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STUDY OF SEISMIC DAMAGE TO POWER GENERATION AND DISTRIBUTION NETWORK AND REMEDY FOR IMPROVING THE EXISTING SAFETY CRITERIA

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SUMMARY

Utilization of hydraulic potential energy and thermal energy by construction of power plants which are generally situated at some remote locations and are far from consumption ports, necessiate the establishment of transmission system (lines) and substations. Due to vastness of regions and existence of different conditions attributed to the ground, the outbreak of various incidents, such as earthquake is probable. Although the damages , inflicted upon power utility system are not significant, but interruption in production of electrical energy and transmission of this energy at any moment and profound investments , requires a special attention to observe the behavior and responses of current seismic forces.

Studying of destructive effects of recent earthquake on the power system (generation, substation and transmission) in Iran (Bam city-2004), Philippines and other countries, proved the significant of the above mentioned studies. Concerning the importance of utilization of energy, improving the current situation, increasing the safety level for availability of electrical equipment and future projects, it is necessary to take some procedures into consideration to prevent or lessen the destructive consequences of earthquakes.

This research work concentrate on the study about "seismic retrofit planning methods, seismic upgrading design for power network facilities based on the foreseen seismic risk assessment of electrical power generation and distribution systems.

INTRODUCTION

The experience of past earthquakes shows that, although damages of the Electrical network installation are very extensive in length and area, they are infrequent. But the significance of these installations makes their protection and stability more important. According to the investigation about past earthquakes and the transmission lines condition in our country, some of them will probably have considerable damages. Since earthquake is unpreventable, the necessity of reliable, fast and simple method to retrofit of the existing installations is obvious. Therefore, Finding practical retrofitting methods for vulnerable installations and preventing them from further damages by improving design methods is of special significance.

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1- STUDY OF EARTHQUAKE DAMAGES

Study of earthquake damages is an important factor for modifying the design and construction of earthquake resistance systems. In earthquakes technical and non technical installations experience a real test. This will reveal their strengths and weaknesses and would be an appropriate experience for designers. Because, when the loads imposed on a structure reaches the design load, calculation and theoretical errors, code's weaknesses, construction problems, etc. are revealed in form of local or global problems.
The damages to power transmission system due to earthquake could be divided into two major groups:

- direct damages
- indirect damages

1-1- Direct damages

These kinds of damages are caused because of weak designs or the method of method. They are revealed in forms of:

- Damages in transmission line towers because of weakness in foundation design
- Damages in equipment support structures because of weakness in structure and/or foundation design methods or some problems such as carelessness in construction procedure
- Damages of buildings in substations, substation peripheral walls and etc. because of weaknesses in design and/or construction.
- Asymmetrical settlement in foundations and therefore uselessness of equipments.

1-2- Indirect damages

These kinds of damages are caused by environmental problems and dissimilarity between equipment real behavior and design assumptions and extraordinary conditions, which can be seen in forms of:

- Soil liquefaction at substations transmission line towers.
- Stone downfall from adjacent mountains and cliffs.
- Falling of transmission towers due to ground sliding.
- Falling and collapse of substations peripheral walls due to ground sliding.
- Over turning of power transformers which are located on distribution poles because of the weight transformers their and inappropriate connections to supports.
- Overturning of batteries in control building due to lack of appropriate supports and position of batteries which will lead to telecommunication systems and PLC cut-off.
- Damages to the equipment located under gantries (like CVTs and CTs) due to pendulous motions of LTs which are suspended from transmission line gantries. Because of the type of LTs connection to gantries, the height of their cables and their weight, LTs have a totally pendulous and reciprocating motion with large amplitude and the lack of conformity between their motion and those of connected CVTs /or CTs would break the equipment porcelain. This kind of damage is very frequent in destroyed substations.
- Horizontal displacement of main and auxiliary transformers and therefore disruption of bushings located on them which make them be useless.
- Overturning of transformers from foundations and breaking of bushings and transformers body.
- Damage to all porcelain material, insulator & bushing due to rigid connection between several equipments together or fall down.

2- DIRECT DAMAGES IN STRUCTURAL MEMBERS

As mentioned before, direct damages are caused because of weakness in design and/or construction methods of structural members. With regard to the type of structural system these kinds of damages can be investigated.
Structural failures are possible in each story and in any kind of structure. They are caused by lateral and torsional displacement, local fracture of supporting members, large displacement of foundations and collision of adjacent buildings. As obvious one of the frequent direct damages in power network systems is uselessness of facilities in past earthquakes. After earthquake although buildings and installations are not severely damaged, because of being not operational, they can not be used. Some kind of these damages are as follows:

- Failure of some of the structural steel members in transmission towers due to damages in foundations which have been designed inappropriately.
- Settlement or disruption of transmission line foundations and thereby tilting of towers or extraction of stubs out of concrete.
- Collapse of external and internal walls in control buildings in spite of soundness of structure.
- Cable channels disruption and/or tilting of control cabinet supports which make the tables useless.
- Equipment supports disruption in Substations such as rupture of bolts and angles, rotation of foundations and rupture of structure support anchor bolts.
- Collapse of fire walls on transformers
- Settlement and cracking in channels and separation of walls from slabs and/or extraction of cables from walls.

It is necessary to consider that equipment in control building and other equipment leaned on steel or concrete structures are more important than the structures.
Anyway, all kinds of damages in steel and concrete structures are classified as follows:

a- **Global Damages:**
Such as large story drifts, fractures, damages and collapses of walls

b- **Gravity load resisting system:**
Including columns sway from vertical position, columns fracture, separation of floors and roofs from walls and columns, fracture of connections and supports and damages of load bearing walls.

c- **Lateral load resisting system:**
Including frame lateral displacement and fracture, severe creaks in shear walls, failure in bracings and other lateral load resisting components.

d- **P-Δ – effects**

e- **Structural and non structural elements falling down:**
Including stacks, parapets, suspended ceilings & false ceiling, lightening systems and building wall s.

f- **Foundation defects:**
Including cracking, settlement and displacement

g- **Member defects:**
Including local and global damages in members

h- **Other damages:**
Including transmission towers falling down, separation of HV cables from bushings and their collisions to equipment and people, breaking of batteries and thereby acid effusion …

3- INDIRECT DAMAGES IN STRUCTURAL AND NONSTRUCTURAL MEMBERS

As mentioned in section (1-2) these damages are caused because of destructive effects of other factors and they often make power systems become out of operation. Therefore, considering this kind of damages are of special importance. Also since their causes are not definite, to eliminate them completely or to prevent from their occurrence is not possible in all cases. However, by considering some notes and regarding initial bases, these kinds of damages and their effects will be minimum. As considered before this kind of damage is classified into two major groups:

3-1- Damages due to direct earthquake factors
Such as liquefaction, rock fall and ground settlement, slope sliding, fault creation and ground vertical motion.

3-2- Damages due to indirect factors
Such as:

- Falling of distribution poles and / or their connections to power transformers and falling of these transformers separately or in a group on buildings, cars, etc.
- Destruction of bushings and porcelain and angles of structural support due to large vibrations of connected equipment.
- Settlement, sliding and destruction of foundations supporting equipment such as transformers and thereby damages in equipment.

4- LESSONES FROM BAM-CITY EARTHQUAKE –IRAN (2004)

Iran is a country with several strong ground motions in recently 50 year, and in each earthquake a lot of people died and a lot of governmental & non-governmental buildings, as well as industrial sites and specially life lines were damaged.
In Bam after earthquake, some substations and transmission lines were destroyed and when people need help for health and car, life line was not ready.
A lot of substation in world and Iran were constructed by "Turn Key" contracts, so contractors used minimum criteria for consider earthquake force or use not match code for evaluate seismic loads such Iran condition for reduce the costs, therefore normally this substations are vulnerable against earthquake.
After Bam earthquake, about 70% of urban area and 90% of life line such as roads, water line and electrical facilities were damaged.
Attached pictures shown some failure mode in Bam substations after earthquake.

Figure-1, shown according to earthquake load which is grater than equipment strength capacity against earthquake (normally this equipments designed for 0.3g which is smaller than Bam earthquake acceleration) and also rigid conductor between insulators and electrical part had not enough gap for movement and sway in earthquake time and result to failed and beaked

(Fig-1)-Breaking and Collapse "DS" And "CVT"

(Fig-2)- Equipments was broken at connection joint between electrical components and fitting which was connected themes to support box and structural part

(Fig-3)- Equipment collapsed at middle longitudinal connection joint due to not fitting parts without enough strength capacity against earthquake and also incorrect embedded shape for porcelain

(Fig-4)- Porcelain part fall down and electrical internal components damaged

5- BRIEF RESULTS BASED ON MODELING AND ANALYSIS SOME EQUIPMENTS AND STRUCTURE WITH EARTHQUAKE LOADING

According to a study project for evaluation of 2 substations in Tehran and Tabriz (Iran),which has been done by author with full modeling the structure and equipment including structural members and non-structural parts, connection accessories and porcelain with SAP2000 and after loading based on IEEE-Std-693 (84 edition and 97 edition)with static and dynamic loading methods, below results were given:

- Foundation of these equipment according to depth and dimension due to overturning moments shall be collapse because depth and foundation weight of these foundation are not enough for resistant moments.
- Bolts for connection the steel structure to foundation has not enough shear strength for transfer loads to foundation and shall be break after seismic loads.
- Connection parts which connect electrical parts to structural supports were not enough and shall be damage due to earthquake loads.
- Insulator and electrical parts which were made by Porcelain, after earthquake loads and due to internal material , casing thickness and joint connection system to other parts normally may be break.

6- EARTHQUAKE RESISTANT DESIGN

After assessment of earthquake resistant behavior of structures used in power transmission systems and their predictable damages, a policy should be determined to treat unsafe structures and / or to encounter inappropriate conditions. In other words, it should be determined, weather it is possible to improve and how the structures should be designed so that they don't experience severe damages during earthquake. Thus there are 2 major subjects:

a- earthquake resistant design during initial design of power systems
b- Strengthening of existing structures

7- METHOD OF IMPROVING EARTHQUAKE RESISTANCE POTENTIAL AND IMPORTANT PARAMETERS IN IMPROVING SAFETY LEVEL OF EXISTING CONDITION

To reach to this goal the first step is to identify the important parameters in improving safety level which includes:
a- Earthquake hazard in the area
b- Economic life of structure
c- Amount and kind of structures vulnerability in case of probable earthquake
d- Architectural requirements
e- Required safety level according to importance and occupancy (use) of structures
f- Time status study
g- Economical aspects
h- Social and political aspects

7-1- Steps of required studies for selecting appropriate strategy and technique

a- Earthquake hazarded analysis
b- Assessment of dynamic characteristic of structures and existing conditions

c- Selection the best strategy to improve structural system and existing condition, considering the importance of structure and available facilities.

7-2- Selecting appropriate practical method

There are generally three practical methods for improving existing condition to prevent structures from damages due to earthquake:
a- reduction of earthquake demand
b- Increasing of structures earthquake resistance
c- Reduction of indirect effects of earthquake on natural conditions, ground and etc.

Therefore, considering the conditions and parameters mentioned above, designer can choose one of the appropriate alternatives. Even for two similar structures located in two different areas with different soil properties and different possibilities to access construction facilities, the ways to improve load bearing capacity and level of safety may be very different. In is worth considering that it is not possible to formulate these solutions and each project should be assessed with its own conditions. However considering the following bases are very useful in selections the best and most practical methods:

7-2-1- Reduction of effective mass by eliminating dispensable weights such as partitions, external walls and heavy claddings weights, weight of structure as the origin of earthquake load will be reduced.

7-2-2- Minimizing the distance between center of mass and center of stiffness and therefore reduction of tensional component of earthquake load.

7-2-3- Reduction of structures fundamental period: by reduction of mass and increasing the stiffness (appropriately and without considerable increase in earthquake loads). This method is useful for equipment support structures that motions through long vibrations have adverse effect on equipment leaned on them and is possible by adding extra members such as bracings or enlargement of section size.

7-2-4- Fastening of lateral load resisting elements to each other to increase yielding and strength limit in structures with low level of ductility: since providing high level of ductility is practically difficult, it would be possible to reduce demand for ductility by increasing strength.
By increasing new members and connecting existing elements to each other reaching this goal is possible. For example in gantries under heavy loads and transmission line towers, using diagonal braces with reduced laterally supported length increases the strength of the system.

7-2-5- Increasing fundamental period and damping of stiff structures, without sufficient strength and ductility subjected to high frequency vibrations: isolators can be used to have appropriate behavior in structures.

7-2-6- increasing stiffness, strength and damping in structures without sufficient ductility or when story drifts or displacements are important. In this condition by using pre-stressed bars, EBF and CBF bracings, shear walls and dampers, stiffness and strength of structures will increase and the level of applied loads will decrease which would lead to a considerable decrease in displacements. This method is generally used for non – laterally resistant control rooms in substations.

7-2-7- Isolation of different structures from each other and using cheep filler to prevent direct effect of displacements in some members on other members or equipment.
For example, when **LTs** suspended from gantries are connected directly to **CVTs**, non coincident pendulous motion with large amplitude cause tension in wires which breaks the upper part of **CVTs** and

make them useless .So, to prevent this event one tactic is to use minor additional equipments, for example **PI** (post isolator) s or cables with high displacement capacity or systems able to prevent displacement transfer from one part to other can be used or change the connection system between **LTs** and other equipments.

7-2-8- Use of supporting systems to prevent batteries in switch rooms from overturning: these systems with horizontal and vertical grids prevent the batteries from overturning during reciprocating ground motions in earthquakes.

7-2-9- Appropriate fixing of main and auxiliary transformer to their foundations by anchor bolts or rail supports to prevent them from sliding and overturning.

7-2-10- Appropriate fixing of distribution line transformers on their respective poles and using sufficient anchors to prevent secondary damages even after overturning.

7-2-11- site grading and clearing the area from damages even after overturning

*7-2-12-*fixing transmission towers location to prevent piers from sliding motion along slopes.

7-2-13- Avoiding from rigid and direct connection between equipment and main transformers bushings and changes this connection type to flexible shape.

7-3- Selecting the best method for retrofitting the design

In selecting the best method for retrofitting and enhancing lateral load resisting capacity of structures , the whole system including site characteristic , foundations and structural and non structural members should be considered .It is worth mentioning that evaluation of geotechnical properties , soil conditions and type of foundations , is an important stage in selecting the best method for retrofitting .

After determining a strategy for improving lateral load resisting capacity of structures, patterns and methods to reach this goal shall be analyzed. Selected final pattern not only shall consider technical aspects and costs but also shall minimize the non – conformity between non structural members and their operations. The appropriate method is a method with minimum heavy and professional work and minimum disorder in initial system. In other works methods which have the most works in external parts of buildings and therefore minimum words, in internal parts are more preferable. In fact the best method is a method that has minimum intervention in operation of buildings.

8- DESIGN AND PROVIDE THE STABLE SYSTEM AGAINST EARTHQUAKE PHILOSOPHY

For design the invulnerable systems must be used recent and before earthquake experience. because behavior of equipments ,structures and buildings due to lateral loads can be shown failure modes and weekly points and members after earthquake motion and displacement.
The response of buildings and structures to earth quake ground motion depends on their strength of construction, ductility and dynamic properties and review the damaged reports of electrical systems according to past earthquakes are very useful for this goal, therefore for upgrade weekly existing condition and design the strength system need to know about structural properties, equipments and also interaction between structural and non-structural components.

Refer to the A.m explanation; new generation of seismic code, recommended to use "seismic performance levels" that these levels defined for stability the structure and condition for continue the maintenances of building.
Many of these codes and also FEMA defined 4 below levels:
- Operational performance
- Immediate occupancy performance
- Life safety performance
- Collapse prventation performance

in other hand ,cost reducing is one of the most important item in engineering design and only design the building and structures with a high resistance and stiffness against the seismic load without considering cost estimate is non economical , then for define the performance level make economical sense is very important .then new building codes evaluate the structure behavior in three levels:

- Structural and non structural damage prevention due to faintly earth quake which may occur severally in the building life long time . These earthquakes must be sanded in elastic stress limit of materials.
- Supplying enough strength capacity for coping of plastic deformation in secondary members and Structural damage prevention due to moderate earth quake which may occur severally in the building life long time.
- Sustaining high earth quakes that occur rarely without collapsing or structural damaging . In the other words structure must sustain against the most forcible earth quake.

But for power systems use the above explanation do not possible and for receive to good performance and have the invulnerable systems ,need to define compatible performance for electrical system ,therefore earthquake codes for substation (like IEEE-Std-693) used 3 levels as:

A) High seismic performance level for high risk earth quake zone:
Equipment that is evaluated by this level, to perform acceptably in ground motion up to the high seismic performance level, without any damage or failure.

B) Moderate seismic performance level for moderate risk earth quake zone:
Equipment that is evaluated by this level, to perform acceptably in ground motion up to the moderate seismic performance level, without any damage or failure

C) Low seismic performance level for low risk earth quake zone

These levels are three qualification levels for equipments and their supports, based on seismic hazard for each substation according to site condition and also owner decide.

A degree of judgment and advanced planning is likely to be involved in selecting performance level for seismic qualification. The site hazard should not be expected to fall directly on the high, moderate or low seismic performance and a decision to take more risk or less risk will need to be made.

Therefore owners can select the one performance s level for their projects according to above subjects, but must be considered minimum requirement of earthquake codes for general buildings.

Design process for a resistant module or analyze and retrofitting an existing structure against earth quake force.

Ordinary design and analyze method use from static analyze for calculation of base shear force, stories drifting, plastic deformations which have many foible. For safety level increasing of an existing structure or designing a new structure it is important to consider following items:

- Calculation of gravitational, wind, electrical force loading and base shear based on static analyze method and also accurate calculation of the structure mass.
- Designing of structure based on upper paragraph result and building design codes.
- Determination of reference acceleration earth quake Selection of most forcible probable earthquake
- Determination of structural proper behavior considering to "M.P.E(max probable earthquake", "D.B.E(design basis earthquake" and performance level
- Plastic Dynamic analysis for model of structure and joint strain (drifting) ,members internal force and plastic deformation.
- Limitation design control, changing member section and try and error repetition step-5 till a confirmed situation on design criteria and balance between strength and ductility .
- Safety level control

Introduction a part of requirements in designing of transmission lines, substations and net power systems.

The following items should be considered in design process by designers.

- Prevention of transmission line passing from the paths which are in land sliding, turnover, cutting, liquefaction hazard area.
- Applying light weight material and mitigation structure mass.
- Using of resisting systems against lateral force.
- Abstention of using brick materials for external walls and use of hallow materials such as hallow clay block.
- Prevention of transmission lines and substations construction where ground property will resonance earth quake force. Such as height grounds with a special geotechnical condition.
- Performing thoroughgoing Soil test
- Considering proper development length and a good connection to equipments for insulators during construction time regarding seismic condition.
- Not to use a direct rigid connection between equipments such as "LT" to "CT" or "CVT".
- Using a proper bracing system for power transformer connection in foundation.
- Performing a subtle designing for equipment column foundation and control the settlement item.
- Performing a subtle designing for equipment column, gantries and steel structures against the earth quake force.
- Produce a proper connection for equipment on structure and foundation with using bolts.
- Performing a proper designing for lightening column in substation yard which may fall on the equipment.
- Performing a proper design for structure component such as fire walls and others which their collapse may affect on equipment.
- Using of ductile bus bars for avoiding striking between equipment.
- Performing a proper design for control building based on real loads and avoiding from increasing the height of building and laying down the weighty loads on high story.
- Performing a proper design for electrical power and control cabinet seating.
- Keeping the batteries in the battery rooms and avoiding of falling them.
- Construction a proper barrier around the substations
- Avoiding of construction elevated water tank near the building and equipment.
- Proper connection of distribution net transformers on the pole and beams and bracing their columns.
- Preparing proper bedding for substation equipment and transmission lines foundation from a compacted soil.

- Whereas possibility of occurring short circuit and earthquake at a moment(select this combination, check and control structural and nonstructural members for this combination must be done by owner ,because design for this condition result to strong foundation, structure and equipments and also cost of project and IEEE std-693 did not recommended

9- CONCLUSION

Looking at electrical system response to earthquake and large damage (due to not enough strength capacity for electrical parts, foundations and anchor bolts failure, incorrect shape for conductor which was connect equipment together and…), is a good guidance for "The Earthquake resistant design for electrical facilities" , then need to study the damaged failure mode in last earthquakes, laboratory test the electrical equipments and their supports dynamic behavior and use the other countries experience for design resistant systems.