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Resilience Assessment for Power Distribution Systems

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***Abstract*—**Power distribution systems are essential and crucial infrastructures for the development and maintenance of a sustainable society. These systems are extremely vulnerable to various types of natural and man-made disasters. The assessment of resilience focuses on preparedness and mitigation actions under pre-disaster conditions. It also concentrates on response and recovery actions under post-disaster situations. The aim of this study is to present a methodology to assess the resilience of electric power distribution poles against wind-related events. The proposed methodology can improve the accuracy and rapidity of the evaluation of the conditions and the assessment of the resilience of poles. The methodology provides a metric for the evaluation of the resilience of poles under pre-disaster and post-disaster conditions. The metric was developed using mathematical expressions for physical forces that involve various variables, such as physical dimensions of the pole, the inclination of the pole, and wind speed. A three-dimensional imaging technology (photogrammetry) was used to determine the inclination of poles. Based on expert opinion, the proposed metric was used to define zones to visualize resilience. Visual representation of resilience is helpful for decision makers to prioritize their resources before and after experiencing a wind-related disaster. Multiple electric poles in the City of Beaumont, TX were used in a case study to evaluate the proposed methodology.

***Keywords*—**Photogrammetry, power distribution systems, resilience metric, system resilience, wind-related disasters.

I. Introduction

ELECTRIC power distribution systems play a vital role in modern societies. Developing and maintaining sustainable and resilient electric power systems is one of the greatest challenges in most societies. Among the generation, transmission and distribution systems, which are the subsystems of an electric power system, distribution systems are the most vulnerable to wind-related disasters such as hurricanes and tornados. The impact of such events has been growing as the frequency of such storms is increasing, in particular for the last 30 years [1]. In the U.S. alone, the annual economic loss due to power outages caused by the wind-related events was estimated to be between \$20 to \$55 billion [2]. Data show that power outages may last between a few hours to several days depending on the intensity of the event. Moreover, the duration of outages has been increasing [3]. Under these circumstances, reliable operation of power distribution systems has become an ongoing and significant concern for the U.S. Government [4]. Electric poles, which are frequently damaged by strong winds, are the major components of power distribution systems. This study thus focuses on the resilience of electric poles.

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The use of wooden poles is preferred due to their low costs and satisfactory performance in electrical and communication industries [5]. Even though wooden poles are preferable, their strengths against natural events such as winds and flooding, and physical decay are questionable for power distribution. Since power outages can cause service disruptions, the cost of immediate corrective actions could be very high. To prevent loss of service and high-cost corrective actions, and determine the health of the wooden poles, several inspection methods are used in the industry. The most common inspection methods are a visual inspection, sound and bore inspection, and full or partial excavation [6]. To prevent human errors and to improve the current practice of the inspection, a methodology is developed.

Thus, the main contribution of this study is developing a methodology for accurate assessment of the health conditions of electric poles, and evaluation of their resilience under pre-disaster and post-disaster conditions caused by wind-related events. A resilience evaluation metric was also developed. It is envisioned that the resilience metric can help decision makers more effectively in prioritizing preventive maintenance work as well as corrective maintenance work. This will allow them to allocate and utilize limited resources for maintaining electric poles in healthy conditions before and after the occurrence of wind-related disasters. A power grid system consists of different elements (e.g. generators, substations, transmission lines, distribution lines, etc.) which all need to be investigated for improving the resilience of the system. The review shows that there is no metric or framework documented or suggested specifically for the resilience of power distribution poles.

II. Literature Review

A resilience approach should constantly investigate the capability of a system to anticipate and absorb threats, take precautionary activities to reduce their adverse consequences, and develop response and recovery actions for the system to resume its normal operations quickly [7]. It is impossible to determine and address all possible vulnerabilities and protect individuals, communities, and society against various disasters. However, it is believed that preparation, response, recovery, and mitigation efforts, which are resilience strategies against these disasters, can help to reduce the adverse consequences of disasters [8]. The concept of resilience has gained so much attention in disaster management area, especially after manmade disaster such as, the September 11, 2001 attack and natural disaster such as, Hurricane Katrina. Recent academic studies and governmental reports prove that resilience is an essential part of establishing a national security policy platform [9].

Since electric power systems have been frequently challenged by natural disasters in recent years, a presidential memorandum was issued by President Obama in 2014 as part of a Quadrennial Energy Review (QER) [10]. The Department of Energy (DOE) conducted a technical workshop mainly focusing on developing resilience frameworks and metrics for electric grid infrastructures, natural gas, and liquid fuels [11]. Several energy companies and national labs such as, Rand Corporation, Argonne National Laboratory (ANL) Infrastructure Assurance Center, Sandia National Lab, ConEdison, Inc., and Dominion participated in this workshop and presented their resilience metrics. Rand Corporation proposed a metric by providing a set of guidelines to measure the resilience where they defined input, capacities, capabilities, performance, and outcome [12]. ANL Infrastructure Assurance Center presented their resilience metrics based on four components, namely preparedness, mitigation, response, and recovery [13]. Each of the components consists of several more components of resilience. Awareness and planning are evaluated under preparedness. Mitigation actions are involved in mitigation construction, alternate site, and dependencies. Vital characteristics of response are determined as onsite and offsite capabilities, incident management, and command center characteristics. Finally, recovery encompasses restoration agreements and recovery time. Sandia National Lab illustrated a resilience metric, where the performance indicators are identified and translated into consequences in terms of safety, economics, and affected population. An informed decision support system is developed with a consideration of uncertainty [14]. A probability density function is used to form the resilience metric in that study.

Economic prosperity, governance, and quality of life are largely depending on critical infrastructure systems, and this dependency is growing rapidly day by day. Ouyang [15] reviewed many literature on critical infrastructure systems and found out existing modeling and simulation of interdependent critical infrastructure. He mentioned that the data access or lack of precise data is the key problem in this field. It is very difficult to develop a generalized resilience model to assess resilience of infrastructures against natural disasters. Usually, system robustness and regional weather conditions vary, which also lead to problems in developing a universal resilience model. A large number of research studies have been conducted on system resilience, and some methodologies and frameworks have been developed in literature [16], [17]. In addition, some researchers suggested some metrics for resilience. Henry and Ramirez-Marquez [18] presented a time dependent metric to quantify system resilience. Although it considers a cost function as well, it involves many variables in practice and it will vary depending on an individual component. Unfortunately, the most of the suggested resilience frameworks in literature are not applicable to real systems. They are rather helpful for conceptualization of resilience.

Lately, it is possible to see some notable research on the quantify response and recovery phases of resilience from a practical perspective. Ouyang et al. [19] proposed a three-stage framework for resilience analysis, where first is the resistant capacity that incorporates with hazard identification, frequency, and initial damage level, second state is the absorptive capacity which means the maximum impact level that a system can adapt, and third stage is restorative capacity that involves with estimation of recovery time and recovery cost. These three capacities ultimately determine the system level resilience in a quantitative term. They set some resilience improvement strategies for single and multi-hazard types and showed resilience improvement using some hypothetical resilience improvement model. Pre-event activities may reduce the cost to repair and time to restore the system with complete serviceability. Ouyang and Duenas-Osorio [5] introduced a probabilistic modeling to quantify the hurricane resilience of electric power systems, which consists of hurricane hazard model, component fragility model, a power system performance model, and a system restoration model. They considered hurricane hazard as a Poisson process and calculated economic cost using above mentioned four models. This model was enhanced since it was hard to implement in real-time operation and it was computationally expensive. Mensah and Duenas-Osorio [20] enhanced the model with computationally efficient algorithms and illustrated in a restoration process considering the probabilistic dependencies. Their new resilience framework considered resource mobilization practices as well as component repair times in restoration model. Francis and Bekera [17] proposed a resilience framework consisting of system identification, resilience objective setting, vulnerability analysis, and stakeholder engagement. This framework was tried to configure and observe three resilience capacities, namely adaptive capacity, absorptive capacity, and recoverability. However, it did not measure the inherent properties of the system.

Resilience evaluation of electric power systems can be done with examining power outage records statistically after a hurricane disaster to make prediction for future outages for same disasters [20]. These techniques are good for resource allocation efforts of utility companies but usually they suffer due to lack of data. Li et al. [21], describes an accelerated failure time (AFT) model using large dataset from three electric power companies to estimate storm-caused power outage durations before the event. The AFT model is a survival analysis model, where time-to-event data are analyzed statistically, and output of this model is the restoration curve. Electric distribution network is mostly affected part during storm, where the distribution poles are main survival. So, the pole based risk assessment can establish a stronger basement for pre-storm planning. Guikema et al.

[22] conducted a regression analysis and used data mining techniques to predict the number of utility poles needed to be replaced based on past damage data. Again, the accuracy of the estimation mostly depends on the precision of collected data. Both the systems inherent properties and events characteristics are equally important for better analysis and precise prediction. Li et al. [23] introduced a probabilistic wind storm model considering frequency, intensity, and duration by using database from National Oceanic and Atmospheric Administration's (NOAA) as well as developed weather-dependent component failure models based on outage record from Northeast Utilities U.S. Then, an enhanced sequential Monte Carlo method is used to determine the system risk. Identification of systems characteristics, response to hazardous events, and their interdependencies are very complex and crucial to quantify resilience level. Arab et al. [24] developed a stochastic model for pre-hurricane restoration planning of electric power systems infrastructure and they used a proactive resource allocation model considering the potential path of future hurricanes to repair and restore anticipated damages of the system. They analyzed both partial and full restoration strategy, and results show that the partial restoration is more cost-effective than full and finally leave the option to decision maker to choose according to operation policy of the company. If the power company can predict the outage time due to wind related disasters ahead of time how long the outage will last, it is possible to better inform to customers, public, and utility commission. Nan and Sansavini [25] observed the failure behavior of infrastructure systems and proposed an integrated resilience metric to quantify resilience capabilities.

However, there are no suggested metrics or frameworks especially for the resilience for power distribution poles to the knowledge of the authors. For a structural based system like a pole based electric distribution network, it is very important to observe the system behavior and model the system according to its characteristics. A structural based system can be characterized by three kinds of models, namely optimization, simulation, and fuzzy logic models [26]. Ryan et al. [27] used an event based Monte Carlo simulation to assess the deterioration of timber power poles and proposed a strategy for time dependent network maintenance. In their study, under wind load, the treated and untreated poles showed similar failure rate where the untreated poles required twice the maintenance to function at the same level of reliability. Darestani et al. [28] developed a boundary model considering the effect of adjacent spans of wood utility poles in overhead distribution lines and measured the probability of pole failure. Results show that there is a noticeable impact on poles if the properties of adjacent spans are different. If a distribution line consists of poles with different properties, then the probability of failure rate for newer poles will increase compared to older ones because of the higher stiffness of new poles.

III. Methodology

The total force on a particular electric pole has been defined as a resilience metric to determine the health of a wooden pole for pre-disaster and post-disaster events. Poles may experience two types of forces; the gravitational force due to the weights of the pole and the lateral force caused by winds as shown in Fig. 1. The total force on a wooden pole was calculated based on the gravitational and wind forces on the pole. These forces were determined based on the angle of the pole with respect to the vertical direction perpendicular to the ground. Present angles of wooden poles were determined by three-dimensional (3D) imaging technology (photogrammetry) to calculate these forces on them. It is possible to get very sharp and realistic images using this technology. Thus, the present angle of a pole can be determined with high accuracy. A detailed description of how to use photogrammetry can be found in [29]-[32]. An image of an electric pole which was taken using photogrammetry is shown in Fig. 2.

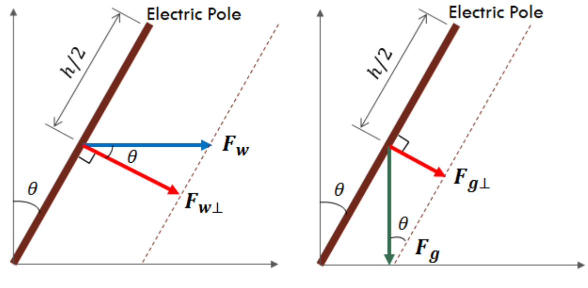

Fig. 1 (a) The wind force and (b) the gravitational force

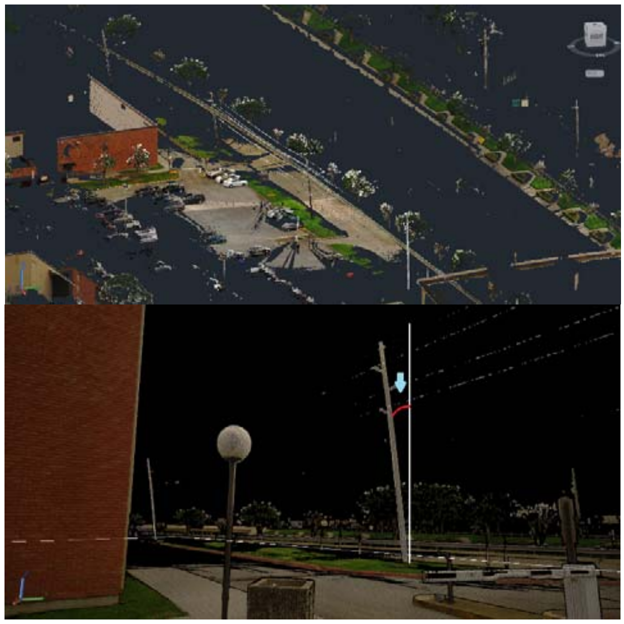

Fig. 2 An example of manual registration of a pole at Lamar University, Beaumont, TX

Ranges of angles were defined to assess the present conditions of poles. If θ is the angle of a pole defined as shown in Fig. 1, the angle ranges, $0 \leq \theta < 15$, $15 \leq \theta < 25$ and $\theta \geq 25$, correspond to healthy, critical, and unhealthy conditions of a pole, respectively. These critical pole angles were determined by an expert who has more than 25 years of experience with power distribution systems. Green, yellow, and red zones corresponding to the healthy, critical, and unhealthy conditions were defined to visualize the resilience of a particular pole. If a pole is in the red zone, it requires an immediate corrective maintenance action. If it is in the yellow zone, it raises a question on whether a corrective action needs to be taken immediately or not. Intuitively, if it is in the green zone, an immediate mitigation action is not needed. Such a visual representation is helpful for decision makers in prioritizing their resources before and after experiencing a wind-related disaster.

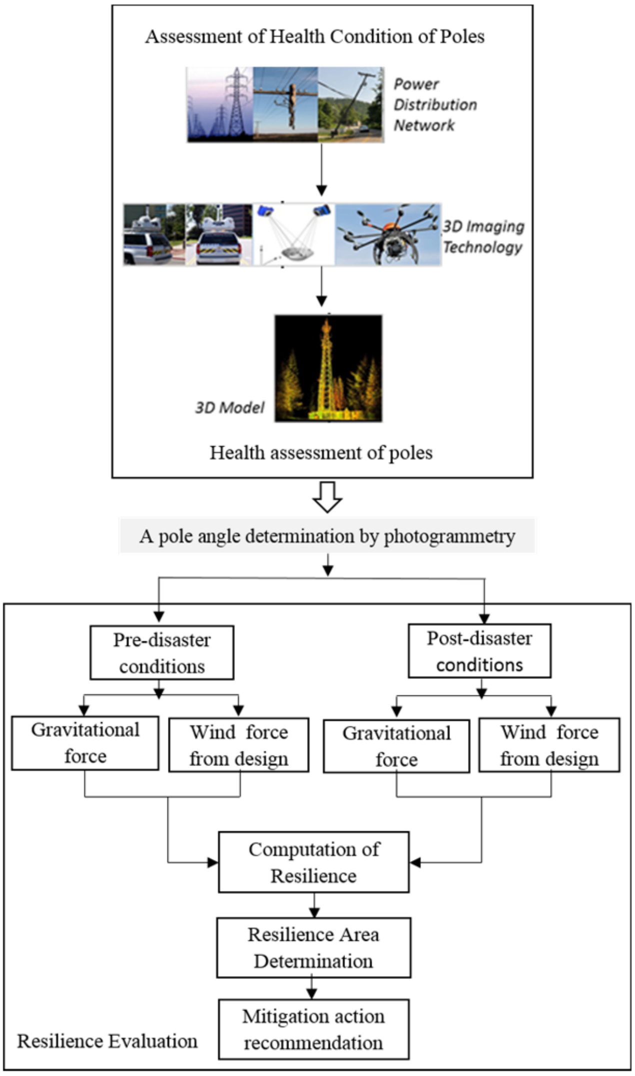

Fig. 3 A resilience framework

The developed resilience framework is shown in Fig. 3. The framework consists of two modules: the first module is part of a larger project investigating the assessment of the present health conditions of poles. The second module was developed for resilience evaluation. Poles have a design based gravitational and wind forces for pre-disaster conditions. The wind force based on design was determined using the 3-second peak gust wind speed, which has a particular value for each region of the US. The total force following a major wind event can be predicted based on gravitational and wind forces for post-disaster conditions.

An electric pole is defined by an overall height of h and a radius of r. If the specific weight (unit weight) of the pole is γ, the mass of the pole can be determined as

$$m = \pi r^2 h \gamma \tag{1}$$

The gravitational force on the pole can be predicted as

$$F_g = mg \tag{2}$$

The component of the gravitational force that is perpendicular to the pole can be expressed as

$$F_{g\perp} = F_g sin\theta = mgsin\theta \tag{3}$$

whose unit is Newton (N). According to the Standard Specifications for Structural Supports for Highway Signs, Luminaires, and Traffic Signals published by The American Association of State Highway and Transportation Officials (AASHTO), the wind pressure on the pole can be found as [33]

$$P = 0.00256 K_z G_h C_d V^2 \tag{4}$$

where V is the 3-second peak gust wind speed in the region where the pole is located, K_z is the exposure coefficient, G_h is the gust response factor, and C_d is the drag coefficient such that [33]

$$K_z = 2.01 \left(\frac{h}{900}\right)^{2/9.5} \tag{5}$$

$$G_h = 0.65 + \frac{0.6}{\left(\frac{h}{33}\right)^{1/7}} \tag{6}$$

$$C_d = \frac{129}{(C_v V d)^{1.3}} \tag{7}$$

where $C_v = 1$ is the conversion factor. The expression for C_d that corresponds to cylindrical structures was selected since the pole is cylindrical. It should be noted that the unit of P will be in pounds per square feet (psf) when the value of V is in miles per hour (mph), and the values for h and r are in feet (ft). The wind force can be computed by multiplying P with the cross sectional area A of the pole that is exposed to the wind as

$$F_w = CPA \tag{8}$$

where $A = 2hr$ and

$$C = 0.454g \tag{9}$$

which is a constant that is used to convert the force from pound-force (lbf) to Newton (N). The component of the wind force that is perpendicular to the electric pole can be expressed as

$$F_{w\perp} = F_w cos\theta = 0.00512 C K_z G_h C_d V^2 hr cos\theta \quad (10)$$

The total force due to the gravitational and wind forces can be predicted as a resilience metric as

$$F(\theta, h, r, V) = F_{g\perp} + F_{w\perp} = mg sin\theta + 0.00512 C K_z G_h C_d V^2 hr cos\theta \quad (11)$$

It is observed that the total force is a function of θ, h, r and V.

IV. Case Study

As the energy capital of the U.S., the Southeast Texas is a vital region in terms of national energy and security. A large number of oil refineries are located in this region. Since the region is very prone to wind related disasters, it has unique needs for the application of resilience initiatives. Pre-disaster and post-disaster conditions must be critically evaluated, and resilience actions must be taken for this region. Beaumont was selected as a case study to examine the resilience of poles in power distribution systems. A series of electric poles along the two major transit roads of Beaumont, which are South Martin Luther King (MLK) Jr. Parkway and Highway 69, were chosen in this study as shown in Fig. 4.

A wooden electric pole is assumed to have an overall height of, $h = 40$ ft, and a radius of, $r = 0.3125$ ft. It is also assumed to be made of southern yellow pine. The specific weight (unit weight) of the southern yellow pine is $\gamma = 36$ lbs/ft^3. The gravitational acceleration is taken as $g = 9.8$ m/s^2. In most of the U.S., the 3-second gust wind speed is 90 mph. Therefore, 90 mph is selected as the reference wind speed used when the pole is designed. When $\theta = 15°$ and $V = 90$ mph, the total force on the pole is predicted as $F_{gy} = F(\theta = 15, h, r, V = 90)$, which is used as the border between the green and yellow areas for resilience. When $\theta = 25°$ and $V = 90$ mph, the total force on the pole is found as $F_{yr} = F(\theta = 25, h, r, V = 90)$, which is used as the border between the yellow and red areas for resilience. If the total force on the pole is less than F_{gy}, its resilience falls into the green area. If the total force is greater than or equal to F_{gy}, and less than F_{yr}, its resilience is in the yellow area. Finally, if the total force is greater than or equal to F_{yr}, its resilience is considered to be in the red area.

Table I shows 22 electric poles with various angles of θ. The total forces on these poles were predicted for 90 mph as well as the maximum speeds of Category 1 and Category 2 hurricanes, which are 95 mph and 110 mph, respectively.

Resilience areas were determined for each pole and each one of these three wind speeds. Therefore, Table I shows how the resilience of the poles changes with wind speed.

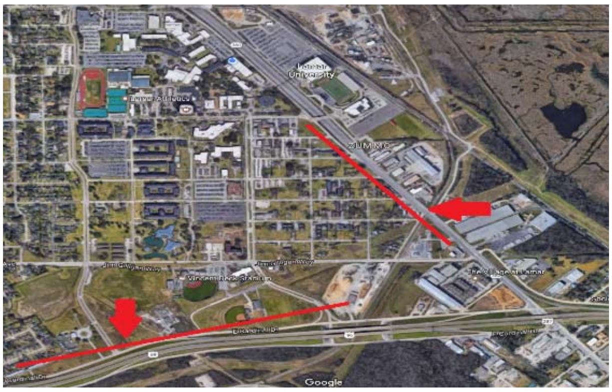

Fig. 4 Aerial view of South MLK Jr. Parkway and Highway 69 in Beaumont, Texas

TABLE I
RESILIENCE EVALUATIONS OF SAMPLE POLES

Area	Pole #	Angle	(Pre-disaster) Design wind speed of 90 mph	(post-disaster) Category 1 Max wind speed of 95 mph	(post-disaster) Category 2 Max wind speed of 110 mph
SML King Jr Pkwy	1	17			
	2	21			
	3	13			
	4	26			
	5	11			
	6	17			
	7	4			
	8	17			
	9	12			
	10	14			
	11	7			
Highway 69	12	2			
	13	4			
	14	5			
	15	3			
	16	17			
	17	12			
	18	9			
	19	18			
	20	12			
	21	15			
	22	8			

V. Conclusion

In this proposed study, a resilience framework and a resilience metric for electric distribution poles are proposed as a preliminary study. Resilience areas for poles were determined based on the judgment of an expert who specified critical pole angles. Resilience was visualized based on the resilience areas determined for specific poles. This visualization approach for resilience is important for monitoring the health of the poles under pre-disaster conditions. The proposed approach can be used for determining the conditions of poles after a major wind event. It also can prioritize corrective maintenance and mitigation actions, based on the conditions of poles. In this study, 3D photogrammetry technology is adapted to cover and examine larger areas and decrease manual inspection time. Limited resources for enhancing resilience based mitigation actions can also be prioritized. In future study, cost-benefit analysis can also be performed and investigated against various wind-related scenarios.

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REFERENCES

[1] T. Gonen, *Electric Power Distribution System Engineering.* New York: McGraw-Hill, ch. 5.
[2] M. Panteli and P. Mancarella, "Influence of extreme weather and climate change on the resilience of power systems: impacts and possible mitigation strategies," *Electric Power Systems Research*, vol. 127, pp. 259-270, 2015.
[3] Y. J. Park, C. R. Glagola, K. R. Gurley, and K. Son, "Performance assessment of the Florida electric-power network system against hurricanes," *Natural Hazards Review*, vol. 4, pp. 1-7, 2014.
[4] R. J. Campbell, "Weather-related power outages and electric system resilience," *Congressional Research Service, CRS Report for Congress*, pp. 1-15, 2012.
[5] M. Ouyang and L. Duenas-Osorio, "Multi-dimensional hurricane resilience assessment of electric power systems," *Structural Safety,* vol. 48, pp. 15-24, 2014.
[6] G. L. Daugherty, "The Realistic Expectation of an In-place Wood Pole Inspection Program," *Utility Poles and Structures* (Revised version of a paper presented at the International Conference on Utility Line Structures). March 1998.
[7] B. Eren Tokgoz, and A. Gheorghe, "Probabilistic resilience for building systems exposed to natural disasters", *International Journal of Critical Infrastructures*, vol.10, no. 3(4), 2014, pp. 375-397.
[8] B. Eren Tokgoz, and A. Gheorghe, "Resilience quantification and its application to a residential building subject to hurricane winds," *Int. J. Disaster Risk Sci,* vol. 4, no. 3, 2013.
[9] L. Carlson, G. Bassett, W. Buehring, M. Collins, S. Folga, B. Haffenden, F. Petit, J. Phillips, D. Verner, and R. Whitfield, "*Resilience: Theory and Applications*," Argonne National Laboratory, 2012.
[10] The White House. Presidential Policy Directive – Critical Infrastructure Security and Resilience. *Office of the Press Secretary,* (February12, 2013) < https://obamawhitehouse.archives.gov/the-press-office/2013/02/12/presidential-policy-directive-critical-infrastructure-security-and-resil>S.
[11] Technical Workshop: Resilience Metrics for Energy Transmission and Distribution Infrastructure. < https://energy.gov/epsa/downloads/technical-workshop-resilience-metrics-energy-transmission-and-distribution>
[12] H. H. Willis and K. Loa, "Resilience Metrics for Energy Systems," RAND Corporation (April 29,2014) https://energy.gov/sites/prod/files/2015/01/f19/RAND.Resiliency%20Metrics%20workshop.pdf
[13] J. Phillips and T. Angeli. "Resilience Metrics," *Argonne National Laboratory*, (April 28, 2014). https://energy.gov/sites/prod/files/2015/01/f19/Argonne%20National%20Lab.Resiliency%20Metrics%20workshop.pdf
[14] Energy Infrastructure Resilience, Framework and Sector-Specific Metrics. Sandia National Laboratories. (April 29,2014). < https://energy.gov/sites/prod/files/2015/01/f19/SNLResilienceApril29.pdf>.
[15] M. Ouyang, "Review on modeling and simulation of interdependent critical infrastructure systems," *Reliability Engineering and System Safety*, vol. 121, pp. 43-60, 2014.
[16] S Hosseini, K. Barker, and J.E. Ramirez-Marquez, "A review of definitions and measures of systems resilience," *Reliability Engineering and System Safety*, vol. 145, pp. 47-61, 2016.
[17] R. Francis, and B. Bekera, "A metric and frameworks for resilience analysis of engineered and infrastructure systems," *Reliability Engineering and System Safety*, vol. 121, pp. 90-103, 2014.
[18] D. Henry and J.E. Ramirez-Marquez, "Generic metrics and quantitative approaches for system resilience as a function of time," *Reliability Engineering and System Safety*, vol. 99, pp. 114–22, 2012.
[19] M. Ouyang, L. Duenas-Osorio, and X. Min, "A Three-Stage Resilience analysis framework for urban infrastructure systems," *Structural Safety*, vol. 36-37, pp. 23-31, 2012.
[20] A. F. Mensah, and L. Duenas-Osoria, "Efficient resilience assessment framework for electric power systems affected by hurricane events," *Journal of Structural Engineering,* vol. 142, no. 8, 2016.
[21] H. Liu, R. A. Davidson and T. V. Apanasovich, "Statistical Forecasting of Electric Power restoration times in hurricane and ice storms," *IEEE Transactions on Power Systems*, vol.22, no.4, 2007.
[22] S. D. Guikema, S. M. Quiring, and S.R. Han, "Prestorm estimation of hurricane damage to electric power distribution systems. *Risk Analysis*, vol. 30, no. 12, 2010.
[23] G. Li, P. Zhang, P.B. Luh, W. Li, Z. Bie, C. Serna and Z. Zhao, "Risk analysis for distribution systems in the Northeast U.S. under wind storms," *IEEE Transactions on Power Systems*, vol.29, no. 2, 2014.
[24] A. Arab, A. Khodaei, S.K. Khator, K. Ding, V. A. Emesih, and Z. Han, "Stochastic pre-hurricane restoration planning for electric power systems infrastructure," *IEEE Transactions on Smart Grid*, vol.6, no. 2, 2015.
[25] C. Nan and G. Sansavini, "A quantitative method for assessing resilience of interdependent infrastructure," *Reliability Engineering and System Safety*, vol. 157, pp. 35-53, 2017.
[26] M. Espinoza, Pantelli and P. Mancarella, "Multi-phase assessment and adaptation of power systems resilience to natural hazards," *Electric Power Systems Research,* vol. 136, pp. 352-361, 2016.
[27] P. C. Ryan, M. G. Stewart, N. Spencer, and Y. Li, "Reliability assessment of power pole infrastructure incorporating deterioration and network maintenance," *Reliability Engineering and System Safety*, vol. 132, pp. 261-273, 2014.
[28] Y. M. Darestani, A. Shafieezadeh, and R. DesRoches, "An equivalent boundary model for effect of adjacent spans on wind reliability of wood utility poles in overhead distribution lines," *Engineering Structures*, vol. 128, pp. 441-452, 2016.
[29] P. Tang, B. Akinci, and D. Huber, "Quantification of edge loss of laser scanned data at spatial discontinuities," *Automation in Construction*, vol. 18, no. 8, pp.1070-1083, 2009.
[30] K. Ghahremani, M. Safa, J. Yeung, S. Walbridge, C. Haas, and S. Dubois. "Quality assurance for high-frequency mechanical impact (HFMI) treatment of welds using handheld 3D laser scanning technology." *Welding in the World*, 59, no. 3, 391-400, 2015.
[31] M. Safa, M. Nahangi, A. Shahi, and C.T. Haas, "An integrated quality management system for piping fabrication using 3D laser scanning and photogrammetry," *30th International Association for Automation and Robotics in Construction (IAARC)*, Montreal, Canada, 2013.
[32] M. Safa, A. Sabet, K. Ghahremani, C. Haas, and S. Walbridge. "Rail corrosion forensics using 3D imaging and finite element analysis." *International Journal of Rail Transportation,* 3, no. 3, 164-178, 2015.
[33] Standard Specifications for Structural Supports for Highway Signs, Luminaires, and Traffic Signals, *The American Association of State Highway and Transportation Officials (AASHTO)*, 6th Edition, 2013.