Design & Manufacturing of 33kV GCB for Seismic Evaluation in Power Substation

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***Abstract* - The performance of substation equipment during an earthquake depends on their configuration, strength of construction, ductility and dynamic properties. Substation equipment's are lightly damped structures having one or more natural modes within the frequency band of ground excitation. The satisfactory operation of substation during and after an earthquake depends on the survival, without malfunction, of many diverse type of equipment. Porcelain components are identified as most vulnerable parts against earthquake vibrations than any other components of the substation. Electrical equipment is mounted on support structure. Support structure and porcelain insulator amplify the ground acceleration at the base of porcelain components. Dynamic characteristics of substation equipment are considered by carrying out finite element analysis. In the present work, maximum response spectral accelerations & displacements of supporting structures, equipment and for both equipment placed on support structures are evaluated with respect to the zone factors. Furthermore, dynamic amplification factor (DAF) of substation support structures and along with its electrical equipment are obtained and effect of different parameters (e.g. support mass, height and stiffness) are discussed along with the recommendations available in International standards.**

***Index terms* - Circuit Breaker, Porcelain Components, Seismic Qualification, Substation Equipment.**

I. INTRODUCTION

The electric power industry cascades at three levels, in the chain between power supply and power generation. Considerable damage to the power systems is occurred due to occurrence of even an elementary fault in substation equipment may disrupt power supply. Besides collateral losses, direct losses could be humongous besides loss of precious human life. The experience of past earthquakes shows that damages of the Electrical network installation are very extensive in length and area but they are infrequent. Power transmission and sub transmission substations must considered as the most vulnerable and also the most risky nodes of power network experienced at the time of earthquakes . The higher number of consumers of substation, higher the voltage of substation, then the higher the consequents and risk of malfunction of substation hence seismic vulnerability of equipment increases with substations voltage due to the fact that higher voltage in substation leads to higher isolation distances and then higher height of substations equipment. Higher performances must be expected from higher voltage substation structures. Unlikely to performance objectives of general structures that are concentrated essentially on the structures and nonstructural performance features, performance objectives of substations structures are oriented toward protection of equipment rather than protection of structures. According to these objectives, the structures supporting equipment may be scarified to prevent the equipment to be damaged, under seismic effects.

About the assessment of equipment seismic vulnerability, the injury studies and similar structures during past earthquakes will always be checked, as a starting point perfectly reasonable and logical is desired. Equipment such as current transformer, power transformer, and the circuit breaker, is fixed components and critical component of every single process. The failure rate of theses equipment have a direct connection with operating voltage, and Failure patterns each of them is nearly equal. The effect of the earthquake occurred because of high vulnerability of substation equipment such as use of brittle materials in the core and critical part of equipment (including ceramic materials) inadequate lateral strength and stiffness. Low levels of equipment damping, interactions between adjacent equipment, interactions with the internal components of equipment, excessive equipment load, Inadequate and irregular distribution of load on height, inappropriate installation and maintenance [1][2].

Experiences from past earthquake records showed that large magnitude earthquakes could cause severe damage to substations and result in major service disruption of a power system. High-voltage substation components that have been designed without full consideration of the site seismicity and/or designed before the introduction of modern seismic design codes are the most vulnerable. The commonly observed failure modes could be listed as failures in transformer oil leakage from bushings and Circuit breaker etc. Given diverse classes of assets exposed to seismic hazard, consistency in the process of risk assessment and management becomes a challenging task. A key component of a substation is the circuit breaker which is one of the single largest capital investments (60% of the total investment). Hence, replacing a damaged circuit breaker with a new one or keeping a spare circuit breaker in a substation is expensive.

This research uses seismic vulnerability and risk in an alternative way as the definition of the vulnerability follows the same logic as that of risk. Risk is related to future events (i.e., a seismic event) and their consequences (i.e., failure of substation components), and vulnerability is related to the combination of consequences (i.e., failure of substation components) and associated uncertainty (i.e., uncertainty of the consequences). Risk assessments are crucial as they reduce the risks of unwanted events, which could be very costly both physically and financially. It is essential for Governments and decision makers to evaluate the seismic risk of substations. It directly contributes to the improvement of safety and security in a power system against seismic hazard of varying magnitudes.

II. BACKGROUND

A. Seismic Qualification Process

The IEEE 693 standard, "Recommended Practice for Seismic Design of Substations," would be more descriptive as the "Seismic Qualification of High Voltage Power Equipment" which is the primary content and purpose of the document. The document focuses on the high voltage power equipment such as the breakers, transformers, disconnect switches, instrument transformers, reactors, circuit switchers and arresters.

The large high voltage equipment has been the most problematic in seismic events and is the most difficult to replace when damaged. The standard is not so much a guide on how to design the equipment to resist the earthquake but instead defines the qualification process for seismic test or analysis to insure they survive a seismic event and maintain function. The standard depends more on shake table tests than analysis to most reliably insure that a piece of equipment will have acceptable seismic withstand capability [1].

- The direct way to get started with applying IEEE 693 is to go first to figure 1 in the standard, "Using this recommended practice," for a flow chart or quick overview of the document.

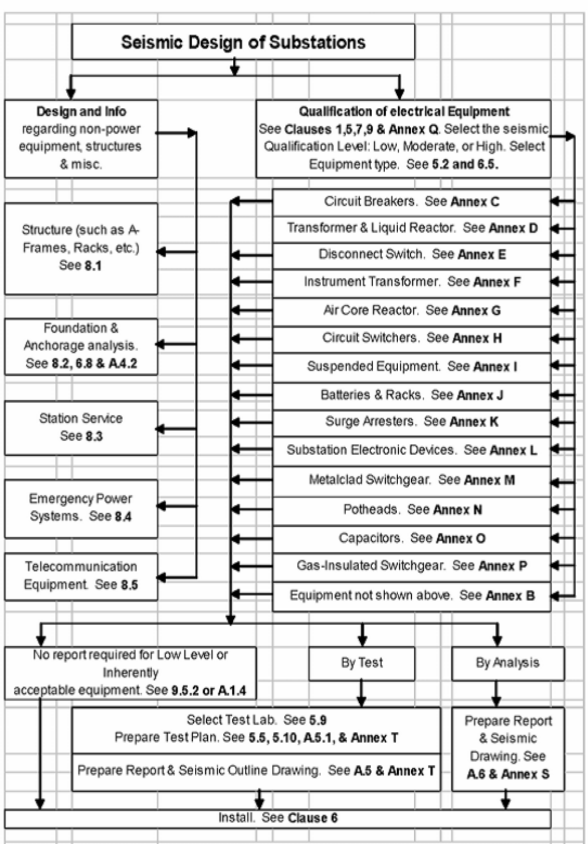


Fig.1 Seismic Qualification Process

- Follow the right branch of the flow chart to find the first step in the process which is to select the seismic qualification level of low, moderate or high. The 2007 version of the standard has qualification levels in Clause 8. You will likely already know which seismic qualification level applies to region. Generally, the high level is required out west and the moderate level applies to active seismic zones in the eastern and central states.
- Move down to the next box to find the Annex for your specific equipment type. The qualifications procedure for your equipment is given according to the voltage rating.

B. Seismic Qualification Levels

Earthquakes events are generally defined by intensity and magnitude. Intensity, such as the Modified Mercalli scale is used to give a subjective description of the earthquake's affect. The Magnitude scale gives a quantitative measure of seismic events based on the amplitude of motion recorded by a seismograph. For design and test purposes we need a more specific definition of the seismic event which can be related to the dynamic acceleration that the ground applies to our equipment.

The highest intensity and magnitude seismic events have peak ground accelerations over 0.5g and some may reach 1g. These accelerations can be applied horizontally as well as vertically to the equipment and may cause even higher dynamic response accelerations in the equipment. The problem arises because high voltage equipment may have resonant or natural frequencies close to the frequency of the seismic waves traveling through the ground during an earthquake. Repeated cycles of the resonant frequency can cause the equipment accelerations to build up to 2 or 3 g. effectively this means that up to three times the weight maybe applied horizontally to center of mass of the equipment or to parts of the equipment. For tall, heavy high voltage equipment, this may cause failure of the foundations, supporting structures or high voltage insulators. A careful study of stresses along the load path from the foundation to the top of the equipment is needed to insure the equipment can resist high seismic accelerations.

The most important tool that we have for seismic design and qualification is the response spectrum. The response spectrum is a graph of the response acceleration of single degree of freedom oscillators, all with the same damping, to the same ground acceleration. For the high seismic qualification level, which has a peak input ground acceleration of 0.5g, the required response spectrum (RRS) for is given in Fig 2 [3].

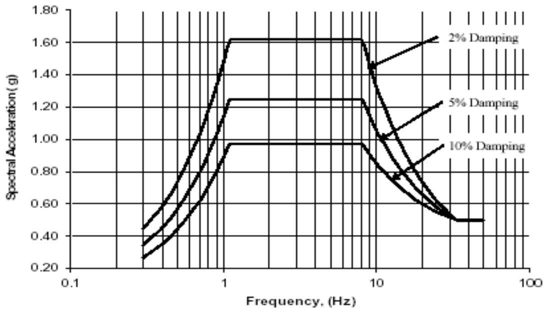


Fig.2 High Required Response Spectrum, 0.5g

The response spectrum is the theoretical response of the equipment and its components which have the resonant frequencies and damping given in the curve. In dynamic analysis, the response spectrum can be used to calculate the response accelerations of equipment. In testing, the shake table acceleration (not the equipment response acceleration) is converted into a test response spectrum (TRS) which can be compared to the RRS to ensure that an acceptable magnitude and frequency content of the input motion was applied.

The Fig 2, RRS, has a broadband (1 to 8 Hz) response of 1.6g (at 2% damping), to the 0.5g peak ground acceleration, due to the amplification from multiple ground oscillations which can occur within this frequency range. The broadband RRS is intended to cover a wide range of earthquakes rather than just to represent a single recorded event for a major earthquake. If the equipment has no resonant frequencies below 33 Hz, then it is effectively a rigid body without increased response acceleration, and experiences only 0.5g (the zero period acceleration).

The standard has simplified the qualification process by condensing the requirements into three levels. The first level is basically for very low seismic zones and has no specific analysis or test requirements. The other two have very detailed analysis and test requirements to meet the qualification level.
The three seismic qualification levels are:

- Low - 0.1g or less. This value roughly corresponds to the 0.2 G static horizontal seismic load in ANSI C37.09 for design and test of high voltage insulators and bushings.
- Moderate - 0.25g. This value has generally been applied to lower acceleration and the less active seismic zones of the eastern and central US. The moderate required response spectrum is 50% of the RRS given in Figure 2.
- High – 0.5g. This level has been generally applied to the very active and high seismic areas of the west coast.

The 33kV circuit breaker with steel supporting structure considered in this study was also a typical model as per the specification of Power utility. This equipment was an outdoor gas circuit breaker. Earthquakes are caused by sudden rupture of a geologic fault. Shock waves radiate from the fault fracture zone & arrive at the earth’s surface as a complex multifrequency vibratory ground motion having both horizontal & vibration components. The relative displacement, forces may be given to that design aspect so that the level of forces is minimized. However, provisions should also be taken in equipment design to take such forces into account.

The highest intensity and magnitude seismic events have peak ground accelerations over 0.5g and some may reach 1g. These accelerations can be applied horizontally as well as vertically to the equipment and may cause even higher dynamic response accelerations in the equipment. The problem arises because high voltage equipment may have resonant or natural frequencies close to the frequency of the seismic waves traveling through the ground during an earthquake. Repeated cycles of the resonant frequency can cause the equipment accelerations to build up to 2 or 3 g. effectively this means that up to three times the weight maybe applied horizontally to center of mass of the equipment or to parts of the equipment. For tall, heavy high voltage equipment, this may cause failure of the foundations, supporting structures or high voltage insulators. A careful study of stresses along the load path from the foundation to the top of the equipment is needed to insure the equipment can resist high seismic accelerations.

III. Architectural Design

A. 33kV GCB Design

Design of 33kV GCB for seismic evaluation in power substation is shown in fig.3 and dimensions are shown in table I. Table II and III contains seismic qualification details and wind details respectively.

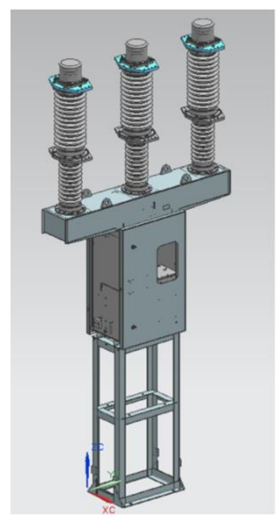


Fig.3 33kV GCB

TABLE I
33kV GCB Details

33 kV GCB Details		
No	Particulars	Value
1	Rated current	40 kA
2	Dynamic break current (Peak)	100 kA
3	Phase spacing	750 mm
4	Interrupter length till support	650 mm
5	Total length (support porcelain + interrupter porcelain)	1200 mm
6	Total length (interrupter porcelain)	650 mm

TABLE II
Seismic qualification details

Seismic Qualification Details		
No	Particulars	Value
1	Maximum seismic level (PGA/ZPA)	0.5g
2	Damping ratio	0.02 (assumption)
3	Spectral acceleration (Peak of RRS)	1.94g
4	Static coefficient	1.0 (as per IEEE 693 - 2005)
5	Spectral acceleration (Horizontal)	1.94g
6	Spectral acceleration (Vertical)	1.55g

TABLE III
WIND DETAILS

Wind Details		
No	Particulars	Value
1	Wind velocity	75 km/hr (assumption)
2	Air density	1.28 kg/m^3
3	Wind pressure	277.78 N/m^2
4	Drag factor	1.0 (for cylinder, as per IEC 61463)
5	Projected area (support porcelain)	0.22 m^2
6	Projected area (interrupter porcelain)	0.16 m^2

B. Design Calculation

Seismic analytical calculation on 33 kV GCB is performed as per IEEE 693 with Maximum seismic level of 0.5g.

1) For section modulus and area of cross section:

Section Module $Z = \frac{\pi}{32}\left(\frac{d_0^4 - d_i^4}{d_0}\right)$

Where d_0 is outer diameter and d_i is inner diameter

Area of cross section $A = \frac{\pi}{4}(d_0^4 - d_i^4)$

2) For spectral acceleration (peak of RRS)

In this case, required response spectrum (RRS) is assumed to be linearly extrapolated from available RRS at high seismic qualification level of IEEE 693 - 2005. The spectral acceleration in horizontal direction is assumed to be 100% of the calculated spectral acceleration while the spectral acceleration in vertical direction is assumed to be 80% of the calculated spectral acceleration [1].

The equation of line in RRS of 0.5g at peak level is given by:

$S_a = 1.5\beta$

$\beta = (3.21 - 0.68\ln(d))/2.1156$

Where d is percent damping (2,5,10etc) and d≤20%

$\beta = 1.2945$ for 2% damping

$S_a = 1.94g$

3) For wind pressure and projected area

Wind Pressure $= \rho.\frac{v^2}{2}$

Where ρ is air density and v is wind velocity

Projected Area$= \frac{(d_s + d_0)}{2}.l$

Where d_s is shed diameter and l is total length

4) For seismic force and bending moment

$F_h = (mS_{ah}k)$, $\quad F_v = (mS_{av}k) + (mg)$

$$M_s = \frac{F_h \times l}{2}$$

m = Total Mass

S_{ah} = Spectral acceleration (horizontal)

S_{av} = Spectral acceleration (vertical)

g = Acceleration due to gravity ≈ 10m/s^2

k= Static coefficient (1.0 as pe IEEE 693-2005)

M_s = Bending moment due to horizontal seismic force

l = Total length

The seismic force in the horizontal direction is considered as bending force while the seismic force in vertical direction is considered as compressive force. The seismic force in horizontal direction is considered for calculating bending moment.

5) For short circuit force and bending moment

$$F_{SC} = \frac{(0.866 \times \mu_0 \times I^2 \times L)}{(2 \times \pi \times d)}$$

$M_{SC} = F_{SC} \times l$

μ_0 = Permeability of free space = $4\times\pi\times10^{-7}\times NA^{-2}$

I = Dynamic break current (peak) = 2.5×Rated current

L = Interrupter length till support

d = Phase spacing

M_{SC} = Bending moment due to short circuit force

6) For wind force and bending moment

F_w=Wind pressure × Projected area

M_w=F_W×l

M_w = Bending moment due to wind force

IV. SEISMIC QUALIFICATION OF 33 KV GCB

Circuit Breaker is one of the most important units in the electrical power system. The protection, stability and continuity of the system depend on the circuit breaker's ability to switch line, load and existing currents and to interrupt fault currents. The SF6 gas circuit breaker assures the high level of performance required for the reliable operation of the electrical system by making full use of the exceptionally good electrical insulating characteristics and excellent are quenching properties of sulphur hexafluoride (SF6) gas. The reliability of the system is further increased by the use of a SF6 gas insulating system and a single pressure dual flow SF6 gas puffer interrupter which reduces the number of moving cylinder and auxiliary system in the circuit breaker. The pressure required to blast the SF6 gas against the arc and interrupt the current is generated by the compression of the gas between the moving cylinder and the stationary position of the interrupter during the opening operation.

A. Finite Element Analysis

Model of equipment is designed in Unigraphics (NX-10) based on all data which is required for FEM analysis. Functioning behavior of porcelain components used in circuit breaker with a supporting structure under damped condition identified. Results will be obtained using finite element analysis. Seismic qualification of the 33kV Circuit breaker by analysis will be carried out using Finite element analysis software ANSYS 12.1.

1)Structural modifications

- The design of support structure is modified where thickness and cross section of the main legs are changed from 65 x 65 x 6 to 75 x 75 x 8.
- The row of horizontal bracings is increased from 1 to 2.
- Additional support angles are added between the main legs and the horizontal bracings.

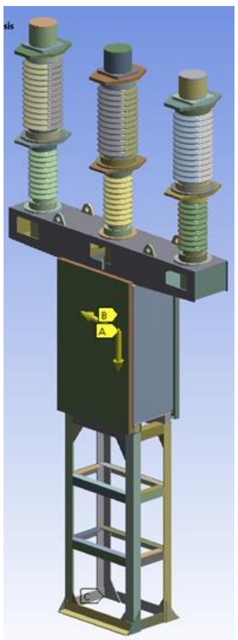


Fig.4Isomatric View of FEM Based GCB

- The 'L' profile between the support structure and the housing is changed to 'C' profile keeping cross section and thickness same. The support plate (gussets) inside this profile are increased from 2 to 4. The additional 2 plates are placed such that the outer face of these plates align with the outer wall of the housing. The thickness is 12 mm which is same as the existing plates.

The 2 angle ribs are added at both sides from inside of the housing. They are aligned with the back face of the 'C' profile and their thickness is kept as 6 mm.

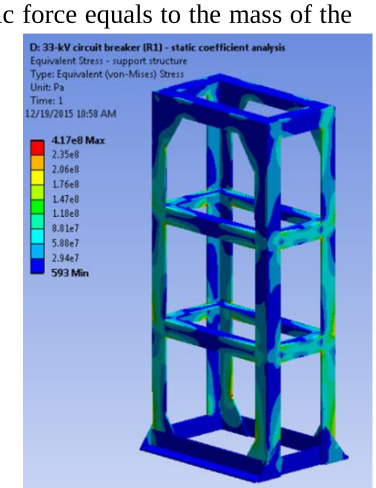
2)Loading & boundary conditions

A static structural stress analysis is done in 1^{st} stage under the effect of standard earth gravity. In this case, base of the support structure is fixed in all directions for translations and rotations. The results of this analysis are linked to modal analysis. Pre-stressed modal analysis is done in 2^{nd} stage under same boundary conditions to calculate natural frequency (resonance).

It is to be noted that sufficient modes should be included to ensure an adequate representation of the equipment's dynamic response. The acceptance criteria for establishing sufficiency in a particular direction should be that the cumulative participating mass of the modes considered should be at least 90% of the sum of effective masses of all modes (Ref: IEEE Std 693-2005). In this case, 10 modes have been extracted in the frequency range of 0 Hz to 35 Hz. The calculated mass participation in both horizontal directions (*x*&*y*) is nearly 95%.

In 3^{rd} stage, the model is analyzed using response spectrum analysis where results from modal analysis have been used. The model is simulated under following inputs:

- Constant damping ratio (Global damping) of 0.02 (2%) is used for all modes.
- The base excitations are given in the form of response spectrum. RS accelerations are defined using required response spectrum (RRS) for 2% damping and for zero period acceleration (ZPA) value of 0.5g as per IEEE Std 693-2005. In this case, the available RRS of 0.25g is extrapolated in order to get RRS at 0.5g. For each horizontal direction, the RS acceleration is defined using RRS with scale factor as 1.0 while for vertical direction, the RS acceleration is defined using same RRS with scale factor as 0.8.
- For each component, a static force equals to the mass of the component times the percentage of mass missing times the ZPA is applied. The missing mass ZPA is defined as 3 m/s^2.
  The total response in each direction is determined by applying the complete quadratic combination (CQC) technique to all modal response components acting in that direction.



3)Result and observations

The maximum deformation at top is reduced nearly by 40% due to modification in the support structure. This shows that this change is worked positively.Due to reduction in the deformation the normal stresses in the interrupter and in the support porcelains reduce further which gives more safety margin.The stress levels on the support structure are significantly reduced and there are hardly any locations where the stresses are beyond yield limit of the material. The maximum equivalent stress is reduced from 730 MPa to 417 MPa.

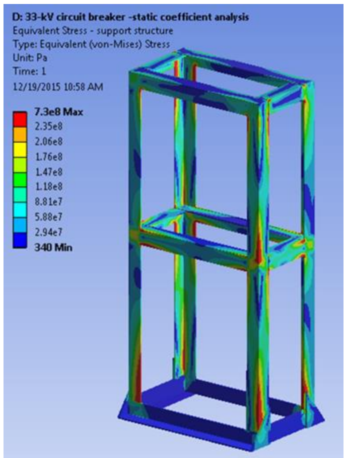


Fig.5 Support Structure

Similarly the stress concentration on top of the base frame becomes less and also the magnitude of the maximum equivalent stress on the base frame came down nearly by 50%. There are very few stresses which are beyond yield limit of the material. But considering their magnitude and the area of concentration, they do not look concerning at all.The major difference is seen on the support structure and at the base of the housing which had shown high stress concentration areas.The overall stress levels are within yield limit or are superficial and local.

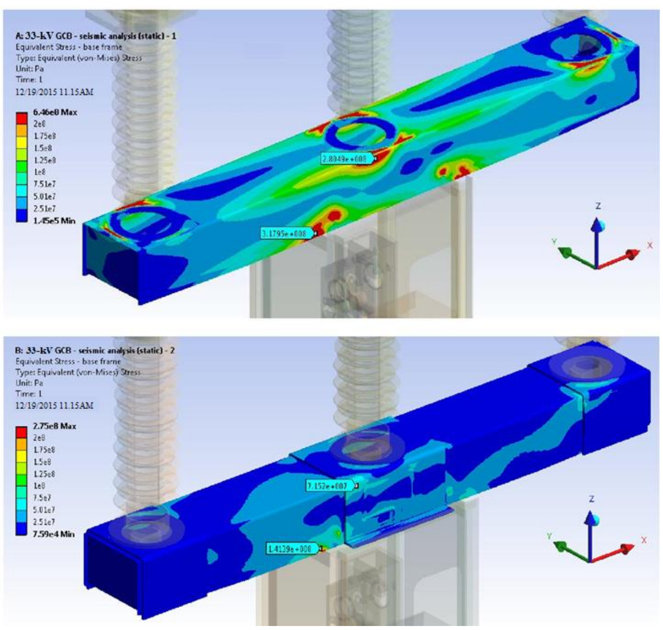


Fig.6 Base Frame Profile

The high stress concentration near base of the housing is also reduced and the stress results near connection between the base profile and the housing are substantially improved. This has mainly happened due to modification in the base profile and the additional reinforcements provided at this location. The stresses on the housing and on the profile are within yield limit of the material.

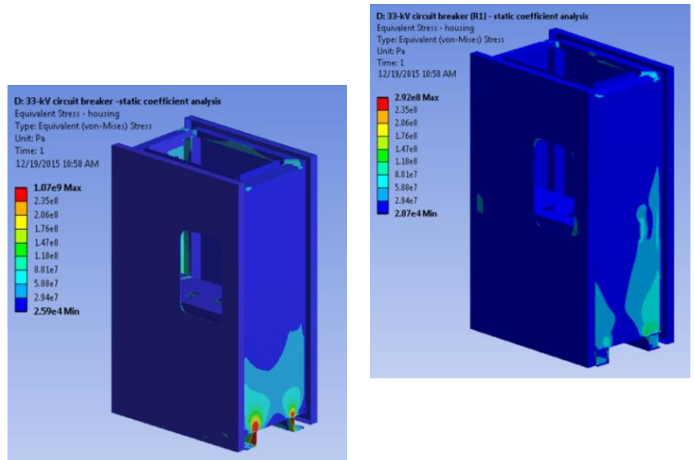


Fig.7 Housing

Considering all above results, it can be seen that there are no concerning or critical areas remain on the equipment. The equipment and the support structure are looking completely safe under given seismic loading.

V. Type Testing of Product

Type testing is carried out in IIT Chennai for qualification level of 0.5g. subjecting the specimen to a simulated seismic excitation independently along the three orthogonal axis, of magnitude 0.5g along two horizontal and one vertical directions with a view to verify the mechanical capability of the body frame, insulators etc. to withstand seismic forces. The frequency range is frame 1.67-33.33 Hz (100-2000rpm) in steps of 1.67 Hz (100 rpm) and at each frequency. Excitation is maintained for 30 sec. strains are also to be measured [4] [5].

A. Test setup

The specimen was mounted vertically on a rigid frame made of steel channel fabrication and the entire frame with the specimen was constrained to vibrate either in a vertical plane or in a horizontal plane according to the requirements by means of a reaction type of exciter. A double mass unbalance exciter rigidly mounted on the framework provided the excitation to the base of specimen. In the case of vertical vibration, the frame was made to rest on elastic supports namely helical springs while for the horizontal vibration test the frame was made to rest on rollers instead.

Three acceleration pickups (seismic accelerometers) were mounted in the direction of excitation, one at the base of the support structure, one in middle (near the base of the insulator) and the other at the top of the specimen to sense the corresponding acceleration levels (Fig. 8). This was done for the longitudinal vibration mode and the transverse (bending) vibration modes of the specimen. Strain measurements were carried out during horizontal modes of excitation by pasting strain gauges at the porcelain base.

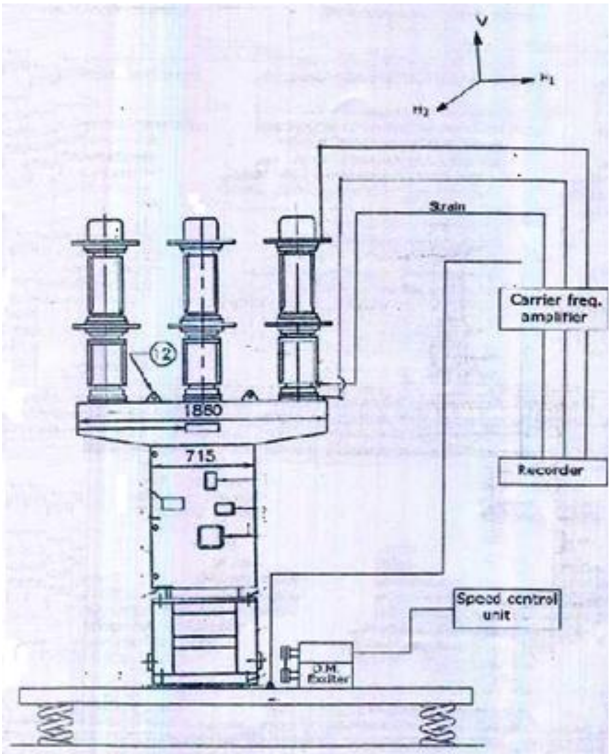


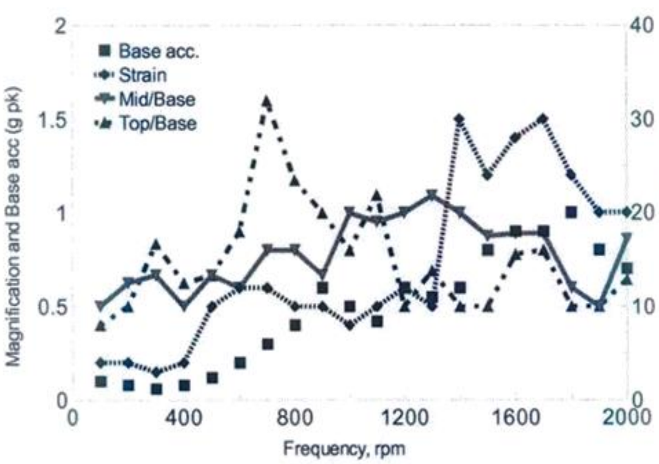
Fig.8 Schematic of the test setup

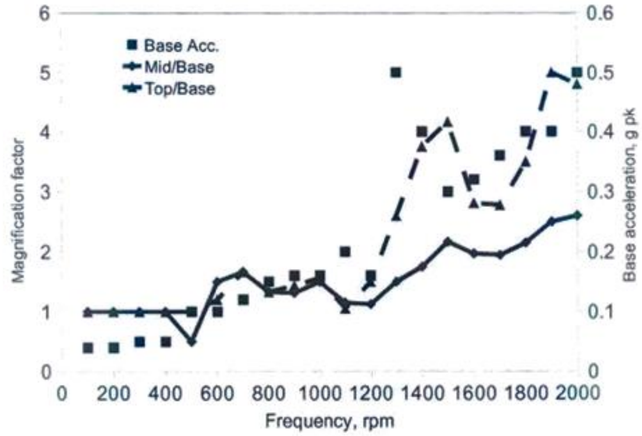
B.Test Procedure

The frequency of vibration of the specimen was varied from 1.67 to 33.33 Hz (100-2000 rpm) and the accelerometer output was monitored and recorded for the three directions. A block diagram (Fig.8) indicates schematically the instrumentation setup. The excitation corresponding to 0.5g pk for the horizontal direction as well as vertical direction was maintained for 30 seconds after which the specimen was checked for any visible damage. The curves of magnification factor vs. frequency of excitation were plotted (Fig 9-11). Base acceleration is plotted for all cases.

C.Results

After the seismic tests the specimen was checked for any visible damage and none was found. Figure 9-11 give the base acceleration levels and magnification factor vs. frequency of excitation. From these forced response curve the natural frequency of vibration can be arrived at. The maximum stress value of 128kgf/cm^{2}occurs in the horizontal direction H_2 at 800cpm. These are within acceptable limits. It





is assumed that the Young's Modulus of porcelain is 0.64×10^6kgf/cm^{2}and the stress level has been linearly extrapolated to 0.5g base excitation level.

Fig.9 Vertical Direction Response

Fig.10 Horizontal H_1 Direction Response

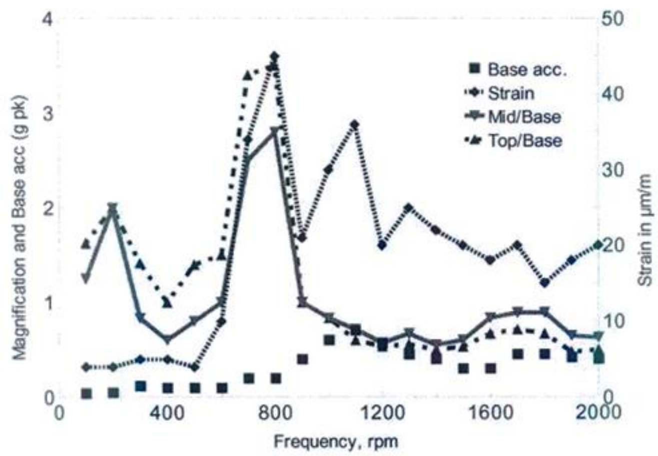


Fig.11 Horizontal H_2 Direction Response

VI. Conclusion

Gas circuit breaker (GCB) is widely used in power substation. Based on the observed failure from the past earthquakes,higher seismic evaluation procedure was studied. It can be concluded that 33 kV gas circuit breaker with the revised design of support structure, housing and the base frame is safe at the seismic qualification level of 0.5gas per IEEE Std 693-2005 using static coefficient analysis method and type testing.

This research can also be extended for higher kV gas circuit breaker as well as for higher seismic qualification level.

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