CONTROLLING THE ECONOMIC RISK FROM CATASTROPHIC FAILURE OF OVERHEAD TRANSMISSION LINES

by

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SUMMARY

A reliable electric power supply is an essential component of economic growth in both mature and emerging economies. Studies indicate that economic growth, as measured by Gross Domestic Product (GDP), is directly related to consumption of electric energy. Overhead transmission lines (OHTL) play one of the most important roles in the operation of a reliable delivery system. At the same time, because of their length and bold exposure to the elements, OHTLs are vulnerable to catastrophic failure from a variety of initiating events.

Internationally, the electric utility industry is in a transient condition brought on by privatization, deregulation and competition. In many countries, it is becoming increasingly difficult to obtain required permitting to build new lines. At the same time, it is often difficult to arrange for adequate funding to build those new lines for which permitting can be arranged. For these reasons, utilities are depending more and more on the capability of their existing lines. This probably explains the increased interest at this point in time in the subject of potential economic as well as political risk from catastrophic failure of key lines and why so much attention is being applied to the subject within international technical societies.

Unfortunately, there isn't a text book or published procedure readily available that deals specifically with the problem of determining the economic risk to a particular electric system due to the loss of a specific OHTL. The principles required to do such an analysis, however, are known and in wide use in other applications such as insurance. This paper will attempt to provide an insight into this specific problem and outline a process that can be applied to identify and quantify the initiatives available to control such risk.

DEFINITION OF RISK

In general terms, risk is composed of two elements: the probability of occurrence of the causal event and the totality of resulting losses (costs).

$ RISK = (PROBABILITY OF FAILURE) x ($ LOSS)

From this simple statement, it is obvious that risk can be limited by either:

- reducing the likelihood of occurrence of the causal event; and/or
- controlling the magnitude of the economic losses

Subsequent sections of this paper will demonstrate the reasoning process required to apply these principles to an OHTL.

CHARACTERISTICS OF AN OHTL

An OHTL is a very complex, continuous electrical/mechanical system. It is composed of many individual components made from the different materials with a wide variety of electrical and mechanical properties. Its function is to transport power from the circuit breaker on one end of the line to the circuit breaker on the other. An OHTL has failed when it can not transport power from one end to the other.

For the economic losses resulting from an OHTL failure to assume catastrophic proportions, it would only be required for the failure to cause power shortages at major load centers, or for the OHTL to have suffered such extensive physical damage that major repairs would take a

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substantial length of time to accomplish. Such failures are dependent on the physical characteristics of the OHTL and the configuration of the transmission grid, and can result from such predictable causal events as infrequent high winds or ice loads, or unpredictable causal events as defective components, sabotage or natural disasters.

Before discussing these causal events, it will be helpful to first discuss the concept of reliability based design methods, and how they can be applied to controlling or reducing the probability of failure of a predictable event.

RELIABILITY BASED METHODS FOR PREDICTABLE CAUSAL EVENTS

Presently, there is a strong movement within the industry internationally to implement Reliability Based Design (RBD) practices for new transmission lines. Under RBD, the "weak link" in the line system is identified and designed to deliver the expected reliability performance level for the line system. The component selected almost universally as the weak link is the tangent structure. All other components are then selected and/or designed to have higher strength; that is, higher performance than the tangent structure. For this reason, the structure is of fundamental importance in assessing the reliability of the line system.

The reliability level of an OHTL is a measure of the ability of the line (or a component of the line) to perform at its expected capability, where capability is defined as capacity times availability. The mechanical system of an OHTL consists of arrays of foundation, structure, hardware and insulator components that provide safe support for the power carrying conductors. Since the system is continuous, each array offers balanced longitudinal restraint to the tension in the conductors in both directions. As mentioned above, the components making up these arrays vary greatly in properties. Some of the materials are rigid, some flexible: some deflect under load and absorb energy while failing, some fracture and do not. Failure of the first component redistributes the forces applied to the support assembly. This can cause overload of other components. Depending on the capability of those other components and their functions, the damage may be restricted to the involved structure/support or may, under certain conditions, cause a serious loss of restraint on the next-in-line support assemblies causing their failures and setting off a progressive cascading effect that can travel down the line resulting in extensive mechanical damage.

To be able to predict the reliability level of an OHTL, it is first necessary to understand the present capabilities of the specific line configuration as built. Most existing OHTLs were designed using conventional deterministic design methods. These conventional deterministic design methods have many shortcomings, inasmuch as they do not:

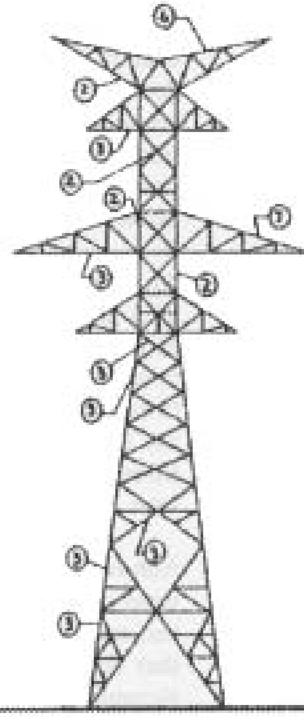
- provide a means to deal with the uncertainties of loading conditions, such as: loads applied at angles instead of only the vertical, transverse and longitudinal directions and more extreme loads in micro-environmental locations.
- provide a means for directly predicting the performance of the line
- provide a way to detect weak links in the line system
- provide a framework for decision making

The rapid advances in the capabilities of computers permitted the introduction of three dimensional analytical design programs. Such programs overcome these shortcomings. Data on: design criteria, installation loads, strength of components, clearances and corridor terrain are all fed into the computer to create a 3D model of the proposed line installed on its intended right-of-way. Such models were first used to optimize the design of a final line configuration within its corridor. By pre-selecting the component desired to be the weak link and adjusting the strength level of all other components in relationship to that weak link, the line could be designed to meet a target reliability level. It was soon discovered that the process could be reversed just as effectively. The as-built line and terrain details are entered into the computer to create a model of the line and corridor reflecting the properties of the components when new. After that, loading conditions, such as different magnitudes of wind velocity at different angular directions, accreted ice or wind and ice, are applied to the model in increasing increments until the first component is loaded up to its capacity. That is the critical loading condition for that component. The probability of occurrence of that loading condition is an indication of the reliability level of that component. This process is continued until all loading events of interest have been applied and the weakest link identified. Overall line reliability is equated to the reliability level of the weak link components. The quality of information for assessing the capability of a line in the as-built condition based on deterministic vs. a 3D analytical analysis is shown in Figure 1.

A double circuit 345kV line was built in the upper Midwest region of the US on steel lattice towers. The loads used in design were believed to be representative of

Load Case	Load Event
1	NESC Heavy
②	One broken OHGW combined with wind and ice
③	One broken conductor bundle combined with wind and ice
4	Heavy wind
5	Wind on bare tower (no conductors or OHGW)
⑥	Vertical load at any OHGW support (not simultaneously)
⑦	Vertical load at any conductor support (not simultaneously)

(a) Deterministic Design



Member	Controlling Climatic Load Condition	Controlling Load Return Period (years)
Legs	Wind, no ice	115
Tension chord of conductor arm	Ice, new wind	110
Tension chord of OHGW arm	Ice, no wind	35
Foundation	Wind, no ice	25

(b) 3D Analytical Analysis

Figure 1

50 year recurrence events in the area where the line was built. Figure 1(a) shows that different members of the structure were under the control of different loading cases from the deterministic loading agenda. While interesting, this display gives no useful indication about the identification of the weak link or its reliability level.

The structure, as originally designed, was modeled in 3D on the computer. Loads of varying magnitudes were applied from different directions until the actual controlling load conditions for key members were identified. The probability of occurrence for those controlling loads was then determined for the micro-environmental location of that structure within that line section.

Figure 1(b) shows that:

- the legs had a probability of failure in that location of once in 115 years
- tension chords in the conductor arm and OHGW arm had probability of failures of 110 and 35 years respectfully
- a wind condition at an angle was found to be critical for the foundation design with a probability of failure at that location of once in 25 years

An interesting observation can be drawn. The foundation was actually found to be the weak link in the line design. Few electric utilities would want this. It is likely that a foundation failure could, in fact, provide the necessary initiation for a line cascade.

The 3D analytical technology used to generate Figure 1 is readily available and fairly easy to use to determine the reliability of new or existing OHTLs. In an effort to assess risk, however, there are additional, significant questions.

In use, the components of a line are subjected to many types of deterioration, such as: wear, fatigue, corrosion, deformation and elongation. Since they are made from different materials with different properties, it is likely that some of these components will deteriorate faster than the intended weak link and will, therefore, become the new weak link.

The present capabilities or all existing OHTL components must be determined using appropriate inspection/assessment technology. The present value of each component's capability would be substituted for its new value in the 3D analysis program and the load application exercise redone. This results in an indication of the likelihood of failure of the components in their present condition and an indication of the line's present reliability level. The technologies are currently available for making these determinations and are described in Reference 1.

UNPREDICTABLE CAUSAL EVENTS

The balance of this discussion will focus on those causal events involving significant damage to the OHTL, and our ability or inability to predict the likelihood of occurrence of the causal event.

Unknown Defective Components Reliability based methods typically use the given material properties of the components as they were specified. Unfortunately, unknown to the designer, some components may be defective; therefore, it is necessary to determine the extent of the line damage that can be expected after the initial failure of a component. Analytical techniques are currently available for making these determinations, provided the weak link in the system is identified and properly analyzed. Typical contingencies of interest are often a broken conductor, broken OHGW, broken insulator or hardware component. Under a non-symmetrical discontinuity, the line system will distort in such a way as to redistribute the unbalanced forces depending on the response characteristics of the structure/foundation element. Routines are available to carry unbalanced transient forces down the line system and predict whether the downstream elements have the capability to withstand them or not. In this way, it can be determined how much progressive damage the line will actually experience. Loss of restraint can set off extensive cascades.

An example of this type of component failure that resulted in a cascade type failure is given in Reference 2. During extreme temperature and wind loading conditions, Los Angeles Department of Water and Power (LADWP) in the US lost a total of seventeen towers on the ±500kV DC Pacific Intertie. On fifteen of sixteen steel guyed towers, one or more forged steel guy fittings were broken, which resulted in collapse of the towers. These guy fittings were later analyzed and found to be brittle. Rapid restoration of this catastrophic failure to limit economic losses will be discussed later in this paper.

Sabotage There have been cases during periods of rebellion or civil disobedience within some countries where the anti-government forces have elected to destroy segments of the power delivery system. Transmission lines seem to be a particularly attractive target because of their importance to the economy and morale of the country as well as being accessible to sabotage. The destructive measures, themselves, can be sufficient to create extensive damage to the line, as well as progressing into cascades of the total line system. It is not possible to predict the likelihood of a sabotage event or to predict the extent of the resulting damage with confidence.

An example of sabotaged OHTLs is given in Reference 3. This paper discusses how during a period of eight years between 1984 and 1992, electric utilities in Colombia South America lost a total of 297 transmission towers due to sabotage, and how one utility, Interconexion Electrica SA (ISA), coped with the unpredictable nature of this sabotage using the emergency restoration system described later.

Natural Disasters Hurricanes, cyclones or typhoons, massive ice storms, fire, floods, tornadoes, earthquakes and earth slides fortunately occur infrequently; but, when they do, can cause total destruction of the above ground elements of OHTLs as well as have a destructive impact on and make serious changes to the very topography along the right-of-way. This makes post event access difficult and complicates restoration processes. The combination can make the total outage time for the facility very long.

There are no existing technologies for predicting the likelihood of occurrence of natural disasters with confidence or engineering initiatives available to limit the total damage in a cost effective way. However, References 4 and 5, which will be discussed later, describes how Comision Federal de Electricidad (CFE) in Mexico limited their economic risk due to cyclones that have destroyed over 378 transmission towers on the CFE system in the past 20 years.

ECONOMIC LOSSES

Total losses resulting from an extended outage of a key transmission line is site specific and can be considerable. Losses accrue to different parties and are composed of lost revenues and monetary out-lays. In the case of industrial customers, they may have critical processes within their operations that require substantial "clean up or reset" activities after a power loss. They may elect to try to recover such expenses from the power supplier. These expenses are summarized in Table 1.

The economic losses resulting from the collapse of a transmission line will depend on the type of transmission system for the particular location. In some emerging

TABLE 1
ECONOMIC COSTS OF AN OHTL FAILURE

	OHTL Failure **DOES NOT** Result in Power Shortages at the Load Centers	OHTL Failure **DOES** Result in Power Shortages at the Load Centers
Power Supplier	1. Increased Line Losses on Alternate OHTL 2. Cost to Rebuild OHTL 3. Increased Cost of Generation	1. Lost Revenue from Customers 2. Power Plant Shutdown 3. Increased cost to Rebuild OHTL due to shortened construction schedule
Industrial and Residential Customers	If NO Voltage Drop No Cost If Momentary Voltage Drop Reset Sensitive Electronic and Process Equipment	1. Plants Close and no Products Shipped 2. Workers Sent Home and no Wages Paid during Plant Shutdown
Regional and National Government	1. Minimal Economic Cost	1. Lost GDP for Region Equal to 20+ Times the Lost Revenue of the Power Supplier 2. If Frequent, Lost Investor Confidence

economies, the load center may be served primarily with a single double circuit radial line. Even in those locations where alternative lines are available, it is often likely the other lines will not have sufficient capacity to support the full load requiring a certain amount of load shedding. The most serious loss is reduction in the Gross Domestic Product (GDP) for a region or nation.

Studies have shown that the lost GDP is approximately 18 to 20 times the cost of the lost revenue to the supplying utility (Reference 6). This is reasonable when it is considered that industrial customers generally pay less than 5% of their gross revenues for power. Analysis of Electric Utilities Data Book (Reference 7) indicates that the ratio of GDP to average utility revenue for the Asian and Pacific Region was approximately 30 in 1990.

As is often the case in developing countries, when one or more major OHTLs feeding a load center are lost, the remaining lines do not have sufficient capacity to support the full load required during the peak periods of the day. Utilities will be forced to shed load during those peak periods shutting down industrial and commercial customers. When this occurs, production is stopped and total lost Gross Domestic Product can be estimated from Figure 2. For example, in this graph, if the average rate charged to commercial and industrial customers is approximately $0.10/kwhr, and it is necessary to shed approximately 300 MW of load during an 8 hour work day, then the lost Gross Domestic Product for the region affected by the power outage will be approximately $5,000,000 in one 8 hour period. This is graphically demonstrated in Figure 2. Figure 2 is a generalized display showing the relationships among reduction of load consumption, per unit cost of power and loss in GDP, assuming the ratio of GDP to utility revenue is only twenty (20).

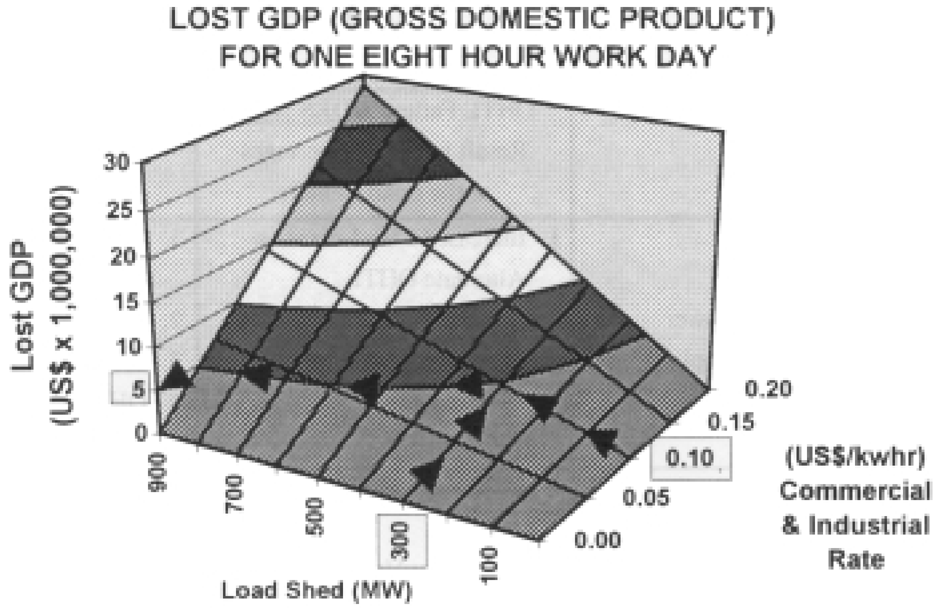


FIGURE 2

RISK MITIGATION INITIATIVES: PROACTIVE AND REACTIVE

Proactive Those initiatives that are done to minimize the likelihood of occurrence of component failures that could progress into line cascades as well as those things that will improve a line's ability to contain a cascade after the failure of the first component are proactive.If the line is new, its reliability level should be determined using present analytical techniques as previously described. Those components discovered to have a probability of failure lower than the desired target level, could be upgraded by increasing their capacity.

The security level, or ability of the line to restrict progressive damage, of the upgraded OHTL system should next be checked. If the security level is still found to be lower than desired, there are a variety of initiatives that can be considered:

- components and structure details located in sensitive areas can be upgraded in capacity or improved in response characteristics
- strong, anti-cascading structure supports can be located strategically along the line to limit a cascade to a tolerable length
- energy absorbing devices can be added into the conductor support system to limit the longitudinal transient energy transfer to safe levels

If the line is aged, its present condition should first be assessed as previously described and the procedure above repeated. The reduced condition of certain key components will have an impact on the effectiveness and priorities of the listed initiatives.

Proactive initiatives, coupled with a reliability based inspection and maintenance regimen, can reduce the likelihood of occurrence of the causal event and limit the probability of occurrence of risk resulting from catastrophic cascade line failures. They provide no control against failures caused by sabotage or natural disasters.

Reactive Those initiatives that limit risk by controlling the length of time the line facility is out of service after the failure has occurred are reactive.

It is likely that conventional restoration will take longer as well as cost more than necessary since many key components, like structures, are designed to be site specific. That means an order for replacement structures or tower steel has to be placed, usually with the original producer, who, in turn, must order materials, fabricate and ship replacement parts to the site. It has been found that the longest lead time for restoration of an OHTL is the time to replace damaged tower steel. When foundations are damaged beyond further use and have to be replaced, adequate time must be allowed for concrete to set. Unique characteristics of some OHTLs may require the need for specialized erection equipment of specially trained erection crews. These may not be readily available at the required time, either. Even if all requirements can be met on an expedited basis, it is very likely that such availability will be provided only at a premium price.

Many utilities in the past, have attempted to control the length of time required for restoration by laying in an inventory of critical components, like structures. This is a move in the right direction since it addresses the likely long and high cost procurement of components; but the total benefits may not be cost effective for the following reasons:

- the design of components are line specific, an inventory would have to be carried for every different line
- the question of availability of needed erection equipment and personnel would remain the same

Because of these factors, several utilities in the US and Canada formed a transmission line mutual assistance group (Reference 8) in 1982 for the purpose of sharing experienced linemen, construction equipment and transmission structures during a major transmission outage. One of the significant features of this plan was the adoption of a universal modular emergency restoration structure that can be easily shared among participating utilities. After reviewing the designs of all temporary structures produced by utilities and tower manufactures around the world, these new universal modular emergency restoration structures were designed with the following features:

- lightweight aluminum modules that are easily transportable by small helicopter or manpower,
- temporary foundations that allow rapid restoration,
- ability to be erected without heavy equipment,
- standard structure components that can build a large variety of structures at all voltage levels,
- structure heights that can be modified in the field,
- an open design allowing the conductor to be lifted onto the structure without having to restring the conductor.

By using this universal design, the components of these emergency restoration structures can be exchanged among participating utilities so that any one utility's required inventory can be reduced. In 1988, the acceptance testing and interchangeable design of these universal modular emergency restoration structures were standardized by ANSI/IEEE Standard 1070, and again reconfirmed in 1995 (Reference 9). To date, over 1600 tons of aluminum emergency restoration structures have been produced to this standard and supplied to over fifty (50) utilities in fourteen (14) countries around the world.

With the addition of insulators, hardware, anchors, crew training and application software, this universal modular emergency restoration structure, has become known in the industry as the Emergency Restoration System (ERS). Unlike typical permanent transmission structures, an ERS

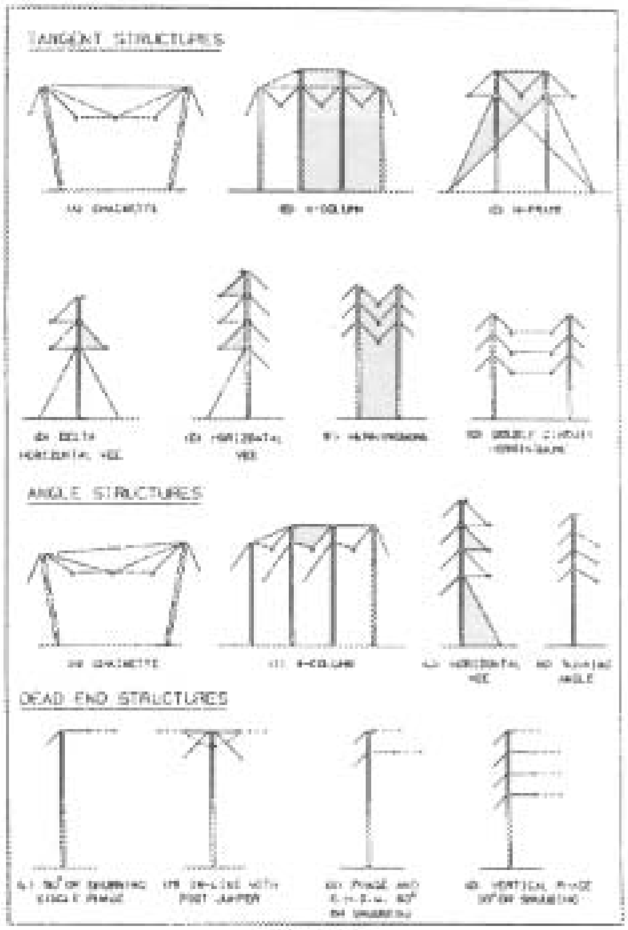


Figure 3

design is not driven by optimization, rather by flexibility providing application within families of different structural concepts. The wide variety of structure profiles that can be constructed from the ERS is suggested in Figure 3.

There are two emergency restoration approaches: in-line and by-pass. The in-line approach is normally used for restoring single circuit towers having horizontal phase configuration. In the in-line approach, the restoration structures are located on the right-of-way ahead and behind the damaged structures and support the line while the rebuild of the damaged support assemblies is accomplished. The by-pass approach is normally used for restoring single and double circuit lines having vertical phase configuration or where additional space is required for restoration of the damaged structures or foundations. In the by-pass approach, restoration structures are located off the right-of-way providing easy clearance for the permanent structure replacement.

It is evident that the total economic cost associated with a causal event, both to the Power Supplier as well as to the GDP, can be substantial. Some risks, such as a cascade failure, can be addressed with proactive and reactive initiatives. Other risks, such as natural disasters or By sabotage, can only be addressed with reactive initiatives. planning for these events, training personnel and acquiring needed materials, the potential economic costs of these causal events can be minimized. Since 1982, the most positive mitigation initiative available to limit risk has been the Emergency Restoration System, as specified in ANSI/IEEE Standard 1070. This system has repeatedly proven its value in rapidly restoring OHTL failures and minimizing the total costs.

ERS EXPERIENCE IN LIMITING RISK

Since the concept of a standardized ERS was introduced to utilities around the world in the early 1980's approximately 40% of the utilities who have acquired ERS have experienced subsequent OHTL failures that gave them the opportunity to apply this system to real emergency situations.

In the US, the Los Angeles Department of Water and Power (LADWP) serves approximately 1.3 million customers in a heavily populated area in California. They receive 25% of their power requirements by way of a ±500kV DC line. In 1988 they experienced a cascade failure involving 17 towers in the DC line caused by

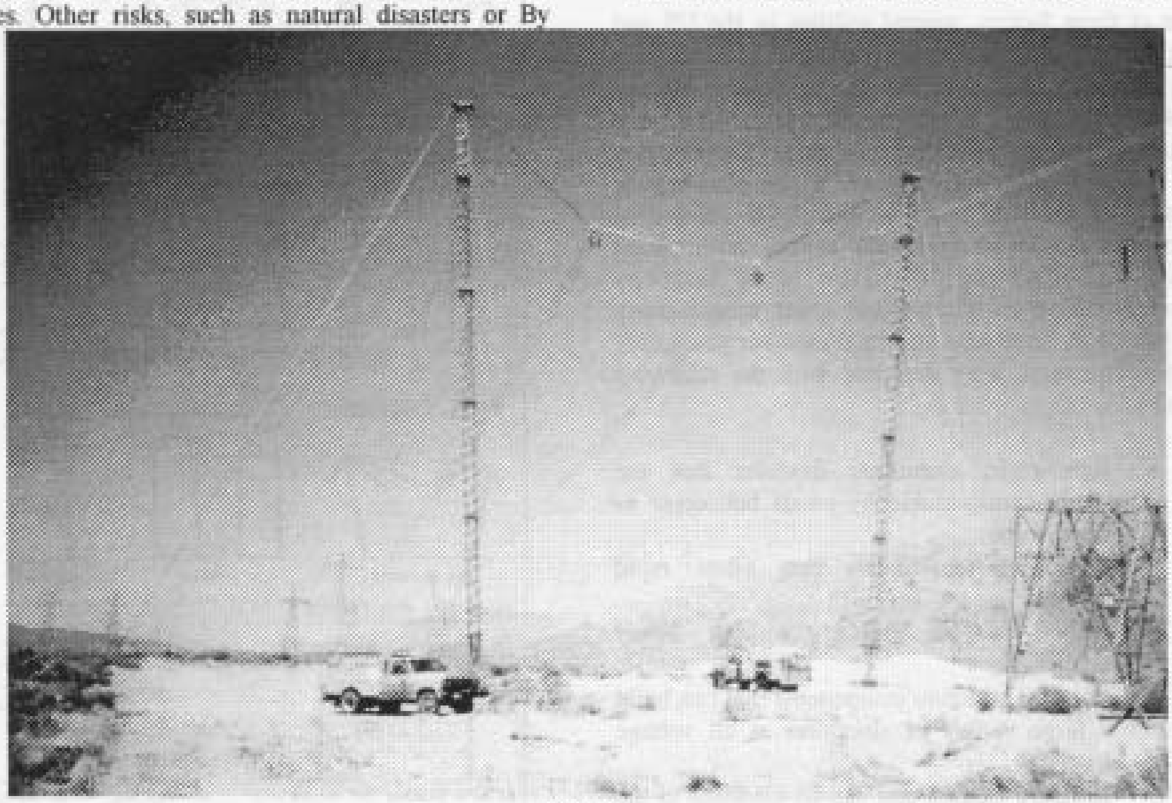


Figure 4
LADWP restored this sabotaged structure in less than six hours

extreme weather. The failure occurred at a location with rough terrain. By implementing their emergency plan centered around the ERS they owned, they were able to borrow additional compatible ERSs from other utilities in order to install temporary modular structures to restore and maintain power flow during the rebuilding of the damaged line sections.

Prior to this incident, one tower of this ±500kV line was sabotaged in 1987. The ERS shown in Figure 4 was constructed in less than six hours, and the line restored in less than two days (Reference 2).

Comision Federal de Electricidad (CFE) is the principal provider of electric power throughout Mexico. Mexico is situated in one of the six regions in the world subject to intense tropical storms, referred to as either hurricanes, tornadoes or cyclones. These storms are violent in nature with wind speeds approaching 200 km/h and often accompanied by high precipitation that can lead to flooding. As mentioned earlier, in the past 20 years cyclones have caused a loss of over 350 towers on 230kV and 115kV transmission lines. In addition, since 1990 storms have caused the loss of 28 towers on CFE's 400kV system. Nearly half of these lost towers are double circuit structures.

In 1992, CFE acquired an initial quantity of ERS to address restoration needs at 400 kV. Since their acquisition, the structures have been used extensively at all voltages from 115kV to 400kV to greatly reduce the outage time when storm damage does occur. In early 1994 CFE decided to utilize these modular aluminum ERS structures throughout the entire country and a significant quantity of additional structures were acquired. One element of CFE's restoration plan undertaken in early 1994 was the extensive training of the engineering staff and field crews in the use of these emergency restoration structures.

A recent example of how this planning and preparation was put to good use occurred on October 14, 1994 when Hurricane Rosa struck the western coast of Mexico near Mazatlan at 6:30 am, with wind speeds measuring at 150 km/h and gusts up to 190 km/h, the storm affected a very large area (References 4 and 5). At 7:00 am shortly after the storms passage, crews began inspection of the important Tepic-Mazatlan II 400kV transmission. Inspection preceded slowly with much of the right-of-way flooded and nearly impassable due to the storm. At 10:00 am on the October 15, three destroyed towers had been discovered, with spans ranging from 400 m to 910 m. It was determined to replace these damaged towers with an in-line restoration of 400kV chainette structures. Access to the sites was extremely limited due to flooding and a vast majority of material was transported into place using helicopters. Restoration structure columns were erected using portable winches and gin poles or tilted up using helicopters. The two bundle conductor was freed from the damaged structures, repaired and raised into position on the restoration structures (see Figure 5). Work was completed at 10:15 pm on October 19 and the line energized at 10:45 pm, less than five days after Hurricane Rosa struck the coast of Mexico.

The National Power Corporation (NPC) of the Philippines is the major provider of electricity on the island of Luzon, Philippines. In 1991 Mount Pinatubo, north of Manila erupted. In October 1995 after a heavy rain storm, a large

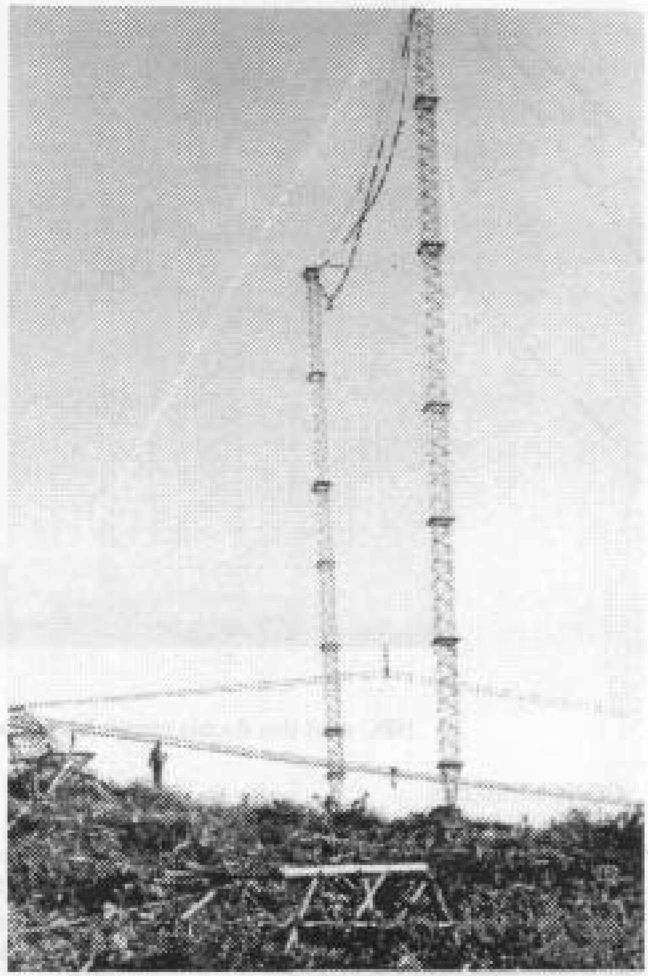


Figure 5
CFE restored this hurricane damaged structure using an open-based chainette, allowing the conductors to be raised between the two columns

flow of Lahar (a mixture of ash and water from Mount Pinatubo) destroyed five circuits of 230kV transmission lines that supplied the city of Manila. In order to stabilize the system and prevent power shortages in the city of Manila, NPC purchased an ERS in order to restore four of the five circuits in the Lahar affected area. Figure 6 shows a double circuit herringbone emergency restoration structure used for an in-line restoration of the double circuit 230 kV

Mexico-Hermosa line. Figure 7 shows a by-pass restoration using a deadend structure and two tangent chainette and deadend structures used to restore one circuit of the San Jose-Hermosa 230kV transmission line. While an ERS system is typically meant to only stay in service for a short period of time, the unusual circumstances in the Lahar affected area has required that these systems stay in place for the last two years. Utilizing this technology, NPC has minimized the risk of line outages at their major load centers in Manila and provided a flexible restoration system capable of being moved as the Lahar flow dictates.

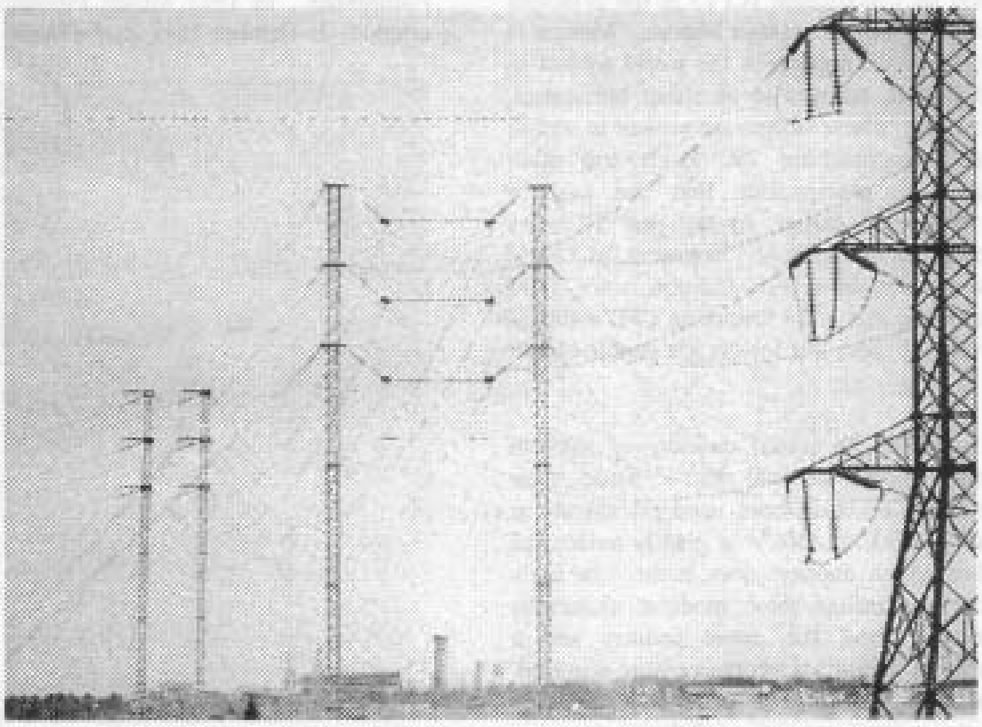


Figure 6
NPC used this double circuit herringbone structure to restore lines damaged by Lahar

CONCLUSIONS

1. Electrical utilities and their OHTLs are an essential part of the economy of all nations. If the service provided through these OHTLs is interrupted it will cause a loss in revenues to the utility and a much greater loss in GDP to the region or nation. If interruptions occur regularly, there will be a loss in investor confidence which will further damage the economic growth of the region or nation. By their very nature, OHTLs are exposed to the risk of catastrophic failure from a wide variety of causes.

2. There are available technologies to limit the level of risk by controlling the probability of occurrence of the initiating event and/or limiting the total amount of losses that occur during the resulting outage period.

3. When OHTL failure does occur, rapid restoration is essential. Of the available technologies, the ANSI/IEEE Standard 1070, Emergency Restoration System (ERS) appears to provide the most positive and cost effective means to limit risk.

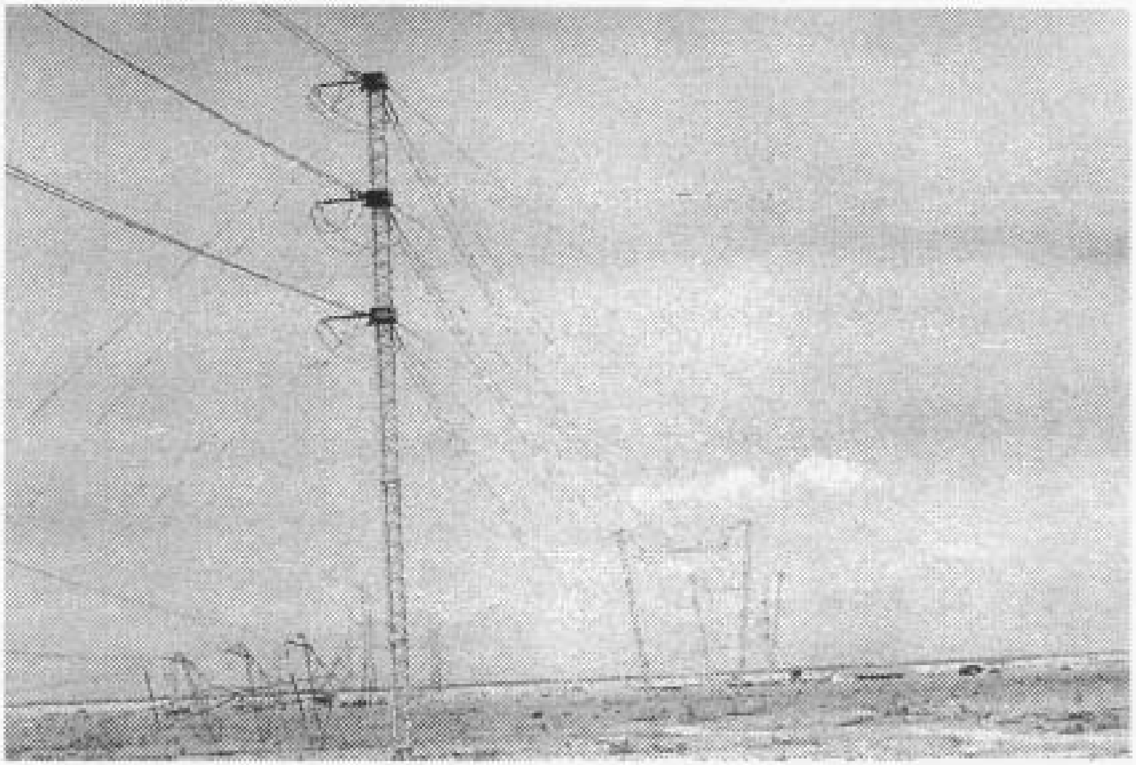


Figure 7
NPC constructed this by-pass restoration using deadend and chainette structures.

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