A PROPOSAL FOR ASEISMIC DESIGN OF SUBSTATION APPARATUS AND THEIR FOUNDATIONS

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SUMMARY

This report discusses the aseismic design method of electrical substation equipments such as insulator type equipments and transformers. It is composed of:

(1) Propriety of two- or three-cycles of sinusoidal wave with the resonant frequency of equipment as design seismic motion.

(2) Proposal of a formula of the natural frequency f_0 of the foundation-subgrade coupled system, and derivation of a unique relationship between the ratio f_1/f_0 and the amplification of earthquake motion due to the presense of foundation.

(3) Effects of the dimensions of foundation on the response of equipment.

INTRODUCTION

In the Shizuoka Earthquake (1965, M 6.1) and Matsushiro Earthquak swarm (1965) which were of relatively small scale, the circuit breakers (168 kV class) which were designed according to the seismic coefficient method so that they would have a strength of safety factor of 2.4, 2.6 against a horizontal seismic coefficient of 0.5, sustained damage. Ever since, various seismic measures were taken and a dynamic aseismic design was employed.

However, in the earthquake occurred off Miyagi Prefecture on 12 June, 1978 (M 7.4), considerable damage occurred to electrical substation facilities so that the aseismic design was reexamined during the past one year.

In the Central Research Institute of Electric Power Industry (CRIEPI), study on the aseismic design of substation has been conducted with particular attention given to the following points.

(1) The substations are distributed extensively throughout the country and are constructed on the grounds of various subgrade conditions.

(2) The aseismic strength of substation equipment composed of brittle insulators is determined by the maximum value of response occurring under an earthquake.

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(3) Notwithstanding the intensive study so far carried out, it is by no means easy to determine the earthquake motion coming to a specified point.

(4) Substation equipments are commercial products which have to be manufactured at a plant with a certain level of aseismic strength.

This paper discusses the results obtained from the study on the aseismic design of electrical substation equipment under these conditions, incorporating the knowledges obtained in the 1978 Miyagiken-oki Earthquake.

DESIGN EARTHQUAKE MOTION

The aseismic strength of equipments can be determined by the maximum value of response generated during an earthquake. Thus, the design earthquake motion must be able to regenerate the response value equal to or greater than that generated by the real earthquake motion.

In order to examine the effect of the earthquake motion on the equipment response, the relationships between the maximum value of the acceleration response spectrum and the period giving that value were examined with 208 of observed earthquake motions and 341 of the substation ground motions culculated by the multi-reflection theory. The result is shown in Fig. 1. In Fig. 1 is also shown the response value to "N cycles of sinusoidal wave with the resonant frequency of equipment".

It will be seen from Fig. 1 that there is no earthquake wave showing greater response value than the input of 3 cycles of the sinusoidal wave with resonant frequency and that the earthquake waves showing greater response value than 2 cycles of the sinusoidal wave with resonant frequency are only less than 10% of the whole. That is, use of "2 or 3 cycles of the sinusoidal wave with resonant frequency of equipment" is considered to be appropriate. It may be considered, especially, from the engineering point of view that the responses to the input of 2 cycles of the sinusoidal wave reflect the actual situation.

DYNAMIC CHARACTERISTICS OF ELECTRIC SUBSTATION EQUIPMENT

The dynamic characteristics of substation equipment must be examined as a system including foundation and subgrade. In this paper, the subgrade supporting the foundation was represented by a model of spring and dash pot, and the model constants were obtained by the Half-space Theory.

natural frequency f_0 of the foundation - subgrade system

The insulator type equipment can be considered to be much smaller in weight than its foundation. Further, the bushing, which is regarded to be a weak point of the transformer to earthquake, is also much smaller in weight than the main body and its foundation. As the main body is rigid, the main body and its foundation can be regarded as the one rigid body, that is, corresponding to the foundation in case of the insulator type equipment. It may then be seen that the dynamic characteristics of the foundation-subgrade system affect the behavior of the equipment or bushing, greatly. As will be discussed later, the natural frequency f_0 of the foundation-subgrade system is one of the important factors for judgment of the earthquake resistance of the equipment. f_0 is given by the equation1)

$$(f_0/f_H)^2 = \frac{1}{2}(X \mp \sqrt{X^2 - 4Y}) \tag{1}$$

where $X = \frac{1}{i_0^2}[(1+\beta)e_0^2 + (1+\alpha)(S^2 + i_0^2) + \alpha L(\frac{L}{3} - S)]$

$Y = \frac{1}{i_0^2}[(1+\alpha)(1+\beta)e_0^2 + \alpha(1 + \frac{1}{4}\alpha)\frac{L^2}{3}]$

$e_0^2 = K_R/K_H$, $i_0^2 = I_G/M$, $f_H^2 = (\omega_H/2\pi)^2 = K_H/4\pi^2 M$

M : Mass of the foundation;
I_G : Mass moment of inertia around the axis of the center of gravity of foundation;
K_R, K_H : Subgrade rocking and horizontal spring constants acting upon the foundation bottom, respectively;
K_{RS}, K_{HS} : Subgrade rocking and horizontal spring constants acting upon the embedment of the foundation, respectively;
α : K_{HS}/K_H; β : K_{RS}/K_R; L : Embedment length;
S : Distance between the center of gravity and the bottom of the foundation;
complex symbol $\mp$ meaning the same order with the first and second natural frequencies

The equipment foundation has a shallow embedment and can be approximated as such having the whole foundation embedded in the form of a cube. Using the Baranov's solution and the Barkan's solution, the natural frequency f_0 of the foundation-subgrade coupled system of any foundation is obtainable by the approximate equation

$$f_o = KV_s\sqrt{\frac{1}{c\sqrt{A}} + \frac{\gamma\sqrt{\pi}}{A}} \tag{2}$$

where V_S : Subgrade S wave velocity;
A : Bottom area (= a x b);
c : Foundation height (= Length of embedment);
γ : Increment of the coefficient of horizontal reaction per unit length of embedment against equivalent radius, or a value of 0.8 may be taken; and

$$K = \sqrt{\frac{1}{2\pi^{3/2}} \frac{1}{2-\nu} \frac{\rho_s}{\rho_o}}$$

ν : Poisson's ratio of subgrade,
ρ_S : Subgrade density
ρ_c : Foundation density.

Eq. (1) or (2) is for estimation of f_0 of direct foundations. But, in case of the pile foundations such as substation equipment foundation in scale, it is shown from some experiments[2)] that Eq. (1) or (2) is usable.

insulator type equipment (ABB, PD, Arr, Isolator, etc.)

An analytical model of insulator type equipment is shown in Fig. 2. The equipment is simplified into a model allowing reproduction of only the primary resonant frequency.

In Fig. 3 is shown the ratio of the response value (x_1) of the equipment obtained as an equipment-foundation-subgrade system to the response value (x_0) of the equipment as a single unit, or x_1/x_C, as a function of the ratio of the natural frequency of equipment (f_1) to f_0, or f_1/f_0. Here, x_1/x_0 means the "rate of the amplification of earthquake motion due to presence of the foundation." From Fig. 3, and the results of examination under other conditions,[1),2)] it is found that if f_1/f_0 is about 0.5 or less, x_1/x_0 and f_1/f_0 show a unique relationship regardless of the earthquake wave, the natural frequency and damping ratio of equipment, dimensions of the foundation and the secondary wave velocity V_s of subgrade. As the result of investigation of the substation equipment of 275 kV class or higher, it is confirmed that f_1/f_0 0.3 is satisfied in the subgrade with V_s 150 m/sec or faster[3)] and the "rate of amplification due to presence of the foundation" is 1.2 or less.

Further, in the case of the insulator type equipment, the effect of the dimensions of foundation on the response of equipment is not appreciable so that it does not seem to be effective to execute the aseismic countermeasure by the alteration of the dimensions of foundation.

transformer

The transformer bushings of 275 kV class sustained damage due to the 1978 Miyagiken-Oki Earthquake. This fact pointed out that the weak point of the transformer to earthquake is present in the bushing. Thus it would be necessary to review the conventional design method. This problem is being examined now at the Society of Cooperative Research in Japan. But, in this paper, some of the findings obtained at CRIEPI are reported.

From the result of investigation of the damage in the Miyagi-Oki Earthquake, it was pointed out as one of the main causes that the rubber laid between the main body and the foundation for noise abatement formed a spring system and induced a rocking vibration to the transformer main body.[4)] Thus, the rubber had better be removed or locked from the standpoint of aseismic countermeasure. In this paper, the behaviors of the transformer without the rubber are discussed.

From the aseismic aspect, the transformer is characterized as follows,

(1) The transformer body may be regarded as a rigid body. Its weight is about 300 tons, and its center of gravity is located at a height of about 2 ~ 3 m above the foundation. Thus, even if the main body was fixed with the foundation, a rocking vibration is apt to occur as a body-foundation-subgrade system and there is, moreover, the possibility

of the resonant frequency f_0 to be below 10 Hz,

(2) The aseismic weak point is present in the bushing, which is composed of insulators and its resonant frequency distributes over 3 ~ 7 Hz,

(3) The bushing including its pocket can be tested using the shaking table, though it is impossible to test the full scale of transformer.

In order to estimate the input earthquake motion to the bushing, examination was made with a simplified model shown in Fig. 4.

An example of the relationship between the ratio of the response value (x_1) of the bushing obtained as a bushing-transformer main body-foundation-subgrade system to the response value (x_0) of the bushing single body or and the ratio of the natural frequency of bushing (f_1) to f_0 or f_1/f_0, is shown in Fig. 5. Here, x_1/x_0 means the "rate of amplification due to presence of the transformer body and foundation." It will be seen from Fig. 5 that there is a possibility for f_1/f_0 approaching to 1.0, different from that in the case of the insulator type equipment. This means that there is a possibility of the input to the bushing being amplified greatly in comparison with the earthquake motion on the ground surface. According to Fig. 5, the rate of amplification seems to be below about 2 times if the transformer was installed on the subgrade with V_s 150 m/s or faster.

In Fig. 6 is shown the effect of the dimensions of the foundation upon the amplification rate (x_1/x_0). Fig. 6 shows that the response of the transformer bushing is dependent particularly on the width of the foundation. Therefore, how to determine the width of the foundation is an important factor for aseismic design of the bushing.

CONCLUSIONS

From the results described in the foregoing, the conclusions were obtained as follows.

(1) For the insulator type equipment, there is proposed a procedure of the aseismic design upon the concept of f_1/f_0 ratio as Fig. 7.

(2) For the transformer, the aseismic weak point is present in the bushing and about 2 times or less of the acceleration amplitude of earthquake ground motion can be used as the input to the bushing, as a tentative value. But, the input of the 2 ~ 3 cycles of sinusoidal wave, must be reesamined including the amplification mentioned above after this, as it is supposed that the earthquake ground motion alters on propagating the subgrade-foundation-transformer body system of which f_1/f_0 may approach to 1.

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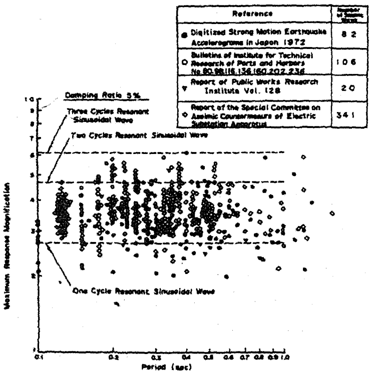


Fig.1 Comparison between the Maximum Response Magnification to Actual Seismic Wave and the Response Magnification to Resonant Sinusoidal Wave

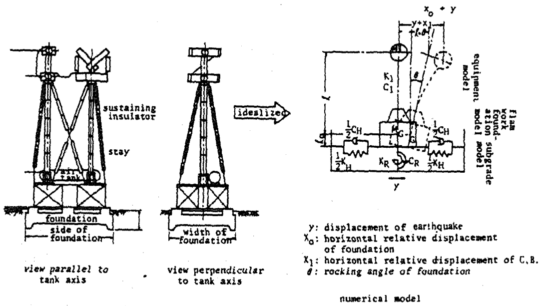
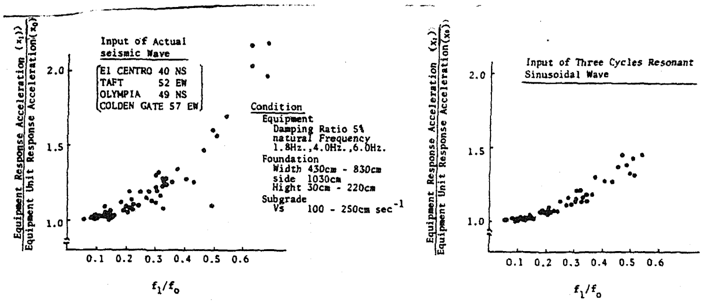
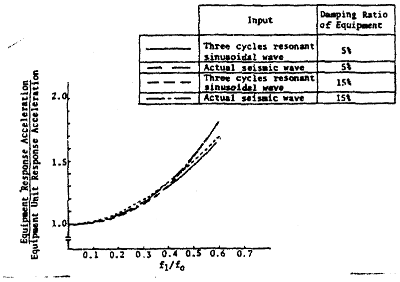


Fig.2 Equipment-Foundation-Subgrade Coupled System



(i)response value obtained by analysis



(ii)relationships between X_1/x_0 and f_1/f_0 obtained by the least square method for (i)

Fig.3 Amplification of Equipment Response due to Presence of Foundation

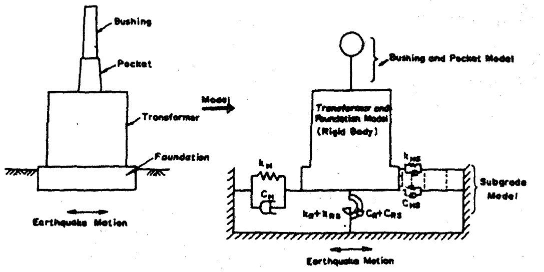


Fig.4 Transformer-Foundation-Subgrade System

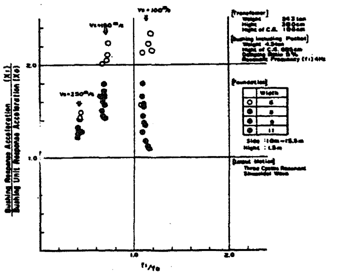


Fig.5 Amplification of Bushing Response due to Presence of the Transformer Body and Foundation

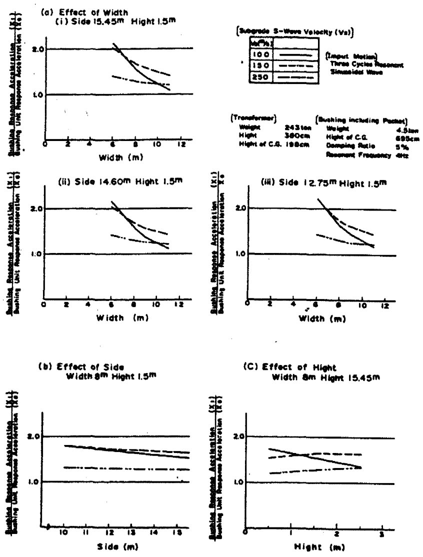


Fig.6 Effect of Dimentions of Foundation on Amplification

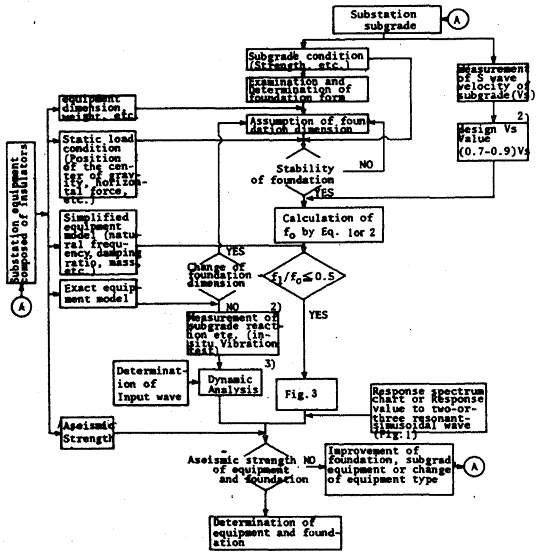


Fig.7 Flow Chart of Aseismic Design of Insulator Type Equipment