STABLE SYSTEMS IN UNSTABLE CONDITIONS: EARTHQUAKE TESTING CONFORM THE IBC

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INTRODUCTION

This paper discusses earthquake load requirements for electric switchgear assemblies and testing methods according to the most recent International Building Code (IBC 2003). Thereupon, the result of seismic tests on a range of Medium Voltage switchgear systems designed and manufactured by company Eaton Holec - formerly Holec- is presented and discussed.

BACKGROUND

In 2004 the integration of Dutch switchgear manufacturer Holec - now Eaton Holec - into the Electric Division of American company Eaton took place. One step in this process was preparation of a range of existing Medium Voltage switchgear systems designed by Holec for new markets, notably in the United States of America and Canada. In those and several other countries worldwide, electrical equipment in essential facilities must be capable to withstand an earthquake event. For such areas Building Codes provide seismic load requirements that must be met by buildings and by electrical equipment forming an integral part of the building.

Six Medium Voltage systems were selected for introduction on the North American continent, where most electrical equipment is designed according to ANSI/IEEE-standards and in addition to that also increasingly to seismic requirements as specified in the Building Codes. The Eaton Holec-systems were designed according to IEC-standards and primarily for European countries where no seismic requirements for switchgear apply. Their design is focussed on compactness, and although mechanical strength is of course an important design factor, the systems were not intently designed to cope with the specific forces that can occur during an earthquake. It was necessary to conduct a seismic test on the systems in order to obtain insight in their capability to withstand seismic loads, with the final aim to obtain a seismic test certificate that clears the way for their introduction on the new markets.

The decision to conduct a seismic test for the first time confronted Eaton Holec with design rules and test procedures in the domain of seismic engineering. An intensive co-operation was started with experienced colleague product specialists from Eaton Cutler-Hammer and a seismic specialist from Westinghouse Electric Company, both in the United States of America. This provided necessary insight in the basics of seismic behaviour and seismic load requirements for the equipment, the effect these loads might have on the critical weaker spots in the construction of the objects, and possible measures that could be taken to maximize the chance of success for the test program.

SEISMIC TERMINOLOGY AND EARTHQUAKE ENGINEERING PRINCIPLES

The general information presented here about seismic phenomena and testing methods is derived from [1], a paper by the co-authors published in the United States of America in 2001 that treats these topics extensively.

EARTHQUAKES AND THEIR MAGNITUDES

Earthquakes happen all over the world, causing considerable loss of life and widespread damage to structures, buildings and equipment. Damage estimates can go into the billions of euros.

Most news reports refer to the magnitude of an earthquake in terms of the Richter scale. The Richter Magnitude **M** can be defined as:

$$M = 3 + \log_{10}(A)$$

Where: A is equal to the trace amplitude (in mm) of a Wood-Anderson Seismograph having a magnification of 2800, natural period of 0.8 seconds, and a damping coefficient of 80 %, located on firm ground and at a distance of 100 km from the earthquake epicentre.

Thus the magnitude of an earthquake in terms of Richter scale **M** could be found as follows:

1. Measure the amplitude of the Wood-Anderson Seismograph in mm at a location 100 km from the

earthquake's epicentre.

2. Take common logarithm of the amplitude.
3. Add 3 to it.

Note that a change of one unit in the Richter scale corresponds with a change of 10 in the amplitude of the displacement of the earthquake.

Table 1 relates the earthquake magnitude to the equivalent energy released during the quake and to other relevant parameters. Although the magnitude of the earthquake is a direct measure of its severity, there are a number of difficulties in using it for equipment design. A specific problem is the fact that maximum displacement alone does not provide necessary information about the frequency and energy content of the motion. Equipment is most susceptible to damage when the earthquake motion contains the equipment's own natural frequencies, and of course when the motion involves high accelerations, that induce high reaction forces in the equipment.

In addition to the magnitude of the earthquake, which relates the total amount of energy released, also intensity is used as a parameter to measure the local destructiveness of earthquakes. One earthquake will have a single magnitude but different intensities, depending on the location of the observer. Most intensity scales are based on personal and subjective observations, including "scary feeling", ability or inability to remain standing. Although partly quantitative and based on actual damage effects, the Modified Mercalli scale that describes earthquakes intensities in these terms, is too subjective to use for seismic equipment certification.

When available, the most accurate descriptions of real earthquake motions are so-called time history records, graphs showing earthquake motion (in terms of displacement, velocity or acceleration) as a function of time. However, while being very accurate in recording the motion of a particular earthquake, time history records are difficult to use as a basis for generalizations about other earthquakes because displacements, velocities and accelerations of separate earthquakes show a great variety.

BEHAVIOUR OF ELECTRICAL EQUIPMENT UNDER SEISMIC LOADS

Two factors are especially critical regarding the behaviour of equipment under seismic loads:

1. The relationship between frequencies present in the earthquake motion and the natural frequencies of the equipment.
2. Inherent equipment damping.

Table 1

Relationship between earthquake magnitude and other parameters

Earthquake Magnitude M (Richter Scale)	Maximum Ground Acceleration (%g)	Duration of Strong Motion (seconds)	Length Of Fault Slip (miles)	Equivalent Energy (tons of TNT)
8.5	50	37	530	70 Million
8	50	34	190	13 Million
7.5	45	30	70	2.2 Million
7	37	24	25	400,000
6.5	29	18	9	70,000
6	22	12	5	13,000
5.5	15	6	3	2,200
5	9	2	2	400

Frequency is critically important in establishing seismic equipment certification because each object will have its own natural frequencies, typically in the 4 to 6 Hz range. If an earthquake motion contains those frequencies to a high degree the equipment will respond strong to that motion, tending to resonate with it and thereby amplifying its own motion. If the earthquake motion would consist of much higher frequencies than the natural frequency of the equipment, the construction would tend to sit still or attenuate the earthquake motion. At lower frequencies than the natural frequencies of the equipment, the construction would rigidly follow the motion, neither amplifying nor attenuating it.

The damping properties of the equipment determine the limit to the amplification that the construction will experience at resonance. With no damping, the equipment response amplification at resonance frequency would increase without bound, resulting in damage of the construction. However with a damping coefficient of 12.5 % the equipment response of a linear oscillating system under a continuous sinusoidal harmonic motion will not exceed 4 times the input motion. A typical damping factor for switchgear is 5%.

THE ACCELERATION RESPONSE SPECTRUM METHOD

Resonance curves based on sinusoidal input motions are helpful in understanding equipment response to earthquakes but do not represent actual earthquake motions that consist of a number of different frequencies. Therefore seismic engineers have developed a method of comparing earthquake response motions as a function of frequency, rather than time. This is called the acceleration response spectrum method, which is based on the theoretically determined spectrum of maximum response accelerations of a linear single-degree freedom oscillator connected to a moving surface over a range of frequencies. The use of this

method for seismic tests can be explained as follows. A piece of equipment is mounted on a test table that simulates an earthquake of a certain magnitude over a range of frequencies. With accelerometers it is possible to measure the response accelerations of that equipment at the various frequencies with which the table and the equipment move. Put together these responses form the so-called Test Response Spectrum (TRS), which can be compared with the theoretically determined maximum response acceleration levels at those frequencies, the so-called Required Response Spectrum (RRS). If the value of the TRS at least equals that of the RRS at a certain frequency, then the equipment has been subjected to at least the required seismic load for that particular frequency, see figure 1.

Figure 1 Equipment certification by the Acceleration Response Spectrum Method

The response level only needs to envelop above the required level for frequencies corresponding with the natural frequencies of the equipment, because resonance would only occur at those frequencies. Furthermore the height of the response spectrum strongly depends on the damping properties of the equipment, because a higher damping capability will result in a lower response acceleration to the motion of the table. For example, a bolted cabinet will in general damp the motion of the shake table to which it is connected much quicker than a welded but otherwise similar cabinet, reducing the time for the seismic response to build up and thus reducing the maximum value of the response spectrum curve. Therefore the equipment must also be subjected to a simple frequency sweep test to identify the lowest natural frequencies and damping factors associated with the equipment. Most earthquakes tend to include low frequencies (1 to 3 Hz) that could produce strong oscillations. It is therefore considered a sign of good engineering practice if equipment has no natural frequencies below 3.2 Hz.

SEISMIC LOAD REQUIREMENTS ACCORDING TO THE INTERNATIONAL BUILDING CODE (IBC)

According to the IBC, the most recent Building Code in the United States of America that has unified the requirements of several older Building Codes used locally, equipment should be able to withstand seismic loads that induce a maximum response acceleration of about 2.4 g (at a damping rate of 5 %). This corresponds with earthquakes of the highest magnitude that could occur in the so-called Seismic Zone 4, areas in the vicinity of major earth cracks, such as the area around Los Angeles.

Equipment is considered acceptable if it withstands a seismic event and performs its function immediately afterwards. Compliance with demands of the IBC is established by a test procedure based on the before mentioned acceleration response spectrum method. Equipment is mounted on a shake table and first subjected to a resonance search in the frequency range of 1 to 35 Hz to establish natural frequencies of the test objects. Then objects are subjected to random seismic input motions simulating an actual earthquake, 30 seconds in duration, in several runs with increasing acceleration forces. In order to maintain structural integrity of the equipment it is critical the design has sufficient damping qualities and shows no natural frequencies below 3.5 Hz that could lead to heavy oscillations.

During test runs electrical continuity of the main breakers is monitored. After each test run normal operating functions of the equipment are checked and hi-pot tests are conducted to establish if no major damage has occurred to the primary and secondary circuits.

TEST RESULTS OF EATON HOLEC MEDIUM VOLTAGE SYSTEMS

In May 2004 the following six Medium Voltage systems of Eaton Holec were tested at the Wyle Laboratories in Huntsville, Alabama, United States of America:

1. **MMS**
2. **SVS/08**
3. **SVS/12**
4. **Xiria**
5. **Magnefix MD4**
6. **Magnefix MF**

Figure 2 shows the test set-up on the shake table of the Wyle lab. The test units were mounted to the bi-axial shake table with their principal axes oriented 45 degrees with the horizontal input. The horizontal input was increased by a factor of square root of 2 above the combined horizontal seismic requirements to account for the vectorial distribution of the horizontal input to the principal directions of the test units. This arrangement insured the test units were subjected to equal and simultaneous test levels in the principal front-to-back and side-to-side directions. In addition the test units were also subjected to

Figure 2 seismic test assemblies of Xiria and MMS on shake table at Wyle lab

Simultaneous vertical input equal to 2/3 of the horizontal inputs, according the IBC-specification.

The tested systems were originally not designed for seismic loads. As precautionary measure the standard construction was analysed and the potentially critical weaker spots were strengthened with additional parts. This resulted for instance in a doubling of the mounting frames of Magnefix MD4 and MF, **figure 3**.

Figure 3 Magnefix MF with double frame on shake table at Wyle lab

The test units were subjected to the following vibration and seismic test runs:

1. Resonance search in the vertical direction.
2. Resonance search in the horizontal direction.
3. Simultaneous random seismic input motions at 50 % of the IBC seismic requirements.
4. Simultaneous random seismic input motions at 100 % of the IBC seismic requirements.

5. A second seismic test run at 100 % of the IBC level, with the added parts on the SVS (additional bolts on lower doors) and Xiria (additional locks on doors) removed.
6. Simultaneous random seismic input motions at 120 % of the IBC seismic requirements. If equipment behaves well at 100 % of the required level, Eaton will test equipment further to establish seismic withstand capability at even higher levels than required at present.

Electrical continuity of the breakers main contacts was monitored using six electrical monitoring channels. The electrical monitors showed that the main contacts of the breakers of all the systems maintained continuity during the entire 30 seconds of all the test runs. Only the breaker in SVS/12 tripped open during the 100% and 120% test runs.

In addition to the electrical monitors, the structural response of the test units was monitored using a total of 20 response accelerometers. The preliminary response data was evaluated and showed no major global structural resonance below 3.2 Hz.

Before and after the seismic testing, the test units were subjected to hi-pot electrical testing. All the tested systems were found acceptable. Only the SVS/12 test unit failed the hi-pot test after the second 100% and 120% seismic test runs.

CONCLUSIONS

In conclusion, the following units are seismically acceptable to the combined IBC and UBC applications:

1. MMS	(UBC Zones 1 to 4 and above)
2. SVS/08	(UBC Zones 1 to 4 and above)
3. SVS/12	(UBC Zones 1 and 2)
4. Xiria	(UBC Zones 1 to 4 and above)
5. Magnefix-MD4	(UBC Zones 1 to 4 and above)
6. Magnefix-MF	(UBC Zones 1 to 4 and above)

Figure 4 shows one of the obtained seismic certificates, this one of Xiria. The graph on the document shows the required response acceleration characteristics of a number of applicable Building Codes, notably the United Building Code Zone 4 requirement (black dotted line), and the International Building Code 2003 (blue dashed line) being even more critical than the Zone 4 requirement of the UBC. The red dash - dotted line represents the test performance of Xiria, one of the systems that passed the test in its standard version, without use of additional strengthening.

Also the certificate mentions the lowest measured resonance frequency of the tested object. For Xiria this is 10 Hz, a relatively high value by the fact that Xiria has a very compact and stiff mechanical construction. The stiffness of Xiria is a direct consequence of its welded

housing. Although welded connections tend to decrease the damping capacity of the construction - which is generally not favourable for seismic circumstances, as explained in this paper - it formed no critical factor for Xiria. The relatively small dimensions of this Ring Main Unit (width x depth x height = 1110 x 600 x 1305 mm) will have contributed to that.

Perhaps needless to say, the members of the American-Dutch team that prepared this seismic test program with some uncertainty about its potentially destructive outcome have taken the final result as a satisfying reward for their work!

Figure 4 Seismic Test Certificate of Xiria

REFERENCES

- [1] Robert G. Towne, David D. Roybal, Mostafa A. Ahmed, 2001, *Earthquake requirements and Cutler-Hammer Distribution & Control Electrical Equipment Seismic Capabilities*, Cutler-Hammer Publication No. SA.125.01.S.E, Pittsburgh, Pennsylvania U.S.A.