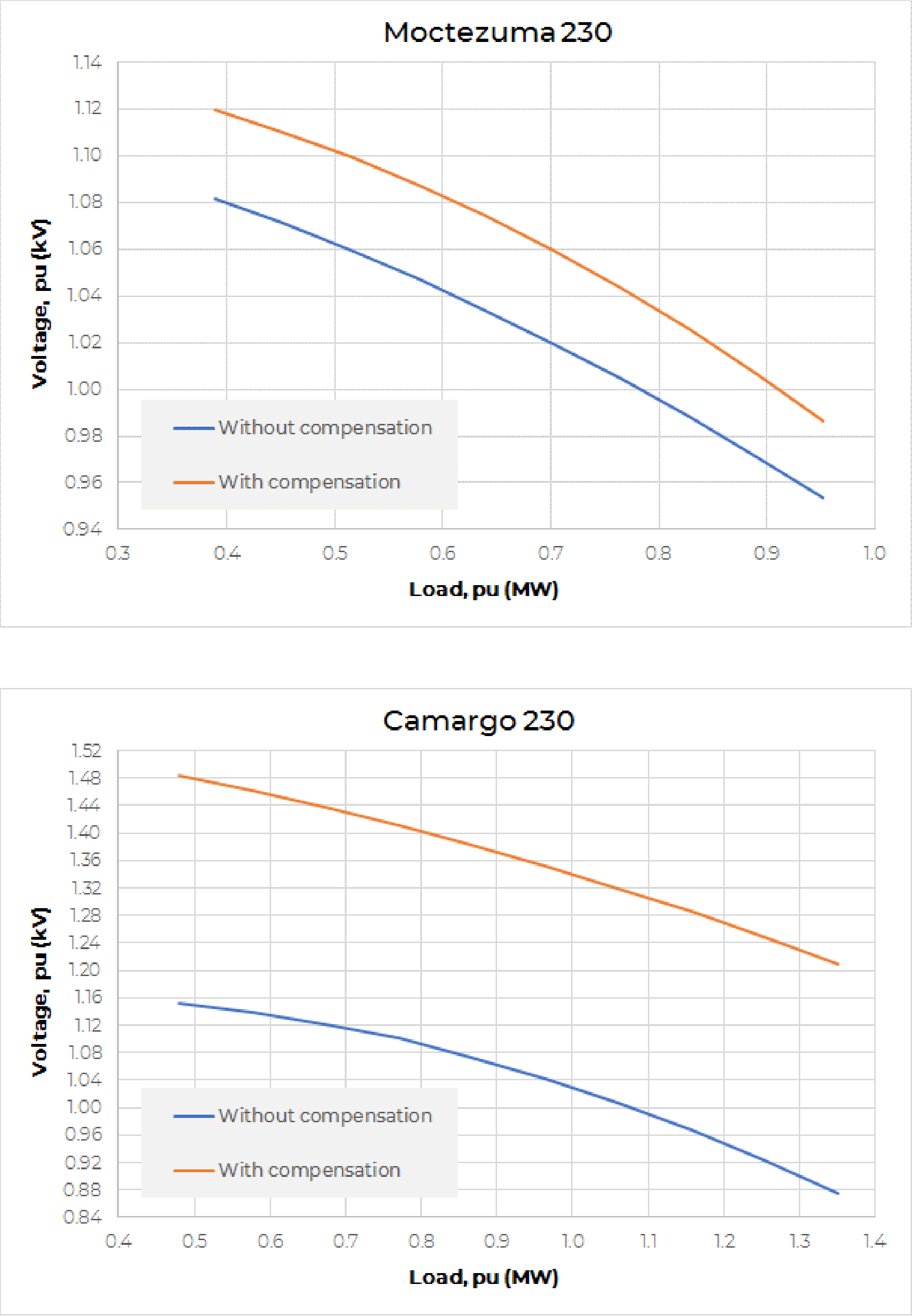
(d) Peninsular




Ramos Arizpe 230
1.06
1.04
1.02
1.00
0.98
0.96
0.94
Voltage, pu (kV)
0.6
0.8
1.0
1.2
1.4
1.6
1.8
Load, pu (MW)
Without compensation
With compensation


Cedros 230
1.02
1.00
0.98
0.96
0.94
Voltage, pu (kV)
0.4
0.6
0.8
1.0
1.2
1.4
Load, pu (MW)
Without compensation
With compensation

(e) Noreste

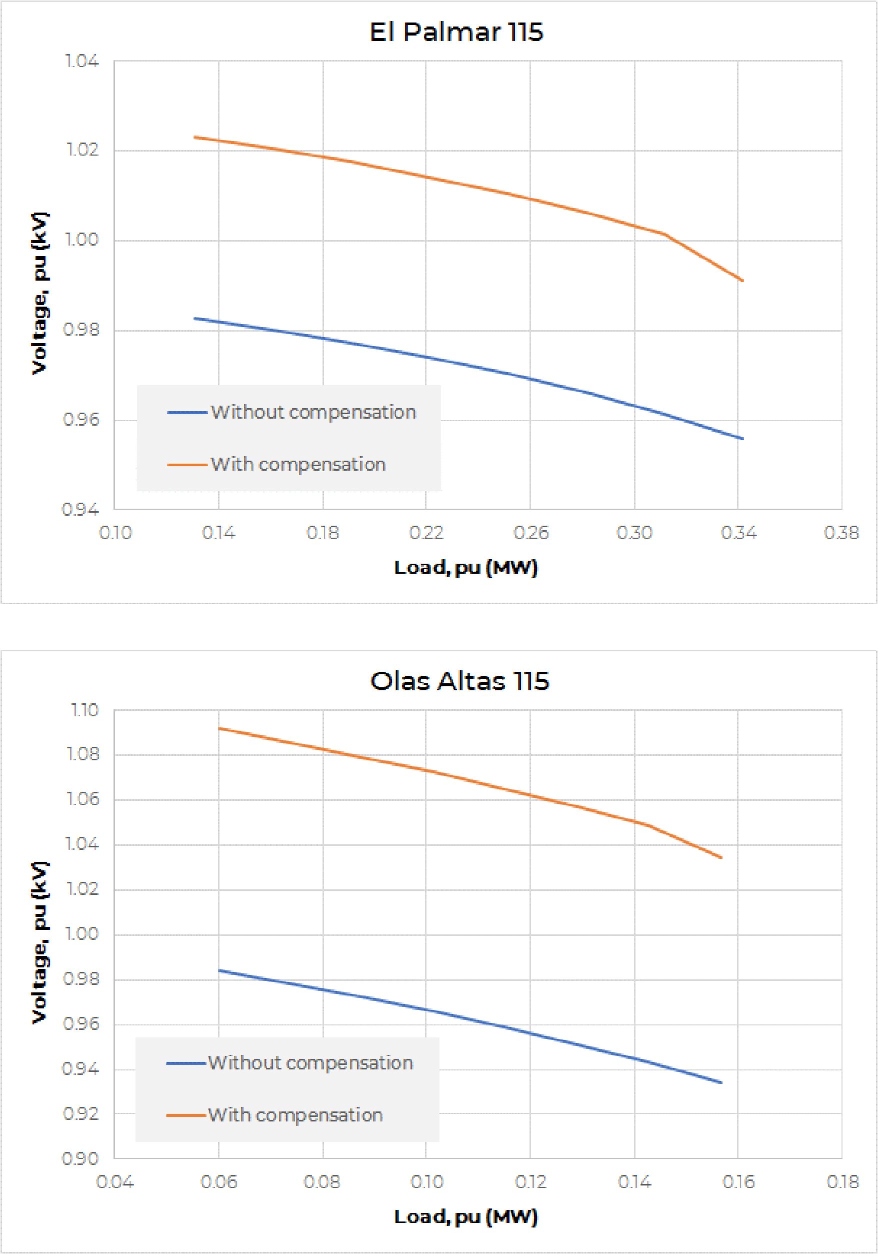


(a) Norte

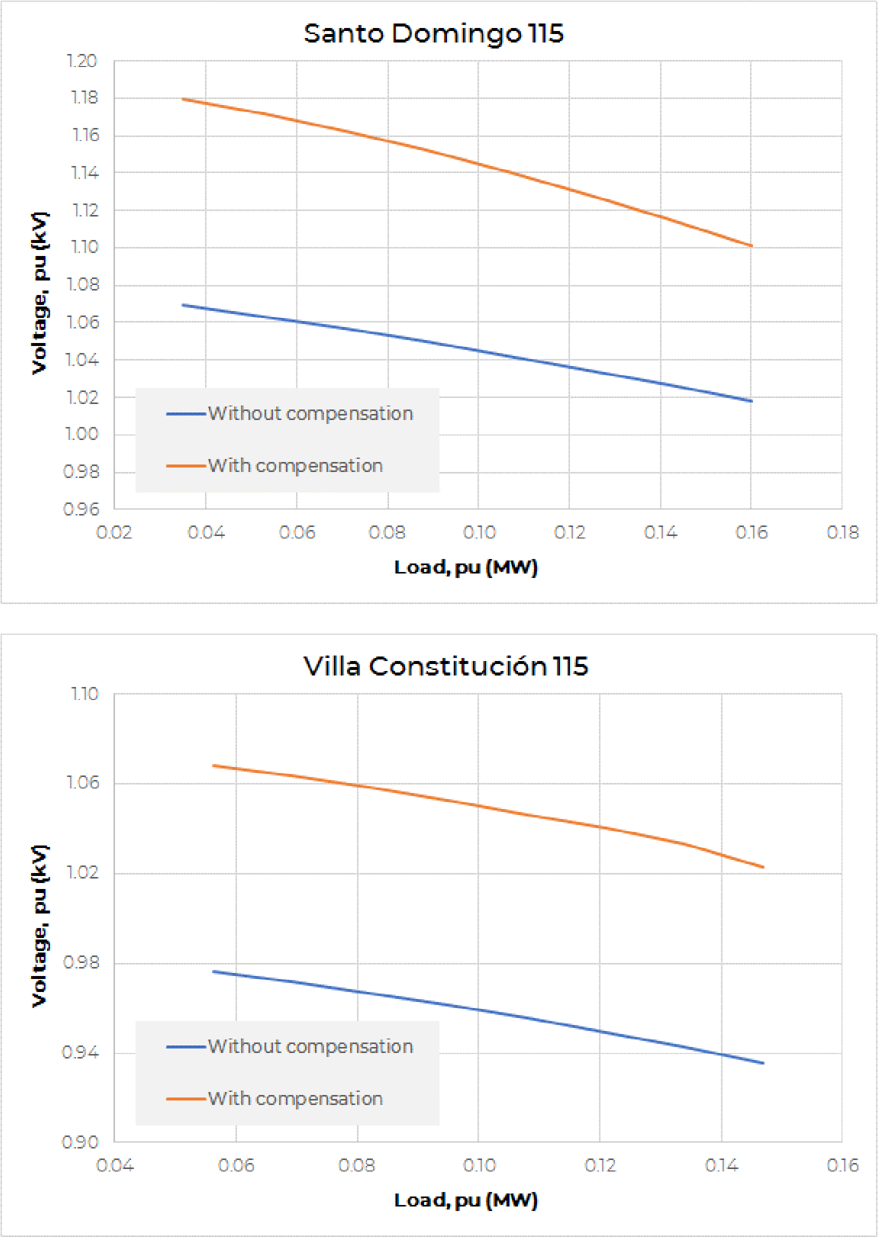
Figure 5.10. P-V curves in some buses of different control areas. Source: Own elaboration.

5.3.1 Baja California Sur

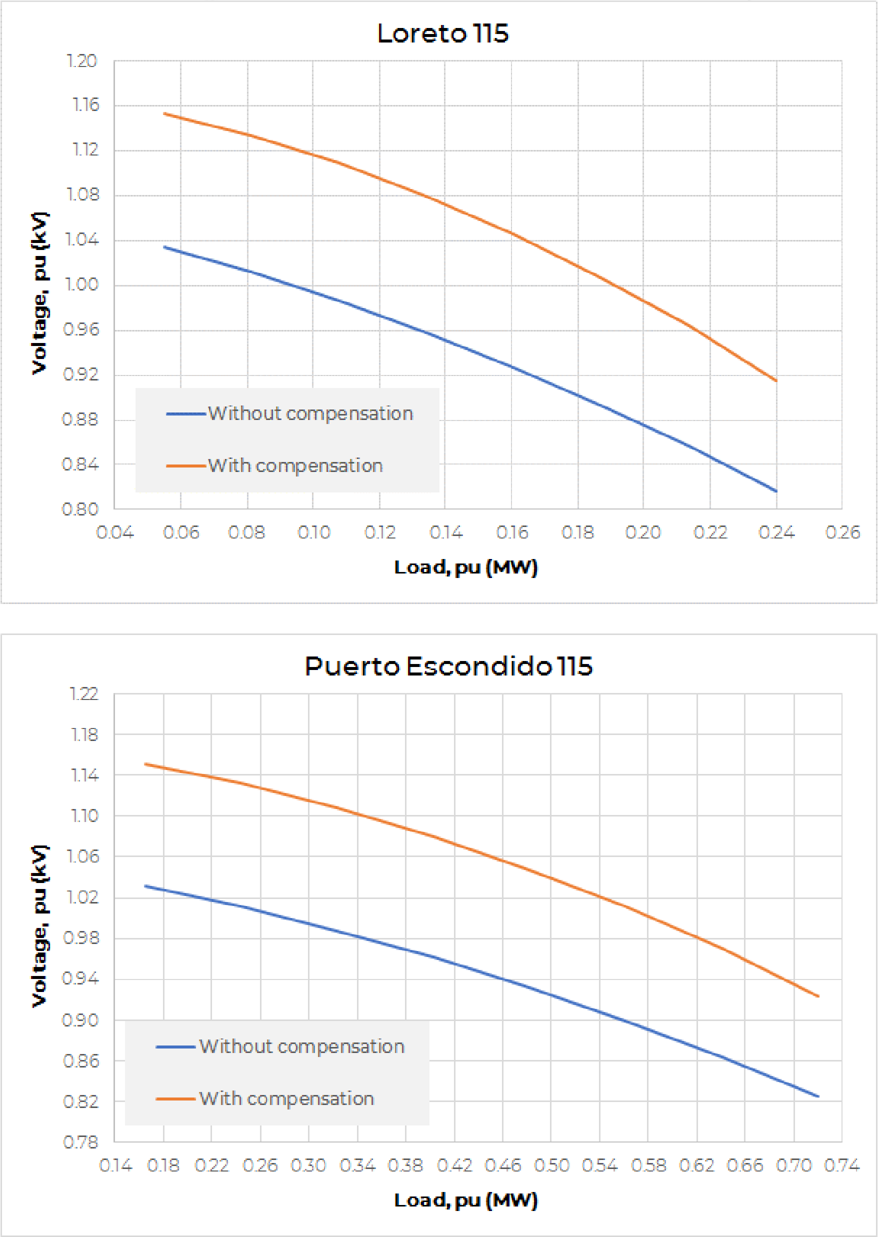
Figure 5.11 displays the P-V curves for three of the furthest buses from the system: LORETO, PUERTO ESCONDIDO, AND SANTO DOMINGO. They represent demand nodes placed towards the end of the system. Therefore, as their load increases a little, the voltage levels become low. Thus, for these buses to be able to supply a bit more load, they require a source of reactive that allows this. Red curves are uncompensated, and blue curves are compensated at 10% of the demand level. Even with this level of compensation, the voltages drop rapidly. The best in these cases is the insertion of a power source (batteries would be very appropriate).



(*a*)


Santo Domingo 115
Voltage, pu (kV)
1.20
1.18
1.16
1.14
1.12
1.10
1.08
1.06
1.04
1.02
1.00
0.98
0.96
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0.18
Load, pu (MW)
Without compensation
With compensation
Villa Constitución 115
Voltage, pu (kV)
1.10
1.06
1.02
0.98
0.94
0.90
0.04
0.06
0.08
0.10
0.12
0.14
0.16
Load, pu (MW)
Without compensation
With compensation

(*b*)



(c)

Figure 5.11. P-V curves for nodes of the BCS system. Source: Own elaboration.

In a general way, it can be indicated that the Mexican electrical system has a relatively robust region, constituted by the Central, Western, Southeastern and Northeastern control areas. This means that such region exhibits relative strength respect to frequency and voltage events. Even so, for this last one, it is notorious the absence of coordination in the management of the reactive power, to reduce the losses, improve the voltage profile, and release some of the generation capacity.

On the other hand, the Northwest, North, Peninsular control areas and the Baja California Sur exhibit lack of robustness. Especially in voltage studies, the lack of reactive power is notorious, which elevates the voltages and allows for higher load management. For this case, the compensation of reactive power becomes a necessity.

5.3.2 Reactive compensation capacity

Appendix C presents an expression that allows calculating approximately the **degree of reactive compensation** *Q* (Mvar, mega-voltampere-reactive) in a bus that exhibits a short circuit capacity (SCC) in (MVA, mega-voltampere), so that the voltage (kV) experiences maximum voltage variations of size ΔV *(Taylor, C., 1994)*,

$$\Delta V \approx \frac{Q}{SCC} \qquad \rightarrow \qquad Q = \Delta V * SCC, (Mvar)$$

Short-circuit capacity (SCC) is the amount of power that the protective elements on a bus must have to withstand without damage the most severe fault on the bus. Table 5.8 presents examples of buses where the degree of compensation (in Mvar) has been estimated, assuming that the maximum tolerated deviation is ± 5% (± 0.05 pu). That means that with the expected degree of compensation, the corresponding bus will experience voltage variations of 5% around the nominal value. The short circuit levels (SCC) were taken from the reference *(CENACE, Dic. 2017)*. Note that in such a source, what is specified is the *short circuit current*. Besides, the equipment specifications should always be for the worst condition, so that three-phase short circuit currents are chosen.

Now, the short circuit capability (SCC) must be calculated, for which the voltage is required. That is, for the same current level and two voltage levels in a 1:2 ratio (e.g. 115 kV and 230 kV), the SCC of the second will be twice as high as that of the first.

The National Energy Control Centre (CENACE) must maintain quality of service based on indicators about the quality of service—in this case, basically hinged on frequency (60 ± 0.1 Hz) and voltage values (1 ± 0.05 puKV).

Buses with high SCC values should not require compensation as they are robust by definition (they have more ability to handle variations in demand). For the isolated system of Baja California Sur, an akin procedure has been followed. **Table 5.9** also presents some examples of the degree of compensation under the same assumptions. **The lower your SCC[5], the weaker the node it is, and you need assistance (compensation).**

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[5] If the resistance or impedance of the load is bypassed or shorted, then, according to Ohm's law, an abnormally high current will flow through the circuit. This situation is called a short circuit. Depending on the remaining resistance or impedance of the circuit, the short-circuit current could be up to 30 times as high as the normal current.At this abnormally high level, most equipment and wiring will be ruined by the excessive amount of heat generated. Furthermore, there will most likely be the fire of combustible components within or in the vicinity. short circuit capacity can refer to two things; 1. The maximum fault current that can be generated in a worst case scenario (a bolted 3phase fault); 2. The ability of a device or system to protect a system and withstand the fault currents in a worst case scenario.

Table 5.9. Degree of reactive compensation (Mvar) in five regions of the SIN.Source: Own elaboration.

Northeast Monterrey-Saltillo	Western Zimapán	North Juárez-Chihuahua	Peninsular Merida- Cancun	BCS Villa Constitucion – La Paz
600 Mvar ESCOBEDO 115 kV	877 Mvar TULA 230 kV	298 Mvar MOCTEZUMA 230 kV	226 Mvar VALLADOLID 230 kV	77 Mvar OLAS ALTAS 115 kV
485 Mvar SAN JERONIMO115 kV	703 Mvar LAS MESAS 400 kV	289 Mvar EL ENCINO 400 kV	169 Mvar DZITNUP 400 kV	66.7 Mvar EL RECREO 115 kV
378 Mvar PRIMERO DE MAYO 400 kV	710 Mvar SANTA MARIA 400 kV	270 Mvar AVALOS 230 kV	149 Mvar NIZUC 115 kV	65.9 Mvar BLEDALES 115 kV
365 Mvar RAMOS ARIZPE 115 kV	560 Mvar POTRERILLOS 400 kV	245 Mvar REFORMA 115 kV	148 Mvar RIVIERA MAYA 230 kV	65 Mvar EL PALMAR 115 kV
278 Mvar SALTILLO115 kV	543 Mvar QRO POTENCIA 230 kV	240 Mvar CHUVISCAR 230 kV	139 Mvar CANCUN 115 kV	57.0 Mvar LA PAZ 115 kV
187 Mvar GUEMEZ 115 kV	405 Mvar SAN LUIS DE LA PAZ 230 kV	240 Mvar PASO DEL NORTE 230 kV	75 Mvar CHANKANAAB 115 kV	38.8 Mvar CAMINO REAL 115 kV
17.3 Mvar JIMENEZ 115 kV	329 Mvar LEON I 230 kV	233 Mvar DIVISION DEL NORTE 230 kV	48 Mvar TIZIMIN 115 kV	35.8 Mvar VILLA CONSTITUCIÓN 115 kV
9.2 Mvar DIVISADERO 115 kV	300 Mvar LEON III 230 kV	231 Mvar VALLE DE JUAREZ 115 kV	90 Mvar PLAYA MUJERES 115 kV	27 Mvar INSURGENTES 115 kV
8.9 Mvar SAN FERNANDO 115 kV	294 Mvar SILAO POTENCIA 230 kV	216 Mvar TERRANOVA 115 kV	66 Mvar SAN IGNACIO 115 kV	26.9 Mvar SANTIAGO 115 kV
5.2 Mvar BACIS 115 kV	254 Mvar SAN JUAN POTENCIA 230 kV	179 Mvar TORRES 115 kV	38 Mvar CHEMAX 115 kV	9.2 Mvar LORETO 115 kV
7.6 Mvar CATEDRAL 115 kV	243 Mvar SANTA FE 230 kV	164 Mvar MOCTEZUMA 115 kV	32 Mvar TULUM 115 kV	13 Mvar PUERTO ESCONDIDO 115 kV
6.3 Mvar GUACHOCHI 115 kV	239 Mvar LEON IV 230 kV	148 Mvar CAMARGO 230 kV	31 Mvar POPOLNAH 115 kV	42 Mvar SANTO DOMINGO 115 kV

Northeast Monterrey-Saltillo	Western Zimapán	North Juárez-Chihuahua	Peninsular Merida- Cancun	BCS Villa Constitucion – La Paz
5.5 Mvar CIENEGA 115 kV	223 Mvar GENERAL MOTORS 230 kV	140 Mvar NVO CASAS GRANDES 230 kV		
	128 Mvar ZIMAPÁN 230 kV	83 Mvar CEREZO JUÁREZ 115 kV		
	96 Mvar JILOTEPEC POTENCIA 115 kV			
	82 Mvar NOCHISTONGO 115 kV			

Nota: In every cell the degree of reactive compensation (Mvar) follow by the name of the bus and the nominal voltage of the transmission (kV). Gray mark means that bus was used for the study.

There is no point in placing compensation in power plant substations (such as Zimapan-hydropower, or Tula-thermal plant) because the generator performs voltage control there. Compensation is typically installed at nodes far from the generating plants (30 km or more), unless the demand is so high that nodes close to a generating plant (less than 30 km) require reactive compensation to operate properly. plants

The degree of reactive compensation (Mvar) could be interpreted as capacity in MW using the next equation and assuming cos θ (power factor, PF) = 1, Fig. 5.9.

$$MW = MVA \cos \theta = MVA \times PF = MVA \times (\text{Active power in MW/rated capacity in MVA})$$

For the buses with high priority in every single control region, the size was estimated.

The use of batteries perfectly satisfies the required reactive power compensation, since, through the power electronics, such service can be provided. When the time comes, the batteries can be the backup for the frequency, designing the necessary controls and protections.

Storage facilities need several hours of capacity to be effective. However, if operators want to use the same facilities for power services, they need to take this into account when scheduling the dispatch of the devices. Thus, for example, to carry out frequency regulation services, an available power range must be guaranteed to rise and fall while participating in this service. Operational and economic criteria will determine what percentage of the installation’s power is dedicated to each service. Something similar occurs with the voltage control service. However, it does not require, in principle the contribution of energy; the converter connected to the grid must have a sufficient power margin to contribute or consume reactive power from the network.

It is also economical and technical criteria that will determine which converter capacity band is dedicated to this service. For storage systems to be able to perform these applications effectively, it is necessary to determine beforehand the dispatch required to adapt the state of charge to the conditions that are expected to occur throughout the programming period. In the case of generation units, the tool that performs this dispatch is a unit commitment, through which it is decided when the unit should be started or stopped—the power to be injected in each programming period. In the case of storage systems, the decision to start or stop the installation is not relevant due to the speed with which these systems can vary the power generated. However, the availability of capacity to store energy in specific periods for later delivery is essential.

6. Renewable energies and the role of power electronics

One of the reasons for the emergence of modern power electronics-based apparatus is related to the need to expand the operating ranges in power networks that were reaching their limits. Based initially on thyristors and then by transistors, the maturity of the power electronics allowed to create devices capable of achieving voltage control, compensation transmission lines, bidirectional flows, and through them to reach, for example, the enhancement of power oscillations or expand operating margins.

The voltage control problem is quite ancient and has been the subject of comprehensive investigations. Currently, the intensive employment of voltage source converters (VSCs) primarily associated with renewable energies, motivates the study of the impact of such elements in the voltage regulation of a distribution network, for instance. Preliminary fieldwork presented in *(Kern EC, 1989)* suggested that the variability in the distributed energy resources system generation is sufficient to cause flicker in the power signal. It also indicated that voltage variations in cases of photovoltaic (PV) penetration levels below 15% do not result in noticeable effects. However, a potential increment in the number of on-load tap changer (OLTC) operations may be observed as the PV output fluctuates. More recent studies imply that the high penetration of PV raises the number of the OLTC operations and that this effect may be mitigated by allowing the smart PV inverters to assist in voltage regulation. Therefore, coordinated voltage control is required to minimise the operation of the voltage regulators while maintaining appropriate voltage levels. Likewise, the voltage-related impacts of PV systems on distribution networks vary with the size of the PV plant.

The IEEE 1547-2003 ***Standard for Interconnecting Distributed Resources with Electric Power Systems*** (IEEE, 2003) did not request dynamic voltage support on distributed energy resources such as photovoltaics. However, the new IEEE 1547-2018 ***Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces*** stipulates specific voltage support requirements, for instance through the smart inverter reactive power control *(IEEE, 2018)*. The inverter reactive power dispatch alleviates the stress of daily operation on voltage controllers. Thus, the new standard indicates that smart converters provide static voltage support *(IEEE, 2018)*, mainly related to (*i*) control of local Voltage via reactive power; (*ii*) reactive power handling.

This means that the stipulated requirements for modern electronic converters are higher than those usually requested to broaden their participation in different contexts; in this case, the voltage regulation in the network.

Likewise, intermittent renewable electricity generation, particularly from wind and solar, has quite a different set of operating and control characteristics than a traditional thermal generation. The last one is fully controllable; a dispatcher can modify the output power of a thermal generator with promptness and precision.

The displacement of conventional generation units with non-conventional energy resources gives rise to the overall system inertia response decreases leading to a more sensitive system from a frequency viewpoint *(Aziza A. et al., 2018)*, *(Zhaoa C. et al., 2018)*. Solar generation resources and energy storage systems *(Jayamaha C. et al., 2018)* are not able to provide inertial frequency response since they do not have any rotating masses. Moreover, as a regular practice, they are not equipped with primary frequency control loops. Even though variable-speed Wind Generation Resources (WGRs) technologies include rotating masses within their turbine and generator structure, they do not provide any inertial frequency response unless their control systems are modified. Consequently, the emergence of high penetration of non-conventional energy resources into the power system raise challenges for power system operators in terms of power system frequency control.

The virtual synchronous generator (VSG) has been presented to emulate the behaviour of a real conventional synchronous generator. It compensates the inertia decline in renewable power systems that results from adding more Renewable Energy Sources (RESs), i.e., non-inertia sources *(Bevrani H., 2014)*. Therefore, the concept of VSG hinges on reproducing the dynamic characteristics of a real synchronous generator by combining the idea of the virtual rotor, i.e., emulating the inertia and damping properties of real synchronous generators (SGs), as well as the concept of virtual primary and secondary control (i.e., following the primary and secondary frequency control loops of real SGs).

Thus, power electronics are at the crossroads with the goals shifting from hardware performance metrics (i.e., smaller size, lighter weight, and lower cost) to more control, more functions, more integration, more flexibility, and more commonality *(Xue Y et al., 2018)*. Thus, system operators and utilities have changed their attitudes towards small-scale distributed energy resources (DER) and have called for their active participation in system frequency control and voltage support.

In summary, power electronics, clean energy sources, and some storage technologies (especially batteries) constitute complementary technologies from which it is possible to offer ancillary services to utilities. It represents the indirect benefit of possible displacement of conventional power generation technologies and the reduction of pollutant emissions.

7. Emissions

The methodology described below is followed to estimate the emission changes in the control regions, based on the percentage reduction in displaced fossil fuel technologies.

Hinged on real historical data, functions to determine the emissions of different technologies for generating electricity were found (Xia Y et al., Dec. 2013), (Kindle A et al., Oct. 2013), (Kindle A, April 2015).

The first relevant topic in (Kindle A, April 2015) is the requirement that specific emission functions be able to appropriately estimate emissions in scenarios where the dispatch of generators changes their traditional operating strategy. The research proposes a very particular emission function that can be applied and customised to specific generators automatically. Such a function takes into account the daily operations of the generator such as starting, stopping and ramping and, in doing so, produces accurate predictions.

The estimated functions are used to analyse five wind penetration scenarios. This is done because several previous references have found that wind generation can cause emission reductions that are smaller than expected. Emission functions that can estimate emissions under all operating conditions of the generator predict emissions under five simulated wind penetration scenarios. After predicting emissions under all scenarios, the results are analysed to find that increased wind penetration results in consistently more significant decreases in CO_2 and SO_2 emissions.

Taking real information from an independent system operator (ISO) in *(Kindle A, April 2015)*, functions were achieved that allow estimating levels of emission reductions, when conventional generation is replaced by clean generation. Figure 7.1 displays forecasting emissions for five wind penetration scenarios. The five scenarios consist of 3,500, 10,000, 16,500, 23,000 and 29,500 MW of renewable capacity.

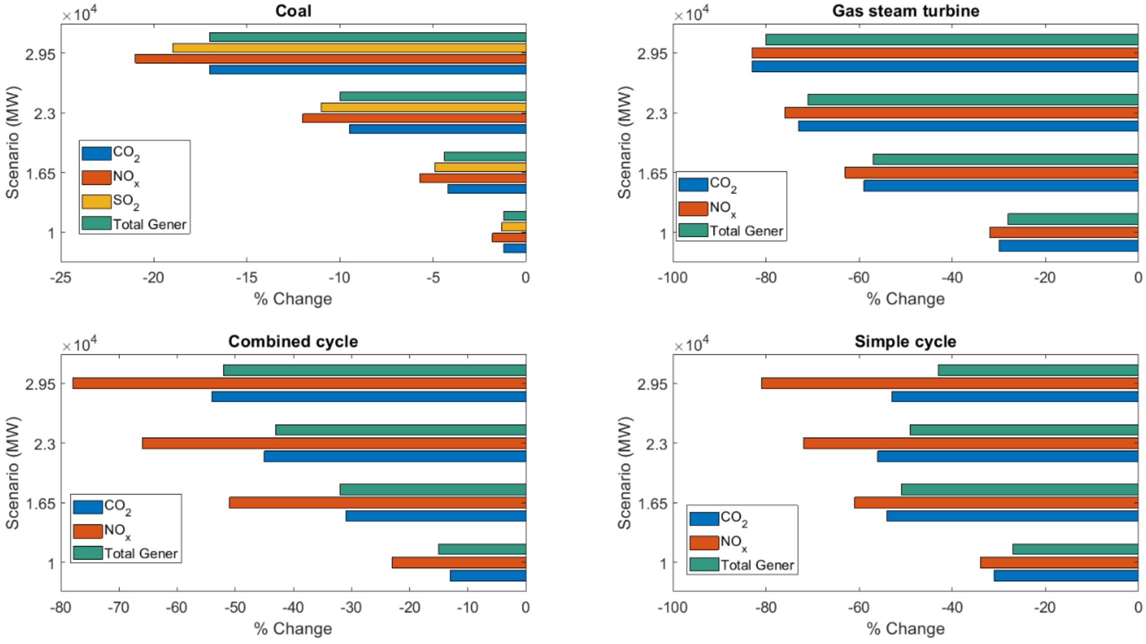


Figure 7.1. Percentage of emissions reduction depending on the renewables penetration scenario (without storage) from 3500 MW - Coal, Gas Steam Turbine, Combined Cycle and Simple Cycle. It was adapted from (Kindle A, April 2015).

Emissions from coal generators

Each group of bars shows the percentage change for each type of emission and generation from the 3,500 MW wind penetration scenario.

Emissions from coal generators decrement in all scenarios. Despite differences in the number of ramps, starts and stops of coal units, their emissions change in similar proportion to changes in a generation.

CO_2 emissions decrease by almost precisely the same percentage as a coal-fired generation in all five scenarios.

Notice that coal generation consistently decreases as wind capacity increases. It reduces in total by 17% of the lowest wind scenario to the highest one. This is significant because it means that coal generation is being replaced by wind generation.

Both NO_x and SO_2 emissions decrease more than the generation decrease. From the lowest to highest penetration scenario, NO_x emissions are reduced by 21%, while SO_2 emissions are reduced by 19%.

These are the percentages of change shown in Fig. 7.1.

In each scenario, CO_2 and NO_x emissions decrease more than the decrement in coal generation from the 3,500 MW wind penetration scenario.

The difference between the changes in SO_2 emissions and generation is minimal, with SO_2 emissions decreasing slightly more than the decreases in the generation.

NO_x emissions may decline more than SO_2 emissions because, as coal units reduce their production, they may be operating at lower heat levels, which would mitigate thermal NO_x emissions.

Emissions from gas steam turbine generators

The gas steam turbine shows substantial decrements in its generation output as the penetration of renewables increases. The 29,500 MW, wind capacity scenario, results in gas-fired steam turbine generators producing 80% less energy than in the lower wind penetration scenario.

In Mexico, the degree of clean energies penetration represents a capacity on the order of 2,500-3,700 MW, taking into account bioenergy, the photovoltaic, wind, and geothermal, *(PRODESEN 2019, Figure 5.7)*. Table 7.1 is an estimate of possible emission reductions by the displacement of technologies that could be achieved in the short-term, hinged on the results of the previous research.

The calculation (See Appendix E) was made by taking the first two scenarios of the case above-described. There is a differential of 6,500 MW of wind capacity (10,000 – 3,500 MW) *(Kindle A, April 2015)*.

If we add up the average capacity of ancillary services per hour required in the SIN (1700 MW) using energy storage technologies and assuming that the same operational policies could be followed as above-explained for the management of clean energy in terms of displacement of technologies, it turns out that the ratio concerning Mexico's ancillary services becomes 1700 MW/6500 MW = 0.26. As an approximation to the possible reduction of emissions due to the use of energy storage technologies to provide related services in substitution of conventional plants, the following calculations are made based on the mentioned study *(Kindle A, April 2015)*.

Table 7.1 is constructed with the reduction percentage of the 10,000 MW scenario (the size of the lower bars in Fig. 7.1), with the mentioned proportion and also taking into account the ratio of demand by control area in Table 5.1.

Notice that for the SO_2 emissions, the results are only for coal generators due to the extremely low SO_2 emissions from natural gas-fired generators. Thus, Table 7.1 illustrates the percentage of emissions at the SIN level, with the 1700 MW associated with the ancillary services, assuming an operational policy of displacement of technologies similar to those taken into account for building up Fig. 7.1

Total reserve (1,700 MW)

Table 7.1. Reduction estimation of the SIN emissions assuming the inclusion of energy storage technologies (1700 MW) corresponding to the provision of ancillary services. Source: own elaboration.

Technology	CO_2 Emissions (kt)	NO_x Emissions (kt)	SO_2 Emissions (Kt)	Generation (GWh)
Coal	395.7	0.3	1.1	417.8
Gas steam turbine	87.9	0.1	0.0	126.9
Combined cycle	1,606.6	1.7	0.0	4427.6
Single cycle gas turbine	109.3	0.3	0.0	129.4
Totals	**2,199.5**	**2.4**	**1.1**	**5,101.6**

For the BCS isolated system, Table 7.2 illustrates the percentage of emissions, with the 60 MW associated with the ancillary services, under the same assumptions made for the SIN.

Table 7.2. Reduction estimation of the BCS emissions assuming the inclusion of energy storage technologies (60 MW) corresponding to the provision of ancillary services. Source: own elaboration.

Technology	CO_2 Emissions (kt)	NO_x Emissions (kt)	SO_2 Emissions (Kt)	Generation (GWh)
Gas steam turbine	0.5	0.0	0.0	0.7
Internal combustion	1.4	0.0	0.0	2.0
Totals	**1.9**	**0.0**	**0.0**	**2.8**

Note: In BCS internal combustion was considered as gas steam turbines for the estimations.

Primary reserve (400 MW)

Table 7.3. Reduction estimation of the SIN emissions assuming the inclusion of energy storage technologies (400 MW) corresponding to the provision of ancillary services only primary reserve. Source: own elaboration.

Technology	CO_2 Emissions (kt)	NO_x Emissions (kt)	SO_2 Emissions (Kt)	Generation (GWh)
Coal	93.1	0.1	0.3	98.3
Gas steam turbine	20.7	0.0	0.0	29.8
Combined cycle	378.0	0.4	0.0	1041.8
Single cycle gas turbine	25.7	0.1	0.0	30.4
Totals	**517.5**	**0.6**	**0.3**	**1,200.4**

Table 7.4. Reduction estimation of the BCS emissions assuming the inclusion of energy storage technologies corresponding to the provision of ancillary services. Source: own elaboration.

Technology	CO_2 Emissions (kt)	NO_x Emissions (kt)	SO_2 Emissions (Kt)	Generation (GWh)
Gas steam turbine	0.013	0.001	0.0	0.017
Internal combustion	0.034	0.001	0.0	0.048
Totals	**0.047**	**0.002**	**0.0**	**0.065**

Frecuency Control reserve (37 MW)

Table 7.5. Reduction estimation of the SIN emissions assuming the inclusion of energy storage technologies (37 MW) corresponding to the provision of ancillary services only frecuency respond. Source: own elaboration.

Technology	CO_2 Emissions (kt)	NO_x Emissions (kt)	SO_2 Emissions (Kt)	Generation (GWh)
Coal	8.6	0.0	0.0	9.1
Gas steam turbine	1.9	0.0	0.0	2.8
Combined cycle	35.0	0.0	0.0	96.4
Single cycle gas turbine	2.4	0.0	0.0	2.8
Totals	**47.9**	**0.1**	**0.0**	**111.0**

Table 7.6. Reduction estimation of the BCS emissions assuming the inclusion of energy storage technologies corresponding to the provision of ancillary services only frecuency respond. Source: own elaboration.

Technology	CO_2 Emissions (kt)	NO_x Emissions (kt)	SO_2 Emissions (Kt)	Generation (GWh)
Gas steam turbine	0.012	0.001	0.0	0.002
Internal combustion	0.031	0.001	0.0	0.006
Totals	**0.043**	**0.002**	**0.0**	**0.008**

8. Location of storage sources

As far as ancillary services are concerned, the speed of response of storage technology is decisive. In that sense, batteries may be currently the best available option, given the technology readiness level.

The location of Energy Storage Systems (ESS) is a complex planning issue.

Load or demand size: In general, it is advisable to locate them near the large demand centres, because that is where substantial variations in demand can occur, which would compromise the stability of the system. In that sense, the closer the source of balance is and the faster it responds, the better.

The weakness of nodes: Normally, the nodes that require reactive compensation are those that exhibit a low short-circuit capacity (SCC). Such nodes are usually those farthest away from the energy sources (power plants), especially if they are large load centres.

As can be seen, these criteria are generally opposed, which means that there must be a tradeoff between them. This is why these decisions must be made optimally, considering at least the following criteria:

a. To choose a point geographically not too far from the great centres of demand;
b. A node not too far from the weakest nodes, because that is where reactive compensation is most required;
c. Not a quite robust node (from the short-circuit capacity point of view), because in that case, it may require high degrees of reactive compensation.

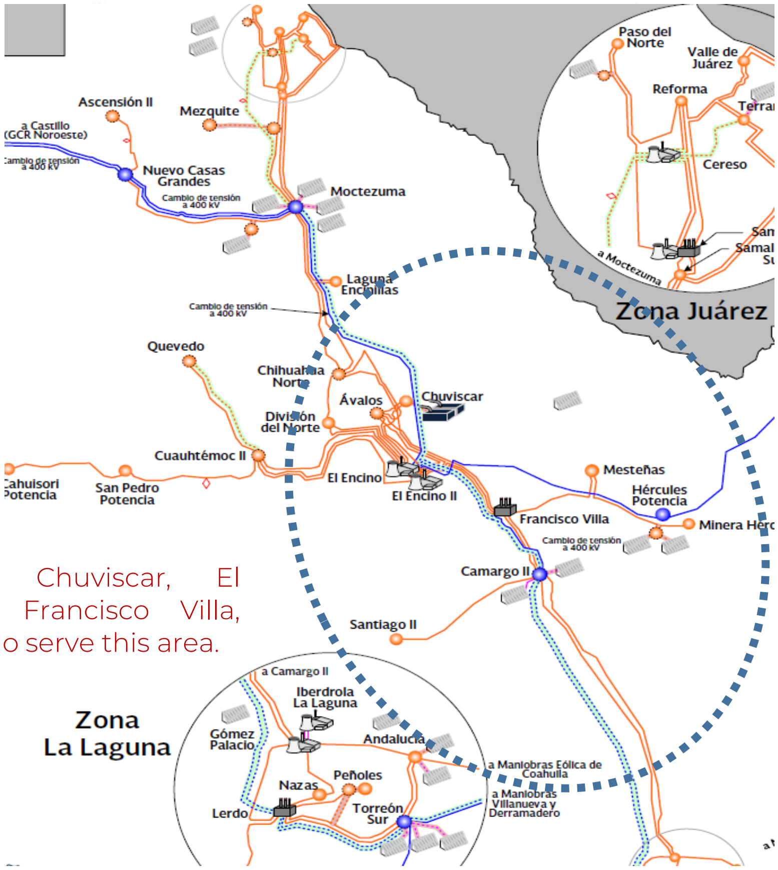
Table 8.1 proposes resource locations (e.g. BESS) to help alleviate the problems of the indicated SIN regions. In some cases, two positions are offered, because the geographic area is so large that placing a resource in one location will hardly solve all the issues. Such sites were chosen at a mid-point between the regions under analysis. Likewise, the joint action of generators and compensated buses can help alleviate voltage problems in a zone.

It is essential to clarify that in the present study, only frequency and Voltage have been taken into account, as they are the two electrical signals that mainly represent the service quality.

However, planning and location of ESS for the future must take into account other factors, such as the actual capacity of transmission lines in areas with evident congestion. The possible insertion of higher generation capacity, both conventional, clean and mostly intermittent technologies, the vulnerability of the region; But the aspect of the investment required cannot be avoided.

Table 8.1. Substations to place energy storage systems to help maintain frequency and voltage in the indicated regions. Source: own elaboration. Source: own elaboration.

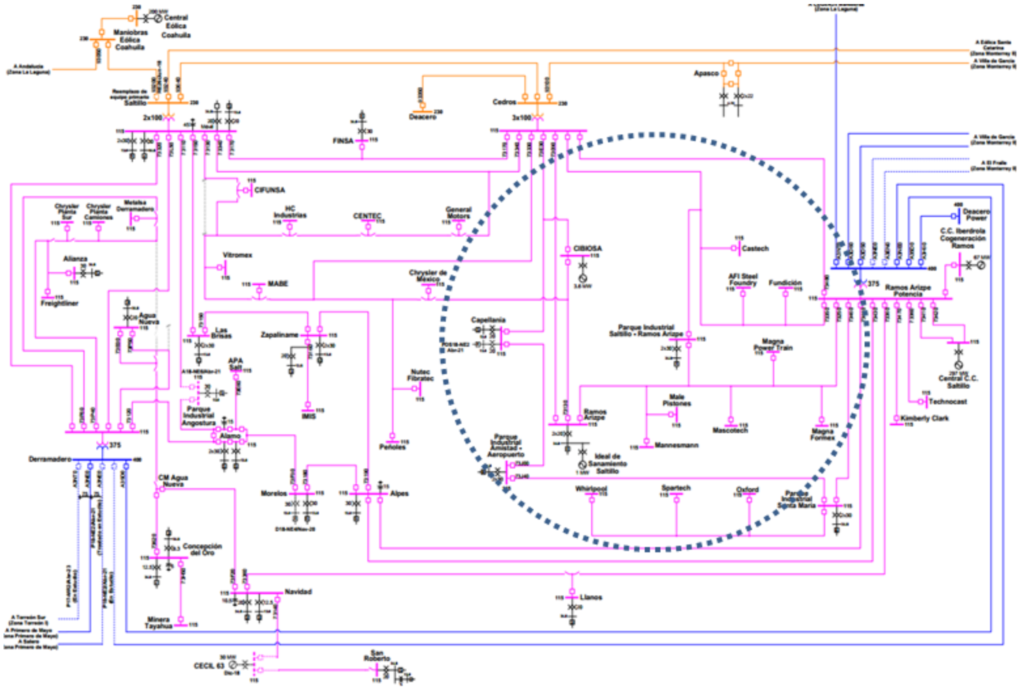
Northeast	North	Peninsular	Western	BCS
Monterrey-Saltillo	Juarez-Chihuahua	Merida - Cancun	Zimapan	Villa Constitucion-La Paz
RAMOS ARIZPE Fig. 5.10 (d)	CAMARGO Fig. 5.10 (e)	A) RIVIERA MAYA Fig. 5.10 (c)	A) SAN LUIS DE LA PAZ B) SILAO Fig. 5.10 (b)	A) EL PALMAR B) VILLA CONSTITUCION Fig. 5.11



Central Chuviscar, El Encino, Francisco Villa, Camargo serve this area.

Figure 8.1. North control región. Source: (CENACE, 2018).

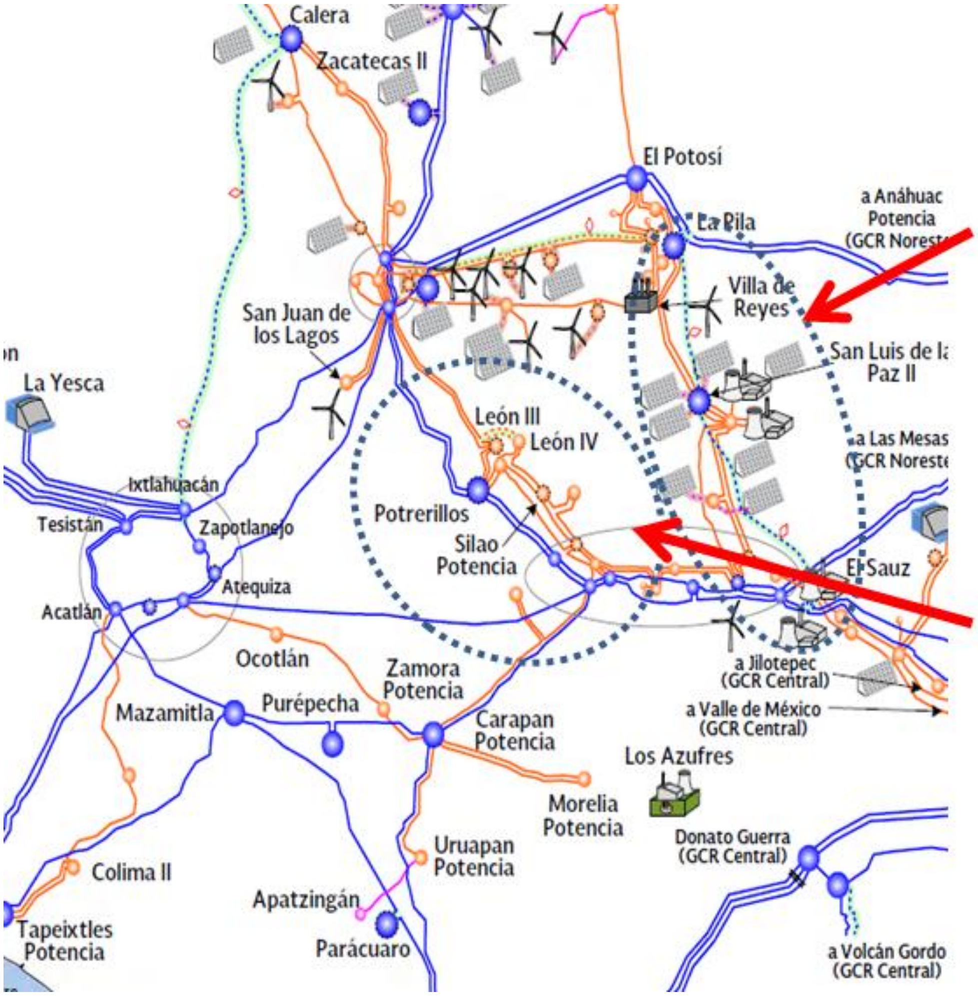
Note: The area within the dotted line represents the compensation theoretical zone of influence



Ramos Arizpe serves this industrial area. Monterrey does not require compensation; it needs to decrease SCC.

Figure 8.2. Northeastern control region. Source: (CENACE, 2018).

Note: The area within the dotted line represents the theoretical compensation zone of influence

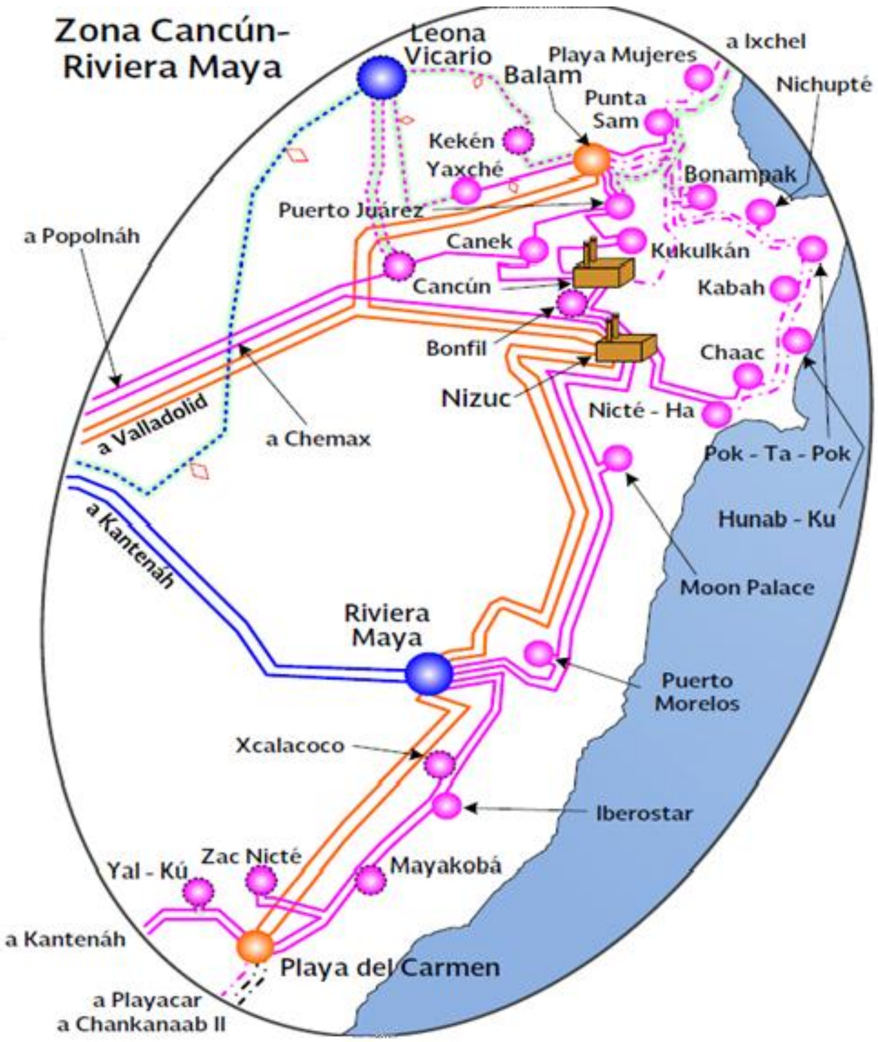


El Sauz, Villa de Reyes, San Luis de la Paz serve this region.

Salamanca, Silao serve this region.

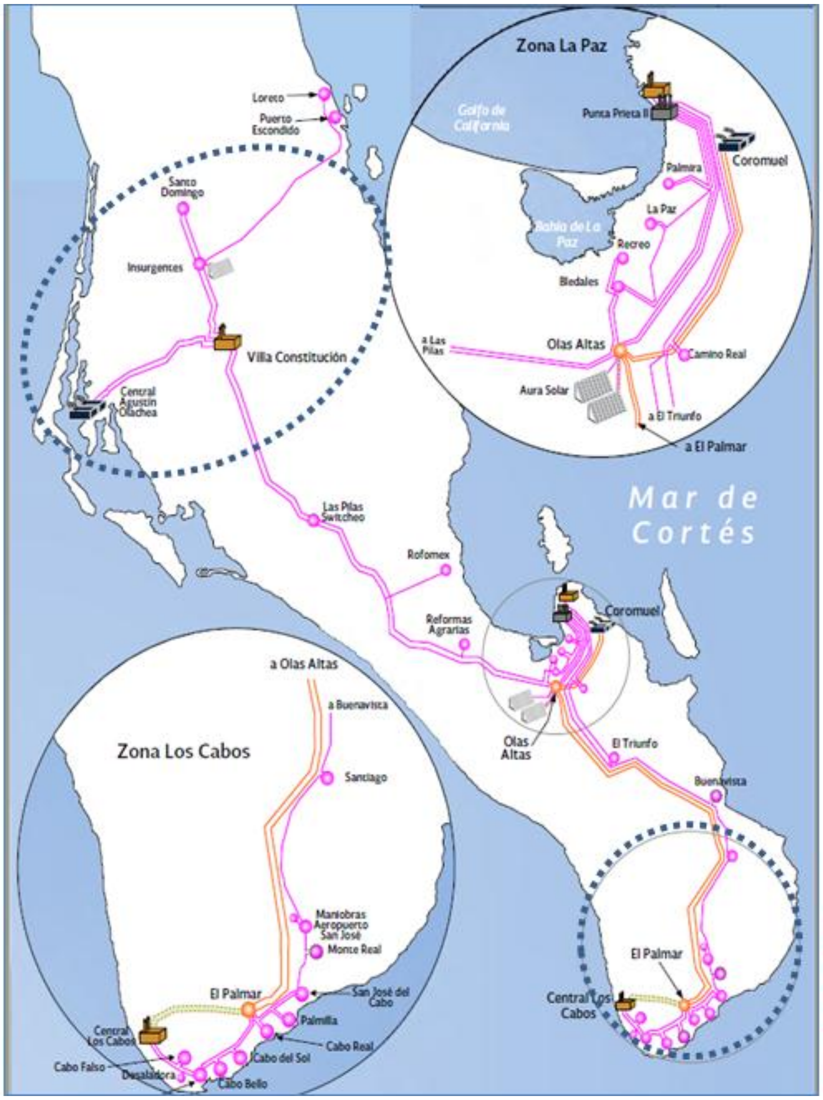
Figure 8.3. Western control region.Source: (CENACE, 2018).

Note: The area within the dotted line represents the theoretical compensation zone of influence



Central Cancun, Central Nizuc, and Riviera Maya can serve this area.

Figure 8.4. Peninsular control region. Source: (CENACE, 2018).



Central Olachea and Villa Constitution compensation can serve this area.

El Palmar and Central Los Cabos can serve this area.

Figure 8.5. Baja California Sur. Source: (CENACE, 2018).

Note: The area within the dotted line represents the theoretical compensation zone of influence

9. Ancillary services sizing

9.1 Demand capacity per type of ancillary service

It is quite essential for reserve capacity that the technology used is available and ready to release it when needed *(Akhil AA et al., 2015).*

For example, a 5 MW/5 MWh lithium-ion battery is operational since 2014 and is considered the first commercial battery in Europe to participate in the primary frequency regulation market. Besides, it is also operated seeking profitability by providing reactive and support services in the event of a lack of supply *(www.fkfoundation.com).*

It is estimated that thanks to its speed and precision in operation, its frequency regulation capacity is equivalent to that offered by a conventional 50 MW generation plant.

Application: frequency regulation

Storage technology size: 10 – 100 MW

Discharge duration: 15 minutes – 1 hour

Minimum cycles/Year: 20 – 50

Quantities calculated in proportion to the control area size.

Voltage must be maintained within specified limits (1 ± 0.05, pu). Typically, this requires a sufficient reactive dispatch to manage resources to offset reactive effects, so that the system can be operated stably.

It is possible to place energy storage within the network at strategic locations, or taking the distributed approach, and put multiple VAR-support storage systems near large loads *(Akhil AA et al., 2015).*

Thus, the presence of storage systems can help to alleviate the voltage issue by using the control capabilities of the switching converters to inject or absorb the necessary reactive power at any given time. The contribution to voltage control is, therefore, more technically related to the connecting device than to the storage equipment itself. Today, most converters used for grid connection are self-switched inverters. These use switching devices that freely control the driving and non-driving states of the switch, such as IGBT and MOSFET transistors. This type of inverter can freely control the waveform of the voltage and current on the AC side, which enables the power factor control of the installation. They can be divided into current source converters (CSC) and voltage source converters (VSC). The former has an approximately constant current source at the DC input, while in the latter the constant input source is a voltage. Most of the devices used in practice are VSC converters.

Application: Voltage control

Storage System Size: 1 – 10 MW

Discharge Duration Range: 30 min

Minimum Cycles/Year: Permanently connected

The storage systems power converters employed for voltage regulation must operate at a non-unity power factor, to inject and draw reactive power. This capability is available in all power conversion system used in today storage systems. In this mode, active power is not needed from the battery so that discharge time and minimum cycles per year are not crucial in such a situation.

The voltage stabilisation may take a few minutes, so your support can be considered with a duration of 30 minutes.

Table 9.1. Capacity per control area (frequency and voltage regulation). Source: Own elaboration

Control area	Capacity ancillary services (MW)
Central	216.58
Eastern	445.86
Western	289.13
Northwest	126.66
North	139.73
Northeast	422.09
Peninsular	59.89
Total	**1700.0**

Table 9.2. BCS (frequency and voltage regulation). Source: Own elaboration

Control area	Capacity ancillary services (MW)
BCS	60

9.2 Ancillary services

The type of ancillary service, by the periodicity with which they are demanded, the length of the service provided and the technology/ies that offer them will be shown.

Storage systems proportionate active reserve of energy and power and can be utilised to energise distribution and transmission lines and provide station power to bring power plants online after a collapse. For instance, in Fairbanks (Alaska, USA), Golden Valley Electric Association employs the battery system for this assistance when there is a contingency with the neighbour buses. The battery operation is illustrated in Fig. 20, which displays the charging current into two transmission paths; likewise, start-up power to diesel generators connected to Fairbanks until the tie is recovered. If the storage system is suitably sited can provide similar startup power to larger power plants *(Akhil AA et al., 2015)*.

<u>Application:</u> black start

Storage System Size: 5 – 50 MW

Target Discharge Duration: 15 minutes – 1 hour

Minimum Cycles/Year: 10 – 20

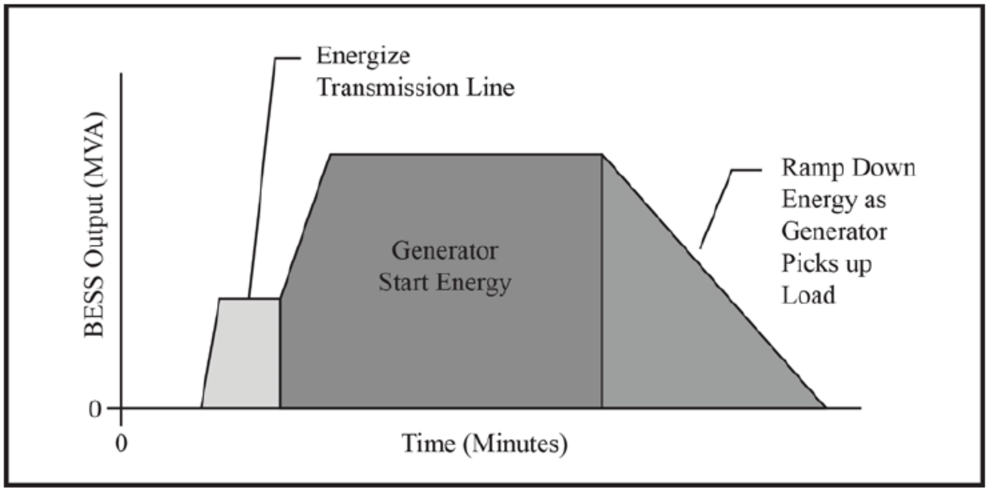


Figure 9.1. Black Start Service by Storage. (SANDIA REPORT, 2015).

In this way, an isolated system could be started up, or even a traditional power system, from a storage system after a blackout with loss of synchronism and fall of all generator park.

Table 9.3. Ancillary services for the SIN. Source: Own elaboration

Service	Spinning reserve[6]	Primary frequency regulation[1]	Inertial response	Black start
Capacity	Between 600 and 850 MW.	Between 300 MW and 400 MW.	Between 1 MW and 100 MW.	Between 5 and 50 MW.
Duration	Between 1 - 10 minutes.	Between a few seconds and 30 minutes.	A few seconds	Between a few seconds to 1 hour

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[6] https://www.cenace.gob.mx/SIM/VISTA/REPORTES/ServConexosSisMEM.aspx, accesed May 18, 2020

Service	Spinning reserve[6]		Primary frequency regulation[1]		Inertial response		Black start	
Response time/ cycles per year	Sec.	Between 200 and 400 cycles/ year	Sec.	Between 200 and 400 cycles/ year	Msec.	Between 200 and 400 cycles/ year	Sec.	Between 10 and 20 cycles/ year
Technology that provides this service	Combined cycle and conventional plants.		Combined cycle and conventional plants.		All conventional synchronised plants.		Sycoronised hydroelectric in operation, synchronised Conventional plants, CT.	
A storage technology that can provide these services	The most suitable options are PHS and CAES to reach hundreds of MW. For systems of tens of MW of power, batteries based on lithium, sodium or lead are a commercially available alternative.		To reach hundreds of MW, the most suitable option is a synchronised PHS. For systems of tens of MW of power, batteries based on lithium, sodium or lead are a commercially available alternative.		Because an almost instantaneous response is required, batteries and flow systems are identified as the most adequate. Between the batteries, Notice that the capacity of the lithium to provide high power peaks defines this technology as especially suitable. Also, the flywheels can easily reach tens of MW and have a faster response time than that of electrochemical storage (and longer life in terms of cyclability).		Because the rapid response is required, batteries and flow rates are identified as the most suitable systems. Among the batteries, the ability of lithium batteries to provide high peak power defines this technology as particularly appropriate. Also, flywheels can easily reach tens of MW and have a faster response than electrochemical storage (and longer life in terms of cyclability).	

Notes: Sec: seconds, Msec: Milliseconds; PHS: Pumped Hydro Storage; CAES: Compressed-Air Energy Storage

Table 9.4. Ancillary services for BCS[*]. Source: Own elaboration.

Service	Spinning reserve[1]	Primary frequency regulation[1]	Inertial response	Black start
Capacity	38 MW.	42 MW.	Between 1 MW and 100 MW.	Between 5 and 50 MW.
Duration	Between 1 - 10 minutes.	Between a few seconds and 30 minutes.	A few seconds	Between a few seconds to 1 hour
Technology that provides this service	Thermoelectric.	Thermoelectric	Thermoelctric, Internal combustion.	Turbogas, Thermoelctric, Internal combustion.

Notes: *The rest of the information is similar to that in Table 9.3

9.3 Sizing ESS at the regional level

The following capacities are suggested to help alleviate the local reactive problems, with the understanding that at the same time they are more than sufficient capabilities to improve frequency behaviour after a strong disturbance (Figures 5.5-5.6). That is, with these capacities, a voltage profile within the technically acceptable range (± 5%), and controlled frequency deviations are ensured for several years. It is also important to emphasise that the benefits of such compensation extend to transmission capacities so that the voltage raising can achieve higher values.

Based on previous studies of frequency deviations and reactive power compensations to improve the voltage profile, Table 9.5 summarises results of the capacities required for an improvement in the quality of electricity service in different areas of the country.

Table 9.5. Regional compensation to enhance electricity service. Source: own elaboration.

Northeast	North	Peninsular	Western	BCS
Monterrey-Saltillo	Juarez-Chihuahua	Merida -Cancun	Zimapan	Villa Constitucion-La Paz
RAMOS ARIZPE 115 kV	CAMARGO 230 kV	RIVIERA MAYA 230 kV	SAN LUIS DE LA PAZ 230 kV SILAO POTENCIA 230	EL PALMAR 115 kV VILLA CONSTITUCION 115 kV
365 Mvar	148 Mvar	148 MVar	400 Mvar 290 MVar	65 MVar 36 Mvar

Northeast	North	Peninsular	Western	BCS
Monterrey-Saltillo	Juarez-Chihuahua	Merida -Cancun	Zimapan	Villa Constitucion-La Paz
& at least 5.1 MW available for frequency regulation	& at least 7.0 MW available for frequency regulation	& at least 1.5 MW available for frequency regulation	& at least 2.5 MW available for frequency regulation for the Western control area.	& at least 6 MW available for frequency regulation for BCS
Possible displaced technologies per region in order of cost (from higher to lower price) / (mean displacement time)				
a. Combined Cycle – 6 to 7 hr	1. Combined Cycle – 6 to 7 hr	1. Single-cycle (gas turbines) – 3 to 5 hr. 2. Thermoelectric (gas steam turbine) – 6 to 7 hr 3. Combined Cycle – 5 to 6 hr	1. Hydro: 5 to 6 hr. 2. Combine cycle: 1 to 2 hr	1. Single-cycle (gas turbines) – 3 to 5 hr. 2. Internal combustion 3 to 5 hr
Discharge Duration: 15 min - 1 hour Minimum cycles/Year: 20-50 Source: (CRE, 2016)				

Of paramount importance in this point is to manifest that the information spilt in the present report has been estimated from public data of diverse entities of the Mexican government and that in the case of the reduction of emissions it is assumed that the conventional technologies (combined cycle, gas turbines, coal) will be displaced by clean technologies and of storage, to reach the quotas expressed in the reduction of polluting agents.

10. Conclusions

General

The results show for the different control areas in the Mexican Interconnected System that energy storage technologies EES could be employed to provide ancillary services. ESS allows deviations in frequency and voltage signals within technically acceptable limits. If permissible deviations are limited, larger installations are required. The speed of response of such ESS technologies is critical to the success of the support they provide, especially concerning frequency.

Regarding VRE integration

There is a sustained trend in the integration of clean generation. However, the most basic technical studies indicate the need to strengthen the transmission infrastructure, since there is a set of corridors that have reached their operational limits.

This implies that it will be difficult for them to assimilate the possible growth in generation and demand if no action is taken. Especially vulnerable are the Peninsular and Northwestern control regions and the isolated system of Baja California Sur.

ESS could support the integration of VRE on those regions with ancillary services and backup requirements. Yet ESS makes sense only if regulations are in place to ensure ESS will be used with clean or exclusively renewal energy.

Flexibility is another relevant factor to be taken into account, especially at the stage of the grid planning, before the integration of renewables and storage technologies. In this case, the use of storage technologies allows us to give flexibility to the system and contribute to improving the quality of the service provided by the utility. In this particular study, concern has been given to the behaviour of frequency and voltage.

Regarding the location of storage systems

Their location is also significant and, as far as possible, should be distributed throughout the system to cover the largest geographical area.

Some geographical regions become exceptional cases, such as León area, Querétaro area, Chihuahua area, Riviera Maya area, Saltillo area, the isolated BCS system. There, due to low voltage levels, it would be convenient to use reactive resources to help support them.

Particularly advantageous is the case where the storage is distributed along with the network, associated with the generation facilities spread or near areas of high consumption since it would mean that the storage devices are close to the points that require a higher input of reactive power.

Regarding frecuency control

The possible contribution of energy storage systems to maintaining the frequency of the system has been presented. This contribution is significant in small systems (for instance, the BCS system), where asynchronous technologies may displace a considerable part of the synchronous machine-based generation. In more extensive networks, storage technologies used in the appropriate locations may achieve significant results for frequency and Voltage.

The high speed of response, characteristic of batteries, allows them to collaborate effectively in primary frequency control. But at the present high-speed frequency control is not a recognised ancillary service and will be no retributed.

The reduction of fossil fuel generators becomes an additional benefit of ESS. Consequently, this brings a correct daily generation policy to satisfy the demand with the use of clean technologies, which requires the use of more robust generation forecast methods.

Results have been shown for each region of the SIN in which storage capacity is proposed to limit frequency excursions within an interval of [0.03, 0.04] Hz, for sudden load changes of up to 1.5% of the control area load value.

Regarding voltage control

Through the voltage profile studies carried out in this project for the SIN, the need for coordination of elements that handle reactive power (Voltage of generators, reactors/capacitors, transformer taps) is evident.

This would allow to improve the voltage profile, decrease losses, and achieve a better network performance.

Power electronics is one of the most suitable tools for managing flexibility, as it offers all the tools for active and reactive power management. Voltage Source Converters VSC-based energy storage facilities have an intrinsic ability to assist in maintaining system voltages.

Within the nominal VSC operating ranges, the facility can provide the necessary reactive power input or consumption to keep the tension at its connection node or adjacent nodes within an adequate interval.

Within the complementary or ancillary services for the operation of transport and distribution, storage systems may play an essential role in the voltage control.

Similar to the case of frequency, for voltage control, reactive compensations have been proposed and calculated to keep it within permissible limits (1 ± 0.05 per unit). Conventionally, such compensations are capacitive, although the use of batteries, for example, may occur, and through power electronics devices, the benefits of active and reactive support could be combined.

Regarding capacity requirements

A technical study has been presented to quantify the capacity required to sustain frequency and voltage in the Mexican network, which is based on data from a specific operating condition in 2018.

The calculated capabilities represent a minimum facility to help improve the operation of the network and serve only a small percentage of the capacity that the CENACE requires every hour as ancillary services.

This study proposes the use of storage technologies as a modern, reliable and robust alternative to provide support to the Mexican electricity network to maintain the quality of service, and in combination with the insertion of clean energy, seek to reduce the emission of GHG and pollutants through increased use.

It can be noted that the formulations are a trade-off between complexity and the handling of actual information. The models can be complemented, although it is estimated that the results will not be substantially modified.

Regarding emissions

It is important to emphasise that the estimate in the following reductions are a consequence of displacing conventional electricity generation by clean generation. Otherwise, they will result in overestimates.

For total reserve (1,700 MW)

Table 10.1. Estimation in CO_{2e} emissions reduction by control area. (FE from INEGyCEI)

Technology	Coal	Simple cycle	Combined cycle	Gas steam turbine	Internal combustion	Total per region
Region	kt CO_2e					
Central	0	26	0	39	0	65
Eastern	0	50	154	200	0	404
Western	274	23	182	230	0	708
Northwest	0	3	102	75	0	180
North	0	8	170	53	0	231
Northeast	256	28	444	107	0	835
Peninsular	0	57	80	22	0	159
BCS	0	46	0	29	57	132
Total	**530**	**242**	**1,131**	**756**	**57**	**2,715**

Table 10.2. Estimation in CO_{2e} emissions reduction by control area. (IFE from IPCC, 2006).

Technology	Coal	Simple cycle	Combined cycle	Gas steam turbine	Internal combustion	Total per region
Region	kt CO_2e					
Central	0.0	25.2	0.0	38.3	0.0	63.5
Eastern	0.0	33.5	149.4	194.7	0.0	377.6
Western	216.3	15.3	176.7	224.0	0.0	632.3
Northwest	0.0	2.2	98.7	73.0	0.0	174.0
North	0.0	5.6	164.7	51.9	0.0	222.2
Northeast	202.4	18.9	431.5	104.0	0.0	756.8
Peninsular	0.0	37.8	77.8	21.7	0.0	137.3
BCS	0.0	46.7	0.0	29.8	58.0	134.5
Total	**419**	**185**	**1,099**	**737**	**58**	**2,498**

Table 10.3. Comparison of CO_2 emissions reduction by technology and method

Method	Kindle	IPCC	INEGyCEI
Technology	kt CO_2e		

Coal	396	419	530
Gas steam turbine	90	737	756
Combined cycle	1,607	138	1,131
Single cycle gas turbine	109	1,146	242
Internal combustion	1	58	57
Total	**2,203**	**2,498**	**2,715**

Table 10.4. Generation reduction due to storage by technology and control area. (Kindle).

Technology	Coal	Gas steam turbine	Combined cycle	Single-cycle gas turbine
Region	(MWh)			
Central		25,526	890,961	
Eastern		34,256	1,195,700	
Western	268,249	28,126	981,710	
Northwest		12,089	421,938	50,853
North		8,186	285,701	
Northeast	149,530	15,678	547,231	65,953
Peninsular		2,989	104,316	12,573
BCS		2,795		
Total	**417,779**	**129,645**	**4,427,557**	**129,379**

For Frecuency Control reserve (37 MW) 2018

Table 10.5. Comparison of CO_2 emissions reduction by technology and control region. 2018.

Method	Kindle	IPCC	INGyCEI
Control region	Total por region		
	kt CO_2e		
Central	7.4	1.2	1.2
Eastern	10.0	6.9	7.3
Western	13.7	11.5	12.9
Northwest	4.5	3.2	3.3
North	2.4	4.0	4.2
Northeast	8.9	13.7	15.2
Peninsular	1.1	2.5	2.9
BCS	0.0	13.5	13.3
Total	47.9	56.4	60.2

Table 10.6. Comparison of CO_2 emissions reduction due to Frecuency Control by technology and method. 2018.

Method	Kindle	IPCC	INGyCEI
Technology		Total por tec	
		kt CO_2e	
Coal	8.6	7.6	9.6
CC	35.0	19.9	20.5
Turbogas	2.4	7.2	8.2
Termoelectrica	1.9	15.8	16.1
Internal Combustion	0.031	5.8	5.7
Totales	**47.9**	**56.4**	**60.2**

For Frecuency control reserve (121 MW) 2033

For estimation of emission reduction in 2033 following assumptions were made:

- Installed capacity and technology participation percentage distribution within the matriz will change in 2024-2033 according to PIIRCE 2019-2033 planning.
- Auxiliary services increase in proportion to the increase in demand.

Table 10.7. Comparison of CO_2 emissions reduction by technology and control region. 2024-2033.

Method	Kindle	IPCC	INGyCEI
Control region	Total per region		
	kt CO_2e		
Central	24.3	1.9	2.4
Oriental	32.6	5.6	7.3
Occidental	44.8	7.5	8.0
Noroeste	14.6	2.6	3.2
Norte	7.8	4.2	2.3
Noreste	29.0	9.1	11.1
Peninsular	3.6	1.2	1.7

BCS	0.047	13.5	13.3
Total	**156.6**	**45.6**	**49.2**

Table 10.8. Comparison of **CO_2** emissions reduction due to Frecuency Control by technology and method. 2024-2033.

Method	Kindle	IPCC	INEGyCEI
Technology		Kt CO_2	
Coal	28.2	3.9	4.9
Single cycle gas turbine	114.4	20.0	22.0
Combined cycle	7.8	6.4	7.0
Gas steam turbine	6.3	9.4	9.5
Internal Combustion	0.034	5.8	5.7
Totales	**156.6**	**45.6**	**49.2**

11. References

Akhil, A. A., Huff, G., Currier, A. B, Kaun, B. C., Rastler, D. M., Bingqing Chen, S., Cotter, A. L., Bradshaw, D. T., Gauntlett, W.D., (January 2015). *DOE/EPRI Electricity Storage Handbook in Collaboration with NRECA*, SANDIA REPORT SAND2015-XXX Supersedes SAND2013-5131.

Akrami, A., Doostizadeh, M., Aminifar, F. (2019). *Power system flexibility: an overview of emergence to evolution*. J. Mod. Power Syst. Clean Energy, 7(5):987–1007, https://doi.org/10.1007/s40565-019-0527-4

Anderson, P. M., Fouad, A. A. (2008). *Power system control and stability*. John Wiley & Sons.

Angarita, JL, Martínez-Crespo, J, Al Sumaiti, A (2020). *Energy Storage Systems Applications in Mexican Power System*. IEEE Smart Grid Newsletter, April 2020.

Apt, J., Fertig, E., & Katzenstein, W. (2012). Proceedings from 2012 45th Hawaii International Conference on System Science, Smart Integration of Variable and Intermittent Renewables. (pp. 1997 - 2001). Maui, HI. Retrieved from http://www.computer.org/csdl/proceedings/hicss/2012/4525/00/4525b997.pdf

Aziza A., Than Ooa, A., Stojcevski, A. (2018). *Analysis of frequency sensitive wind plant penetration effect on load frequency control of hybrid power system*. Electrical Power and Energy Systems 99, 603–617.

Bevrani, H. (2014). *Robust Power System Frequency Control, Power Electronics and Power Systems*, DOI: 10.1007/978-3-319-07278-4_12, © Springer International Publishing, Switzerland.

Calisti, R., L'Abbate, A., Migliavacca, G., Zani, A., Overholt, P., Valentine, O., Marchionini, B. (2016). *Storage and balancing as key elements for future network planning and electricity markets design*. ISGAN Annex 6 Power T&D Systems, Discussion paper, http://www.iea-isgan.org/storage-and-balancing-as-key-elements-for-future-networkplanning-and-electricity-markets-design/.

CENACE (2016). *Metodología para el cálculo de los requerimientos de reserva de regulación y reserva rodante en el Sistema Interconectado Nacional.* https://www.cenace.gob.mx/Docs/MercadoOperacion/CalculoReqServCon/Metodolog%C3%ADa%20C%C3%A1lculo%20Req%20SC%20SIN%20v2016%20Enero.pdf

National Energy Control Center (CENACE). (2017). Ancillary Services. Mar 2020, CENACE web: http://www.cenace.gob.mx/SIM/VISTA/REPORTES/ServConexosSisMEM.aspx

CENACE (Dic. 2017). *Niveles de cortocircuito de la red nacional de transmisión 2020*. Dirección de Planeación y Operación del Sistema. Subdirección de Planeación.

National Energy Control Center (CENACE). (2018). One-line diagrams of the national electricity system 2018-2023. Mar 2018, CENACE web: https://www.cenace.gob.mx/Docs/MercadoOperacion/ModGralPlaneacion/Mod%20Gral%20Planeaci%C3%B3n%202018-2023%20Diagramas%20Unifilares%20RNT%20y%20RGD%20del%20MEM.pdf

Cohn, N (1967). *Considerations in regulation of interconnected areas*, IEEE Transactions on Power Apparatus and Systems, vol. 87, no. 2, pp. 513-520.

COMISION REGULADORA DE ENERGIA, (April 08, 2016). *Grid code* (in Spanish), DIARIO OFICIAL.

Elgerd O.I. (1982). *Electric energy systems theory: an introduction*, New York, NY: McGraw-Hill Book Company.

Glossary of Term Task Force of North America Electric Reliability Council (August 1996), *Glossary of Terms*.

Hillberg, E., (2019). Flexibility needs in the future power system, Discussion paper. ISGAN Annex 6 Power T&D Systems.

https://www.fkfoundation.com/es/lithium-ionen.html, accessed May 18, 2020

IEA (2018). *Status of Power System Transformation 2018: Advanced Power Plant Flexibility*. IEA, Paris.

IEEE Standards Coordinating Committee 21 on fuel cells, photovoltaics, dispersed generation, and energy storage (2003). *IEEE standard for interconnection and interoperability of distributed energy resources with associated electric power systems interfaces*.

IEEE Standards Coordinating Committee 21 on fuel cells, photovoltaics, dispersed generation, and energy storage (2018). *IEEE standard for interconnection and interoperability of distributed energy resources with associated electric power systems interfaces*.

IRENA (2017). *Electricity storage and renewables: Costs and markets to 2030*. International Renewable Energy Agency - IRENA.

ISGAN and the Swedish Smart Grid Forum (2018). *Opportunities to Accelerate Smart Grid Deployment through Innovative Market Design*. [Online]. Available: http://www.iea-isgan.org/isgan-side-event-during-cem9-intelligent-market-designboosting-global-smart-grid-deployment/.

Jayamaha C., Costabeber A., Williams A., Sumner M. (2018). *An independently controlled energy storage to support short term frequency fluctuations in weak electrical grids*. Electrical Power and Energy Systems 103, 562–576.

Kern EC, Gulachenski EM, Kern GA (1989) *Cloud effects on distributed photovoltaic generation: slow transients at Gardner, Massachusetts photovoltaic experiment*. IEEE Trans Energy Convers 4(2):184–190

Kindle A, Shawhan D, Swider M, (Oct 2013). *An Empirical Test for Inter-State Carbon-Dioxide Emissions Leakage Resulting from the Regional Greenhouse Gas Initiative*. New York Independent System Operator.

Kindle A (April 2015). *Four Essays Analyzing the Impacts of Policy and System Changes on Power Sector Emissions.* Dissertation. Rensselaer Polytechnic Institute, Troy, N.Y.

http://digitool.rpi.edu:8881/R/YNJX9QENF7SHCLDR3SQ813P4M4BX1LPG5FQ844PMXJ9H4KRIFI-01751?func=search-simple-go&local_base=GEN01&find_code=WTI&request=Four%20essays%20analyzing%20the%20impacts%20of%20policy%20and%20system%20changes%20on%20power%20sector%20emissions

Kundur, P., (1994). *Power System Stability and Control,* McGraw-Hill Education.

SANDIA REPORT (2015), SAND2015-XXX, DOE/EPRI Electricity Storage Handbook in Collaboration with NRECA.

Secretaría de Energía MÉXICO, (2018). *Manual de Criterios para el Despacho y la Desagregación de Energía para las Unidades de Propiedad Conjunta en el Mercado Eléctrico Mayorista* (in Spanish), DOF 11.01.2018.

Secretaría de Energía MÉXICO, (2019). *Programme for the development of the national electricity system PRODESEN 2019-2033* (in Spanish).

Taylor, C. (1994). *Power System Voltage Stability*. McGraw-Hill Education – Europe

US Federal Energy Regulatory Commission (FERC). (April 24, 1996). Promoting Wholesale Competition Through Open Access Non-Discriminatory Transmission Services by Public Utilities; Recovery of Stranded Costs by Public Utilities and Transmitting Utilities Final Rule. *Docket Nos. RM95-8-800 and RM94-7-001*, Issued Orders No. 888 and 889, 1-10.

Wood, A., and B. Wollenberg. (1996). Power Generation, Control, and Operation, Second edition. New York: John Wiley and Sons.

Wu. F. F. (November 4, 1998). Ancillary Services, *EE290N Lecture Notes* from University of California, Berkeley.

Xia Y, Ghiocel SG, Dotta D, Shawhan D, Kindle A, Chow JH (Dec 2013). A Simultaneous Perturbation Approach for Solving Economic Dispatch Problems With Emission, Storage, and Network Constraints. Published in: IEEE Transactions on Smart Grid, Vol 4, Issue 4.

Xue Y, Starke M, Dong J, Olama M, Kuruganti T, Taft J, Shankar M (2018) *On a future for smart inverters with integrated system functions*. In: 2018 9th IEEE international symposium on power electronics for distributed generation systems (PEDG). Charlotte, NC, USA

Zhaoa C., Malladab E., Lowc SH, Bialek J. (2018). *Distributed plug-and-play optimal generator and load control for power system frequency regulation*. Electrical Power and Energy Systems 101, 1–12.