Improving Situational Awareness in Power Grids of Developing Countries: A Case Study of the Nigerian Grid

Amarachi Umunnakwe, *Student Member, IEEE*, Abolaji Alimi, *Student Member, IEEE*, Katherine R. Davis, *Senior Member, IEEE*, and Karen L. Butler-Purry, *Fellow, IEEE*.

***Abstract*—Electric power grids, especially in developing countries, are typically riddled with reliability issues, electricity theft, and vandalism exacerbated by minimal situational awareness available to operators. In this work, we propose a framework that optimizes situational awareness in power grid operations while integrating the need to prioritize economics as well. With the knowledge that limited economic resources could be a hindrance, the framework optimizes situational awareness by integrating budget over the specified time horizon. This hence provides a cost-efficient way towards a smarter and cyber-physical grid. The proposed framework is implemented by optimally placing phasor measurement units (PMUs) on the Nigerian 330KV, 28-bus transmission system, demonstrating the rolling horizon. Results show that situational awareness can be optimized with limited budget over a period of time, hence incentivizing power system stakeholders in developing countries.**

***Index Terms*—Electric power grid, situational awareness, developing countries, Nigeria, cost-effective, rolling horizon asset integration, cyber-physical Nigerian grid.**

I. INTRODUCTION

Lack of situational awareness causes a handful of reliability issues in the power grid. The Energy Management System (EMS) operating traditionally in a deterministic mode, which is insufficient to uphold reliability in a stochastic system which consists of rapid dynamics. This can be seen from cases like the 2003 Northeast blackout, tangibly attributed to limited situational awareness that led to a failure to act on the loss of key transmission lines due to insufficient information about the state of the grid [1], [2]. Situational awareness is enabled by field measurement data (e.g., bus voltage magnitude) that are sent from remote terminal units to supervisory control centers where the system state and other informative variables are estimated. These can then be used for different applications in grid control such as contingency analysis to improve operational efficiency and hence, reliability of the power grid.

In developing countries, the reliability of the grid is less than optimal leading to very frequent blackouts that could leave customers days without electricity hence affecting critical loads. The lack of situational awareness also leads to frequent grid collapse. For instance, the Nigerian power grid has partially or fully collapsed 546 times over an 18 year period beginning from the year 2000 [3]. In 2022, the Nigerian grid had collapsed 6 times as at July, averaging a collapse every month. On July 20th 2022, major cities including the Federal Capital Territory were not left out of resulting blackouts.

Nigeria is Africa's largest economy ahead of countries like South Africa, Ethiopia, and Egypt. The country is endowed with large oil, gas, hydro and solar resources, with grid potential to generate 12522 MW, however the country's economy has largely been limited by erratic electric power supply with only about 4000 MW available to end users [4]. In 2015, power supply in Nigeria averaged 3.1 GW, approximately one-third of the country's minimum demand [5], while projections show that electricity demand will increase exponentially with the growing population [6]. Furthermore, the Nigerian power grid, especially the transmission grid, is riddled with issues such as obsolete equipment, high vandalism incidents, inability to perform real-time operations, and electricity theft. Currently, utilities heavily depend on customer calls and manual labor for information on the state of the physical grid. However, the integration of phasor measurement units (PMUs) could greatly improve the power system operation, reliability, and ultimately overall system security by providing system-synchronized real-time phasor measurements [7], with promising effectiveness in the predictability of real power flow [8], among other applications as shown in Fig. 1.

Real-time monitoring of the electric power grid is essential under dynamic conditions and hence aids in strategizing remedial actions against physical contingencies [9] or adversarial threats that ultimately result in dangerous situations and possibly outages [10], [11]. The advantages of PMUs in improving power system operations has gained a lot of literary attention [12], [13]. In [14], the system state estimation and line failure detection is carried out using a graph-based power

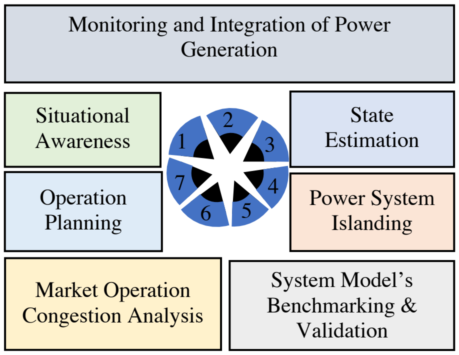

Fig. 1: Towards a smarter grid: PMU Applications.

A. Umunnakwe, A. Alimi, K. Davis, and K. Butler-Purry are with the Department of Electrical and Computer Engineering, Texas A&M University (e-mail: *amarachi*, *alimiabolaji*, *katedavis klbutler@tamu.edu*).

system analysis and an optimization framework, while in [15], a hybrid of conventional and linear methods are utilized for state estimation using PMU data. Furthermore, [12] uses parallel synchrophasor-based state estimators to identify and detect system faults in real-time. Similarly, [16] investigates the reliability of the Nigerian power grid using synchrophasor measurements, and in [17], undetectable line outages, that could eventually lead to cascading failures, caused by coordinated cyber-physical attacks on the power grid are analyzed. In this paper, the integration of PMUs as a step towards a data-oriented cyber-physical Nigerian power grid is proposed.

In particular, this paper proposes an optimized, cost-efficient location of these assets to improve system reliability. This can further be used in data-based intelligent anomaly detection as illustrated in Fig. 2. Moreover, the incentivization for adapting the proposed framework is further projected by a rolling horizon implementation where budget relaxation and optimized reliability is fore.

The rest of this paper is organized as follows. Section II presents the proposed PMU integration framework. It discusses the proposed optimization for PMU allocation in the Nigerian power grid. Simulation results on the Nigerian 330KV, 28-bus transmission grid model are presented in Section III, furnishing details of the grid, numerical results, discussions and recommendations. Conclusions are drawn in Section IV.

II. THE PROPOSED FRAMEWORK

This section presents the proposed framework discussing the grid model and the optimization of PMU parameters.

A. The Optimization Model

Here, PMU bus placement and cost are optimized while a rolling horizon of PMU installation is integrated as an incentive for adaptation by optimally spreading the installation cost over a time period. The optimization problem is formulated as a binary integer linear programming where decision variables [0,1] establish the installation of PMUs at unique buses. The advantage of using PMU measurements is that they can be distinguished from conventional meters since they measure their bus voltage phasors, as well as the current phasors of the neighboring connected buses, hence, improving system observability. For example, in Fig. 3, we demonstrate the PMU functionality with a simple 4-bus system.

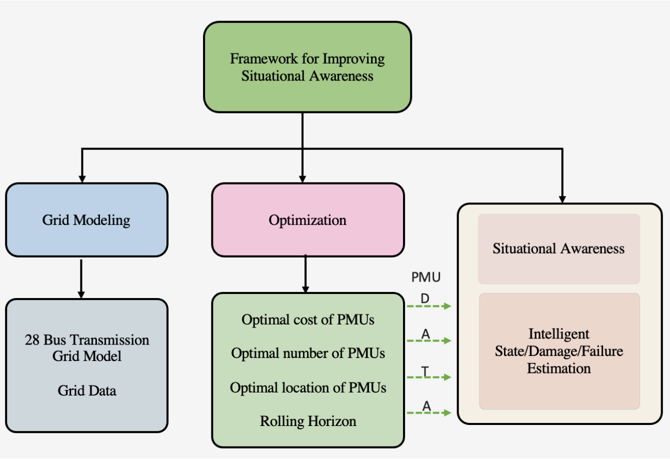

Fig. 2: Framework for improving situational awareness

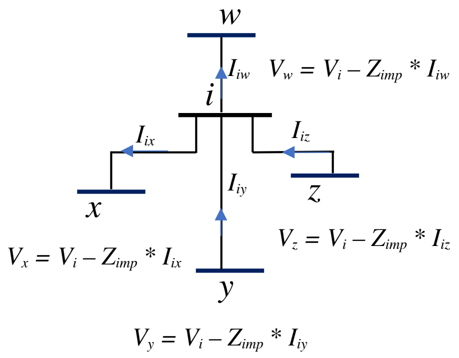

Fig. 3: Demonstrating PMU Observability functionality

Let bus i have it's voltage and phase known (observed), and Z_{imp}, the line impedance, assumed equal for all lines. Then,

- The voltages at buses w, x, y, and z can be observed by subtracting the voltage drop caused by the current travelling through the connecting line.
- A zero-injection bus which is unobserved but connected to observed buses is observable.
- Given that a zero-injection bus i and all but one, w, of it's connected buses are observed, the unobserved bus becomes observed (summation of nodal currents).

In order to find the optimal bus location for a minimum number of PMUs that enable system observability, the model solves for the optimal allocation of these measurement resources as follows.

$$\begin{aligned} \text{Min} \quad & \sum_{i=1}^{N} w_i x_i \\ \text{Subject To} \quad & CMX \geq b; \\ & X = [x_1, x_2, \ldots, x_N]^T; \\ & x_i \in [0,1] \end{aligned}$$

where w_i is the cost of installing a PMU on bus i, x_i is the binary variable for PMU placement which takes the value 1 if a PMU is located in a bus and 0 otherwise, b is a column matrix of ones and size $(N \times 1)$, and CM is the system connectivity matrix with unique entries defined as:

$$c_{i,j} = \begin{cases} 1, & \text{if} \quad \text{i = j} \\ 1, & \text{if} \quad \text{connection between i and j} \\ 0, & \text{otherwise.} \end{cases} \tag{1}$$

However, given that we are performing analysis on a real system, we step further to improve our placement optimization model by considering zero-injection buses and a rolling horizon of implementation. In particular, zero-injection buses refer to buses that have neither generation nor demand, and hence are observable if their adjacent buses are observable. Hence, if n_z is the set of zero injection buses, n_a is the set of buses adjacent to n_z, the observability of each bus is guaranteed with the observability of $n-1$ of them [18], then the optimization constraints update to:

$$
\begin{aligned}
\text{Min} \quad & \sum_{i=1}^{N} w_i x_i \\
\text{Subject To} \quad & CMX \geq b; \\
& CM_{zj}X \geq (|n_z| + |n_a|) - 1; \\
& X = [x_1, x_2, \dots, x_N]^T; \\
& x_i \in [0,1]
\end{aligned}
$$

where b remains a column matrix of ones and size $(N \times 1)$ to preserve the entire system observability. From the above optimization problem, we obtain the number of PMUs and their placement to maximize system observability while considering zero-injection buses.

Next, is the incorporation of the rolling horizon asset integration. Say the number of horizons is h, then for every h, we seek to maximize the number of observable buses while taking into account the number of PMUs obtained from the first optimization stage. Let the number of PMUs to be installed in horizon h, be P_h, then we seek to additionally solve the following optimization problem.

$$
\begin{aligned}
\underset{x_i, b_i}{\text{Max}} \quad & \sum_{i=1}^{N} b_i \\
\text{Subject To} \quad & CMX \geq b; \\
& \sum_{i=1}^{N} x_i \leq P_h; \\
& X = [x_1, x_2, \dots, x_N]^T; \\
& x_i, b_i \in [0,1]
\end{aligned}
$$

where $b_i \in [0,1]$ as in certain early horizons, the system will not be fully observable, however, observability is maximized.

B. The Nigerian Power Grid Model

The Nigerian 330KV power transmission grid, as shown in Fig. 4, consists of 28 buses with transmission lines with 5523.8 km total line distance connecting 8 generator sources to 18 load buses. The 330KV transmission grid has a transformation capacity of 7044MVA, 28 substations, 60 330KV circuits, 2 regional control centers and 1 national control center [19], [20]. However, the Nigerian grid supplies about a third of the demand as the grid is plagued with issues such as voltage and frequency instability issues stemming from inadequate monitoring (data acquisition) and control infrastructure, vandalization by adversaries leading to depletion of limited funds for restoration thus potentially affecting system resilience [21], and inability to perform operations in real-time impeding on system reliability [22]. The model of the Nigerian grid is developed in PowerWorld Simulator [23] which provides various power system analysis tools such as contingency analysis, transient analysis, time step simulations, etc., and supports external programs to interact with internal functions and auxiliary files. Hence in this paper, we seek to contribute towards mitigating these issues facing the grid of developing countries with the use of real-time monitoring from sensors such as PMU synchrophasor measurements.

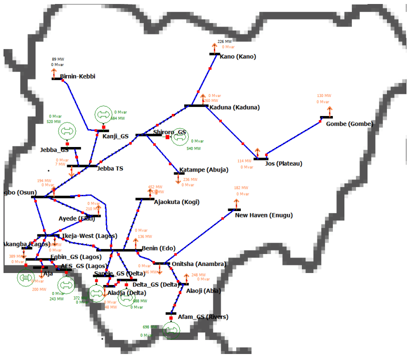

Fig. 4: The Nigerian Power grid

III. Study Results

The framework is implemented on the Nigerian 330KV, 28-bus transmission system. Results are computed using a computer with an i7 1.80 GHz processor and 16 GB of RAM.

A. Simulation Settings

The oneline diagram of the Nigerian power grid is shown in Fig. 5 and the grid model data and bus identification is furnished in Table I with the slack bus located at Egbin. The system consists a total of 35 transmission lines, 18 load buses and 9 generators operating at 90% capacity. For this work, we assume zero injection buses at Egbin GS and Gombe to demonstrate economic savings.

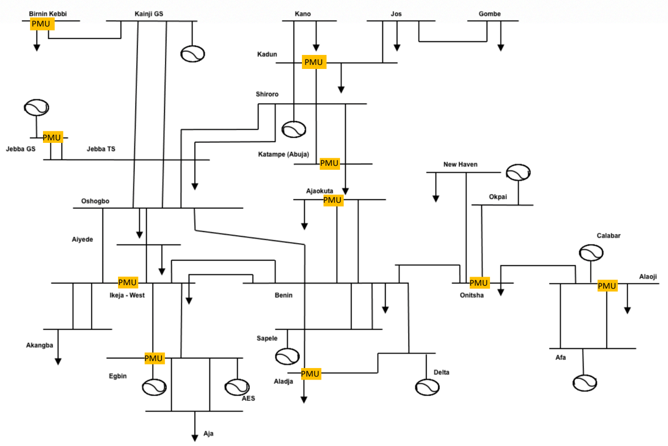

Fig. 5: Optimal PMU allocation in the power grid

B. Numerical Results

There are different ways in which PMU data can be utilized to improve power grid operations as discussed. However, in this work, we focus on illustrating advantages in improving the situational awareness of the grid operator given budget constraints for developing countries. For the optimal PMU allocation, we consider four different case studies as in Fig. 6. These include the minimization of cost and the results are demonstrated for cases where the zero injection buses are considered vs. cases where the zero injection buses are not

TABLE I: Grid model data used for PowerWorld simulation with Gombe and Egbin considered zero injection buses

Bus Number	Name	Area Name	Nom kV	PU Volt	Volt (kV)	Angle (Deg)	Load MW	Load Mvar	Gen MW	Gen Mvar	Switched Shunts Mvar	Act G Shunt MW	Act B Shunt Mvar	Area Num	Zone Num	Latitude (DDD:MM:SS N/S)	Longitude (DDD:MM:SS E/W)
1	Kanji_GS	1	330	1	330	124.92			684	0		0	0	1	1	09:51:38.00 N	04:36:41.00 E
2	Birnin-Kebbi	1	330	1	330	121.56	89	0				0	0	1	1	12:26:06.00 N	04:11:42.00 E
3	Kano (Kano)	1	330	1	330	91.59	226	0				0	0	1	1	12:00:18.00 N	08:30:54.00 E
4	Jos (Plateau)	1	330	1	330	92.09	114	0				0	0	1	1	09:33:54.00 N	09:05:06.00 E
5	Gombe (Gombe)	1	330	1	330	87.92	0	0				0	0	1	1	10:17:06.00 N	11:09:54.00 E
6	Kaduna (Kaduna)	1	330	1	330	97.91	260	0				0	0	1	1	10:30:54.00 N	07:26:06.00 E
7	Shiroro_GS	1	330	1	330	106.42			540	0		0	0	1	1	09:58:30.00 N	06:50:06.00 E
8	Jebba_GS	1	330	1	330	119.56			520	0		0	0	1	1	09:08:06.00 N	04:47:06.00 E
9	Jebba TS	1	330	1	330	119.06	7.44	0				0	0	1	1	08:30:18.00 N	04:32:42.00 E
10	Katampe (Abuja)	1	330	1	330	102.29	236	0				0	0	1	1	09:06:18.00 N	07:26:42.00 E
11	Oshogbo (Osun)	1	330	1	330	106.04	194	0				0	0	1	1	07:45:54.00 N	04:33:54.00 E
12	Ajaokuta (Kogi)	1	330	1	330	115.27	452	0				0	0	1	1	07:33:18.00 N	06:39:18.00 E
13	New Haven (Enugu)	1	330	1	330	141.74	182	0				0	0	1	1	06:27:54.00 N	07:31:30.00 E
14	Ayede (Ekiti)	1	330	1	330	97.62	210	0				0	0	1	1	07:54:54.00 N	05:18:54.00 E
15	Ikeja-West (Lagos)	1	330	1	330	91.09	484	0				0	0	1	1	06:36:18.00 N	03:21:18.00 E
16	Benin (Edo)	1	330	1	330	124.5	136	0				0	0	1	1	06:18:54.00 N	05:36:54.00 E
17	Onitsha (Anambra)	1	330	1	330	143.86	146	0				0	0	1	1	06:09:54.00 N	06:47:06.00 E
18	Alaoji (Abia)	1	330	1	330	160.82	248	0				0	0	1	1	05:03:18.00 N	07:19:30.00 E
19	Akangba (Lagos)	1	330	1	330	90.28	389	0				0	0	1	1	06:29:54.00 N	03:20:40.00 E
20	Sapele_GS (Delta)	1	330	1	330	127.93			372	0		0	0	1	1	05:54:54.00 N	05:39:18.00 E
21	Egbin_GS (Lagos)	1	330	1	330	83.61						0	0	1	1	06:34:30.00 N	03:36:18.00 E
22	Afam_GS (Rivers)	1	330	1	330	162.94			698	0		0	0	1	1	04:50:42.00 N	07:15:18.00 E
23	Aja	1	330	1	330	83.22	200	0				0	0	1	1	06:28:30.00 N	03:34:12.00 E
24	Aladja (Delta)	1	330	1	330	129.4	48	0				0	0	1	1	05:29:06.00 N	05:45:18.00 E
25	Delta_GS (Delta)	1	330	1	330	130.33			688	0		0	0	1	1	05:30:18.00 N	05:59:06.00 E
26	AES_GS (Lagos)	1	330	1	330	83.61			243	0		0	0	1	1	06:34:38.00 N	03:35:12.00 E
27	Calabar	1	330	1	330	160.82			561	0		0	0	1	1		
28	Okpai	1	330	1	330	143.87			480	0		0	0	1	1		

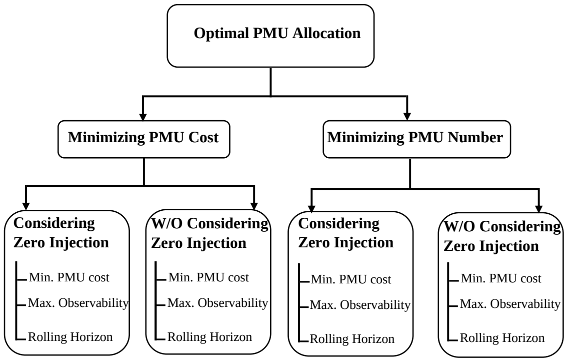

Fig. 6: Bus Observability with and without ZIB with minimization of PMU cost

TABLE II: Minimization of PMU cost for the Nigerian Power grid with and without ZIB

	No. of PMUs	Cost of PMUs	PMU Bus Location
With ZIB	10	12.4	[2,6,8,10,12,15,17,18,21,24]
Without ZIB	11	13.3	[2,3,5,8,10,12,15,17,18,21,24]

considered. As well, the minimization of the number of PMUs is also considered to aid in improving the economic incentive for the system stakeholders.

In the first case as in Table. II, it is observed that considering zero injection buses in the placement optimization is advantageous as it reduces the overall number and cost of required PMUs. Furthermore, as seen in Table III, by minimizing the number of PMUs, the optimal placements vary for full observability in the system where optimization considering zero-injection buses reduced the number of PMUs to be deployed. Next, the system observability from different buses are visualized. In Fig. 7, by minimizing PMU cost. In the case considering the zero injection buses with the optimization, the observability is highest at bus number 15 with b_i about 8, followed by bus 21 with b_i about 4. In Fig. 8, by minimizing PMU count, the observability is still highest at bus number 15 in the case considering the zero injection buses with the optimization, while the observability at bus 21 decreased and some other bus' increased.

TABLE III: Minimization of Number of PMUs for the Nigerian Power grid with and without ZIB

	No. of PMUs	PMU Bus Location
With ZIB	10	[2,6,9,10,11,16,17,18,19,24]
Without ZIB	11	[2,5,6,9,10,15,16,17,18,21,24]

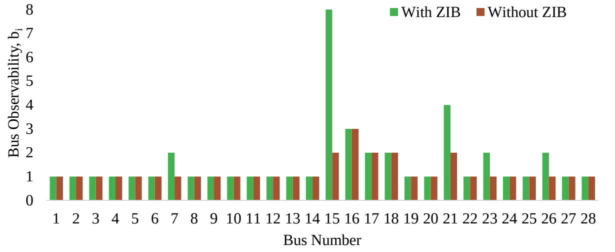

Fig. 7: Bus Observability with and without ZIB with minimization of PMU cost

For the rolling horizon analysis, we presume that the timeline for implementation will be 5 years with (3,2,2,2,1) PMUs for each of the years respectively while maximizing observability and the results are as shown in Fig. 9. This

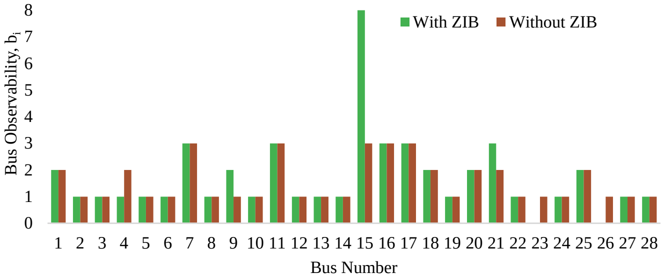

Fig. 8: Bus Observability with and without ZIB with minimization of PMU number

TABLE IV: Five Year Rolling Horizon Adaptation

	Year 1	Year 2	Year 3	Year 4	Year 5
Total No. of PMUs	3	5	7	9	10
PMU bus location	[6,16,21]	[6,9,16,17,21]	[6,9,15-18,21]	[6,9,10,15-18, 21,24]	[5,6,9,10,15-18, 21,24]
No. of Obeservable Buses	14	20	24	26	27
Observable Buses	[3,4,6,7,11,12,15-17, 20,21,23,25,26]	[1,3,4,6-9,11-13,15-18, 20,21,23,25,26,28]	[1,3,4,6-9,11-23, 25-28]	[1,3,4,6-28]	[1,3-28]

should incentivize the system stakeholders economically by working with their budget while keeping situational awareness optimal through the horizon of the implementation.

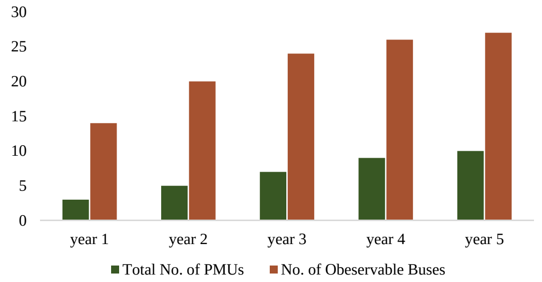

Fig. 9: Buses Observable with PMU installation over 5 years

C. Discussions and Recommendations

Further from the budget-incentivized improvements, there are several other ways that the proposed framework can be used by the power system stakeholders in order to fully harness the utility of the proposed investment. The power system data collected from the PMUs are not only spatially correlated but also temporally synchronized [24]. Moreover, logically, in the PMU power grid data temporal sequence, we can assume reasonable influence between past and future data. Hence, the data provided by PMUs can be used for detecting and locating issues such as vandalism because even if a PMU is vandalized or the line vandalized does not have a PMU installed, the observability of the neighboring PMUs will be able to detect the issue in the system. Also, this can be used in the case of cyber attack detection [25]. The PMUs outside the target area of the adversary can be used for anomaly detection given the observability of neighboring PMUs. Moreover, issues such as vandalism and electricity theft can also be detected.

IV. CONCLUSION

This paper proposes the budget-incentivized rolling horizon implementation of PMU sensor placements to improve situational awareness and hence reliability in the grid of developing countries. The framework, for different cases, is implemented on the Nigerian power grid which has faced multiple grid collapse averaging one collapse/month in 2022. The results show that the observability of the system can be greatly improved even in face of economic limitations.

REFERENCES

[1] A. Muir and J. Lopatto, “Final report on the august 14, 2003 blackout in the united states and canada: causes and recommendations,” 2004.

[2] Y. Chen, Z. Huang, and N. Zhou, “An advanced framework for improving situational awareness in electric power grid operation,” *IFAC Proceedings Volumes*, vol. 44, no. 1, pp. 12 162–12 170, 2011.

[3] T. Nation, “Why nigeria’s power grid keeps collapsing,” https://energycentral.com/news/why-nigerias-power-grid-keeps-collapsing, [Online; accessed 31-August-2022].

[4] USAID, “Nigeria power africa fact sheet,” https://www.usaid.gov/powerafrica/nigeria, [Online; accessed 28-October-2022].

[5] [Online]. Available: https://www.get-invest.eu/market-information/nigeria/energy-sector/

[6] K. Ley, J. Gaines, and A. Ghatikar, *The Nigerian Energy Sector: An Overview with a Special Emphasis on Renewable Energy, Energy Efficiency and Rural Electrification*. Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, Nigerian . . . , 2015.

[7] R. F. Nuqui and A. G. Phadke, “Phasor measurement unit placement techniques for complete and incomplete observability,” *IEEE Transactions on Power Delivery*, vol. 20, no. 4, pp. 2381–2388, 2005.

[8] T. Ferryman, F. Tuffner, N. Zhou, and G. Lin, “Initial study on the predictability of real power on the grid based on pmu data,” in *2011 IEEE/PES Power Systems Conference and Exposition*. IEEE, 2011, pp. 1–6.

[9] M. R. Narimani, H. Huang, A. Umunnakwe, Z. Mao, A. Sahu, S. Zonouz, and K. Davis, “Generalized contingency analysis based on graph theory and line outage distribution factor,” *IEEE Systems Journal*, vol. 16, no. 1, pp. 626–636, 2021.

[10] N. O. Adelakun and B. A. Olanipekun, “Outage analysis and system disturbances on 330 kv and 132 kv transmission system in nigeria,” *Available at SSRN 3579952*, 2020.

[11] C. Okoye and S. Omolola, “A study and evaluation of power outages on 132 kv transmission network in nigeria for grid security,” *The International Journal of Engineering and Science (IJES)*, vol. 8, pp. 53–57, 2019.

[12] M. Pignati, L. Zanni, P. Romano, R. Cherkaoui, and M. Paolone, “Fault detection and faulted line identification in active distribution networks using synchrophasors-based real-time state estimation,” *IEEE Transactions on Power Delivery*, vol. 32, no. 1, pp. 381–392, 2016.

[13] I. Kolosok, E. Korkina, and E. Buchinsky, “The test equation method for linear state estimation based on pmu data,” in *2014 Power Systems Computation Conference*. IEEE, 2014, pp. 1–7.

[14] S. Soltan, M. Yannakakis, and G. Zussman, “Power grid state estimation following a joint cyber and physical attack,” *IEEE Transactions on Control of Network Systems*, vol. 5, no. 1, pp. 499–512, 2016.

[15] J. James and S. Bindu, “Hybrid state estimation including pmu measurements,” in *2015 International Conference on Control Communication & Computing India (ICCC)*. IEEE, 2015, pp. 309–313.

[16] E. Oleka, S. Ndubisi, and G. L. Lebby, “Synchrophasor for enhancing operational reliability of nigerian electric power grid,” in *SoutheastCon 2017*. IEEE, 2017, pp. 1–6.

[17] Z. Li, M. Shahidehpour, A. Alabdulwahab, and A. Abusorrah, “Bilevel model for analyzing coordinated cyber-physical attacks on power systems,” *IEEE Transactions on Smart Grid*, vol. 7, no. 5, pp. 2260–2272, 2015.

[18] D. Dua, S. Dambhare, R. K. Gajbhiye, and S. Soman, “Optimal multistage scheduling of pmu placement: An ilp approach,” *IEEE Transactions on Power delivery*, vol. 23, no. 4, pp. 1812–1820, 2008.

[19] S. Ohiare, “Financing rural energy projects in developing countries: a case study of nigeria,” 2014.

[20] G. A. Ajenikoko, A. W. Eboda, O. Adigun, A. Olayinka, S. Oladimeji, and L. Adelowo, “Analysis of power sector performance: Nigeria as a case study,” *Mathematical Theory and Modeling*, vol. 8, no. 8, pp. 64–71, 2018.

[21] A. Umunnakwe, H. Huang, K. Oikonomou, and K. Davis, “Quantitative analysis of power systems resilience: Standardization, categorizations, and challenges,” *Renewable and Sustainable Energy Reviews*, vol. 149, p. 111252, 2021.

[22] F. O. Akpojedje and E. Mormah, “Transmission system and rural electrification scheme in nigeria: issues, challenges, constraints and way forward,” *Journal of Advances in Science and Engineering*, vol. 2, no. 2, pp. 9–28, 2019.

[23] PowerWorld Corporation, available at http://www.powerworld.com, 2018.

[24] R. Klump, P. Agarwal, J. E. Tate, and H. Khurana, “Lossless compression of synchronized phasor measurements,” in *IEEE PES General Meeting*. IEEE, 2010, pp. 1–7.

[25] O. Boyaci, A. Umunnakwe, A. Sahu, M. R. Narimani, M. Ismail, K. R. Davis, and E. Serpedin, “Graph neural networks based detection of stealth false data injection attacks in smart grids,” *IEEE Systems Journal*, 2021.