Design of a Seismic Hazard Risk Assessment Model for EHV Transmission Grid

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Abstract. The Chi-Chi earthquake is one of the biggest earthquake occurred in Taiwan and caused a huge damage to the power system, especially the extra-high voltage (EHV) towers. Therefore, seismic hazards for EHV transmission towers should not be underestimated. In particular, earthquakes are especially a significant threat to EHV transmission towers in Taiwan. Thus, this study establishes a quantitative risk assessment model for the seismic hazard analysis on the EHV transmission tower. Fragility curves of EHV towers were established by nonlinear dynamic analysis to describe the probability of structures at different damage levels caused by earthquakes. The damage level of an EHV tower after an earthquake can be accurately estimated by the proposed model, and emergency repair operations can be arranged. In addition, before an earthquake occurs, the proposed model can be used as a tool for estimate the damage potential of EHV towers.

Keywords: Smart grid · Transmission tower · Seismic hazard risk assessment · Nonlinear dynamic analysis · Fragility curve

1 Introduction

Issues regarding power system stability, reliability, and the capability to recover from power failure incidents become more important nowadays. The extra-high voltage (EHV) transmission system, as a core, is the most important lifeline engineering structure for power systems, and its safety is paramount. Taiwan is located in the circum-Pacific seismic belt. Therefore, earthquakes frequently occur. Approximately 23,000 earthquakes strike Taiwan every year. Since 1901, Taiwan has been attacked by 101 disastrous earthquakes [1]. In 1999 a disastrous earthquake, which is the largest earthquake in Taiwan's history, occurred in Chi-Chi, Nantou County, and caused huge damage to Taiwan. The damage of transmission towers and distribution lines caused the Taipower Company losing NT$5.94 billion. And the social cost only in northern Taiwan brought by the constraints on electricity supply was estimated up to NT$63.68 billion [2, 3]. There were 3,741 EHV tower at that time, and a total of 307 EHV transmission towers were damaged by the earthquake [4]. The result showed that the

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damage of the EHV transmission towers by Chi-Chiearthquake is a unique and far-reaching form of the power system seismic damage in Taiwan [5].

The earthquake loss assessment was proposed to calculate the seismic hazard at all sites of interest and to convolve this hazard with the vulnerability of the exposed building stock such that the damage distribution of the structure stock can be predicted; damage ratios, which relate the cost of repair and replacement to the cost of demolition and replacement of the structures, can then be used to calculate the loss. Constructing an earthquake loss model involves compiling databases of earthquake activity, ground conditions, ground-motion prediction equations, building stock and infrastructure exposure, and vulnerability characteristics of the exposed inventory [6, 7]. For earthquake risk assessments, a fragility curve is used for determining the damage level of a structure and the potential of seismic hazard for a given area. The fragility curve can describe the probability of structures at different damage levels caused by an earthquake. Researchers have been proposed to use four different methods, judgement-based, empirical, analytical, and hybrid, to create the fragility curve according to whether the damage data used in the methods mainly come from observed expert opinions, post-earthquake surveys, analytical simulations [8–11].

Thus, a seismic hazard risk assessment model for EHV transmission towers is established and fragility curves of the EHV transmission tower are created in this paper. And the rationality of the model is verified to provide effective hazard risk assessment for the constructed towers. Therefore the damage level of an EHV power transmission system after an earthquake can be accurately estimated by the proposed model, and emergency repair operations can be fast arranged.

The content of each section is summarized as follows. Section 2 explains the method and procedure to establish the seismic risk assessment model of EHV transmission towers. Section 3 examines the accuracy of the established EHV transmission tower model. Section 4 summarizes the results of this study and describes some research issues for future studies.

2 Seismic Hazard Risk Assessment Model

In order to establish a seismic hazard risk assessment model for 345 kV towers, a research process was developed in this paper. The flowchart of the proposed procedure is shown in Fig. 1. The historical information of seismic stations that measured different intensities of the Chi-Chi earthquake was chosen to be studied. Then, the characteristics and types of EHV towers were classified to establish an EHV tower structural model. And, the seismic damage probability for an EHV tower was analyzed to establish the fragility curve for the tower. Among the methods used to establish fragility curves, the nonlinear dynamic analysis method can more realistically reflect the true response of EHV towers in earthquakes. In the nonlinear dynamic analysis, the tower is viewed to be directly affected by historical earthquakes with varying degrees. In order to establish the tower model and perform the analysis, the finite element analysis software “SAP2000” was used in this study. The SAP2000 is developed by Computers and Structures, Inc., and is widely used in civil engineering, and its credibility is well known in civil engineering [12]. Finally, after considering the maintenance cost of an electrical tower, a

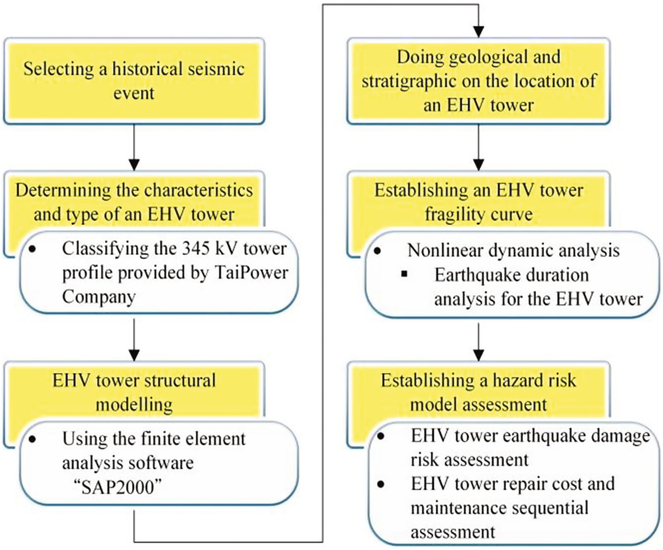

Fig. 1. The flowchart of establishing a seismic hazard risk assessment model for the EHV transmission tower

complete set of the seismic hazard risk assessment model was developed. The established model can increase the speed and efficiency in dealing with seismic incidents for an EHV transmission grid. Each research methods will be sequentially introduced in the following subsections.

2.1 EHV Transmission Tower Structural Modelling

The A4 and the C5 type EHV transmission tower were the most seriously damaged types of towers in the Chi-Chi earthquake, as indicated by Table 1, according to the earthquake statistics [13]. In this study, the A4 EHV transmission tower was studied as an example. According to the detailed information about the A4 provided by Taipower, a three-dimensional tower structural model was established by using the SAP2000. The model components were defined as members and joints, and all elements were established following the exact size and material properties of an A4 tower. The structural members were connected with fastened joints in the simulation. A total 1406 members and 527 joints were used in the A4 tower model. The static load of a tower included the tower self-load and the weight of ground wires, conductors, and insulators. All static load settings were based on the information provided by Taipower.

In order to ensure that the tower model represented the real situation, the weight of the connected plates and bolts was added to the corresponding joints. Moreover, the ground wire used by Taipower was 19NO.8 Aluminum Clad Steel Wire (ACW), the unit weight W_g was 1.062 kg/m, the cross-sectional area A_g was 159 mm2, and the elastic modulus was 10500 kg/mm2. The conductor was 795MCM (26/7) Aluminum

Conductors Steel Reinforced (ACSR), the unit weight Wc was 1.628 kg/m, the cross-sectional area A_g was 468.5 mm^2, and the elastic modulus was 8900 kg/mm^2. The weight of insulator I was 1030 kg. The weight of the conductors and ground wire was evenly distributed on the towers at the both ends of the span in the assessment. And, according to the statistics, the average distance between the 345 kV towers is about 360 m. Thus, on average, the static load of a 345 kV tower should include its own weight and the weight of a 360 m line, and the weight of an insulator.

2.2 Modal Analysis

A modal analysis is the study of the dynamic properties of structures under vibrational excitation without external forces. The modal analysis can be used to determine qualitative structural responses, and provide relevant design requirements of a structural concept. It is also the basis of other dynamic analyses, including the response spectrum analysis and time history analysis. Therefore, the nonlinear time history analysis used the results of the modal analysis as an auxiliary in this study. Many factors affect the dynamic responses of the structure. In addition to the loads and external factors such as environmental conditions (e.g. seismic force) and other internal conditions, the dynamic characteristics of the structure itself (e.g. natural frequency, structural damping) are also related to the dynamic responses of the structure. However, before analyzing the seismic dynamic response of transmission towers, the structural natural vibration duration and frequency and the modal shapes which show the structure vibration form under a certain frequency must be understood, and the parameters can be obtained by using the modal analysis. A modal analysis solves differential equations of motion to obtain the natural frequencies and mode shapes. A transmission tower can be regarded as a degree of freedom (D.O.F.) system. The differential equation of motion can be expressed as

$$\mathbf{M} \cdot \overrightarrow{\ddot{u}}(t) + \mathbf{C} \cdot \overrightarrow{\dot{u}}(t) + \mathbf{K} \cdot \overrightarrow{u}(t) = 0, \tag{1}$$

where $\mathbf{M}$ is the mass matrix, $\mathbf{C}$ is the damping matrix, and $\mathbf{K}$ is the stiffness matrix. $\overrightarrow{\ddot{u}}(t)$, $\overrightarrow{\dot{u}}(t)$ and $\overrightarrow{u}(t)$ are acceleration, velocity, and displacement vector, respectively.

Because the modal analysis does not consider the non-linear factors, the damping is negligible. (1) can be reduced to

$$\mathbf{M} \cdot \overrightarrow{\ddot{u}}(t) + \mathbf{K} \cdot \overrightarrow{u}(t) = 0. \tag{2}$$

The solution of the differential equation of motion is defined as

$$u(t) = u \sin(\omega t). \tag{3}$$

(3) is substituted into (2):

$$(\mathbf{K} - \omega^2 \cdot \mathbf{M}) \cdot \overrightarrow{u} = 0. \tag{4}$$

Table 1. The types and quantity of EHV towers damaged in the Chi-Chi earthquake

Type	Number of damaged towers	Type	Number of damaged towers
A	8	D5	1
A1	1	DH43	5
A4	15	DH48	3
A5	14	E	3
B	2	E5	3
B2	2	E5G	4
C	11	F	7
C2	1	F1	1
C4	1	F5	2
C5	15	FT	1
D	3	G	3
D1	2	G4	5
D3	2	G5	1

(4) represents an eigenvalue problem, and ω^2 is the eigenvalue. The square root of ω^2 is the natural frequency, ω, of the system. The minimum value of ω is the basic natural frequency, and each natural frequency value may correspond to a modal shape. In this study, the modal analysis tools provided by SAP2000 were used to perform the modal analysis. The calculation of the structural weight and mass in the SAP2000 were based on the definitions of the material density, weight, and the setting load.

2.3 Nonlinear Time History Analysis

A time history analysis can simulate the dynamic response of structures in earthquakes. The time-history analysis provides for linear or nonlinear evaluation of dynamic structural responses (displacement, force, stress, spectrum, etc.). This study employed a nonlinear evaluation in the time history analysis. The time functions used in this study were the peak ground acceleration (PGA) data from the Chi-Chi earthquake provided by CWB [14]. The data length of the Chi-Chi earthquake was 90 s, and the sampling rate was 200 Hz. The information of the selected station of the Chi-Chi earthquake is listed in Table 2. After performing a time history analysis, the horizontal displacement of each tower joint as well as the PGA response spectrum of the tower at the Chi-Chi earthquake can be obtained. These data can be used to establish subsequent fragility curves.

2.4 Seismic Fragility Curves

In this study, the seismic fragility curves were developed to provide information necessary for predicting the damage to transmission towers caused by earthquakes. The development of seismic fragility curves requires the synergistic use of nonlinear dynamic structural analysis results. The seismic fragility curves were derived by using

Table 2. The Chi-Chi earthquake data from the selected stations

Station name	Epicenter distance (km)	Intensity	PGA direction		
			X (gal)	Y (gal)	Z (gal)
TCU078	5.53	7	171.00	302.48	439.70
TCU071	15.07	7	415.54	639.00	517.82
CHY006	40.23	6	211.02	351.46	348.00
TCU075	20.06	6	223.88	257.32	325.34
TCU102	44.93	6	173.28	168.98	298.36
CHY025	31.74	5	169.70	152.04	158.56
CHY087	59.94	5	55.14	125.32	132.36
HWA013	80.07	5	61.26	111.26	139.78
TAP010	150.04	5	27.22	85.96	114.90
TCU087	55.07	5	91.10	111.50	119.16
TCU096	105.29	5	36.66	106.00	54.02
CHY070	115.15	4	16.62	47.56	38.04
ILA008	135.06	4	33.32	56.52	77.40
KAU044	159.82	4	10.52	37.74	35.76
TAP024	145.20	4	23.38	75.96	61.60
TAP069	175.01	4	12.08	35.36	25.78
TTN041	85.31	4	38.88	64.24	79.14
TTN044	100.16	4	32.06	54.84	49.22
KAU052	211.22	3	4.84	7.48	10.40
KAU040	184.04	2	6.31	7.64	7.81

the maximum likelihood estimation method in this study. Shinozuka *et al.* assumed that the curves can be expressed in the form of two-parameter lognormal distribution functions, and the estimation of the two parameters (median c and log-standard deviation ζ) was performed with the aid of the maximum likelihood method [15]. For this purpose, the PGA was used to represent the intensity of the seismic ground motion. The likelihood function for the present purpose is expressed as follows:

$$L = \prod_{i=1}^{N} [F(a_i)]^{x_i}[1 - F(a_i)]^{1-x_i}, \tag{5}$$

where $F(\bullet)$ represents the fragility curve for a specific state of damage; ai represents the PGA value of tower i; xi = 1 or 0 depending on whether or not the tower sustains the state of damage when PGA = ai; and N represents the total number of towers inspected after the earthquake occurred. With the current lognormal assumption, $F(a)$ takes the following analytical form:

$$F(a) = \Phi\left[\frac{\ln\left(\frac{a}{c}\right)}{\zeta}\right] \tag{6}$$

in which a represents PGA; and $\Phi[\bullet]$ is the standardized normal distribution function. The two parameters c and ζ in (6) are computed as c_e and ζ_e satisfying the following equations to maximize ln L and hence L:

$$\frac{d\ln L}{dc_e} = \frac{d\ln L}{d\zeta_e} = 0. \tag{7}$$

Finally, the value c_e and ζ_e of the curves can be obtained. The story drift ratios of a tower as the damage index produced by time history analysis described the threshold of damage states for the evaluation of fragility curves. If the story drift ratio was greater, the extent of the damage was greater. The story drift ratio was determined by using the time history analysis provided by the SAP2000. The time history analysis outputted the layer horizontal displacement relative to the base, and then the displacement difference between tower layers δ was calculated and divided by the height of tower layers h to obtain the story drift ratio θ as the following formula:

$$\theta = \frac{\delta}{h}. \tag{8}$$

Thus, when a layer of the story drift ratio was particularly high, it may indicated that this weak layer was more likely to suffer from the damage. The HAZUS MR4 represented the extent of the damage defined by a different story drift ratio [16]. As mentioned in the document, the damage state from light to heavy was divided into four categories: Slight, Moderate, Extensive, and Complete for 16 basic structural types. The transmission tower used in the analysis belonged to Steel Braced Frame Type (S2). The story drift ratio thresholds of various damage states for S2 are shown in Table 3. Because no other valid damage state specifications for transmission tower were available, this study used the story drift ratio thresholds of HAZUS MR4 to establish fragility curves.

3 Simulation Result

In this study, A4 tower is assumed being mounted on the ground, so the feet edge of tower is set as fastened joint in sap2000. According to the study procedures of Sect. 2, fragility curves of A4 is eventually established by the results of nonlinear dynamic analysis.

3.1 Story Drift Ratio

Through the time history analysis in SAP2000, A4 tower horizontal displacement under the chosen stations can be calculated. Figure 2(a) shows the horizontal displacement under station CHY006. Substituting the horizontal displacements obtained above into (8) story drift ratio can be calculated, as shown in Fig. 2(b). According to

Table 3. The story drift ratio thresholds of various damage states for S2 ates

Building properties		Story drift ratio thresholds of damage states			
Type	Height (m)	Slight	Moderate	Extensive complete	
S2L	7.3152	0.0050	0.0100	0.0300 0.	0800
S2 M	18.288	0.0033	0.0067	0.0200 0.	0533
S2H	47.5488	0.0025	0.0050	0.0150 0.	0400

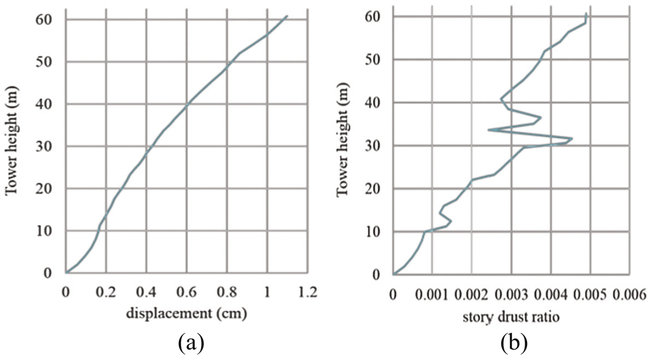

Fig. 2. (a) A4 tower horizontal displacement at CHY006 station, and (b) A4 tower story drift ratio at CHY006 station

the statistics results in the study, the maximum drift ratios are all on the top area of A4 under each station data. It can be presumed that the top area may be the most vulnerable place for transmission towers.

3.2 PGA Response Spectrum

The A4 tower PGA response spectrum under the different station data can also be obtained through the time history analysis. Since the transmission tower belongs to steel structure, the damping ratio choose 2%. Also, the fundamental period of A4 calculated by modal analysis is 0.369985 s. Figure 3 shows the A4 tower PGA response spectrum at different station. The PGA response value of each station which is corresponded to the fundamental period is also listed in Table 4.

3.3 Fragility Curve

In this study, the fragility curves is established inaccordance with the damage state distinguished by story drift ratio provided by HAZUS MR4. Then the calculated story drift ratios combined with the PGA values, and the relationship between story drift ratio

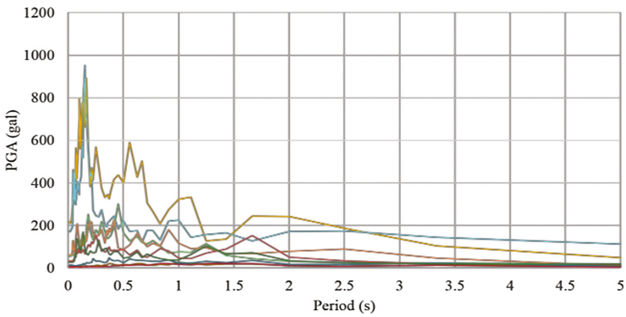

Fig. 3. A4 tower PGA response spectrum at different station

Table 4. PGA response values of the stations at fundamental period point

Station	PGA value	Station	PGA value
TCU078	315.21	TCU096	68.709
TCU071	424.28	CHY070	5.2535
CHY006	340.9	ILA008	81.592
TCU075	365.34	KAU044	27.99
TCU102	198.87	TAP024	65.518
CHY025	192	TAP069	87.343
CHY087	139.24	TTN041	91.018
HWA013	174.96	TTN044	101.61
TAP010	92.258	KAU052	7.0764
TCU087	225.69	KAU040	12.651

Table 5. The medians and standard deviations of each damage state

Damage state	Median c (gal)	Deviation ζ (gal)
Light	275	624
Moderate	551	624
Extensive	1102	615
Complete	2203	615

and PGA has been calculated. According to story drift ratios of A4 the damage state is divided into four categories: slight, moderate, extensive, complete. And the number of each damage state corresponding to the PGA value are counted, and substitute into (6), (7) to calculate the median c and deviation ζ. The medians and standard deviations of each damage state are listed in Table 5, and four fragility curves of A4 are drawn as shown in Fig. 4.

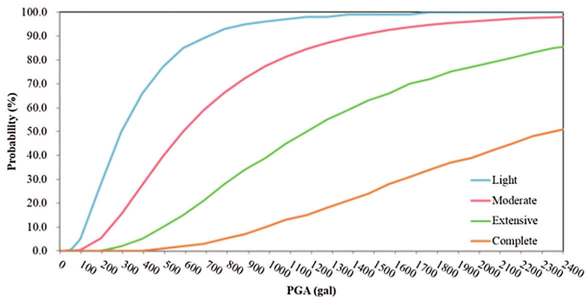

Fig. 4. Fragility curves of A4

4 Conclusions

This study establishes a seismic hazard risk assessment model for A4 tower structure. The damage level of a power transmission system after an earthquake can be accurately estimated by the established fragility curves. However, the seismic hazard risk assessment model is not only for this case. It can be set into any types of transmission towers and easy to build. Therefore, this model is looking forward to be widely used. This model will add the building and maintenance costs of towers in the future. Therefore, the emergency repair operations can be fast arranged. In addition, before an earthquake occurs, the reliable assessment data obtained by the proposed model can be used as a tool for establishing a pre-disaster risk management system for Power Company or the government. Also, In order to be closer to the state of the installed tower, the bases under towers and geological factors will be considered to achieve integrity of simulation.

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