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Evaluating and Comparing Substation Threat Mitigation Tactics: Substation Improvements for a More Resilient Power Grid

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SUMMARY

Maintaining grid operability is a top priority for every utility. The performance required by substation infrastructure and the network that it serves has continually become more demanding recently with the increasing amount of electrification, migration towards renewable assets and geographical shifting of load centers. In addition to these demands accompanying a technologically developing modern world, threats both manmade and environmental endanger grid infrastructure even more. The increase in frequency of both natural disasters caused by an ever-changing climate and terrorist events motivated by tumultuous political atmospheres add a new dimension to utilities risk planning strategies. These types of events can render substation infrastructure and even portions of the grid network inoperative, causing severe economic impact to the area affected and putting many citizens' lives at risk. In the past few years, technologies in the areas of physical security and equipment protection are developing and being incorporated rapidly. Accompanying these technologies with a strong planning strategy and risk mitigation tactics will position utilities to maintain substation resiliency moving forward. In this paper, the authors will discuss threat mitigation tactics utilized by utilities in the United States to protect against both manmade and environmental threats. Advantages and disadvantages of these measures will also be discussed. The goal of this paper is to provide utilities with a more comprehensive understanding of how to harden substation infrastructure for a more resilient power grid.

KEYWORDS

Substation resiliency, Substation reliability, Substation security, Threat Mitigation, Terrorist attacks, Extreme events, Substation hazards

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INTRODUCTION

Providing customers with safe and reliable power is a top priority for every utility. Threats to a consistent power supply come in many forms including environmental or weather-related events, terrorism or vandalization, lack of system redundancy, improper asset management, and more. Strict demands by customers and policy makers increasingly put pressure on utility operators to minimize interruption of power supply, both in terms of the duration and the frequency. Over the past two decades, sustained power disruptions have increased significantly, from less than 20 incidents in the year 2000 to more than 180 incidents in the year 2020 [1]. Due to the heightened awareness of this issue, in 2022 the Department of Energy authorized a $2.3 billion grant program aimed at improving grid resilience for U.S. territories and Native American tribes [2]. As the demand for power grows due to increased electrification, migration towards renewable assets, and the shifting of power and load centers geographically, utilities will need to evaluate the risk of collective threats to substation resilience and implement appropriate mitigation tactics as necessary.

Over the last couple decades, both the types of threats and number of threats to substation resiliency have increased. Terrorist attacks on substations have been on the rise as terrorists utilize firearms and other means to cause damage to substation infrastructure. For example, in just a short period of time, from late 2022 to early 2023, there were a total of 13 substation attacks in various locations throughout the United States [3]. These terrorist attacks and vandalizations can disrupt power supply to thousands of customers for days at a time. Environmental threats from natural disasters also pose a unique threat to the integrity of the grid and have occurred with higher intensity and greater frequency. The largest blackouts in the United States over the last 40 years result from hurricanes in the Atlantic region [4]. Other environmental threats including earthquakes, tsunamis, wildfires, and tornadoes can potentially cause severe damage to grid infrastructure as well. Several documents published by the Federal Emergency Management Agency (FEMA), including FEMA P-55, P-361, and P-424, provide an extensive list of environmental-related events such as hurricanes, typhoons, tsunamis, tornadoes, and other storms that have occurred in the United States over the past 120 years, [5]–[7].

As technologies and philosophies continuously develop within the industry, threat mitigation tactics become more sophisticated. For example, utilities have instituted measures to protect critical equipment from simply disrupting line-of-sight to more sophisticated systems such as alarms and gunshot detection technology. As more threat mitigation tactics become available, it can be difficult for utility personnel to sift through the plethora of options to harden substation infrastructure. In addition, determining the effectiveness of implementing certain measures can sometimes be challenging.

In this paper, threats to substation resilience, including both manmade and environmental, will first be discussed in more detail. The available mitigation tactics for each corresponding threat will next be presented as well as their advantages and disadvantages. Then, mitigation costs and effectiveness will be examined and compared. At the end, the authors will outline some potential challenges that utility owners and operators may face in implementing these mitigation tactics to improve overall substation resiliency.

SUBSTATION THREATS

There are numerous types of threats to substation infrastructure, but all physical threats to substation resilience are caused by one of two categories: manmade or environmental.

Manmade or human threats to substation infrastructure originate from various sources, including those with economic motivations (material theft) and political motivations (terrorism). Material theft is a common motivator for thieves looking to make a quick profit by scrapping precious metals such as copper and/or aluminum. Many manmade threats also involve unauthorized personnel attempting to break into the station to cause damage. Breaking through the substation perimeter can be as overt as ramming a vehicle through the substation perimeter fence or wall or in a more clandestine manner by using bolt cutters to cut or ropes to climb over the fence. In addition, damage to vulnerable substation components can be a result of an attack even from outside of the station perimeter, like a gunfire attack.

Environmental threats to substation infrastructure include weather-related events, such as extreme winds, hurricanes, tornadoes, and floods, and other extreme events like earthquakes and tsunamis. Hurricanes, tornadoes, floods, and tsunamis have unique load characteristics and generally only affect certain geographical locations. Extreme wind conditions are a base component of both hurricane and tornado events, and this high wind load and the debris accompanying them can pose a significant threat to substation structures and infrastructure. The flood condition accompanying tsunami and hurricane events can result in damages to critical substation equipment when submerged.

Wildfires are another type of extreme event that can disrupt widespread grid operations. The frequency of wildfires has also been on the rise, and utilities are increasingly identifying this as a risk to their assets. Several mitigation tactics to identify and prevent wildfires tend to focus more on transmission line infrastructure, for example vegetation management planning, therefore, it is excluded from discussion in this paper.

THREAT MITIGATION TACTIC CATEGORIES

Threat mitigation techniques available to utilities can generally be categorized into four main groups including system redundancy, environmental resiliency, physical security, and equipment hardening. Each of these can be implemented within different stages of a project, as shown below in Figure 1.

Mitigation Tactic	New Substation	Existing Substation
System Redundancy	●	○
Environmental Resiliency	●	◐
Physical Security	●	◐
Equipment Hardening	●	◐

● Applicable ○ Not Applicable ◐ Applicability can vary

Figure 1: Mitigation Tactics and Applicability of Implementation.

For new substations, most mitigation tactics can be implemented as they usually have more flexibility in the planning and design stages compared to existing substations for some of the typically restrictive site characteristics relating to infrastructure buildout, such as land availability and interconnection layout. Planners and designers can sift through the options and develop various alternatives. Then, the most cost-effective option or the option that best suits the targeted level of resiliency can be incorporated while developing the station general arrangement.

For existing substations, mitigation tactic options are more limited, and some options are not even available, such as system redundancy. For other mitigation tactics, the applicability can greatly vary from one site to another depending on the existing conditions of the substations. For example, existing structures supporting electrical equipment may be retrofitted or replaced to withstand higher environmental loadings, but a limiting factor could be existing foundations. Replacing existing foundations can be much more challenging, involving factors such as a longer outage duration, limited space, or constraints due to overhead and underground obstructions.

AVAILABLE SUBSTATION THREAT MITIGATION TACTICS

Substation threat mitigation measures have developed substantially over the past few years. For each mitigation tactic category mentioned previously, there are several options available targeting various characteristics of a substation to improve its resiliency. Utilities commonly prioritize the protection of substation equipment based on its criticality to operation. This equipment, such as a transformer or a control building, is typically expensive and difficult to replace because of long lead procurement times. Although improving resiliencies for all substations within the bulk electric system definitely provides a more reliable power grid, it is burdensome and often not possible primarily due to a lack of funding available. For this reason, utilities normally elect to install robust mitigation measures at the stations most critical to the bulk electric system. The following sections provide more details on common threat mitigation tactics implemented by utilities today.

System Redundancy

Providing system redundancy, either at the network or the substation level, can be accomplished only at the planning stage. One way in which utilities can make their grid infrastructure more resilient is by creating additional system redundancy at the network level. Substations that are radially fed are going to be less redundant than stations that are looped into the electrical network. Looped stations improve reliability as the substation is fed from multiple sources coming from different directions. If one source fails or an outage is required, the substation can maintain operation through the feed from the alternative sources.

At the substation level, various substation bus configurations can provide different levels of resiliency. For example, a single breaker single bus arrangement is one of the most cost-effective configurations as it requires less land area, less equipment, and is much simpler to operate and configure protection. However, it also provides the least amount of reliability in comparison to other bus configurations. A breaker and a half bus arrangement is significantly more reliable but requires approximately 50% additional cost and 50% additional land area to install. In general, a more robust bus arrangement leads to a higher level of resiliency, but there may be other constraints that may prevent utilities from selecting a certain bus configuration even if it is the most reliable and providing the maximum level of resiliency. Those constraints include cost, system requirement and need, land availability, utility's standard practice, etc. More details for commonly used substation bus configurations can be found in Table 1 of IEEE 605 (2008) [8].

Environmental Resiliency

Damages from environmental extreme events pose a significant threat to grid infrastructure, and the mitigation tactics available are unique and constantly developing. Environmental threats consist of loadings applied to power grid from events such as extreme wind, seismic, ice with concurrent wind, extreme ice, hurricane, tsunami, and tornado. Each of these extreme events has unique characteristics to be considered when performing substation structural designs.

Utilities within the United States normally refer to ASCE 113, titled *Substation Structure Design Guide* (2008) [9], to assist in performing substation structural designs. While it includes information relating to load development for extreme wind, extreme ice, ice with concurrent wind, and seismic events, design criteria for the more extraordinary events are not mentioned in this publication including hurricanes, tornadoes, and tsunamis. For these more extraordinary events, several other design documents from various sources are available. For example, ASCE 24 "*Flood Resistant Design and Construction"*[10], and ASCE 7, Chapter 5, *"Minimum Design Loads and Associated Criteria for Buildings and Other Structures"*[11] are commonly referenced for flood designs. ASCE 7 does not have a specific chapter addressing hurricane loads, but instead addresses the effects of hurricane events in separate chapters (Chapter 5 for flood loads and Chapter 26 for extreme wind loads). ASCE 7 also contains design requirements and information for tsunami events, for the first time in the 2016 edition, and tornado events, for the first time in the 2022 edition.

Although these documents provide utilities with guidance to design or retrofit substation structures to withstand loadings from all extreme events, this may not prove to be the most cost-effective option. Bowen, Jergensen, and Somboonyanon performed a case study comparing loadings between an ordinary inland extreme wind event and the load effects of hurricanes and tsunamis applied to a substation control enclosure [12]. Results from the case study, as shown in Figure 2, showed that the effects of the coastal extreme events dramatically exceed the baseline inland extreme event of a 115mph wind speed, as much as seven times higher for the worst case. To design substation structures to withstand this magnitude of load, would result in a substantial increase in material cost for structures and foundations. Structural member or foundation sizes could also be too large and could hinder normal operations. For these reasons, utilities should carefully consider design options to best fit their requirements and fundings while maximizing a targeted system resiliency.

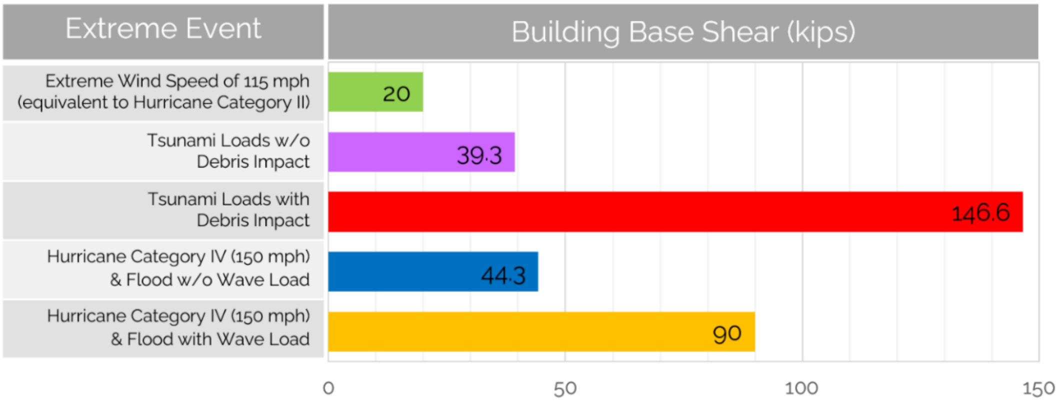

Figure 2: Building Base Shear Comparison for Various Extreme Coastal Events.

Flood mitigation techniques for substation design begin in the planning stage. Starting at the site locations, where possible, a site outside of flood prone area is obviously preferred, but if that option is not available, there are alternative measures that can be taken to protect a new substation from flood damage. One of the alternatives is through the establishment of flood design criteria for a substation. While elevating critical substation equipment above a 100-yr flood elevation is common, depending on the risk and tolerance of a substation, increasing this design requirement to a 500-yr flood elevation can improve substation resiliency. Another alternative is through a site development design either by raising the whole site or only critical substation equipment above a considered flood elevation, or by building floodwalls to protect a substation from flood effects. For this option, it should be noted that environmental permits may be required and the downstream effects post development from a flood to adjacent landowners need to be evaluated according to local agency requirements. For existing substations, there is less flexibility. As equipment is already installed and operating, it is more common to only raise critical equipment above the considered design flood elevation. Even so, this can involve significant outages and complex construction sequencing, and it is important that utilities understand these implications prior to construction.

Tsunamis also contribute significantly to substation structural designs, and there are a few mitigation tactics available specifically mentioned in Chapter 6 of ASCE 7-16. The first option involves raising the critical equipment above the inundation depth. The next option is to protect critical infrastructure from inundation via a tsunami barrier designed in accordance with ASCE 7. The barrier is required to have a height equal to 1.3 times the maximum inundation elevation at the site. Lastly, the components could be designed to resist tsunami load effects, which could be challenging similar to those designing to withstand other extreme events mentioned earlier.

For substations located in coastal areas, there are a few other tactics mitigating the effects of hurricane debris loads to improve overall substation resiliency. Substation control building envelopes such as doors and windows should be designed to resist missile loads as specified in ASTM E1996. The control building doors should be tested in accordance with ASTM E1886. Foundation types should be selected accordingly based on site conditions. Slab-on-grade foundations should be avoided in areas vulnerable to rising waters, and erosion and scour effects should be considered for deep foundation designs. Also, due to corrosion concerns in coastal environments, thicker coatings than normal on substation structures may be specified.

Physical Security

Incidents like Metcalf in 2013 [13], Puget Sound Energy in 2022 [14], and Duke Energy in 2023 [15], highlight the necessity for increased attention to substation physical security. These incidents can cause tens of thousands of outages for a long period of time. As the commonality of these threats continually increases, utilities will need to become substantially more forward-thinking.

One of the most common measures to deter substation attacks and invasions involves the use of security cameras. Often, substations will have cameras installed around the perimeter of the site as well as near critical equipment to assist in identifying trespassers and alerting authorities. Features of these security cameras range in sophistication and cost. Cameras can be equipped with pan, tilt and zoom technology that sense motion and/or sound and move towards people. At night, when visibility is more obscured, motion activated lighting and/or thermal detection technology can be utilized to identify intruders and alarm control center operators and/or law enforcement.

Even more sophistication in substation physical security is available for utility owners and operators with more robust security fences where threats are identified. Utilities are increasingly opting to replace legacy eight-foot-tall chain link fences with a taller fence that is more climb and penetration resistant. These fences are often manufactured to be mostly opaque to prevent line of site and visibility of critical assets within the substation yard. A smaller fence mesh size inhibits cutting and climbing of the fence as box cutters and fingers are difficult to slip through the mesh. The American Society of Testing and Materials released a standard practice for testing of security fence systems in 2015, ASTM F2781 [16]. While not completely comprehensive, this document discusses the testing of certain fencing materials and their resistance to forced entry using common tools. Examples of various substation security fence options are shown in Figure 3.

Figure 3: Substation Perimeter Fence Options.

Firearm attacks on substation infrastructure are increasingly more common in the United States, leading to more common specification of perimeter fences made of ballistic material. ASTM F2781 also contains requirements for ballistic and impact testing of security fence systems. Many utilities have begun installing fences manufactured in accordance with ASTM F2781 at their substations to increase resilience and security. Underwriters Laboratory, an American materials and products testing company, released a standard UL 752, which outlines testing and classification requirements for ballistic rated materials, that can be adopted and incorporated into specifications to provide protection against firearm attacks [17].

Aside from climbing, cutting, or shooting through security barriers, intruders can also attempt to gain access to substations through other means. Utilities are more commonly installing anti-dig and anti-ram infrastructure around a station's perimeter. These anti-dig measures typically consist of gabion baskets or plain concrete to make those areas less penetrable. Culverts and stormwater drains that run between the interior and exterior of the station footprint also need to be secured. To achieve this, thick metal grates can be installed with openings sized such that stormwater can still pass through, but humans cannot. Figure 4 presents different options for substation perimeter fence anti-dig options.

Gabion Basket | Concrete Grade Beam | Culvert Grate Guard

Figure 4: Substation Perimeter Fence Anti-Dig Options.

Anti-ram measures consist of steel crash gates or crash cabling designed to halt vehicles traveling at high speeds. ASTM F2656 includes guidance testing perimeter barriers against vehicular collisions [18]. Examples of substation perimeter fence anti-ram options are presented in Figure 5.

Anti-Ram Drive Gate | Anti-Ram Crash Cabling

Figure 5: Substation Perimeter Fence Anti-Ram Options.

Table 1 below provides a summary containing cost data, advantages, and disadvantages for some of the security fence types discussed in this section. It should be noted that the sources for cost data shown in this table come from aggregated data in a range of geographical regions in the United States and can greatly vary based on site location to be installed and material availability.

Physical Security Mitigation Tactics	Approximate Cost*	Advantages	Disadvantages
8-ft Chain Link Fence	$15/ft	• Owner and contractor familiarity • Low cost	• Minimal security
12-ft Security Fence with 5/8” mesh	$250/ft	• Higher site security • Additional resistance to climbing and cutting	• No line-of-sight prevention • Owner and contractor unfamiliarity • Higher cost
20-ft Security Fence with 75% minimum screening	$1350/ft	• Maximum site security • Provide with line-of-sight prevention	• Owner and contractor unfamiliarity • Highest cost
12-ft Decorative Wall	$1000/ft	• Provide with line-of-sight prevention • Aesthetically pleasing • Climb resistant	• Owner and contractor unfamiliarity • Specific to certain manufacturers • Very high cost

*Can vary based on site location to be installed and material availability

Table 1: Substation Perimeter Fence Alternatives.

Equipment Hardening

Occasionally, installing a security fence around an entire substation perimeter may not prove to be the most cost-effective option or may not be a viable option due to other constraints, such as limited space or required outages. Rather, utilities may prioritize protecting substation equipment that is critical to operation and/or has long lead times from threats outside of the station perimeter, particularly from a gunfire attack, with bullet resistant barriers. Typically, this includes transformers and control houses. These bullet-resistant barriers can be designed to have a certain footprint and placed around critical substation equipment to protect against attacks. They are also often manufactured to be opaque to obscure line of sight. Footprints can be custom designed to snake around obstructions near the equipment being protected. Figure 6 shows some examples of protection options for a substation transformer.

At-Grade Precast Wall | Cast-in-Place Concrete Firewall | Transformer Bullet Resistant Shielding

Figure 6: Substation Transformer Protection Alternatives.

Utilities can also protect transformers by installing concrete firewalls. Firewalls are already often utilized in substations to prevent fires from spreading to adjacent equipment. In addition to being designed to have a certain fire rating, firewalls can be designed with a ballistic rating to protect critical components from terrorists shooting from outside the substation by disrupting line of sight. Another option to protect transformers involves installing transformer armor to protect transformer tanks, cooling equipment, and the bottom of bushings, all while still allowing air circulation around the unit. These types of panels can be manufactured for new and retrofit applications and can provide a greater level of equipment protection from threats. Table 2 presents alternatives for transformer protection. Figure 6 presents depictions of these alternatives.

Transformer Protection Tactics	Approximate Cost*	Advantages	Disadvantages
At-grade Precast Concrete Walls	$1,000/ft	• No foundation required • Customizable footprint to facilitate access to equipment	• Lack of full line-of-sight prevention in most applications
Cast-in-Place Concrete Firewall	$300,000	• Customizable design for height to provide line-of-sight prevention and thickness for ballistic rating	• Limited line-of-sight prevention • Significant cost
Transformer bullet-resistant shielding	>$400,000	• Full line-of-sight prevention	• Specific to certain manufacturers • Significant cost

*Can vary based on site location to be installed and material availability

Table 2: Substation Transformer Protection Alternatives.

For control houses, the concept remains the same. Thicker, bullet resistant control house walls can be specified in accordance with UL 752 to make them more resilient. In locations where firewalls are necessary between a transformer and a control house, the firewall can also serve both as a ballistic barrier and to obstruct line of sight from outside the station boundary. Precast concrete walls on grade can be placed in vulnerable locations to inhibit line of sight but minimize impact on footprint and space constraints.

POTENTIAL CHALLENGES AND SOLUTIONS

There are a significant number of decisions that utility owners and operators will face when making their infrastructure more resilient. The primary consideration when determining how and when to implement resiliency measures is available funding. As demonstrated in Table 1 and Table 2 for some mitigation options, the cost to increase resiliency of substation infrastructure can be significantly more expensive than the default or typical installation.

The effort to collectively evaluate all the variables associated with these substation resiliency improvements can sometimes be challenging. One possible solution for utilities to overcome this challenge is to create a rubric that defines a hierarchy of substation priority for implementation of resiliency measures based on station characteristics. This would classify substations based on characteristics including, but not limited to, voltage, number of customers supplied, type of customers supplied, number of transformers, number of line positions, and station location. Once all stations were classified, they would be organized based on their significance to the function of the grid, and utilities could then prioritize necessary upgrades to make them more resilient.

Several permitting and environmental obstacles are prevalent when considering some of the mitigation measures listed in the previous sections. Taller security fences can often trigger additional requirements from neighborhoods that request a more visually pleasing substation perimeter wall. For substations located in flood hazard areas, installation of equipment and foundations could trigger downstream effects, and disturb neighboring landowners. Elevating critical equipment above the flood elevation in urban environments could expose line of sight between that equipment and the substation exterior, triggering additional requirements such as a taller perimeter wall or additional landscaping to increase obscurity.

Maintenance and operation of the substation equipment after the implementation of some of these resilience measures also presents a unique challenge. With taller and more opaque fences, visibility inside the substation not only deters intruders, but also obscures the ongoings inside from emergency personnel. Firefighters may not be able to sufficiently strategize how to maintain and suppress station fires due to this lack of transparency. Unique fences and gates as well as platforms leading up to elevated equipment also may pose challenges for station maintenance personnel who are unfamiliar with these measures.

CONCLUSION

Continuously increasing power demand due to shifting of load centers, transition to renewables, and overall electrification all contribute to an ever-expanding electrical grid. As threats to grid infrastructure become increasingly more numerous in terms of type and number, the demand for utilities to be proactive and diligent in how they design and plan their network has never been greater. With the greater awareness from utilities, methods to harden infrastructure and protect against these threats, both environmental and manmade, are continually developing and becoming more readily available. Mitigation techniques range in variety from simple and straight forward to more complex and robust. The mitigation measures mentioned in this paper provide utilities with perspective and insight as to how utilities within the United States are protecting their assets and maintaining resiliency. There are a multitude of advantages and disadvantages to each alternative, and utilities should continually evaluate risk and cost effectiveness to ensure their critical assets are protected. With a better understanding of the threats to substation resiliency, utilities will be better prepared and equipped to maintain grid operability moving forward.

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