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Extreme Weather Effects on the Energy Infrastructure

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Abstract

Power systems are exposed to a variety of extreme weather conditions, which bring new and unexpected challenges to power system design and operation. This paper discusses some of the lessons learned to increase system hardening and ride-through (minimizing the damage caused by extreme weather) and achieving some level of resilience (minimizing the impact of extreme weather damage) to extreme weather events.

Keywords: extreme weather, distribution, transformers, generation plants

Résumé

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1. Introduction

In the last decade, the occurrence of extreme weather events has increased, and the damage from some of them has been devastating to the infrastructure, including the power grid. Extreme weather can impact the loading, efficiency, and failure rate of the components. Additionally, high failure rates caused by extreme weather conditions can increase the likelihood of overlapping outages, which can lead to widespread outages and cascading.

This paper provides a discussion on some of the ways to enhance the hardening and resiliency of power system. It also provides a deep look into the effects of droughts and heat waves.

1.1 Definition of Extreme Weather

Extreme weather covers weather phenomena that are especially severe, unseasonal or at the extremes of historical distributions. There is no official definition for extreme weather, but it has been characterized by conditions with probabilities of less than 5% in a specific geographic area. Extreme weather effects are thus relative to both the historical weather record and to the regional design basis of the infrastructure.

Extreme weather does not always have to result in significant damage to infrastructure, such as what Sandy did in New Jersey and Long Island, but typically results in much stressed system conditions and numerous electric service interruptions to customers.

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1.2 Extreme Weather Events in the USA

In the United States of America several unique severe weather conditions exist, such as:

- Hurricanes that typically roll up from the tropics toward the United States making landfall somewhere in the Southeast (Gulf Coast, Florida, and the Outer Banks). Occasionally they make it up to New England. The hurricanes in the Northeast Pacific almost never hit the USA. A distinct hurricane season occurs from June 1 to November 30, sharply peaking from late August through September.
- Tornadoes occurring in the area of northern Texas (including the Panhandle), Oklahoma and Kansas with boundaries of the “Tornado Alley” not clearly defined. Ninety percent of tornadoes hit this region of the USA. because cold, dry air from Canada and the Rocky Mountains meets warm, moist air from the Gulf of Mexico and hot, dry air from the Sonoran Desert, which causes atmospheric instability, heavy precipitation, and many intense thunderstorms.
- Flooding that can be generated by river floods, flash floods and ocean storm surges/ tides, with the main difference being the onset of the flooding, with river floods being the slowest building floods. Flash floods are typically associated with heavy downpours that can lead to surges of water turning dry flood plains into raging torrents in minutes. Storm surges are caused by the high winds pushing on the ocean’s surface, causing the water “to pile up” as well as the low pressure at the center of a weather system. The water level rise due to the combination of storm surge and the astronomical tide is referred to as the “storm tide”. The rise in water level from the storm tides can cause extreme flooding in coastal areas, particularly when a storm surge coincides with normal high tide, resulting in storm tides reaching up to 15 ft to 20 ft (5 m to 6 m)¹. Hurricanes Sandy (2012), Ike (2008) and Katrina (2005) all caused major coastal flooding. In Sandy, flooding occurred in a matter of minutes or even seconds, according to some eye witnesses. [6]

¹ The term “storm surge” is often used in a non-scientific way to mean “storm tide”.



Figure 1: Storm Surge Damage During Superstorm Sandy

- Derechos in the Midwest. These are widespread, long-lived, straight-line windstorms associated with a fast-moving band of severe thunderstorms. They travel quickly with winds generally exceeding hurricane-force. A warm-weather phenomenon, derechos occur mostly in summer, especially during June and July

Other extreme weather events in the USA are:

- Droughts and heat storms in Texas
- Winter storms in the Northeast and Midwest
- California firestorms
- Northwest windstorms

2. Impacts of Extreme Weather on Power Systems

Figure 2 depicts the systems affected by extreme weather. One area which is covered in this paper is the effects of droughts on the distribution and generation system. Impacts of extreme weather on the different elements of the power systems are covered in references [1], [2], [3], [4], [5] and [6].

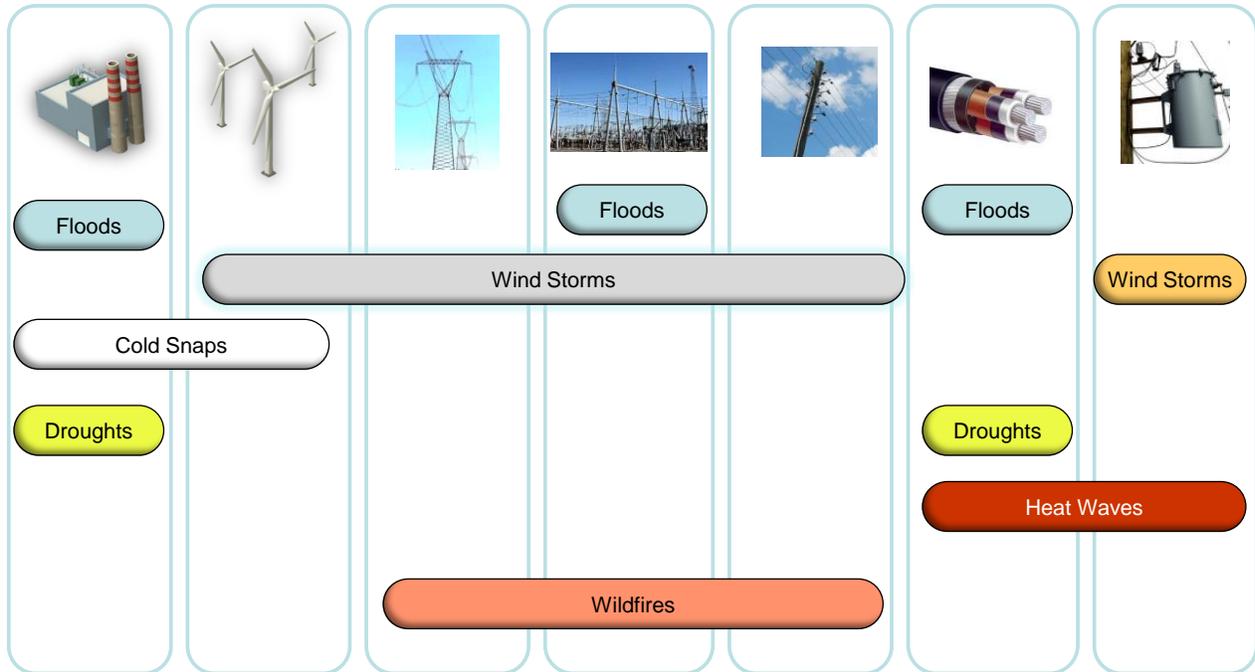


Figure 2: Mapping of the Effects of Extreme Weather on Power Systems

3. Examples of Measures to Increase Hardening and Resiliency to Extreme Weather Events

Hardening refers to physically changing the elements of the infrastructure to make it less susceptible to damage from extreme weather and improves its durability and stability. Basically *minimizing the damage caused by extreme weather events*.

Resiliency refers to the ability to recover quickly from damage from the extreme weather event. Resiliency measures do not prevent damage; rather they enable electric facilities to continue operating despite damage and/or promote a rapid return to normal operations when damages and outages do occur. Basically *minimizing the impact of extreme weather damage*.

3.1 Hardening

3.1.1 Undergrounding

The undergrounding of distribution and transmission lines and feeders has been one of the most often discussed against wind and winter storms.

- Several studies for utilities in the USA have been conducted on the subject yet not a single study has recommended a complete conversion of overhead infrastructure to underground facilities.
- Undergrounding can reduce the frequency of outages, but restoration times may increase due to the complicated nature of the underground systems.

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- Undergrounding is expensive (costing about 5 to 10 times more than overhead), but is a viable solution when targeted towards critical loads, worst performing feeders, or feeders that have affected high numbers of customers.
- In coastal areas prone to storm surge, as demonstrated by Superstorm Sandy, underground systems are much more susceptible to damage from flooding and even risk further damage during clean-up efforts.

3.1.2 Vegetation Management

A major component of hardening for extreme weather is tree trimming. Vegetation management represents the highest recurring maintenance cost. Deferral of vegetation management tended to be more costly in the long run. Revisiting in-place vegetation management programs is vital to minimize the effects of wind and winter storms on power lines. For these vegetation management programs to be effective, it is important to recap some of the salient points collected from different wind and winter storms, such as in [6]:

- Utility actions typically include expansion of existing right-of-way (ROW), clearance of overhang in urban areas and removal of dead or dying trees (hazard trees).
- Inspections of damage from wind storms and hurricanes have revealed that distribution pole failures were principally a consequence of fallen trees (secondary failures) and not due to the impact of the wind on the power delivery system directly (primary failures).
- For distribution systems, there is a direct correlation between the proximity of trees to distribution lines and the vulnerability of the lines to severe wind and winter storms.
- Tree-related failures increase exponentially when wind speeds are over 60 mph.
- In high wind situations, risk from airborne debris from trees outside the right-of-way (ROW) can exceed the risk of trees within the ROW by factors as much of 3- or even 4-to-1.
- Increasing the intensity of the hazard tree program would not noticeably improve electric system performance during major storm events. Some assessments have shown that even if all hazard trees are removed from areas around power lines, outages could not have been avoided. This is because sometimes over half of the trees causing outages have no visible defect (not hazard trees).
- Line outage frequency is highly correlated to the number of trees per mile edge of the line, and weakly correlated to variables such as line and tree heights and clearance between the trees and the line.
- Reductions in wind-related outage rates can be achieved by reducing the span length and increasing the number of poles per mile for the cases where the majority of the damage is due to power line (poles, hardware, etc.) failures (primary damage). However, if secondary damage to the power is more prevalent for most pole failures, then this approach could result in more pole failures rather than fewer and the time needed to restore service could be prolonged.

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3.1.3 Design and Construction Practices and Standards

To achieve hardening of the power systems elements to extreme weather, design and construction standards for transmission and distribution system elements should be based on the local conditions of the facilities. Some observations on means to achieve hardening are:

- Widespread system hardening could be cost-prohibitive and the most effective use of hardening tools could be through a targeted approach. It is recommended thus to identify the most critical elements, the worst performing elements, those elements that have aged or weakened or those elements most in danger of failure and work to replace them with improved system designs.
- Identifying and mitigating potential structural problems through thorough inspections and maintenance plans. Infrastructure hardening should not come only as a result of storm damage tear-downs.
- The most common hardening practice for electric T&D systems is upgrading poles and structures with stronger materials. This typically comprises upgrading wooden poles to steel, concrete, or a composite material. It may also include the installation of guys and other structural supports. Transmission structures are usually upgraded from aluminum to galvanized steel lattice, or concrete.
 - Adding guy wires can increase the strength of a pole without the need for full pole replacement.
 - Upgrading crossarm material allows for the strengthening of a structure with minimal material replacement.

3.1.4 Smart Grid

The Smart Grid has the potential of offering some hardening for extreme weather. However, for Smart Grid technologies to work adequately, they may need to be paired with other system hardening mechanisms, as covered above. For some of its features (e.g., automatic system reconfiguration) to work, portions of the distribution system need to remain intact and not affected by the extreme weather damage. In addition, certain system topologies (e.g., loop rather than radial) need to be in place. If these are true, then the Smart Grid may offer some significant advantages in reducing the footprint of weather-related outages, as well as enhancing and speeding up restoration efforts. The Smart Grid makes it better equipped to detect and correct supply problems in extreme weather. One utility has reported that mapping smart meter outages allowed it to expedite recovery and response after a tornado by precisely identifying the path of the storm damage.

3.1.5 Microgrids

Microgrid can seamlessly connect and disconnect from the main grid in times of widespread outages and allow customers to operate in “island” mode, for extended periods of time. The widespread power outages in the wake of Superstorm Sandy spotlighted the benefits of distributed power generation and microgrids. A number of locations reported that on-site power generation and the ability to operate independently of the grid allowed organizations, such as

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colleges and businesses, to have electric power, at least partially, during the worst of the storm². Some other salient points on microgrids follow.

- Microgrid applications are generally end-user driven and funded, yet utilities need to be involved to ensure systems are optimized for interoperability and security. By controlling interconnected loads and managing customer voltage profiles, utilities can reduce the cost of voltage and power control at microgrid locations. Microgrids remove some of the load that would otherwise be served by the utility on the main grid, and thus can reduce peak demand or area load growth, and defer new power delivery capacity investments.
- Because of the low price of natural gas, cogeneration or gas turbines are often used for local generation and microgrids. Other sources of power, e.g., fuel cells, are also used³.
- Campuses and military bases are considered good candidates for microgrids, especially if there is a strong need for back-up power.

3.1.6 Advanced Technologies

Many of the advanced technologies currently being studied and rolled out which can lead to increased system hardening resiliency are closely related to Smart Grid and microgrids applications. In addition, some other promising technologies for achieving system hardening include hydrophobic, nano-particle coatings on conductors to enhance waterproofing, prevent ice formation on power lines, and combat corrosion and shorting caused from saltwater.

3.2 Resiliency Measures

The following are some of the lessons learned from many utilities, which could enhance the resiliency of the electric grid for extreme weather events:

- Adequate weather prediction.
- Advanced planning for restoration crews from mutual assistance or outside contractors. Widespread storms encompassing large areas and multiple service territories will lead to increased competition for resources and thus adequate planning is essential.
- Pre-staging enables immediate response.
- Adequate backup, accessibility, restoration supplies such as poles, wires, transformers mobile transformers, mobile substations, diesel generators and other system components easily obtained through contracts with suppliers.
- Arrangements for response equipment to be on standby and readily available (e.g., extra trucks, supplied with necessary materials including GPS devices, maps, flashlights, communication devices).
- Secure enough fuel for its service trucks.

² During Hurricane Sandy, Princeton University was able to power part of the campus with local generation. A cogeneration plant at New York University was able to provide heat and power to part of the campus during Sandy in Manhattan. Also, 40-megawatt combined heat and power plant in the Bronx was able to provide electricity and heat to a large housing complex.

³ A number of fuel cells installed in New York and New England were able to keep operating during Sandy.

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- Mobile command centers with state-of-the-art technology, including satellite and cellular communications, telescoping masts with cameras, etc.
- Enhanced communication, planning and coordination to negate/minimize logistical challenges associated with dispatching restoration crews and keeping customers, regulators and press up-to date with accurate information.
- Designating a central working team to deal with crews, state and federal/state officials, news agencies and customers.
- Monitoring of customer feedback (from customer service representatives, text messaging, mobile application notifications, utility websites, and social media: Twitter and Facebook).
- Using the two-way communication capabilities of the smart meters to monitor service continuity, identify outages and “ping” customer meters.
- Implementing effective outage management system.

4. Heat Waves and Droughts Impacts on Distribution and Generation Systems

No universal definition exists for a heat wave, yet it can be thought of as a long period of abnormally high temperatures at a certain geographic location. Along with the excessive heat, it is often accompanied by high levels of humidity. These two characteristics increase the relative temperature or heat index to elevated levels. Heat waves and droughts differ from other extreme weather events as they mainly impact distribution and generation systems.

4.1 Effects of heat Waves on Distribution Systems

On the distribution system level use of more air conditioning increases the demand on energy and reduces, very importantly, the diversity among loads. The higher consumption leads to higher loading on the distribution lines, underground cables, transformers and other components. If these are not derated to allow for more demanding thermal limits they may age faster or even fail. Power outages may thus ensue within areas experiencing heat waves due to the increased demand for electricity and the associated stress on certain equipment.

4.1.1 Effects of Heat Waves on Distribution Transformers

Failure of distribution transformers during heat waves have occurred [1]. During heat waves, distribution transformers, which typically cool off at night, are unable to cool down sufficiently during warm nights and thus begin the next day with higher starting temperatures. An analysis done on distribution transformer failures during a heat wave that affected the west coast of the USA in 2006 and 2007 confirmed that the combination of elevated air temperature and high load levels played an important role in the elevated failure rates witnessed.

Higher temperatures⁴ accelerate many of the physical and chemical mechanisms involved in materials deterioration, with the rate of deterioration increasing exponentially with temperature. When the temperatures reach certain levels, bubble formation in the oil will ensue. The bubbling reduces the oil's ability to act as an insulating medium, and a "bubble path" may lead to a flashover and immediate catastrophic failure. The deterioration caused by high

⁴ The heat sources in distribution transformers are:

- Load current effects and the associated electrical losses, and
- Ambient temperature and solar induced heating

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temperatures is cumulative: the deterioration that will not be "undone" when temperatures fall. A distribution transformer will suffer gradual deterioration of its components equal to the cumulative stress of high temperature over its service life to date.



Figure 3: A Failed Distribution Transformer Due To A Heat Wave - Courtesy LADWP

Preparing for heat waves/summer peaks entails inspections of substations for peak load readiness and identification of load-relief projects with projected overloads, identification distribution transformers with potential thermal overloads and updating emergency load-transfer and contingency switching plans. LADWP reverted to using transformers with a 55-degree rise for better overload capabilities, lower losses and longer life [6].

4.2 Effects of Heat Waves on Power Generation Plants



Figure 4: Power Plants Depend On Bodies Of Water For Cooling

A large number of power plants are located next to large bodies of water (e.g., ocean, river, lake) and their cooling is achieved simply by running a large amount of water through the condensers in a single pass and discharging it back into the water body. Weather conditions that may cause a rise in the temperature of the cooling agent would result in lower thermal efficiency of the plant. The thermal efficiency depends on the temperature difference between the internal heat source and the external environment, and is decreased by reducing the

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temperature differential. A difference of 5 degrees in cooling water inlet temperature might be expected to change unit heat rate by around 1%.

4.2.1 Regulatory Conditions

Typically, any power plant that is normally cooled by drawing water from a body will have regulatory limits imposed either on the temperature of the returned water or on the temperature differential between inlet and discharge. In hot summer conditions, when the inlet water from a river approaches the limit set for discharge, the plant could be restrained to run at less than full power using once-through cooling only, as has happened several times in the USA and elsewhere. One notable example is associated with the heat wave of 2003 in Southern Europe. In that heat wave, temperatures in June through mid-August exceeded seasonal temperatures by 20 to 30% over a large portion of the continent resulting in soaring demand for electricity. Accompanying the heat wave was a “water balance deficit” in Southern Europe. River water levels dropped to levels that affected the cooling process of the power plants, while elsewhere the water temperatures after the cooling process exceeded certain allowed environmental levels. As a consequence, a number of plants in France, Germany and Spain had to shut down, or operate at a reduced load levels. France also cut its power exports by as much as 50%, and actually imported an estimated 2000 MW in some days.

4.2.2 Adaptation to Droughts

Some adaptation measures which can be used at power plants affected by droughts include:

- Night-time load reductions
- Water conservation practices (reduction of evaporation losses)
- Use of ice to cool air before entering gas turbine
- Renting modular cooling towers
- A modification to the plant’s cooling system, such as:
 - Retrofitting the existing cooling towers
 - Additional cooling and helper towers
 - Use of hybrid cooling
 - Dry cooling towers
- Altering location or elevation of intake

5. **Concluding Remarks**

The increased incidence and severity of extreme weather events and related high-profile power outages are creating new challenges for utilities, even for those which have taken proactive system hardening initiatives. While the public and regulators are

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demanding that utilities do more to prevent lengthy and widespread outages following storms, large scale replacements of the infrastructure with new components are unrealistic. Thus, a prioritized, incremental and targeted approach for hardening and making improvements in system design and operation and most importantly restoration is more likely to prevail. Such plans to achieve hardening and resiliency need to be specific to each system and based on a thorough analysis of the performance of the assets during the extreme weather events.

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7. Biography

Nicholas Abi-Samra (Nicholas.abi-samra@dnvkema.com), Senior Vice President, Electricity Transmission and Distribution, is experienced in power systems, planning, operations and maintenance. Abi-Samra served as the General Chair and Technical Program Coordinator for the IEEE General Meeting of 2012. He is a professional engineer.