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ASSESSMENT OF ELECTRICAL COMPONENTS UNDER GROUND VIBRATION LOADING

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ABSTRACT

During their operation electrical components are exposed to vibrations. These vibrations typically do not affect the component's functionality. The vibrations are generated by the component itself (e.g. from a rotating motor / generator, switching operations) and / or the component is affected by vibrations which are originating from surrounding components, systems or the environment. If previously unconsidered load cases occur e.g. due to near-site demolition or ground impacts during decommissioning, it may become necessary to evaluate their effect on the component's functionality in advance. The basic approach for verifying the functionality under such 'new' short-time ground vibrations is in nuclear and non-nuclear environments the same. In the nuclear environment, the verification is adopted from the detailed and established verifications applied for seismic ground motions, using response spectra as load description. In the non-nuclear environment more pragmatic and less extensive solutions are applied, using maximum velocities for load definition. (Maximum) velocity is a common quantity in vibration prognosis in structural dynamics. Based on the expected component's vibration level and acceptance criteria the verification of the component's functions under short-term ground vibration loading can be established.

The paper presents two examples of electrical components which have to be assessed in their capability to withstand the ground vibration loading occurring after blasting e.g. of a cooling tower. One example is from the nuclear field: a 110 kV transformer which, which was reinforced to stay functional under ground vibrations from cooling tower blasting. The second example addresses 'switchgear' equipment, which has to stay functional after blast demolition of the neighbouring coal-fired power plant 'Lünen'.

INTRODUCTION

The correct functioning of electrical equipment, especially if it is safety related, is vital for the safe operation of nuclear as well as conventional facilities. Therefore, the equipment must stay functional under a wide range of operating conditions and loads. One of these loads are vibrations of the ground that occur from short-term external events. For proper functioning, the devices have to prove their functionality during and/or after the occurrence of the ground motion. The main methods of such a qualification are physical testing or numerical analysis or a combination of both. If previously unconsidered, but foreseeable load cases occur, e.g. short-time shock and vibration loads from near-site demolition or ground impacts from blasting or during decommissioning (see Figure 1) e.g. of a cooling tower, it may become necessary to additionally evaluate their effects on the functionality of the equipment in advance. In order to carry out such an assessment, a prognosis of the vibration at the equipment's installation location is required and acceptance criteria must be available to assess functionality.

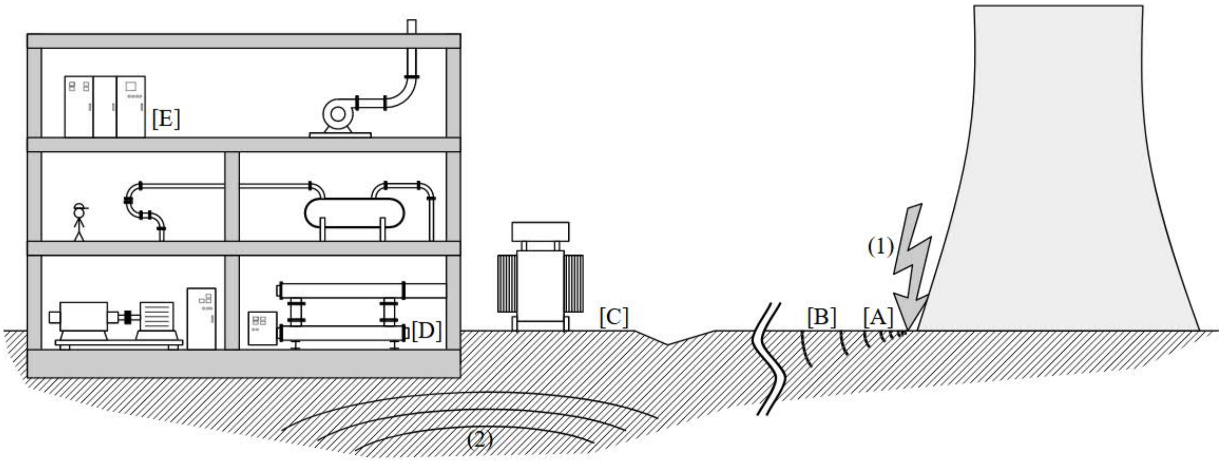


Figure 1. Equipment under short-term ground vibration loading: e.g. near-site demolition (1), impacts during decommissioning (1); earthquake loading (2)

In contrast to earthquake loads (see Figure 1), which are almost constant over the entire plant site, short-term ground vibration loads from demolition, blasting, etc. have a local point of origin and show a significant decrease in loading amplitude with increasing radial distance from their point of origin. Thus, not all equipment has to be qualified for the shock and vibration loading; usually only vital and closely located equipment has to be qualified. Typical electrical equipment, which could be affected by such shock and vibration loads, are e.g. transformers, switchgear, pumps, etc. If such equipment is located in a facility, which is under nuclear regulation, the requirements on qualification are typically more demanding and detailed than for a plant under non-nuclear regulation. However, for nuclear equipment usually the available documentation and qualifications are more comprehensive than for non-nuclear facilities.

After general considerations, this paper essentially presents two examples where electrical component qualification is required prior to (cooling tower) blasting. One example stems from nuclear industry and one from non-nuclear industry: a '110 kV transformer' and 'switchgear' equipment. The 110 kV-plant-feeding transformer was required for safe operation of a nuclear facility during and after the short-term ground motions. The second example 'switchgear' is associated with the blast demolition of the coal-fired power plant 'Lünen', where closely located switchgear had to continue functioning after occurrence of the ground vibrations.

GENERAL CONSIDERATIONS

In order to prove that equipment can withstand the vibration loads, the vibration effect at the respective installation location must be determined first. This is done by evaluating the vibration transmission from the source of the vibration (e.g. impact at location [A] in Figure 1) to the installation location of the considered equipment, e.g. a cabinet at location [E] (see Figure 1).

Seismic events are typically described by earthquake spectra, defined for free-field conditions. By looking at Figure 1, this means, the loading is equal at the free-field locations [A], [B] und [C]. For locations [D] and [F] in the building, at least the influence of the building dynamics on the vibration has to be considered, soil-structure interaction can also be regarded. Detailed evaluation of the transmission behaviour is done by numerical calculation resulting in building (floor) response spectra.

For external short-term impact loads, the loading amplitude drops significantly, the further the distance from the point of origin [A] is (see Figure 1). This means the loading level at location [C] is smaller than at location [B] that is smaller than loading at the point of origin [A]. In the non-nuclear industry the vibration loading from impact is typically described by a maximum velocity v_{max} at a certain location. The velocity value can be determined by applying DIN 4150-1 (2001) "falling masses"-equation which requires as input data the potential energy of the cooling tower, the distance to the impact location and parameters from empirical data. It is annotated, that usually ground vibrations from the blasting itself can be neglected as they are small in comparison to the impact loading of the collapsing structure. The DIN 4150-1 gives also hints on coupling factors for loading transfer from the ground into the building. For the amplification in the building empirical data is used. In the nuclear industry typically more detailed data has be provided on the description of the excitation – only a maximum velocity is not sufficient. Since vibration evaluations of buildings and components for the load case earthquake are usually already available, it is obvious to aim for a load description that corresponds to that of earthquake. Thus, it becomes easy to refer to existing qualifications and regulations. In Karapetrou et al. (2022) a methodology is presented to predict ground vibrations resulting from structural demolition by explosive blasting using numerical simulations combined with vibration measurements. The results are free-field response spectra at different locations, the spectra can be used for further qualification of SSC (systems, structures, components).

With knowledge of the vibration load at the installation location of a component, the qualification can then be carried out by showing that the required acceptance criteria are met. Acceptance criteria are requirements in terms of stability, integrity or functionality.

In the nuclear industry, the typical verification methods are analysis, performing a test or similarity considerations or combinations of the methods. In the non-nuclear industry the same methods are available in principle, but often less comprehensive and more pragmatic approaches are required.

QUALIFICTATION OF A 110 kV TRANSFORMER

The first example is nuclear industry related. For a planned dismantling operation, e.g. blast demolition of a cooling tower, additional requirements for the safety classification of electrical equipment may arise, since during the demolition process, the power supply situation of the plant can take a state that was not considered during the initial approval processes several decades ago. This makes an additional evaluation of the affected components necessary. In the following, such a re-evaluation of a 110 kV feeding transformer is considered. The basis for the analysis is the KTA 2201.4 (2012).

Figure 2. 110 kV-plant feeding transformer (original configuration without structural improvements)

The considered 110 kV-plant-feeding transformer is depicted in Figure 2. It was upgraded in terms of safety-classification during the dismantling process, thus it had to pass additional qualifications. One of these is the proof of the transformer to stay fully functional during vibrations resulting from the dismantling process itself. The chosen approach is using a qualification methodology as established for earthquake qualification. Based on the response spectrum at the installation location, a numerical calculation of the stability of the transformer structure is performed. In addition, accelerations at functionally relevant installation parts like the Buchholz-relay are determined from the calculations in order to compare them with available tests to prove the functionality during the demolition process.

The transformer is located on the earthed transformer building. The transformer has four wheels, which are supported by rails. Movement of the transformer in rail direction is prevented by metal brake blocks, mounted on both sides of the respective wheel and mutually bolted. The transformer has several radiators on its left and right side. On its top, the oil expansion tank is located, sitting on a steel support structure. The function critical Buchholz relay is installed in the feeding pipe to the expansion tank. The active part (especially transformer core, windings, tap changer) is located inside the tank. By means of two cable junction boxes, which have their own support, the current is routed to the plant. The rough outer dimensions are approx. (length x width x heigth) 7,5 x 4,5 x 6,5 m. The transformer has a total mass of approx. 100 tons.

The vibration loading at the transformers installation location is determined by the methodology described in Karapetrou et al. (2022), the response spectra are depicted in Figure 3.

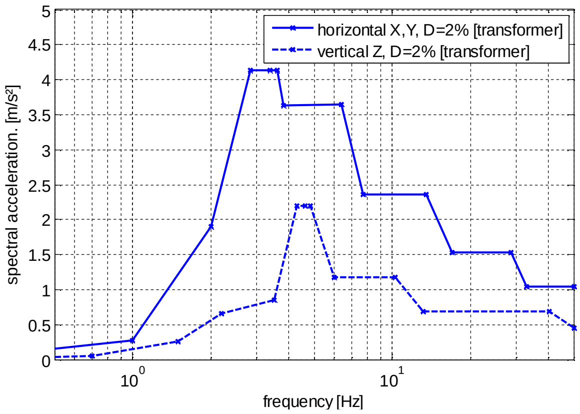


Figure 3. Response spectra (D = 2 %) of 110 kV-plant feeding transformer at installation location

The distance between the transformer location and the source of vibration is several 100 meters. In vertical (z) or horizontal (x, y) direction, the max. spectral acceleration is approx. 2.2 m/s² resp. approx. 4.13 m/s². The rigid body acceleration is approx. 0.46 m/s² resp. 1.05 m/s² in each case.

In order to verify the stability/strength of the transformer under dead load and the vibration load from Figure 3, a finite element model (FE model) of the transformer is created. The model of the transformer itself is depicted in Figure 4; the cable junction boxes (see Figure 2) were also evaluated, but this is not presented here.

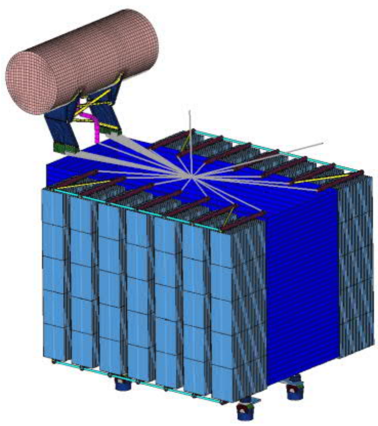
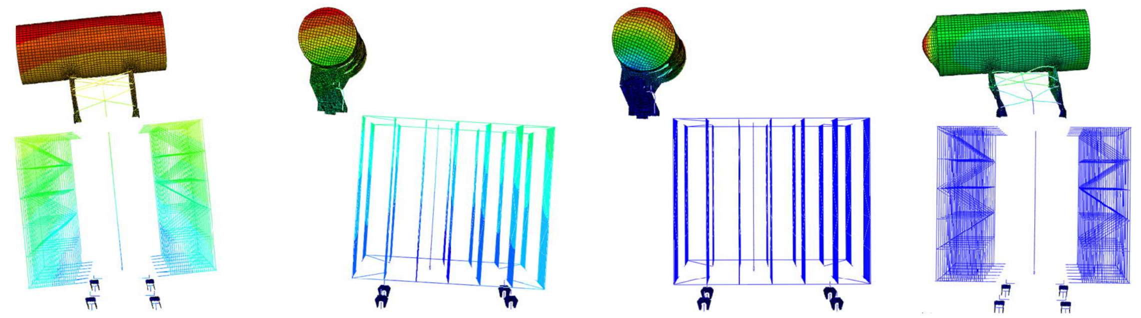


Figure 4. FE-model of the transformer

The FE model is especially focused on the expansion tank with its reduced oil filling, the support structure of the expansion tank with piping, the transformer tank with internals, the radiators and the wheels. Oil behavior in the expansion tank is considered in a simple way, as the sloshing frequency is very low.

Results from the modal analysis are shown in Figure 5. The first modes are global rocking modes at 4.3 Hz and at 5.9 Hz. No experimental validation of these results was available, but a comparison with the findings of a swiss study (Résonance, 2011) shows a good agreement of the fundamental rocking eigenfrequencies of the transformer.



4.3 Hz	5.9 Hz	9.3 Hz	15.5 Hz
global rocking, lateral	global rocking, longitudinal	expansion tank nodding	expansion tank lateral

Figure 5. Selected modes of the transformer

With the FE model a response spectrum modal analysis (RSMA) was performed using the spectra from Figure 3. As the frequencies are located in the plateau-range of the spectra from Figure 3, significant loading is expected. After evaluation of dead load and superposed vibration loading, the results show, that several structural improvements had to be established, before the transformer is verifiable: e.g.

- Contact area of the saddle bearings of the expansion tank has to be enlarged
- support structure of the expansion tank: Additional bracings and additional stiffeners and improved welding in the connection area to the transformer tank
- establishing of lift-off and slip protection devices

Two main aspects are considered to evaluate the transformers functionality:

- Relative displacement between the transformer and the cable junction box: The connection is "soft", it is made via the connected electrical cables and the external rubber bellows. The calculations showed a maximum displacement smaller than the permissible total displacement of approx. ± 20 mm.
- Acceleration Buchholz relay: From the RSMA calculation a maximum resulting acceleration of 9.9 m/s² was calculated. Based on this result a vibration test consisting of sine sweep and shock loading according to KTA 2201.4 (2012) was defined. A comparison of these test loads with a successful vibration test of the Buchholz relay dated back in the 1980’s showed, that the test load at that time covers the newly defined test load. For additional safety, administrative measures could be established.

Additional verifications for the transformer’s supporting building show that e.g. the reinforcement of the substructure is dimensioned sufficiently and the building connection loads can be safely entered into the building. Thus, it is successfully shown, that the transformer remains stable and functional under the influence of the ground vibration load from the blasted cooling tower – which was confirmed during and after the blasting.

QUALIFICTATION OF SWITCHGEAR EQUIPMENT

The second example is from the blast dismantling of the non-nuclear coal-fired power plant Lünen. On March 28th in 2021 the cooling tower, the boiler house block and the 250 m chimney of the power plant were blasted. Closely located switchgear from a neighbouring distribution grid operator was supposed to be switched off during blasting, but had to continue functioning after blasting. The site map of the local situation is depicted in Figure 6.

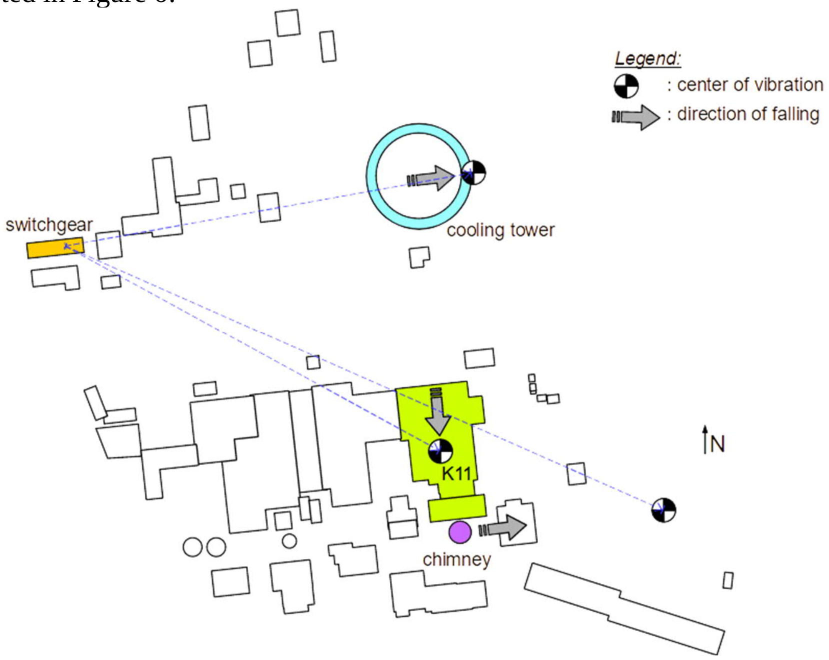


Figure 6. Site map: location of switchgear building, cooling tower, block K11 and chimney as well as sketches of surrounding buildings

The site maps shows the locations of the switchgear building as well as the location of the cooling tower, the block K11 (boiler and pump house and bunker) and the chimney. Additionally the foreseen falling directions of the three structures after blasting and the center of vibration when impacting the ground are depicted. Looking at the distances between the location of the switchgear building and the three centers of vibration, the cooling tower is closest, followed by the boiler house and the most distant point is the chimney's center of vibration.

Figure 7. Switchgear

The three blasts are carried out with a time delay so that there will be no detrimental vibration overlay. To assess the capability of the switchgear (see Figure 6) to withstand the impact vibrations after the consecutive blasts of the buildings, a three-stage concept is performed:

- Prognosis of vibration levels at the foundation of the switchgear building.
- Experimental determination of an amplification factor between vibration at the switchgear itself (gas compartment) and the building's foundation.
- Experimental determination of an allowable vibration level.

The vibration prognosis of the expected maximum velocity is carried out on the basis of previous and comparable structural blastings and a vibration propagation prognosis according to DIN 4150-1 (2001). The results are maximum vibration velocity components $v_{90\%}$ predicted at the foundation. The actual or measured values will be below the predicted values with a probability of 90 %. Table 1 shows the prognosis results for the switchgear building foundation.

Table 1: Distance from switchgear building to vibration center of blasted structure & vibration prognosis.

blasted structure	distance R from switch-gear building to vibration center of blasted structure	vibration prognosis $v_{90\%,Foundation}$
cooling tower	280 m	7.8 mm/s
chimney	450 m	9.6 mm/s
block K11	290 m	8.3 mm/s

For the experimental determination of an amplification factor between the vibrations at the switchgear itself (gas compartment) and the building's foundation, a pragmatic approach was chosen. An excavator was used to perform drop tests in front of the switchgear building. The vibrations on the foundation of the switchgear building and on the switchgear itself (see vibrations sensors on switchgear in Figure 7, right) were measured.

Table 2: Maximum vibration level from drop tests and switching operations.

	Drop test			Switching operations		
Measurement location	v_x	v_y	v_z (vert.)	v_x	v_y	v_z (vert.)
MP 1 (gas compartment) [mm/s]	2.41	2.82	1.84	30000	26000	./.
MP 3 (foundation) [mm/s]	0.78	0.2	0.2	./.	./.	./.
ratio MP1/MP3	3	14	9	./.	./.	./.

Table 2 shows the results from the drop test, a maximum amplification (ratio MP1/MP3) between foundation and gas compartment of 14 is determined. As no information on allowable vibration levels for the switchgear equipment is available, the limits have to be figured out by testing. For the experimental determination of the allowable vibration level of the switchgear, switching operations are performed. The switching gives very high vibrations in the area of the gas compartment/ switch; Table 2 shows the results from these tests. Conservatively applying the amplification factor of 14 to the vibration prognosis from Table 1, gives a maximum acceleration on the gas compartment of 109 mm/s for cooling tower blasting and 134 mm/s for chimney blasting. Both values are significantly below the recorded vibration levels resulting from switching operations. Thus, vibrations from the blasting operations at Lünen will not negatively influence the functioning of the switchgear.

According to plan, during blasting, various measuring points in the vicinity are equipped with vibration measuring equipment for monitoring purposes. One of the measuring points 'MP 8' was on the foundation of the switchgear building. Figure 8 shows the recorded velocities.

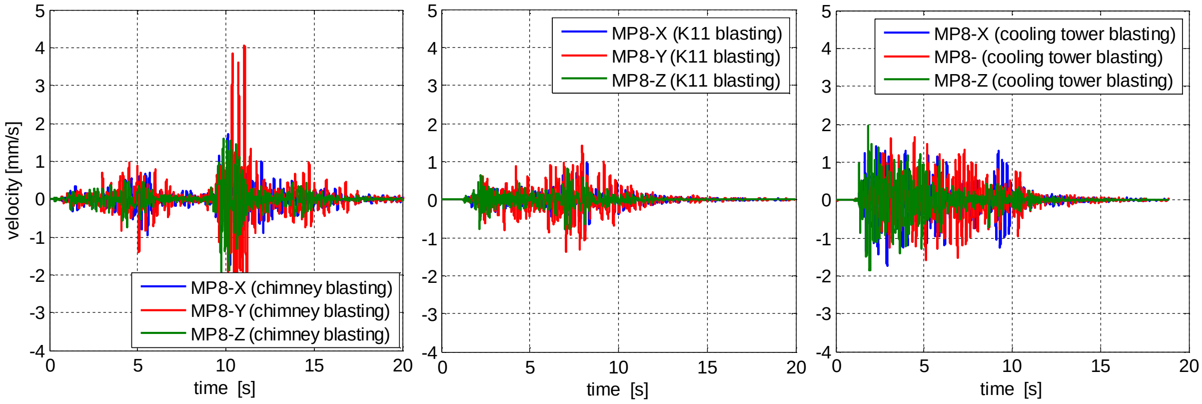


Figure 8. Velocity recordings at the foundation of switchgear building during all three blastings

All three blastings show different time histories at 'MP 8'. Although the distance to the chimney is the largest (see Figure 6), the highest velocity of 4 mm/s is recorded during it's impact on the ground (horizontal Y-direction). The lowest vibration occurs during impact of K11 block on the ground. The cooling tower blasting leads to a maximum of 2 mm/s in vertical direction. A comparison with the predicted vibrations $v_{90\%,\ Foundation}$ from Table 1 indicates a comparably conservative prognosis. The overall shapes of the signals during the three blasting are quite different; they can be interpreted from the collapse sequence of each structure. It is mentioned, that the frequency content of all signals is concentrated below 10 Hz.

CONCLUSION

For the load case of short-term ground vibrations, which are caused by the ground impact of blasted structures e.g. cooling towers, there are known approaches to reliably evaluate the functionality of affected electrical components. Depending on the industry (nuclear / non-nuclear), its established methods are applied. In the shown example of the '110 kV transformer', which is from the nuclear industry, the methods known from earthquake qualification are applied, response spectra are used for load description. In the second example 'switchgear', which is located in the non-nuclear environment, the (maximum) vibration velocity is used for the load description.

Depending on the industry in which the task is carried out, verification that meets the industry-specific requirements can reliably be established.

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