Enhancing the Seismic Resilience of Aerial Substations: A Case Study of a Mid-Line Two-Pole 315 kVA Transformer

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ABSTRACT

Experience from past earthquakes has shown that transformers installed on aerial utility poles are among the most vulnerable components in power distribution networks. Significant vibrations and rotations of transformers during seismic events can damage transformer accessories such as bushings, and compromise the connections of their mounting platforms, potentially leading to sliding or overturning of the transformer. In most existing aerial substations in Iran, one or both ends of the transformer platform are connected to the reinforced concrete poles using friction-based joints instead of standard bolted connections. This paper investigates the underlying reasons for the widespread use of frictional connections in conventional pole-mounted substations and evaluates the seismic behavior of a 315 kVA two-pole transformer installation located at mid-span of a distribution line. The main contribution of this study lies in diagnosing prevalent technical flaws in standard aerial substation connections nationwide and introducing a novel seismic retrofit strategy. The proposed retrofit method is founded on two key principles: simplicity and technical refinement. Simplicity ensures the solution avoids execution complexity and costly equipment, while technical refinement guarantees a coherent, well-balanced design with no mismatches or inconsistencies. Nonlinear time history analyses reveal that the seismic performance of the frictional platform-to-pole connections is inadequate, rendering the substation vulnerable under design-level earthquake scenarios. Subsequently, retrofit solutions are proposed to improve the resilience of the transformer platform connections. The seismic response of the retrofitted substation is then compared to its original, unstrengthen state. The proposed retrofit measures significantly enhance the performance level of the aerial substation by limiting transformer rotation to below 0.015 radians, thereby improving transformer stability under design-level seismic events.

KEYWORDS

Overhead utility substation; distribution transformer platform; resilience; concrete pole; seismic retrofitting

1. Introduction

Significant transformer rotation in overhead distribution substations is a common seismic failure mode, often causing damage to attachments or transformer collapse. Research on typical aerial substations in Iran is limited. Jafari et al. [1], through dynamic analysis of a two-pole aerial substation, identified the weak torsional resistance of the platform-to-transformer connection as the main vulnerability and proposed retrofitting details. Zekavati et al. [2], in assessing damage to distribution networks following the 2013 Bushehr earthquake, attributed most failures to excessive transformer rotation and confirmed the effectiveness of standard bolted connections with bracing through finite element analysis. Similarly, Motaei and Akashe [3] identified failure or loosening of platform connections during seismic excitation as the dominant failure mode in Tehran's aerial substations.

This study investigates the seismic behavior of a mid-line two-pole aerial substation through a case study. The transformer platform-to-concrete pole connection reflects commonly used construction practices observed across many regions of the country. The research assesses the seismic performance of this connection, identifies its technical deficiencies, and proposes an innovative retrofitting detail. Finally, the performance of the retrofitted substation is evaluated through time-history analyses.

2. Problem Statement and Contributing Factors

According to National Guideline No. 375 [4] and the Tavanir Aerial Distribution Line Standard [5], the metal platform supporting pole-mounted transformers must be bolted to each concrete pole. The platform consists of two main longitudinal C sections; each anchored to the pole via a pair of transverse brackets. Lateral and out-of-plane stability of the platform-transformer assembly under lateral loads or eccentric gravity loads is provided by diagonal straps, bolted at one end to the pole and at the other to the transverse brackets.

The transformer platform must be installed 485 cm from the top of the taller pole [4]. However, in practice, implementing the bolted connections as detailed in Ref. [4] is not feasible. This is because, at the required installation height, the standard 12 m poles (constructed per [6]) lack predrilled holes needed to fasten the transverse brackets and diagonal braces to the poles. As a result, various nonstandard connection details are used in practice. A common feature among them is the reliance on uncontrolled and unreliable frictional resistance between the transverse brackets and the concrete poles to transfer gravity loads and overturning moments from the transformer to the structure.

3. Modeling

The substation includes a 315 kVA transformer with a 970×1560 mm footprint and 1543 mm total height. As this study focuses on the structural behavior of the poles and transformer platform; internal modeling of the transformer components is excluded. Per International Electrotechnical Commission, IEC 60076, transformers must withstand up to 0.3 g without damage. Assuming standard-compliant units, only the transformer's dimensions, mass (1355 kgf), and center of gravity are modeled in SAP2000 [7]. The transformer is represented as a cuboid in the model, with thick steel shell elements (18.23 mm) used to simulate its mass distribution and center of gravity accurately.

The transformer platform consists of two continuous longitudinal C14 resting on and bolted to transverse brackets (C12 sections). Since the concrete poles are modeled as dimensionless line elements, the transverse brackets are placed at a distance equal to the pole cross-section width at the platform level.

The bearing connection between the brackets C12 and concrete poles is modeled using a nonlinear link with a multi-linear isotropic hysteretic model. Estimating the torsional resistance of the frictional platform-to-transformer connection is challenging due to variations in execution, inconsistent manual bolt tightening, and the absence of calibrated tools like torque wrenches. Nevertheless, in this study, the sliding and torsional resistance of the frictional connections is conservatively estimated to be 20 kN and 3 kN.m, respectively.

The platform-to-pole connection is modeled using two nonlinear links, attached to the midpoints of the transverse brackets bearing on either side of the pole cross-section. These links are restrained against translational motion in the x and y directions and rotation about the z-axis. Their yield capacities are defined as 10 kN in the z-direction (sliding force) and 1.5 kN·m for rotation about the x and y axes.

4. Performance Evaluation

Time-history analyses used accelerograms from four major Iranian earthquakes: Tabas (1978), Manjil (1990), Bam (2003), and Serpol-e Zahab (2017). Each three-component record was scaled to the design spectrum per Iran Standard 2800 [8], considering hazard level and the substation's 0.92 s fundamental period. Stations on Type III soil matched the site conditions. The 1990 Manjil earthquake caused the strongest response, so its results are presented.

Original Platform: Figure 1 (blue) presents the transformer platform rotation time-history during the 1990 Manjil earthquake, showing significant amplitudes that risk serious damage to sensitive components. These rotations assume constant frictional resistance; however, seismic slip can reduce normal pressure on sliding surfaces, lowering friction, destabilizing the connection, and increasing overturning risk.

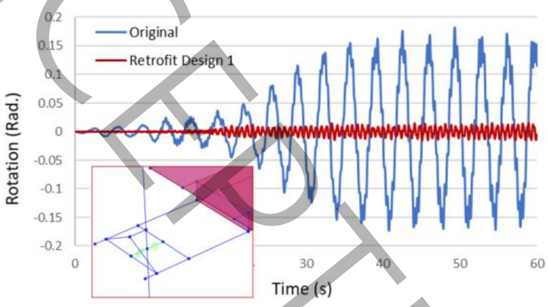

Figure 1. Time history of aerial transformer rotations during the 1990 Manjil Earthquake

Retrofit Design 1: The platform's transverse brackets are braced to the concrete poles with two diagonal straps on each side, while the frictional connections remain unchanged. The braces are made from 8×40 mm steel straps. A rigid horizontal element, representing the distance between the pole's centerline and the outer edge where braces attach, models the brace-to-pole connection (Figure 1). As seen in Figure 1 (red) a significant reduction is achieved in transformer rotations after installing the diagonal braces.

Retrofit Design 2: In Retrofit Design 1, friction connections carry loads, so weakness risks failure. Retrofit Design 2 replaces friction with bolted transverse channels to the concrete pole, matching standard details [4] and ensuring static stability. This reduces transformer rotations significantly.

Retrofit details for the platform connections are shown in Figure 2. Two 16 mm holes, spaced about 30 cm apart along the 12 m pole's web at the platform level, enable bolting the transverse channels. Low-density shear reinforcement allows drilling without obstruction. The web thickness (7–8 cm) permits easy drilling with specialized tools.

5. Conclusions

A simple yet professional retrofit detail for strengthening frictional platform-to-concrete pole connections was proposed and validated through computer modeling. This detail is applicable for upgrading many existing aerial substations.

6. Acknowledgements

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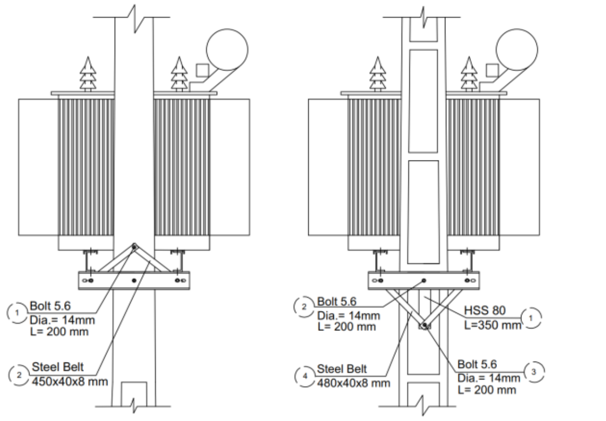

(a) **(b)**

Figure 2. Retrofit details for the platform-to-concrete-pole connection of the aerial substation: a) connection to the 9 m pole, and b) connection to the 12 m pole

7. References

[1] M.A. Jafari, Rahnavard, A., Zekavati, A.A., Vulnerability of Aerial Transformers in Earthquakes and Their Retrofit Solutions in: 26th International Power System Conference, Tehran, Iran, 2011.
[2] A. Zekavati, Jafari, M.A., and Rahnavard, A. , Performance assessment of power distribution network in 2013 Bushehr, Iran, Earthquake, in: 7th International Conference on Seismology & Earthquake Engineering (IIEES), Tehran, Iran, 2015.
[3] Y. Motaei, Akashe, B., Earthquake hazard in Tehran and the study of failure moods of power distribution equipment during earthquake, Journal of New Research in Seismology, JNRS, 10(35) (2015) 5-8.
[4] General and Technical Specifications and Execution Procedures for 20 and 33 kV Aerial and Ground Distribution Substations., in: Publication 375, Management and Planning Organization of Iran, Tehran, Iran, 2007.
[5] Standard for Aerial Distribution Lines - Cross Arms and Pole Arrangements Used in the Distribution Network, in, Ministry of Energy - Tavanir Company - Research and Technology Deputy - Standards Office - Volume 6, Tehran, Iran, 1998.
[6] Guidelines for Determining Requirements, Technical Evaluation Criteria, and Tests for Reinforced Concrete Square Poles., in, Tavanir Company, Distribution Coordination Deputy, Technical and Engineering Distribution Office, Concrete Poles Specialized Committee, 3rd Edition Tehran, Iran, 2017.
[7] CSI, SAP2000 Integrated Software for Structural Analysis and Design, Version 20, Computers and Structures Inc., Berkeley, CA, 2017.
[8] Building Design Code for Earthquake Resistance (Standard 2800) - 4th Edition, in, Road, Housing, and Urban Development Research Center Tehran, Iran, 2014.