Eliminating Hurricane-Induced Storm Surge Damage to Electric Utilities via In-Place Elevation of Substation Structures and Equipment

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Abstract - ***When coastal communities suffer the consequences of multiple "hundred year" tropical storms within the span of just a few years, electric utilities must take action to increase the resistive strength of their system's operating assets to the destructive forces of these storms. This paper will describe a cost-effective technique – elevating existing substation structures and equipment in-place – that has been employed to eliminate damage caused by hurricane-induced storm surge flood waters to existing electric power transmission and distribution substation equipment, all while avoiding disruption of power to the communities serviced by the utility. This paper will examine (1) the process by which the structural engineering and technical obstacles were identified at the onset of the project and (2) how the details of these challenges were overcome in a collaborative team approach involving the electric utility and two specialty contractors. Finally, this paper will examine (3) the results of in-place substation elevation.***

***Index Terms*—High Voltage Techniques, Substations, Structural Engineering, Engineering Drawings, Project Management.**

I. INTRODUCTION

A. Increasing Frquency/Magnitude of Tropical Storm Activity

The 2008 Atlantic hurricane season was one of the most intense on record. Within a two-month period in 2008, three hurricanes and two tropical storms made landfall in the United States. Hurricanes Gustav and Ike, which struck the Gulf Coast within two weeks of one another, were extremely costly storms in terms of property damage (up to $20B) and lives lost (dozens) [1], [2].

But even the 2008 season was not as severe as the one in 2005, which remains the most active in recorded history. The 2005 season set records for the number of named storms, the number of hurricanes, and the costliest hurricanes.

Figure 1. Path of Major Hurricanes in 2005 and 2008 [3].

In September 2005, Hurricane Rita hit rural Louisiana just a month after Hurricane Katrina caused widespread destruction in New Orleans with a 30-foot storm surge. Rita brought storm surges up to 10 feet in height, resulting in the devastation of numerous coastal communities and the loss of power to thousands of residencies and business in these communities.

Three years after Hurricane Rita pommeled the western Gulf Coast in 2005 as the fourth most intense Atlantic hurricane ever recorded, Hurricane Ike ravished many of the same areas and still stands today as the third most destructive storm in US history. Only Hurricanes Katrina (2005) and Sandy (2012) were more destructive.

Hurricane Ike's devastating storm surge struck across the gulf coast and killed 123 Americans. Many of those areas were still recovering from wind and flood damage and power outages caused by Hurricane Gustav just three weeks prior.

Both the 2005 and 2008 hurricane seasons caused severe damage with a lasting impact at all points along the energy infrastructure.

B. Impact on Coastal Electric Utilities

Power outages caused by Hurricanes Gustav and Ike were similar in magnitude, albeit shorter in duration, than those caused by Katrina and Rita.

Damage to the electricity transmission and distribution (T&D) systems along the Gulf Coast caused electricity outages during both the 2005 and 2008 hurricane seasons. And while Hurricane Katrina took down twice as many miles of lines as Hurricane Rita, Rita hit substations harder, taking over 500 off-line. Table 1 details the enormous impact on electric infrastructure from the major hurricanes in 2005 and 2008 [4].

TABLE 1. Hurricane impact on U.S. Gulf electric infrastructure, 2005 v. 2008 [5]

Infrastructure Impacted	**2005**		**2008**	
	Katrina	***Rita***	***Gustav***	***Ike***
Utility Poles Destroyed	72,447	14,817	11,478	10,300
Transformers Damaged	8,821	3,580	4,349	2,900
Transmission Structures Damaged	1,515	3,550	241	238
Substations Off-line	300	508	368	383

The energy supply and distribution infrastructure requires electricity at all points to operate. As a result, electricity outages from hurricanes have widespread impact and result in the closing of refineries, gas processors, pipelines, ports, and other facilities. Extended electricity outages delayed the restoration efforts at these facilities and caused ripple effects nationwide.

II. Public Utility Commission Demands Action By Electric Utilities

A. The Need For Cost-Effective Storm Hardening

The period of heightened tropical storm activity between 2005 and 2008 prompted numerous public utility commissions (PUCs) to thoroughly study the devastating impact hurricanes have on public welfare. The PUCs, working closely with utilities and the public, have issued rule-makings that incentivize and, in some cases, mandate storm hardening for electric utilities' T&D assets.

Figure 2. Storm Surge Damage

As a result, coastal electric utilities have been challenged with balancing competing responsibilities: (1) delivering highly reliable electric service, (2) minimizing the cost of hardening and (3) increasing the resiliency of both their linear assets, such as transmission and distribution lines, and also their discrete assets, such as substations and control buildings.

Flooding from storm surge is the most common and serious cause of hurricane-induced damage to electric power stations. Furthermore, the damage often cannot be repaired. For example, according to an NIST report, saltwater flooding results in such rapid corrosion of the moisture-sensitive components that even pressure-washing immediately after a storm surge recedes is insufficient to save equipment [6].

B. Assessment of Alternative Solution Candidates

During the last decade, coastal utilities in search of an optimal solution have increasingly experimented with numerous approaches to protect sensitive substation equipment. Many of these approaches, such as constructing perimeter levees (floodwalls) around existing sites or relocating existing power stations to newly constructed site pads, have proven to be either technically flawed or highly cost-prohibitive. Tables 2, 3 and 4 (below) highlight three substation hardening techniques evaluated by coastal utilities.

TABLE 2. Analysis of constructing levee (floodwall) around existing substation site

Criteria	**Notes**
Description	This solution would implement a protective berm in combination with electric pumping equipment to remove entrapped water.
Cost Criterion	**Economically viable**. Avoids cost associated with demolition and new site construction.
Schedule Criterion	**Acceptable**. Minimal Construction duration, abundance of qualified contractors
Potential for Service Disruption	**Little to None**.

Performance Criterion	**Unacceptably high risk**: The electric pump presents additional equipment monitoring and maintenance requirements. A breach of the levee results in complete operational failure and greatly extends the duration to return-to-normal operation.

TABLE 3. Analysis of relocating existing substation on to a built-up site pad adjacent to existing site

Criteria	Notes
Description	This solution would relocate the existing substation onto higher ground by building up the entire substation site pad.
Cost Criterion	**Not economically viable**. High site development costs escalate dramatically when considering the need to expand the built-up pad size to accommodate mobile transformer access requirements and coupled with the cost of abandoning "embedded" assets at the existing site.
Schedule Criterion	**Unacceptably long completion duration**. Land acquisition and site pad development time are prohibitive.
Potential for Service Disruption	**Significant**. Circuits could be minimally protected and overloaded during portions of the relocation.
Performance Criterion	**Satisfactory**. The substation should adequately resist the effects of hurricane induced storm surge once relocated to the new elevated site pad.

TABLE 4. Analysis of structurally elevating substation equipment in-place

Criteria	Notes
Description	This solution would raise sensitive substation equipment utilizing existing structures.
Cost Criterion	**Economically viable**.
Schedule Criterion	**Acceptable**.
Potential for Service Disruption	**Moderately high**.
Performance Criterion	**Satisfactory**. No change in performance risk only moderate increase in operation and maintenance risk.

C. Establishing Execution Criteria for the In-place Structural Elevation of Existing Substations

As identified in the tables above, the in-place structural elevation solution provides optimal results for qualified projects for storm hardening of existing substation equipment sensitive to storm surge flooding.

One coastal utility identified the specific engineering problem to be solved as "complete all work affiliated with elevating in-place the existing 115-24.5kV outdoor open-air substation flood sensitive equipment to a point of 5 feet above the previous hurricane induced storm surge high water mark or 13 feet above mean sea level." Their project specifications aditionally stipulated the following conditions:

1. No change in power station performance or system reliability permitted
2. No appreciable change in operational and maintenance practices permitted
3. No service disruption throughout the life of the project permitted
4. No increase in construction safety risk permitted
5. Total installed cost cannot exceed authorized budget
6. Solution must be delivered on schedule

III. Substation Elevation: The Engineering Solution

The total scope of the substation hardening project consisted of 4 distinct aspects, as listed below. The balance of this paper will focus only on the portion of the project affiliated with hoisting the existing 25kV distribution substation structures.

1. Four (4) 115kV circuit switcher electronic control cabinets
2. Two (2) 33MVA 115-25kV power transformers
3. One (1) control building
4. Two (2) 25kV distribution substation structures and associated circuit breakers

An iterative process requiring initial assessment of the existing above-grade and below-grade structure conditions was used to generate the engineering solution to the problem defined by the stakeholder utility. The preliminary assessment was followed by a refined assessment, which included new loading conditions resulting from the application of current building codes to the elevated structure.

The iterative design process developed for this problem is illustrated below.

1. Assess the structural condition of the existing substation to be hoisted
2. Assess the structural condition of the existing foundations to be subjected to increased loadings
3. Establish design criteria
4. Design the column extensions
5. Design platform for operations and maintenance
6. Design lifting plan to accommodate existing equipment and site constraints

A. Assessment of Existing Strucutre

Substation structure engineers, possessing specialty expertise in performing exhaustive structural analyses using a variety of methods ranging from hand-calculations to comprehensive finite element analysis (FEA) techniques, created an exact as-is model replicating the existing structure. The FEA model accounted for actual section property data of all structural members and employed specialty techniques to simulate connection stiffness for each joint in the existing structure. Additionally, the model included simulations for all the existing high-voltage equipment and open-air conductors.

Figure 3. Equipment Lifting

The engineers, in consultation with the rigging subcontractor, assessed the comprehensive structural model under various lifting configurations and were able to confirm that the structure was indeed capable of being hoisted without the need to install additional temporary bracing or utilizing any custom lifting equipment or devices. The team closely analyzed the adequacy of each of the structural bolted connections and instructed the contractor to provide a close visual inspection report of the condition of each connection.

B. Assessment of Existing Foundations

Since actual construction drawings of the 1970s era cast-in-place concrete spread-footer foundations supporting the existing substation structure were not available, a conservative and iterative approach was taken to assess the suitability of these below-grade structures. The assessment of the existing foundations was initiated by ordering a comprehensive geotechnical report, indicating in-situ site soil conditions, in conjunction with the excavation of individual test pits in order to determine the overall dimensions and the current condition of each foundation.

A preliminary assessment indicated that the existing cast-in-place concrete foundations and embedded galvanized steel anchor bolts appeared adequate to resist the expected increase in over-turning moments and lateral shear loads attributable to the application of current design loading conditions coupled with the increased structure height once the structure was elevated.

C. Establishment of the Enviromental and Performance Design Criteria

The environmental design criteria for the project was established based on the then-current versions of the National Electric Safety Code (NESC), the industry standard which safeguards electric utility practices, and RUS Bulletin 1724E-300 Design Guide for Rural Substations, both of which incorporate provisions of the American Society of Civil Engineers (ASCE) Standard 7 “Minimum Design Loads for Buildings and Other Structures”. ASCE 7, which is revised every 5 years, serves as the technical basis for the establishment of portions of most building codes.

The governing loading condition for outdoor open-air substation structures located in tropical coastal regions is lateral pressures induced by hurricane force winds as calculated by formulas cited in ASCE-7. The wind pressure applied to the project’s electrical equipment, conductors and structural components was derived from utilizing an extreme 3-second wind gust velocity of 130 miles per hour (mph) in conjunction with the ASCE-7 formula coefficients specific to the site conditions and the structural attributes. The calculated wind pressures ranged from just over 35psf to be applied to cylindrical surfaces to just over 56psf for flat surfaces.

D. Creation of Detailed Design Plans/Shop Drawings

1) Strucutre Performance – Strength Checks

The engineering and design plan required a strength check of not only the new galvanized steel column extension but also of the existing structure, since the elevated existing structure is subjected to more severe loading conditions, as required by modern design codes.

The primary structural support system designed by the substation structure engineers consisted of four (4) individual galvanized steel column extension each with an overall height of 6’-6”. The design process resulted in an optimized solution utilizing 8x8x5/8” HSS column extensions with 5/16” weld joints for both the 1 ¼” thick base plate reinforced with 3/8” plate stiffeners, for connection to the existing foundation anchor bolts, and for the 1 ¼” cap plate also reinforced with 3/8” plate stiffeners for connection of the existing structure base plate to the column extensions during the hoisting operation.

2) *Deflection Resistance*

The design process also included a comprehensive analysis of the elevated structure's performance capability to limit horizontal deflections, due to lateral wind pressure loading, to within acceptable limits. That ensured that mechanical power delivery equipment, such as circuit breakers and disconnect switches, remains functional during and following an extreme loading event such as hurricane force winds. The deflection limits for this project were established utilizing the recommendations stated in ASCE Manuals and reports on Engineering Practice No. 113 – Substation Structure Design Guide; however, the design resulted in actual deflections much lower than the allowable deflections. ASCE 113 provides for an allowable deflection of .675" at the operator platform elevation level, the deflection in this model was calculated not to exceed 0.3".

3) *O&M Platfrom Design*

The original problem statement, as defined by the utility stakeholder, required a solution that would not increase the risk associated with conducting routine O&M procedures on an elevated substation and required no special tools or training to conduct these routine operations. Details of specific design attributes that addressed the project constraints are described below.

1. Through a rigorous design comment and review process, the substation structure engineers engaged closely with the utility stakeholder's O&M management and technicians in order to design a system of interconnected elevated platforms that accounted adequately for the space required to safely operate the equipment as if done at grade level.

2. The platform design accounted for the required number of OSHA stairway access points and emergency escape ladders, galvanized steel pipe hand rails and fall guards.

3. The operator platform design utilized a grid of primary steel wide flange beams and secondary intermediate beams set-on centerlines spacing of approximately 5" to support 1 ½" thick Industrial platform grating. In order to provide a solid under foot platform with little-to-no bouncy feel to the operators, the design utilized a safe uniform load of 300psf to determine the thickness of the deck grating and the structural member sizes and grid spacing of the primary and secondary members.

4. The structural engineers determined that the use of 9 additional vertical supports was necessary in order to improve walkability and eliminate sag in the platform. The addition of these support columns drove the need to construct a reinforced concrete slab foundation interconnected with the existing structure foundations with steel smooth bar dowels. The engineering plan called for a slab foundation since it was not possible to construct drilled pier foundations underneath the existing energized distribution substation structure. In order to avoid power disruption, this aspect of the work required that the substation breakers be suspended from the existing substation structure to accommodate the construction of the reinforced concrete platform support slab foundation.

IV. Substation Elevation: Project Completion Assessment

The successful completion of this project primarily resides in the coupling of clear expected outcomes with a thorough project planning process and a stakeholder focused iterative design process that provided ample design review and comment opportunities. The following list identifies the satisfaction of the project's purpose as stated by the stakeholder utility:

- Project completed within the established budget
- Project completed within the allotted time frame
- No power loss to customers
- No unusual maintenance required after completion
- Final elevation measured 13 feet above sea level

The completion of this project has provided evidence that solid engineering and exacting execution can deliver a cost-effective method of hardening critical T&D assets against the devastating effects of hurricane-induced storm surges.

References

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