ASEISMIC TESTS ON SOME ELECTRO-MECHANICAL SYSTEMS

by

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SYNOPSIS

Natural frequencies of some electro-mechanical systems estimated from aseismic tests in the laboratory are within earthquake frequency range of 2 to 15 cps while the same have increased beyond this range due to influences of supporting and foundation conditions at site as revealed by in situ tests. Moreover, these systems behaved satisfactorily during natural earthquake of Richter magnitude 7.0 and when subjected to simulated earthquake forces of 0.50 g (horizontal) and 0.25 g (vertical) on vibration tables.

INTRODUCTION

The Koyna earthquake of Dec. 10, 1967 demonstrated the need to study the dynamic behaviour of various electro-mechanical systems used in the power transmission network for their safety during such earthquakes. Similarly, the San Fernando Valley earthquake of Feb. 9, 1971 subjected many items of various systems to major damages. The observations and analyses of the various failures provided an opportunity to evaluate and improve upon existing procedures (1). Many agencies world-over have initiated the research programme to (i) develop improved design criteria and (ii) obtain experimental data on seismic responses by conducting forced vibration studies on electro-mechanical systems (2). This paper describes laboratory and in situ aseismic tests carried out for 20 electrical relays, 120 and 198 KV lightning arresters and 220 KV disconnecting switch of Koyna Hydroelectric Project (India) to (i) estimate their frequency responses and (ii) assess their capability of sustaining strong ground motions during earthquakes.

THEORETICAL ANALYSIS

A mathematical model describing the dynamic behaviour of an electro-mechanical system requires, alongwith the suitable mathematical framework, various parameters such as mass (m), coefficient of viscous damping (c) and spring constant (k) of the system. The equation for a single degree of freedom system consisting of these parameters and subjected to harmonic force $A \sin \omega t$ with amplitude, A and circular frequency, ω can be written as :

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$$m\ddot{x} + c\dot{x} + kx = A \sin \omega t \qquad \ldots (1)$$

Unknown variables in the above Eq.(1), viz., m, c and k can be estimated by indirect measurements such as exciting the system by means of a sinusoidally varying dynamic force or by any other type of force and measuring response of the system.

Dynamic amplification (X) of the system given in Eq.(1) can be written as :

$$X = \left\{ \left[1 - \left(\frac{\omega}{\omega_n} \right)^2 \right]^2 + \left[2D \frac{\omega}{\omega_n} \right]^2 \right\}^{-1/2} \qquad \ldots (2)$$

where,

ω_n = circular natural frequency of the system = $2\pi f_n$

f_n = natural frequency of the system

D = fraction of critical damping = $(f_2 - f_1)/2f_n$

f_2 and f_1 = frequencies at which the responses are 0.707 of the response at resonant frequency

Above Eq.(2) describes what is called as frequency response of the system. It is possible to estimate experimentally the natural frequency (f_n) and damping (D) from such responses.

PROTOTYPE LABORATORY TESTS

The Koyna earthquake of Dec. 10, 1967 had Richter magnitude 7.0 and maximum recorded epicentral acceleration 0.60 g with predominant frequency of about 10.0 cps in the ground motion as estimated from the accelerogram of above earthquake and its harmonic analysis (3). Significant frequency range of earthquake waves is expected to be from 3 to 15 cps in the epicentral region. Aseismic tests were confined to the predominant frequency range of 2 to 15 cps for 0.50 g (horizontal) and 0.25 g (vertical) accelerations. Vibration tables indigenously developed in this Research Station were used to simulate equivalent earthquake conditions. Details of the tables are given in Table I. The tables were excited by sinusoidally varying dynamic force produced either by an electrodynamic vibrator or by mechanically driven system. Fig.1 shows the photograph of vertical and horizontal vibration tables with lightning arresters. Natural frequencies of each system were first estimated by exciting the vibration tables at small amplitudes and then were subjected to specified horizontal and vertical accelerations and frequencies. Vibrations at each frequency were recorded at the tables as well as at the top of the system with the help of Askania Hand Vibrograph which is a versatile device for the purpose. Frequency response curves were plotted as dynamic amplification, X (ratio of amplitude at top of the system to that at table) against the frequency of vibration. Figs.2 to 6 show some typical frequency response curves for each system. No resonance was observed in vertical vibrations for all the systems studied in the expected frequency range. Fig.7 shows, for example, desired level of acceleration attained for 220 KV disconnecting switch. Natural frequencies and damping coefficients estimated under different experimental conditions are given in Table II.

PROTOTYPE IN SITU TESTS

A number of panels for relays are generally installed on a common foundation as per requirements in the power house. Similarly, lightning arresters and disconnecting switches are mounted well above the ground level under various supporting conditions to meet the safety requirements. The results, therefore, obtained from the laboratory tests where equipment was placed on the vibrating table do not represent actual dynamic behaviour of the system, specially of frequency responses. The erection set-up at site normally consists of an electrical equipment, steel frame support, concrete foundation and supporting soil. Theoretical analyses and experiments have shown that the earthquake response of the electro-mechanical systems depends remarkably upon the dynamic reaction coefficient of soil and concrete block (4). In order to verify experimentally the influences of such erection set-up on the response of the system, in situ aseismic tests were carried out on 220 KV disconnecting switches installed in the switchyard of underground Pophali Power House, Koyna H.E. Project (India). A powerful electrodynamic vibrator was fixed rigidly on the concrete foundation and was driven with a suitable power amplifier system. The vibrations were recorded by sensitive seismographs in both the horizontal components in the expected frequency range. Typical frequency response curve is shown in Fig.8. Dynamic characteristics estimated from response curves are also given in Table II.

DISCUSSIONS AND CONCLUSIONS

It is observed from Table II that the natural frequency of vibrating system, viz., Table-Panel-Relay in transverse component varies from 6.4 to 6.7 cps and that in longitudinal one varies from 7.5 to 9.0 cps and are within the earthquake frequency range for all the relays. The performances of relays under different experimental conditions are summarised below :

1. No. of relays did not trip or operate : 5 Nos. in horizontal component and 18 Nos. in vertical component
2. No. of relays did trip/tend to trip/operate in horizontal component at an acceleration less than 0.50 g = 11 Nos.
3. No. of relays did trip/tend to trip/operate in horizontal component at an acceleration greater than 0.50 g = 2 Nos.
4. No. of relays : contacts make and break/appearance of flag etc. in horizontal component at an acceleration less than 0.50 g = 2 Nos.
5. No. of relays did trip/operate in vertical component at an acceleration less than 0.25 g = 1 No. and at an acceleration greater than 0.25 g = 1 No.

It is further observed that the relays tripped/operated/ shown tendency to trip etc. did so at or around the resonant frequency of the vibrating system. This shows that though the simulated accelerations at the table were small (< 0.50 g), large displacements at the top of the panel due to resonance were mainly responsible for tripping etc. of the relays.

Aseismic tests performed on the electro-mechanical systems for 0.50 g (horizontal) and 0.25 g (vertical) accelerations in the frequency range of 2 to 15 cps have shown no adverse effects or distress in any form during the laboratory experiments. In Table II, the natural frequency of 198 KV lightning arrester as estimated in the laboratory in horizontal component (1.8 cps) is not within the earthquake frequency range of 2 to 15 cps while the same for 120 KV lightning arrester and 220 KV disconnecting switch are within this frequency range as observed in case of relays indicating possibility of their large response during earthquakes. On the other hand, prototype aseismic tests carried out on 220 KV disconnecting switch at Pophali switchyard have shown that under the supporting and foundation conditions prevailing there, the natural frequencies in horizontal components (21.0 and 19.5 cps) are beyond the earthquake frequency range indicating that the structure is rigid against the earthquake forces thus confirming their safe behaviour during the Koyna earthquake of Dec. 10, 1967. Hence, as stated earlier, the influences of steel frame support, concrete foundation and supporting soil are predominant in reducing the earthquake response of the system.

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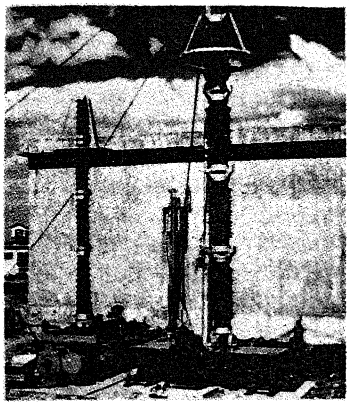

FIG. 1: VIBRATION TABLES WITH LIGHTNING ARRESTERS

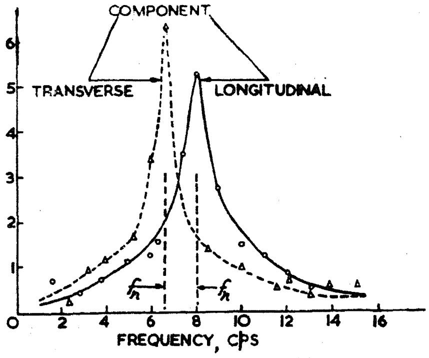

FIG. 2: RESPONSE OF RELAY

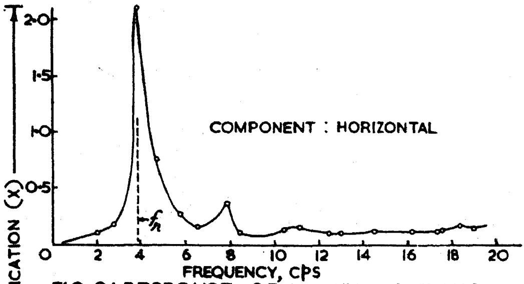

FIG. 3: RESPONSE OF 120 KV LIGHTNING ARRESTER

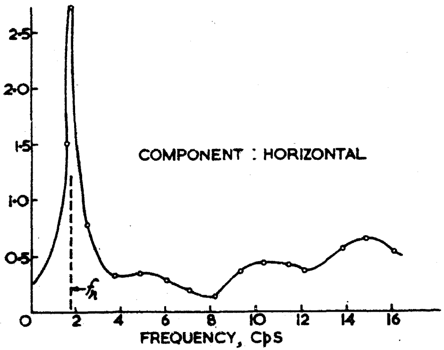

FIG. 4: RESPONSE OF 198 KV LIGHTNING ARRESTER

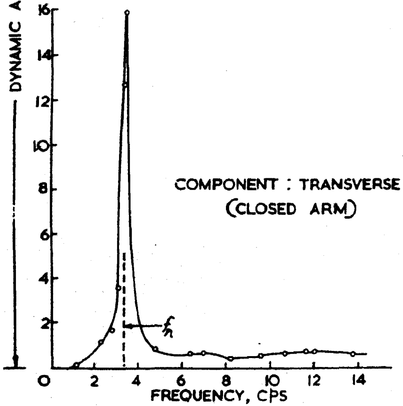

FIG. 5: RESPONSE OF 220 KV DISCONNECTING SWITCH

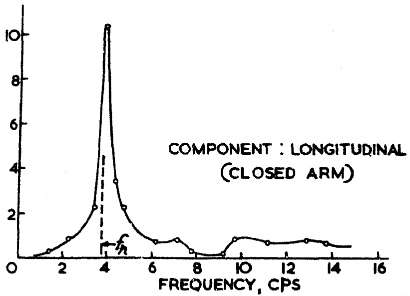

FIG. 6: RESPONSE OF 220 KV DISCONNECTING SWITCH

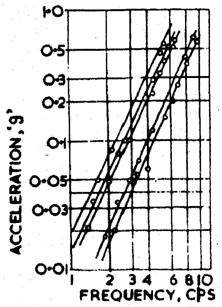

FIG. 7: TABLE ACCELERATION AGAINST FREQUENCY, 220 KV DISCONNECTING SWITCH

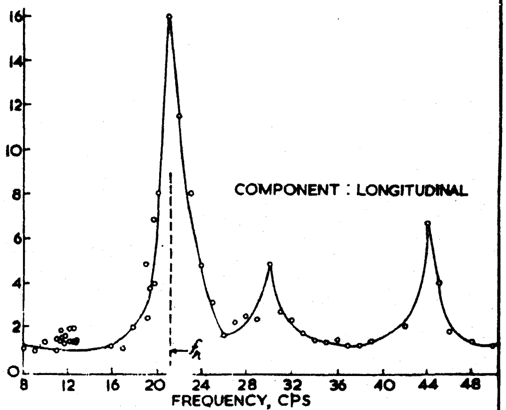

FIG. 8. RESPONSE OF 220 KV DISCONNECTING SWITCH (IN SITU)

TABLE I

Details of Vibration Tables

Type of Vibration Table	Component of Vibration	Dimensions	Frequency range, cps	Excitation
Rolling	Horizontal	2m x 1m	upto 15	Mechanical
Rolling	Horizontal	2m x 0.8m	upto 50	Electrodynamic
Spring mounted	Vertical	1m x 1m	upto 50	Mechanical

TABLE II

Typical Test Results Obtained from Laboratory and in situ Prototype Tests

Electro-mechanical system	Component	Natural frequency (f_n), cps	Damping, % of critical (D)	Condition of experiment
Electrical relays (mounted on panel)	Longitudinal(I)	7.5-9.0	-	Relays working under prototype conditions
	Transverse(II)	6.4-6.7	-	
	Vertical	>15.0	-	
120 KV Lightning Arrester	Horizontal	3.8	3.9	Grading ring attached
	Vertical	>15.0	-	
198 KV Lightning Arrester	Horizontal	1.8	3.6	-do-
	Vertical	>15.0	-	-do-
220 KV Disconnecting Switch (Laboratory)	Longitudinal	3.8	3.4	Closed arm
	Longitudinal	3.6	3.3	Open arm
	Transverse	3.3	3.0	Closed arm
	Transverse	3.4	3.8	Open arm
	Vertical	15.0	-	Open arm
220 KV Disconnecting Switch (In situ)	Longitudinal	21.0	2.4	Closed arm
	Transverse	19.5	2.0	Closed arm

I Longitudinal : Plane of relay/Arm of switch parallel to direction of force

II Transverse : Plane of relay/Arm of switch perpendicular to direction of force