Restoring Electricity Supply After the 2010 Chilean Earthquake

Disaster Management

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ON 27 FEBRUARY 2010, AN EARTHquake registering 8.8 on the Richter scale struck the central part of Chile and a tsunami subsequently hit coastal areas, affecting the most populated area of the country (see Figure 1). This earthquake was the fifth-strongest recorded in modern history; the strongest one also struck Chile, in 1960, and had a Richter magnitude of 9.5. The total economic loss in Chile for the 2010 earthquake was estimated at US$30 billion. The earthquake's fault rupture exceeded 100 km in width and extended for nearly 500 km parallel to the coast; more than 2 m of uplift along the coast was observed near Arauco, and a 10-m average displacement of the continental plates took place. All the principal supply systems—electricity, water, gas, and telecommunications—collapsed, making matters even worse for the suffering population.

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Experiences reported in the literature indicate that transmission and distribution facilities are more vulnerable to major earthquakes than generation facilities.

Preparedness is the key to confronting a disaster like a major earthquake. Given the seismic history of Chile, electrical facilities, civil infrastructure, and equipment have all been designed to survive strong earthquakes. In effect, Chile has developed a high standard of seismic requirements for its civil infrastructure. Building codes in Chile are substantially the same as U.S. codes; they adhere to ACI 318, a leading concrete design reference for building codes worldwide issued by the American Concrete Institute, which incorporates requirements for earthquake-resistant structures. In the case of high-voltage electrical facilities, the national technical standard requires facilities to fulfill the ETG 1.015 Chilean standard or the IEEE 693 standard in the "high performance level" condition. This specifies that a maximum 0.50 g acceleration and a maximum horizontal displacement of 25 cm be considered in the design as the seismic intensity at the facility location.

With respect to the specific electrical requirements for installation construction and maintenance, in Chile there is a technical norm of security and quality of service that defines the technical and economic evaluations needed to determine the reliability level for the planning and operation of the power system.

But it is not only equipment that must be designed and installed to cope with violent earthquakes. An autonomous and prompt response of field crews and at dispatch centers is just as important in order to manage the aftereffects of such an event and the recovery of electricity supply. The February 2010 earthquake demonstrated that there are aspects of disaster management that need attention if Chile is to achieve better results in the future.

Impact on Electricity Supply

The Chilean Central Interconnected System (SIC), which provides electricity to more than 93% of the Chilean population, was affected by the earthquake. An immediate blackout took place in the context of a total load of 4,522 MW (the peak demand of the system is 6,145 MW). The system's installed capacity at the time was 11,023 MW, with demand recovering to a steadier growth of 5% after two years of almost no increase due to global financial turmoil and high energy prices.

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

Conditions were different for electricity transmission. Given the geographical shape of the country, the Chilean main grid is a longitudinal one, extending for approximately 2,000 km. Most of the grid—except for transformation equipment—was built to cope with N-1 security conditions. Although the earthquake damaged some transmission equipment, the grid was still able to operate (though

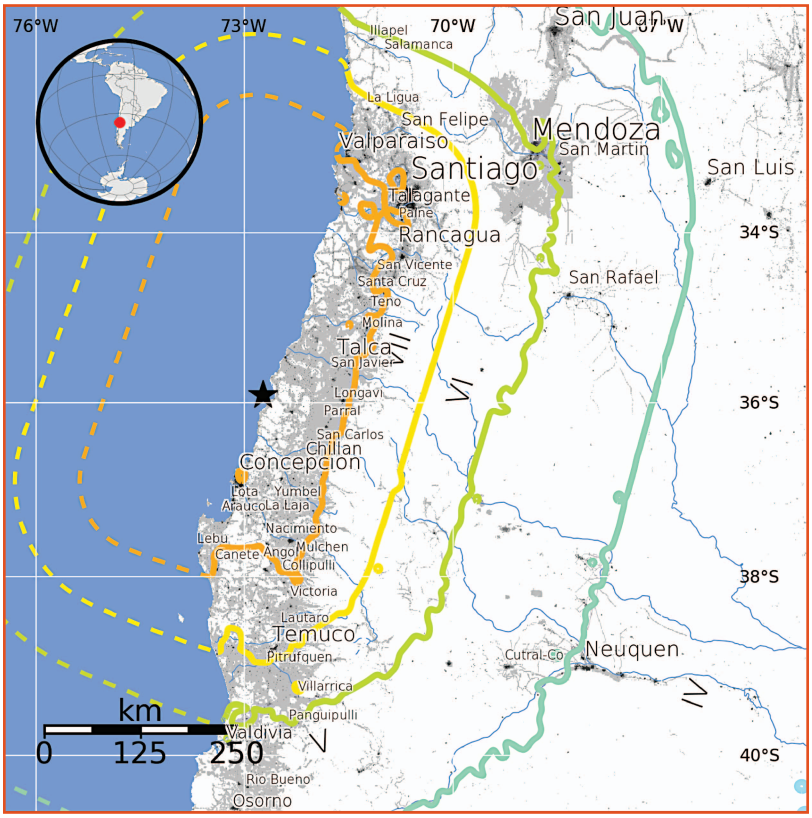

figure 1. Exposure map of the 2010 Chilean earthquake (credit: U.S. Geological Survey).

with an N condition in several places). In fact, supply at the main grid level was recovered within a few hours of the quake. A two-island scheme was used for operation: the central part of the country was separated from the south, given the damage at some substations and isolated problems in transmission. Two days later, the two islands were interconnected. Figure 2 illustrates how supply evolved over time.

Nevertheless, the fast supply recovery at the generation-transmission level did not necessarily mean that supply to the end consumer was recovered as quickly. Distribution networks were significantly damaged in several parts of the country, and although urgent repairs were made, restoring more than 90% of the load by the end of the first week, it took several more weeks to fully complete the task. There were coastal regions where the distribution network was completely destroyed. Load dropped by 3,000 MW and recovered slowly, as Figure 3 illustrates.

A more detailed analysis will now be given for each of the segments of the electricity supply chain; it will be seen that there were major difficulties at the network level.

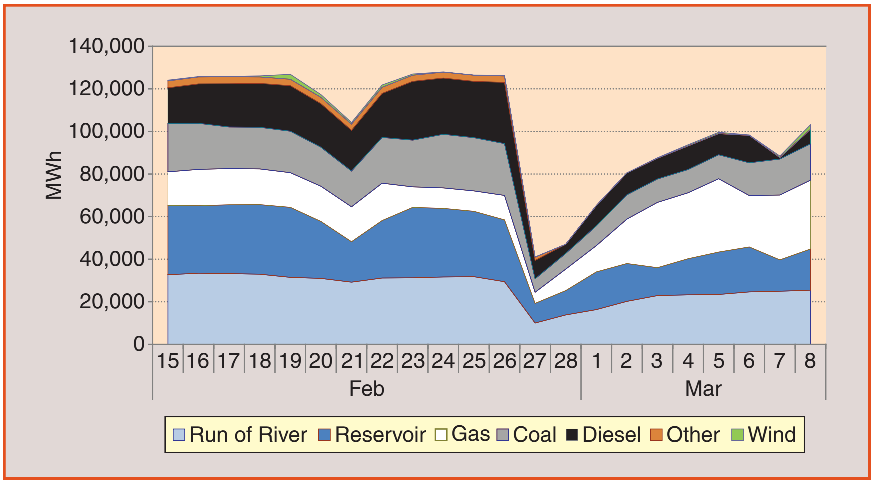

figure 2. Evolution of supply before and after the earthquake (courtesy of Systep).

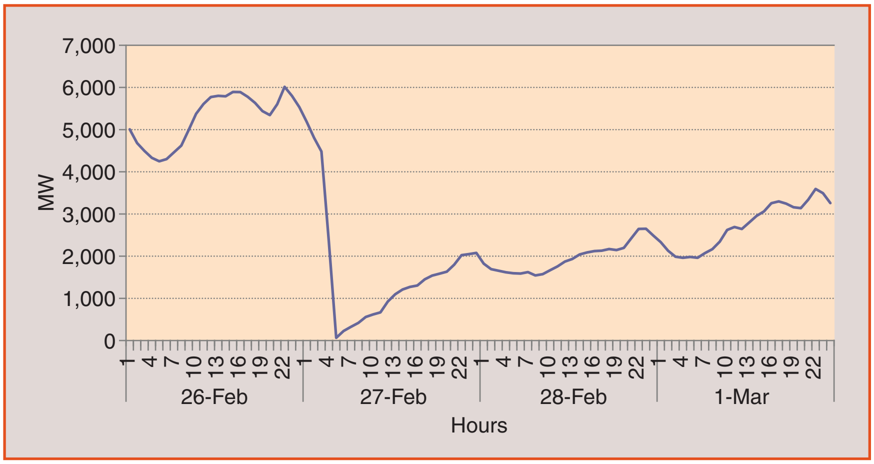

figure 3. Evolution of hourly load after the earthquake (courtesy of Systep).

The Impact on Generation

At the time of the earthquake, dispatched generation amounted to 4,522 MW, where an assortment of technologies was dispatched (reservoirs, run of river, coal, natural gas, and diesel). 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 in service. Most of the damages suffered were minor but required repairs, such as faults in cooling systems, loss of communication, damage to transmission lines and transformers, and so on. On the other hand, 693 MW from 16 power plants required major repairs; some of the plants were out of service for as long as six months due to the severity of the damage.

The Impact on Transmission

The main transmission company in Chile is Transelec, with 8,239 km of transmission lines, 53 substations, and 10,486 MVA of transformation capacity in the two interconnected systems in Chile, SIC and SING. The earthquake was a first-class test for the seismic specification of equipment and civil infrastructure, but some equipment was damaged in the SIC (see Table 1). Damage at the substation level, shown in Figure 4, was mainly focused on:

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

table 1. Affected transmission.

Facilities Affected	
High-voltage substations	12
High-voltage transmission lines (km)	1.6
Equipment Affected (66–500 kV)	
Breakers	9
ATR and reactor bushings	12
Surge arresters	10
Instrument transformers	20
Disconnectors	21
High-voltage towers	3

> Apart from the satisfactory power system recovery, Chile is still somewhat uneasy about its country's response to the earthquake.

Whether the magnitude of the earthquake surpassed the seismic requirements or some of the equipment did not respond according to its nominal specifications is still being studied. These studies will determine whether the specifications need to be revised.

The failures that affected equipment belonging to utilities across the country share an important common element. Standard procedures in the design of wire connections between pieces of equipment in the layout of the switchyards were not always followed. It is fundamental that the span of these connections allow the equipment to move almost freely during an earthquake. In many cases, the tension transmitted through these wire connections exceeded the design requirements of the equipment. And certain solutions, like the installation of surge arresters at the top of a transformer's fire protection walls, seem to be flawed, since several of these devices failed.

figure 4. Transmission equipment damage (used with permission from Transelec).

Emergency response plans are part of the expected preparation of a transmission company for a disaster like this, and they proved to work fairly well, although the sheer size of the area affected revealed some weaknesses. Action plans for reacting to specific kinds of damage were identified as part of the emergency response plan and had been in place for many years, but the thinking had always considered events involving a limited number of facilities. Emergency plans had considered the availability of all the resources required to face specific contingencies, i.e. spare parts, cranes, and so on. But in some places these resources were not available at all where needed in the first days of the response because the earthquake had disrupted road infrastructure.

The conditions mentioned above obliged the transmission company and system operator to plan the recovery process in three main stages. The first stage was to restore service in those areas with no facilities affected, using local generation resources to form islands. The second stage involved making basic repairs to restore the trunk transmission system, and the goal of the third stage was to restore system reliability.

In the second stage, the autonomy of transmission personnel played a fundamental role. The directives they received after the earthquake from their headquarters concerned the principal equipment to be restored. But they had to manage this with limited resources. Using light equipment, and without spare parts to repair the system, a wide variety of solutions had to be used: dismantling failed bays to use their elements in another bay, bypassing broken breakers and extending the range of their protections from the other side, and so on. Another important aspect of the response was the availability of personnel, especially taking into account the time the earthquake struck (3:34 a.m. on a Saturday morning at the end of summer). Within two hours of the earthquake, there were crews working in the affected substations. In areas that were not affected, brigades started preparing to move to the damaged areas. All these efforts allowed the main transmission network to be restored to service in less than 13 hours, albeit in a weakened condition.

Only in the third stage, which took several months to complete, did the availability of spare parts present difficulties. In certain cases, the support of neighboring countries'

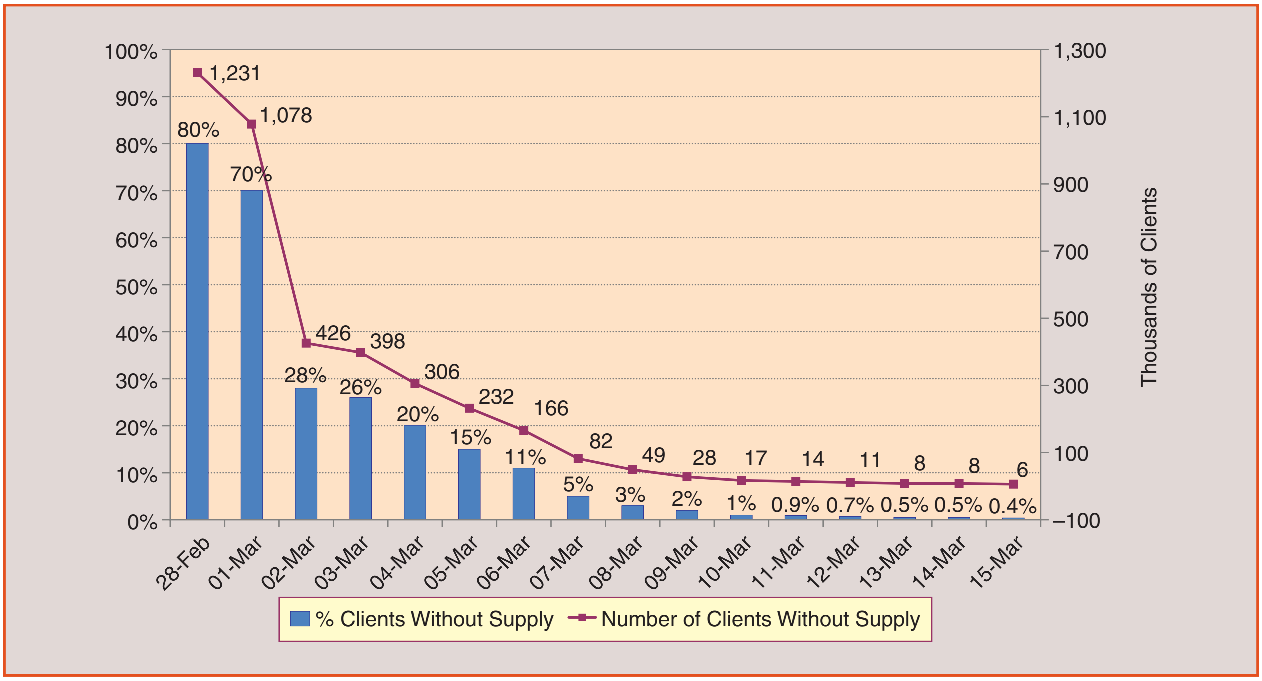

figure 5. Impact on distribution and restoration of electricity supply (source: CGED).

transmission companies helped to restore the reliability of the system.

The Impact on Distribution

Total normal load supply was achieved only after several days, due to problems that arose in the distribution network. In effect, 4.5 million people were initially affected by an extended blackout caused by the earthquake, and it took days and even weeks in some areas to recover full supply. Chilectra distributes energy in Santiago, the capital, while two other distribution companies service the areas most affected by the earthquake: CGE Distribucion and its subsidiary Emelectric (both entities will hereafter be identified as CGED). Figure 5 illustrates the impact on distribution in the most affected areas and how electricity supply was restored over time by CGED. Although 80% of CGED's clients were without supply the day after the earthquake, this was reduced to 0.4% two weeks later. The last clients to have supply restored were mainly in Concepcion and Talcahuano, very close to the epicenter of the earthquake; the latter area was also hit by the subsequent tsunamis.

Some distribution poles and line spans were directly destroyed by the effects of the earthquake, as houses fell over street lines or were simply washed away by the tsunamis (Figures 6 and 7). In all, 40,000 houses were destroyed out of 1.5 million supplied by CGED. The materials and

figure 6. Damage from the earthquake in Talca (used with permission from CGED).

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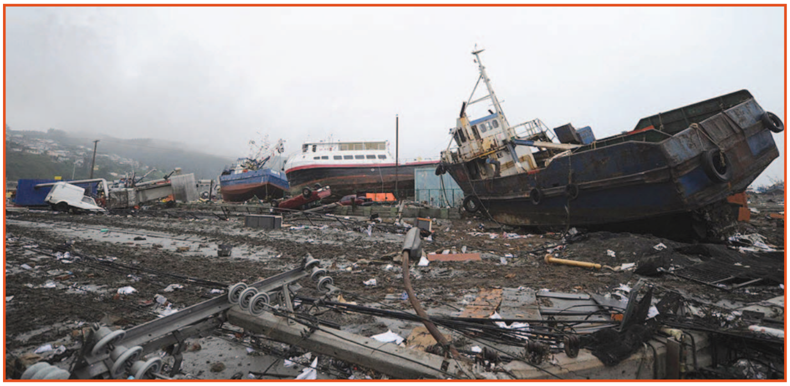

figure 7. Effects of the tsunami in Talcahuano (used with permission from CGED).

equipment used in distribution did not suffer from design or construction failures, however; damage was principally due to the collapse of nearby walls, landslides, or the tsunamis, and there was little damage elsewhere. Distribution poles in Chile are mainly compressed prestressed concrete poles set on sturdy foundations that can tolerate significant mechanical stresses. The electric wires supported by these poles do not impose any significant mechanical requirements. In urban areas, however, the poles also support communication cables (cable TV and telephone) that are heavier and impose larger requirements than the electric wires. In several cases, it was the poles supporting the additional heavy loads that were damaged. Aerial distribution transformers are often placed between two poles and a steel support; thus they also tolerate earthquakes well.

On the whole, damage to distribution installations was minor, in percentage terms. Table 2 lists the total number of poles and transformers and the percentage of each that was damaged for the two main distribution companies: in Santiago (supplied by Chilectra) and in the area around Concepcion and Talca (supplied by CGED).

The direct cost impact of the earthquake for CGED, taking into account the operation, logistics, and materials used to repair and/or reconstruct the electricity installations, amounted to less than 1.3% of the book value of CGED's assets. From an economic point of view, increasing distribution design standard requirements does not seem justifiable, since recovery of supply is essentially related to the speed of operational reaction, logistics, and other repair issues.

table 2. Distribution equipment damage (source: Chilectra and CGED).

	Poles	Damaged (%)	Transformers	Damaged (%)
CGE	760,000	0.21	50,000	0.16
Chilectra	300,000	0.33	20,000	0.14

In reality, the main difficulties in restoring supply to houses arose with certain spans in medium- and low-voltage lines and at the connection points between the low-voltage lines and the buildings. Those connections do suffer damage at other times. Severe rains or storms in a city are capable, in a single day, of damaging 1,000–5,000 connections. Distribution companies soon find out which connections are damaged, as consumers report them directly 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 simultaneously, as in an earthquake, the problem is quite different. There are communication problems, and there is no easy way to find out which connections have failed. In addition, after the earthquake, physical access to the locations was complicated. Overall, distribution companies simply do not have the resources to manage the huge number of needed repairs in a timely manner. Distribution companies imported human and technical resources from other parts of the country and even from subsidiaries in neighboring countries, but the task was still enormous; accomplishing it required a huge effort.

CGED is the distribution company that supplies most of the large area affected by the earthquake. It had to make operational adjustments to its recovery procedures on the fly, especially with respect to the size and administration of workforces deployed in different locations. Under normal conditions, CGED operates emergency crews that consist of approximately 230 professionals and technicians and 90 vehicles. During this emergency, it was necessary to coordinate 2,135 people in 750 vehicles. The logistics of ensuring an adequate supply of materials, providing sufficient supervision, and minimizing electrical risks in the field also needed to be worked out.

For supply recovery, particularly in such extended networks (CGED has 44,500 km of medium- and low-voltage installations, including 50,000 transformers in the affected regions), it is important to have in advance

table 3. Lessons learned for distribution.	
Critical Function in Distribution Networks	**Key Learning Factors**
Dispatch and operation of the network	✔ efficient and adaptable operations ✔ decentralized regional dispatch centers typically supervising 300,000–400,000 customers ✔ systemic network restoration independent of the calls made by customers affected
System restoration plans and protocols	✔ adapt protocols to increase significantly the amount of personnel assigned to the work areas in a short period of time (less than five days) ✔ construct pragmatic network recovery plans for critical services such as regional government offices, hospitals, and public water facilities
Field personnel	✔ highly motivated and qualified in the tasks at hand, well equipped and disciplined, trained in risk assessment and prevention, and supported by a logistics chain for their basic needs and those of their families
Communications	✔ robust and wide coverage private radio system for voice communications (not public nor shared) ✔ ensuring high levels of coordination and communication with local authorities ✔ satellite phones to communicate with central offices
Backup generation	✔ usefulness of several mobile generators of small to medium size (1–250 kW), typically using 100–250-kW generators for work areas and small (1–10-kW) units for confined urgencies of service ✔ also consider fuel deployment and logistics
Logistics chain	✔ maintain a robust logistics chain in the supply and procurement of materials; must be agile and dynamic to access the different work areas ✔ similar considerations for logistics of fuel, lodging, and food.

a decentralized and local focus in distribution dispatch activity. This is a key factor in the restoration of electrical service, requiring autonomous protocols and recovery plans. Such a structure lets each dispatch center adapt itself to the local realities and prioritize its resources and operations while maintaining close communication with local authorities. In contrast to a transmission framework, it is recommended that distribution system controls not be grouped into a single central unit but operate within a distributed architecture, e.g., monitoring a total of 300,000–400,000 customers per center.

Mobile generation sets were brought to support supply recovery, particularly in more isolated areas and in towns affected by the tsunamis. CGED's experience indicates that these units must be transported easily and quickly using both trucks and small vehicles and taking into consideration the need to provide enough fuel for at least 24 hours of continuous operation. This type of equipment normally offers operational ranges up to 1,000 kW, with the most appropriate sizes being between 100 and 250 kW and the least effective being the 1,000-kW units. Smaller mobile generators—those producing 1–10 kW—were especially effective in the days following the earthquake. They were able to deliver electricity to critical users such as medical facilities, police stations, fire stations, gasoline stations, dialysis clinics, communication antennas, and so on.

The challenges for distribution companies did not end with reestablishing supply to consumers but lasted for months after the earthquake. There were, as one would expect, some latent faults caused by the earthquake that could not be detected when repairs were being made days after the event (or if they were detected, they were secondary to the objective of supplying consumers as fast as possible). The arrival of the winter, with its rain and wind, began igniting these faults, requiring the companies to act. Table 3 summarizes the lessons the distribution companies learned from the earthquake.

Impacts Common to Transmission and Distribution

An important aspect common to all segments of the chain that must be evaluated when assessing preparedness for an event like an earthquake is the behavior of telecommunication systems. Normally, an electric utility has different private telecom systems—microwave (MW), UHF and VHF, and power line communication (PLC)—to carry the different services required. As the performance of the public services has increased, however, less attention has been paid to private systems, and workers are increasingly relying on cell phones, intranets, and the Internet to communicate.

Immediately after the earthquake in Chile, all public communication was useless because some systems collapsed or were saturated by users. In the hours that followed, the private systems (MW, VHF, and UHF) worked well, and repeaters were fed through the still operational low-voltage lines, batteries, and PV panels. These local networks also collapsed once the backup batteries used up their capacities, although they lasted long enough for the initial energy restoration activities to begin. Emergency generators had to be

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dispatched, sometimes by means of helicopters, to restore the repeaters.

As practically no high-voltage transmission lines suffered damage, PLC became the most important communications system for the transmission company, as it was possible to continuously support the transmission of basic protection signals and operational communications. Distribution companies had to resort to satellite phones to maintain the link between the regional dispatch centers and their main headquarters.

Fuel for emergency trucks and vehicles was another problem in the hours following the earthquake. Due to the behavior of the population, damaged roads, and fallen bridges, fuel was almost completely unavailable. Emergency trucks had to be refueled using the army's strategic reserves until fuel tanks dispatched by the utilities reached damaged areas. A similar situation existed regarding currency: when the communication system collapsed, banks and ATMs stopped working. There was no cash available to support the work of the emergency brigades. Again, special deliveries from areas that were less hard hit were the solution.

The Impact on National Main System Operation

As indicated above, 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, and 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 place for more than ten years, was not able to provide the 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 obtain information about local conditions and supervise actions for equipment and system restoration. Nevertheless, the challenges were not as severe as in a typical blackout, as load had been reduced dramatically because of the earthquake.

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

The need to invest in a new SCADA system is urgent. The government has recognized the need for such a system and for the corresponding protocols to permit direct communication with the National Emergency Office (Onemi), a government office that has been at the center of criticism for not responding adequately to the earthquake.

Operationally and marketwise, when the two islands were isolated, spot prices at the main busbar at the earthquake area reached the nonsupply cost, as shown in Figure 8.

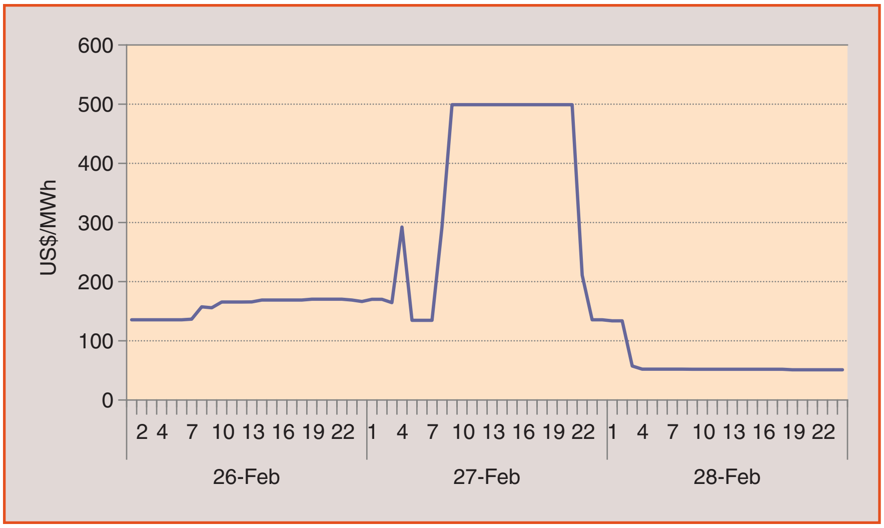

figure 8. Hourly spot prices at Charrua (source: CDEC-SIC).

March Blackout

Special attention must be paid in the recovery process after an earthquake to hidden conditions that could produce major faults. To begin the restoration work, visual inspections were made by the electric companies in Chile, and most of the equipment with no sign of damage was placed back in service. On 14 March, a couple of weeks after the earthquake, while

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all efforts were focused on restoring the reliability of the system, a 750-MVA 500/220 kV transformer bank at Charrua substation was disconnected by its protection system, causing a blackout. Further investigation showed that a control cable connection had lost its tightness, producing a minor fire that damaged some control wires. This was probably produced by the main earthquake or by one of the dozens of aftershocks. An exhaustive review that lasted two months involving all control connections on main equipment in all substations in the affected areas was carried out to prevent additional failures. A careful review of major equipment (transformer banks and reactors) was also made.

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

The security level in the transmission system in Chile is measured via the use of the N-1 criterion. The N-1 or single-contingency criterion, commonly used in the planning and operation of power systems throughout the world, allows the system to operate normally in spite of any outage of equipment or facilities (line circuit or generating unit), without a cascade-type propagation in the rest of the system. Several sections of the Chilean system do not have the infrastructure to operate in accordance with the N-1 criterion. In fact, the 500/220-kV transformation capacity at Charrua did not operate with N-1 security, and its disconnection was what overloaded the networks and caused their collapse .

Conclusions

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

The Chilean earthquake was a very severe one, and the initial feeling in the country is that the grid and the power system as a whole were well prepared for such an event. The earthquake and the consequent tsunami were so strong that it would be impossible (and uneconomic) to try to avoid a power failure in similar conditions. There is probably room 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 with respect to earthquake damage, response, and system restoration must be shared countrywide, as it will of course be useful for the future. Chile is a country permanently menaced by earthquakes, and a severe one is projected for the north of the country. It could take place tomorrow or at any time 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. In today's Chile, essential services are increasingly dependent on continuous power supply to function properly.

Apart from the satisfactory power system recovery, Chile is still somewhat uneasy about its national and government response to the earthquake. As indicated above, basic communication systems did not operate as desired and caused additional harm. Existing national early warning measures and emergency management schemes proved inapplicable, particularly in relation to the tsunamis. Opportunities for improvement will necessarily be part of the government's agenda, and the lessons learned will clearly help other countries.

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

For Further Reading

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