SEISMIC DESIGN PRACTICE FOR ELECTRIC POWER SUBSTATIONS

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SUMMARY

A procedure for improving the seismic design of electric power substations is summarized. This paper is based on a design guide directed at regions in which there is moderate to high seismic hazard, long intervals between major events, and low awareness of the risk. The guide has been developed to reflect the need for low cost measures because of the long interval between events and to provide background information about earthquakes and their effects on power systems because of the low seismic awareness in the target regions. The major sections deal with the description of a substation from an earthquake engineering perspective, seismic hazards as they relate to substations, a design philosophy, and steps to improve earthquake response.

INTRODUCTION

Many parts of the world are subjected to very large earthquakes which occur very infrequently. This situation lends itself to repeated catastrophic damage because awareness of the seismic damage quickly fades with time and the long return periods makes it difficult to justify the cost associated with improved earthquake resistance. Not withstanding these problems it is vital that certain critical facilities, such as power systems, have an acceptable earthquake response.

Numerous earthquakes have demonstrated that electric power substations are the most vulnerable element of power systems. The recently published "Recommended Practice for the Seismic Design of Substations" (Ref. 1) provides design criteria, smoothed ground motion response spectra keyed to the UBC 1982 Seismic Zone Map, and methods of equipment qualification which, if implemented, would greatly improve the earthquake response of substations. Unfortunately, the technical skills and the cost of implementing the recommended practices makes it unlikely that they will be implemented in the regions discussed above. To address this problem, a design guide has been developed (Ref. 2) in which the major thrust is to reduce disruption from catastrophic earthquakes in regions of low seismic awareness. It is directed to utility personnel who are familiar with power systems but not familiar with earthquakes or their effects.

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SUBSTATIONS - AN EARTHQUAKE ENGINEERING PERSPECTIVE

Substations can be classified in several ways. First is the distinction between transmission and distribution stations. A distribution station will contain transformers which supply low voltage power to the distribution system of a small service area. A transmission station would connect two or more transmission lines at different transmission voltages and supplies power to a large service area, including several distribution stations. Often the functions of two or more of the stations are combined at a single site. In general, a transmission station would be considered more important than a distribution station because of the greater effect on the system if its operation is disrupted. In many cases, however, transmission lines pass through the distribution station to which they are supplying power and damage to the substation which affects that line could be very disruptive. Thus, the importance of any part of the system should be judged by the effect that its disruption would cause rather than just on its voltage level. However, voltage does play an important role in the vulnerability of equipment and facilities to earthquake damage since the size of ceramic members, such as bushings and post insulators, increases with voltage and it is these larger members which are most vulnerable.

The seismic vulnerability of substation equipment and the effect of their damage on system response is reviewed. They are ordered as they might be encountered as power passes through the substation. Damage to transformers and circuit breakers have been most disruptive to power systems because of their vulnerability and the vital function they perform.

Dead End Tower

In general, the sesimic performance of transmission and disruption lines has been good. The major cause of failure of transmission towers has been foundation damage due to soil failure or damage resulting from landslides. Thus, current good practice for the design of dead end towers would appear to be adequate. The repair of dead end towers to restore service is relatively easy.

Lightning Arrestors

From a structural point of view, a lightning arrestor is very simple, a vertical beam cantilevered at its base, with a bus, or a drop from the bus, connected to its "free" end. Typically, it is mounted on a transformer or an independent support. Failures, which are quite common, occur in the ceramic material near its base. Failure may apply additional load to adjacent bushing or post insulators. In some configurations, the damaged lightning arrestor may strike nearby bushings causing additional damage. Damaged lightning arrestors can be bypassed to restore service.

Line Traps

Line traps are often found on each phase of higher transmission voltage lines or on just one phase for intermediate and low transmission voltage lines. The line trap is a cylindrical member consisting of a coil of wire on a support frame. They are typically supported by one of three methods, horizontally by a post insulator at each end, vertically by a single post insulator, or suspended from a cable. Post insulators often fail in the first two installation methods.

Failures of line traps have adverse effects upon the system. They represent a direct financial loss. Repair will require allocation of resources, both material and human. While the system can operate without a damaged line trap, if it is bypassed, its loss will reduce the protection of the system at a time when repeated disruptions can be expected due to aftershocks and when field crews will be working on the lines and in the substation.

Voltage and Current Monitoring and Metering Devices

Structurally, these devices are very similar to lightning arrestors. The effect of the loss of these devices will depend on their function and on the particular situation. In some cases, the operation of the system can continue without the information which the particular device provides. In other cases the control signals may be needed; for example, for the proper operation of circuit breakers.

Busses and Interequipment Conductors

From the perspective of earthquake resistance, two aspects of the bus must be considered. First, is the critical function of connecting the bus to equipment. The dynamic response of the bus and the equipment which is connected to it often leads to the failure of the connection or the porcelain member to which the bus is connected. While rigid bus is designed so that thermal expansion does not overload porcelain members, there is a widely held misconception that this also provides adequate protection for seismically induced relative motions. However, thermal expansion connections are relatively rigid perpendicular to the direction of the bus and only allow limited motion.

A second consideration is the failure of the bus support system, either the post insulators or insulator string which support the bus. While the bus and its supports are easy to repair, the damage of the ceramic members connected to the bus can be time consuming and require critical replacement parts. The equipment which is damaged may have critical functions.

Transformers

Recent earthquakes have shown transformers to be vulnerable to earthquake damage. Several failure modes have been observed. They are related to the dynamic response of the transformer and its components, damage to bushings induced by inadequate slack in interconnections,and by overturning or severe motion of the transformer due to inadequate anchorage.

Transformers represent the most critical element in a substation because they perform a vital function, voltage conversion, which cannot be temporarily bypassed as is the case for most other substation equipment. The limited availability of spares, particularly for large three phase transformers, their long repair times, and the time required to move in a replacement means that their damage hold the potential for extended disruption.

Circuit Breakers

Recent earthquakes have shown circuit breakers to be very vulnerable to damage, particularly those operating at high voltages. While systems are typically designed with spares which can quickly replace a damaged breaker, their high vulnerability has resulted in a large number of failures at a given site so that there were insufficient spares readily available. While a transmission line will have a circuit breaker at each end, so that a case can be made that only one circuit breaker per line is required, power system requirement precludes this type of operation under faulted conditions.

Because of their high vulnerability and the limited number of spares, particularly of high voltage units, their damage holds the potential for extended disruption.

Switches

Switches have proven vulnerable to earthquake damage and several modes of failure have been observed. While a damaged switch can be bypassed, the loss of automatic switching in the post earthquake environmental can be quite restrictive to system operations. Even low voltage switches have been damaged when the two parts of the switch are mounted on different support structures.

Reactive Elements

Both passive and active reactive elements have proved to be vulnerable to earthquake damage. Depending on the type of element, several different types of failure modes have been identified. In most cases, the system can continue to operate without the damaged reactive elements, although with degraded performance.

EARTHQUAKE HAZARDS AND THEIR IMPLICATIONS TO POWER FACILITIES

Ground Shaking

A major earthquake can generate severe ground shaking over several thousand square miles. The vibration of the ground will induce vibration in the structure or equipment resting on the ground. Equipment mounted on structures will experience, at its base, the motion induced by the response of the structure to the ground motion.

Equipment vibration is the major cause of power system damage and disruption. The vibration of the equipment has two effects. First, the dynamic response, which can be amplified due to resonance, can induce stresses in the equipment that can cause failure. Second, the dynamic response can cause relative deflections that can over load connections between adjacent pieces of equipment. In addition to induced shaking, large structures or widely separated structures which are interconnected can experience differential ground motions which can induce strain causing damage or failure.

Soil Liquefaction

Under certain conditions, when soils experience vibrations, the phenomenon of soil liquefaction can be observed. Factors contributing to liquefaction are the amplitude and duration of shaking, height of the water table, the soil density and the granular character of the soil. When a soil liquefies, it loses its shear strength. Liquefied soil has been observed to flow on 1% grades and surface supported structures have settled several feet below grade; buried tanks or enclosures which were lighter than the material in which they were buried have floated to the surface. While there is a tendency to emphasize vertical motion associated with soil liquefaction, extensive horizontal spreading has been observed. While most earthquake experience has been gathered from western earthquakes in the United States, the relatively low water table there as compared to other parts of the country suggests that liquefaction may have a much larger impact in other regions.

Ground Faulting

Faults are fracture planes where there is relative motion between the rock on each side of the fracture. Thus, anything spanning the fault, such as buried pipe, cables or a structure, can experience severe shear deformations. In the 1906 San Francisco earthquake, the maximum displacement along the fault was 20 ft. Depending on the earthquake, the motion across the fault can be both horizontal and/or vertical. As in the case of liquefaction, regional differences will influence the severity of the problem as many regions have thick alluvial deposits which may prevent surface faults.

Earthquake Induced Landslides

There are many regions in which the earthquake induced shaking triggers landslides. The situation can be aggravated if the earthquake should occur during a rainy season when soils are wet and in a weakened state. The slides can cause excessive deformations in the grounds, causing severe distortions as with faulting, or the motion of the soil may sweep away structures and equipment in its path.

Subsidence

Under certain conditions, earthquake-induced vibrations may cause extensive settling of the ground. In past earthquakes this has caused flooding and differential settlement with attendant severe loads in structures similar to that caused by surface faulting.

Earthquake Induced Water Waves

If an earthquake should occur offshore and the motion have a significant vertical component, large long wavelength water waves can be induced. Typically, these waves are barely perceptible in deep water; however, with certain types of shoreline topographies they can generate massive waves when encountering a land mass. Water level can rise tens of feet and, depending on the topography of the coast, can extend inland a mile or more.

A DESIGN PHILOSOPHY FOR INFREQUENT EVENTS

The approach adopted here for improving the earthquake resistance of substations is based not only on the earthquake hazards and risks to power systems but also on economic, technical and administrative factors. Some of the elments which have helped mold the design philosophy are given below.

- The occurrence of a catastrophic earthquake in a region means that similar events can be expected in the future.
- Power system facilities are becoming more vulnerable with the increased use of higher transmission voltages and the larger porcelain members that this dictates.
- Utilities have limited control over the seismic resistance of the equipment purchased.
- Substation designers in regions of low seismic awareness have limited technical expertise with seismic design.
- It is difficult to justify cost for improved earthquake resistance in regions with infrequent earthquakes.
- The incremental cost of improving the response of much equipment is small and much can be achieved through proper installation.
- Comparing the service life of most facilities to the interval between earthquakes indicates that instituting good practice will have a major impact in regions with infrequent earthquakes.

In light of the above factors, the following design philosophy has been adopted.

- Measures to improve the earthquake resistance of power systems will concentrate on new construction and facilities, only in rate instances would retrofit be considered.
- Measures which are adopted must represent a small incremental cost to the project.
- Measures stressed are those under the direct control of the utility rather than depending on equipment suppliers.

- o The actual loads used to design any particular part of a facility are based on the maximum anticipated loads associated with a catastrophic earthquake and the incremental cost associated with providing the desired earthquake resistance. Thus, uniform design loads may not be used within a given facility.

- o When the desired degree of earthquake resistance cannot be provided at an acceptable cost, plans for repair should be made.

IMPROVING THE EARTHQUAKE RESPONSE OF SUBSTATIONS

While criteria and procedures for improving the earthquake response of substations have been developed (Ref. 1) as noted earlier, the cost of executing them will probably preclude their being implemented in regions of low seismic awareness. Measures directed at regions with infrequent earthquakes are summarized below.

Facility Planning

Experience has shown that site selection can be one of the key elements in an acceptable earthquake response at a facility. There are many criteria which govern site selection and seismic considerations will not be at the top of the list, even in highly seismic regions. Of particular concern is that key substation sites should be given special seismic consideration and concentration of facilities at a poor site should be avoided.

Site layout can also significantly influence earthquake performance. If site preparation requires cut and fill, the most important and sensitive equipment should be placed on the cut part of the site.

Earthquake Design Practice for Substation Equipment

Equipment supported directly on the ground, such as transformers and some types of circuit breakers, should be firmly secured to their slab foundations. It is important to remember that horizontal restraint loads are proportional to the weight of the equipments so that gravity can not be counted on restraining heavy equipment, such as transformers. For equipment on support pedestals, the stiffness of the pedestral can be just as important as its strength. Flexible pedestals can lower the natural frequency of the mounted equipment so that it is in the region of high earthquake energy content.

Adequate slack to interconnections between equipment must be provided.

The need for emergency power provided by stations batteries dictates that battery racks have adequate bracing and that the batteries are secured to the racks.

Preparedness

Several preparedness measures can be taken to improve the mitigation, response and restoration phases associated with a major earthquake. The first step in a mitigation program is a seismic assessment to determine the adequacy of current seismic practice. The assessment should start with the highest voltage substations used by the company or with the next transmission station that is to be constructed for which design has not yet been started. The voltage of the substation should be over 150 kV as these have performed poorly.

Spare parts play a vital role in the post earthquake environment so their safe storage is important.

New facilities should be inspected by an individual who is knowledgeable about earthquake mitigation practices.

ACKNOWLEDGEMENTS

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REFERENCES

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