NUMERICAL SIMULATION OF SEISMIC RESPONSE OF A BASE-ISOLATED POWER TRANSFORMER

Bridgestone Corporation, Japan Member ○ Nobuo MUROTA
University of California at Irvine, USA Member Maria Q. FENG
National Center for Research on Earthquake Engineering, Taiwan Member Gee-Yu LIU

1. Introduction

Power transformers of substations, which is one of the crucial equipment in electrical power network, sustained significant damage in recent destructive earthquakes, and base isolation is considered as one of the possible measures for seismic protection of the transformers. Tri-axial earthquake simulator testing with a large-size model of a transformer with bushing was conducted with two different types of isolation systems, a sliding bearing (SLB) system and a high-damping rubber bearing (HDR) system [Murota et al., 2000 and 2003]. Through the tests, the effectiveness of the base isolation system in reducing the response of the power transformers was demonstrated. However, during the tests with SLB systems under tri-axial shaking, the acceleration at the top of bushing was amplified, whereas no amplification phenomenon was observed with HDR system. It was deduced that the friction force generated by high-frequency vertical vibration under tri-axial shaking stimulated the high-frequent mode of bushings. In this paper, results of analytical study on the amplification phenomenon of bushing top conducted by non-linear time history analysis using numerical model of an existing transformer was described.

2. Numerical Model of Power Transformer and Base Isolation Systems

The selected system was in the Tottori-prefecture, Japan, damaged in the 2000 Tottori-ken Seibu Earthquake, as introduced in [Sato et al, 2002]. The transformer system, fixed-base, was a 500 kV/220 kV size installed in an ultra-high voltage substation, located about 5 km to the northeast of the epicenter. The secondary-bushing (220 kV), which was fractured at the fixed end, was the target of this simulation. The model of the system is shown in Figure 1. The bushings had lengths of 5.788 m and a total weight of 5.99 kN. The weight of the transformer body was 1784.7 kN. Modal damping of 5 % was considered for all modes. HDR system and SLB system, which consists of sliding bearings and low damping rubber bearings for restoring elements, were designed for comparison. The natural period of the HDR system at displacement of 135 mm, which agree with shear strain of 100% of the rubber bearing, was computed as 1.60 seconds. Equivalent damping ratio of HDR was around 16% at 100% strain. The periods of 1st mode for fixed-base and base-isolated systems were 0.125 seconds and 1.59 seconds, respectively. The friction coefficient of SLB system was designed as 0.073 and the stiffness of low-damping rubber bearing was set as 0.958 kN/mm so as to have same bi-linear characteristics of HDR system.

Ground motion for analysis was; Art-693, 1941 El Centro-(NS,UD) 1995 Kobe (Takatori)- (EW,UD). Intensity of the PGA for each motion was unified as 0.5g in x-direction, and 0.4g in z-direction.Art-693 was the artificially generated wave based on the Required Response Spectrum IEEE-693 [IEEE, 1998]. The phase angles of the composed waves were randomly chosen and superimposed. The simulation was carried out with a commercial program, SAP2000 Nonlinear (Computers and Structures Inc). The nonlinear element for HDR systems used in this analysis was based on the research of Wen (1976). The horizontal force characteristics of SLB model is linked with the vertical load through friction coefficient. The friction force F_s, friction coefficient μ_d of SLB is related with vertical load P_v as follows (Constantinou et al., 1990):

$$F_s = \mu_d \cdot P_v \tag{1}$$

$$\mu_d = \psi - (\psi - 1) \cdot \exp(-a \cdot v), \quad \psi = \mu_{\max} / \mu_0 \tag{2a,b}$$

where, $\mu_{\max}$: maximum friction coeff., μ_0 : minimum friction coeff. under low rate sliding, a : constant

In this simulation, each parameter was set as $\psi = 1.02$, and a =0.08.

3. Results

Response acceleration at the bushing-top, the transformer-top, and the transformer-bottom (just above isolation system), of fixed-base, base-isolated using HDR, and base-isolated using SLB under x-0.5g z-0.4g shaking of three different earthquakes are compared in Figure 2, and hysteresis curve of SLB system with μ_d =0.073 is shown in Figure 3. The hysteresis curve indicates the high-frequent vibration of friction force affected by vertical ground motion. In the fixed-base system, the amplification of the bushing-top exceeded 5.0. This level of acceleration will cause damage on the connection of the bushing to the sleeve. With the base-isolation system, the amplification was about 0.65, and displacement of the isolator was 250 mm. In the SLB system, the response at the bushing-top was stimulated up to 1.17 g, which had been indicated in the previous earthquake simulator test.

The effect of friction coefficient of sliding bearing to the response of transformer/bushing was studied. The results are summarized in Figure 4. It is interesting to note the response amplification will become smaller when the friction coefficient becomes smaller. Displacement becomes larger as friction coefficient becomes smaller. However, the displacement in friction coefficient of 0.03 was 262mm, and was still acceptable for the isolation system. The lower friction coefficient, such as 0.03, is desired for sliding bearing system of transformers.

Key words : Base Isolation, Power Transformer, Bushing, High-Damping Rubber Bearing, Sliding Bearing
Address : 1 Kashio-Cho, Totsuka-Ku, Yokohama-Shi, Kanagawa-Ken, Japan, TEL 045-825-7543, FAX 045-825-7676
e-mail : murota-n@bridgestone.co.jp

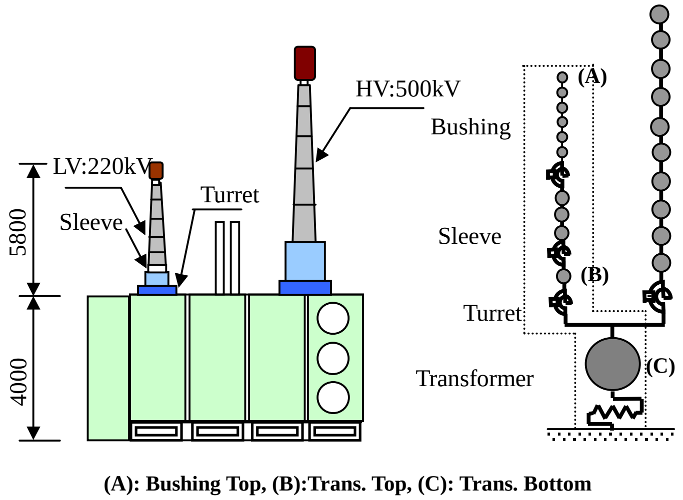

Figure 1. 220kV/500kV Transformer

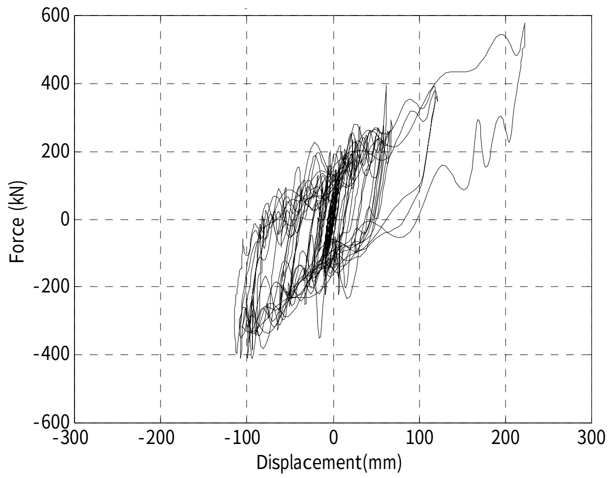

Figure 3. Hysteresis Curve of SLB under Art-693 x-0.5g/z-0.4g, μ=0.073

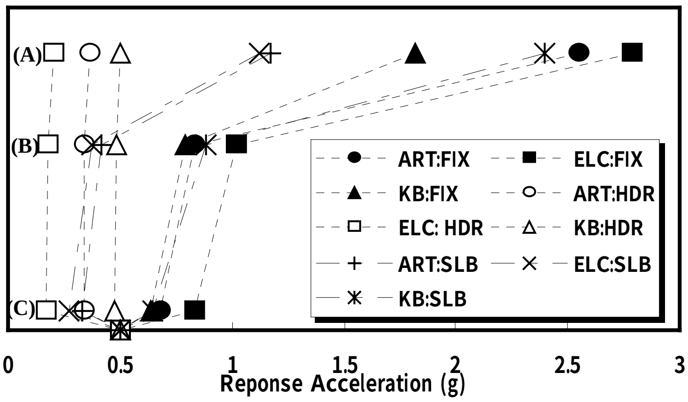

Figure 2. Comparison of Response Acceleration in x-dir. of Each Case

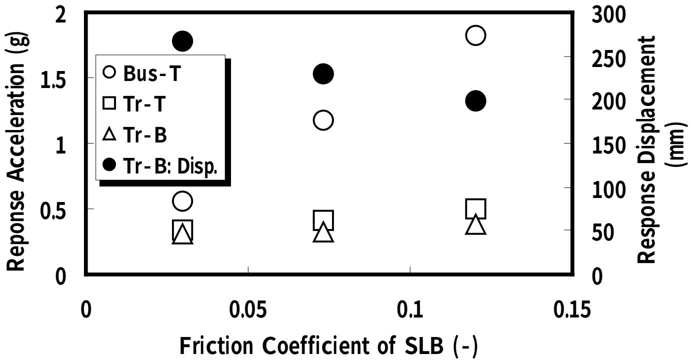

Figure 4. Effect of Friction Coefficient of SLB on Response Acc.&Disp. of System / Art-693 x-0.5g z-0.4g

4. Conclusions

A case study of an existing power transformer system was studied by a time-history analysis. Detailed information of the transformer/bushing system was obtained from the literature, and an isolation system was designed for this study. Artificial waves based on the response spectrum of IEEE-693, 1940 El Centro, and 1995 Kobe (Takatori) were used as ground motions. In the base-isolated system with segmented high-damping rubber bearings (HDR), the peak response acceleration at the top of bushing was 60% of PGA, whereas in the fixed-base system it was more than 5 times PGA. However, as predicted in the sliding bearing system, the acceleration at the bushing top was amplified and the peak acceleration was about 2 times PGA. The sliding systems with different friction coefficients, 0.04 and 0.16, were subjected to simulation. The results show that the lower friction coefficient will keep the amplification of the acceleration at the bushing low with some increase in displacement. The low friction system is desired as an optimized solution of the sliding system for protection of power transformers.

References

- Murota N., Feng M.Q. (2001), “Hybrid Base-Isolation of Bushing-Transformer Systems”, *Proceedings, 2001 Structures Congress*, ASCE, Washington, DC, May 21-23
- Murota N., Feng M.Q., and Liu G-Y. (2003), “Experimental and Analytical Study of Base-Isolated Power Transformers”, *ATC 29-2-1 Seminar on Seismic Design, Performance, and Retrofit of Nonstructural Components in Critical Facilities*, Newport Beach, California, October 23-24
- Sato H., Sato K., Tohma J., and Higashi S. (2002), “Estimation of Strong Ground Motion Using KIK-NET Records and its Application for Investigation of the Cause of Structure Damage – A Case Study of Electrical Substation Structure Damage during the 2000 Tottori-ken-Seibu Earthquake”, *AIJ J.Technol.Des*, No.15, p93-98, Jun
- IEEE (1998), *IEEE Std 693-1997*, “Recommended Practices for Seismic Design of Substations”, Piscataway, N.J.: IEEE Standard Department
- Wen Y.K. (1976), “Method of Random Vibration of Hysteretic Systems”, *Journal of Engineering, Mechanical Division*, ASCE, 102(EM2), 249-263
- Constantinou M.C., Nokha A., and Reinhorn A.M. (1990), “Teflon Bearings in Base Isolation II: Modeling”, *Journal of Structural Engineering*, ASCE, 116(2), 455-474