# SEISMIC PERFORMANCE OF ELECTRICAL SUBSTATIONS' EQUIPMENTS IN IRAN'S RECENT EARTHQUAKES

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**ABSTRACT:**

Substations are among the most important parts in the electric power networks, and play a vital role in the stability, controllability and serviceability of the electric energy, yet the experiences gained from the earthquakes have shown that these elements are very vulnerable and the direct and indirect losses resulting from their damages are sometimes really considerable. This high degree of vulnerability is due to the using of brittle materials such as porcelains, using massive elements with a non-proper distribution of mass in height of the equipment, interaction of adjacent equipments, rigid connections, poor anchorage, insufficient lateral stiffness and strength and so on. Based on the experiences of the recent earthquakes in Iran, the pot-head transformers with a large mass at the top, power transformers with poor anchorage, disconnecting switches and post insulators with brittle materials, rigid connections without insufficient slack between the two adjacent equipment, damages to the racks and panels in the control building and even the structural damages were the most common damages in the substations. In this paper the seismic performance of the electric substation equipments and their causes in Iran's recent earthquakes (Bam 2003, Gorgan 2004 and Zarand 2005) are discussed and the lessons learned from those are expressed. Finally, some recommendations to reduce this vulnerability and upgrade the seismic performance of the existing equipments are given.

**KEYWORDS:** Electric Substation Equipment, Seismic Vulnerability, Iran

## 1. INTRODUCTION

Iran is located in a region with high level of seismicity. During the past 20 years great earthquakes with high fatality and losses have struck different parts of the country. Earthquakes cause extensive direct and indirect losses in which the damages to lifelines play an important role. Electric power network and its complex components are a key element among all other groups of lifelines such as transportation networks, pipelines, communication networks, etc. According to vast usage of electrical energy in different industries and its vital role in the industrial production of a country, saving the flow of this energy during and after an earthquake could prevent extensive direct and indirect losses, such as physical vulnerability and severe damages of electric equipments which are very expensive, or business interruption losses due to the electricity outage. On the other hand, it has been learned from the past earthquakes that the existence of electricity could facilitate the rescue and relief operations and this leads to saving more lives which is very important.

Several researchers have studied the effects of past earthquakes on the electric power systems since early 70s to recent years. Schiff (1973) has studied the response of electrical power systems to the San Fernando Valley earthquake of February 9, 1971. From that study he has made the following major recommendations: (1) standards for system planning, operation, and performance should be established; (2) standards enforcement procedures should be implemented; (3) methods for modeling transmission systems should continue to be improved; (4) instrumentation to provide data to check model validity should be added; (5) special methodologies appropriate for evaluating system vulnerability to catastrophic disturbances such as earthquakes should be developed; (6) a "seismic safety inspector" position for earthquake related matters should be established; (7) a "damage evaluation log" should be established and maintained to document earthquake damage to electrical power systems; and (8) more extensive requirements for the use and security of emergency electrical power should be established.

Anagnos (1999) has developed a database that documents the performance of substation equipments in twelve California earthquakes. The purpose of the database is to provide a basis for developing or improving equipment vulnerability functions. Data have been summarized by earthquake, site, and equipment type. Probabilities of failure are calculated by dividing number of damaged items by the total number of items of that type at the site. Using peak ground accelerations as the ground motion parameter, failure probabilities have been compared with opinion-based fragility curves for a few selected equipment classes. The comparisons have indicated that some of the existing fragility curves provide reasonable matches to the data and others should be modified to better reflect the data.

The main objective of this paper is to study the damages imposed to substations' equipments in three recent earthquakes in Iran, and proposing the remedies for upgrading these facilities.

## 2. DESCRIPTION OF ELECTRICAL SUBSTATION

In Iran the electrical power network consists of three basic parts:
1- Generation (i.e. power plants)
2- Transmission (i.e. transmission lines and substations between the cities having high voltages)
3- Distribution (i.e. distribution lines and substations in cities which have low voltages)

All of these components are vulnerable to earthquakes, which may result in significant disruption of power supply, yet the past earthquakes have indicated that the substations have a high degree of vulnerability and according to their vital role in the stability of the network this study concentrates on this component. An electrical substation is a facility that serves as a source of energy supply for the local area and has the main following functions:
- Change the level of voltage
- Provide the operation safety of the network by means of eliminating the lightning and surges
- Provide control of the power line by means of measuring instruments

Substations consist of different equipments. The most important equipments are:
- Power Transformers
- Current Transformers
- Voltage Transformers
- Circuit Breakers
- Disconnect Switches
- Lightning and Surge Arresters

These equipments are usually in the switch yard. The control panels and the battery room are located in the Control Building which is near the yard. These substations are classified according to their voltage. The high voltage substations are 400 kV and 230 kV ones.

## 3. SUBSTATION DAMAGES IN BAM EARTHQUAKE (MATN 2003)

The 2003 Bam earthquake with a moment magnitude of M=6.5 struck the Bam area in the south-east of Iran in Kerman province. The reported horizontal and vertical peak ground accelerations are respectively 0.8g and 0.98g. The focal depth of this earthquake was almost 8 km and the effects of near source were obvious. There was a high voltage substation in the affected area, the Shahid Abbaszade substation. This substation has two different parts, a 230 kV area and a 132 kV area which are discussed in the following sections.

### *3.1. The 230 kV Area of Abbaszadeh Substation*

In figure 1 the single line diagram of this substation is illustrated. As it is shown, this part consists of six transmission lines and six circuit breakers supported by current transformers and disconnect switches. There are two main rigid bus bars. The configuration of this substation is almost one and half breaker which has a high degree of redundancy. Current transformers in 4 of the 6 modules were pot-headed and therefore very vulnerable in which 70% of them experienced severe damages and toppling. In figure 2 a broken CT is shown. Toppling of an equipment can cause damage to adjacent ones. Figure 3 shows a broken circuit breaker due to the failure of the attached current transformer. It should to be noted that in some cases the connection of the conductor to the top of the equipment has been flexible enough and this has helped the equipment not to fall. One of these flexible along with the weak clamps are shown in figure 4.

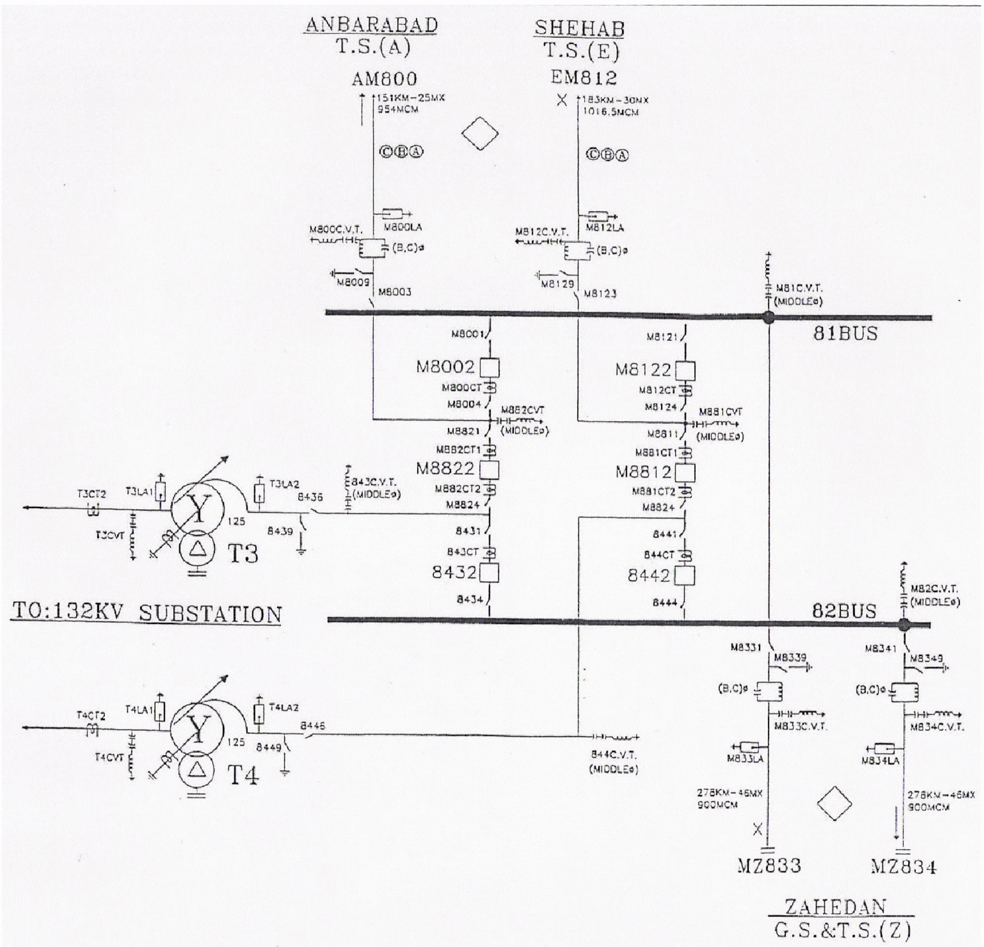


Figure 1: The single line diagram of Abbaszadeh 230 kvV substation (MATN 2003)

Figure 2: A broken CT

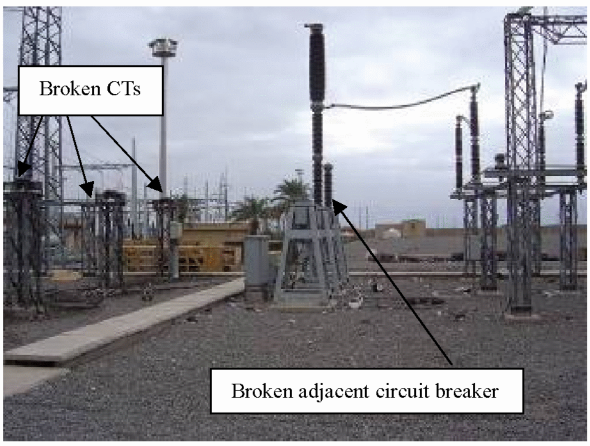


Figure 3: Fallen adjacent equipments

In the cases of current transformers with an electrical core near the base or supporting lattice structure no damage has been reported. As seen in figure 5 the adjacent equipments are not damaged as well.

Figure 4: A flexible clamp

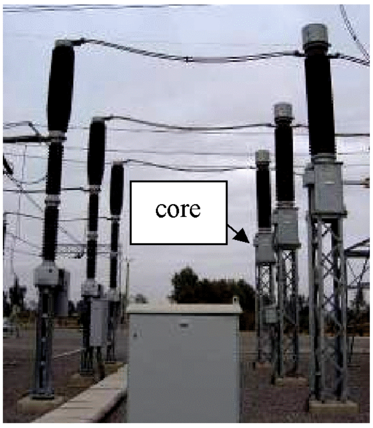


Figure 5: standing equipments

In this substation an electrical reactor with no anchorage at the base has slid about 30 cm. The weight of this equipment was almost 70 tons. According to this sliding movement the disconnect switch connected to this component has been pulled by the conductors and has gotten damaged. Figures 6 and 7 show this interaction.

Figure 6: Pulled conductor

Figure 7: Sliding of non-anchored equipments

The surge arresters in this substation experienced extensive damage. Figure 8 illustrates one of these equipments. The voltage transformers in this substation and the post insulators, as shown in Figure 9, were completely safe and only the flexible connection to the equipment was broken.

Figure 8: Broken surge arresters

Figure 9: PI and voltage transformers

At this part of the substation two similar power transformers had been installed. One of this transformers (T3) did not experience any damage because it has been under service and all the connections were off, but the other one slid on the concrete pad about 50 cm due to lack of base anchorage. Figure 10 shows this movement. Due to this sliding the transformer bushings were pulled and cracked at its base, where connected to the steel part, and this led to oil leakage. The cracked bushing is shown in figure 11.

Figure 10: Transformer base after retrofit

Figure 11: Cracked bushing

There was no damage in the guyed towers, and in the foundations and the lattice supporting structures of the equipments. It should to be noted that geotechnical damages such as liquefaction was not observed in the substation area. The summary damage cases is given in Table 1.

Table 1: Data of the damaged equipments in 230kV substation

| Equipment | Total quantity | No. of damaged ones | Percent | Description |
|---|---|---|---|---|
| Power transformer | 2 | 1 | 50% | Anchorage failure |
| CT (top core) | 18 | 12 | 67% | Toppling |
| CT (bottom core) | 6 | 0 | 0 | - |
| Breaker (adjacent to top core CT) | 12 | 4 | 33% | These 4 also caused damage to the adjacent switches |
| Breaker (adjacent to bottom core CT) | 6 | 0 | 0 | - |
| Voltage transformer | 18 | 0 | 0 | Only conductor clamps got damaged |
| Suspended line trap (wave trap) | 4 | 0 | 0 | - |
| Surge arrester | 18 | 2 | 11% | Broken from base |
| Disconnect switches | 24 | 6 | 25% | Pulled by adjacent equipments |
| Reactor | 1 | 0 | 0 | Sliding movement |

### *3.2. The 132 kV Area of Abbaszadeh Substation*

In this part of the substation the damages were similar to the other part, but the important point is that these components are light so the damages were limited. The data of the damaged equipments are given in Table 2.

Table 2: Data of the damaged equipments in 132 kV substation

| Equipment | Total quantity | No. of damaged ones | Percent | Description |
|---|---|---|---|---|
| Power transformer | 2 | 2 | 100% | Both anchorage failure |
| CT (top core) | 6 | 1 | 17% | Toppling |
| CT (bottom core) | 21 | 10 | 48% | Oil leakage |
| Breaker (adjacent to top core CT) | 6 | 0 | 0 | - |
| Breaker (adjacent to bottom core CT) | 18 | 0 | 0 | - |
| Voltage transformer | 5 | 3 | 60% | Oil leakage |
| Surge arrester | 12 | 0 | 0 | - |
| Disconnect switches | 42 | 0 | 0 | - |

### *3.3. The Control Buildings in Abbaszadeh Substation*

There is a control building in each of the two mentioned areas. The nonstructural elements in these buildings got stlightly damaged, especially the batteries in the battery room which were not supported sufficiently. The control panels were bolted to the building floor, and they did not experience any damage. Figures 12 and 13 illustrate the damages to the building and DC batteries respectively.

Figure 12: Damages to control building

Figure 13: Damaged batteries

## 4. SUBSTATION DAMAGES IN GORGAN EARTHQUAKE (MATN 2004)

The 2004 Gorgan (Agh Ghala) earthquake with a local magnitude of M=6 struck the Agh Ghala area in Golestan province in northern Iran. The reported horizontal and vertical peak ground accelerations are 0.12g and 0.05g respectively. The focal depth of this earthquake was around 15 km. This minor earthquake did not result in any death or severe injuries in the stricken area.

There was a very important high voltage substation in the affected area, the Ali Abad substation. All the equipments in this 400 kV substation were safe and the only problem was the crack at the base of the power transformer which led to oil leakage. This crack was at first very narrow and the transformer was under load without any problem, but due to the aftershocks the crack was opened and the bushing was completely drained after 10 hours. This 600 cm bushing had the weight of 1450 kgf and was replaced after the earthquake. Figures 14 and 15 illustrate the transformer and the cracked bushing respectively.


Figure 14: Replaced bushing


Figure 15: Damaged bushing

The safe equipments of this substation are shown in figure 16. Another 230 kV substation in the affected area was Gorgan substation. Due to the small amount of PGA all the equipments in this station were safe and no damages were reported. Figure 17 shows the equipments of this substation.


Figure 16: Equipments in Ali Abad substation


Figure 17: Equipments in Gorgan substation

## 5. SUBSTATION DAMAGES IN ZARAND EARTHQUAKE (MATN 2005)

The 2005 Zarand earthquake with a moment magnitude of M=6.4 struck the Zarand area in Kerman province in south-east of Iran. The reported horizontal peak ground acceleration of this earthquake was 0.33g and the focal depth was almost 14 km. Two high voltage substations of Zarand and Mottahar Abad were placed in the affected area and suffered some damages as described in the f0llowing sections.

### *5.1. Zarand Substation*

This substation is adjacent to the Zarand powerplant. It works under 132 kV, hence the equipments are not as vulnerable as the ones in higher voltage substations. The recent earthquake in Zarand confirmed this point, yet there were some moderate damages such as the overturning of batteries because of poor anchorage, and sliding movement of the power transformer, but fortunately this did not cause any damage to adjacent equipments because of the slack of the connections to the bushings.

### *5.2. Motahar Abad Substation*

In this 230kV substations some moderate damages were reported, includig sliding of control panels on the floor of control building because of the lack of anchorage, damage to the battery racks, sliding of the power transformer and toppling of the top core CTs (similar to Bam). Other equipments performed satisfactorily. Figures 18 to 20 illustrate the damages.


Figure 18: Trans sliding


Figure 19: Damaged batteries


Figure 20: Panel sliding

## 6. CONCLUSIONS

The studied three recent earthquakes have proved that substations are very vulnerable. There are some obvious reasons for the observed such as:

- Use of brittle materials as the main part of several equipments
- Inadequate anchorage to the base
- Insufficient lateral stiffness and strength
- Low redundancies
- Low level of damping
- Interaction between adjacent equipments
- Interaction between the equipment and its contents
- Having heavy mass
- Improper mass distribution at the height of some equipments
- Poor installation and maintenance besides their remarkable ages in some cases.

It can be seen that most of the imperfections and shortcomings mentioned above can be removed and fixed with an easy attempt.

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