

## Evaluation of the Performance of High Voltage Substation Equipment to California Earthquakes

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### ABSTRACT

Damage to electrical substation equipment from California earthquakes has been reviewed to document the equipment that has been damaged and determine the failure modes and factors that have contributed to the damage. Equipment that has performed well is also documented. Substation equipment operating below 200 kV is seismically robust. Live-tank circuit breakers, transformers, lightning arrestors, voltage-current transformers, disconnect switches, current transformers, and station batteries are vulnerable to earthquake damage. Damage to most of this equipment is the catastrophic failure of porcelain components. Factors contributing to much of the damage were inadequate equipment anchorage, lack of slack in equipment-bus electrical connections, and overly flexible support structures.

### 1 INTRODUCTION

The availability of electric power after a damaging earthquake is vital for many emergency response functions and to the entire community. For nuclear power generating stations the loss of off-site power is a major contributor to the probability of core damage. Within the last twenty years the vulnerability of high voltage (voltages higher than about 200 kV) substation equipment has been repeatedly demonstrated. Even small ground motions, as occurred in the 1988 Tejon Ranch earthquake, where the accelerations were about 0.08 g, there was significant damage to substation equipment which resulted in the closing of the California Aqueduct for four days.

Although post-earthquake reports describe damage from specific earthquakes, to date there has not been a comprehensive review of past damage to substation equipment. Information about what equipment has failed, damage thresholds for specific types of equipment, dominant failure modes for each type of equipment, and the factors that have contributed to damage can serve to improve seismic design of equipment and its installation and improve methods for estimating the impact of future earthquakes on power systems. For equipment that has performed well, past earthquakes also can serve to define ground motion levels for which specific equipment types survived without damage. Earlier earthquake investigations focused only on numbers of generic types of

equipment that were damaged. There has not been a systematic determination of failure modes for specific equipment items or factors that may have contributed to failures.

The Electric Power Research Institute (EPRI), in conjunction with major California power utilities, the Los Angeles Department of Water and Power, the Pacific Gas and Electric Co., and Southern California Edison, has undertaken a multi-phase study of the impact of past earthquakes on substations in California. The first phase of this study collected and aggregated substation damage data and got estimates of ground motion at each damage site. For each type of equipment studied, the damage threshold levels, failure modes, and factors that contributed to the failure were identified. In addition, for undamaged equipment, maximum ground motion exposures were identified. This paper will identify failure modes and factors contributing to failure for generic equipment types.

## 2 METHODOLOGY

To identify damaged equipment, published reports and company damage reports were reviewed. Typically, only generic descriptions, such as "circuit breaker" or "transformer", are identified in records from all but the most recent earthquakes. Damage pictures were used when available to get more details about the equipment, such as the manufacturer, model, and method of installation. General corporate records or interviews with facility designers were used to determine equipment age. The damage sites were then visited to get additional information on methods of installation and other factors that may have contributed to the damage, such as connections to adjacent equipment. Some of the equipment damaged in earlier earthquakes has been replaced in the normal course of system upgrading, so that the original equipment was no longer available for inspection.

One of the major difficulties in estimating fragility data was the lack of good descriptions of the seismic exposure at the site. Most sites did not have strong-motion seismographs and many had records only from locations several miles from the site. Local site conditions can have a significant impact on the magnitude of the ground motion and its frequency content so that inferring site exposure from distant records introduced significant uncertainties.

## 3 EARTHQUAKES CAUSING POWER EQUIPMENT DAMAGE

The damage survey gathered data from 8 earthquakes. Several additional earthquakes outside of the U.S. contributed data but were not included because not enough detailed information was available. The earthquakes and their magnitudes are listed in Table 1.

Table 1

Earthquake	Year	Magnitude
San Fernando Earthquake	1971	6.4
Santa Barbara	1978	5.6
Coalinga	1983	6.5
Morgan Hill Earthquake	1984	6.2
Whittier Narrows Earthquake	1987	5.9
North Palm Springs Earthquake	1988	5.6 (Ms)
Loma Prieta Earthquake	1989	7.1

## 4 EARTHQUAKE PERFORMANCE OF SUBSTATION EQUIPMENT

### 4.1 Equipment that performed well

Review of substation earthquake damage indicates that certain equipment is very robust and not vulnerable to earthquake damage. Essentially all substation transmission and distribution equipment that operates below 200 kV has performed well, unless it was damaged by falling objects. For example, lower voltage live-tank circuit breakers were not damaged in any earthquakes. This contrasts with their higher voltage counterparts that were frequently damaged.

Bulk-oil circuit breakers, even at voltages above 200 kV have performed well if they are adequately anchored. High voltage dead-tank circuit breakers have performed well, but they have had limited seismic exposure. Underground cables, both transmission lines and control cables within a switchyard have performed well, even at locations that have experienced significant ground deformations from liquefaction and lateral spreading. Seismically-induced vibrations have had no effect on transmission lines and their support towers, as long as there are no foundation failures or landslides.

### 4.2 General factors contributing to equipment damage

**Installation details** of two types commonly contribute to equipment damage - anchorage and slack in bus connections. Inadequate anchorage allows equipment to rock and impact against its foundation pad or to shift on its foundation. In extreme cases, equipment has moved entirely off of its foundation pad and tipped over. The use of friction clips as the means of anchorage is frequently at fault.

Inadequate slack provided in bus connections can induce damaging loads due to relative motions between equipment and bus supports. This has caused damage to bushings, lightning arrestors, current transformers, current-voltage transformers, and post insulators.

**Overly flexible equipment support structures** also contributes to equipment failures. First, they allow larger deflections so that bus connections can be overloaded. For tall slender structures there is a P-delta effect that increase cantilever loads. Second, the fundamental frequency of the equipment is lowered so that it is often in the region of high earthquake energy so that earthquake excitations are more severe. Equipment support structures are frequently fabricated from structural members and bolted together. To facilitate assembly, slotted connections are sometimes used. After assembly, these bolted connections cannot be tightened enough to prevent slipping of the connections during earthquake excitation. As a result, the stiffness of the structure is reduced and if a bolt hits the end of the slot in which it is installed, impact loads are introduced to porcelain members on the equipment that is being supported.

**Failure of porcelain** is associated with most of the damage to substation equipment. The brittle fracture failure mechanism of porcelain can be triggered when the stress approaches the average ultimate stress of the material and the failures are always catastrophic.

#### 4.3 Failure modes related to specific types of equipments

**Live-Tank Circuit Breakers** (220 kV and above) in which the interrupter head is contained in a large tank are very vulnerable, some showing damage at ground accelerations as low as 0.05g. They exhibit three failure modes. The most common failure mode is leaking gaskets. Two types of gasket failures have been observed. Interrupter head bushing gaskets were blown, primarily on the bushings that connect adjacent interrupter heads. The interrupter head bushings connected to adjacent equipment were not affected. Porcelain interrupter head support columns that have gaskets often develop leaks at these gaskets. The porcelain support columns frequently fail. Since these columns are pressurized, they tend to fail explosively and the flying fragments of porcelain can damage nearby equipment. Some units have a high pressure air supply contained in small porcelain insulators. These are vulnerable to damage from earthquake-induced vibrations or relative motions of interrupter heads. The extensive loss of circuit breakers may require a relaxation of system protection to maintain service, a less than desirable situation when damaging aftershocks can be expected.

**Lightning arrestors** frequently have porcelain failures where the porcelain is connected to its lower flange. While inadequate slack in bus connections and amplification of their support structures may contribute to these failures, units appear to be inherently vulnerable.

**Current-Voltage transformers** have responded similar to lightning arrestors. Unlike lightning arrestors, their damage can be very disruptive to power system operations as they play an important role in system protection.

**Transformers** have had several failures modes. Chocks used to restrain rail-mount transformers were often inadequate, as they would loosen and allow the transformer to roll along the rails and fall. Retrofits to rail-mounted transformers and welding to embedments on pad mounted transformers are often inadequate in that the designs can not restrain the tremendous weight of the transformers.

Radiator leaks have also been a problem. Most problems are associated with designs in which several radiator cores are connected to a manifold and the manifold is then supported to the transformer tank by one or two pipes (at top and bottom) that also serve as fluid connections between the radiators and the transformer case. Upper pipe connections are more vulnerable. A lack of lateral bracing may contribute to the failures.

Leaks in the upper part of pressurized oil bushings often developed. The upper part of the bushing is secured by tension and seismic loads allow bushings to leak and sometime to shift at this interface. There have been some leaks at the interface between the transformer tank and bushing flange due to flange deformation. Bushings have also been observed to fracture.

Sudden pressure relays in transformers were often activated by seismically induced pressure changes. While this is not damage in the normal sense, extensive, short-term system disruption can result. This can have one beneficial impact. Due to earthquake-induced vibrations, distribution lines frequently swing and touch. If they are deenergized, they will not burndown and the chance of fires caused by dropped lines is also reduced.

**Disconnect switches** have exhibited two failure modes. Post insulators used to fabricate the switches have failed. Vertical-break switches in the open position are most vulnerable. A factor contributing to some of these failures is that the switches can be

located high on bus support structures. This is often done by some utilities for disconnect and bypass switches for circuit breakers. While this configuration has the advantage of reducing substation area, the switches are subjected to significant dynamic amplification introduced by the support structures. Bus sectionalizing switches that are located high on the bus support structure are also very vulnerable to damage due to relative motions between bus sections. Because of failures and more stringent specifications, some California utilities are using post insulators with high strength porcelain. Unfortunately it is difficult or impossible to determine porcelain strength simply by looking at the insulator, which complicates earthquake damage evaluation.

In some disconnect switches, the metal rotating connection at the base of the some post insulators deforms or breaks so that they were not operational. Failures have also occurred in castings that form the hinge of the blade. Failures in one type occurred at the weld that connects the support bearing to the plate that accepts the post insulator flange. This failure allowed rotation of the actuator mechanism without rotating the post insulator. As a result, the position of the switch could not be changed.

**Current transformers** frequently failed when their porcelain members broke. Two factors appear to contribute to this. First, some designs are inherently weak. Second, a lack of slack in connections to adjacent equipment, usually a circuit breaker, adds to the loads. Interaction has been due to flexibility of the current transformer support structure or the flexibility of the circuit breaker.

**Station Batteries** are frequently damaged from one of several failure modes. Most frequently, batteries are not restrained to their racks so that they are damaged when they fall from their rack and strike the floor. When they are restrained to their rack, a gap is often left between adjacent cells or at the sides and end of the rack. As a result, motion and impacting of the cells against each other or against their restraints have cracks the cell case, caused internal damage to the cell, or damaged the battery terminals. The battery racks can fail or tip over if they are not adequately braced and anchored.

## 5 CONCLUSIONS AND RECOMMENDATIONS

- Power system performance after damaging earthquakes has been good.

While power system performance, as measured by service disruptions, has been good in past earthquakes, most earthquakes have been of small to moderate magnitude so that typically only one substation has been seriously damaged. Past performance suggests that an earthquake impacting a larger area may overwhelm redundancy designed into power networks.

- Power transmission and distribution equipment operating below 200 kV is not vulnerable to earthquake damage if it is adequately anchored.
- Most substation damage is associated with the failure of porcelain components so that an alternate material or improved design is needed to reduce failures.
- Inadequate equipment anchorage, lack of slack in bus connections, and overly flexible support structures contribute to failures.

Overly flexible support structures causes larger motions that can aggravate interconnection problems. It also lowers the fundamental frequency and often brings to closer to higher energy content of earthquake, increasing the excitation level.

- There is a need for strong motion instrumentation at substation sites.

The characterization of ground motions from off-site instruments makes it difficult to estimate equipment damage parameters. A free field instrument should be placed at substations and at power generating stations.

- The power industry needs to focus on post-earthquake investigations.

In the aftermath of a damaging earthquake, the overriding concern is to repair damage and restore service. As a result there is limited opportunity for the utility to make a detailed examination of equipment damaged and evaluate its cause. It would be desirable to have an industry emergency response team that included designers from manufacturers to evaluate damage without disrupting the restoration process.

- The use of high strength porcelain should be indicated on the equipment.

California utilities are starting to use high strength porcelain for certain applications including post insulators. It is important that purchase specifications require that these units be marked so that their properties can be taken into account in evaluating seismic performance. It is difficult or impossible to trace specifications long after they have been installed.

- The rarity of damaging earthquakes and the diversity of equipment limits the robustness of fragility statistics.

The diversity of manufacturers, equipment designs, operating voltages, equipment age, installation practices, and site conditions coupled with poorly characterized site ground motion yields rough fragility estimates. The evaluation of damage does show a pattern of failure modes and factors contributing to them.

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