Lessons from the 2010 Chilean earthquake and its impact on electricity supply

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***Abstract*—Security of energy supply is a main concern worldwide, given the strong dependence on society functioning on its adequate delivery. Surges in fuel prices, political conflicts, wars and natural disasters threaten directly energy supply, and countries look at ways to protect themselves.**

On February 2010 an 8.8 Richter scale earthquake hit the central part of Chile and a tsunami following the earthquake hit coastal areas, affecting the most populated area of the country. Main supplies collapsed, electricity, water, gas, telephones, contributing to make matters worse for the suffering population. This paper illustrates events that took place in electricity supply during and after the earthquake in Chile, its impact on the generation, transmission and distribution infrastructure, and the lessons to be learned. The challenges in reconstruction are also discussed.

The main interconnected system, generation and main transmission grid, was able to resume partial operation within a few hours, although in a weak condition. Damage took place in some main substations, and alternative paths and operational conditions had to be found. Security criteria had to be degraded in the system operation and handling of the main grid.

The Chilean codes impose strict anti seismic standards for all electricity infrastructure construction, but the earthquake strength still produced damage in some grid installations. However, the most severe damage took place in the distribution networks, vast areas were left with no supply for weeks, including the large city of Concepcion being severely affected.

***Index Terms*--Security of supply, seismic performance, natural disasters, earthquake, power system restoration.**

I. INTRODUCTION

Security of energy supply is a main concern worldwide, given the strong dependence on society functioning on its adequate delivery. Surges in fuel prices, political conflicts, wars and natural disasters threaten directly energy supply, and countries look at ways to protect themselves. Electricity is at the centre of attention as today many essential services (water, gas and communications just as examples) depend on its continuity for a smooth functioning of modern society.

The impact of natural disasters and their impact on power system functioning has been of interest for countries worldwide, particularly in relation to earthquakes. Several countries such as Chile, China, Haiti, Indonesia, Italy, Japan, Mexico, Philippines, Turkey, and the US have experienced severe earthquakes that resulted in serious damages to their energy supply infrastructure and their economic development, in addition to the loss of lives and properties [1].

Thus, research in energy security and earthquake disasters has developed worldwide, focusing on earthquake risk assessment and management, power system resilience, energy supply systems preparedness, and disaster countermeasures and response plans, with different publications . Advances have been made in different fields, for example seismic performance analysis of electric power systems are reported in [1], [2] and [3], on power installation design criteria to cope with earthquakes in [4], on modeling the fragility of system components [5], on electrical power availability after an earthquake [6], and others [7,8,9].

Reference [1] indicates that the main challenges faced by APEC member economies with regard to reducing the damage of energy supply system caused by a severe earthquake are to:

- Identify and verify the causes for the earthquake.
- Operate the emergency communication system and make it functional after the earthquake.
- Re-locate the emergency energy supply system.
- Investigate the damage condition for the energy supply system resulted from earthquake.
- Execute the rescue action according the rescue plan.
- Implement the plan for the rebuilding of energy supply system

II. CHILEAN EARTHQUAKE AND ITS IMPACTS

An 8.8 Richter scale earthquake lasting about 140 seconds hit the central part of Chile on Saturday February 27th, 2010, at 03:34 AM, affecting the most populated area of the country (Figure 1). It is the fifth strongest ever recorded earthquake worldwide. At least 1.8 million people were affected in Araucania, Bio-Bio, Maule, O'Higgins, Santiago and surrounding areas, and Valparaiso. 521 people were killed, 56 missing, about 12,000 injured, 800,000 displaced and at least 370,000 houses, 4,013 schools, 79 hospitals and 4,200 boats damaged or destroyed by the earthquake and tsunami in the Valparaiso-Concepcion-Temuco area [10]. The total economic loss in Chile was estimated at 30 billion US dollars.

The earthquake fault rupture exceeded 100 km in width and extended nearly 500 km parallel to the coast. Maximum ground acceleration of 0.65 g was recorded at Concepcion,

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more than 2 m of uplift along the coast was observed near Arauco, and a 10 meter average displacement of the continental plaques took place [10]. Concepcion moved over 3 meters west due to the event.

Main supplies collapsed, electricity, water, gas, telephones, contributing to make matters worse for the suffering population.

Figure 1.- Exposure map of Chilean 2010 earthquake (US Geological Survey)

Chile, given its history of violent earthquakes, has developed a high standard of seismic requirements for its civil works. Building codes in Chile are substantially the same as US codes (ACI 318, a leading concrete design reference for building codes worldwide issued by the American Concrete Institute, incorporating requirements for earthquake-resistant structures). In the case of high voltage electrical facilities, the national technical standard establishes that facilities must obligatorily fulfill the ETG 1.015 Chilean standard or the IEEE 693 standard in the condition of High Performance Level. It specifies a maximum 0.50 g acceleration and a maximum horizontal displacement of 25 cm. to be considered in the design as the seismic intensity at the facility location.

On the specific electrical requirements for installation construction and maintenance, in Chile there is a Technical Norm of Security and Quality of Service, which defines technical and economic evaluations to determine the reliability level on the planning and operation of the power system.

A. Impact on electricity supply

The Chilean Central Interconnected System (SIC), which provides electricity to over 93% of the Chilean population, was damaged by the earthquake. An immediate blackout took place for a load of 4522 MW (the peak demand of the system is 6,145 MW). Its installed capacity, as of February 2010, was 11,023 MW, with a demand recuperating to a steadier growth of 5 % after two years of almost nil increase.

A total of 693 MW of existing generation plants (6.1% of the installed generating capacity) was affected and was left out of service for repairs, while 950 MW of generation plants being built was put on hold, pending assessments. However, that missing capacity did not risk supply of generated energy, in an electrical system where investment in power plants was growing well, responding to a predicted high demand growth and recent regulatory changes.

Conditions were different for electricity transmission. The Chilean main grid, given the geographical shape of the country, is a longitudinal one extending for around 2000 km, with most of the grid built to cope with N-1 security conditions, except for transformation equipment. Although the earthquake damaged some transmission equipment, the grid was still able to operate (now with an N security condition in several places) and, in fact, supply at the main grid level was recovered in a few hours after the quake. A two island scheme was used for operation, the central part of the country separated from the south, given the damage at some substations and isolated problems in transmission. Two days after the two islands were interconnected. Figure 2 illustrates the way supply evolved over time.

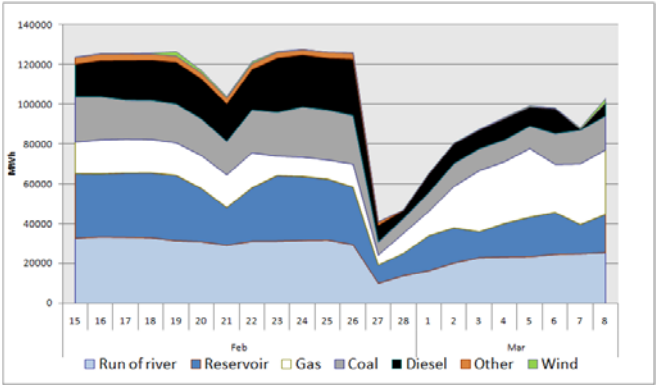

Figure 2.- Evolution of supply before and after earthquake (Ref: Systep)

Nevertheless, the fast supply recovery at the generation-transmission level did not necessarily mean that supply to the end consumer was recovered as fast. The distribution networks were severely damaged in several parts of the country, and although repairs were made, it took several days or even weeks to complete. There were coastal regions where the distribution network was completely destroyed. Load dropped 3,000 MW and recovered slowly, as figure 3 illustrates.

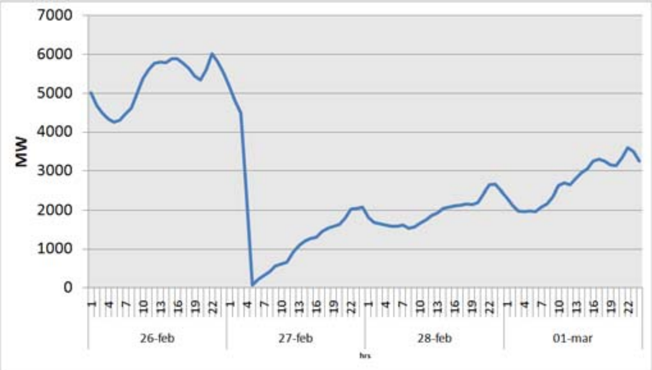

Figure 3.- Evolution of hourly load after the earthquake (Ref.:Systep)

A more detailed analysis is made of each of the segments of the electricity supply chain.

III. IMPACT ON GENERATION

At the time of the earthquake, dispatched generation was of 4522 MW, were an assortment of technologies were dispatched. Figure 4 shows the composition of generation by technology the day of the earthquake. As a consequence of the earthquake, a generation capacity of approximately 3,000 MW became unavailable immediately after the event. In the following 30 days, 2,257 MW were put back into service. However, 693 MW remained out of service requiring major repairs. Figure 5 shows the evolution of the availability of the generation facilities in the following 30 days after the earthquake.

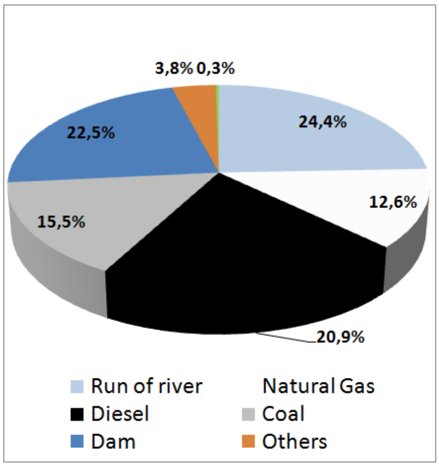

Figure 4.- Generation on the day of the earthquake, by technology

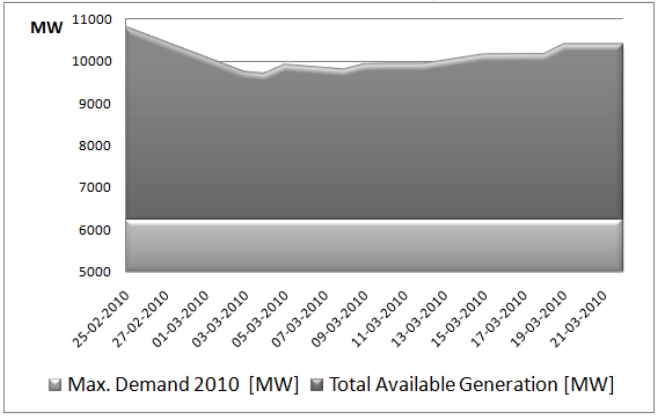

Figure 5.- Evolution of the availability of the generation facilities.

A total of 2,257 MW from 24 generation plants, most of them thermal, were damaged but were available for dispatch in the following days after the earthquake. Most of the damages suffered were minor, but required repairs, such as faults in cooling systems, loss of communication, transmission lines and transformers, etc. In the other hand, 693 MW from 16 generation plants require major repairs and some of them can be out of service up to six months due to the severity of the damages.

IV. IMPACT ON TRANSMISSION

The main transmission company in Chile is Transelec, with 8,239 kilometers of transmission lines, 50 substations and 10,486 MVA in transformation capacity in the two interconnected systems SIC and SING. Transelec suffered multiple damages on SIC facilities, as shown in table 1 [11].

TABLE I
TRANSMISSION DAMAGES

	Number	Damaged	%
Substations	46	12	26%
Transmission lines (km.)	7280	1.6	0.02%

Damages at the line level concentrated on 3 towers of the Hualpen-Bocamina 154 kV line. Damages at the substation level were mainly focused on (Figure 6):

- 500 kV bushings
- 500 kV pantograph disconnector switches
- 220 kV circuit breakers (live tank type)
- 154 kV circuit breakers (air compressed type)

Figure 6.- Transmission equipment damage (Transelec)

The transmission system went first through a fast service recovery process, in successive stages, as indicated in table 2.

Then, main post-recovery actions were:

– From 18 March critical control systems for the application of the N-1 criteria were thoroughly checked.

– On 25 March, the exhaustive inspection of transmission facilities was completed, focusing on diagnosis of damaged equipments at affected substations.

– On 30 March, the 154 kV Hualpen-Bocamina line was repaired: two towers without damages at pylons and another was replaced by an emergency structure.

– Damaged bushings from 500 kV reactors at Polpaico substation were sent to its factory in Sweden to investigate its seismic behavior, rectify its design and then repair them.

TABLE 2
RECOVERY PROCESS

City	Event	Date	Time
	Earthquake and blackout	February 27	3:34
Santiago (capital)	Supply recovered		3:58
Temuco	Supply recovered		4:05
Copiapó	Supply recovered		5:05
La Serena	Supply recovered		6:35
Puerto Montt	Supply recovered		10:31
Rancagua	Supply recovered		14:46
	Two islands interconected		18:48
Concepción	Supply recovered	February 28	10:24
Talca	Supply recovered		11:38

Key factors in the fast recovery of transmission service were not only related to the constructive quality of the infrastructure, that in general successfully met the seismic norm test, but in the fast and competent response from Transelec staff, with a rapid reaction soon after the earthquake, and the commitment on the field of both the technical personnel and the company third party contractors.

V. IMPACT ON DISTRIBUTION

Most of the load was not supplied for weeks due to problems that arose in the distribution network. In effect, four and a half million people were initially affected by the extended blackout that took place because of the earthquake and it took days, and even weeks in some areas, to recover full supply. Chilectra distributes energy in Santiago, the capital, while three distribution companies service the most affected areas, CGE, Emelectric and Emelat. Figure 7 illustrates the impact in the most affected area, and how electricity supply was recovered over time [12]. 80% of clients were without supply the day after the earthquake and this reduced to 0.4% two weeks after. This last percentage related mainly to Concepcion and Talcahuano, next to the earthquake epicenter, the latter being also hit by the consequent tsunamis.

Some distribution networks were destroyed by the effects of the earthquake, as houses fell over street lines or simply were washed away by the tsunamis (Figures 8 and 9). As an example, 40,000 houses were destroyed out of 1.5 million supplied by CGE.

Besides those distribution installations directly damaged by falling houses, fissures and land slippage, or the tsunami, there was little damage elsewhere. Distribution poles in Chile are mainly compressed pre-stressed concrete poles, which are well founded, and support important mechanical stresses. Electric wires supported by poles do not impose any significant mechanical requirements to the poles. Different is the case when, mainly in urban area, those poles also support communication cables (cable TV and telephone), that are heavier and make larger requirements. Several damaged poles supported heavy additional loads.

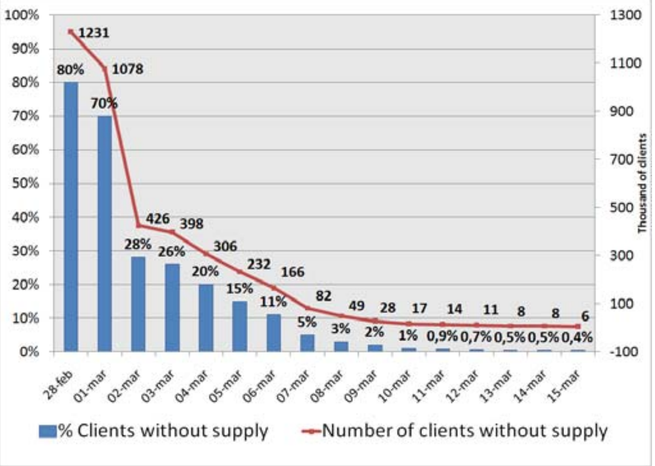

Figure 7.- Evolution of clients without electricity supply (Source: CGE)

Figure 8.- Effect of earthquake in Talca (Source: CGE)

Figure 9.- Effect of tsunami in Talcahuano (Source: CGE)

Distribution aerial transformers are often placed between two poles and a steel support, thus they also withstand well an earthquake.

Overhead aerial distribution networks were more easily repaired than underground installations that took longer to repair.

Therefore, the main difficulties in restoring supply to houses took place at the connection point between the low voltage lines and the buildings. Those connections do suffer damages at other times. Severe rains or storms in a city may, in one day, typically damage 1,000 to 5,000 connections. Distribution companies soon learn which connections are damaged, as consumers directly report them to the company. The companies have the equipment and human resources to repair those connections within one or two days. But when several hundred thousand of those connections fail, as in an earthquake, the problem is quite different. There are communication problems and there is no easy way to learn which connections failed. Physical access to the locations complicate, because of the earthquake. But overall, distribution companies do not have the resources to manage the huge number of needed repairs. Companies involved human resources brought from other parts of the country and even from subsidiaries in neighboring countries, but the task was still enormous, and took long time to accomplish it.

On the whole, damage to distribution installations was minor, percentage wise. Figure 10 illustrates the percentage of damaged poles and transformers over the total in the two main distribution companies in Santiago (supplied by Chilectra), the capital, and the affected area around Concepcion (supplied by CGE and its subsidiaries). These percentages are for a population of 760,000 poles for CGE and 300,000 for Chilectra, and 50,000 transformers for CGE and 20,000 for Chilectra.

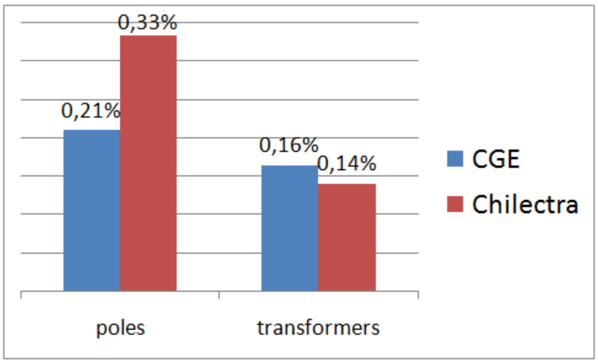

Figure 10.- Distribution equipment damage (Source: Chilectra and CGE)

Mobile generating sets were brought to support recovery of supply, particularly in more isolated areas.

The challenges for distribution companies did not end with reestablishing supply to final consumers, but are lasting months after the earthquake. This is so because there were, as one would expect, many latent faults, caused by the quake, that could not be detected when repairs were been made days after the event, or if detected, were secondary to the objective of supplying consumers as fast as possible. The arrival of the winter, with rain and wind, started igniting these faults in a a massive way, demanding the companies to comply.

VI. IMPACT ON OPERATION

The earthquake had severe impacts on the communication systems in the country as a whole. Basic communication systems, such as mobile networks, emergency alert schemes, public order control, support to damaged communities, among others, did not operate as desired and caused additional harm.

Difficulties also arose in the communications and telecontrol schemes of most electricity installations, transmission substations and generating plants, complicating plant and system recovery and operation. The system operator had additional difficulties throughout the emergency as the SCADA system in use, which has been in place for over ten years, was not able to provide information required for system recovery, for example alarms could not be trusted as they were often incorrect. Traditional phone calls had to be used to learn on local conditions and supervise actions for equipment and system restoration. Nevertheless, challenges were not as severe as in a typical blackout, as load reduced dramatically because of the quake.

In spite of those restrictions, system restoration, as indicated before, was fast at the generation-transmission level. The system operator was able to successfully apply its extreme contingency procedures. Recovery started with five islands, which were later integrated into two, until full integration was achieved. Breakers, which had been damaged, were bypassed in several substations and facilitated interconnection.

The need to invest in a new SCADA system is a must. The government has also indicated the need for such a system, and the corresponding protocols, to directly communicate with the National Emergency Office (Onemi), an office that has been at the center of criticism for not responding adequately to the earthquake.

Operation and market wise, when the two islands were isolated, spot prices at the main busbar at the earthquake area reached the non-supply cost, as shown on figure 11.

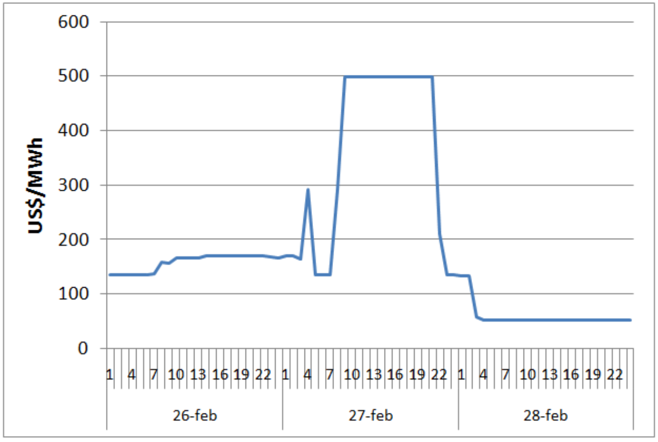

Figure 11.- Hourly spot prices at Charrua (Source: CDEC-SIC)

VII. MARCH BLACKOUT

A week after the earthquake, on Sunday March 14th, at 20:44 hrs, a global blackout took place. It was caused by the disconnection of a 750 MVA 500/220 kV transformer bank at Charrua substation, due to a loosen protection control cable of the transformer, originated in the earthquake.

The blackout raised discussion on the security levels the country should adopt (both in transmission investment and in system operation), a discussion that will probably remain on the table for some time. It is acknowledged that increasing security levels necessarily implies raising the cost of electricity in a country that already has higher prices than other countries in the region.

The security of service level in the transmission system in Chile is measured via the use of the N-1 criteria. The N-1 criteria or single contingency criteria, commonly used in the planning and operation of power systems throughout the world, allows the system to operate normally in front of any outage on equipments or facilities, either a line circuit or a generating unit, without a cascade propagation on the rest of the system facilities. Figure 12 shows the current security level in the SIC main transmission system [11]. Several sections in the system do not have the infrastructure to operate with N-1 criteria. In fact, the 500/220 kV transformation capacity at Charrua did not operate with N-1, and its disconnection overloaded networks and caused the collapse.

VIII. CONCLUSIONS

Experiences reported in the literature indicate that transmission and distribution facilities are more exposed to major earthquakes. Design of generation facilities adopts higher design and building standards and generation equipment can usually withstand important earthquakes, this is even more so in Chile where seismic civil engineering standards are high.

The Chilean earthquake was a very severe one and the initial balance in the country is that the grid and the power system as a whole were well prepared for the event.

The earthquake and the consequent tsunami were so strong that it would be impossible (and uneconomic) to avoid a power failure in similar conditions. Probably, there is space for improvement in power recovery, especially at the distribution level, and studies will have to be made for that purpose in the near future. The experience gained on earthquake damages, responses and system restoration must be shared country wide as it will necessarily be of use for the future. Chile is a country permanently menaced by earthquakes and a severe one is projected for the north of the country. It may take place tomorrow or within the next ten years, so that preparedness is a must for companies in the area.

Power supply alternatives for critical loads will probably be a growing issue as, in today's Chile; essential services are becoming increasingly dependent on continuous power supply to function properly.

Chile is uneasy, in general, about its response to this 8.8 earthquake. As indicated before, basic communication systems did not operate as desired and caused additional harm. Existing early warning measures and emergency management schemes proved inapplicable. Opportunities for improvement will necessarily be in the agenda of the country, and the teachings will clearly help other countries.

Nevertheless, the country's infrastructure (roads, buildings, civil infrastructure, etc.) performed well, under the severe stress that was imposed. The seismic norms in place implied that damage, although striking, was very limited, and this applies particularly to the power grid. This experience can be most useful for countries in similar risks of exposure to natural disasters.

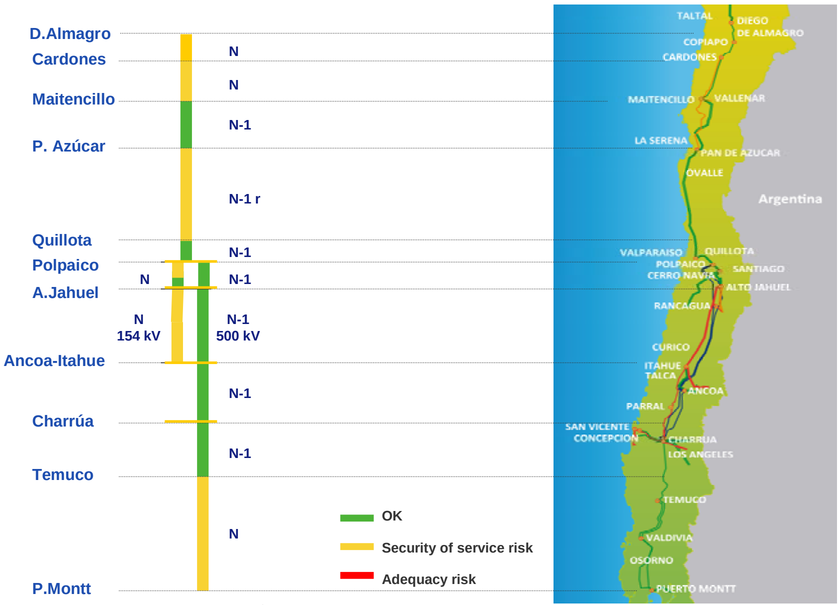

Figure 12.- Security of service level in the SIC main transmission system

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X. BIOGRAPHIES

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Pedro Miquel graduated as Civil Electrical Engineer from Universidad de Chile. He has had an extensive experience in the power industry, with responsibilities in the National Energy Commission, Endesa and Chilectra, where he was Operations Vice Manager for Distribution. He is presently the Technical Manager at Systep Ingeniería y Diseños, where he has directed several power system studies for utilities in Chile and abroad.