

# MODELLING OF A PRE-EVENT CHECKLIST BILL OF QUANTITIES FOR POWER SYSTEM NETWORK RESILIENCE ENHANCEMENT AGAINST NATURAL EVENT

\*<sup>1</sup>OMOGOYE S. O., <sup>2</sup>FOLLY K. A., <sup>2</sup>AWODELE K. O., <sup>1</sup>OGUNDARE A. B.,  
<sup>1</sup>OYETOLA J. B., <sup>1</sup>GBOTOSO G. A.

<sup>1</sup>Lagos State University of Science and Technology, Lagos State Nigeria. <sup>2</sup>Electrical Engineering Department, University of Cape Town, Rondebosch, Western Cape, South Africa.

\*Email: [samelect2017@gmail.com](mailto:samelect2017@gmail.com) +23408038022099

Received: 22<sup>nd</sup> January 2023

Accepted: 20<sup>th</sup> February 2023

Published: 30<sup>th</sup> March 2023

<https://doi.org/10.47545/etrj.2023.8.1.093>

## ABSTRACT

Hardening the power distribution system network (PDSN) lines have demonstrated to be one of the foremost successful techniques to decrease the defencelessness of the PDSN to hurricane events attacks over the years. Usually, system network hardening is carried out by under-grounding the cables or strengthening the construction materials that carry the cables. But since the system network infrastructural hardening budget is constrained, more studies are presently centered on how to distinguish the basic system network critical components under hurricane events to make more cost-effective hardening choices. The past cost-efficient proposed models suffered greatly at the point of implementation due to the inflated bill of quantities from the power system's contractors. To solve this problem, this article applied a proposed hybrid statistical PDSN pole's fragility curve (FC)-Monte Carlo Simulation (MCS)-Scenario reduction (SCENRED) predictive model to a modified IEEE 14-bus PDSN using general algebraic modelling (GAMS) platform, to predict the most likely power system network pole's damage scenario under the anticipated oncoming hurricane events. The anticipated PDSN pole damage scenario is then employed to develop a near-normal system pole's repair bill of quantities to moderate the system hardening cost. The simulation result informs the power distribution system operators (PDSO) awareness to plan and prepare a cost-effective system operational and hardening planning to check the power system contractor's system network repair cost proactively. Hence, reduced the burden of the highly inflated cost of power restoration from electrical contractors.

**Keywords:**Hurricane event, network hardening, pre-event checklist bill of quantities, power distribution system network (PDSN).

## 1. INTRODUCTION

Customarily power system reliability is ensured by utilizing a long-standing N-1 security model. On the contrary, the idea of power system resilience improvement against high impact low likelihood (HILL) events, surpasses the traditional consideration of power system reliability [1]. These days, power system resilience has been re-defined as the capability of the power systems operation to predict, plan for, survive and effectively re-establish from disturbances rapidly [2], [3]. Researches in various aspects of power system resilience enhancement against extreme catastrophic weather attacks are still ongoing with many authors applying both hardening and operational measures [4], [5] with special attention given to service restoration of critical infrastructures at the advent of extreme weather attack. The review of the strategies employed to achieve power system network resilience enhancement has been presented in [6], [7], [8], [9], and so on. Hardening strategies of PDSN mean physically improving the power systems' critical infrastructures to decrease its susceptibility to power supply disruptions from both external and internal HILL events [10], [11]. Power system operational planning strategies, on the other hand, are power system control-based operations, that are capable of assisting the PDSO in dealing with the power supply disruptions coming from predictable HILL events such as hurricanes [12], [13].

Hardening the PDSN had proven to be one of the most efficient methods to decrease the vulnerability of the PDSN to predictable or seasonal weather attacks over the years [14]. This is often ordinarily carried out by under-grounding

cables or fortifying the power system network structure construction materials. Many research papers such as [9] reported that the power system hardening planning suffers greatly from poor system hardening budget. Therefore, since the power system network structure hardening is limited because of poor funding globally, more research now focuses on identifying the critical power system network components to take cost-effective system network hardening decisions. In this view, the maximum attack model proposed in [15], was to assess the basic components of the power system network against the natural event. The model is based on a heuristic maximum attack with its protection plan. It considered only the transmission line as the vulnerable component, neglecting other vital transmission components like transformers, switches, PDSN and so on [16],[17], presented a global benders decomposition (GLBD) algorithm to identify the power grid's components that are most critical or vulnerable during extreme weather events. Although the GLBD algorithm recorded poor computational efficiency, the simulated results also cannot provide a reference for the system's hardening decision-making. In [18], a defender-attacker-defender (DAD) strategy for power system network hardening based on the assumption that each system components in the PDSN are vulnerable to natural events unless it is hardened against high impact low likelihood events (HILL) is developed. The used DAD model considered power system network hardening decisions based on insufficient system hardening limited budget, noting that the power system control operator would implement all possible system network restoration actions to restore the load shedding on the grid after a natural event had occurred. Although, the proposed DAD model is designed for human-caused large scaled power outages like a terrorist attack, whose goal is to maximize the hardening budget for the system line damage under a certain constraint level of HILL events. In [19], a resilience-oriented design (ROD) method to protect the PDSN against HILL events was proposed. The ROD model redefines the proposed DAD model by specifically considering vegetation management and pole undergrounding. [20], moved a step further by adding the spatial-temporal characteristics of natural disasters into the already existing DAD model to harden the PDSN. The proposed model arranges the optimal system network hardening planning and distributed generator (DG) asset arrangement. Many studies have been carried out on hardening the power system network critical infrastructure to enhance its resiliency against HILL events as presented in this article. Most of these proposed models are either concentrated on the power transmission network or do not take into consideration the new components of the smart PDSN which now contain micro-grids, tie-switches, distributed generator (DG), and so on. In the same vein, only a few articles paid attention to the impact of corruption as it affects the implementation of power system hardening planning in the developing nations [21].

Corruption in the public project execution over the years has been reported as one of the major problems of public infrastructural development [21]. In the case of power system network infrastructure upgrades, most of the power system network bills of quantities from the contractors are either "padded" or "inflated" for the contractors to make more money oftentimes using bill of quantities. "Bill of quantities is a document prepared by the cost consultant that provides project-specific measured quantities of the items of work identified by the drawings and specifications in the tender documentation" [22]. As a result, Government found it very difficult to adequately upgrade the power system infrastructure due either insufficient fund or budget constraints. To check this problem, this paper proposes the use of proposed hybrid statistical predictive PDSN's FC-MCS-SCENRED model in, [12], [23], [24], [25] to predict the most probable PDSN' component damage to develop the most probable bill of quantities for system restoration, before, during and after the HILL event. The proposed model will serve as a tool to check the inflated power system infrastructural upgrade's cost quoted by the power system contractors after a hurricane event. This aspect is largely unexplored in power system resilience studies. Hence this study is channelled towards achieving cost-effective decision-making in proactive power system network operational and hardening planning. The proposed PDSN near-normal bill of quantities against the predicted approaching hurricane events will serve as a cost-effective tool to check the inflated system hardening budget from the electrical power system contractor. Hence, aid easy system component's hardening planning to improve the PDSN resilience against the anticipated oncoming hurricane events. This is the **research gap** that this article is aiming to fill, and **contribute** to knowledge from this perspective. Section II of this article describes the research data and methodology, section III provides the research simulation results and discussion, and section IV presents the research conclusion.

## 2. MATERIALS AND METHODS

### 2.1 Research Data

This section describes the material and techniques utilized in this research. It also organizes the necessary analysis to achieve the research objective. Hurricane extreme wind speed intensity (HEWSI) is the predictable extreme weather event considered in this study because of its devastating impact on the PDSN in the past [26]. Fig.1 presents the

modified IEEE 14-bus PDSN. Although, any PDSN can be used for the development of this proposed model. The modified IEEE 14-bus PDSN in this paper has been utilized in [27], for system line prediction in the face of a hurricane event using the Bayesian network approach. This makes the network suitable for this research investigation. The network data is taken from [28]. The HEWSI (m/s) of hurricane Ewiniar[29] is utilized to model the probabilistic impact of hurricane events on the modified IEEE 14-bus PDSN components [30]. In this research, each of the PDSN poles is taken to have a unit of insulator, gay and stay, cross-arm, primary wires, and copper wire grounding as proposed in [31].

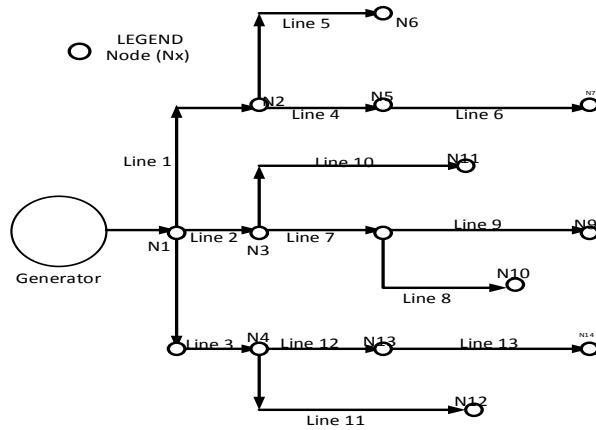


Figure 1: Modified IEEE 14-bus PDSN [27]

## 2.2 Research Methodology

### 2.2.1 Fragility-curve development using predicted hurricane historical data

The PDSN pole's fragility curve concept was originally derived based on the concept of structural reliability in Civil Engineering [32]. The concept is adopted in this study. It is proposed that if the wooden electric pole defects are distributed within the PDSN pole, crack propagation in any part of the pole during a hurricane event would eventually lead to power supply disruption. The PDSN pole broken probability due to the HEWSI is modelled utilizing the equation presented in (1) [30], [33].

$$P_F(\sigma) = 1 - e^{-\left(\frac{\sigma}{\sigma_0}\right)^m} \quad (1)$$

where  $P_F(\sigma)$  represents the PDSN pole broken probability caused by the stress ( $\sigma$ ) from the HEWSI. ( $\sigma_0$ ) represents the calculated HEWSI reference stress, and ( $m$ ) represents the statistical Weibull modulus estimated to determine the territorial HEWSI probability density function (PDF), cumulative density function (CDF) in Figs. 2 and 3. The modified IEEE 14-bus PDSN poles broken probabilities caused by the predicted oncoming hurricane Ewiniar [34], are presented in Fig. 4. Equation (1) can be re-arranged numerically to get (2).

$$1 - P_F(\sigma) = e^{-\left(\frac{\sigma}{\sigma_0}\right)^m} \quad (2)$$

take the log function of both sides to obtain (3)

$$L_n \left( L_n \left( \frac{1}{1 - P_F} \right) \right) = m L_n \sigma - m L_n \sigma_0 \quad (3)$$

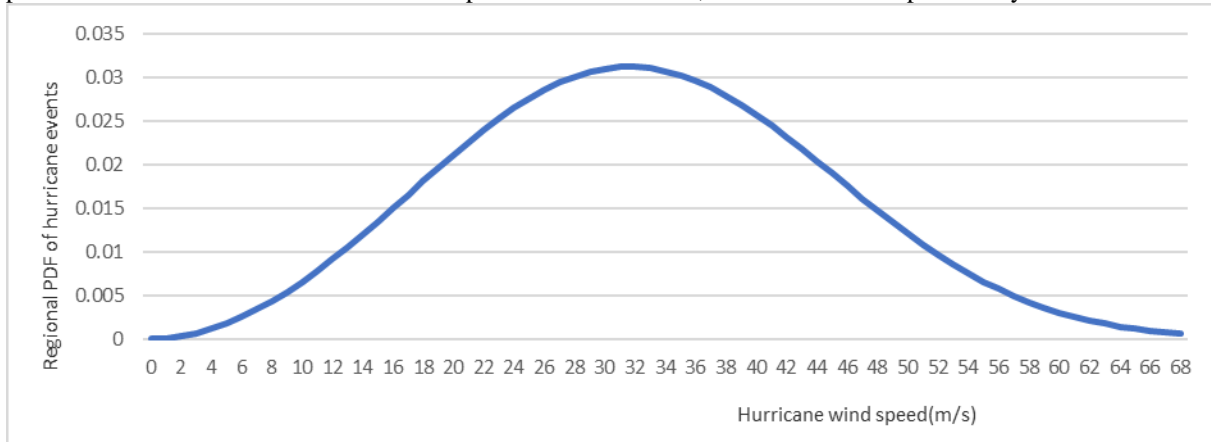
Equation (3), depicts a straight-line graph equation of  $y = x + mc$  displayed in Tab. 1.

Table 1: Statistical PDSN pole's broken probability

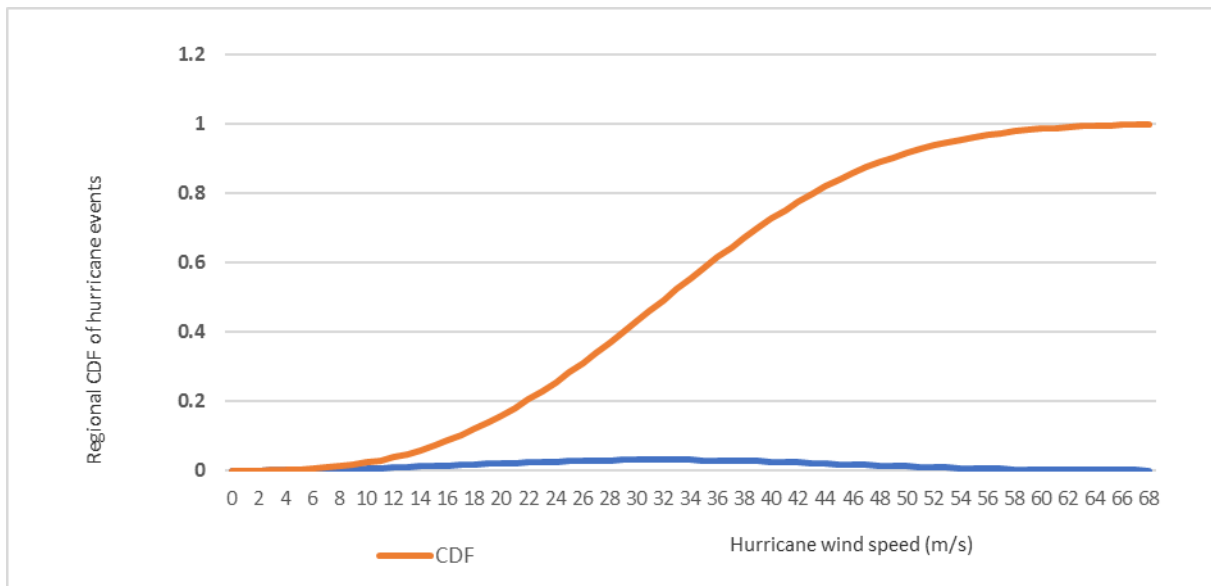
y - axis	M (slope)	x - axis	c (Intercept)
$L_n \left( L_n \left( \frac{1}{1 - P_F} \right) \right)$	m	$L_n \sigma$	$-m L_n \sigma_0$

Table 1 is used to develop the statistical IEEE 14-bus PDSN pole's failure probabilities shown in Fig. 4. Using (1),  $\sigma_0$  of 36.59 and  $m$  of 2.867 are calculated, and utilized as the curve fitting data in the Weibull distribution to model the territorial HEWSI's probability distribution function (PDF) and cumulative distribution function (CDF) across the modified IEEE 14-bus PDSN as shown in Figs. 2 and 3 respectively. The PDSN pole failure probabilities against the

predicted approaching HEWSI at a time (t), are portrayed in Fig. 4. Figure 4, using (1) demonstrates that the PDSN pole would be broken at a hurricane wind speed above 66.66 m/s, at a PDSN failure probability of 1.



**Figure 2: Topographical PDF of hurricane wind speed (m/s)**



**Figure 3: Topographical CDF of hurricane wind speed (m/s)**

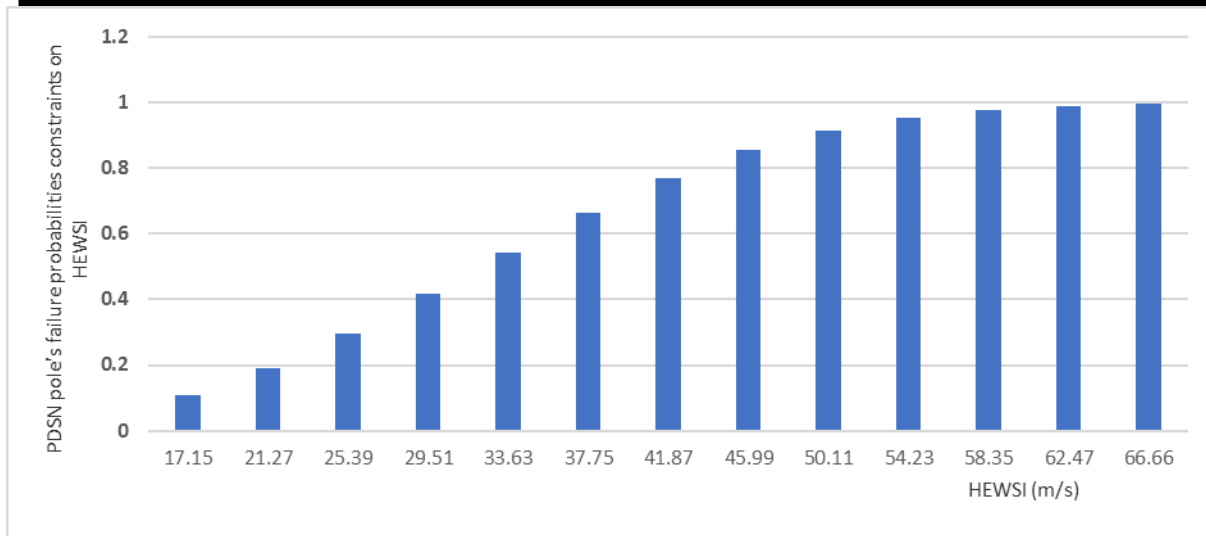


Figure 4: The modified IEEE 14 bus PDSN's pole failure probabilities

### 2.2.2 The Monte-Carlo Simulation modelling:

Using (1), the electric pole broken probabilities because of hurricane event is developed, and their corresponding random numbers, ( $r_n \sim 0,1$ ) are generated. The random numbers are compared with the PDSN pole broken probabilities to know if the pole that suspends the wires would be broken or not at a particular wind speed, at the time (t) using (4) [35].

$$P_F^L(H_t^{HEWSI}) = \begin{cases} 0, & \text{if } r_n < P_F(I) \\ 1, & \text{if } r_n > P_F(I) \end{cases} \quad (4)$$

where  $P_F^L(H_t^{HEWSI})$  is the PDSN failure function, when  $P_F^L(H_t^{HEWSI}) = 0$ , and otherwise when  $P_F^L(H_t^{HEWSI}) = 1$ . Samples from the predicted 1000 PDSN pole damage scenarios simulated utilizing the PDSN's pole FC-MCS model are presented in Table 2 with their corresponding PDSN pole failure probabilities. The used 1000 PDSN scenarios in this article have been proposed to guarantee probabilistic system optimization result accuracy in [35]. Therefore, 1000 system pole damage scenarios are adopted in this study. Each generated PDSN pole failure depicts the PDSN response to the probabilistic characteristic of the anticipated approaching hurricane events.

Table 2: Samples from the 1000 predicted system line's damage scenarios from the hybrid statistical PDSN's FC-MCS-SCENRED predictive model

LBN	$n_i \rightarrow n_j$	PDSN poles	Failure probability (Fp)	Random number (Set 1)	Random number (Set 2)
1	2	1	0.1076	0.6350	0.2549
1	3	2	0.1903	0.4190	0.5906
1	4	3	0.2958	0.0079	0.7610
2	5	4	0.4171	0.0640	0.8425
2	6	5	0.5439	0.8045	0.1070
3	8	6	0.6649	0.0477	0.8937
3	11	7	0.7704	0.4045	0.5248
4	12	8	0.8543	0.0309	0.1415
4	13	9	0.9140	0.1317	0.4725
5	7	10	0.9540	0.2615	0.0343
8	9	11	0.9778	0.0857	0.5724
8	10	12	0.9900	0.2866	0.7927
13	14	13	0.9960	0.9104	0.8409

$n_i \rightarrow n_j$	PDSN poles	$H_t^{HEWSI} \left(\frac{m}{s}\right)$	Damage scenario 1=Sq1	Damage scenario 2=Sq2
1 2 1	1	17.15	1	1

1	3	2	21.27	1	1
1	4	3	25.39	0	1
2	5	4	29.51	0	1
2	6	5	33.63	1	0
3	8	6	37.75	0	1
3	11	7	41.87	0	0
4	12	8	45.99	0	0
4	13	9	50.11	0	0
5	7	10	54.23	0	0
8	9	11	58.35	0	0
8	10	12	62.47	0	0
13	14	13	66.66	0	0

**2.2.3 Fragility curve-MCS-SCENRED model:**

One of the ways to solve the problem of computational time cost is known with the use of large numbers of predicted PDSN pole FC-MCS probable damage scenarios to perform proactive stochastic system optimization is to develop an optimal PDSN pole damage reduction scenario algorithm using the fast-backwards-forward approach utilizing the general algebraic modelling system (GAMS) [36]. The model is developed in this article and applied to the predicted 1000 PDSN pole failure scenarios from the PDSN’s FC-MCS model to optimally reduce it to a single system pole damage scenario without jeopardizing its prediction accuracy.

**3. SIMULATION RESULTS ANALYSIS AND DISCUSSION**

After developing the predictive statistical hybrid PDSN’s FC-MCS-SCENRED model, the PDSN pole’s 1000 probable PDSN pole failure scenarios are generated. Samples of the PDSN pole damage are shown in Table 2, [35],[37],the SCENRED program is then employed to optimally reduce the 1000 PDSN pole damage scenarios from the system component’s FC-MCS model to any required number of system pole broken scenarios. This approach is used to determine the IEEE 14-bus PDSN's most probable pole damage scenario proactively. The simulated reduced system pole damages are presented for 20, 10 and 1 PDSN pole damage cases as shown in Tables 3,4,5 and 5 respectively. The optimality of the PDSN’s FC-MCS-SCENRED approach is tested by reducing the probable PDSN pole damage scenarios to 20 and 10. From Tables 3 and 4, the highest allocated probabilities of the PDSN pole damage scenario are the same, confirming the optimality of the SCENRED algorithm. This implies that the SCENRED program decides the subset of the starting scenario set and allocates new probabilities to the preserved system pole’s damage scenarios and all deleted PDSN pole scenarios have a probability of zero [38] . The reduced scenarios in Tables 3 and 4 can be used to perform the proactive system optimization operational planning depending on the available time that the system operator has before the approaching hurricane events hit the grid. On the other hand, for the system hardening purposes, the reduced PDSN pole failure is reduced to 1 scenario as presented in Table 5. Table 5 is utilized to develop the proactive predicted system hardening’s bill of quantities in Table 6. The quantities rate is determined by the current market value. With this tool, inflated system hardening cost can be checked and more hardening planning can be implemented to enhance the PDSN structure against the predicted oncoming hurricane event in the future.

**Table 3:** 20 reduced predicted PDSN pole’s damage scenarios

Predicted PDSN poles damage scenarios	The line of the affected poles	Probabilities of hurricane event occurrence
Scenario1	(2-6),(3-8),(4-12),(4-13),(5-7),(8-9), (8-10),(13-14)	0.032
Scenario2	(1-4),(2-6),(3-11),(4-12),(4-13),(5-7), (8-9),(8-10),(13-14)	0.031
Scenario3	(2-5),(3-8),(3-11),(4-12),(4-13),(5-7),(8-9),	0.072



	(8-10),(13-14)	
Scenario4	(2-6), (3-8),(3-11),(4-12),(4-13),(5-7), (8-9),(8-10),(13-14)	0.106
Scenario5	(2-5),(2-6),(3-11),(4-12), (4-13), (5-7), (8-9),(8-10),(13-14)	0.074
Scenario6	(3-8),(3-11),(4-12),(4-13),(5-7),(8-9), (8-10),(13-14)	0.056
Scenario7	(2-5), (2-6), (3-8),(3-11),(4-12),(4-13), (5-7),(8-9),(8-10),(13-14)	0.071
Scenario8	(3-11),(4-12),(4-13),(5-7),(8-9),(8-10),(13-14)	0.086
Scenario9	(2-6), (3-8),(3-11),(4-13),(5-7),(8-9),(8-10), (13-14)	0.022
Scenario10	(1-4),(2-6),(3-8),(3-11),(4-12),(4-13), (5-7),(8-9),(8-10),(13-14)	0.060
Scenario11	(2-6),(3-11),(4-12),(4-13),(5-7),(8-9), (8-10),(13-14)	0.070
Scenario12	(1-4),(2-5),(3-8),(3-11),(4-12),(4-13), (5-7),(8-9),(8-10),(13-14)	0.028
Scenario13	(3-8),(4-12),(4-13),(5-7),(8-9),(8-10),(13-14)	0.026
Scenario14	(2-5), (3-11),(4-12),(4-13),(5-7),(8-9),(8-10), (13-14)	0.070
Scenario15	(2-5),(2-6),(3-8),(4-12),(4-13),(5-7),(8-9), (8-10),(13-14)	0.030
Scenario16	(1-4),(2-5),(2-6),(3-8),(3-11),(4-12),(4-13), (5-7),(8-9),(8-10),(13-14)	0.048
Scenario17	(1-3),(3-8),(3-11),(4-12),(4-13),(5-7),(8-9), (8-10),(13-14)	0.021
Scenario18	(1-4),(3-8),(3-11),(4-12),(4-13),(5-7),(8-9), (8-10),(13-14)	0.041
Scenario19	(2-6),(4-12),(4-13),(5-7),(8-9),(8-10),(13-14)	0.021
Scenario20	(2-5), (3-8),(4-12),(4-13),(5-7),(8-9),(8-10), (13-14)	0.033

**Table 4:** 10 reduced predicted PDSN pole’s damage scenarios

<b>Damaged scenarios</b>	<b>The line of the affected poles</b>	<b>Probabilities of hurricane event occurrence</b>
Scenario1	(2-5),(3-8),(3-11),(4-12),(4-13),(5-7),(8-9), (8-10),(13-14)	0.133
Scenario2	(2-6),(3-8),(3-11),(4-12),(4-13),(5-7),(8-9), (8-10),(13-14)	0.160
Scenario3	(2-5),(2-6),(3-11),(4-12),(4-13),(5-7), (8-9),(8-10),(13-14)	0.074
Scenario4	(3-8),(3-11),(4-12),(4-13),(5-7),(8-9), (8-10),(13-14)	0.105
Scenario5	(2-5),(2-6),(3-8),(3-11),(4-12),(4-13), (5-7),(8-9),(8-10),(13-14)	0.101
Scenario6	(3-11),(4-12),(4-13),(5-7),(8-9),(8-10),(13-14)	0.086
Scenario7	(1-4),(2-6), (3-8),(3-11),(4-12),(4-13),(5-7), (8-9),(8-10),(13-14)	0.132
Scenario8	(2-6),(3-11),(4-12),(4-13),(5-7),(8-9),(8-10), (13-14)	0.091
Scenario9	(2-5),(3-11),(4-12),(4-13),(5-7),(8-9),(8-10), (13-14)	0.070
Scenario10	(1-4),(2-5),(2-6),(3-8),(3-11),(4-12),(4-13), (5-7),(8-9),(8-10),(13-14)	0.048

**Table 5:** 1 reduced predicted PDSN pole’s damage scenario

<b>The most Probable PDSN damaged scenario</b>	<b>The line of the affected poles</b>	<b>Probability of events occurrence</b>
Scenario1	(2-5),(2-6),(3-8),(3-11),(4-12),(4-13),(5-7), (8-9),(8-10),(13-14)	1.000



**Table 6:** The proposed proactive bill of quantities

Date	Summary	Quantities	Rate
21/01/2023	<b>Insulator</b>	<b>30</b>	<b>To be determined by the current market price</b>
	<b>Gay and stay</b>	<b>10</b>	
	<b>Cross-arm</b>	<b>10</b>	
	<b>Copper wire grounding</b>	<b>10</b>	
	<b>Pole</b>	<b>10</b>	

#### 4. CONCLUSIONS

In this article, the pre-disaster predictive checklist bill of quantities model based on the system component's FC-MCS-SCENRED model to enhance short-term proactive operational and hardening planning of the PDSN resilience against hurricane events is proposed. The predicted bill of quantities serves as a guide or a working tool for the power distribution system operator to check the inflated power system network hardening bill of quantities. Hence, moderate the quotation for the power system component's hardening proactively. The prices of the system hardening are determined by the market price of where the proposed model is utilized. Also, the reduced system pole broken scenarios can be used to perform proactive system optimization which includes PDSN optimal network reconfiguration via optimal switching actions to decrease the system load shedding proactively, and hence improve power system operational and hardening resilience against the predicted oncoming hurricane event in future.

#### 4. ACKNOWLEDGEMENT

Authors acknowledged Boda Li et al., [27] for providing the hurricane data. Babak Taheri et al., [37] for his contribution in developing the hybrid statistical predictive model. Thanks to LASUSTECH/TETFund for the release of 2019 PhD grant to University of Cape Town, South Africa. Thanks to NRF South Africa with grant number 118550 for research part funding.

#### REFERENCES

- [1] Y. Lin and Z. Bie, 'Tri-level optimal hardening plan for a resilient distribution system considering reconfiguration and DG islanding', *Appl Energy*, vol. 210, no. 1, pp. 1266–1279, 2018, doi: 10.1016/j.apenergy.2017.06.059.
- [2] T. Aven, 'On Some Recent Definitions and Analysis Frameworks for Risk, Vulnerability, and Resilience', *Risk Analysis*, vol. 31, no. 4, pp. 515–522, 2011, doi: 10.1111/j.1539-6924.2010.01528.x.
- [3] J. Liu, A. Bose, S. Brown, B. Chalamala, D. Immerman, A. Khodaei and M. V. D. Novosel, A. paaso, F. Rahmatian, J. R. Agüero, 'PES-TR83: Resilience Framework, Methods, and Metrics for the Electricity Sector', *IEEE Power and Energy Society*, no. October, pp. 1–35, 2020.
- [4] H. Farzin, M. Fotuhi-Firuzabad, and M. Moeini-Aghaie, 'Enhancing Power System Resilience Through Hierarchical Outage Management in Multi-Microgrids', *IEEE Trans Smart Grid*, vol. 7, no. 6, pp. 2869–2879, 2016, doi: 10.1109/TSG.2016.2558628.
- [5] M. Panteli and P. Mancarella, 'The grid: Stronger, bigger, smarter?: Presenting a conceptual framework of power system resilience', *IEEE Power and Energy Magazine*, vol. 13, no. 3, IEEE, pp. 58–66, 2015. doi: 10.1109/MPE.2015.2397334.
- [6] O. S. Omogoye, K. A. Folly, and K. O. Awodele, 'Review of sequential steps to realize power system resilience', *International SAUPEC/RobMech/PRASA Conference*, pp. 1–6, 2020, doi: 10.1109/SAUPEC/RobMech/PRASA48453.2020.9040967.
- [7] N. Lee and S. Stout, 'Planning a Resilient Power Sector', *Resilient energy platform*, pp. 1–2, 2019.
- [8] Y. Lin, Z. Bie, and A. Qiu, 'A review of key strategies in realizing power system resilience', *Global Energy Interconnection*, vol. 107, no. 8, pp. 70–78, 2018, doi: 10.14171/j.2096-5117.gei.2018.01.009.

- [9] N. Bhusal, M. Abdelmalak, M. Kamruzzaman, and M. Benidris, 'Power system resilience: Current practices, challenges, and future directions', *IEEE Access*, vol. 8, no. 1, pp. 18064–18086, 2020, doi: 10.1109/ACCESS.2020.2968586.
- [10] Y. Tan, A. K. Das, P. Arabshahi, and D. S. Kirschen, 'Distribution systems hardening against natural disasters', *IEEE Transactions on Power Systems*, vol. 33, no. 6, pp. 6849–6860, 2018, doi: 10.1109/TPWRS.2018.2836391.
- [11] X. Wang, Z. Li, M. Shahidehpour, and C. Jiang, 'Robust Line Hardening Strategies for Improving the Resilience of Distribution Systems with Variable Renewable Resources', *IEEE Trans Sustain Energy*, vol. 10, no. 1, pp. 386–395, 2019, doi: 10.1109/TSTE.2017.2788041.
- [12] O. S. Omogoye, K. A. Folly, and K. O. Awodele, 'Review of Proactive Operational Measures for the Distribution Power System Resilience Enhancement against Hurricane Events.', in *2021 Southern African Universities Power Engineering Conference/Robotics and Mechatronics/Pattern Recognition Association of South Africa (SAUPEC/RobMech/PRASA) | 978-1-6654-0345-0/20/\$31.00 ©2021 IEEE*, 2021, pp. 1–6. doi: DOI: 10.1109/SAUPEC/RobMech/PRASA52254.2021.9377252.
- [13] O. S. Omogoye, K. A. Folly, and K. O. Awodele, 'A review of power system predictive failure model for resilience enhancement against hurricane events', *The Journal of Engineering. The institute of Engineering and Technology (IET)*, pp. 1–9, 2021, doi: 10.1049/tje2.12092.
- [14] A. M. Salman, Y. Li, and M. G. Stewart, 'Evaluating system reliability and targeted hardening strategies of power distribution systems subjected to hurricanes', *ReliabEngSystSaf*, vol. 144, no. (2015), pp. 319–333, 2015, doi: 10.1016/j.res.2015.07.028.
- [15] V. M. Bier, E. R. Gratz, N. J. Haphuriwat, W. Magua, and K. R. Wierzbicki, 'Methodology for identifying near-optimal interdiction strategies for a power transmission system', *ReliabEngSystSaf*, vol. 92, no. 9, pp. 1155–1161, 2007, doi: 10.1016/j.res.2006.08.007.
- [16] Y. Wang, L. Huang, M. Shahidehpour, L. L. Lai, and Y. Zhou, 'Impact of cascading and common-cause outages on resilience-constrained optimal economic operation of power systems', *IEEE Trans Smart Grid*, vol. 11, no. 1, pp. 590–601, 2020, doi: 10.1109/TSG.2019.2926241.
- [17] J. Salmeron, K. Wood, and R. Baldick, 'Worst-case interdiction analysis of large-scale electric power grids', *IEEE Transactions on Power Systems*, vol. 24, no. 1, pp. 96–104, 2009, doi: 10.1109/TPWRS.2008.2004825.
- [18] G. Brown, M. Carlyle, J. Salmerón, and K. Wood, 'Defending critical infrastructure', *Interfaces (Providence)*, vol. 36, no. 6, pp. 530–544, 2006, doi: 10.1287/inte.1060.0252.
- [19] S. Ma, L. Su, Z. Wang, F. Qiu, and G. Guo, 'Resilience enhancement of distribution grids against extreme weather events', *IEEE Transactions on Power Systems*, vol. 33, no. 5, pp. 4842–4853, 2018, doi: 10.1109/TPWRS.2018.2822295.
- [20] W. Yuan, J. Wang, F. Qiu, C. Kang, and B. Zeng, 'Robust optimization-based resilient distribution network planning against natural disasters.', *IEEE Trans Smart Grid*, no. 16396343, pp. 2817–2826, 2016, doi: 10.1109/TSG.2015.2513048.
- [21] G. Locatelli, G. Mariani, T. Sainati, and M. Greco, 'Corruption in public projects and megaprojects: There is an elephant in the room!', *International Journal of Project Management*, vol. 35, no. 3, pp. 252–268, 2017, doi: 10.1016/j.ijproman.2016.09.010.
- [22] Designing Buildings, 'Bill of quantities BOQ - Designing Buildings', [https://www.designingbuildings.co.uk/wiki/Bill\\_of\\_quantities\\_BOQ](https://www.designingbuildings.co.uk/wiki/Bill_of_quantities_BOQ), 2021. (accessed Jun. 02, 2022).
- [23] O. S. Omogoye, K. A. Folly, and K. O. Awodele, 'Review of sequential steps to realize power system resilience', *2020 International SAUPEC/RobMech/PRASA Conference, SAUPEC/RobMech/PRASA 2020*, 2020, doi: 10.1109/SAUPEC/RobMech/PRASA48453.2020.9040967.
- [24] O. S. Omogoye, K. A. Folly, and K. O. Awodele, 'Enhancing the distribution power system resilience against hurricane events using a bayesian network line outage prediction model', *The Journal of Engineering. The institute of Engineering and Technology (IET)*, pp. 1–14, 2021, doi: 10.1049/tje2.12091.
- [25] S. O. Omogoye, K. A. Folly, and K. O. Awodele, 'Situation Awareness to Enhance the Distribution System Network Operational Resilience against Hurricane Event', *IEEE PES/IAS Power Africa*, vol. 9, pp. 1–5, 2022.
- [26] [www.cnn.com/2017/09/27/3\\_storms\\_3\\_responses\\_Comparing\\_Harvey\\_Irma\\_and\\_Maria\\_CNN](http://www.cnn.com/2017/09/27/3_storms_3_responses_Comparing_Harvey_Irma_and_Maria_CNN), United States Of America, p. 1, 2017. [Online]. Available: [www.cnn.com/20170927](http://www.cnn.com/20170927)

- [27] B. Li, Y. Chen, S. Huang, H. Guan, Y. Xiong, and S. Mei, 'A Bayesian Network Model for Predicting Outages of Distribution System Caused by Hurricanes', *IEEE Power & Energy Society General Meeting (PESGM)*, pp. 1-6, 2020, doi: 10.1109/PESGM41954.2020.9281923.
- [28] J. Zhu, *Optimization of power system operation*, 2nd Editio. WILEY, 2009.
- [29] I. H. Kong, T. Po, I. H. Kong, and Wikipedia, 'Tropical Storm Ewiniar', *Wikipedia*, 2018.
- [30] R. B. and R. N. Allan, 'Basic Probability and Reliability Concepts.', NERC, 2017, pp. 1–136.
- [31] S. R. Han, 'Estimating Hurricane Outage and Damage Risk in power distribution systems', Texas A&M University, 2008.
- [32] G. A. Pagani and M. Aiello, 'The Power Grid as a complex network: A survey', *Physica A: Statistical Mechanics and its Applications*, vol. 392, no. 11, pp. 2688–2700, 2013, doi: 10.1016/j.physa.2013.01.023.
- [33] M. SadeghiKhomami and M. S. Sepasian, 'Pre-hurricane optimal placement model of repair teams to improve distribution network resilience', *Electric Power Systems Research*, vol. 165, no. (2018), pp. 1–8, 2018, doi: 10.1016/j.epsr.2018.08.016.
- [34] M. Panteli, P. Mancarella, D. N. Trakas, E. Kyriakides, and N. D. Hatziargyriou, 'Metrics and Quantification of Operational and Infrastructure Resilience in Power Systems', *IEEE Transactions on Power Systems*, vol. 32, no. 6, pp. 4732–4742, 2017, doi: 10.1109/TPWRS.2017.2664141.
- [35] S. Poudel, A. Dubey, and A. Bose, 'Probabilistic Quantification of Power Distribution System Operational Resilience', *IEEE Power & Energy Society General Meeting (PESGM)*, vol. 1, no. 1, pp. 1-5, 2019, doi: 10.1109/pesgm40551.2019.8973967.
- [36] J. M. Wilson, 'Introduction to Stochastic Programming', *Journal of the Operational Research Society.*, vol. 49, no. 8, pp. 897–898, 1998, doi: 10.1057/palgrave.jors.2600031.
- [37] B. Taheri, A. Safdarian, M. Moeini-aghtaie, and M. Lehtonen, 'Enhancing Resilience Level of Power Distribution Systems Using Proactive Operational Actions', *IEEE Access*, vol. 1, no. 1, pp. 1–13, 2019, doi: 10.1109/ACCESS.2019.2941593.
- [38] M. Ready, 'Release Notes –GAMS/SCENRED introduced', GAMS Distribution 20.6, pp. 713-719 ,2002.