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Seismic Assessment of Electrical Equipment in Power Substations: A Case Study for Circuit Breakers

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ABSTRACT

Electric power is essential in post-earthquake periods for the continuous functionality of disaster management and emergency services. In addition, interruption of electric power can cause significant economic losses due to downtime of critical facilities. Therefore, it is very important to maintain seismic safety of electric power systems and components. There are existing seismic regulations and standards regarding electric power systems, especially in the United States of America (USA) and Europe. A similar regulation has been prepared recently in Türkiye, which is a country in a seismically active region. This study focuses on the current state of practice regarding the seismic assessment of electrical equipment in power stations and implementation of the regulations on seismic qualification of these systems. Among many electrical equipment, circuit breakers have been selected for case study. The seismic assessment of the selected high voltage equipment has been performed according to the new regulation under the seismic hazard specifically defined for Türkiye. The case study experiment presents the new methodology in evaluating and classifying the seismic response of high voltage electrical equipment and provides insight to the expected behaviour of circuit breakers under earthquake induced action.

Keywords: seismic assessment, electrical equipment, power station, circuit breaker, seismic qualification

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1. INTRODUCTION

In today's world, economical losses have become more important than the physical losses after major earthquakes, especially in the developed countries. There exist many efforts to cope with financial issues caused by seismic action in post-earthquake periods. Therefore, the focus of earthquake engineering has been shifting to the performance assessment of lifeline systems and industrial facilities in order to avoid downtime and loss of functionality of these critical structures due to earthquake damage.

Electric power stations are essential components of lifeline systems, for which there is no tolerance to seismic damage induced loss of functionality or interruption of the service after a major earthquake. Therefore, it is very important to maintain seismic safety of electric power systems and components for the post-earthquake continuous functionality of disaster management and emergency services. Especially in the last three decades, many major earthquakes that occurred in different parts of the world (including Loma Prieta USA 1989, Northridge USA 1994, Kobe Japan 1995, Chi-Chi Taiwan 1999, Pisco Peru 2007, Wenchuan China 2008, Chile 2010, Port-au-Prince Haiti 2010, New Zealand earthquakes of 2010 and 2011, Tohoku Japan 2011, Lushan China 2013 and Kumamoto Japan 2016) have revealed the seismic vulnerability of numerous electrical substation components to moderate and severe ground shaking, particularly in equipment with 230 kV and above. For example, Schiff [1] states that the economic losses due to structural damage of the electrical substation equipment during the Loma Prieta, USA (M_w=6.9, 1989) and the Northridge, USA (M_w=6.7, 1994) earthquakes can be approximately estimated as \$283 million. In 1999, the power stations that transmit the power from the south part of the country to the industrialized and populated regions in the northern part were partially collapsed during the Chi-Chi, Taiwan earthquake (M_w=7.7) as seen in Figure 1 [2]. Eventually, the nation-wide interruption of electric power caused by this major earthquake resulted in serious economic consequences with a total estimated loss of \$10-\$12 billion.

Figure 1 - Partial collapse in power stations during the 1999 Chi-Chi Taiwan earthquake [2]

During the great earthquake that shook the Wenchuan region of China in 2008 (M_w=7.9), the electrical equipment in many of the power stations were severely damaged while some stations experienced total collapse due to the progressive failure of the interconnected system with bus bars as seen in Figure 2 [3]. During the 2010 Chile earthquake (M_w=8.8), the strong shaking caused severe damage in tens of electrical equipment (including bushings, insulators, conductors, circuit breakers, disconnect switches, voltage transformers and surge arresters) in different substations all over the country [4]. The earthquake induced liquefaction during the 2011 Christchurch New Zealand earthquake (M_w = 6.3) caused failures in the supporting structures of different electrical equipment and excessive displacement that caused stress concentrations on the electrical network connected by rigid buses [5].

Figure 2 - Ertaishan Switchyard which had experienced total collapse during the Wenchuan China (2008) earthquake [3]

There are also incidents regarding seismic damage in substation equipment and interruption of electrical power during major earthquakes in Türkiye. For instance, after the devastating Kocaeli earthquake (M_w=7.4) in 1999, seismic damage at various levels was reported in 9 electrical substations and the electricity was cut off in 7 cities for a considerable period of time ranging between 3 hours and 7 days [6-7]. During the sequential earthquakes in Van Türkiye in 2011 (M_w = 7.2 in 23 October and M_w = 5.6 in 9 November), 9% of the elevated electric transformers were damaged and 600 km of interconnecting cables were replaced although there was no significant damage in substation equipment in the affected area [8]. Site investigations performed after the 6th February 2023 Kahramanmaraş earthquakes document that high voltage transmission systems suffered damage aftermath of these destructive events [9]. Damage to substation components was also observed by the authors during their site visits to the affected area.

In summary, most of the electrical equipment in substations possess seismic vulnerability due to their inherent characteristics. First, they are generally cantilevered and flexible structures with elevated mass or with unbalanced mass concentration. Hence, they are highly sensitive to amplified vibrational motion caused by earthquakes. Second, they contain many fragile and brittle components like porcelain bushings, oil or gas filled equipment under high pressure, mechanical bearings, linkages, and electro-mechanical parts with close internal tolerances. These types of materials and components can be easily damaged during severe ground motion shaking. Especially the seismic vulnerability of such equipment becomes more critical as the voltage of the equipment gets higher due to requirements of larger clearances from the ground or between phases and longer dimensions that increase the flexibility of the component. Besides, the failure in a high voltage equipment during an earthquake cannot be tolerated in most of the cases since such equipment are located in critical substations that provide electrical power to large areas of population and industrial facilities. Third, the connectivity of electrical equipment through rigid bus bars or similar conductors is another issue during the excessive and amplified displacements effectuated by the seismic action if there is insufficient slack or tolerance in the connections. Meanwhile excessive slack is also unfeasible since it may lead to violations in electrical clearance requirements, cause instability of the equipment due to excessive lateral movement even under wind loading [3].

The aforementioned seismic vulnerability of electrical equipment in substations has drawn much attention after critical cases of equipment damage and malfunction in several electrical power stations after major earthquakes in urban areas of California in the United States in a period from 1970s (with the San Fernando earthquake of 1971) up to mid-1990s (with the Northridge earthquake of 1994), which initiated the first efforts to develop seismic design standards for such equipment. Accordingly, IEEE-693 Standard was first released in 1984, and then revised in 1997, 2005. The final version of the IEEE-693 Standard was released in 2018 [10]. Hence, due to its continuous development and technical superiority , this IEEE standard has become a worldwide popular document and leading seismic qualification standard for electric equipment.

For seismic qualification of electrical equipment in Europe, the most commonly used standards belong to the International Electrotechnical Commission (IEC). Unlike the IEEE-693 standard as a single document, the IEC standards IEC62271-300 provide a family of seismic qualifications which cover different types of electric equipment or part of the qualification process found in substations. Other than these internationally accepted standard, there are also national guidelines developed in different countries like China (GB standards) and Japan (JEAG standards).

In Türkiye, there have been no seismic regulations for the components of electrical power systems up to a recent time although Türkiye is an earthquake-prone country. The Turkish national seismic code covers only the legislations for building structures. However, the major earthquakes in the last three decades, especially the 1999 earthquakes in highly populated and industrialized Marmara region and the 2023 Kahramanmaras earthquakes that affected significant percent of the national power system in the South-east region of Türkiye have revealed the significance to mitigate the monetary losses and to manage post-disaster affairs by enhancing the seismic performance of special and critical engineering structures or components other than ordinary buildings. This issue triggered the efforts to develop guidelines for non-building structures, which also include the electrical power systems and their components. Hence a seismic qualification guideline was prepared for electric power transmission systems in Türkiye with the governance of General Directorate of Highways, which is a governmental organization under the Turkish Republic Ministry of Transport and Infrastructure, the guideline has been published in the official gazette and it has been operative in 2024 as seismic qualification code [11]. The contents of this guideline with emphasis of its interference with other national codes and standards has been discussed by Sucuoglu *et* al [12].

As mentioned in the previous paragraphs, most typical seismic damage types for electrical equipment in the past earthquakes are the failure of the porcelain bushings, derailment of the transformers, poor anchorage, failure of surge arrestors, voltage transformer, circuit breaker, and current transformer due to excessive vibration or interconnectivity effects [3,13]. Among this equipment, the seismic vulnerability of circuit breakers, which are used for electrical load switching and fault current interruption, becomes very critical since they are essential equipment in a power station for continuous service and functionality. Therefore, this paper focuses on the seismic performance assessment of this specific type of electrical equipment, by putting emphasis on the importance of seismic safety evaluation of electrical equipment in a power substation for the purpose of earthquake loss mitigation. The seismic assessment is carried out by using the new Turkish earthquake code for power systems (TEC-PS) [11]. Hence this is a pioneer study in Türkiye to present seismic safety calculations for a case study electrical equipment (i.e. circuit breaker) by introducing and using the new guideline that has been recently under legislation.

2. TURKISH EARTHQUAKE CODE FOR POWER SYSTEMS

Development of a national code for seismic qualification of electric power related systems and equipment was initiated in 2017 as a part of an extensive project to develop a series of guideline documents for lifelines and critical infrastructures in Türkiye. The project was sponsored by the General Directorate of Highways, which is a governmental organization under the Turkish Republic Ministry of Transport and Infrastructure. In 2019, the guideline was completed and submitted to the sponsoring agency for approval. Currently, the guideline has been officially approved as Turkish earthquake code for power systems (TEC-PS) [11] and it has been operative by the start of the year 2024.

Since there have been no such documents in Türkiye before to assess the seismic performance of electrical equipment, TEC-PS [11] had been prepared in accordance with some well-recognized international standards and the national seismic design and construction practice that takes into account seismic qualification of electrical equipment in power substations. This code is mainly divided into three sections labeled as A, B and C.

Section A is the core and the most detailed part of the code. It includes general seismic safety considerations, seismic hazard identification, definition of seismic qualification levels, qualification methods, seismic performance criteria for different equipment and installation requirements for the equipment.

One of the most important parts in Section A is the seismic hazard identification. In TEC-PS [11], seismic hazard is defined in two different levels as high and moderate with the selected seismic hazard parameter as the peak ground acceleration (PGA). In high and moderate seismic hazard levels, the PGA values have been considered as 0.5g and 0.25g respectively. Figure 3 presents the required response spectra for these two different hazard levels for damping ratios of 2%, 5% and 10%. It should be stated that the proposed response spectra in TEC-PS [11] is in accordance with the design spectra in TBSC-18 [14].

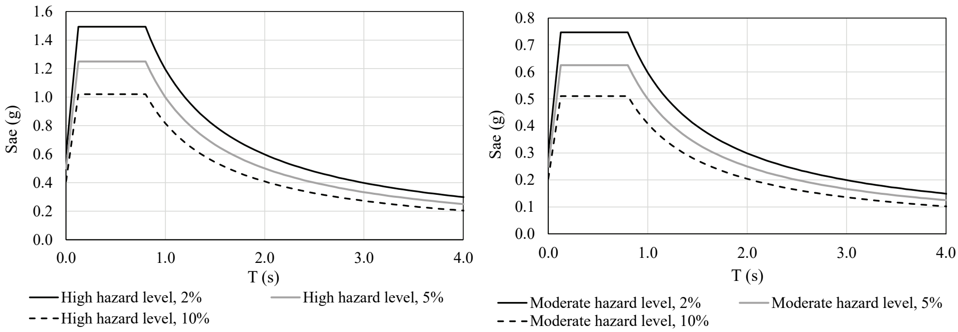


Figure 3 - Required response spectrum for high and moderate hazard levels in terms of 2%, 5% and 10% damping

Another important issue in Section A is the attainment of the seismic qualification levels. In TEC-PS [11], seismic qualification levels for electrical equipment are considered as high, moderate, and low in terms of the PGA value at the considered site (Table 1). The on-site PGA value for the default stiff (rock) site condition can be obtained from the Turkish Seismic Hazard Map (https://tdth.afad.gov.tr/) for a seismic hazard level with a return period of 2475 years (DD-1 level in TBSC-18 [14]) and then modified with appropriate coefficients to get the actual value for the local site condition of the substation. For high and moderate seismic qualification levels, the corresponding required response spectra for high and moderate hazard levels (see Figure 3) are employed. In the case of low seismic qualification level, there is no need to examine the seismic safety of the electrical equipment. On the other hand, there exist some technical requirements related with the anchorage of the equipment during installation to satisfy the required level of structural safety for continuous operation.

Table 1 - Seismic qualification levels defined in TEC-PS [11]

PGA intervals	Qualification level
PGA ≥ 0.5g	High
0.1g ≤ PGA <0.5g	Moderate
PGA < 0.1g	Low

For seismic qualification of the electrical equipment, TEC-PS [11] offers analytical or experimental methods, which depend on different criteria like the equipment type, its function within the substation and voltage level. The analytical methods that can be used within the context of the code can be listed from simple to complex as static analysis, static coefficient analysis and response spectrum dynamic analysis. The challenges in analytical modeling are the development of numerical models for equipment of complex geometry and with numerous sub-assemblages and the determination of material properties of the parts of the equipment to be used in numerical modeling. The second alternative is experimental testing, especially in the case of critical equipment with many small parts that are sensitive to vibration and for which numerical modeling is not feasible. TEC-PS [11] recommends static pull test, resonant frequency search test, sine beat test and time history test as the alternatives according to the type of the electrical equipment. Except for the static pull tests, a shake-table facility is required for all the other tests, which is currently a major issue in Türkiye.

The next part in Section A of TEC-PS [11] is devoted to the general seismic qualification requirements for all equipment and specific seismic qualification requirements for each individual electrical equipment. The main criteria for the general seismic qualification requirements are the equipment voltage level, past earthquake performance of the equipment class and the equipment importance.

For instance, since higher voltage means more seismically vulnerable equipment, the general requirements are more stringent for high voltage electrical equipment. Likewise, the past performances of some classes of electrical equipment reflect their damageability potential during seismic action. For instance, cantilever-structured electrical equipment (circuit breaker, instrument transformer, disconnect switch, bushing, insulator, etc.) is more susceptible to seismic damage. In addition, the importance of the electrical equipment within the substation also plays a crucial role as a general seismic qualification requirement.

According to general seismic qualification requirements, the stresses in critical parts of the equipment, which have been calculated by combining dead load, earthquake load from required response spectrum and other service or operating loads, should not exceed the allowable material stresses. In addition, the calculated tip deflections of cantilever-structured equipment should not exceed the allowable deflection limits, which are functions of the voltage level. During shake-table tests, there should be no damage in the equipment body, at the connections or at the support.

Specific seismic qualification requirements are determined according to the type and properties of the equipment. In TEC-PS [11], these specific rules have been defined individually for 15 different electrical equipment that can be installed in a substation, including the circuit breaker. The requirements can be relaxed if a more conservative and reliable seismic qualification approach is to be used for the considered equipment. However, the earthquake loads applied to the equipment are increased by 50% in the case of using a simpler or less reliable seismic qualification approach.

The last part in Section A of the code deals with the installation issues of electrical equipment such as suspended equipment, adjacent equipment interaction, support structures, anchorage, and base isolation. The detailed discussion related to the equipment installation is covered in Sucuoglu *et* al. [12].

Section B of TEC-PS [11] is focused on the seismic design of structural systems in substations. The design rules stated in this part are generally in accordance with the regulations in TBSC-18 [14]. The last part of the code, i.e., Section C, considers the seismic design of transmission and telecommunication towers.

2.1. Comparison of Seismic Hazard Definitions in TEC-PS and International Codes

Dynamic response analysis is a general approach used for seismic qualification of power substation equipment, as included in international codes such as IEEE-693 [10] and IEC62271-300 [15]. IEEE-693 [10] defines two different levels of qualification: performance level and design level. The code specifies that high and moderate-level spectra for performance level are double that of the design level. IEEE-693 only permits dynamic tests for performance level qualification and ensures that the equipment remains functional during and after the test without considerable structural damage. IEEE-693 was last revised in 2018 [10], with the previous version being published in 2005 [16]. Although the definitions of spectra (high and moderate level) for design and performance levels are the same in both versions, the latest version of IEEE-693 [10] extends performance level dynamic testing for most equipment that needs to be qualified by the time history test method. Additionally, it includes some revisions regarding seismic loads for anchorages, test requirements for the qualification of bushings, and conductor seismic load effects for the qualification of certain equipment. IEEE-693 [10] allows dynamic analysis only in design level qualification, similar to the other two codes TEC-PS [11] and IEC62271-300 [15]. These three codes define high and moderate-level acceleration spectra for different damping values for dynamic response analysis. Figure 4 shows comparison of high and moderate-level acceleration spectra as defined in TEC-PS, IEEE-693, and IEC62271-300 for 2% and 5% damping. Unless any other damping value is justified for the electrical component, these three codes suggest to assume 2% damping for dynamic analysis.

Figure 4 shows that the high-level spectral ordinates of TEC-PS and IEEE-693 with 2% and 5% damping are higher than those of IEC62271-300. The period limits of constant acceleration region also show differences among the spectra curves. The constant acceleration region for high and moderate level spectra with 2% and 5% damping are defined within the period range of 0.125 s to 0.9 s, 0.125 s to 0.8 s, and 0.1 s to 0.4 s in IEEE-693, TEC-PS, and IEC62271-300 spectra, respectively. In the constant acceleration region, the high-level 2% damped spectrum of TEC-PS are 8% lower than that of IEEE-693 and 4% higher than that of IEC62271-300. The margins increase to 20% between TEC-PS and IEEE-693, and 30% between TEC-PS and IEC62271-300 in the descending branches of the spectral curves. The 5% high-level TEC-PS spectrum closely matches that of IEEE-693 up to T = 0.8 s. However, the TEC-PS spectral ordinates are 14% lower than those of IEEE-693 in the descending branch. These two spectra yield demands almost 2.5 times higher than the spectrum given IEC62271-300 up to T = 1 s. On the other hand, it is deduced from Figure 4 that the moderate level spectra of TEC-PS are lower than those of IEEE-693 with the same percentage of difference is attained for their 2% and 5% damped high-level spectra comparison, The 5% percent damped moderate-level spectra of TEC-PS and IEEE-693 yield higher spectral acceleration values than that of IEC62271-300 throughout the whole period range. On the other hand, the moderate-level acceleration spectrum given in IEC62271-300 for 2% damping possesses 16% and 9% higher acceleration values than those of TEC-PS and IEEE-693, respectively for up to 0.6 s. For periods larger than 0.6 s, the trend of three spectra is close to each other. Based on the discussion above, seismic demands given by TEC-PS and IEEE-693 are generally similar, while IEC62271-300 opts for somewhat lower spectral acceleration values for 5% damping.

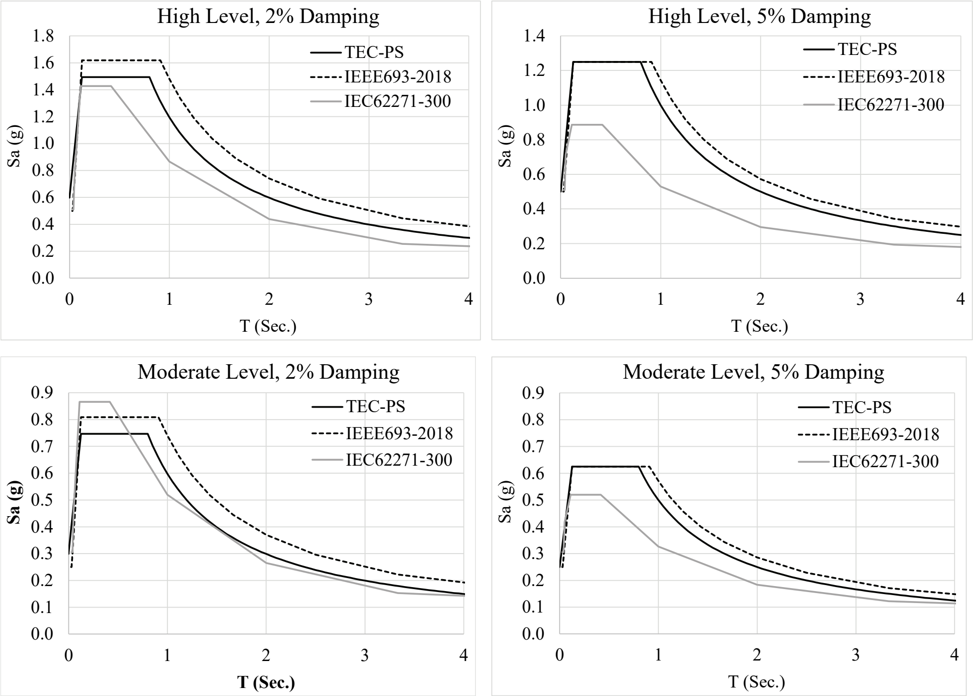


Figure 4 - Comparison of high and moderate seismic hazard level response spectra for 2% and %5 damping

3. SEISMIC SAFETY CALCULATIONS FOR THE CASE STUDY EQUIPMENT

This paper focuses on the seismic safety assessment of electrical equipment in power substations by considering circuit breakers for case study. In other words, similar seismic safety calculations can also be carried out for the other electrical equipment. All the considerations and calculations are conducted in the context of the new Turkish earthquake code for power systems (TEC-PS) [11]. Hence the paper also presents the state of practice for seismic qualification of electrical equipment in Türkiye by applying the new national code for the first time.

Circuit breakers have been used for electrical load switching and fault current interruption in power substations. Therefore, they are one of the critical components in the protection system of a power station for continuous service and functionality. There are two types of circuit breakers according to the chamber that houses the interrupter mechanism: live tank and dead tank. Live tank circuit breakers have their tank at line potential and they are supported by insulating columns (Figure 5, left). Dead tank circuit breakers possess a current transformer at the base of their bushings and the tank is at ground potential (Figure 5, right). Both of these types of circuit breakers are mounted on supporting frames made of steel profiles and they are directly anchored to a rigid foundation [17].

Live tank circuit breakers are more economical and require less space within the station whereas they are more vulnerable to seismic action due to their elevated mass and slender or cantilevered structure. Seismic fragility of live tank circuit breaker has been verified by the reported cases of damage and failure after past earthquakes [3, 18]. Accordingly, potential modes of failure can be listed as follows: tipping of the equipment due to anchorage failure, buckling or yielding of the members within the supporting frames due to excessive vibration, failure of brittle porcelain breaking unit or support insulator under high internal pressure and leaking of gaskets separating column members.

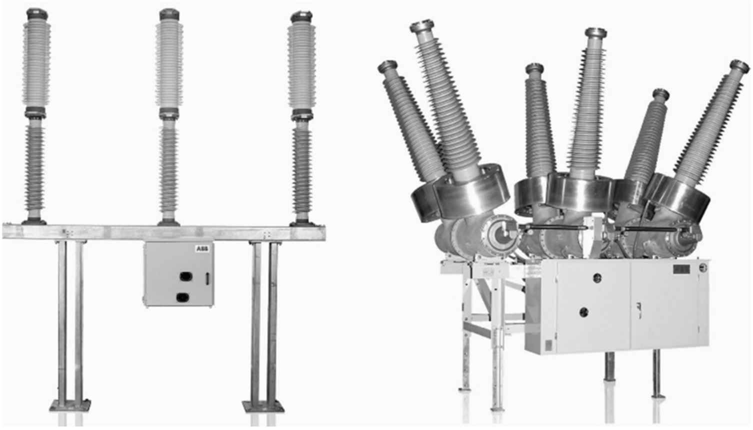


Figure 5 - A typical live tank circuit breaker (left) and a dead tank circuit breaker (right)

The above discussions reveal that seismic design and qualification of circuit breakers is important to ensure the safety of power substations. Hence this section of the paper focuses on the seismic performance evaluation of two different (1-pole and 3-pole) live tank circuit breakers by referring to the Turkish seismic qualification guideline for electrical equipment. The following sub-sections cover seismic qualification requirements, the identification of seismic loads through the related design spectrum, numerical modeling of the selected circuit breakers, the details of seismic analysis and the interpretation of the analysis results.

3.1. General Description of Case Study Equipment

General view of 1-pole type circuit breaker is given in Figure 6, left. The insulator and interrupter mechanism are connected to a steel support structure which is 2.3 meters high. The support structure is composed of four vertical steel angles connected by braces. The vertical elements are L.80.80.8 equal-leg angles while braces are L.65.65.5 equal-leg angles. Horizontal steel plates having dimensions of 60mm × 8mm are placed at top and bottom ends of the support structure connecting the vertical elements. The vertical elements are anchored to reinforced concrete footing at the base via steel anchorage bars. The operation of the circuit breaker is maintained and controlled from a cabinet with a mass of 240 kg. The control cabinet is bolted to the support structure at one side. Total mass of the circuit breaker is 1200 kg including the control cabinet.

3-pole type circuit breaker has an interconnected electromechanical interrupter mechanism between poles which is operated from a single control cabinet. The construction is similar to that of 1-pole system; however, individual poles and support structures are connected by two structural steel channel section beams in transverse direction. The spacing between poles is 3 meters and the mechanical connections running through the spans enable the circuit breaker equipment in poles perform the opening-closing operation simultaneously. General layout of the 3-pole circuit breaker structure is presented in Figure 6, right. The support structure geometry of the equipment is same as that of one-pole system albeit all members are L.70.70.5. Two NPU320 type channel profile steel beams are connected to three support structures via four M24 bolts per support. NPU320 profiles having 320 mm height, 90 mm flange length with web and flange thickness about 10, and 13 mm, respectively are 6.6 meters long. Three circular holes with 182 mm diameters in beam webs are located at several locations along the span to provide access to the interrupter mechanism located between the beams. Three poles with the same geometry and dimensions to that of 1-pole breaker are bolted to steel beams with M24 bolts as shown in Figure 6, right. The total height of the circuit breaker is 6 meters. The control cabinet is bolted to the steel beams between the second and third poles and has a mass of 600 kg. The system, in total, has a mass of 3200 kg.

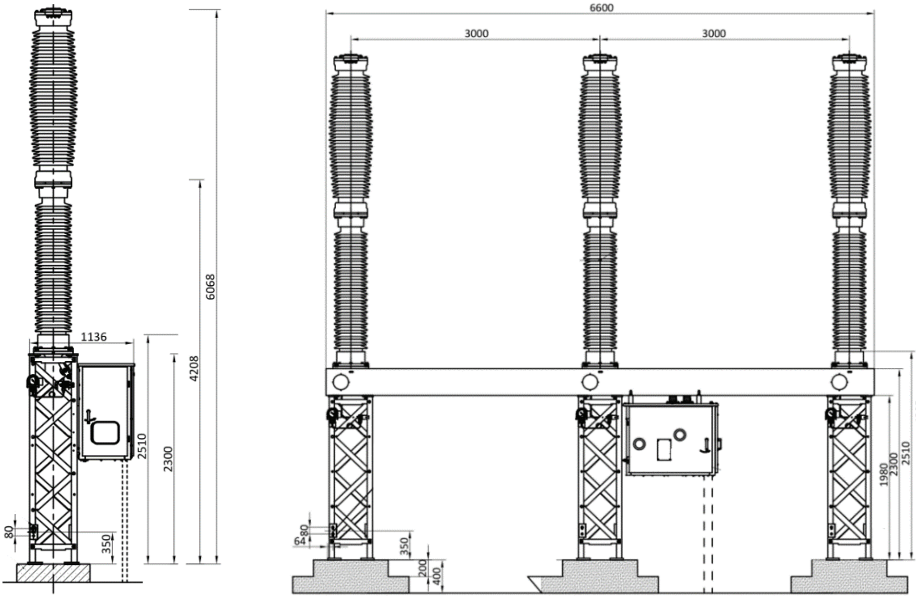


Figure 6 - General views of the 1-pole (left) and 3-pole (right) circuit breakers (units in mm).

The pole structure is composed of an insulator element and an interrupter which contains the circuit breaker mechanism. Both insulator and interrupter elements are made of porcelain with electrical components located inside. The insulator has a tubular profile with an equivalent diameter of 210 mm and 35 mm thickness. The interrupter atop the insulator contains the circuit breaker mechanism and has a tubular section with varying diameter which is largest at 325 mm with 30 mm thickness. Both elements are 1.83 m high. Between two elements as well as at the bottom end of the pole are tubular aluminum connection members which are 150 mm in height. Material properties of structural steel, aluminum and porcelain elements of circuit breakers are given in Table 2.

Table 2 - Material properties of the elements of the inspected high voltage circuit breakers.

Material	Modulus of Elasticity (GPa)	Unit Weight (kN/m^3)	Strength (MPa)
S235JR Structural Steel	210	77.0	235
Porcelain	124	26.5	55
2014 – T6 Aluminum	73.6	26.6	70

3.2. Seismic Action and Service Loads for the Case Study Equipment

Turkish earthquake code for power systems (TEC-PS) [11] specifies that high voltage circuit breakers should meet high seismic performance level in order to be qualified. As for the qualification method, response spectrum dynamic analysis could be performed under the seismic hazard compatible with the required performance level. The qualification procedure also requires that the circuit breaker equipment should be investigated under the combined action of service and seismic loads.

The high-performance level that circuit breakers should meet requires the use of the high seismic hazard level response spectrum. Modal damping ratios of both circuit breaker types are determined as 2% as specified in the TEC-PS [11]. Consequently, the response spectrum given in Figure 3 for the associated damping ratio is used in the dynamic analyses for horizontal excitation. Vertical excitation is also considered by defining the vertical response spectrum which is obtained by multiplying the selected horizontal design spectrum by a factor of 0.8.

Both allowable stress and load and resistance factor design methods are permitted to be used in evaluation of seismic response obtained by performing dynamic analysis. As allowable stress approach is adopted in this study, associated load combination (Equation 1) specified by the TEC-PS [11] is employed. Vertical seismic loads computed according to vertical response spectrum which is obtained by imposing a scale factor of 0.8 to the horizontal acceleration spectrum, as per TEC-PS [11]. They are incorporated into $E_D$load case which is included in the load combination given in Equation 1.

$$1.0\,G + 1.0\,E_D + 1.0\,S \tag{1}$$

In Equation 1, G denotes self-weight, S denotes the service loads acting on the circuit breaker during operation. E_D is the earthquake load combined for two horizontal and vertical orthogonal directions as defined in Equation 2.

$$\begin{aligned} E_D &= \pm E_D^X \pm 0.3\,E_D^Y \pm E_D^Z \\ E_D &= \pm 0.3 E_D^X \pm E_D^Y \pm E_D^Z \end{aligned} \tag{2}$$

High voltage circuit breakers generate impact loads in their poles during instantaneous opening and closing actions. The opening operation acts compression (downward) loads to the poles. Similarly, closing operation results in a tension (upward) load. According to its specifications, 1-pole circuit breaker generates 44 kN compression and 22 kN tension loads in closing and opening operations, respectively. In the case of 3-pole system, a compression load of 90 kN and a tension load of 40 kN during opening and closing, respectively are applied to all 3-poles simultaneously. These services loads for both types of circuit breakers are taken into account in the load combination given in Equation 1.

In a high voltage circuit breaker, each pole is connected to bus bars or high voltage lines at their two end terminals. Environmental factors cause deformations and movement in connected elements, resulting in point loads acting on terminal ends of circuit breakers. According to Substation Structure Design Guide [17], these loads are determined as 1250 N in direction of bus bars, 750 N in perpendicular direction and 1000 N in direction of gravity. The terminal loads which are the external connection loads are acted in both senses (positive and negative) in the analyses. The service load case, *S* in Equation 1 represents the result envelope of the analyses performed under terminal loads acting in different directions.

3.3. Numerical Modeling of the Case Study Equipment

Three-dimensional finite element analytical models of high voltage circuit breakers are created using a commercially available structural analysis software. Discrete elements are utilized in modeling all members of 1-pole circuit breaker. In the case of 3-pole system, two steel beams connecting the individual breaker poles are regarded critical members in terms of expected stress demands. Due to this consideration, two steel beams are modeled using a continuum approach while other parts of the equipment are represented as discrete elements. A fine mesh of four-node finite elements has been created for the steel beams of the 3-pole circuit breaker. Pole structures are represented in the model with equivalent diameters and thicknesses of their members. The equivalent thickness of the porcelain insulators was determined according to their bending stiffness. Consequently, the complex cross-sectional geometry of the porcelain members was transformed to a tubular cross section which is more convenient for numerical modeling. The self-mass of the equivalent sections was also modified so that the total mass of the tubular sections is the same as actual porcelain insulators. Hence, the dynamic characteristics of these members, namely stiffness and mass properties, were incorporated into the numerical model with satisfactory accuracy. Discrete elements representing the porcelain insulators are connected to the support structures via massless link members at the actual position of the bolts. By doing so, the force transfer between the insulator and the support structure is attained at the bolt interfaces. The control cabinets, which contribute the total mass, are included in the analytical models as point masses placed at their respected locations and connected with rigid elements to the rest of the models. Analytical model visuals of both systems are presented in Figure 7.

Dynamic properties of two circuit-breaker systems are determined via modal analyses. The first four free vibration periods of 1-pole circuit breaker are computed as $T_1 = 0.153$ s, $T_2 = 0.150$ s, $T_3 = 0.035$ s and $T_4 = 0.034$ respectively. Due to its geometry, 1-pole circuit breaker behaves like a cantilever column. The mode shapes and associated free vibration periods of 3-pole circuit breaker are given in Figure 8.

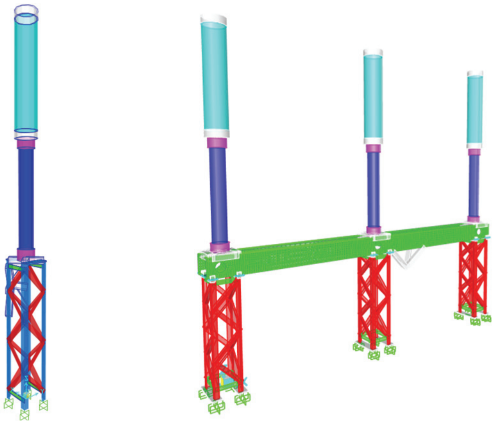
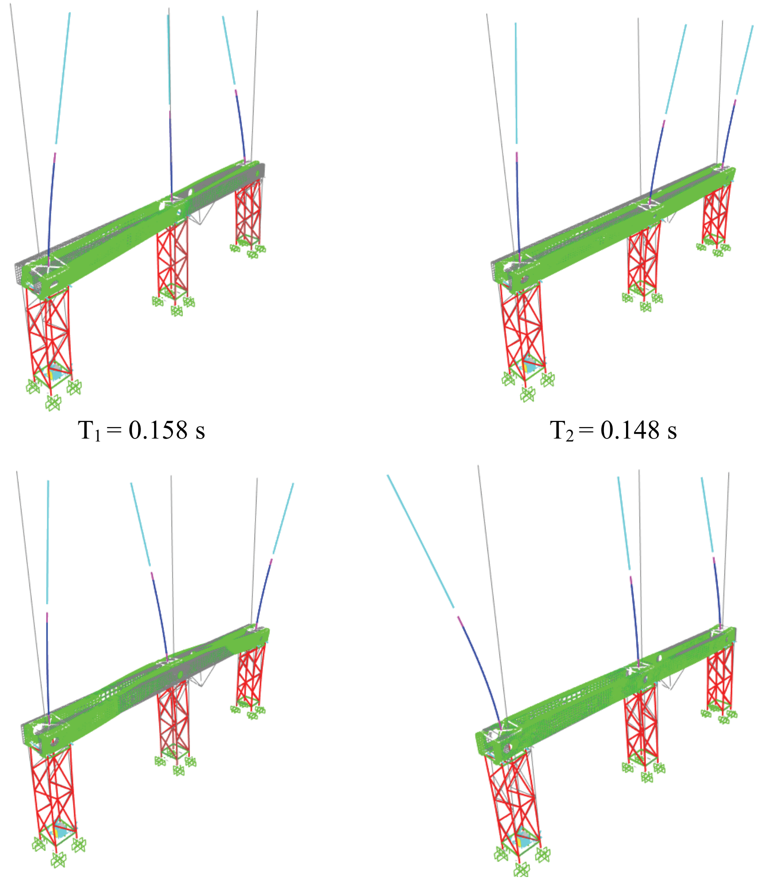


Figure 7 - Analytical model views of the 1-pole (left) and 3-pole (right) circuit breakers



$T_1 = 0.158$ s

$T_2 = 0.148$ s

$T_3 = 0.137$ s

$T_4 = 0.115$ s

Figure 8 - The first four free vibration modes and their periods of the 3-pole circuit breaker.

3.4. Analysis Results

3.4.1. 1-pole Circuit Breaker

Stress demands on elements of the circuit breaker is compiled from the most unfavorable loading conditions obtained from the load combinations defined in Equation 1. These demands and allowable stress limits for each type of material are given in Table 3. In accordance with the allowable stress approach, a safety factor of 1.67 is used for steel members as defined in Turkish Steel Design Code [19]. Porcelain members are classified as brittle under loading. Therefore, TEC-PS [11] limits the allowable stress by 50% of the strength. Hence, a safety factor of 2 is utilized according to the regulation. In the case of aluminum members, the safety factor is used as 1.65 conforming to Aluminum Design Manual [20].

Table 3 - Computed stress demands and allowable limits for 1-pole circuit breaker (results in MPa).

Element Type	Maximum Stress Demand	Minimum Stress Demand	Allowable Stress
Steel members	115.3	-132.7	140.7
Porcelain insulator and circuit breaker equipment	24.9	-23.7	27.5
Aluminum (2014 – T6) connection members	30.1	-28.5	42.4

Maximum and minimum stresses as well as allowable limits for M24 bolts connecting the pole to the support structure and anchorage bars at the foundation level are given in Table 4. A safety factor of 2 which is required for both type of members according to Turkish Steel Design code [19] is satisfied for the given loading.

Table 4 - Comparison of maximum and minimum stress levels of connection bolts and anchorage bars with allowable limits.

Member	Maximum Tension Force (kN)	Maximum Stress in Tension (MPa)	Strength (MPa)	Computed Safety Factor (SF)
M24 connection bolts	126.4	279.4	640.0	2.30
Foundation anchorage bars	94.2	133.3	640.0	4.80

Results in Tables 3 and 4 indicate that the 1-pole circuit breaker satisfies the seismic qualification requirements defined in the TEC-PS [11] for the high hazard seismic level.

3.4.2. 3-pole Circuit Breaker

Stress demands computed from the seismic analyses are compiled in a similar manner to 1-pole system and evaluated according to allowable stress approach. Results are given in Table 5 for all steel, aluminum, and porcelain components of the 3-pole circuit breaker.

Table 5 - Computed stress demands and allowable limits for 3-pole circuit breaker (results in MPa).

Element Type	Maximum Stress Demand	Minimum Stress Demand	Allowable Stress
Steel members	127.6	-138.6	140.7
Porcelain insulator and circuit breaker equipment	25.3	-26.8	27.5
Aluminum (2014 – T6) connection members	26.1	-28.0	42.4

Finite element results of steel beams connecting 3-poles are processed for the most unfavorable load combination and shown in Figure 9 for two principal axes.

Local stress concentrations are observed in Figure 9 at connections to poles and support structures as well as circular openings as shown in the insets. The maximum and minimum stress demands compiled from these results are shown in Table 6. The safety factor is 1.67 as in the case of other structural steel members.

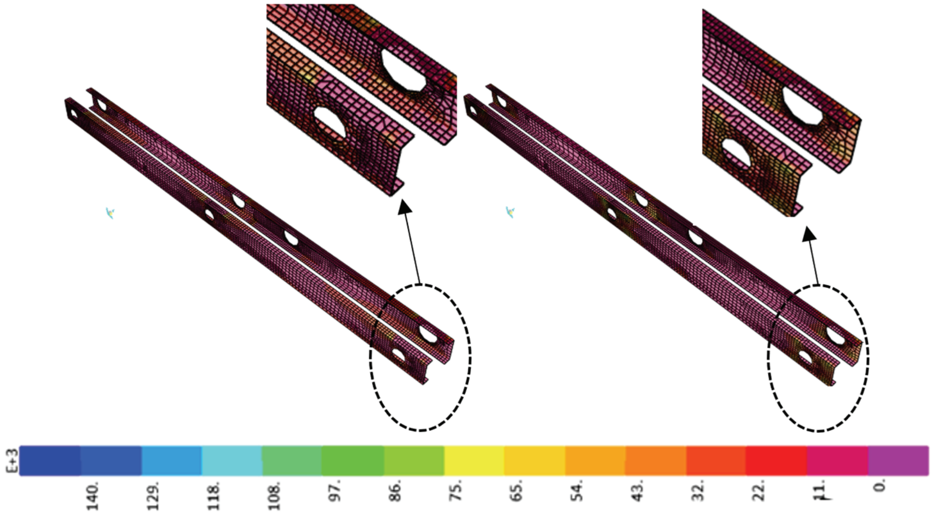


Figure 9 - Stress demands (kPa) obtained from finite element analysis of steel beams for 1-1 (left) and 2-2 (right) principal axes.

Table 6 - Stress demands of NPU320 steel beams and allowable limits (results in MPa).

Load Combination	1-1 principal axis	2-2 principal axis	Allowable Stress
Maximum	92.0	95.2	140.7
Minimum	-90.8	-101.9	140.7

Stress evaluation for M24 bolts connecting the poles, beams and support structures is given along with anchor bars in Table 7. Computed safety factors for these members are higher than the required safety factor of 2.

Table 7 - Comparison of maximum and minimum stress levels of connection bolts and anchorage bars with allowable limits.

Member	Maximum Tension Force (kN)	Allowable Stress in Tension (MPa)	Strength (MPa)	Computed Safety Factor (SF)
M24 connection bolts	99.5	219.9	640.0	2.90
Foundation anchorage bars	66.3	93.8	640.0	6.8

It is determined from the results that 3-pole circuit breaker system also satisfies seismic qualification criteria for high hazard level which is defined by the TEC-PS [11].

3.5. Discussion of the Analysis Results

The 1-pole circuit breaker predominantly behaves as a single mode pendulum under the seismic action due to its geometry. Hence, the highest demands presented in this study are computed at the bottom ends of its components. However, stress concentrations that could implicate a localized area of vulnerability are not observed in any particular part of the circuit breaker.

It has been noted that the dynamic behavior of the 3-pole circuit breaker is different than that of the 1-pole circuit breaker due to more complex geometry. This situation, in turn, causes an increase in seismic demands determined for the 3-pole circuit breaker. The steel beams running along the transverse length of the system play an important role in the out of plane behavior of the circuit breaker in terms of transferring loads between support structures and providing torsional rigidity. Their failure may lead to serious instability of the system. It has been observed that some stress concentrations occur along steel beams in places such as holes or connection regions. Although computed demands are close to allowable stress limit in these members, they perform as required when subjected to code defined seismic hazard.

4. CONCLUSIONS

The seismic safety of non-building structures has become the new focus of earthquake engineering research in the last two decades. This is due to the fact that in today's world it is also important to mitigate economical losses and loss of functionality as well as the physical losses after a major earthquake. This new paradigm turns the spotlights on electrical equipment in power substations, which should continue their functionality in post-earthquake periods. Hence, this study focuses on the seismic safety assessment of the electrical equipment by introducing the recent efforts on national scale regarding their seismic qualification and then by putting the emphasis on a specific electrical equipment within the substation; namely the circuit breaker.

There are reasons for selecting circuit breakers as a case study. First, it is an essential electrical equipment in a power station for continuous service and functionality since it is used for electrical load switching and fault current interruption. Second, like most electrical equipment, it is highly sensitive to amplified vibrational motion caused by the earthquakes due to its cantilevered and flexible nature with elevated mass and fragile components. Hence, the study focuses on the seismic safety calculations of two different types of circuit breakers (1-pole and 3-pole) by using the new Turkish Earthquake Code for Power Systems (TEC-PS). The following conclusions can be drawn based on the obtained results:

- Circuit breakers can be regarded as one of the most critical equipment in a power substation due to their cantilevered structures of the poles which are made of fragile and brittle material. Hence, they should be designed carefully to resist the earthquake loads in the most critical zone with the highest level of seismic action in addition to the other service loads.
- 3-pole circuit breaker seems to be more vulnerable to seismic action than the one-pole circuit breaker due to geometrical complexity that triggers the higher vibration modes. In that case, the critical zones in terms of stress concentration are located at the load transfer sections between different components of the equipment (i.e. insulator-interrupter, insulator-beam, beam-support structure). In the case study equipment, the values seem to be within allowable limits although they are considerable under high hazard level that is dictated by the response spectrum.
- The analysis results show that it is also important to check the seismic safety of the supporting frame and its anchorage to the base plate in order to avoid any premature failure during the vibration of the equipment.

This study is novel in the sense that it presents the new methodology in evaluating and classifying the seismic response of high voltage electrical equipment and provides insight to the expected behavior of circuit breakers under earthquake induced action. It also demonstrates the current state of practice regarding the seismic assessment of electrical equipment in power stations and implementation of the new Turkish Earthquake Code for Power Systems that will be effective very soon. In that respect, the study also serves as a pioneer document for those who will use the new national code for electrical equipment in the near future.

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