Improving the Performance of Porcelain Insulators Under Seismic Conditions

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PPC Insulators

Abstract

This paper's objective is to explain the forces from seismic activity with relationship to porcelain insulators and how insulators can be optimized. Resonant frequencies can cause immense dynamic forces. Porcelains weight and brittle nature make it susceptible to destructive harmonic frequencies. With good design practice, advanced materials and modern manufacturing methods, porcelain insulators can be a dependable form of insulation.

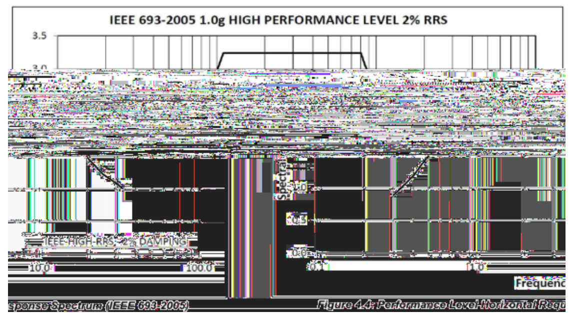
Material characteristics play a major role in equipment design under such dynamic forces. While steel and aluminum are ductile and have predictable strength, porcelain is non ductile and the material strength can vary greatly. Insulator performance can be enhanced by maximizing strength and reducing weight.

1. Introduction

Porcelain insulators have been a crucial part of the energy system for over 100 years. Porcelain's rigid nature maintains minimal flex, assuring alignment of the components in substation equipment. In the last 25 years, great advancements in the understanding of Seismic events have been gained. Insulators are just one component of a complex array making up a device in a substation. The entire device will need evaluation. In many cases, insulators will be mounted on concrete or steel structures and support the actual equipment. Bushings on the other hand are found at the top of the equipment. The response of the equipment and the components to input frequencies is dependent on many factors.

2. Forces

When the natural frequency of a piece of equipment closely matches the input frequency, resonance occurs, amplifying the resulting dynamic motion and acceleration response. The Required Response Spectrum, RRS, simulates amplitudes, frequencies and energy in typical seismic events. Equipment having 1.1 to 8 Hz natural frequencies, are covered most closely in the RRS.



The typical High voltage equipment has several characteristics that make them more responsive to seismic inputs. By being tall and heavy, they exhibit lower levels of Natural Frequency normally found in seismic events. When two items vibrate at the same natural frequency, increased motion is seen. This motion induces great cantilever loads.

Understanding the forces subjected to an insulator in comparison of the strengths and weakness of ceramic material is an important first step. The insulator mechanical ratings are a) Cantilever/Bending moments, b) Torsion, c) Tension and d) Compression. Cantilever loads determine the core diameter and thus weight.

$$D = 2.\sqrt[3]{\frac{4.F.l}{\pi.\delta_{oh}}}$$

Where: D ς core diameter

F ς Required strength (min. breakage load)

l ς Length

δ_{oh} – Specific strength of porcelain

Ceramic materials have very high Compression ratings and low Tension ratings. Bending moments induce Compression and Tension stress. Tensile stress is amplified by the lever action of the height of the insulator. See Figure 1.

Figure 1

Bending Moments increase with greater force and/or taller insulators. See Figure 2. In the case of dynamic motion, the force is based on 1) the mass of the insulator and mass mounted above the insulator and 2) the acceleration due to the seismic event.

Figure 2

Though trying to make design changes to insure the equipments Natural frequency is outside the seismic events frequency, it is often impossible.

In calculating the force/energy that goes into to the equipment during a seismic event, weight is a key factor. The challenge is optimize the design to maximize the Strength to weight ratio.

3. Weight Reduction

There are several methods to reducing weight of a given strength insulator. The insulator should be designed for the needs. Maximum section lengths can reduce weight on multi-stack insulators. Manufactures have material choices that have higher strength. Maintaining tight quality assurance standards will enhance the materials overall strength.

3.1 Optimizing the Design.

The design of the insulator needs to account for the application under seismic conditions. Often insulators used in substations are based on standard designs. These designs are for general purpose and are designed to work in different applications. An example is an insulator with Uniform cylindrical core. They can be applied Upright, Under hung but are considerably more heavy. Tapered insulators are often used in HV applications due to the size; determining the taper is very important.

When a pc of equipment is first considered for seismic conditions, the entire assembled and mounting structure needs to be evaluated with software. Finite Element Analyze, FEA, will identify high stress areas per a given configuration. At the same time, low stress zones will be identified. The equipment designer/consultant should work closely with the insulator manufacturer to insure all zones have equal safety margin. It can take several iterations to fully identify all of the optimum increases and decreases in strength at given locations though out the insulator. As lower stress areas are identified and remedied, weight is being reduced in that area. As a result, top section weight reductions can then reduce strength needs in lower sections. This all leads to less mass, less motion caused by the mass and less overall stress. The cost of shaker table testing can exceed $150,000 USD for large substation equipment. A thorough evaluation by a competent seismic specialist can often result in significant savings by avoiding the need to re-test.

The location of an insulator in the equipment is fundamentally important. In many cases an insulator is used to support a heavy piece of equipment. If the equipment is compact with the mass near the top, very little bending stress will be on the top fitting. The analysis will show an extreme tapered insulator will be appropriate. See figure 3

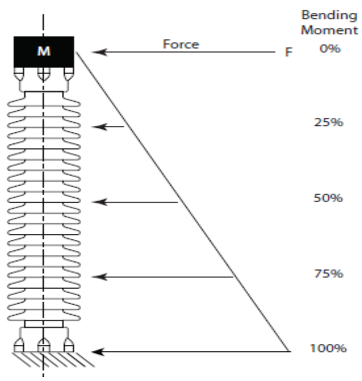


Figure 3

If the equipment has a high center of gravity with the mass well above the insulator, a much greater bending stress will be subjected on the top fitting. A more robust design for the top portion is called for. In figure 4 the top of the insulator is subjected to 50% of the maximum bending loads.

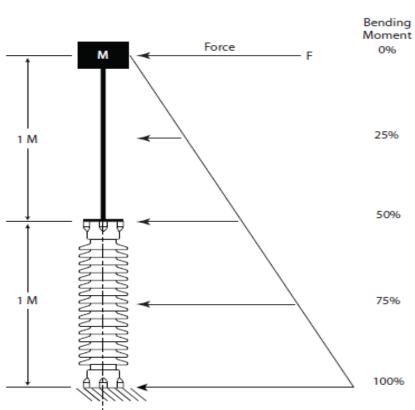


Figure 4

Mass at the top of the insulator, has the greatest bending effect. In the case of an air break switch in the open position with the mast fully extended, high bending moments are found at the top of the insulator. See figure 5

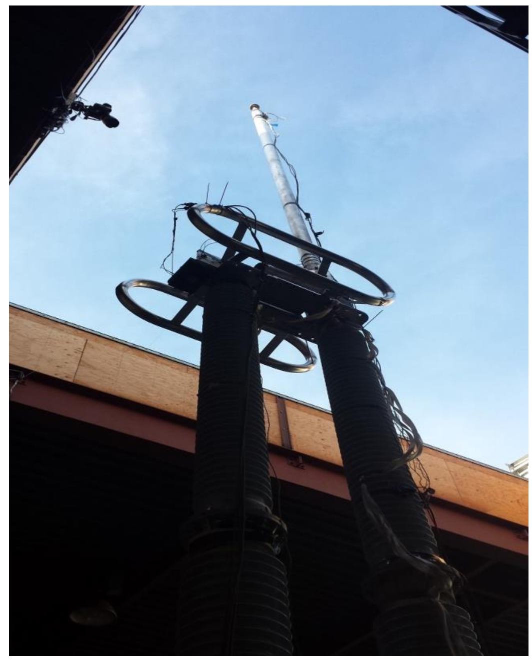


Figure 5, 500 kV SEECO switch, Mast Open

A typical 500 kV air break switch is mounted 4.6m up on a structure. The switch in the open position can be 9.75. From ground level to top of mast can be 14.35 m. Optimizing the needed strength for the insulator top can be a critical material reduction zone, as the weight reduction is at the top on the insulator where the mass is furthest from the bending moment.

Shed weight

The Shed profile is a means to increase the Creepage distance. The sheds contribute weight to an insulator. In the past, sheds have typically been up to 19mm at the core tapering down to 12mm at the tip. With improved material science, the shed size can be reduced resulting in a 20% reduction in shed weight.

3.2 Reduced sections

Insulators are comprised of single or multiple sections bolted together. Insulators are typically single piece construction up to 750 kV BIL. High voltage insulators can be made up of many sections depending on the voltage level. Stress concentrations are found at the joints where the cast iron fittings are cemented onto the porcelain. The diameter of the porcelain at the fitting is increased due to the concentrated stress levels. Reducing the number of sections will reduce high stress locations and the weight of the additional fittings. See Figure 7

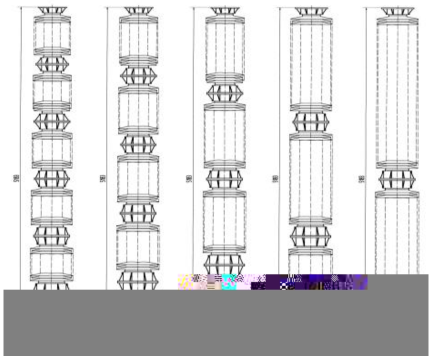


Figure 7

3.3 Material

Porcelain Insulators are technical Ceramics containing a mix of Kaolin, Alumina, Feldspar and Silica (Quartz). IEC 60672-3 refers to three main types C-110, C-120 and C-130; of which the C-110 is called Quartz Porcelain and C-120 and C-130 Alumina Porcelains. C-120 contains 20%-30% Alumina when C-130 normally has alumina content >30% which increases the strength and thus obtains the highest strength to weight ratio.

Further, the strength values seen in Table 1 are minimum values and can be far exceeded. Insulators manufactured with C-130 clay with much higher than minimum levels, can have weight reduced by up to 40%.

Table 1, ICE 60672-3 1984

3.4 Production process.

The Manufacture of clay materials has an inherently wide range of resulting material strengths. This variation can occur within the batch, or vary between batches. Achieving consistent body strength can be challenging if processes are not tightly controlled. Ceramic material strength can have over 35% standard deviation. The larger the deviation, the heavier the design of the insulator must be to insure the Specified Mechanical Load, SML is met. Reducing the Standard Deviation directly reduces weight of any given manufacturer’s design parameters. Cases based on 2 standard deviations; A design of an insulator with a SML of 10kN and has a Std Dev of 3.5kN. Then the design must be such that the average is 17kN. On the other hand, if the Std Dev is 1kN, the design shall be based on an average of 12kN. This results with approximately 40% reduction in insulator weight. See figure 8 and 9

Figure 8, Large Std Dev

Figure 9, Small Std Dev

What are the causes of body strength variation? First, let’s explore how insulators are manufactured. Insulators are manufactured by a process called Wet or plastic methods. Clay recipes are measured and mixed with water to create the base material, called Slip. A Ball mill grinds the slip to insure proper partial size and contains approx 50% water. Slip is then filtered to remove natural contaminants found in clays. These contaminants can be organic to iron. The slip is then pressed into filter cakes at approx 22% water. The filter cakes are chopped and extruded into blocks. Finally cylindrical blanks are extruded. Over a 5-6 week period the blank is turned and dried to less than 1% moisture content.

To have a consistent body strength, all steps leading up to a finished product must be consistent. Particle size, chemical composition, water content of filter cakes, hardness of blanks and drying techniques, all determine predictability of body strength. The multiple drying steps of the wet clay, from the pressing of the filter cakes to the use of dryers preparing the turned insulators for firing, are sensitive steps of manufacturing insulators. The most critical drying step is the drying of the wet turned shape from 18% moisture to less than 1%. This is due to the thin sheds and the thick core needing to dry at the same rate. The thin sheds are far more like to give off water compared to the core. Up to 6 weeks is required to slowly dry an insulator. Many manufactures have proper controls in place, but it requires skilled employees with attention to detail.

Alternative porcelain manufacturing methods have been developed that eliminate the many steps of the drying process. An important feature is a much more consistent process, reducing the wide variation of measured material strength. This method is commonly called Isostatic. The key to Isostatic production is drying the slip to a fine powder, and pressing into a dry cylinder.

The isostatic process has many other inherent advantages. The Isostatic process creates dry cylindrical blanks in a very short period of time. Insulators produced with the Isostatic method have a production time of less than two weeks vs. six weeks or more found with Plastic production. The turning step is performed dry thus eliminating the shrinkage from wet turned profiles to dried/ready for firing state, resulting in tighter tolerances.

The dry pressed blanks have no particular grain orientation found in wet extruded blanks. As the wet body is extruded through the extruder throat, the clay flow can be much slower along the walls due to friction between the clay and the extruder wall. Internal to the blank, shear will occur causing internal stress, which can lead to failures in the kiln and reduce mechanical strength. Depending where in the blank the insulator comes from, these shear areas can end up near the surface. One notable trait is the camber formed as the insulator is dried.

4. Conclusion

Improving the performance of porcelain insulators in seismic conditions is possible through weight reduction methods. Optimizing the design based on actual needs, using high strength materials and consistent manufacturing processes, will ensure optimum designs. PPC has been developing design practices over the last 20 years to optimize insulators for specific challenging applications.

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