Annals of the Academy of Romanian Scientists
Series on Science and Technology of Information
ISSN 2066 - 8570 Volume **1** Number **2**/**2009**

METHOD FOR SEISMIC CAPABILITY ASSESSMENT OF THE HIGH VOLTAGE CIRCUIT BREAKERS

Ion MANEA[1], Constantin RADU[2], Ovidiu TĂNASE[3]

Abstract. *The international norms recommend verification of the circuit breakers seismic capability by tests on seismic platform, but accept assessment through experimental and theoretical combined analysis, too. The paper presents a methodology for seismic capability assessment of the high voltage electric equipments using combined analysis through experimental modal analysis methods. The methodology was applied on some representative types of circuit breakers and disconnecting switchers situated in the working place.*

The same methodology was applied on a circuit breaker type IO 220 kV/2500A, situated on seismic platform from SC EUROTEST SA Bucharest, after finishing the tests with vibratory signals applied to the base. The equipment, in the same mounting conditions, was tested by means of the present methodology. Were determined the frequency response functions, modal parameters, and theoretical response of some representative points to theoretical vibratory motions applied to base, the same as applied during the direct experimental tests.

At the end of paper it is effectuated the comparative analyses of the results obtained through the two methods: direct tests on seismic platform and combined analysis by modal analysis methods.

Keywords: modal analysis, seismic capability assessment

1. Introduction

The good operation of the power system must be assured in both normal and limit working conditions as well as in case of seism or short-circuit events. From this point of view, special problems appear at the switching equipment with column type construction such as high voltage circuit breakers. At this type of equipment, due to their characteristic construction and their specific tasks to carry out, depending on the network location, network topology and type of switching events the mechanical stress can vary over a very wide range. All these events have cumulative effects and are leading to weariness of structure and a seism or short-circuits, due to their violent actions, can have destructive effects on circuit breaker mechanical structure. Consequently, with a view to ensure a high reliability, it is a good idea that each main switching equipment should be submitted to some experimental tests in order to assess the structural resistance state and their capability to stand out to future severe events.

[1]Senior Researcher, University of Craiova, Romania, (manea53@yahoo.co.uk).
[2]Engineer, SC SMART SA Bucharest, Romania, (cradu@transelectrica.ro).
[3]Engineer, CN „Transelectrica" SA Bucharest, Romania, (ovidiu.tanase@transelectrica.ro).

On the other hand, for high voltage electric equipment the international norms, like IEC 61166:1993 "High voltage alternating current circuit-breakers – Guide for seismic qualification of high voltage alternating current circuit breakers" and IEC TS 61463:2000 "Bushings – Seismic qualification", recommend verification of the seismic capability by tests on seismic platform, but admit assessment by combined analysis, too.

The combined analysis offer a good solution by determining the equipment mathematical model based on experimental data obtained by experimental modal analysis (EMA). The equipment is excited in well defined conditions and determining the evolution laws of excitation and response, it can be identified a minimum number of parameters which are intrinsic equipment characteristics, independent of the external conditions. A correct mathematical model permits the evaluation of the structure response to different external theoretical excitations like: seism, electrodynamics forces and wind action. The technical base necessary for seismic assessment by combined analysis is more accessible than the technical base used for testing on seismic platforms, having the advantage of portability, being useful for the equipment assessment in the working area.

The paper presents the theoretical background of the experimental modal analysis and seismic capability assessment of high voltage electric equipment. The methodology was applied on some representative types of circuit breakers and disconnecting switchers situated in the working place. The same methodology was applied on a circuit breaker type IO 220 kV/2500A, situated on seismic platform from SC EUROTEST SA Bucharest, after finishing the tests with known vibratory signals applied to the base. During the tests was recorded the vibratory motion applied to the base and the vibratory response on some representative points. The equipment frequency response functions (FRF) were determined. The equipment, in the same mounting conditions was tested by means of below presented methodology. Were determined the frequency response functions, modal parameters, and theoretical response of the representative points to theoretical vibratory motion applied to the base, the same as applied during the experimental tests. The paper presents a comparative analysis of results appointed by both experimental modal analysis and tests on seismic platform.

2. Theoretical background

Any mechanical system can be modeled by a system consist of 'n' concentrated mass points 'm_k', joints by elastic elements with 'k_k' stiffness and damping elements with 'c_k' damping coefficient. For this damped system with 'n' degrees of freedom, loaded by external excitation $\{Q(t)\}$, the motion equations are given by the following relation:

$$[M]\{\ddot{x}(t)\}+[C]\{\dot{x}(t)\}+[K]\{x(t)\}=\{Q(t)\} \quad (1)$$

-[M], [C], [K], the mass, damping and stiffness matrices,

- $\{\ddot{x}(t)\}, \{\dot{x}(t)\}, \{x(t)\}$, the acceleration, the velocity and the displacement vectors,

- $\{Q(t)\}$ generalized forces vector.

The system response to the external excitation is presented as a sum of 'n' modal contributions due to each separated degree of freedom:

$$\{X(\omega)\}=\sum_{k=1}^{N}\left[\frac{\{\psi^k\}\cdot\{\psi^k\}^T\cdot\{Q(\omega)\}}{a_k(-\mu_k+i(\omega-\nu_k))}+\frac{\{\overline{\psi^k}\}\cdot\{\overline{\psi^k}\}^T\cdot\{Q(\omega)\}}{\overline{a}_k(-\mu_k+i(\omega+\nu_k))}\right] \quad (2)$$

- $\{X(\omega)\}$ - the Fourier Transform of displacement,

- $\{\psi^k\}$ *and* $\{\overline{\psi}^k\}$ -the "k" order eigenvector and its complex conjugate,

- μ_k - the "k" order damping ratio,

- ν_k - the "k" order damped natural frequency,

- a_k *and* $\overline{a}_k$ - the normalization constants of the "k" order eigenvector,

- ω - the frequency of the external excitation.

In the practical applications, the modal vectors are replaced by two modal constants U_{ij}^k *and* V_{ij}^k defined by:

$$\frac{\psi_i^k\cdot\psi_j^k}{a_k}=U_{ij}^k+i\cdot V_{ij}^k \quad and \quad \frac{\overline{\psi}_i^k\cdot\overline{\psi}_j^k}{\overline{a}_k}=U_{ij}^k-i\cdot V_{ij}^k \quad (3)$$

Using these notations it can be determined the system admittance, $\alpha_{ij}(\omega)$ defined as ratio between frequency displacement response and force excitation:

$$\alpha_{ij}(\omega)=\sum_{k=1}^{n}\left[\frac{U_{ij}^k+i\cdot V_{ij}^k}{-\mu_k+i\cdot(\omega-\nu_k)}+\frac{U_{ij}^k-i\cdot V_{ij}^k}{-\mu_k+i\cdot(\omega+\nu_k)}\right] \quad (4)$$

In the approximations made during the mathematical modeling, it was used the concept of discrete system with concentrated mass in 'n' material points. For a good approximation of the real system through the discrete system, it must have $n\to\infty$. This is not possible because of the excitation and the response measurement technique, computing technique and also because of the necessary time for data processing. In practical applications the frequencies domain is limited to a reasonable width determined by the major resonances of the analyzed equipment and the frequency domain of the application goal. In these conditions the sum from relation (4) is reduced to some components, noted in the following with 'n' too. The contributions of inferior and superior modes are included in two correction factors known as "inferior modal admittance" $-\frac{1}{M_{ij}^{'}\omega^2}$ (for inferior modes) and "residual flexibility", $S_{ij}^{'}$ (for superior modes).

The system admittance will be written as:

$$\alpha_{ij}(\omega)=\frac{-1}{M_{ij}^{'}\cdot\omega^2}+\sum_{k=1}^{n}\left(\frac{U_{ij}^{k}+i\cdot V_{ij}^{k}}{-\mu_k+i\cdot(\omega-\nu_k)}+\frac{U_{ij}^{k}-i\cdot V_{ij}^{k}}{-\mu_k+i\cdot(\omega+\nu_k)}\right)+S_{ij}^{'} \quad (5)$$

So, an eigenmode is defined by a set of $4n+2$ parameters: $\mu_k, \nu_k, U_{ij}^{k}, V_{ij}^{k}, -\frac{1}{M_{ij}^{'}}, S_{ij}^{'}$. Using relation (2) it is possible to calculate the system response to different excitation types, which are:

-Seismic motion applied to base, when the concentrated forces are $\{Q(\omega)\}=-u_0(\omega)\cdot[M]$, where $u_0(\omega)$ represents the ground acceleration.
- Electrodynamics forces, due to commutation phenomena;
- Distributed forces, due to the wind.

The problem consists in determination of the correct modal parameters based on tests effectuated on equipment brought up in a controlled excitation state, with simultaneous determination of excitation and response. For the high voltage equipment situated in the working area, the excitation can be realized by one of the following low level energy methods: relaxed force or impulse force.

2.1. Modal parameters identification

The modal parameters identification is made by the following steps:

1. Determination of FRF, for all pairs of excitation / response points.

2. Identification of the modal parameters $\mu_k, \nu_k, U_{ij}^{k}, V_{ij}^{k}, -\frac{1}{M_{ij}^{'}}, S_{ij}^{'}, \quad k=1,2,...,n$.

The identification is made using successively linear and nonlinear procedures of recursive approximation, determining those modal parameters which replaced in relation (5) generate theoretical characteristics which approximate with minimal error the experimentally determined frequency response functions.

2.2. Seismic response assessment

The seismic response assessment is made in time or frequency domains, function of the definition mode of entry accelerogram. For this it is necessary to know the modal parameters as well as the geometrical and material characteristics of equipment. The equation which describes the motion of the system subject to seismic loads with $\ddot{u}_0(t)$ acceleraton is the following:

$$[M]\{\ddot{x}(t)\}+[C]\{\dot{x}(t)\}+[K]\{x(t)\}=-[M]\{\ddot{u}_0(t)\} \tag{6}$$

Equation (6) is identical to motion equation (1), considering the generalized forces:

$$\{Q(t)\}=-[M]\cdot\{\ddot{u}_0(t)\} \tag{7}$$

The system response to imposed motion applied to base defined by Fourier Transform of acceleration base, $\ddot{U}_0(\omega)$, is determined by the equation:

$$X_i(\omega)=\sum_{j=1}^{m}\left\{\sum_{k=1}^{n}\left[\frac{U_{ij}^k+iV_{ij}^k}{(-\mu_k+i(\omega-\nu_k))}+\frac{U_{ij}^k-iV_{ij}^k}{(-\mu_k+i(\omega+\nu_k))}\right]\cdot(m_j)\right\}\cdot\ddot{U}_0(\omega) \tag{8}$$

So, knowing the modal parameters $\mu_k,\ \nu_k,\ U_{ij}^k, V_{ij}^k, -\frac{1}{M_{ij}^{'}}, S_{ij}^{'},\quad k=1,2,\ldots\quad ,n$ and mass distribution of equipment it is possible to determine their response to all known vibratory loads, defined by base acceleration $\ddot{U}_0(\omega)$. The international norms IEC 61166/1993 and IEC TS 61463/2000 recommend using of the seismic Required Response Spectra (RRS) given as nomograms or tabular form of acceleration amplitude related to frequency and damping. There are three types of seismic loads defined, AF2, AF3 and AF5 with “zero period acceleration” of 2 m/s^2, 3 m/s^2 and 5 m/s^2. Table 1 presents the Required Response Spectra (RRS) for the three types of seism, AF2, AF3 and AF5. The RRS are defined for the ground mounted equipment.

Considering a linear distribution of accelerations on the equipment structure, by linear interpolation it can be determined the distribution of seismic acceleration or displacement on the equipment structure. Knowing the geometrical and material characteristics of the equipment one can determine the seismic force, the seismic bending moment and the mechanical stress distributions on the equipment surface.

$$F_j(\omega)=m_j*\ddot{X}_j(\omega)\qquad and \qquad f_j(t)=m_j*\ddot{x}_j(t) \tag{9}$$

$$M_j(\omega)=\sum_{k=0}^{j}F_k(\omega)*l_k \quad \text{and} \quad m_j(t)=\sum_{k=0}^{j}f_k(t)*l_k \tag{10}$$

$$\sigma_j(\omega)=\frac{M_j(\omega)*Y_{\max j}}{I_j} \quad \text{and} \quad \sigma_j(t)=\frac{m_j(t)*Y_{\max j}}{I_j} \tag{11}$$

Table 1. Required Response Spectra (RRS) for ground mounted equipment.

	Amplitude(m/s^2) / Damping(%)											
Frequency	2%			5%			10%			20%		
(Hz)	AF2	AF3	AF5	AF2	AF3	AF5	AF2	AF3	AF5	AF2	AF3	AF5
0,5	1,7	2,6	4,3	1,2	1,8	2,9	0,8	1,4	2,1	0,6	0,8	1,8
1	3,4	5,1	8,5	2,2	3,2	5,2	1,7	2,3	4,3	1,2	1,6	3,2
2,4	5,6	8,5	14	3,4	5,1	8,7	2,6	3,8	6,4	2	2,9	5,2
9,0	5,6	8,5	14	3,4	5,1	8,7	2,8	4,2	7,3	2,4	3,6	6,1
20,0	5	4,5	7,5	2,8	4,1	7	2,6	3,8	6,4	2,4	3,1	5,2
25,0	2	3	5	2	3	5	2	3	5	2	3	5

3. Application on a circuit breaker

In order to validate the above presented methodology, tests have been effectuated on a circuit breaker type IO 220 kV/2500A by both, experimental modal analysis and seismic tests on the seismic platform of SC EUROTEST SA Bucharest.

Comparative to other circuit breakers, the IO 220 kV/2500A have a relatively complex construction consisting of two isolating columns having above one carter and two breaking chamber in V form. The carter is fixed above of the upper isolating column by intermedium of a damping system, which confers a great flexibility to breaking chambers. The spatial model is represented by bar type elements, having the nodes positioned in the joining place of the columns, carter and breaking chambers, and the mass concentrated in the nodes at the end of the elements. This modeling process covers all the necessary for experimental modal analysis, taking into account that the interested frequency domain is the seismic domain of 0.5...35 Hz and that the vulnerable elements are the isolating columns which have the eigenfrequency over this range.

3.1. Vibratory tests on seismic platform

The tests were effectuated on the seismic platform SC EUROTEST SA Romania. During the tests the circuit breaker was rigid mounted on the platform surface.

The left part of the figure 1 represents the mounting schema, and distribution of the measuring and the excitation points for both seismic test and experimental modal analysis tests.

Fig. 1. Position of measurement and excitation points for IO 220 kV/2500A circuit breaker.

Taking into account the equipment configuration and its working conditions, the vibratory motion was applied only in horizontal direction, perpendicular on the plane that contains the breaking chambers. One determined the acceleration response in points P1 ... P7, in the same direction with the vibratory motion applied to base. One effectuated two types of vibratory tests:

- Sine sweep with constant acceleration of 0.8 m/s^2 in the frequency domain 1…35 Hz.
- Random wave with acceleration level of 0.8 m/s^2 in the same frequency domain.

The figure 2 represents the acceleration response of points P1 … P7 for a complete test.

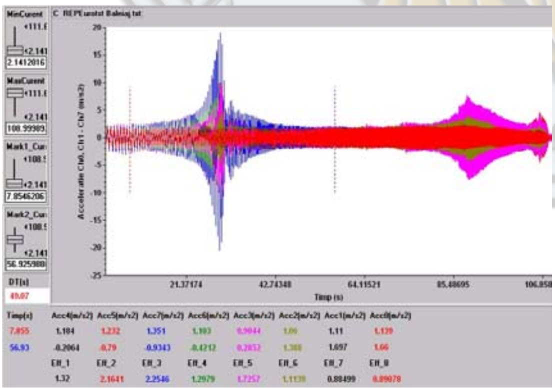


Fig. 2. Time acceleration response of IO 220kV/2500A on seismic platform.

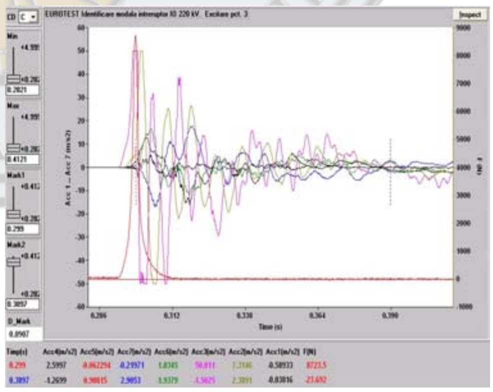


Fig. 3. Time characteristics corresponding to excitation in the point P3.

3.2. Tests for modal identification

After finishing the vibratory tests, with the platform blockage in the brought down position, using the same measuring equipment in the same mounting position, one effectuated a test for modal identification of the circuit breaker. For the circuit breaker excitation one used a hammer of 7 Kg, having in the front a force transducer equipped with a rubber damping device in order to increase the period of impact, concentrate the force in the lower frequency domain, and to protect the equipment. The excitation was successively applied in points P2…P7, and simultaneously one recorded the impact force and the acceleration response in all points P1…P7. The direction of the excitation force and of the measured response was the same as that of the direct vibratory tests on the platform.

The figure 3 presents the time characteristics corresponding to excitation in the P3. The lower displays show the instantaneous values of characteristics at the time selected by the two cursors.

The figure 4 shows in the Cartesian (left size) and polar (right size) coordinates the frequency response functions corresponding to excitation in point 3 and measuring in point 7.

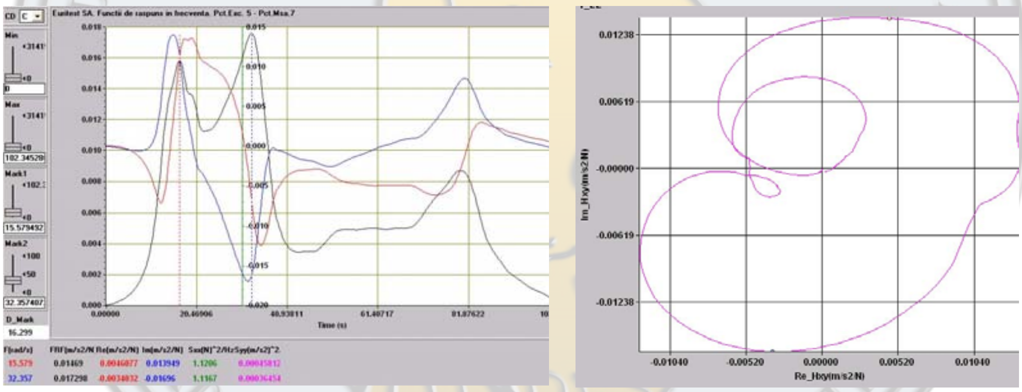


Fig. 4. Frequency Response Functions corresponding to PctExc. 3 / PctMsr. 7.

3.3. Modal parameters identification

For modal identification one successively selected pairs of excitation / response channels and following the steps of modal identification specified in the paragraph 2.1, finishing with writing of results in the file that contains the modal parameters.

The figure 5 presents, in the final stage of identification, related to the same ordinates, the both real and imaginary parts of theoretical (continuous path) and experimental characteristics (dashed path). There are small deviations between theoretical and experimental characteristics due to equipment complexity and because of the fact that for a given pair of Pct_Exc.- Pct_Msr. not all the vibration modes manifest with the same force, so that some modes are difficult to separate. Not all modes were kept for subsequent calculations. The modal parameters are represented in the lower part of the figure 5. These parameters are written in the output file of the modal parameters.

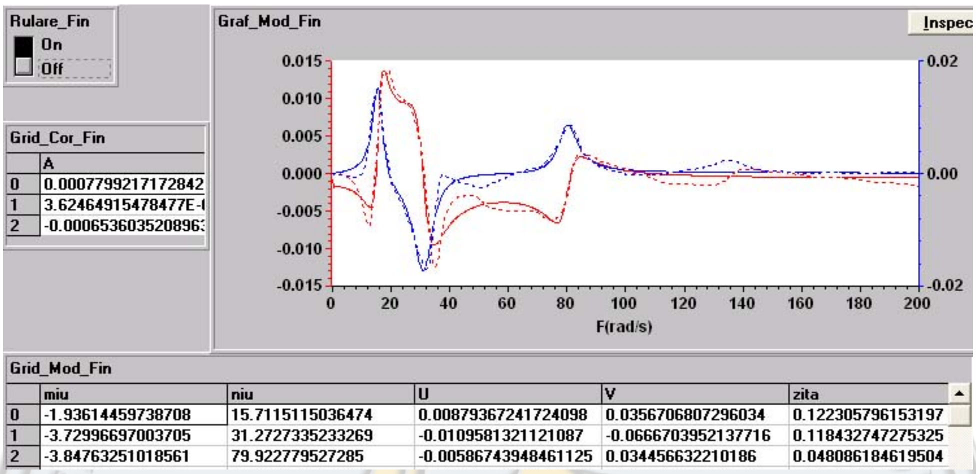
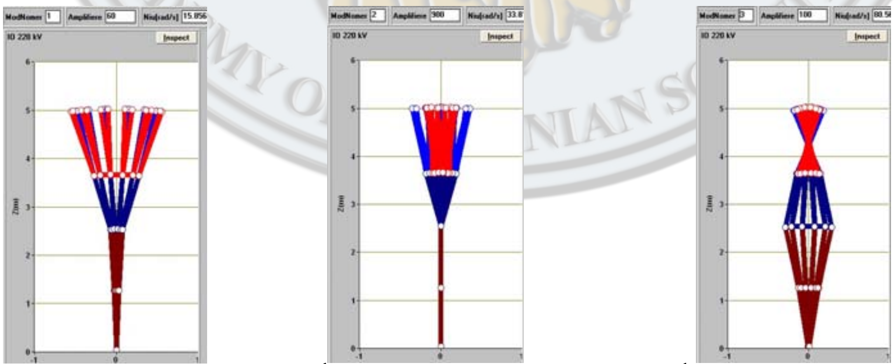


Fig. 5. Final panel of the modal parameters, corresponding to PctExc. 3 / PctMsr.7.

3.4. Seismic response evaluation

With the identified modal parameters we can make the evaluation of the response at seismic solicitation, according to norms IEC61166:1993, IECTS 61463:2000.

In the first step one determined the eigenfrequencies and modal shapes of circuit breaker. In the seismic domain the circuit breaker type IO 220 kV/2500A has 3 eigenfrequencies at: 15.85 rad/s (2.52 Hz), 31.81 rad/s (5.38 Hz), 80.56 rad/s (12.82 Hz). Figure 6 represents the circuit breaker in their eigenmodes within the seismic frequency domain. The figure represents the circuit breaker oscillating in the plane perpendicular on plane that contains the breaking chamber.



1st Eigenmode, 2.52 Hz   2nd Eigenmode, 5.38 Hz   3rd Eigenmode, 12.82 Hz

Fig. 6. Modal shapes of IO 220 kV/2500A.

In the following step the circuit breaker components (isolating columns, charter and breaking chambers) was divided into a specified number of elements (11 in this case) for which one calculated the distribution of mass, lengths, elasticity and polar moment for all elements "j". Through linear interpolation one calculated the acceleration distribution on structure. For each division one calculated the distributed response of acceleration, displacement, seismic force, bending moment, and stress. At the end one obtained the seismic response concentrated in points P1...P7, or distributed on the structure of each "j" point.

One determined the circuit breaker response to different types of vibratory solicitation like seismic solicitation type AF2 (<5.5 degrees Richter), AF3 (5.5…7 degrees Richter), AF5 (> 7 degrees Richter).

The figure 7 represents the circuit breaker acceleration response to a seism type A5. The maximum stress solicitations were obtained for the bottom isolating column. The figure 8 represents the stresses distributed on the bottom isolating column to the same seism type AF5.

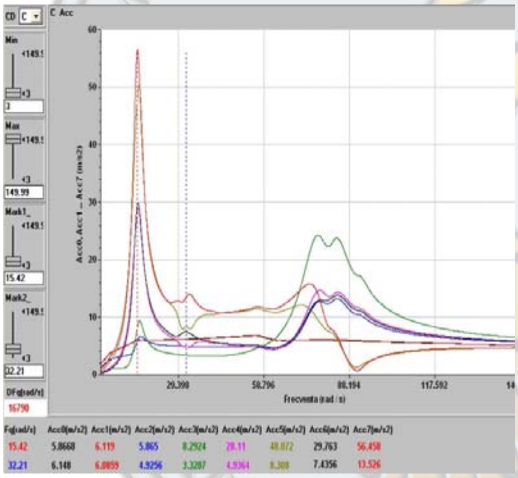


Fig. 7. Acceleration seismic response of IO 220 kV/2500 A to a seism type AF5

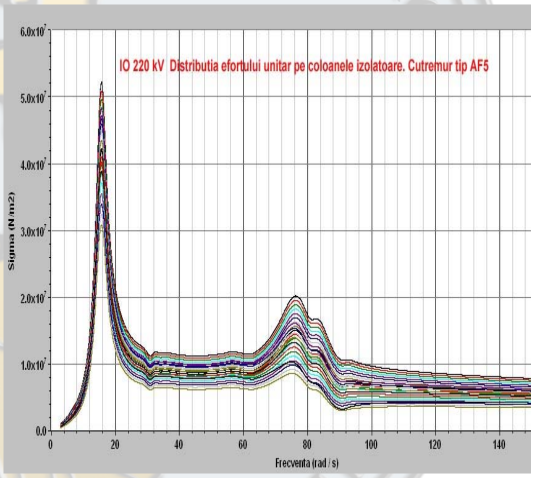


Fig. 8. Stress distribution on bottom isolating column to a seism type AF5

For assessment of the seismic capability one compared the stress obtained by applying the EMA methodology with the admissible stress specified by the manufacturer for vulnerable elements. In this case the maximum admissible stress for isolating column is $\sigma \leq 6 \cdot 10^7$ N/m^2. By comparing with the value of $5.2 \cdot 10^7$ N/m^2 determined by EMA methodology for the lower part of bottom isolating column it can be considered that the IO 220 kV/2500A circuit breaker stands out to a seism type AF5. For a complete seismic capability assessment besides the seismic solicitation must be considered the solicitations due to the other functional tasks (internal pressure of SF6, loads due to connecting cables, etc.) and environmental conditions (wind, etc.).

These solicitations are arithmetically added with seismic solicitations and resulting solicitation are compared to the admissible stress specified by the manufacturer.

4. Comparative analysis with tests on seismic platform

The criteria for comparative analysis between results obtained by the two methods, direct tests on seismic platform and EMA are: eigenfrequencies value and amplitude of FRF at eigenfrequencies.

In order to make the comparative analysis the figure 9 presents the two frequency response functions obtained by both methods, EMA methodology in the left side and direct tests in the right side.

The table 2 presents the eigenfrequencies and FRF amplitude for direct tests on platform.

The table 3 presents the eigenfrequencies and FRF amplitude by applying the EMA methods.

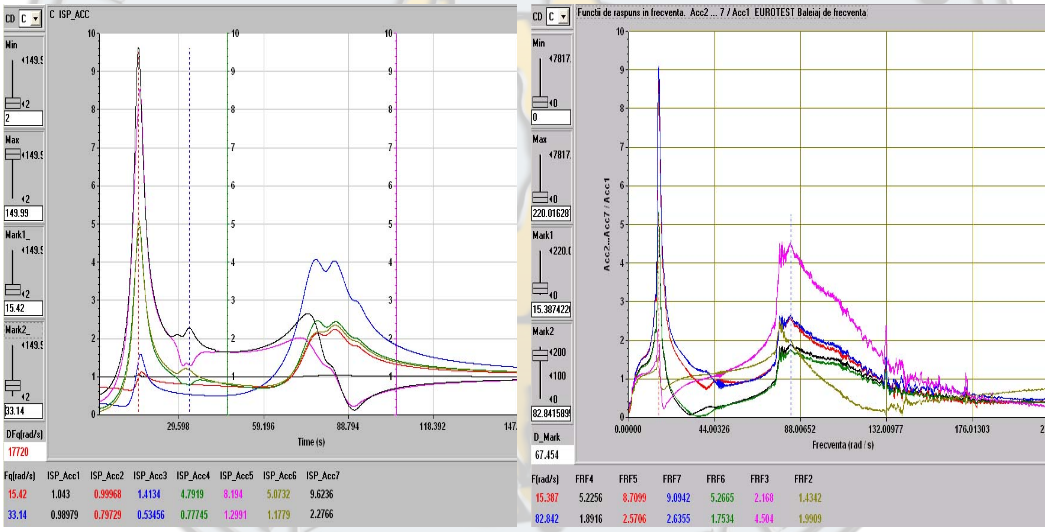


Fig. 9. Frequency Response Functions for applying the EMA (left) methods and direct tests (right).

Table 2. Eigenfrequencies and FRF amplitude for direct tests on seismic platform

Pct2		Pct3		Pct4		Pct5		Pct6		Pct7	
F(rsd/s)	Ampl	F(rsd/s)	Ampl	F(rsd/s)	Ampl	F(rsd/s)	Ampl	F(rsd/s)	Ampl	F(rsd/s)	Ampl
15.03	1.55	15.15	2.3	15.26	5.27	15.38	8.71	15.26	5.3	15.38	9.09
77.17	2.35	82.84	4.5	82.84	1.89	82.78	2.57	82.78	1.75	82.72	2.62

Table 3. Eigenfrequencies and FRF amplitude by applying the EMA methods

Pct2		Pct3		Pct4		Pct5		Pct6		Pct7	
F(rsd/s)	Ampl	F(rsd/s)	Ampl	F(rsd/s)	Ampl	F(rsd/s)	Ampl	F(rsd/s)	Ampl	F(rsd/s)	Ampl
15.89	1.12	15.89	1.59	15.89	4.91	15.99	8,53	15.51	5,09	15.42	9.62
32.2	0.801	32.2	0.541	31.77	0.803	32.22	1.35	31.95	1.21	33.15	2.27
77.74	2.24	77.74	4.06	77.74	2.45	77.74	2.02	77.74	2.34	74.63	2.64

Analyzing the data from the tables 2 and 3 one can conclude that:

- Maximum error for eigenfrequencies estimation: ± 10 %;
- Maximum error for seismic response estimation: ± 30 %.

Conclusions

(1). The combined analysis is a strong instrument, very useful for both manufacturer and customer of the high voltage electric equipment.

(2). Applied on the new equipment it can give useful information about the correctitude of design conception and concerning to the optimization of the vibration response of the equipment.

(3). Applied on the new mounted equipment, or on in situ equipment, it can give information concerning the quality of the mounting process, the material weariness, possible cracks or weakness.

(4). For in the working area equipment it is the unique method for seismic capability assessment, or evaluation of the impact of some grave short-circuits events on the high voltage electric equipment.

REFERENCES

[1] Ewins, D.J. « *Modal testing. Theory and Practice* », Bruel & Kjaer, 1987;

[2] I. Manea « *Experimental modal analysis* », Universitaria Craiova, 2006;

[3] IEC 61166:1993 « *High voltage alternating current circuit-breakers – Guide for seismic qualification of high voltage alternating current circuit breakers* »;

[4] IEC TS 61463:2000, « *Bushings – Seismic qualification* ».