Proposed Input Waves for Seismic Design of Power Substation Equipments

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SUMMARY
Dynamic analysis of the seismic performance of power substation equipment is time-consuming, expensive and uses responses that are sensitive to ground motion. This research proposes a method to derive input waves for dynamic analysis in place of original records from seismic events in Iran. In this study, a power transformer, current transformer, circuit breaker and disconnect switch are analyzed using fifty records from the far-field and near-field earthquake ground motions. Statistical analysis is done on the maximum acceleration and displacement responses to obtain their pushover curves. Sinusoidal waves were created using the fundamental frequencies of the equipments and PGA of 0.1g through 0.5 g as the amplitude. The results are compared with the original records and show that the proposed input waves provide a reasonable fit for an extensive range of near-field and far-field ground motion results.

Keywords: Input wave, Seismic design, Power substation equipments

1. INTRODUCTION

Electricity network facilities are among the most important lifelines that after the disaster such as earthquake, needs not only for lighting, heating, ventilation systems, but continue to operate the telecommunications and transportation and all land and air traffic control systems, as well as commercial and industrial activities associated with their electricity supply. As in general, in the past earthquakes in whole the world, power substations were as the most vulnerable element among all elements of a power supply system [Anshel, 1999]. For example, Figure 1.1 shows damage to high voltage equipments of Caopo Power Plant in the 2008 Wenchuan earthquake in China. In this research, seismic behavior and seismic evaluation procedures have been studied which employed for the main equipments of power substations, with the main emphasis on power transformer, current transformer, live-tank circuit breaker and disconnecting switch. Generally, this research provides input waves for dynamic analysis of electrical substation equipments in Iran. For this purpose, fifty past major earthquake ground motion records with scale over six magnitudes and in two domains namely far field and near field have been collected from Iran Strong Motion Network (ISMN) [BHRC, 2011].

2. METHODOLOGY

Ground motions in near field have more limited frequency domain compared to ground motions which recorded in far field and its energy have been transmitted in limited frequency domain. In this case, the major elastic seismic energy has been transmitted with intense pulse and with long periods which occurs usually at the beginning of the record. Other effects of the strong long-period pulses in ground motions recorded in near field are that strong motion time history of those earthquakes is out of broad band and become as pulse-like. This means that spectral domain in their Fourier spectrum has the maximum value in a very small range or to a specific period, instead of an extensive range of periods. Another criterion for near field recorded motions which are near field earthquakes have been referred to areas that their distance from earthquake center is less than a certain extent. A number of researchers considered this distance limit to be equal to 20 km and others notify 15km [Sharif, 2002].

Figure 1.1 Damage to high voltage equipments in Caopo Power Plant in the 2008 Wenchuan, China earthquake [China Earthquake Administration, 2008]

General characteristics of the near field ground motions can be summarized as: these records have typically higher ratio of PGV to PGA compared to records in far field; moreover, they have pulse-like motion especially at the beginning of the record and further have seismic energy in a short time. The ground motions are classified in two groups namely near field and far field records. Longitudinal acceleration, velocity and displacement generate an impact force to the structures, ratio of vertical peak acceleration to horizontal peak acceleration in these records are more than those in far field [Sharif, 2002]. Acceleration, velocity and displacement histories of the 1990 Rodbar-Manjil (Ab-bar station) and the 1978 Tabas earthquakes as far field records and the 2003 Bam earthquake as near field records are illustrated in Figures 2.1 to 2.3.

The aforementioned equipments modeled by 3-D finite-element method and after performance modal analysis to obtain natural frequency; these models have been analyzed under the collection records by time-history analysis. The Maximum results of displacement and acceleration in critical situations were recorded under far field and near field ground motions. Japan Electric Association Guideline, JEAG-5003-1999, developed a technique to derive input waves for dynamic analysis power substation equipments in place of original records from seismic events in Japan [JEA, 1999]. The technique is derived based on 615 recorded ground motions of past earthquakes in Japan as shown in Figure 2.4 [JEA, 1999].

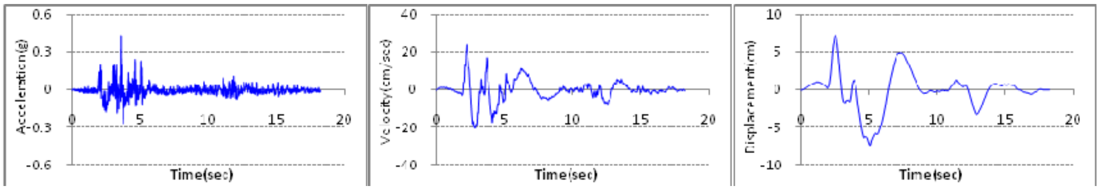

Figure 2.1 Acceleration, velocity and displacement histories of the 1990 Rodbar-Manjil earthquake (Ab-bar station)

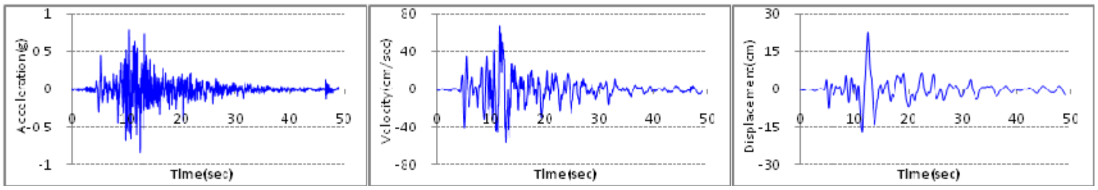

Figure 2.2 Acceleration, velocity and displacement histories of the 1978 Tabas earthquake

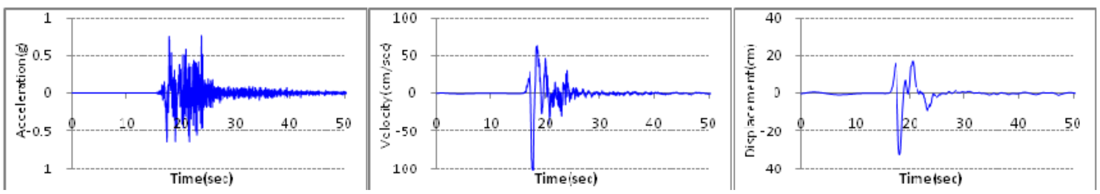

Figure 2.3 Acceleration, velocity and displacement histories of the 2003 Bam earthquake

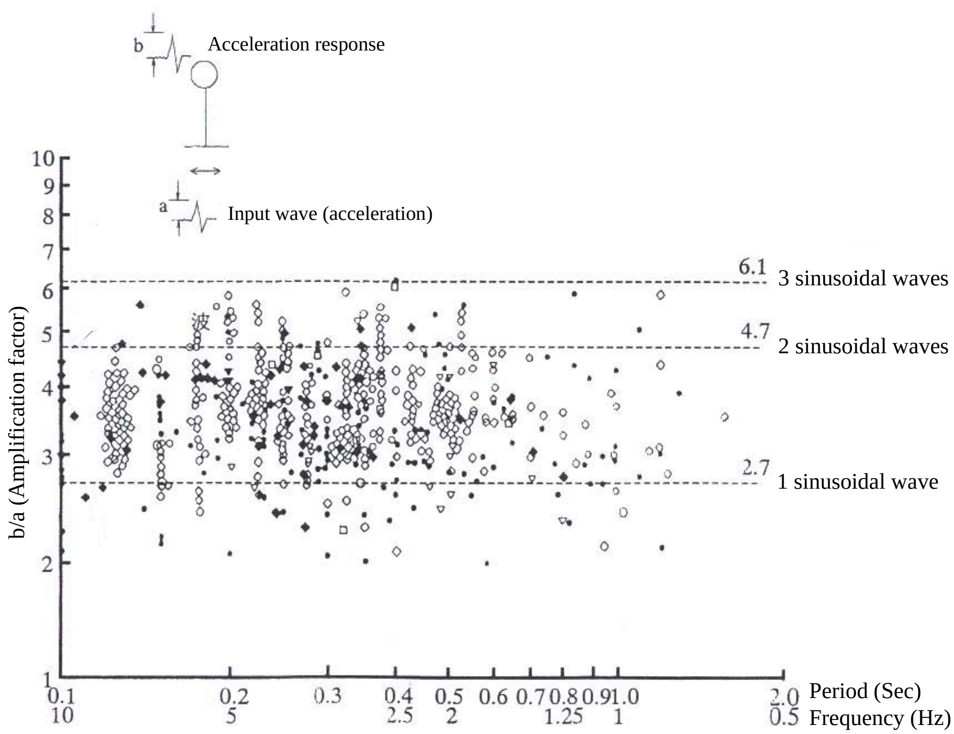

Figure 2.4 Amplification factor for one, two and three waves by fundamental frequency with PGA of 0.5g for a single-freedom degree structure and comparison with 615 recorded ground motions of past earthquakes in Japan [JEA, 1999]

In the next stage, similar to the technique that purposed by JEAG-5003-1999, sinusoidal waves by fundamental frequency with PGAs as amplitude of the sin waves were created. The recommended technique by the Japanese Guideline is developed for one-freedom-degree system composed of lumped mass and spring for the substation equipments as complicated equipments by various elements. In this study, the actual equipments are completely modeled by 3-D FEM in order to verify the technique for Iran. In the next stage, the results obtained from analysis under fifty actual records and the sin waves are compared, in far field and near field categories to propose the final appropriate sinusoidal wave for the equipments. The last issue is not taken into account in the Japan Guideline.

3. MODELING THE EQUIPMENT

The finite-element method provides a suitable platform to perform additional studies for more reasonable evaluation of the equipments response characteristics. Functionally, important equipments within a power substation are power transformer, current transformer, live-tank circuit breaker and disconnecting switch [Bastami, 2007]. In this study, these equipments are modeled by 3-D finite-element method.

All components of the equipments are modeled by proper structural elements. The transformer tank, reservoirs, steel pockets, porcelains and other plates are modeled by the shell elements. Masses of the contained oil inside the transformer and reservoir were added to the masses of the transformer tank and reservoir. Braces, aluminum conductors, and stiffeners are modeled by beam elements. The core and coil inside the transformer are modeled as mass elements. The radiators are modeled by 3-D solid elements. Gaskets are continuous elements, which are modeled by dividing the area between the sixteen oriented elements. Tables 3.1 and 3.2 indicate several structural and geometry specifications of the equipments. Mechanical properties of the porcelains are based on results from an experimental study in International Institute of Earthquake Engineering and Seismology (IIEES) [Khalvati et al., 2011]. Figures 3.1 and 3.2 display finite-element modeling of the live-tank circuit breaker and disconnect switch. Time history analysis are carried out for the equipments under the fifty recorded ground motions which categorized into classes associated with near or far fields.

Table 3.1 Structural and geometry specifications of the 230-kv Power transformer

Specifications	Power Transformer
Dimensions of main tank (m)	2.55*7.7*3.9
Total height of bushing(m)	4.24
Height of porcelain part (m)	3.6
Thickness of top plate of main tank (mm)	20
Dimension of stiffener of main tank (cm)	Plate 0.2*.02
Modulus of elasticity of aluminum core (MPa)	71000
Modulus of elasticity of porcelain (MPa)	99800
Modulus of elasticity of gasket (MPa)	48
Diameter of porcelain at bottom (cm)	30
Thickness of porcelain (cm)	3
Diameter of aluminum core (cm)	3.05
Type of supports	Fixed
Number and size of volts in each support(mm)	4*M20

Table 3.2 Structural and geometry specifications of the 230-kv Current transformer, Disconnecting switch and Circuit breaker

Specifications	Current transformer	Disconnecting switch	Circuit breaker
Dimensions of main structure (m)	0.62*0.62	9.4*2.7	4.75*1.125
Height of main structure (m)	1.7	2.79	1.85
Total height of bushing (m)	3.65	2.45	4.02
Height of total system from the top of foundation (m)	6.2	5.24	5.87
Section of brace elements (mm)	L50*50*6	L45*45*4	L45*45*4
Section of column elements (mm)	L65*65*8	L100*100*10	L70*70*8
Modulus of elasticity of steel parts (MPa)	206,000	206,000	206,000
Modulus of elasticity of porcelain (MPa)	99,800	99,800	99,800
Diameter of porcelain at bottom (cm)	40.0	30.0	30.0
Thickness of porcelain (cm)	2.5	2.5	2.5
Diameter of head part of bushing (cm)	45	30	50
Number and size of volts in each facility(mm)	8*M16	16*M12	24*M14
Type of supports	Fixed	Fixed	Fixed

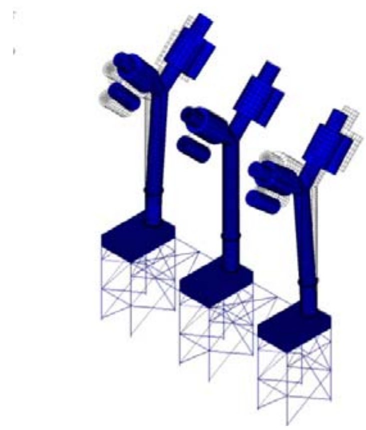

Figure 3.1 3D finite element model of live-tank circuit breaker

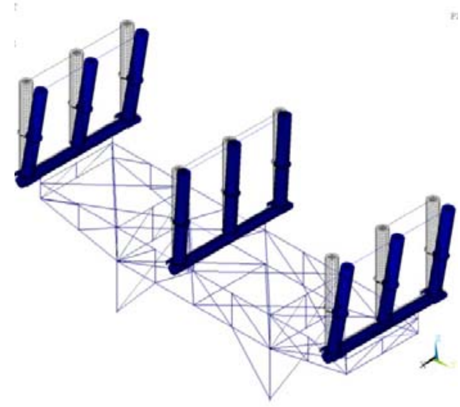

Figure 3.2 3D finite element model of disconnect switch

4. Proposed Input Waves

The technique developed by JEAG-5003-1999 intended to be used as the basis of a method to obtain seismic load in dynamic analysis for performance-based seismic design of insulator and bushing in Seismic Design Guideline of Electric Systems in Iran. Since the worst in dynamic behavior of structures happened when resonance occurred, a series of single, two and three sin waves for each equipment was created.

Frequency of the wave is the natural frequency of each equipment and amplitude is considered being equal to: 0.1g, 0.15g, 0.2g, 0.25g, 0.3g, 0.35g, 0.4g, 0.45g and 0.5g respectively. Since restriction on the movement of equipments at the highest level of bushing is important, this leads to the interaction with adjacent equipments. Value of the acceleration response is a parameter which is necessary for seismic design of the equipments. The maximum lateral translation and acceleration of the equipments at the highest levels under fifty ground motions records and sinusoidal waves are compared to obtain the appropriate input sine waves.

First, the displacement and acceleration in near field records with Sin waves and then the results in far field records are compared. Finally, based on the conventional method, to examine this issue the wave which covers median plus one standard deviation (in other words 84.1%) of displacement and acceleration responses (i.e. the most critical states), the results of this evaluation is summarized in Tables 4.1 and 4.2. Results of evaluation of full coverage of displacement responses and acceleration responses by sine waves are shown in Tables 4.3 and 4.4 respectively.

Table 4.1 Evaluation of coverage 84.1 percent of displacement responses by sine waves

Amplitude	Current transformer		Power transformer		Circuit breaker		Disconnect switch	
	2wave	3wave	2wave	3wave	2wave	3wave	2wave	3wave
0.1g	☒	☒	☒	☒	☒	☒	☒	☒
0.15g	☒	☒	☒	☒	☒	☒	☒	☒
0.2g	☒	☒	☒	☒	☑	☑	☒	☒
0.25g	☒	☒	☒	☑	☑	☑	☑	☑
0.3g	☒	☑	☒	☑	☑	☑	☑	☑
0.35g	☑	☑	☒	☑	☑	☑	☑	☑
0.4g	☑	☑	☑	☑	☑	☑	☑	☑
0.45g	☑	☑	☑	☑	☑	☑	☑	☑
0.5g	☑	☑	☑	☑	☑	☑	☑	☑

Table 4.2 Evaluation of coverage 84.1 percent of acceleration responses by sine waves

Amplitude	Current transformer		Power transformer		Circuit breaker		Disconnect switch	
	2wave	3wave	2wave	3wave	2wave	3wave	2wave	3wave
0.1g	☒	☒	☒	☒	☒	☒	☒	☒
0.15g	☒	☒	☒	☒	☒	☒	☒	☒
0.2g	☒	☒	☒	☒	☒	☒	☒	☒
0.25g	☒	☑	☒	☑	☑	☑	☑	☑
0.3g	☑	☑	☒	☑	☑	☑	☑	☑
0.35g	☑	☑	☒	☑	☑	☑	☑	☑
0.4g	☑	☑	☑	☑	☑	☑	☑	☑
0.45g	☑	☑	☑	☑	☑	☑	☑	☑
0.5g	☑	☑	☑	☑	☑	☑	☑	☑

Table 4.3 Evaluation of full coverage of displacement responses by sine waves

Amplitude	Current transformer		Power transformer		Circuit breaker		Disconnect switch	
	2wave	3wave	2wave	3wave	2wave	3wave	2wave	3wave
0.1g	☒	☒	☒	☒	☒	☒	☒	☒
0.15g	☒	☒	☒	☒	☒	☒	☒	☒
0.2g	☒	☒	☒	☒	☒	☒	☒	☒
0.25g	☒	☒	☒	☒	☒	☒	☒	☒
0.3g	☒	☒	☒	☒	☒	☒	☒	☒
0.35g	☒	☒	☒	☑	☒	☒	☒	☒
0.4g	☑	☑	☑	☑	☑	☑	☑	☑
0.45g	☑	☑	☑	☑	☑	☑	☑	☑
0.5g	☑	☑	☑	☑	☑	☑	☑	☑

Table 4.4 Evaluation of full coverage of acceleration responses by sine waves

Amplitude	Current transformer		Power transformer		Circuit breaker		Disconnect switch	
	2wave	3wave	2wave	3wave	2wave	3wave	2wave	3wave
0.1g	☒	☒	☒	☒	☒	☒	☒	☒
0.15g	☒	☒	☒	☒	☒	☒	☒	☒
0.2g	☒	☒	☒	☒	☒	☒	☒	☒
0.25g	☒	☒	☒	☒	☒	☒	☒	☒
0.3g	☒	☒	☒	☒	☒	☒	☒	☒
0.35g	☑	☑	☒	☑	☒	☒	☒	☒
0.4g	☑	☑	☑	☑	☑	☑	☑	☑
0.45g	☑	☑	☑	☑	☑	☑	☑	☑
0.5g	☑	☑	☑	☑	☑	☑	☑	☑

5. DISCUSSION AND CONCLUDING REMARKS

The recommended technique by the Japanese Guideline is developed for single-degree-freedom model which composed of lumped mass and spring for the substation equipments as complicated equipments by various elements. In this study, the actual equipments are completely modeled by 3-D FEM to verify the technique for Iran.

1. The results obtained from the analysis under fifty actual records and sin waves are compared together in far field and near field categories to find appropriate sin wave for the equipments which is not taken into consideration in the Japan Guideline.
2. Unlike the common procedure which the maximum acceleration is important in the criteria for seismic design; the results in several cases indicate more critical states as for displacement responses (e.g. current transformer). In this case, the equipment which is designed based on the maximum acceleration can be damaged due to the exceedance of the displacement at top of the insulator from the allowable limits. Since equipments in power substation are connected together with conductors, this is a highly significant issue which can easily cause damage to other connected equipments.
3. In general, the results in near field were at least two times higher compared to the results in far field, and these records can be employed to offer the proposal for a suitable input wave. The ratio of acceleration response in near field to far field for power transformer, current transformer, live-tank circuit breaker and disconnecting switch are obtained 2.45, 2.75, 2.66 and 2.78 respectively. This ratio for the displacement response in near field to far field for the equipments is obtained 2.38, 2.85, 2.84 and 2.83 respectively. The minimum amount in the both cases obtained for power transformer. As far as displacement is concerned, the mean value of these ratios for current transformer, live-tank circuit

breaker and disconnecting switch are 2.84 while it was 2.73 for acceleration.

4. The proposed input wave based on coverage 84.1 percent of the responses for seismic analysis and design of power transformer is two Sin waves with domain 0.4g or three Sin waves with domain 0.25g, and for current transformer, it is three Sin waves with domain 0.3g or two Sin waves with domain 0.35g, and for circuit breaker and disconnecting switch, it is obtained two or three sin waves with domain 0.25g. Furthermore, the proposed input wave based on full coverage of the responses for seismic analysis and design of power transformer is two Sin waves with domain 0.4g or three Sin waves with domain 0.35g, and for current transformer, circuit breaker and disconnecting switch is two or three Sin waves with domain 0.4g. It is noteworthy that the recommended input wave in Japan's Guideline for power transformer is three Sin waves with domain 0.5g, while for the other equipments is three Sin waves with domain 0.3g.

5. However, due to the diversity of the existing equipment in the country, more extensive studies are required.

REFERENCES

Anshel, S. (1999). "Guide to Improve Earthquake Performance of Electric Power Systems", ASCE

Bastami M. (2007). "Seismic Reliability of Power Supply System Based on Probabilistic Approach", PhD Thesis, Kobe University, Japan.

BHRC (Building & Housing Research Center), (2011), Iran Strong Motion Network (ISMN), Tehran, Iran.

China Earthquake Administration, (2008). General Introduction of Engineering damage of Wenchuan Ms 8.0 Earthquake. *Journal of Earthquake Engineering and Vibration*.**Vol. 28**, pp 81.

IEEE, (1997&2005): Recommended practices for seismic design of substations. IEEE Std. 693, IEEE Standards Dept., USA.

Japan Electric Association (JEA), (1999). "Earthquake Resistant Design Guideline for Electric Facilities in Power Substation". JEAG 5003-1999, Japan, (in Japanese).

Khalvati A.H., Hosseini M., and Mohammadpour S. (2011), Seismic Behavior of 63kV and 132kV Substation Post Insulators with Flexible Conductors, an Experimental Approach, *Journal of Seismology and Earthquake Engineering*. **Vol. 13**, **No. 2**.

Sharif, V. (2002). "Near-field earthquake effects on the dynamic behavior of structures", Seminar Report, International Institute of Earthquake Engineering and Seismology, Iran (in Persian).