3-D BASE CONTROL SYSTEMS FOR SUBSTATION EQUIPMENT

P. Nawrotzki[(1)], D. Siepe[(2)], M. R. Alvarado Iñiguez[(3)]

[(1)] *Managing Director, GERB Schwingungsisolierungen GmbH & Co.KG, peter.nawrotzki@gerb.de*
[(2)] *Project Engineer, GERB Schwingungsisolierungen GmbH & Co.KG, daniel.siepe@gerb.de*
[(3)] *General Manager, GERB Aislamiento de Vibraciones S.A. de C.V., moises.alvarado@gerb.com.mx*

Abstract

Equipment, like air core reactors, switch yard structures, capacitor banks or platforms, in electrical substations frequently consists of sensitive material or a vulnerable assembly. In areas with high seismicity special seismic protection measures are required as electricity is of extreme importance for the operation of lifeline structures as hospitals, emergency centers and power plants. The experience in earthquake protection of machinery and buildings, as discussed in [1], can also be applied to substation equipment. This article illustrates basic principles of 3-dimensional Base Control Systems (BCS). These systems consist of elements with helical steel springs and viscous dampers. Depending on the project specific details spring elements with special stiffness properties, e.g. as described in [2], in combination with an increase of damping are used to reduce the seismic accelerations levels of the supported structures. Practical examples present the high efficiency of the suggested control system for the protection of equipment against seismic impacts in horizontal and vertical direction. Details of the seismic protection of air core reactors, located in a high seismic zone in California, USA are discussed as well. The main mass is placed on a substructure consisting of ceramic footings and stiffening steel cradles. The footings are extremely fragile and in danger of failure during a seismic event. The seismic requirements are related to [3]. For the seismic protection the base cradle is arranged on a BCS leading to a significant improvement of the seismic behavior of the important equipment.

Keywords: seismic protection; passive control; base control system; substations

1. Introduction

A substation is an important part of an electrical generation, transmission and distribution system. Different equipment structures in these substations have to be designed carefully for the load case "seismic". Due to the sensitivity of these systems the collapse of them has to be avoided. The requirements related to earthquake demands are increasing worldwide. Suitable seismic protection systems can be used to protect the equipment and provide adequate safety margins as a possible counter measure.

The present contribution puts emphasis on the reduction of structural responses due to seismic loading. The first section after the introduction covers general seismic protection strategies and the description of the basics of Base Control Systems. As a corresponding example the project about two apartment buildings at Mendoza, Argentina is discussed. Here, the seismic response of a base-controlled building and an identical adjacent building without springs and dampers was measured in 2005. The recorded response is very useful to verify the design and performance of structures fitted with a BCS. The following section focusses then on substation equipment. Details of some practical examples, e.g. seismic protection of an air core reactor and a capacitor bank, present the high efficiency of the suggested elastic support system for the protection of equipment against seismic impact in horizontal and vertical directions.

2. Strategies for Seismic Protection

The main objective of earthquake protection is the modification of the response of a structure due to seismic loading. The mentioned modification could be achieved by different methods as for example by modifying the shape of the fundamental mode, increasing the fundamental period (= reduction of frequency) and increasing the damping. These methods could be applied as a single measure or even as a combination of all three methods.

A structure like a building, machinery with its foundation, or equipment of substations can be dynamically uncoupled from the sub foundation or soil using an elastic support system. Assuming the supported structure as rigid itself the one mass system on top of a three dimensional elastic support system will possess six low natural frequencies and corresponding rigid-body mode shapes. This yields a change of the mode shape, leading to smaller internal deflections of the structure itself compared to a structure with a rigid base.

Having a look at the seismic input the two other strategies become clear. The seismic demands for a project are typically defined by the description of the design response spectrum. Ground motions in horizontal as well as in vertical directions have to be considered. It is strictly recommended not to neglect the vertical excitation as done in many current design codes. Fig. 1 shows the high required seismic input spectra according to [3] for three different damping values.

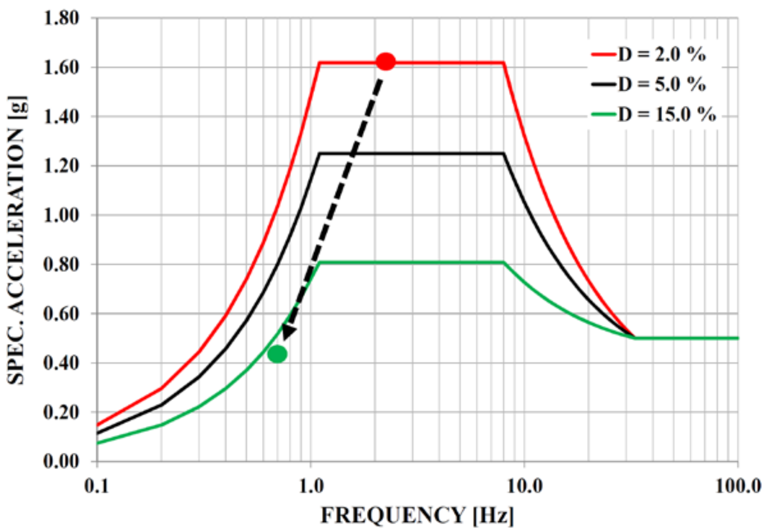

Fig. 1 – Elastic high required response spectrum, 0.5 g

Assuming a rigidly restrained structure with low material damping the spectral accelerations will be found in the frequency range of the highest induced seismic accelerations (plateau area of spectrum) as shown by the red dot in Fig. 1. The efficient reduction of accelerations from the plateau values down to lower levels is possible due to a reduction of the predominant frequency using an elastic support system. In Fig. 1 this strategy is directly combined with the increase of damping. In general, the seismic input spectra are defined for a damping ratio of 5.0 %. The correction factor for a different damping value can be taken from different national and international earthquake standards. The current example uses the corresponding factor according to [3]. Here, the increase of structural damping from 2.0 % to 20.0 % causes a reduction of input accelerations, structural stress, strain and displacement in a range of about 60.0 %. In combination with the reduced frequency the seismic demands could be reduced by more than 70.0 % as shown by the green dot in Fig. 1.

The optimum adjustment of frequencies and corresponding damping ratio by the use of a passive control system could lead to a significant improvement of the seismic behavior of the protected structure. During the layout of the control system the project specific requirements have to be considered. For example, a very low frequency may lead to very low seismic accelerations, but may yield large displacements of the supported structure. Thus, it is important to find an optimum between earthquake protection and boundary conditions. Elements with helical steel springs and viscous dampers are one type of passive control devices that are suitable for the mitigation measures. Fig. 2 presents a typical example of these devices.

Fig. 2 – Spring element (left side) and viscous damper (right side)

The springs are flexible in their axial direction, but they also possess a horizontal flexibility and corresponding load bearing capacity. The mechanical parameters can be described by a linear elastic behavior in all three directions. The viscous damper yields linearly velocity-dependent forces in all three spatial directions. The dynamic behavior of the system can be characterized by the general equation of motion with constant coefficients. It is easily possible to determine the system's behavior by standard procedures in regard to system frequencies, critical damping ratios and seismic effects, due to the linearity of the devices. The arrangement of spring and damper devices leads to a three dimensional seismic protection system.

It is always possible to adjust the parameters of the devices, in a certain range, in regard to the requirements of the project, as the elements vary especially in the bearing capacity, in the horizontal and vertical stiffness properties, in the ratio between horizontal and vertical stiffness and in the damping resistance. Concerning the type of individual spring and damper devices a wide variety is available. During the layout stage of a project the most important structural frequencies of the entire system, the travel in the devices, the structural damping as well as important reactions (e.g. acceleration at the center of gravity of equipment) are optimized. The combination of frequency reduction and increasing structural damping yields efficient seismic protection of the supported structure. Acceleration values and hence internal forces and stresses are significantly reduced. The system is entitled as Base Control System (BCS) to distinguish it from well-known base-isolation systems, where e.g. rubber bearings or friction pendulum systems are used.

A typical example of the successful implementation of a BCS for the seismic protection of a structure is presented in this paragraph. The Mendoza Campus of the Technical National University of Argentina commissioned in 2004 the construction of a set of buildings with the main purpose of providing housing facilities to students. The Mendoza province is located in western part of Argentina, in the most seismically active region of that country. Two of the dormitory buildings constructed in the Mendoza Campus were identically designed and built. The only difference is that one of the buildings was installed on a Base Control System, whereas the other sister building has a rigid traditional foundation. The two buildings were instrumented with seismic accelerometers. Fig. 3 shows a view of both structures.

Fig. 3 – Building with rigid base (right side) and supported on a BCS (left side)

The buildings consist of three floors of reinforced concrete and masonry infill. The total weight of one building amounts to about 260 tons. The dimensions are approximately 8.2 x 8.7 m in plan with a height of 9 m. The drawing for the installation of the BCS below the base slab of the building and the final situation of the devices are presented in Fig. 4.

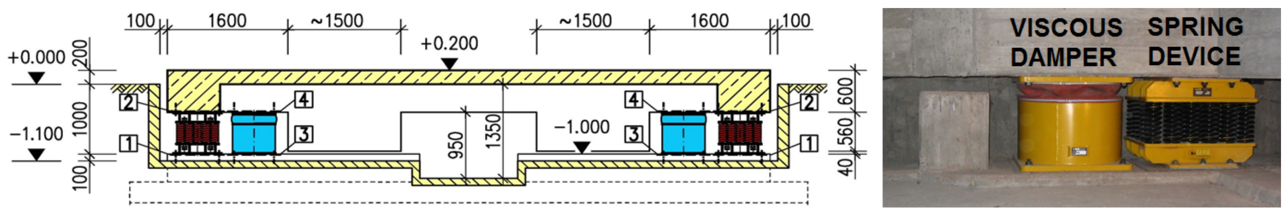

Fig. 4 – Cross section of apartment / arrangement of devices of BCS

The spring elements carry the dead load of the structure and are designed to have sufficient safety margin to bear also additional loads (in both horizontal and vertical directions) from seismic excitation. The viscous damper supplies high damping forces in all 3 directions. The implementation of dampers leads to an increase of structural damping and serve as a displacement control of the structure and the devices themselves. For most of the projects the efficiency of a seismic control system is proven by theoretical analyses before the structure is built. In 2005 it was possible to measure the seismic response of the base-controlled building at Mendoza in direct comparison to the identical adjacent structure without spring and dampers. The comparison of the two systems under the same seismic event with a peak ground acceleration of about 0.12 g showed a significant reduction of acceleration at the top of the building. At the building with BCS the acceleration values are reduced by more than 70 % as shown in Fig. 5.

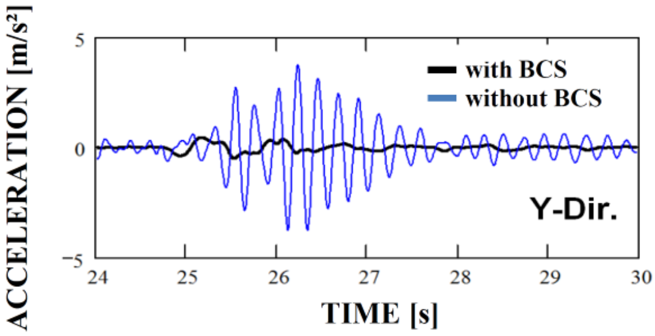

Fig. 5 – Measured accelerations at top of the buildings in one horizontal direction

After adjusting the characteristics of the analysis model due to the measured results it also shows the corresponding reduction factors in regard to internal stress and strain values as well as to the corresponding subsoil reaction loads. According to [4] the axial forces were reduced by more than 60 %, the shear forces more than 75 %, and bending moments on different columns were decreased by about 90 %.

3. Seismic Protection of Equipment

In substations many sensitive items of equipment shall be protected against seismic loading. The experience in seismic protection of machinery and buildings can be used to control structures that originally do not require vibration isolation, typically provided by an elastic support system. Equipment in substations can be supported by helical steel spring and viscous dampers exclusively against earthquakes. This chapter provides some details of corresponding examples.

The first example discusses an air core reactor with ceramic footings. The structural assembly of this equipment consists of a mass of about 45 tons. The center of gravity is located approximately 11 m above ground and as its substructure there are ceramic footings and stiffening steel cradles. These footings are extremely fragile and in danger of failure during a seismic event. Thus, a seismic protection system was required to protect the structure. Fig. 6 illustrates the arrangement of the structure and the spring and dampers devices (shown as blue boxes at the bottom).

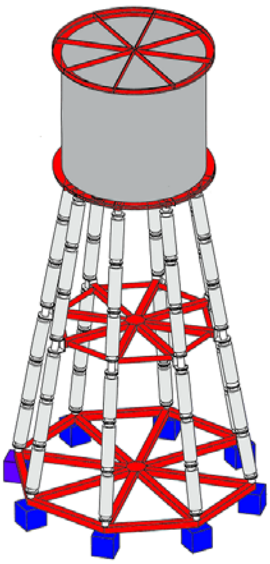

Fig. 6 – Layout of air core reactor on BCS in California

The seismic requirements are related to [3] and the spectral acceleration figures showed on Fig. 1 had to be multiplied additionally by a factor of 2. In case of a conventional installation the footings would be anchored directly to the foundation and the structural frequencies would be between 2 -3 Hz with a (prescribed) damping ratio of 2 %. Thus, the seismic acceleration would exceed 3 g and the corresponding collapse of the system would be probable. After a detailed seismic study it was decided to arrange a BCS below the basecradle. The arrangement of helical steels springs and viscous dampers causes a significant change of the main system frequencies as well as of the corresponding modes shapes and damping ratios. The achieved system frequencies and related damping ratios can be described as follows. The vertical mode amounts to about 2 Hz with a damping ratio higher than 5 %. The first horizontal rocking modes are found around 0.6 Hz with a damping ratio higher than 20 %. The first elastic bending mode was calculated to about 3.7 Hz. Regarding the spectral acceleration it becomes obvious that the occurring acceleration of the air core reactor as well as the internal stresses in the ceramic footings under seismic loading can be significantly reduced due to the reduction of frequencies and increase of damping. The axial, shear and bending stresses were found within acceptable limits. In this case the parameters of the spring devices were chosen to force the structure into a mode shape with a larger part of rocking. This change of the mode shape yields low frequencies and even satisfactorily small horizontal displacements at the base and at the top of the air core reactor. Similar efficient results can be found for many air core reactors, one similar example is discussed in [5] – where a smoothing reactor is based on a BCS for protection against seismic loading.

The second example presents another important equipment in a substation. The capacitor bank also consists of sensitive ceramic footings. The discussed project is located in China and the capacitor has got 6 single banks, which are arranged on top of each other. Each bank is separated by and resting on ceramic isolators and the lowest footings are especially in danger of collapse during a seismic event. Fig. 7 shows the final situation in the background and the system during construction in the foreground.

Fig. 7 – Capacitor banks on BCS

The total weight of the equipment is about 14.5 tons. The main dimensions are 3.5 m in length with a width of around 2.5 m and a height close to 8.5 m. Here, the seismic input is also related to the recommendations according to [3]. For a typical, common layout the footings are fixed to the concrete foundation block, which is directly resting on the subsoil. In this case the horizontal frequencies would be around 4 -5 Hz and the corresponding damping in the structure would be very low. Thus, for the given seismic demands the collapse of the capacitors would be very probable. A Base Control System is arranged below the foundation mat to protect the structure against seismic events. As the structure is high and slender special attention to the stiffness ratio of the spring devices has to be paid. To prevent large rocking motions of the structure a higher ratio between vertical stiffness and horizontal stiffness was chosen. The resulting frequencies and related damping values can be described as follows. The vertical mode amounts to about 2.4 Hz with a damping ratio of nearly 20 %. The horizontal mode shape in longitudinal direction was found at approximately 1.0 Hz with a damping ratio of about 18 %. The second horizontal mode, in transversal direction, was calculated to about 0.8 Hz with a corresponding damping ratio of about 12 %. Using the BCS the induced acceleration of the capacitor as well as the internal stresses in the ceramic footings under seismic action can be reduced significantly, regarding the spectral acceleration values according to [3] for the new mode shapes and damping values. The controlled rocking causes low frequencies and even sufficiently small horizontal displacements at the base of the capacitor.

Regarding differential displacements in the surface of the support devices it is important to consider the general effect, that lower frequencies cause larger displacements. Using a simplified single degree of freedom system with a damping ratio of 5 % the relationship between seismic acceleration and displacement can be calculated. Here, the seismic input curve according to Fig. 1 was used. Fig. 8 shows the resulting curve.

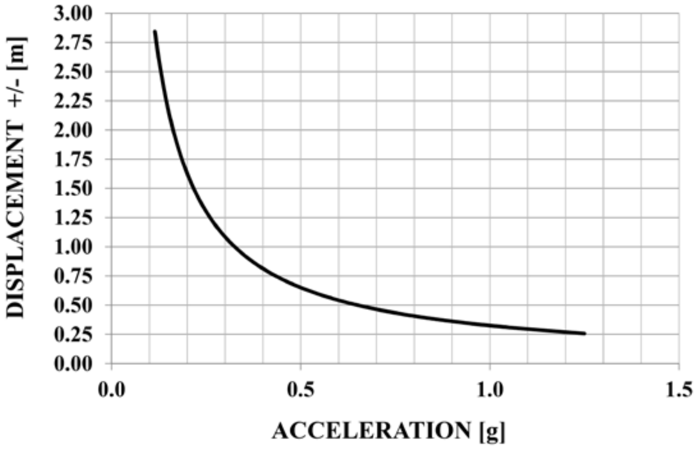

Fig. 8 – Relation between displacement and acceleration

This figure exemplifies the requirement of finding an optimum between the reduction of accelerations and occurring displacements. It is not recommended to yield extremely low accelerations with enormous displacements. In this case it would be better to use a different support system – with a little bit higher displacements but in combination with an increase of damping, if required. For each project the requirements, e.g. in terms of an acceleration limit should be clearly described. Then it would be possible to find a suitable support system.

In special cases there may be also further requirements regarding the available space and details for the elastic support system. Fig. 9 shows the model of a switch that requires seismic protection. As it was not possible to arrange a foundation block below the structure, a special spring device was developed.

Fig. 9 – Model of switch based on one spring device

The structure with a mass of about 3 tons at a height of approximately 3 m is extremely slender and the widening of its footprint was very limited, even without arranging a typical concrete block below. The spring element consists of three single springs and three dampers. The parameters are chosen to enable the support of the switch on top of only one single device. Therefor the springs and dampers are arranged in a tripod shape inside the device to provide a stable support for the system. This type of element could be used as basis for the seismic protection of switches or similar structures.

4. Conclusion

Following the introduction, a brief outline of the fundamentals of seismic control strategies is presented. Some examples for the earthquake protection of equipment in substations are discussed in the paper. The proposed elastic support on a Base Control System, consisting of helical steel springs and viscous dampers, leads to a three dimensional passive control system. Due to the change in the support conditions the fundamental mode shapes of the supported structure are changed. In combination with reduced eigenfrequencies and a significant increase of structural damping the seismic behavior is improved. Accelerations, forces acting on the substructure and internal stresses and strain are reduced. In comparison to other strategies the horizontal relative displacements in the surface of the support system are in the range of only a few millimeters, even under severe seismic action.

5. References

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