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Research Article

Rapid power outage estimation for typical electric power systems in Turkey

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ABSTRACT

Electric power systems have critical importance in the sustainability of social life and economy. The past and recent earthquakes showed clearly that these systems have high vulnerability due to earthquakes. In this study, the typical electric power systems which are commonly preferred and located at five different sites in high seismic zone of Turkey, Marmara region, have been examined. In the first part of the study, the earthquake hazard for Marmara region has been accomplished. The earthquake hazard curves at five different sites for two different earthquake levels, and two different site conditions as soft and stiff site classes according to the Turkish Building Seismic Design Code 2018 have been obtained. The seismic vulnerability assessment of substation and distribution circuits for two different design states, namely anchored and unanchored, achieved by the fragility functions. The probability of power outage durations have been evaluated based on the restoration curves. It has been observed that the results obtained within the scope of the study are highly consistent with post-earthquake studies in the literature. The proposed methodology through the power outage graphics enable a quick preliminary evaluation of the power outage based on the current design status and location for any electric power systems in the Marmara region.

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1. Introduction

Electric power systems (EPSs) are one of the critical infrastructures, exposed to threat of natural hazards, especially earthquakes. In general, EPSs contain generation facilities, substations, and distribution circuits. The EPSs are considered as the lifeline systems, which are essential for the modern life and maintaining the functionality of emergency services and other lifelines such as water supply, fuel supply, wastewater treatment, and communications. The EPSs have direct relation with the economy. An interruption in the EPSs due to an earthquake event will cause serious loss in economic and social life (Kwasinski et al., 2014). Any earthquake damage on the substations, distribution circuits and/or on their specific components will lead to disruption in the whole system. Such a disruption in the EPSs will certainly affect the commercial and industrial activities in the region (Shinozuka et al., 1999). The observations in the recent earthquakes showed that EPSs and their sub-elements, including components of high/low-voltage substations and power transmission systems, have suffered damages and subsequently stoppage in power transmission. The seismic vulnerability of these sub-elements has been studied by researchers in recent years (Watson, 2010; Massie and Watson, 2011).

Fujisaki et al. (2014) has studied seismic performance of high-voltage electric substation equipment and transmission lines after major worldwide earthquakes. He had comprehensive observations and had some component based recommendations. A significant damage was observed after the 11 March 2011 Tohoku Earthquake in Japan in the two important EPSs in their high voltage transformers, circuit breakers, air disconnects, instrument

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transformers and cable terminations elements. All these electric power components were restored in 90% within six days (Eidinger et al., 2012). The EPSs component such as 220kV CVT, 66kV transformer bushings, 11kV switchgear, porcelain surge arresters and non-structural elements in the substation buildings showed mainly slight and partly moderate damages after the 4 September 2010, MW 7.1 Darfield (Canterbury) earthquake, the 22 February 2011, Mw 6.3 Christchurch earthquake and the 13 June 2011, MW 6.0 Christchurch earthquakes in the city Christchurch in New Zealand. The restoration of the transmission systems was completed within less than 6 hours after each earthquake events (Eidinger et al., 2010; Giovinazzi et al., 2011; Transpower, 2011a; Transpower, 2011b). Park et al. (2006) studied the performance of urban electric utility distribution system after the February 28, 2001, MW 6.8 Nisqually earthquake. They estimated the distribution of outage durations and proposed fragility curves for lifelines.

Significant damages to the bus support connectors (Fig. 1-a), surge arrestors (Fig. 1-b), transformer bushings (Fig. 1-c) and disconnect switch corona rings (Fig. 1-d) of 500kV yard of San Diego Gas & Electric's (SDG&E) Imperial Valley Substation were observed after the 4 April 2010, MW 7.2 Mexico earthquake. In the Howard et al. (2015) study, the critical elements for the SDG&E substation were identified and alternative retrofitting approaches were investigated through the nonlinear analysis.

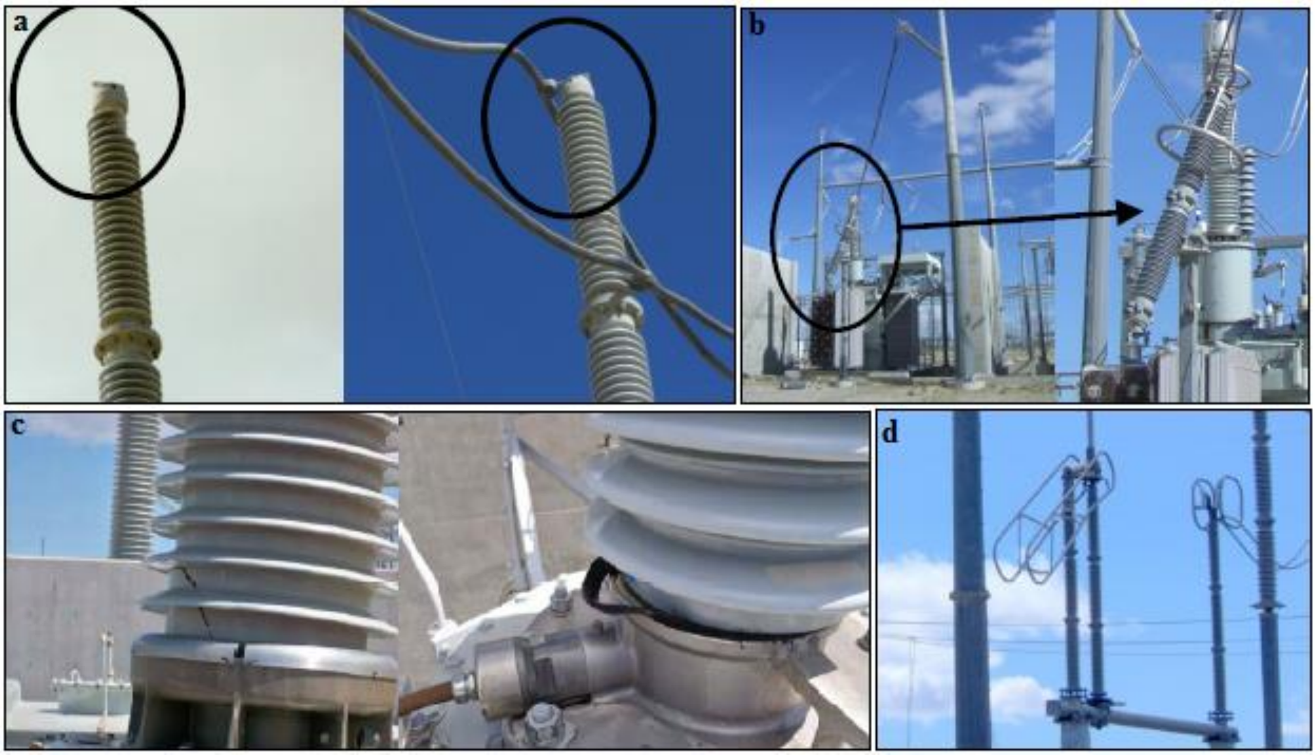

Fig. 1. Common failure types in the typical EPS components.

Buritica´ Corte´s et al. (2015) studied seismic vulnerability of bulk electric power systems by considering form and strength parameters with the hierarchical decomposition method. Different scenarios were considered and obtained results were compared with the traditional methods. Shinozuka et al. (2005) proposed a method for performance evaluation of EPSs of the Los Angeles Department of Water and Power's (LADWP's). 47 earthquake scenarios were used to develop the risk curves and relations with economical parameters were established. In the study of Liu and Feng (2006), seismic safety assessment method of electric power system was evaluated and alternative system flow load control method was proposed. Similarly, seismic vulnerability assessment studies for EPSs and its network with different approaches and methodologies exist in the literature (Bompard et al., 2011; Kwasinski et al., 2014; Li et al., 2008; Ma et al., 2010; Holmgren and Molin, 2006).

In this study, rapid seismic vulnerability assessment has been realized for a typical EPS in Turkey and accordingly probabilities of possible restoration durations have been evaluated. Marmara region which has a high seismic hazard and locates many EPS facilities have been considered. The probability of seismic vulnerability of EPSs, mainly substations and distribution circuits have been assessed based on the fragility curves due to two levels of seismic hazard and two different site conditions of stiff (ZB) and soft (ZD) site classes according to the Turkish Building Seismic Design Code 2018 (TBSDC-2018). The probability of power outage duration has been calculated for different periods using the damage probability matrices and restoration curves.

This study will provide a reliable foresight for possible power outage duration in the typical EPSs in Marmara region and it will also give insight to energy producers to develop their post-earthquake activity plans.

2. Typical Electric Power System and Seismicity of Marmara Region

In general, EPSs consist of substations, distribution circuits and generation facilities. All of these components are exposed to structural damages during major earthquakes. These potential damages may cause significant disruption of power supply. Comparing to conventional building structures, the EPSs comprise rather complex contents due to their sub-elements such as; busbar system, bypass bus, busbar disconnector, circuit breaker, feeder disconnector, bypass disconnector, current transformer, voltage transformer, earthing switch, surge arrester and post insulator, etc. Especially in the high seismic zones, a damage to any sub-element of the EPSs will lead to break entire network's functionality (Nuti and Vanzi, 2004; Wang et al., 2019).

In this study, the substations and distribution circuits as the components of EPSs are considered in the analysis for the power outage estimation methodology. A substation is located in a region where it supplies energy. The key tasks of a substation are changing/switching/regulating voltage level, housing disconnect switches, circuit breakers etc, providing protection from lightening and switching surges, in case of necessity frequency change and AC/DC conversion. A distribution system can be considered as the number of circuits including poles, wires, in-line equipment and utility-specific devices.

In this study, five typical EPSs with different design forms located in Marmara region have been considered for the power outage estimation due to different earthquake hazard levels. The main assessment steps considered are shown in the flowchart in Fig. 2.

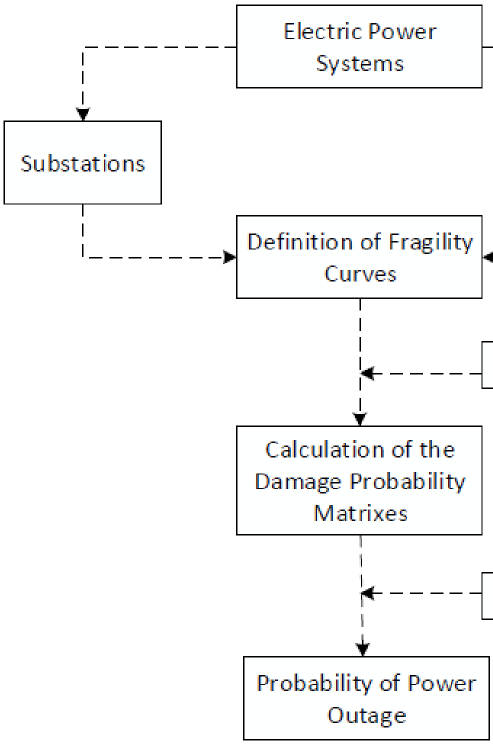

Fig. 2. Assessment methodology for EPSs performance evaluation and power outage estimation.

The seismic vulnerability of substations and distribution circuits are well correlated with the Peak Ground Acceleration (PGA) parameter (HAZUS-MH., 2011).

In the current study, Probabilistic Seismic Hazard Assessments (PSHAs) have been performed in order to evaluate seismic hazard in Marmara region by considering seismic characteristics of the region, and ground motion attenuation models. The PGA distribution has been calculated as the ground motion intensity measure. The EC-FP7 SHARE project delivered a comprehensive seismic hazard model referred as 2013 European Seismic Hazard Model (ESHM2013) for the region (Woessner et al., 2015). In the hazard analyses, reference shear wave velocities, $V_{s,30}$=760m/s and $V_{s,30}$=300m/s, have been used for stiff and soft sites, respectively as shown in Figs. 3 and 4. The PGA distribution maps corresponding to 475 years (DD2) and 72 years (DD3) return period of earthquakes have been derived from hazard analyses results. These results have been used in seismic risk assessment of EPSs.

Probabilistic seismic hazard analyses of EPSs located on the Marmara region have been performed by considering Poisson model (time independent model) under assumption that earthquakes occur with constant average frequency, but independently of each other (Woessner et al., 2015; Cornell, 1968; Scherbaum et al., 2009). Computational model has been implemented in OpenQuake engine for seismic hazard calculations (Pagani et al., 2014). PSHA model includes two important parts; definition of seismic source model that gives information about seismicity of the region and; ground motion model that conducts with attenuation of ground motions by ground motion prediction equations (GMPEs) (Woessner et al., 2015). In this study, source model has been constructed with area sources, background sources and line sources for the region. Area sources were included in the analyses with 0.60 weight, line sources and background sources were included in analyses with 0.40 weight. As the ground motion attenuation models, Abrahamsan and Silva (2008), Boore and Atkinson (2008), Chiou and Youngs (2008), Campbell and Bozorgnia (2008) ground motion prediction equations (GMPEs) were included with 0.25 weight in the probabilistic hazard analyses. Probabilistic seismic hazard curves for EPSs located on Kirklareli, Kocaeli, Balikesir, Bandirma and Canakkale were calculated by seismic hazard analysis based on local site conditions shown at Fig. 5 (Site Class ZD and Site Class ZB).

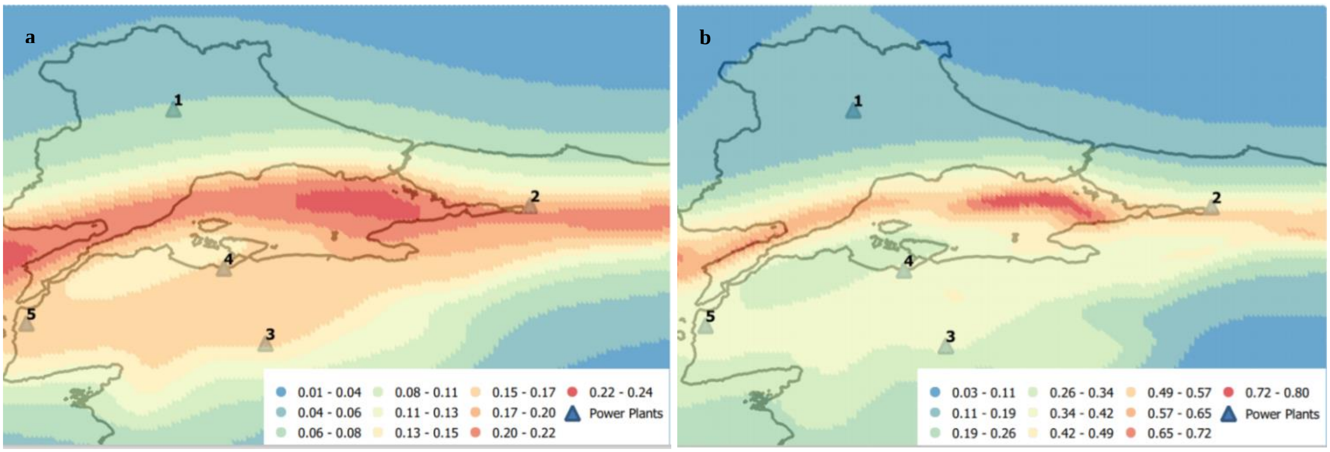

Fig. 3. PGA distribution map for $V_{s,30}$=760m/s:
a) 50 % probability of exceedance in 50 years; b) 10 % probability of exceedance in 50 years.

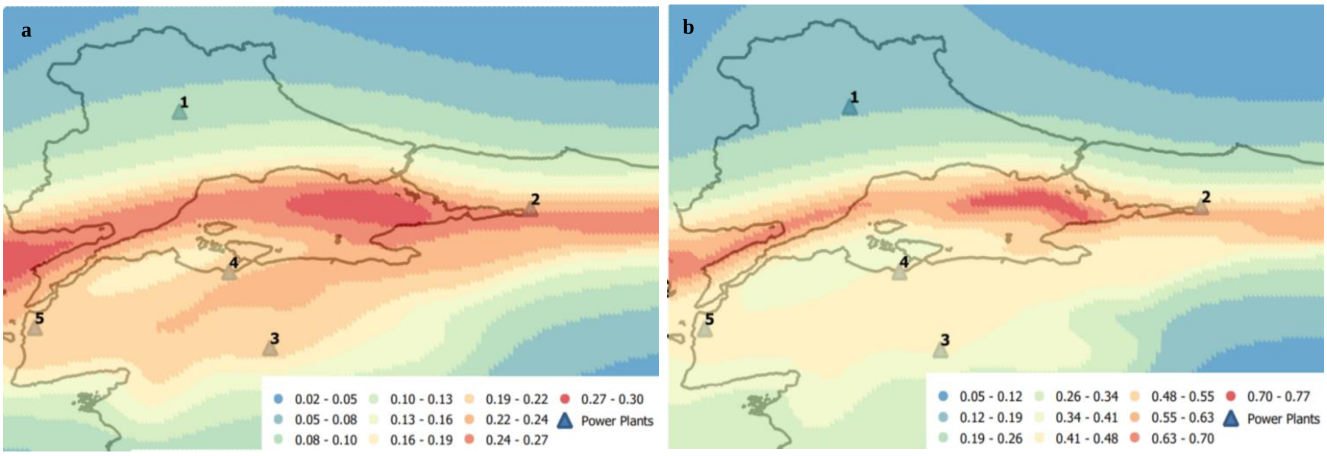

Fig. 4. PGA distribution map for $V_{s,30}$=300m/s:
a) 50 % probability of exceedance in 50 years; b) 10 % probability of exceedance in 50 years

3. Seismic Damage Assessment Based on Fragility Curves

EPSs are one of the vital facilities supplying functionality to other critical infrastructures, lifelines and community. They have also economic and social impact in regional level. The performance assessment of these types of facilities can be achieved by the fragility functions. These curves express the probability of reaching or exceeding structural damage value 'D' for the d_i damage state at that given intensity parameter measure 'Y'. The fragility curve can be considered as a formula of two parameters (median and standard deviation) lognormal distribution functions, is modelled as:

$$P(D \geq d_i|Y) = \phi\left(\frac{lnY - lnY_{mi}}{\xi}\right) \tag{1}$$

where, Y_{mi} is median threshold value of i^{th} damage state, ξ is the lognormal standard deviation and ϕ represents the standard normal cumulative distribution probability function.

In this study, the fragility functions developed for typical substations and distribution circuits have been adapted for seismic assessment of existing EPSs in Marmara region, Turkey by considering two different design states as proposed in HAZUS-MH (2011). Subsequently, the power outage duration has been estimated by restoration curves depending on the regional seismicity and exposed damage distribution (G&E Engineering Systems, 1994). The adapted fragility curves for the substations(S) and distribution circuits (DC) located in the EPSs for the anchored design (AD) and unanchored design (UD) states are given in Fig. 6.

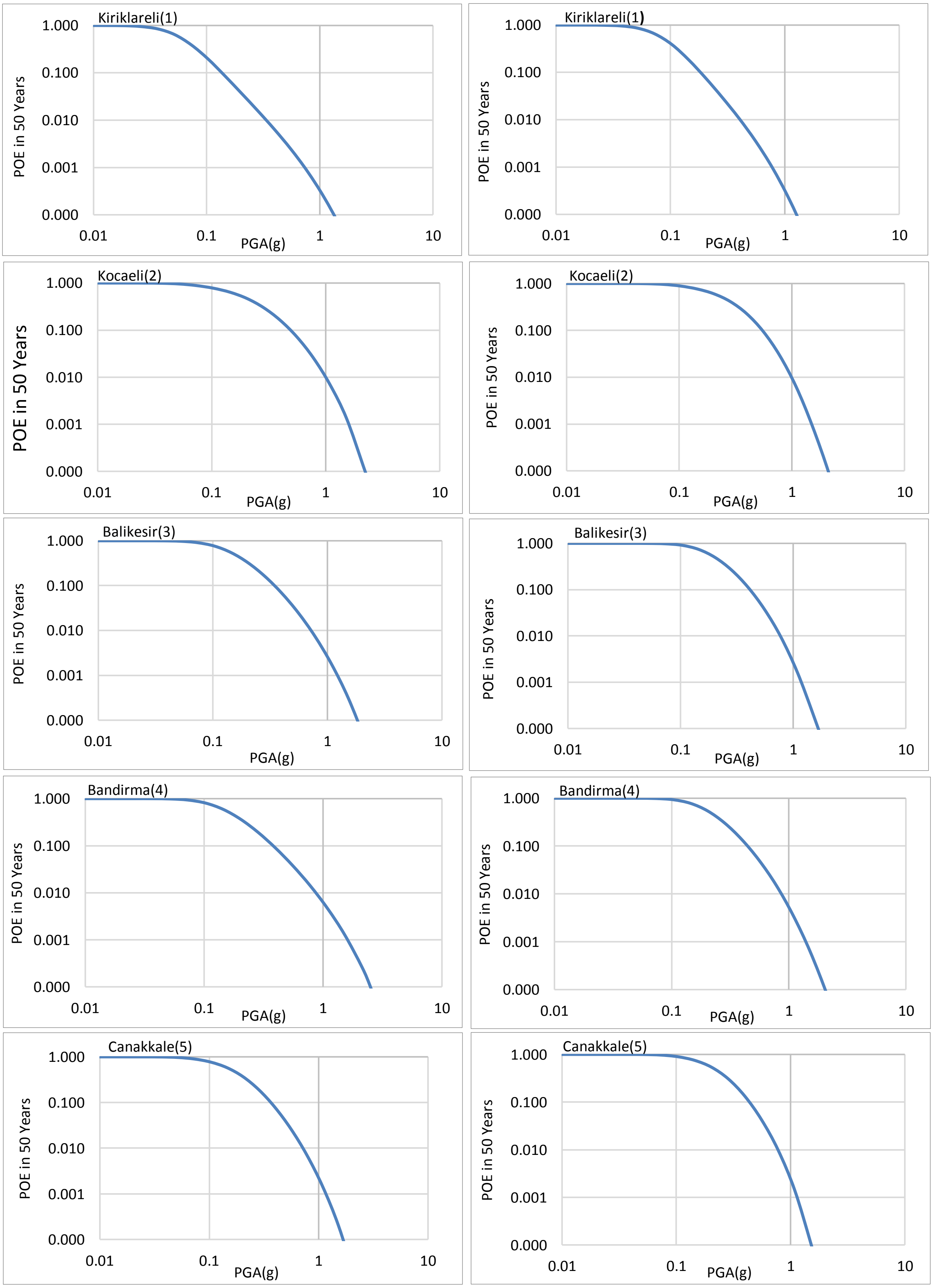

Fig. 5. Considering each location, hazard curves in 50 years of PGA for ZB site class (left side) and ZD site class (right side).

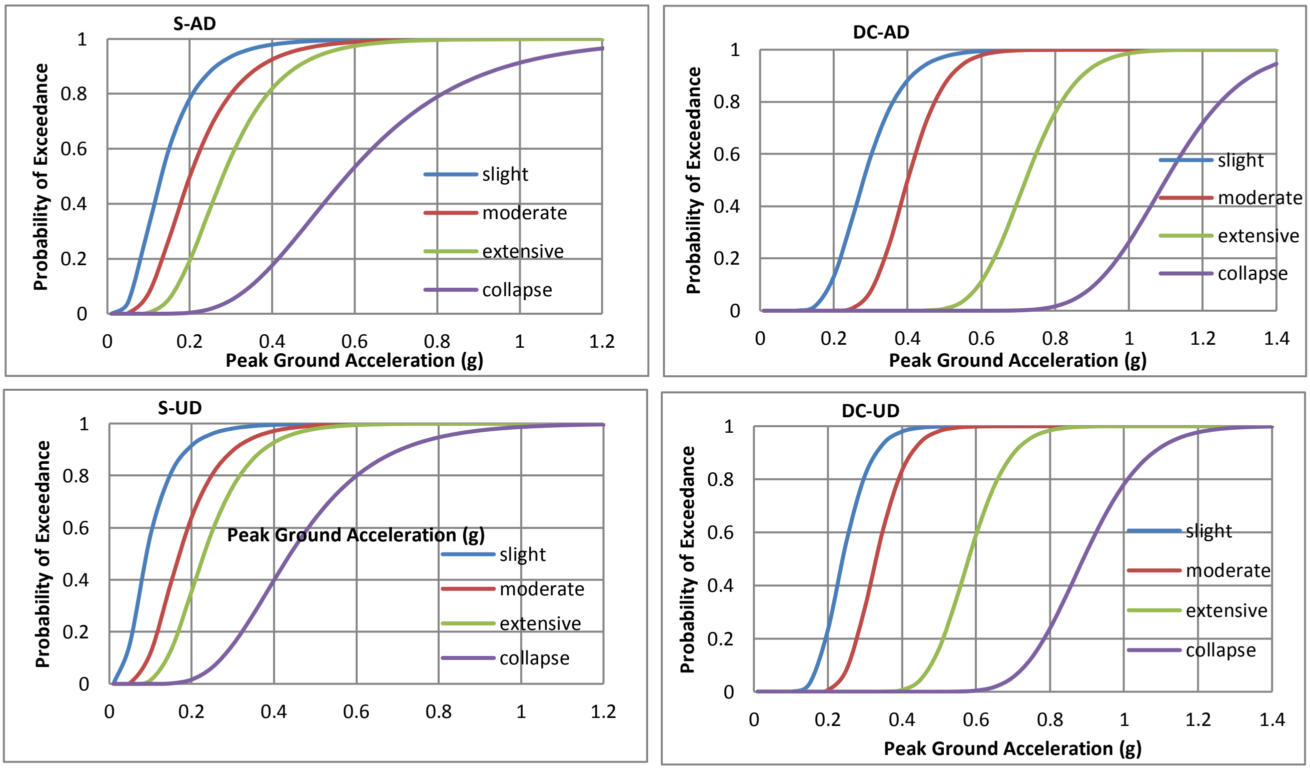

Fig. 6. The adapted fragility curves of the substations (S) and distribution circuits (DC) for the rapid risk assessment.

A total of five damage states as "none, slight, moderate, extensive, and collapse" have been identified in the Fig. 6. In the development of fragility curves, all sub-elements' vulnerability have been considered and mean damage have been extracted for the substations and distribution circuits in each damage state (HAZUS-MH., 2011). Therefore, it is acknowledged that these curves are suitable for the rapid seismic risk assessment of EPSs. In this study, the calculation of power outage in the target facilities have been achieved by considering the restoration curves as shown in Fig. 7 proposed by the G&E report (1994).

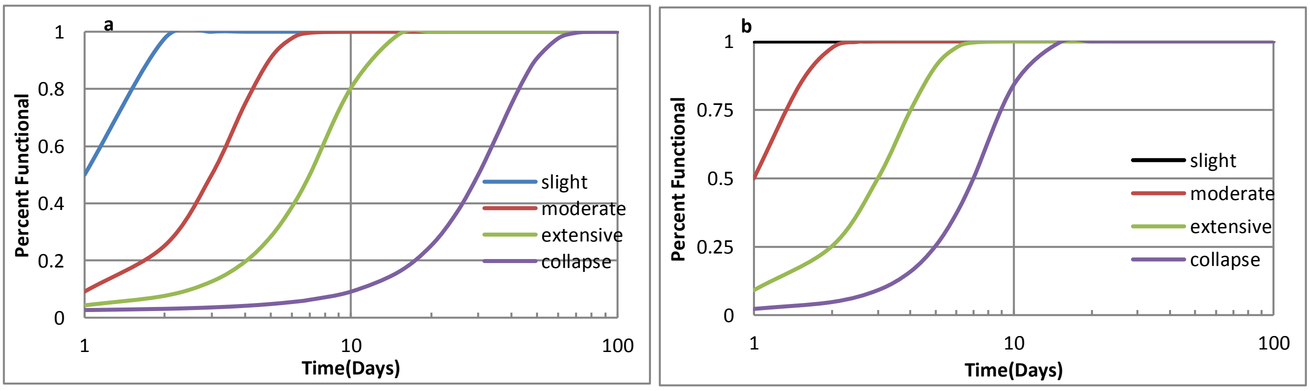

Fig. 7. Restoration curves for electric power systems: a) substations; b) distribution circuits.

The power outages duration at the target sites are defined as the interval of non-functionality of substations and distribution circuits. As it has been mentioned earlier, the substations and distribution circuits are sensitive to earthquake ground motion and in the case of a potential damage it will affect the wide region where these facilities are located.

4. Power Outage Estimation of Electric Power Systems

As described earlier, rapid risk assessment has been applied depending on the seismic hazard for the region and implementing main steps for the assessment as shown in the flowchart in Fig. 2. Using earthquake demand and fragility curves, probability of damage at different damage states (P_{ds_i}) has been calculated. Afterwards, the probability of power outage (PPO) has been calculated based on the Eq. (2) through different days period (T_k) dependent restoration curves (RC).

$$PPO_{T_k} = \sum_{i=1}^{i=5} RC_{d_i,k} \cdot P_{ds_i} \qquad (2)$$

The PPO_{T_k} has been calculated and illustrated in Figs. 8 and 9 for 'S' and 'DC', respectively for DD2 earthquake level (probability of exceedance 10% in 50 years corresponding to 475 years return period earthquake) which is the standard design earthquake level. PSHA has been carried out for ZB ($V_{s,30}$=760m/s) and ZD ($V_{s,30}$=300m/s) site classes representing the stiff and soft site conditions, respectively.

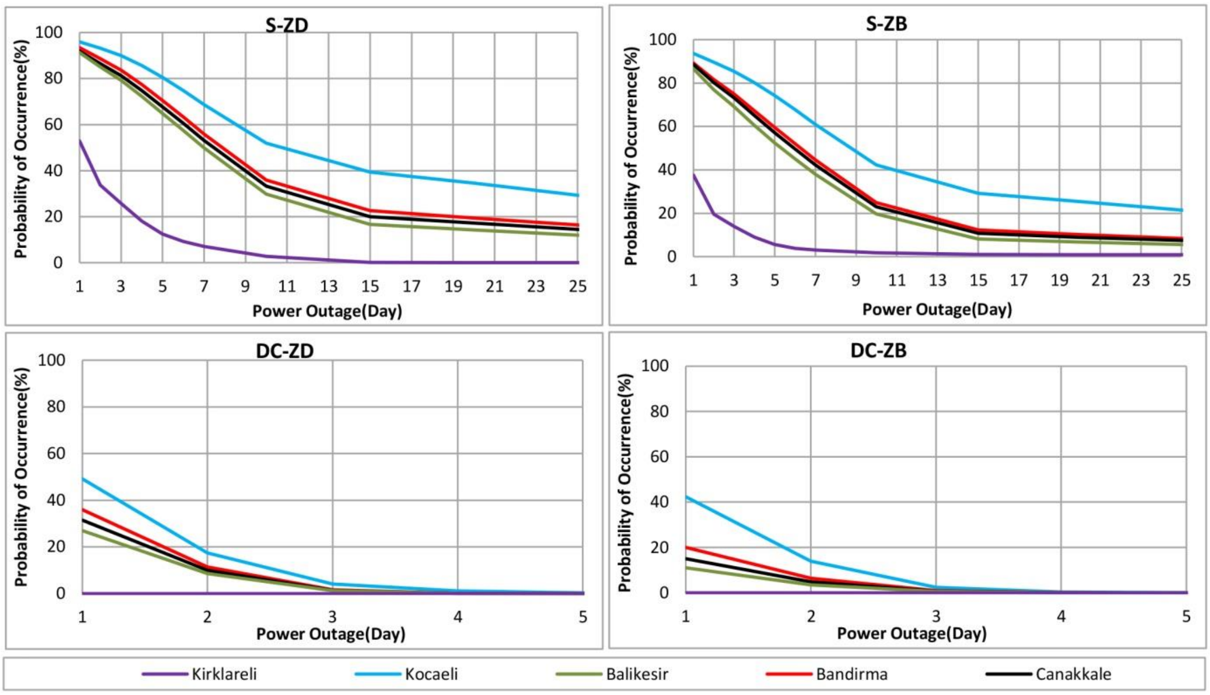

Fig. 8. Power outage estimation for DD2 earthquake level for anchored design substations and distribution circuits.

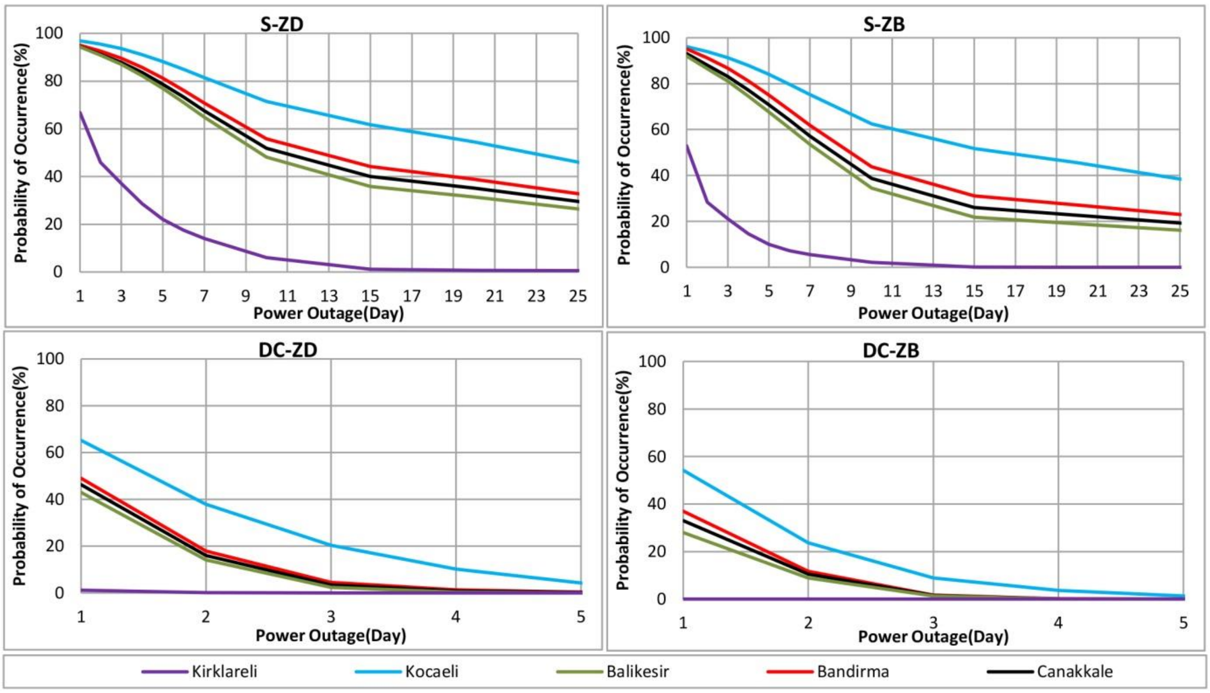

Fig. 9. Power outage estimation for DD2 considering unanchored design substations and distribution circuits.

As it can be seen from Fig. 8 clearly, 'S' has higher probability comparing with the 'DC' in different period duration of power outage. In this regard, the substations can be considered as critical elements in the current assessment. In the evaluation of five typical EPSs located in Marmara region, the estimated power outages vary dramatically especially in Kocaeli (2) and Kirklareli (1) sites. For example, for 7 days of *PPO* at 'S' on ZB site class in Kocaeli (2) is 61% whereas it is 3% in Kirklareli (1).

In Fig. 9, the evaluation of 'UD' case for 'S' and 'DC' at two site classes are given. In ZD site class, the probability of two-days of Power Outage occurrence is obtained as above 90% for the 'S' in all sites except Kirklareli site in which the Power Outage occurrence is found as 45%. For the 'DC', whereas the highest value was 38% in Kocaeli site. There was no Power Outage expected in Kirklareli site. At the other sites, the expected power outage values become between 14% - 20%. The evaluation for DD3 earthquake level (probability of exceedance 50% in 50 years corresponding to 72 years return period earthquake) which is the frequent earthquake as described in TBSDC-2018 has been illustrated in Figs. 10 and 11.

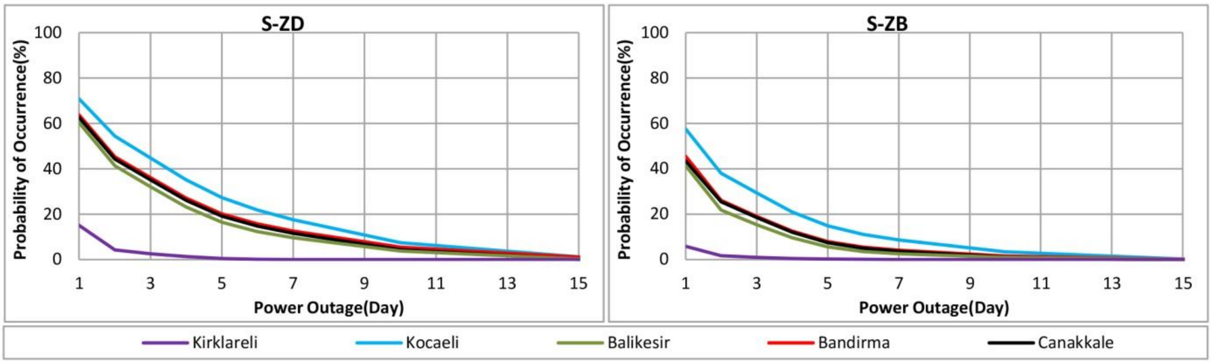

Fig. 10. Power outage estimation for DD3 level considering anchored design substations.

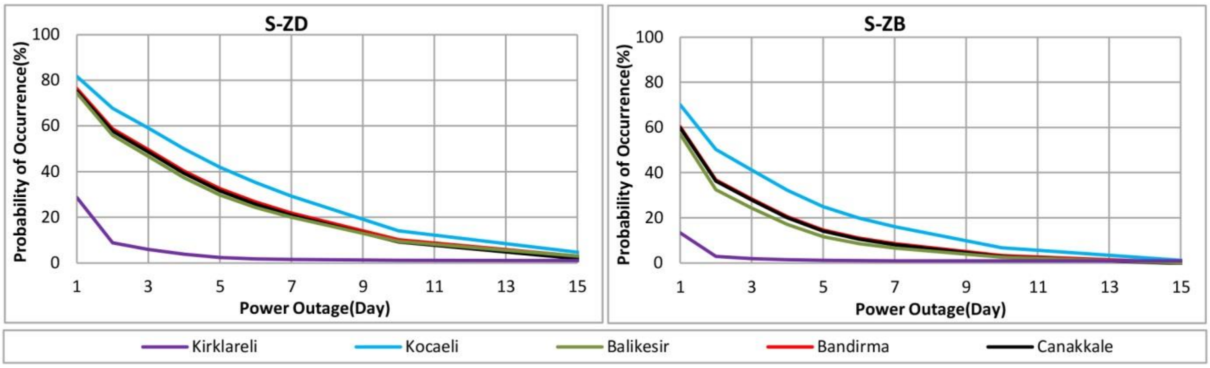

Fig. 11. Power outage estimation for DD3 considering substations with unanchored.

For the typical EPSs in 5 different locations, in the frequent earthquake level in two different site conditions of ZB and ZD, the performance of 'S' is shown in Fig. 10. In the first day, except the Kirklareli site, the *PPO* varies between 60% and 71% in ZD site conditions. In the ZB site condition, this value ranges between 41%-58%. However, in the fifth day after the earthquake the *PPO* varies between 16% and 27% for the ZD site class. It varies between 6% and 14% for ZB site Class. For the Kirklareli site, the first day the *PPO* value becomes 15% for the ZD site and 6% for the ZB site. In the fifth day after the earthquake case it is seen that the facility will be operational in 100% for ZB and ZD site conditions.

In Fig 11, results for the 'S' are taken into account and it is seen that *PPO* values at the end of the 10th day becomes lower than 15% for both site conditions. In the DD3 earthquake level, in the case of 'DC' ('AD' and 'UD' states) with different site conditions *PPO* value is obtained less than 1% and only slight damage is expected for all sites. It is estimated that the possible repairing duration is less than 1 day. It is observed that the acquired results for the two earthquake design levels are compatible with the past earthquake damage data (Eidinger et al., 2012; Giovinazzi et al., 2011).

5. Conclusions

EPSs have critical importance in the sustainability of social life and economy. The past and recent earthquakes showed clearly that these systems have high vulnerability due to earthquakes. In this study, the typical EPSs which are commonly preferred and located at 5 different sites in Marmara region in Turkey have been examined. The vulnerabilities for the two design states of (anchored-unanchored) cases have been assessed. In the first part of the study, the earthquake hazard for Marmara region has been accomplished. The earthquake hazard curves at 5 different sites for two different earthquake levels of DD2 and DD3, and two different site conditions of ZD and ZB site classes according to the TBSDC-2018 have been obtained. In the calculation of *PPO* due to a potential future earthquake, the assessments have been carried out through the substations (S) and distribution circuits (DC). The *PPO* values have been calculated for different durations using the fragility curves and restoration curves.

The obtained results showed that there is significant variation in the *PPO* values in different sites in Marmara region. Considering the *PPO* values obtained depending on the vulnerability, it is seen that 'S' is in a much more critical situation when compared with 'DC'. In general, considering the seismicity of the target region for the earthquake level DD2, the probability of interruption for the 7-days restoration period in the anchored (AD) design of the substations in all locations except Kirklareli on the ZD site condition is 50%-69%, whereas in unanchored (UD) case it becomes 65% -82%. At DD3 level, this value was obtained around 9% -17% for 'AD' and 20% -29% for 'UD'. In Kirklareli location for the DD2 earthquake level and ZD site condition, the *PPO* value of 'S' is 7% for 'AD' and 14% for 'UD'. At the same location, at DD3 level, there is no power outage probability for 'AD', but 1.5% for 'UD'.

It has been observed that the results obtained within the scope of the study are highly consistent with post-earthquake studies in the literature. Therefore, for any EPSs to be considered in the Marmara region, the results of this study through the power outage graphics enable a quick preliminary evaluation of the power outage for the current design status and location in a very practical way. This allows the development of action plans for the EPS facilities before the potential future earthquake.

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