GUIDE TO DOCUMENTING EARTHQUAKE DAMAGE TO POWER SYSTEMS

Anshel J. Schiff

Consulting Professor, Civil Engineering, Stanford University
Principal, Precision Measurement Instruments

ABSTRACT

Recent earthquakes have identified new issues about and elevated the importance of older issues that need more scrutiny so that they can be better understood. Guidance is provided to aid investigators in identifying these areas of concern. New methods of documenting damage are also presented through the use of prepared substation schematic diagrams. Guidance is provided for identifying damage when investigating substations. It is recommended that the electric power industry establish and implement a procedure for an inter-utility group to conduct post-earthquake investigations. It is recommended that a follow up investigation be made several months after the earthquake to identify additional damage and to get a better understanding of the causes of damage. It is recommended that strong motion seismographs be placed at major power facilities so that equipment performance can be quantitatively evaluated.

INTRODUCTION

Role and History of Post-Earthquake Investigations of Power Systems

Information gained from post-earthquake investigations is the major source of data for improving earthquake design, practice, standards and codes. Observations from the 1925 Santa Barbara and 1933 Long Bear earthquakes were the main impetus for adding earthquake provisions in building codes. After 1933 some power companies in Southern California started to anchor bulk power transformers and to use flexible bus rather than rigid bus in the construction of substations. A group of engineers and seismologists, which would eventually become the Earthquake Engineering Research Institute (EERI), were active in "chasing" earthquakes, although their primary interest was construction based on civil engineering, such as buildings and bridges. Early lifeline investigations of power systems were directed primarily at identifying items that were damaged, such as circuit breakers, transformers, etc. Even after the 1971 San Fernando earthquake, very little effort was devoted to formally identifying failure modes and factors that may have contributed to the failures, although observations were used to improve designs and installation practices. In 1974 the Technical Council on Lifeline Earthquake Engineering (TCLEE) was established in the American Society of Civil Engineers. Under TCLEE the Earthquake Investigations Committee was formed and has been active in investigating earthquakes, often in conjunction with EERI. In the mid 1980's the Electric Power Research Institute (EPRI) became active in investigating earthquake damage and it has gathered more detailed information defining the equipment. Their emphasis has been on equipment that is found in nuclear generating plants, particularly safe shutdown equipment, although other power facilities are investigated. EERI and TCLEE earthquake investigation efforts are primarily professional volunteer activities with partial support for travel expenses. EPRI funds its investigators to gather the detailed data they need for their program.

In 1985 the TCLEE Earthquake Investigation Committee began to develop a guide for the post-earthquake investigation of lifelines. This Guide was developed to address a situation that is unique to lifeline investigations. Most lifelines are complicated systems made up of many facilities (nodes), that are usually linked to form a network. These systems are often designed with a high degree of redundancy to enhance system reliability. Redundancy is incorporated not only into the links that form the lifeline network, but also at the system nodes. To properly investigate a lifeline, equipment and structural damage must be identified. The impact of equipment damage on each facility and the resulting effect on system performance should be evaluated. Each of these evaluations should identify failure modes and design features and installation practices that contributed to the damage or failure. The Guide reviews the elements in the lifeline, their function within the facility and their performance in past earthquakes. The role of various facilities in system operations is also reviewed.

This paper provides additional information on how to find and evaluate power system earthquake damage. The paper is organized into the following sections as follows: objectives of post-earthquake investigations, review key of issues discussed in Guide, items requiring special attention that were not emphasized in the Guide, new methods of documentation, finding damage and factors contributing to it, and recommendations and conclusions.

OBJECTIVES OF POST-EARTHQUAKE INVESTIGATIONS

The objectives of a post-earthquake investigation are to identify equipment that was damaged or that failed to operate and identify equipment that performed well when subjected to significant seismic exposure. The investigator should attempt to identify in quantitative terms the seismic exposure by searching out strong motion records. In addition to identifying equipment performance, factors that could influence its performance should be documented. Information about site conditions, installation practices including details of anchorage, support structures and electrical connections should be recorded. The investigator is in the best position to make engineering estimates about the failure modes and the factors that contributed to the failures, as the local setting can be observed. In addition to damage, other factors, such as system configuration and operating procedures, that may have influenced the performance of the system in a post-earthquake environment should be noted. Where the cause of a failure is not clear, tests and analysis should be suggested that could resolve the issue. Changes in design and practice should be put forward for consideration to improve seismic performance. Also, changes in procedure and methods to improve post-earthquake investigations should be identified. Finally, the observations of the investigation should be communicated to the professional community.

REVIEW KEY ISSUES DISCUSSED IN THE GUIDE

The "Guide to Post-Earthquake Investigation of Lifelines," TCLEE, Monograph No. 3, August 1991 provides general information on conducting an investigation and specific information on power systems. Information on pre-departure preparation, personal and investigation equipment needs, gaining access to facilities, interviewing techniques, and general information that should be gathered at most sites that are investigated is given. Packing lists and check lists of information that should be gathered in the field for each lifeline are provided. In addition, an overview of the configurations, facilities, equipment operation, and functions and seismic performance of equipment and facilities are reviewed for each lifeline. These topics will not be reviewed here. It is recommended that the Guide be studied to gain insight into these aspects of earthquake investigation of power systems.

ITEMS REQUIRING SPECIAL ATTENTION NOT EMPHASIZED IN THE GUIDE

Damage in recent earthquakes indicates that several items not emphasized or discussed in the Guide should be given more attention so that they can be better understood. Some of the damage has been observed previously, but the perception of its prevalence or significance has changed. It is emphasized that the following topics are to be investigated in addition to those identified in the Guide.

Transformer Bushings

Transformers are one of the few items in a power system whose function cannot be eliminated or substituted. Bushings can crack and must be replaced. There can also be slipping or oil leaks at the interface between the porcelain and the metal flange that make up the bushing. Figure 1 illustrates an extreme example of bushing offset. This interface should be carefully observed for signs of oil leaks, small offsets, or gaskets protruding from the interface. Epoxy is often placed on the outside of the bushing - flange interface in an attempt to stop oil leaks.

Surge Arresters

Surge or lightening arresters are one of the more vulnerable items in a switchyard. Within a substation they are typically connected to each conductor on each side of power transformers and are often supported on a boom mounted on the transformer. The surge arrester is frequently supported on small porcelain standoffs with a ground path through a strike counter. Surge arresters can be connected directly to the bushing or they may have their own drops from an overhead conductor. In the former case, if the surge arrester fails and falls, it can put a direct load on the transformer bushing and damage it. Additional information is needed on the performance of surge arresters, their standoffs, the method in which they are connected into the circuit, and their impact of transformer bushings.

Leaking Transformer Radiators

Prior to the development of the Guide, it was known that large, manifold-mounted radiators are vulnerable to leaks. New data shows that "large" individual radiator elements that are connected directly to the transformer are also vulnerable. Additional information is needed to better define what constitutes a "large" radiator.

Disconnect Switches

Two failure modes have been observed in disconnect switches. The first is the failure of post insulators used to fabricate disconnect switched. The second is the misalignment of the switch so that the contacts do not engage properly. An indication that this problem has occured is the use of rope to hold the misaoligned disconnect switches together so that circuits can be quickly and temporarily put back into service before final repairs are made, as indicated in Fig. 2. The misalignment can be caused by several effects that should be checked. Differential settlement of the disconnect switch footings may distort the disconnect switch support structure, the metal platform to which the post insulator is bolted or the bearing just below it may deform, the channels at locations that support the lower disconnect switch bearing housing may deform, or the operating leakage may slip or be deformed. This information can best be obtained from service personnel at the site.

Emergency Power

Emergency power in the form of station batteries and engine-generators has performed poorly. The diverse causes of emergency power failures and the impacts of the loss of emergency power need to be more fully documented.

Interactions with Suspended Wave Traps or Current-Voltage Transformer s

Wave traps and current-voltage transformers are occasionally suspended from conductor support structures. They are restrained from below by column supported post insulators or insulator strings, which are anchored to a pedestal, a ground anchor, or some other support structure. Earthquake induced lateral motion of the suspended item may interact with adjacent equipment if adequate slack in conductors is not provided. Information on the seismic performance of the various configurations of this equipment is needed.

Rigid Bus

There have been several failures associated with loads transferred by rigid bus or by connections to rigid bus that has fallen from its supports. In some cases, the falling bus has damaged equipment. The performance of various configurations needs to be documented.

Communications Equipment

Most substations have communication equipment associated with protective relay systems and other control and monitoring functions. This equipment is typically installed in communication racks that are anchored to large aluminum angles that are bolted to the control room floor. These racks tend to be very flexible and equipment in the rack may be inadequately anchored. The performance of various configurations needs to be documented.

Quality Assurance of Anchorage Details

One of the better methods of anchoring heavy equipment, such as power transformers, is to weld the case of the equipment to steel plates embedded in the concrete foundation pad. This method has failed due to inadequate design capacity of welds, welds smaller than called for in designs, poor weld penetration and poor design associated with the anchorage load path. The performance of various configurations needs to be documented.

Black Start Capability

The performance of black start capability has been very poor. It is important to get a detailed evaluation of the diverse causes that disrupt black start systems.

METHODS OF DOCUMENTATION

Since the Guide was originally written, small, light-weight moderately priced video cameras have become available. The use of video has some advantages over photographic slides or prints. While a video does not have as large a dynamic range as film, it can get pictures in poorer lighting conditions. The video also has an audio channel so that the pictures can be documented with voice descriptions as it is being shot, one of the main advantages of using a video recorder. It is often difficult to document slides, even if a small tape recorder is used. When taking pictures of substation damage, it is often difficult to identify the location of the picture when the film is evaluated later, because substation equipment looks very similar. For example, a large 230 KV rack may have 20 breaker-and-a-half positions (a common configuration used in substations). With a video recorder, the sound track can be used to identify the position, or the video recorder can be panned from the position identification number to the item of interest. The large zoom available on newer recorders allows both wide angle and telephoto shots to be made without changing lenses. Low cost audio-visual computer equipment is becoming more common and it can be used for analyzing video data and generating hard copy that can be directly incorporated into reports.

Video does have some disadvantages. It is another item that must be carried, a burden when getting in and out of vehicles and in climbing around facilities. There is also a need to have an adequate supply of power, which may require that several extra battery packs be used. In cold weather and when power is disrupted, power for the camera may be a severe problem. In analyzing data, it is not convenient to compare different shots or find a specific shot using video. For publication purposes and general preservation, pictures have much better quality. It is necessary to be able to stop the video to analyzed picture contents. When this is done using a VCR and a television monitor, the quality of the picture may not be preserved with some equipment. The resolution of video is much poorer than that of film and in some situations the large zoom of the video may not be able to compensate for the poor resolution. For example, things in the background frequently provide valuable information. This is often not observed at the time so that a close-up picture was not obtained. The need to take both video and photographic pictures requires additional time. Like any tool, it may take some practice to become familiar with all of its advantages and disadvantage.

While a broad range of items have been damaged in power system facilities, damage is concentrated in high-voltage substation. Damage must be documented in such a way that the data can be analyzed later to identify potential failure modes and factors that may have contributed to the failures. For example, if a wave trap fails, its method of support and the locations of the damage should be documented. The use of a standard preprinted form can speed data collection and provide a more accurate and complete record of the damage. Most substations take one of a few standard configurations. Two configurations are considered here, a breaker-and-a-half configuration and a double-bus-double-breaker configuration. Copies of these forms can be used in the field to document damage. The configurations shown in the schematic diagrams have been fully "stuffed", that is, the maximum number of auxiliary items is shown. For example, in Figure 3, each of the three phases for a breaker-and-a-half position has a wave trap and current-voltage-transformer. In practice, many of the wave traps and current-voltage-transformers will not be used. A standard procedure for indicating that some items are not present and the exact location of damaged items allows damage to be quickly documented. At the bottom of the figure several common configurations of equipment are illustrated. These can be used to document items at a given site. The collection of the diagrams for a switchyard allows damage patterns to be observed, which can help in identifying failure modes.

FINDING DAMAGE AND FACTORS CONTRIBUTING TO IT

Finding and documenting damage is complicated by the fact that utility personnel start to clean up and restoration damage within an hour or two after the earthquake, even when there is major damage. If only one or two sites are slightly or moderately damaged, clean up and restoration starts almost immediately. As a result, restoration will almost always be in progress or may be completed before the investigator arrives at the site. The procedures given in the Guide should be followed, that is, start where the high voltage lines enter the site and work though the system. It can be useful to go to the "grave yard" and "bone pile" before inspecting the equipment. The "grave yard" is usually located along the boundary fence on one side of the switchyard and contains the remains of damaged equipment, such as circuit breakers and current-voltage transformers. The "bone pile" is usually a collection of damaged post insulators that were used to support equipment, such as wave traps or bus or were part of damaged disconnect switches (disconnect switches are fabricated using post insulators). This will give an indication of the types and amount of damage at the site, if the damaged equipment has not already been removed from the site. When restoration work has started, it may be difficult to identify damage.

When broken porcelain is still in place at the time of the investigation it is clear what equipment has been damaged. This is also the best situation for identifying failure modes and factors contributing to them. This is why it is important to investigate sites as soon after an earthquake as possible. If porcelain items are missing, in general it is reasonable to infer that the item was damaged and removed. However, undamaged items are frequently cannibalized to reconstruct other circuits. Porcelain shards on the ground under the missing item is a good indication that it was damaged.

Some equipment may be reconstructed at the time of the investigation, so that it may be necessary to infer damage by some tell-tale signs. Broken porcelain on the ground has already been mentioned. Mismatched porcelain on an item is also an indication that equipment has been restored with spares that were available or by cannibalizing damaged equipment. For example, one type of disconnect switch contains six porcelain post insulator stacks, two for each phase. It is very rare to find stacks that are mismatched, that is, different colors or different shed (small fins to shed water) patterns. Figure 4 shows a conductor near a circuit breaker bushing that has had its aluminum rope lay opened when the post insulator on an adjacent disconnect switch failed, fell, and pulled on the conductor. Figure 5 shows a series of chipped paint marks on a circuit breaker case caused by a falling post insulator that failed and fell from the adjacent disconnect switch. Porcelain chard at the base of the circuit breaker is also a sign that the adjacent disconnect switch failed. Chipped sheds on post insulators or bushings is an indication of secondary damage, so that the failure that caused this damage should be sought out. Exposed surfaces of chipped porcelain that is still usable are often given a protective coating to prevent moisture absorption. The typically barn-red color of this coating makes the repair obvious. Many equipment items, such as transformers, current-voltage transformers, and current transformers contain oil, so that signs of a recent oil spill is an indication of damage. Indications of an oil leak are a sheen on equipment surfaces or their support structures, discoloration of paint on support structure, as indicated in Fig. 6, oil absorbing material below the item, or discoloration of the gravel below the item. Transformer bushings that have developed leaks at the porcelain-flange interface may have an epoxy coating to stop the leak. New looking conductor connecting hardware or unoxidized conductor may indicate that the connections had to be reworked to accommodate different sized replacement equipment. On rigid-type conductor, shiny conductor near a weld indicates recent repairs Distress at anchor bolts will be a sign of large loads and possible equipment failure. A stretched bolt is indicated if nuts on studs or anchor bolts are loose. Frequently nuts are staked with a center punch, painted over, corroded, or jammed so that they can not turn, but a loose washer below the nut indicates the stud has stretched. Also look for chipped or cracked paint or deformations near gussets or anchor points. Temporary repairs made with rope or wire to hold conductors or other items are an indication of failed connecting hardware, as indicated in Fig. 7. Freshly poured footing suggests that a pad for new equipment has been installed.

One of the major problems in identifying failure modes is to distinguish between interaction problems due to inadequate slack and inertial loads. Two features of the fracture surface of porcelain can be used to identify the location where the failure started. If this point is not lined up with the orientation of the conductor, interaction is probably not the cause of the failure. When observing one of the fractured surfaces, there may be a large hump or depression on the side opposite the point where the failure started. This is referred to as the hinge. Another feature that may be present is referred to as waves. These waves have the appearance of waves at a beach that have broken and have then been flattened. These waves are directed towards to point where the failure started.

After completing an initial inspection of the site, try to do a quick walkdown of the site with the foreman who is in charge of work at the site. It is best to set this up when arriving at the site so that he or she can work it into their schedule. Damage that has been missed or repaired and cannibalized items can be identified.

CONCLUSIONS AND RECOMMENDATIONS

Observations on the actual performance of power system equipment and facilities are one of the best ways to improve equipment design and installation practices. Careful observations using all clues are needed to identify damaged equipment and their failure modes.

When there is major power system damage, the affected utility will often be overwhelmed in attempting to restore service and there may not be adequate resources available to document damage While informal arrangements between major California power companies exist to facilitate post earthquake inspections, there is a need to develop this capability in other regions of the county and to assure that it will work in California if there is a catastrophic earthquake.

There is a need to get power equipment manufacturer engineers in the field after an earthquake so that they better understand the performance of their equipment under seismic loads. In the long run this may improve the design and seismic performance of equipment.

There is a need for strong motion instruments to be located at important sites so that data will be available to evaluate and better understand the performance of the equipment.

There should be a follow up investigation several months after the earthquake, as additional damage may have been identified and the utility may have a better understanding of the failures

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The cooperation of utilities are gratefully acknowledge for providing access to facilities so that damage could be documented.

FIGURES

Fig. 1 Shifted Transformer Bushing