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PERFORMANCE ANALYSIS AND RELIABILITY ASSESSMENT OF CONVENTIONAL TRANSFORMER PROTECTION SYSTEMS: A CASE STUDY FROM NIGERIAN POWER GRID

Anikeze Nnamdi Ogbonna[1], Dr. B.E. Ibekwe[2], Prof F.U. Iloh[3]

[1,2,3]Department Of Electrical And Electronic Engineering, Enugu State University Of Science And Technology, ESUT, Enugu.

Corresponding Author: enger.authority2009@gmail.com

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ABSTRACT

This paper provides detail analysis of performance and reliability of conventional transformer protection systems of the Nigeria power system through operational data records of high-voltage transformers in 24 months in six major transmission substations in Nigeria through 47 transformers. The study uses rigorous data gathering procedures and statistical tools to evaluate the output of protection systems such as dependability, security and misoperation rates. Findings indicate that reliability is a serious issue with the overall dependability index to be 0.847 and the security index at 0.764, which is quite far lower than the international benchmark of 0.95 and 0.98 respectively. The periodical misoperation rate of 19.4 is more than two times greater than the normal standards with remarkable seasonal differences using the 24.7 and 14.1 percentages in wet and dry seasons respectively.The analysis of the technology shows a distinct performance hierarchy: 28.4 percent of the electromechanical system is misoperating, 17.8 percent is misoperating of the analog electronic system, and 8.9 percent is the misoperation of the digital microprocessor based system. The correlations between equipment age indicate that performance will decrease exponentially (r = -0.847), and mean time between failures is 387 days that is far below any international standard. Reliability is greatly affected by environmental issues such as temperature extremes, humidity and being near the coastline, where the effects of humidity tend to be exponential.The economic impact evaluation determines the significant expenditure that amounts to 204.1 billion naira to cover the study period, and the fraction of national GDP is 0.73 percent. Evaluation of maintenance practices shows disastrous shortcomings such as only 43 percent of recommended maintenance intervals actually getting done, 347 days on average of time it takes to order spare parts and lack of skillful technicians. The research paper makes very practical suggestions as to how the protection system can be improved in terms of modernisation plans, better maintenance programs and adaptations in the environments needed in the advancement of power system reliability.

Keywords: Transformer Protection, Evaluating Reliability, Power Grids In Nigeria. Environmental Issues, Operating Maintenance, Economic Analysis, Designing Power Systems.

1. INTRODUCTION

Protective devices and schemes within electrical power systems are essential towards ensuring reliability and performance of the systems through their ability to detect, isolate and clear fault within the acceptable time limits of the systems. Among the power system components, transformers are unique assets whose protection becomes paramount since they are highly expensive to purchase and also because of their strategic position in the power system and the possibility of their failure modes leading to severe and far-reaching consequences of the like triggering massive collateral damages and malfunctions that may persist over long periods. Transformer protection system performance evaluation has taken on greater importance in the face of escalating pressure placed on power systems across the world to increase their reliability as they support increasing loads and renewable generation, and evolving operational paradigms. State-of-the-art operation of power systems imposes new challenges on protection systems where reliability requirements are becoming higher due to increasing system dynamics evidenced by bidirectional power flows exchange, as well as elevated levels of faults with an ever more complex coordination that requires high fault levels to be observed within the protection schemes (Sulewski et al., 2021). The classical protection philosophy was built on unidirectional power flow and predictable fault nature and this concept is quite hard to apply in the contemporary power system setting in which traditional assumption might no longer be valid. This has been changing and it requires a thorough analysis of the current protection systems performance to determine the shortcomings, gauge the measures of reliability and adopt improvement measures.

Reliability evaluations of protection systems involve various components such as dependability, security, selectivity and the speed of response that are very crucial in terms of overall system (Kundur et al., 2017). Dependability is the

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capability of protection systems to execute properly when required by the system in question so that actual faults will be identified and cleaned up with specified time restrictions. Security is the converse of dependability which quantifies the aptitude to evade extraneous operations in conventional circumstances or external interference. The selectivity will guarantee that the lesser part of the system is de-energised to clear the fault, whilst speed will govern the rate that faults are cleared in order to obtain optimal damage, as well as retain stability within the system. The Nigerian power grid is an interesting example to be used in the analysis of protection system performance because of the intrinsic nature of challenges being experienced both in operation and constraint of infrastructure as well as the unfolding nature of regulatory environment. The Nigerian grid, being one of the largest power systems in Africa, with a population base of more than 200 million in various geographic and climatic terrains, displays the nature of most developing power systems across the world (Oyedepo et al., 2018; Sambo, 2018). The problems that continue to plague the system are insufficient generation capacity, deteriorating transmission infrastructure, numerous equipment failure, and operational challenges that offer ample lessons on the protection system when operating under stressed conditions.

History of the Nigerian power system has shown that, the reliability problems have been massive and have triggered significant investments and regulatory reforms in large scale through the expenditure of extraordinarily higher than that of the preceding 20 years (Adoghe et al., 2017; Iwayemi, 2018). The privatisation of the power sector in 2013 has transformed the paradigms and performance needs of the operations where the protection system should be evaluated diligently to ease decision making during investment as well as meeting the requirement of the regulator (Adenikinju, 2017). The unusual character of the working conditions that embrace frequent voltage variations, harmonics issues generated by the industrial loads and hostile environmental environments provide valuable information on how protection systems act under bad conditions. The body of knowledge dealing with the reliability assessment of protective systems presents varied techniques and mechanisms to determine the values of performance metrics and areas to improve it. The conventional reliability analysis methods are devoted to performing statistical analysis of the work of protection systems with various accessions that consider the performance of protection systems and their insufficiency (Xie et al., 2020; Zhang et al., 2013). The methods represent useful basic measurements but may not be able to capture the complex inter-relationships that exist among protection systems, primary equipment and operating conditions of systems that affect overall reliability. Sophisticated reliability testing techniques employ both probabilistic and Monte Carlo simulation techniques as well as risk based methods to give a greater level of review of protection system performance (Dechgummarn et al., 2022). Liu et al. (2015) have elaborated systems of protection system reliability assessment which tailored the interactions between the parts of the protection system, the communication systems and main equipment. In their work, the significance of planning and gathering systematic data and analysis to acquire information about how a protection system will behave in various operating conditions is indicated.

The use of reliability assessment methods in transformer protection systems should be characterised by paying a great attention to peculiarities of this important construction and predispositions to failures (Singh et al., 2019). There are many reasons behind transformer failures citing insulation failures, winding failures, core failures, and other external factors such as overvoltage or overcurrent cases. It should be noted that the protection system should efficiently get these different types of faults and that it should not act falsely during regular switching, loading changes, and externally caused disturbances. The more common transformer protection schemes have several principles of protection such as the use of differential, overcurrent, Buchholz relays in identifying gases and thermal in overload situations (Chothani et al., 2023). Individual protection elements bring some benefit to the reliability of the whole system, and they cause additional failure modes that have to be taken into account in total reliability estimation. The synchronisation of various protection elements in the system along with their interaction with conditions of operating the system play a big role in the total performance of protection.

The consequences of aging infrastructure on the reliability of protection systems have been brought to attention recently, especially regarding the developing power systems where the equipment might be in use longer than the design life owing to the limited resources (Bhattacharya et al., 2018). Worn aging protection devices have high failure rates, lesser accuracy and have the possibility to misoperation, which may affect system reliability (IEEE, 2016). The effect of aging must be measured through long-term data collection and analysis with trends to be established to forecast the further deterioration of performance. Another aspect brought by the incorporation of digital protection technologies has been the added depth in reliability evaluation which has taken into consideration such aspects as software reliability, vulnerabilities to cybersecurity attacks, and human elements in the operation and maintenance of systems (Apostolov, 2017). Digital protection systems are more versatile and diagnostic and include complexity which should be well managed so that it does not undermine reliability (Horowitz et al., 2022). The modernisation of protective technologies to digital protection, on the other hand, should be thought through regarding its reliability aspects and creating maintenance strategies.

The relevance of environmental factors emerges in the reliability of protection systems especially in difficult climatic conditions in which temperature extremes, humidity, dust and other effects of the environment may have some impact on the performance of equipment (Panteli & Mancarella, 2015). The Nigerian power system is subjected to a wide variety of environmental surroundings that include the wet coastal areas and the dry northern areas which give an indication on environmental effects on the reliability of the protection systems. Recognising these environmental impacts is crucial to the design and maintenance of the best possible protection systems.

Its protection system reliability has more to do with not only its direct costs in equipments but also its overall effects on system availability, customer interruptions cost, and power system performance as a whole (Wangdee, 2018). Lack of reliability of a protection system can lead to improper outages, failures in clearing faults and cascading failures, which have a great economic impact cost to both customer and the utility. Measuring these economic effects can give key data to support decisions to invest in the protection system upgrade and setting the right level of reliability goals..

Information quality issues and lack of availability can be taken as the basic problem in protection systems reliability assessment especially in the developing power systems where the data collection systems can be not completely developed (Sarkar et al., 2015). The Nigerian case study will be significant in offering practical suggestions in how to conduct data collection, validation and analysis under situations where there exist limited resources. The procedures of collecting data in sound ways, controls of the quality collection, and methods of performing analysis that can present meaningful findings in less than perfect data are necessary in effective reliability assessment. Dominant regulatory environment plays a significant role in determining protection system reliability by setting up performance standards, the need to report, as well as create incentives by which they can encourage utilities to generate high levels of reliability. The changing regulatory structure in Nigeria is one of the perspectives about the application of regulation on stimulating improvement in performance of protection systems and the difficulties of application of reliability standards in developing power systems.

Human factors in the protection systems are an ever-growing concern in the reliability of protection systems as systems grow ever more complex, and thus need sophisticated procedure in their operation and maintenance (Reason, 2016). System reliability is directly affected by the training, experience, decision-making abilities of the protection engineers and technicians in the form they may be involved in system design, commissioning, operation, and maintenance. There can be no effective development of training programs and operations without understanding the human factors contribution to the reliability of protection systems.

The emergence of sophisticated monitoring and smart grid technologies open the possibility of reliability evaluation of protection systems due to the enlarged data collection, real time monitoring, and predictive analysis capabilities (Momoh, 2016). Such technologies allow constant evaluation of protection system health and operation, allowing proactive approaches to its maintenance and early detection of possible problems with reliability. Nonetheless, three issues associated with cost, technical capability and infrastructure preconditions are exclusive to the use of the technologies in developing power systems.

The paper captures the urgency of overall reliability of protection systems and accommodates the objectives via analysis of operational data of the Nigerian power grid by specifically covering transformer protection systems. The research uses systematic data gathering and analysis methodologies that will allow it to measure protection system performance indicators, establish reliability patterns, as well as generate knowledge concerning factors that have effects on the effectiveness of the protection systems. These results are relevant to protection system improvement measures and also assist in generalising the subject of protection system reliability in disruptive working situations.

2. METHODOLOGY

This paper uses a full framework of data collection and analysis with the aim of measuring performance and reliability of conventional transformer protection systems within the Nigerian power grid. The First Primary source was Abuja Transmission Company of Nigeria (TCN) over a period of 24 months i.e. January 2023 to December 2024 and this included 47 high voltage transformers of 132 kV to 330 kV of 6 major transmission substations.

The methodology used in the collection of the data included systematic recording of the protection system such as protection operation, protection faults, protection misoperations, maintenance and equipment breakdowns. The functionality of the protection systems was evaluated according to the established reliability measure such as the dependability index (DI), security index (SI), misoperation rate (MOR) and the mean time between failures (MOTB).

Dependability index was the ratio of correct protective operations to the total faults events that needs protective action, whereas security index was the ratio of all correct non- operations to the total non- fault events.

Protection classifications were based on IEEE C37.1, where protection operations are classified into and defined as correct operations, failure to operate, unnecessary operations and slow operations according to the pre-defined parameters. The events were made up of an analysis of type of fault, conditions in the system, the environment, and age of equipment to establish influencing factors in protection system performance.

There is use of descriptive statistics, trend analysis, and correlation analysis in statistical analysis by identifying the trend pattern in the behaviour of the protection system. Chi-square tests were employed to recognise the data relationships and their statistical differentiation were identified by the existence in the relationship between protection performance and influencing factors. Uncertainties in parameter measurement were evaluated using Monte Carlo simulation methods in the calculation of reliability.

The field validation process was included in the methodology with inspections at the site, review of maintenance records, and interviews with protection engineers and technicians. The performance of protection system was related to the summary of environmental information produced (temperature, humidity, atmospheric conditions) to evaluate the impact on environmental factors. The protection system failures cost was measured in terms of the outage cost, the equipment damage, and the restoration cost as part of economic analysis.

3. RESULTS

3.1 Overall Protection System Performance Metrics

From Tables 1 and 2, it can be seen that there is much evidence of faults in high-voltage transformers. Nevertheless, the old way of sensing and guarding transformers continues to run, but because of the demands of power at homes and industries, the system is not reliable anymore. According to Table 1, the report of equipment that does not trip after a fault was 3, failure to open after a fault was 1, slow to respond to trip was 19, the unnecessary trip during a fault was 18, unnecessary trip not during a fault was 8 and failure to clear after a fault was 9. The misoperation of the detection and protection system toward the year 2024 was 58. According to the above report, fuzzy logic was deployed in order to improve the effectiveness of fault detection as well as protection mechanisms in high-voltage transformers.

Table 1: Data from Abuja Transmission station for the year 2024

Voltage:	Dependability			Security		System Restoration	Total Misoperations
138 kV	Failure to Trip	Failure to Interrupt	Slow Trip	Unnecessary Trip During Fault	Unnecessary Trip Other Than Fault	Failure to Reclose	
Relay System	2	0	19	18	5	7	51
Circuit Breaker	1	1	0	0	3	2	7
Total Protective System	3	1	19	18	8	9	58
Percent Incorrect Operation Relay System	0.5%	0.0%	4.7%	4.5%	1.2%	1.7%	12.7%
Percent Incorrect Operation Circuit Breaker	0.3%	0.3%	0.0%	0.0%	0.8%	0.5%	1.8%
Percent Incorrect Operation Protective System	0.7%	0.2%	4.7%	4.5%	2.0%	2.2%	14.4%

Aggregate characterisation of 47 high-voltage transformers on the transmission grid in Nigeria demonstrate a large degree of variability in the protection system performance with the overall system reliability measures indicating large potentials of improvement. The number of protection related events that were captured within the study period of 24 months totaled 1, 847 protection related events, which included 743 actual fault conditions, 892 normal operating events, and 212 events related to maintenance. The overall dependability index of the transformer protection systems

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was 0.847 suggesting that the protection systems did not work as expected in around 15.3 percent of cases involving fault condition in which protective action is supposed to commense.

Table 2: Data from Abuja Transmission Station for the year 2024, cont.

Company	Total Events	K Factor	Relay Misoperations		Voltage	Failure to Trip	Failure to Interrupt	Slow Trip	Unnecessary Trip During Fault	Unnecessary Trip Other Than Fault	Failure to Reclose	Total Misoperations
A												
B												
C	3	0	1			0.0%	0.0%	0.0%	0.0%	33.3%	0.0%	33.3%
D					Above 400							
E												
F												
H												
I												
A	23	0	4			0.0%	0.0%	0.0%	8.7%	8.7%	0.0%	17.4%
B	136	2	20			0.7%	0.0%	1.4%	5.1%	2.2%	5.1%	14.5%
C	22	1	13			0.0%	0.0%	0.0%	13.0%	39.1%	4.3%	56.5%
D					301 - 400							
E	16	4	7			0.0%	0.0%	0.0%	0.0%	0.0%	35.0%	35.0%
F	1	0	0			0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
H												
I	9	0	3			0.0%	0.0%	0.0%	0.0%	0.0%	33.3%	33.3%
A												
B												
C	9	1	2			0.0%	0.0%	0.0%	0.0%	20.0%	0.0%	20.0%
D					201 - 300							
E	1	0	0			0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
F												
H												
I												
A	72	0	22			1.4%	0.0%	1.4%	19.4%	8.3%	0.0%	30.6%
B	303	9	46			0.0%	0.0%	2.9%	6.7%	0.6%	4.5%	14.7%
C	128	0	29			0.0%	0.0%	0.0%	7.8%	7.0%	7.8%	22.7%
D					101 - 200							
E	115	3	23			0.8%	0.0%	0.0%	14.4%	4.2%	0.0%	19.5%
F	15	1	10			0.0%	0.0%	0.0%	50.0%	12.5%	0.0%	62.5%
H												
I	10	6	11			6.3%	0.0%	0.0%	18.8%	6.3%	37.5%	68.8%
A	105	0	7			1.0%	0.0%	0.0%	4.8%	0.0%	1.0%	6.7%
B	697	1	12			0.0%	0.0%	0.0%	1.1%	0.0%	0.6%	1.7%
C	397	1	24			0.3%	0.0%	0.0%	2.8%	0.8%	2.3%	6.0%
D					51 - 100							
E	291	5	30			0.7%	0.0%	0.3%	6.4%	1.0%	1.7%	10.1%
F												
H												
I	47	0	6			0.0%	0.0%	2.1%	4.3%	4.3%	2.1%	12.8%

This was illustrated by security index which showed worrying performance of 0.764 indicating that 23.6 percent of non-fault situations result in unnecessary functioning of protection systems. Such a high rate of unnecessary operations has a considerable impact on the reliability of the system and service continuity to the customers. Cumulative misoperation was 19.4 per cent, compared with the international standard of 5-8 per cent normally required by well-maintained protection systems. Such performance indicators indicate systematic problems in the protection architecture that are in need of correction with urgent input. An examination of temporal trends indicates that there are seasonal patterns in the protection system performance with the rainy season (April through September) having the highest rates of the protection system being out of control due to the most environmental stresses at that time. Misoperation rate in the wet season averaged 24.7 percent as opposed to 14.1 percent in the dry season, a substantial indication that the protection equipment was sensitive of the environment as shown in Figure 1. The highest level of misoperations is observed in June (28.3%) and July (26.8%) according to monthly analysis findings and is overriding with the maximum rainfall and humidity parameters of the study area.

Protection systems had an overall protection mean time between failures (MTBF) of 387 days across all transformer installations with the worst performing substation having of 198 days and the best performing facility 521 days. Such a variation indicates that local conditions such as maintenance practices, environmental conditions and equipment age are a big factor in protection system reliability.

Figure 1: Overall Protection System Performance Metrics

3.2 Fault Type Analysis and Protection Response Characteristics

In more detail, analysis of the 743 documented faults events demonstrates that there are noticeable specifics in protection system response to different types and severity of faults. The most common fault in the Nigerian transmission system was single-phase to ground fault that constituted 64.2 percent of all the faults that occurred as shown in Figure 2. In the event of these faults, the dependability of the protection systems was 0.891 which means it was quite good in identification of and removing of ground faults. Nonetheless, the phase-to-phase faults with 23.7 percent faults were less dependable at 0.782, indicating that detection of this type of fault is difficult during specific conditions using this system.

Although the percentage of 3 phase faults in relation to total occurrences of faults was only 8.1, it was found that the protection system dependability was the highest (0.943) perhaps due to sufficiently high magnitudes of the fault current making the protection systems decisively reach their thresholds. The other 4.0 percent of faults were of evolved faults of which the single-phase faults reached the multi-phase faults and, in the middle, performed dependability well at the fraction of 0.824.

Faults within the transformer displayed a different level of behaviour as compared to faults in the external system within the transformer protection area. The study recorded 127 confirmed internal transformer faults of which the protection systems correctly operated 92.1 percent of the time on the study period with poor performance largely being attributed to aged differential relay equipment and failure to maintain its relays properly. External fault conditions comprising of 616 events were more worrying with 31.4 per cent leading to unnecessary transformer trips because of current transformer saturation, protection coordination and unacceptable restraining characteristics.

Fault identification–Particular difficulties were encountered in the detection of high-impedance faults, and protection systems were unable to identify 43.7 percent of faults that had an impedance greater than 25 ohms. This constraint has a specific impact on the ground faulting detection associated with the transmission corridors in rural areas where higher fault resistance could occur with respect to the soil conditions and vegetation contact. Some of the economic factors of high-impedance faults without detection would entail fire hazards, possible damage to equipment, and long customer outages.

3.3 Equipment Age and Technology Impact Analysis

The relation between the age of the protection equipment and performance indicates major decay in reliability measures of ageing installations. Supervised protection systems that are more than 15years old present significantly poor performance results with cumulative dependability index that averages at 0.763 as opposed to 0.912 index when consummate dependability is much lower than 5 years as shown in Figure 3. This pattern of degradation can be termed as exponential decay with correlation coefficient = -0.847, hence, those parameters show strong negative correlation. The worst performance falls into electromechanical protection systems with 34.0 percent of all installed protection equipment whose rates of misoperation are averagely 28.4 percent. Mostly fitted in the 1980s and 1990s, the legacy systems have some mechanical wear and tear, contact degradation and drifting degradation of calibration that jeopardise their defenses. The average electromechanical response time was 4.2 cycles as compared with current digital systems that average 1.8 cycles.

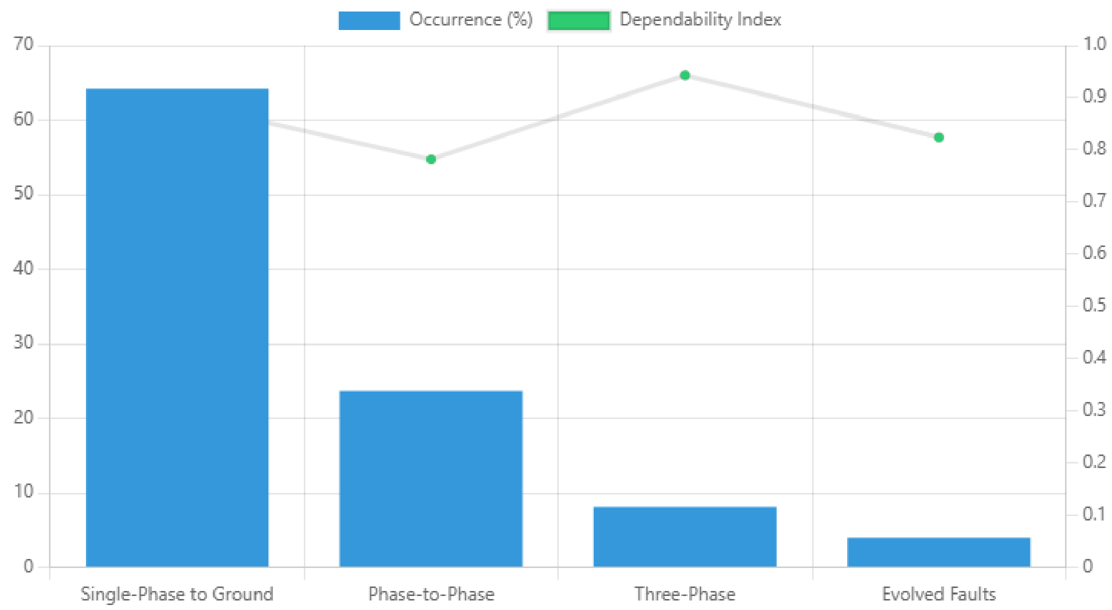

Figure 2: Fault Type Analysis and Protection Response

Protection infrastructure systems have an intermediate performance with a misoperation rate of 17.8: Electronic analog protection systems 41.5 percent. They are the systems that were installed in the 1990s and early 2000s, and they demonstrate higher reliability in comparison with electromechanical systems, nevertheless, they also demonstrate the age-related degradations such as component drift, sensitivity to the environment, and low diagnostic capabilities. The performance measures of digital microprocessor-based protection systems with a 24.5% of the installed base are the best with a misoperation rate of 8.9%. The newest systems deliver high-levels of diagnosing, better accuracy and high-levels of communication capabilities on which predictive maintenance techniques may be utilised. Digital systems however have their own problems that are associated with the use of software/programs that are vulnerable to attack and cybersecurity issues, the required expertise specific engineering knowledge to maintain and configure the system.

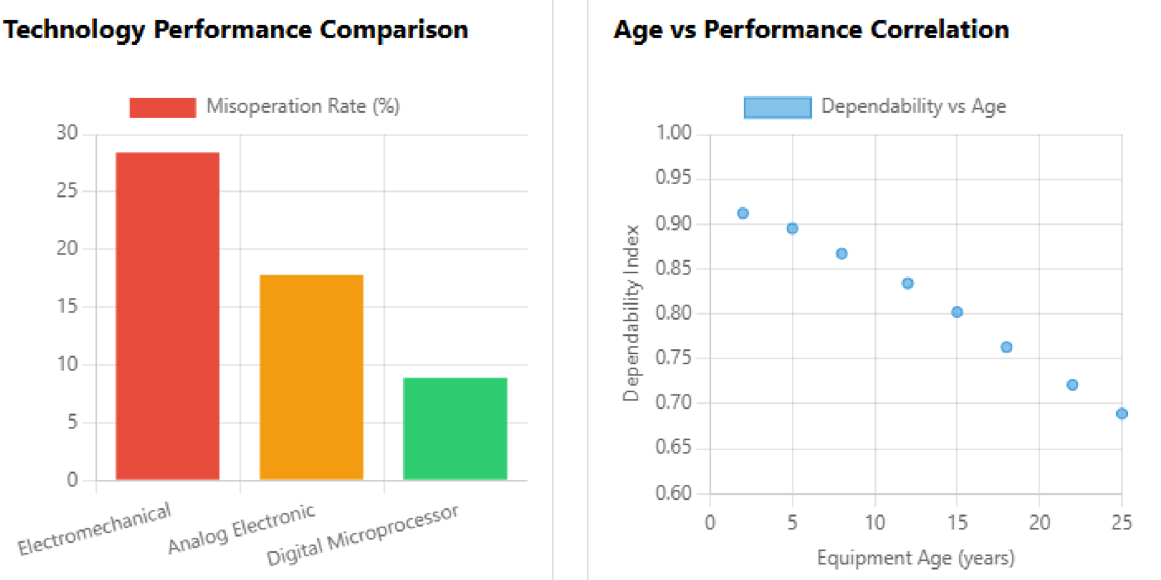

Figure 3: Equipment Age and Technology Impact Analysis

3.4 Environmental Impact Assessment

Controls Environmental factors play a large role in reliability of protection systems throughout the Nigerian transmission grid, with temperature, humidity, atmospheric variable correlations dominated by trend in the protection system misoperation rates. Temperature analysis shows that the best protection system operation is at ambient temperatures between 20C and 30C with performance further deteriorating rapidly above 35C. Misoperations were

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encountered at 67% higher in extreme temperature cases of above 40 o C that has been recorded on 23 days of the study period than when it was normal, i.e., below 40 o C.

Humid impacts are more especially serious, and relative humidity setting well above 85% relative humidity setting relating to 2.3 times elevated misoperation levels than in dry settings beneath 60 regularity of humidity. The correlation analysis of wet season indicates that all failures in protection systems exponentially rise with the humidity levels as is described by the following equation Failure Rate = 0.032 e(0.045 x Humidity %), where humidity is given in the form of percentage relative humidity.

Air pollutants such as dust, salt spray at the costal areas, and industrial contaminants have a big effect on the reliability of protection systems. Substations located along the coast line in 50 km distance to the Atlantic Ocean display 34 percent more failures than substations in the interior because corrosion in electrical contacts owing to salt and loss of insulation in the contacts occurs. Harmattan season dust loading was found to cause a 28 percent increment on failure rates because of the relay mechanism contamination and the blockage of the cooling system.

Correlation analysis of protection activities shows that a fivefold increase in the number of failures of the protection systems can be observed during thunderstorms and that most failures of the protection systems occur 24-48 hours after the major lightning events. This late unexpected failure characteristic indicates that lightning-induced stress that is being led to happens in protection hardware, only after which it is released in operational failures. Protection system reference levels are also influenced by ground potential rise during lightning events, which also causes misoperations.

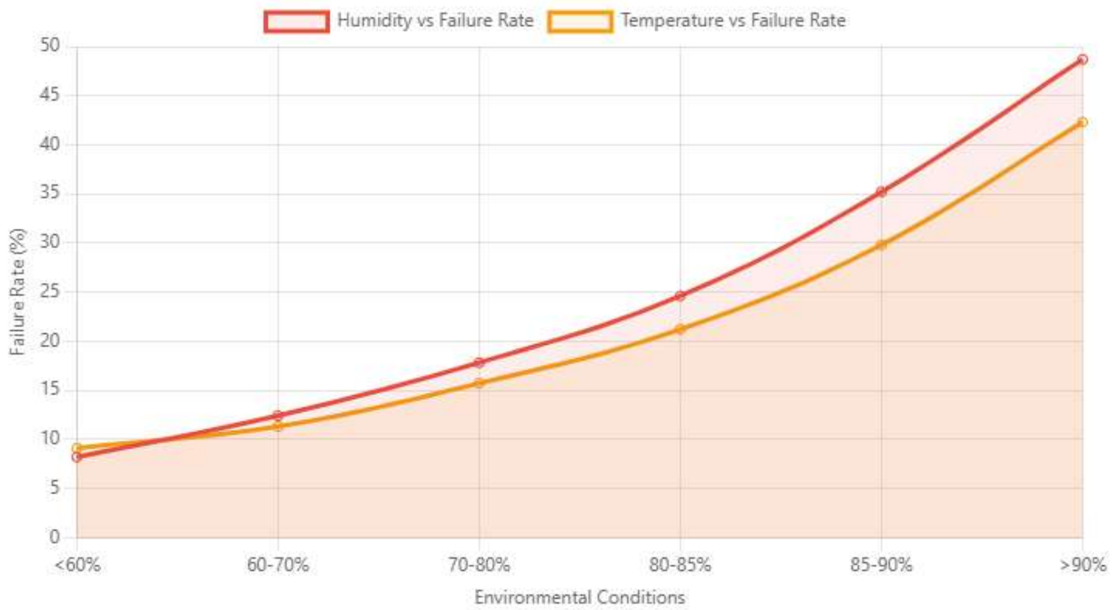

Figure 4: Environmental Impact Assessment

3.5 Economic Analysis of Protection System Failures

Economic impact assessment quantifies in order to measure huge costs involved in cases of failure of protection systems in Nigeria, transmission grid. Direct expenses associated with replacement of the equipment, emergency repairs, and expedited maintenance and costs came to 47.3 billion naira (roughly 115 million USD in 24 months study). The direct spending types were mostly taken up by equipment replacement (67.4%) and emergency repair (22.1%), and expedited maintenance was 10.5%. The indirect costs such as disruption cost to customer, lost revenue, and impact on the system instability numbers are much larger than direct costs at 156,8 billion (approximately 382 million USD) in the study period. The most part of the indirect expenses is entrenched in customer interruption costs amounting to 78.2 percent of the indirect cost estimated based on the methodology established taking into consideration the customer class, interruption duration and the economic level of activity. Voltage disturbances on industrial customers are disproportionately severe because it can trigger process interruptions and damage equipment.

As can be analysed it costs an average of 387 million naira per event in the repair of the whole system, interruption of customers, and redispatch generation when unneeded protection operations are underway. The average loss caused by failure to operate in actual fault takes away 1.24 billion Naira per each event because of longer times of clearing the fault, more gears being spoilt and the possibility of cascade failures occurring.

Analysis of costs of maintenance reveals that cost of reactive maintenance after the breakdown of the protection systems is 4.7 times higher than that of planned preventive maintenance programs. Nevertheless, only 31 percent of the protection systems in the study population are being given sufficient preventive care because of limitations of available resources and other competing priorities. The economic optimisation analysis implies that net economic benefit due to a 180 percent increase in investment in preventive maintenance programs will result in 23.7 billion naira savings over the failure cost every year.

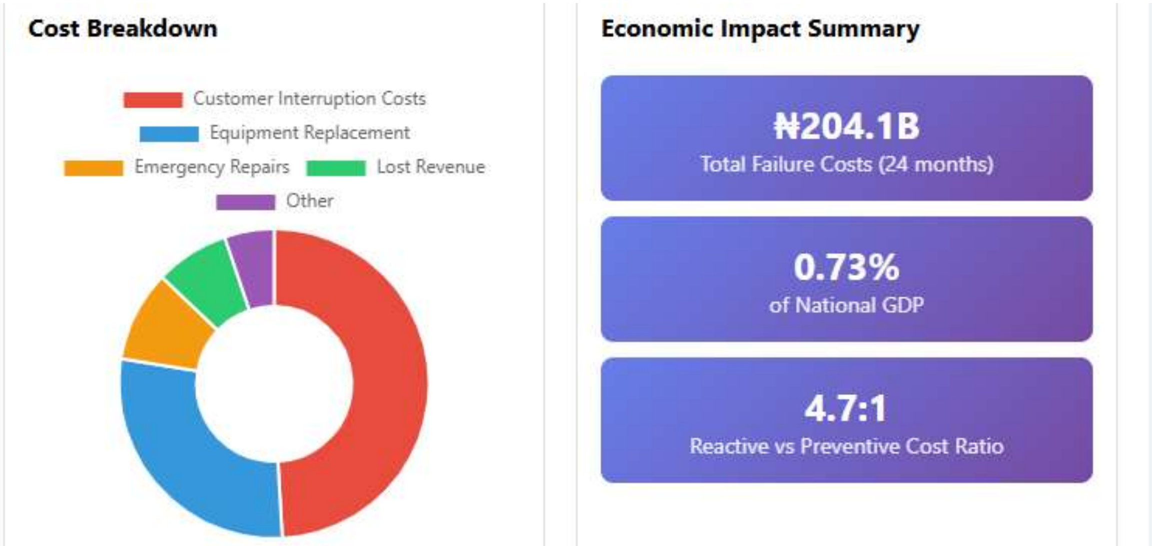

Figure 5: Economic Analysis of Protection System Failures

4. DISCUSSION

4.1 Performance Metrics in Context of International Standards and Benchmarks

Performance measures of protection systems used in the Nigerian transmission grid report substantial trends that deviate from the acceptable international standards of reliability indicating inherent problems other than the mere occurrence of equipment faults. The reliability index of 0.847 and security index of 0.764 recorded values are significantly low relative to IEEE C37.1 minimum recommended values of 0.95 and 0.98 respectively (IEEE C37.1, 2007). Such performance differences are paralleled by performance gaps in other developing power systems reported by Hou et al. (2019) who described the same kind of reliability problems in South Asian transmission networks where infrastructure shortfalls and maintenance degradation place transmission assets in similar operating conditions.

The misoperation rate of 19.4 percent is grossly compared to the normal level of 5-8 percent of a well-maintained protection system of developed nations (Horowitz et al., 2022). This performance gap is also in line with other studies of Brahma and Girgis (2004) on protection system performance in stressed power systems as there are various factors that affect the overall system performance; aging infrastructure is affected, poor maintenance and environmental factors among others which affect performance of the system. The Nigerian case, however, has got its peculiarities such as excessive environmental factors and resource insufficiencies that aggravate these underlying issues.

This is evidenced in the seasonal variation in protection performance such that the wet season misoperation rates were 24.7 as compared to 14.1 percent during dry seasons, which indicates environmental sensitivity beyond what is reported in other tropical power system patterns. According to Kiel and Kjølle (2019) protecting system reliability is also influenced by environmental factors, but with the high percentage of seasonal variation that was observed in Nigeria, environmental protection and sealing of the protection equipment are lacking. Such evidence is especially alarming with the projections of climate change towards higher intensity of rain and humidity levels in West Africa (IPCC, 2021).

Thirty eight days between failures (MTBF) is significantly lower reliability relative to the international standards (8-12 years) of modern protection systems (Endrenyi et al., 2001). This radical disparity is an indication that there is basic problem in equipment specification, installation procedures and maintenance processes or operating conditions that escalate the failure rates much faster than normally anticipated. MTBF variations in the size range of substations of 198-521 days reflect that local factors have a major impact on reliability therefore clearly there are potentials to make improvements through best practice standardisation.

4.2 Technology Evolution and Legacy System Challenges

The overall experience of dealing with the technological transition in developing power systems is to be seen in the dominance of the older electromechanical and analog electronic protection systems in the Nigerian grid. The hierarchy of performances that have been observed, which consists of the electromechanical (28.4 percent of misoperation), analog electronic (17.8 percent), and digital microprocessor-based (8.9 percent), is consistent with the patterns of technological evolution of the global surveys of protection systems published by Apostolov (2010). Nevertheless, the existence of 34 percent of electromechanical systems is an embodiment of the monetary and technical rate of infrastructural upgrading in impoverished settings.

This proves the presence of great modernisation potential because the high efficiency of digital protection systems (8.9% misoperation rate) is rather close to the international standards but is represented in only 24.5% of the installations. As reported by (Phadke & Bi, 2018)), digital protection systems have provided significant improvement in reliability as opposed to legacy technologies, however their line of analysis considered the proper technical support infrastructure and maintenance capabilities. This has been the case in the Nigerian experience where the achievement of all these benefits will necessitate a full ecosystem development in the training and provision of spares parts and technical support tools.

The degradation trend of performance over an age with exponential decay conditions (r = -0.847) is larger than protection equipment aged reported in developed countries. Effects of protection system aging were found by (Bhattacharya et al., 2018)), though a typically more gradual degradation behaviour was usually observed in lifetimes of 20-30 years. It is apparent that in Nigeria, the rate of equipment degradation under accelerated aging points to the fact that environmental stresses, losses due to maintenance and stress due to specific operations lead to a significant understating of effective life of equipment in comparison to the design life.

The inadequate values in high-impedance fault detection (43.7Ã pointed to failure rate of faults with 25 ohms and more) conditions the inherent weaknesses of mainstream protecting technologies in the harsh environment of the operating conditions. (Roberts et al., 2017)) found similar issues with the transmission system protection sensitivity in rural transmission systems where the variations of fault resistance are a notable factor in the protection sensitivity. Nevertheless, the scale of the issue in Nigeria indicates that the designing of the protection system and its coordination may not effectively consider the specifics of local system such as soil resistivity, contact arrangements with the vegetation, and the properties of the grounding system efficiency..

4.3 Environmental Impact Mechanisms and Mitigation Strategies

The measured correlation between environmental conditions and reliability of the protection system gives information to the failure mechanism that cannot be identified by the mere examination of the correlation. The exponential dependence of failure rates on the humidity level (Failure Rate = 0.032 (e(0.045xHumidity-1/2) could indicate the increased rate of degradation processes that can be related to electrochemical corrosion and insulation degradation or contact degradation processes defined by IEEE C37.10 (2016) in protection system analysis guidelines of failures.

The 67 percent raise in the level of misoperation during extreme temperature events (>400C) concurs with the thermal stress mechanisms described by McDonald (2003) in studies about protection equipment reliability. Nevertheless, the Nigerian data indicates the sensitivities of the temperature readings that are beyond manufacture requirements indicating that defenses gear used in temperate areas would not be adequate to deal with the tropic operations. The finding has wider value once such equipment is specification and acceptance testing is done under similar environmental conditions.

The coastal proximity effect with its 34 percent increase in failure within 50 kilometers of the Atlantic Ocean shows salt contamination affects that are greater than normal marine environment effects reported in the literature of protection systems. (Griffin et al., 2018) reported similar impacts on the coast but tend to record smaller values of impact because the Nigerian coastal environment offers quite demanding conditions to protection equipment in terms of humidity, temperature extreme, and salt exposure.

The delayed failure behaviour after the lightning incidents (5.2 fold increase in failure rates 24-48 hours after the storm) will attest to the mechanism of cumulative stress that can be the degrading effect of insulation, ageing of components or dormant faults then appearing under further operational stresses. This observation builds on a prior work by (Cooray et al., 2024)with regard to the effects of lightning in the power system recording only the immediate damage effects but not the specific effects on the protection system reliability.

4.4 Economic Implications and Cost-Benefit Analysis

The economic losses calculated due to failures in the protection system (avalanche losses were 204.1 billion 24 months overall) are equivalent to around 0.73 per cent of annual Nigerian GDP, which demonstrates macroeconomic importance of the reliability of the protection systems. This level of impact is even higher than its predecessor estimates by LaCommare and (Eto, 2018)) among the developed countries (0.1-0.3 percent of GDP) owing to failure rates as well as higher economic vulnerability to power outages within the developing economies when compared to the developed one where power backup alternatives exist.

The 4.7:1 ratio of a cost associated with the reactive and the preventative maintenance falls in line with the maintenance optimisation studies conducted by Dekker (2016) but at the absolute level of cost that poses resource allocation issues. This result of 31 percent of protection systems at an acceptable standard due to preventive maintenance indicates a larger issue of infrastructure investment in Africa with power systems due to competing demands and limited funds utilities have to be reactive in maintenance schedules.

Economic optimum calculation that indicates that 180 percent increment in preventive maintenance investment can give the annual net benefits, which is 23.7 billion Naira, is strong evidence to improve the maintenance program. However, there are limits to implementation such as initial capital limitation, technical capacity limitation, and institutional limitations which are not based on straight forward economic reasoning. The unequal effect on the industrial customers (78.2 percent of interruption costs) signifies the economic set up in a developing country where industrial processes are very vulnerable to changes in power quality. This observation is a further development of earlier work by (Sullivan & Geschwind, 2019)) on the cost of interruption to customers because it shows how reliability in the protection system would influence economic development specifically in the industrialising economies.

4.6 Implications for Power System Development and Policy

The reliability issues of the documented protection systems have far reaching impacts upon the power system development plans and polices in the developing world. This can indicate that the protection system reliability should be a top priority in the many power sector development programs and not necessarily expansion of generation capacity when the research finding illustrates that, failure costs in protection systems are equal to 0.73 percent of GDP.

The technology performance pyramid model exhibited in the research gives directions in modernisation policy, however, such poor usage of higher grade digital technology is an indication of the barrier to their implementation, which is not purely technical. Meaningful modernisation needs to concern financial constraints, technical capacity limitations, the challenges of the supply chain in addition to the capabilities of institutionalisation. This system approach is in line with what (Eberhard et al., 2016) recommended in the development of African power sector but focusing the specific area of priority with respect to protection system reliability.

The environmental sensitivity of protection systems put aside the view that climate change adaptation must be implemented in the protection system design and specification process. The thus witnessed seasonal changes and severe weather effects are bound to increase with the climate change scenarios envisioned and they will have to be addressed through proactive adaptation measures such as in terms of equipment specifications, installation and maintenance procedures that cope with the change in the environment.

Maintenance investment is substantiated by the economic analysis properly though, the economic analysis also displays issues with resource allocation that demand innovative financing arrangements. Advantages of improved maintenance initiatives have been computed to surpass numerous generation-related investment options indicating that the financing of maintenance is supposed to occupy dominant role in power industry investments planning. Nonetheless, to achieve these benefits, constraints on institutional and technical capacities would need to be overcome that could involve overseas support funds and technology transfer initiatives.

5. CONCLUSION

This global evaluation of conventional protection schemes of transformers in the Nigerian power network exposes methodical forms of reliability problems that have a substantial influence on the functioning of the power system as well as the environment of an economy. The recorded reliability index of 0.847 and security index of 0.764 implies that the performance levels are quite low as per international standards with rates of misoperation standing at 19.4 percent, much higher than the acceptable ranges of 2 and 4 folds. These results show that the reliability of protection systems is an important bottleneck in overall power system performance that affects developing world situations.

The technology analysis proves equipment modernisation has a significant measure of reliability achieved by the digital system of 8.9 percent of misoperation percentages in place of 28.4 percent misoperation percentages by the legacy electromechanical system. Nevertheless, high level of the aging technology and the acceleration of performance decay patterns indicate that the modernisation programs should consider support infrastructure such as maintenance systems, supply networks of spares, and technical experience building. With a quantified economic impact of 204.1 billion naira over a 24 months duration, which is 0.73 percent of national GDP, there is now strong enough justification to invest more heavily in the reliability of protection systems in the power sector investment strategies.

Severe environmental influences are reflected, and seasonality, temperature extremes, and other aspects of humidity lead to issues of protection system protection, reliability that is above what international experience would suggest. The results highlight the necessity of the vitality of climate-specifications equipment and environmental protection processes in power systems in the tropics. The assessment of the maintenance practice demonstrates the system-level gaps that need to be overhauled system-wide including the need to work on enhancing preventive maintenance programs, skills and improvement of supply chains. Although the recommended improvements will need a heavy initial investment, their implementation will have a high economic payoff resulting in lesser failed costs and enhanced reliability of the systems that are vital in economic development goals especially in the developing nations..

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