SEISMIC STUDY OF SUBSTATION BUSBARS

by

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SUMMARY

Two similar substations are being built near Lisbon. The dynamic beha-
vior of the 400, 220 and 150 kV busbars (frames+insulators+bars)under seismic
loads was carried out using the following procedure: experimental determina-
tion of dynamic properties of their components, development of an analytical
model fitting experimental data and computation of structural response. The
most important conclusions are: 1 - experimental testing is necessary for an
accurate determination of damping and natural frequencies of a few components
of the system; 2 - the supporting frames were found to be highly flexible,
particularly the central 150 kV post-insulators and bars, responding to seis
mic loads with very large deflections.

In order to improve seismic safety the design of these type of frames
should be controlled by the deflections allowed.

INTRODUCTION

Substations are critical facilities in the distribution of electric
power. Malfunction of one of these facilities inside a network, normally cau
ses tremendous economic loss to the community. That is what happened to the
Sylmar Coverter Station and the Switching Station in California which were
badly damaged during the 1971 San Fernando earthquake (Ref. 1), with an esti -
mated dollar loss of 28 millions. The first station was out of service for
more than one year.

To start a program of retrofiting old substations in Portugal under elec
trodynamic and seismic loads, a selection of two substations being built at
sites near Lisbon was made with the aim of developing a methodology of analy-
sis for assessing their present safety and to provide consequent reinforce -
ment.

This paper emphasizes the seismic study of 400, 220 and 150 kV busbars
carried out at LNEC.

DESCRIPTION OF THE STRUCTURES

The 400, 220 and 150 kV busbars are all alike in general structural
terms, with differences in dimensions and detailing of member components.
Each one is formed by a group of parallel frames (in one case up to 20), evenly
spaced, supporting by means of post-insulators, three aluminum pipe conduc -
tors, (bars), Fig 1. The one-bay frames, Fig 1 and 2, whose members are meta
lic elements, support three rigid porcelain insulators topped with connecting

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devices, (connectors). The design of the frames for each busbar is shown in Fig 2. It should be noted that the 400 kV frame members are made of light truss elements whereas the 220 and 150 kV's are made of channel sections laced with diaphragms. A picture of insulators and connectors is presented in Fig 3 a (400 kV) and 3 b (150 kV). Each insulator is formed by porcelain units joined with glue to metalic connections. They differ from busbar to busbar in number and size of units. The 400 and 220 kV connectors, Fig 3 a, very similar to each other, are provided with rollers and allow quasi-free axial movements and rotations. For these two busbars the bars are simple supported between adjacent frames. In the 150 kV busbar the connectors have no rollers and the bars are two span continuous beams. Table I contains general dimensions, geometry and weight of elements, and elastic properties of materials. A more complete description is given in (Ref. 2). Soil at the sites show geotecnic characteristics of shallow soft layer.

EXPERIMENTAL DETERMINATION OF DYNAMIC PROPERTIES

The dynamic behavior of the whole system was studied by testing separately (i) the porcelain insulators, (ii) the connectors and (iii) the prototype system at the site (frame+insulators and frame+insulators+bars).

Frequencies, mode shapes and damping ratios of insulators were measured using a shaking table under harmonic displacement control (0-100 Hz). Fig 4 presents a typical transfer function (displacement amplitude at a given point/displacement amplitude at the table, versus exciting frequency), and three mode shapes of the 400 kV insulator. Free vibration tests performed by a sudden release of an applied load at the top of the insulator, give similar results for the 1st frequency but lower damping ratio, (Table II). Due to the hetero geneity of materials and complexity of geometry of the units, the experimental characterization was shown to be absolutely necessary. The frequencies of insulators are high above the frequencies of the overall system, in a spectral region with very small ordinates of seismic loads.

400 and 220 kV connectors were statically tested in the lab to study the behavior of their rollers under the weight of the bars and to evaluate the spring constants existing between adjacent bars: an horizontal load, F_H, was applied to one bar (span), the adjacent ones being kept fixed, and its displacement, X, measured, Fig 5 a. One can see that the load for which friction is replaced by rolling ("yielding") is around 150 kgf for the 400 kV connector and 75 kgf for the 220 kV's (the installed vertical forces, Fv were the correspondent to the weight of bars). The 150 kV connector was tested under static and dynamic loading to simulate the expected motion due to seismic action. The tests, run in a few specimens, were conducted until failure. Fig 5 b shows the result of a dynamic test for a monotonic increasing amplitude (f=0.5 Hz). It should be referred that the material (duraluminum) is highly brittle, and the decrease of stiffness is due to the formation of a crack in the upper side of the section. Tests were not in sufficient number to make any evidence on low cycle fatigue.

The characterization of the prototype was obtained from a two-phase experimental forced vibration study performed at the site using a mechanical shaker acting in the longitudinal and transverse direction (0-8 Hz). The tests were first carried out on a single 400 kV frame with its three insulators installed. Due to the advance of the construction, these tests were not done in the 220 and 150 kV busbars. After the bars had been assembled, the complete system was tested again, Fig 1. While the first phase was useful to check

the elastic properties of the frames and see the influence of foundation, the second was important to analyse the interaction between frames due to the bars, to comprove the properties and efficiency of connectors, particularly the "yielding" of rollers and to check the overall behavior of prototype. "Normalized" displacement transfer functions (displacement/square of exciting frequency) were obtained for different locations in the structure. Fig 6 presents typical ones for longitudinal and transversal directions. Frequencies and damping ratios obtained from transfer functions and from free vibrations tests are summarized in Table II. It would be possible to evaluate damping ratios for a few different modes of vibration. However, it seemed more realistic, in view of the dynamic analysis that follows, to simply assess the range of damping factors. The following points should be emphasized: a) it was possible to detect the first 5 modes of vibration of each busbar; b) the modes of vibration are differently ordered in the three busbars; c) the damping ratio for the lowest mode, obtained using different methods, is very small, below 1%, despite one or more cables are free installed inside the pipes; d) rollers yield for values approximately identical to the ones obtained in the static test, and consequently bars and connectors do not show relative displacement below those values; e) 150 kV connectors are very much affected by the lowest mode of vibration which corresponds to the torsion of the beam; f) rocking of footing is neglectable.

ANALYTICAL MODEL

Three dimensional beam elements were used to represent the structural system, Fig 8. This corresponds to the minimum number of elements needed to induce the participation of a reasonable number of modes of vibration. The 6 - geometric properties of each frame beam element were obtained from a detailed study of a significant portion of the 3 - dimensional truss structure. The elastic properties of the equivalent insulator beam element were derived to have a cantilever with the natural frequencies measured during the experimental test (i).

Using a standard linear program, SAP IV (Ref.3), mode shapes and frequencies were computed. Comparison between analytical results and experimental determinations are shown in (Table II b). Maximum differences range from about 1% at the first mode to about 5% for higher modes. However the analytical value for the lower frequency of the 150 and 220 kV busbar did not coincide with measured one, because of the great difficulty in correctly assessing the torsional characteristics of the frame beam (2 paralel channel sections laced by evenly spaced diaphragms). From this result and taking into account the observed inverted pendulum behavior of central bars, equivalent torsional inertia was derived. Two points should be mentioned: a) quite good agreement between experimental and analytical results for the 5 lower frequencies; b) large number of modes, some associated in clusters, in a relative narrow range of frequencies (more than 10 below 5 Hz) Fig 8.

STRUCTURAL RESPONSE TO SEISMIC LOADS

Due to the importance of both these substations to network reliability, and although the collapse of their structures does not envolve human threat, the consequences of a temporary malfunction are sufficient to recommend the use of a 1000 year mean return period seismic response spectrum, as proposed by the "New Portuguese Seismic Code" (Ref.4), with a peak acceleration of 175 cm/s^2, Fig 9. Maximum values of displacement, shears and bending moments

were computed using linear analysis (Ref.3) for the 3 - dimensional spectrum (soft soil and 2% damping ratio). The main results are summarized in (Table III) and emphasized: a) as maximum shears at the top of insulators for the 400, 220 kV busbars are below the yielding forces in the connectors, linearity of modeling is preserved; b) the frames are very flexible and induce, under seismic loads, large displacements due to flexion and torsion, specially in the longitudinal direction for the 220 and 150 kV central bars, comparing to test results shown in Fig 5 b.

A model similar to the one described above, but more adapted to the higher frequency content of the excitation, was used do study the dynamic behavior of busbars when subjected to electrodynamic loads resulting from maximum predictable values of short circuit current at short and medium term (Ref.2). The resulting stresses in insulators for the worst case, are approximatly 50% of the obtained in the seismic analysis.

FINAL REMARKS

The following general remarks can be drawn from this study: 1 - in earthquake-prone areas, detailed seismic safety analysis of busbar should be undertaken; 2 - experimental tests need to be done for assessing dynamic properties of the whole system, but for this type of structures, selected free vibration tests will be enough; 3 - seismic loads are much more critical than electrodynamic; 4 - the structures are very flexible and may create problems to adjacent elements. Consequently, it is advisable that this type of frame design is reviewed particularly in what regards the torsional capacity of beams.

ACKNOWLEDGMENTS

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TABLE I - Geometric and elastic characteristics of busbar members (kgf, cm)

DESCRIPTION	COLUMN OF FRAME			BEAM OF FRAME			POST-INSULATOR			BAR		
BUSBAR	150	220	400	150	220	400	150	220	400	150	220	400
LENGHT	657.5	705.0	871.0	600.0	800.0	1400.0	184.0	230.0	355.0	1100.0	1500.0	2400.0
OUTER DIAMETER	-	-	-	-	-	-	-	-	-	14.0	20.0	25.0
INNER DIAMETER	-	-	-	-	-	-	-	-	-	12.0	18.8	23.6*
CROSS AREA, Az	40.7	46.9	27.64	34.0	48.0	27.7	95.	116.0	185.0	40.8	36.6	84.0*
FLEXURAL INERTIA, Ix	13610.	32650.	1740.	4275.	6343.	17390.	687.	1065.	3250.	868.	1722.	4192.*
FLEXURAL INERTIA, Iy	1209.	1847.	25050.	728.	1850.	44440.	687.	1065.	3250.	868.	1722.	7466.*
TORSIONAL INERTIA, Iz	185.	300.	7155.	58.	152.	10070.	1374.	2130.	6500.	1736.	3444.	8400.
SHEAR AREA, Ax	22.6	19.3	5.0	16.9	24.2	5.0	81.0	98.0	158.0	20.4	18.3	42.0
SHEAR AREA, Ay	0.4	0.6	5.5	0.2	0.3	5.9	81.0	98.0	158.0	20.4	18.3	42.0
WEIGTH	263.	343.	360.	201.	348.	760.	109.	232.	393.	137.	170.	626.
YOUNG'S MODULUS	2. x 10^6			2. x 10^6			0.7 x 10^6			0.7 x 10^6		
POISSON COEFFICIENT	0.25			0.25			0.25			0.20		

*The section is stiffened in the vertical plane

TABLE II a) - Comparison of resonant frequencies (Hz) and damping ratios, ζ.

POST-INSULATOR	f1		f2	f3 (torsion)	f4	ζ
	free	forced				
400	6.8	6.3	32.	66.	98.	4%
220	-	9.0	42.	-	100.	-
150	-	16.5	96.5	-	100.	-

TABLE II b) - Frequencies of the sistem (Hz)

MODE NUMBER	150 kV			MODE NUMBER	220 kV			MODE NUMBER	400 kV	
	EXP.	ANAL.			EXP.	ANAL.			EXP.	ANAL.
1	0.97	0.96		1	0.86	0.84		1	0.83	0.81
2	1.53	1.47		2	1.38	1.33		2	-	1.15
3	-	1.68		3	1.50	1.49		3	1.33	1.17
4	2.7	2.59		4 - 6	-	2.20-2.22		4 - 6	-	1.20
5 - 7	2.9	2.77-2.79		7 - 8	-	1.92-1.94		7 - 8	-	1.21
8	-	2.84		9	-	2.36		9	-	1.64
9 - 10	-	3.45-3.53		10	2.59	2.39		10	-	1.95

TABLE III a) - (Overall stresses due to seismic loading) (kgf, cm)

	150	220	400	150	220	400	150	220	400	150	220	400	150	220	400	150	220	400
ELEMENT	N (AXIAL)			T_2 (TRANSVERSE)			T_3 (TRANSVERSE)			M_t (TORSION)			M_2 (BENDING)			M_3 (BENDING)		
1	284	365	557	249	350	660	238	340	509	81	173	9072	172872 / 120834	278222 / 198646	570100 / 424400	98784 / 44365	144746 / 62524	341700 / 150600
3	284	365	557	223	321	634	213	313	496	81	173	9072	70373 / 24226	121128 / 49450	281300 / 146100	20041 / 5904	18689 / 9376	40450 / 22360
5	12	156	35	107	150	340	132	206	239	3705	6260	43990	21903 / 9800	45423 / 19777	79380 / 37040	17659 / 7820	33820 / 14318	111800 / 51600
7	80	365	225	283	365	554	55	85	243	6993	11417	58660	3655 / 7733	6200 / 15885	43520 / 69190	77234 / 35143	130144 / 58731	343500 / 150590
8	64	364	177	283	364	557	44	62	206	6993	11417	58660	7733 / 13563	15885 / 27107	69190 / 134900	35143 / 9927	58731 / 22226	150500 / 50210
10	46	115	37	80	115	254	73	92	302	2930	4917	31010	12602 / 5908	20933 / 9572	99820 / 46200	12956 / 5657	24451 / 10163	83170 / 38300
21	25	14	58	12	14	34	22	29	110	18	50	175	8131 / 3705	15357 / 6260	87970 / 43990	6409 / 0	1017. / 0	41210 / 0
'23	13	17	57	14	17	36	17	23	77	0	0	0	6440 / 2930	12054 / 4917	61690 / 31010	7682 / 0	12514 / 0	42990 / 0

TABLE III b) - Displacements δ (cm)

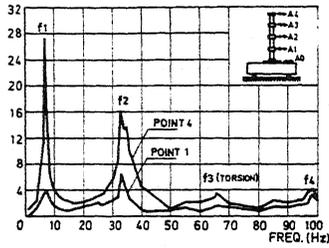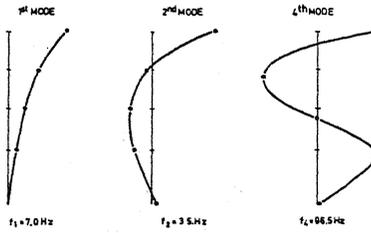| BUSBAR	NODES						16 (VERT)	21 (VERT)
	5 (T)	7 (T)	10 (T)	12 (T)	16 (T)	21 (T)		
150	1.4	2.3	1.7	9.7	6.4	4.6	1.1	1.8
220	1.3	2.9	1.6	11.0	8.0	5.6	1.6	2.0
400	5.2	9.6	6.1	12.6	11.3	7.8	3.8	4.0

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Figure 4 a) - Transfer functions for the 400 kV insulator.
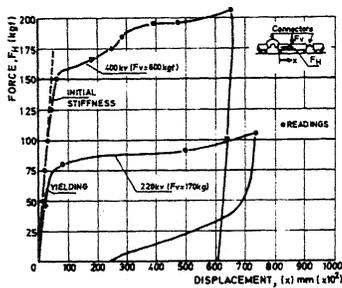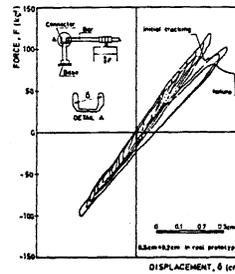
b) Three observed mode shapes

Figure 5 - Testing the connectors. a) Static on 400 and 220 kV;
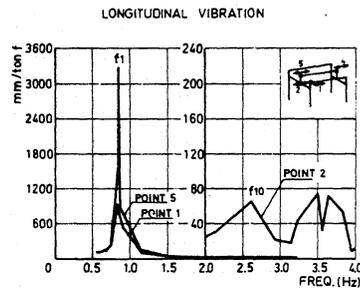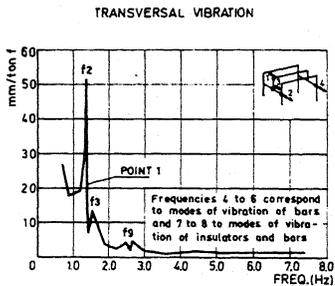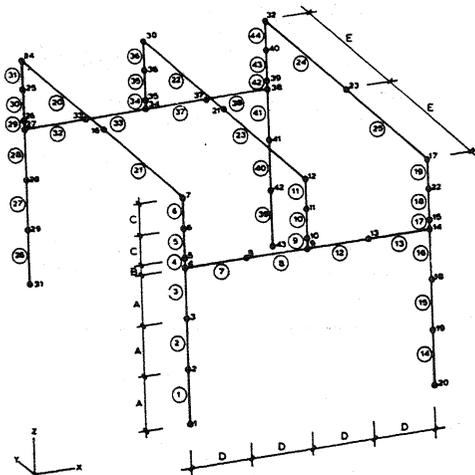
b) dynamic on the 150 kV

Figure 6 - "Normalized" transfer functions for the 220 kV busbar

(The mechanical shaker is located close to the central insulator's base)

	a	b	height of frame	height of insulator
400 kV	7.0	24.2	8.7	3.5
220 kV	4.0	15.2	7.1	2.3
150 kV	3.0	11.0	6.8	1.6

Figure 1 a) - General view of the 400 kV busbar;   b) plant view in sketch with general dimensions in meters

Figure 2 - Detailed design of frames a) 400 kV; b) 220 and 150 kV. The numbers (.) refer dimensions of the 150 kV.(Units in mm

Figure 3 - View of top elements of insulators and connectors a) 400 kV; b) 150 kV

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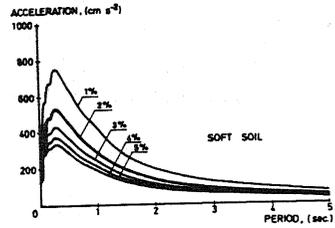|	A	B	C	D	E
400 kv	290.3	54.0	177.5	350.0	1200.0
220 kv	235.0	19.5	115.0	200.0	750.0
150 kv	225.2	19.5	92.0	150.0	550.0

units in cm

Figure 9 - Seismic response spectrum

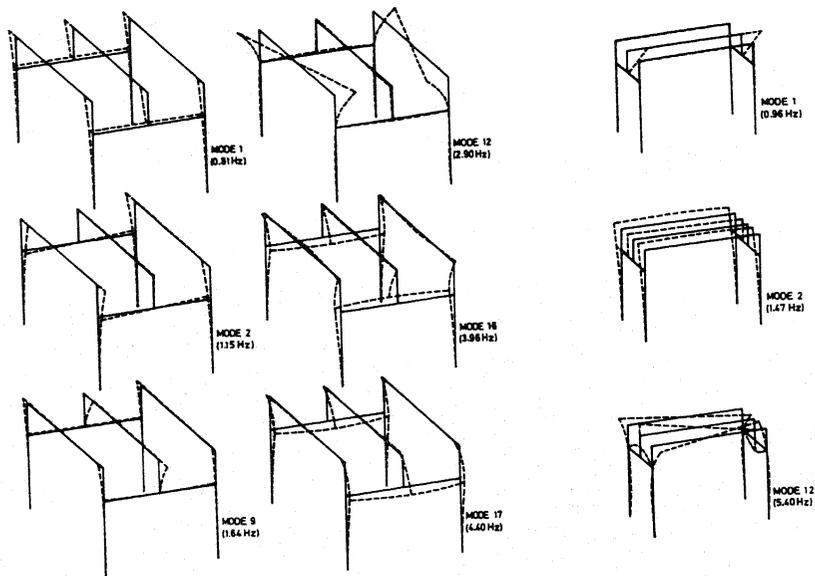Figure 7 - 3 Dimensional model of the analysed structure

Figure 8 a) - Principal mode shapes for the 400 kV busbar

Figure 8 b) - Typical mode shapes for the 150 kV busbar

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