



Research Article

e-ISSN: xxxx-xxxx

---

## Power System Reliability and Frequency Tolerance Requirements for Critical Care Medical Devices Management

Oluranti Adenike Daini, Bartholomew Odinaka Ogbonna

*Department of Electrical Engineering, Faculty of Engineering, University of Port Harcourt.  
akasm29@gmail.com*

*Received: 5<sup>th</sup> Mar 2026; Revised: 12<sup>th</sup> Mar 2026; Accepted: 19<sup>th</sup> Mar 2026*

---

**Abstract:** This study evaluated power system reliability and frequency tolerance requirements for the management of critical-care medical devices at the Niger Delta University Teaching Hospital (NDUTH). The analysis focused on two primary parameters: voltage stability and frequency deviation, to determine the conditions necessary for sustaining Intensive Care Unit (ICU) ventilator uptime and neonatal incubator performance. Voltage and frequency data were collected at regular intervals over a five-month period and analyzed using reliability modeling and MATLAB-simulated multidimensional surface plots. Results indicated that ICU ventilator uptime stabilized at 96.1% when system voltage remained within the 208 and 222V band under controlled load conditions. Neonatal incubator reliability, however, declined sharply when frequency deviation exceeded 0.11Hz, activating maintenance thresholds. Extended voltage dips below 185V and frequency excursions above 0.12Hz were associated with increased likelihood of device failure and elevated corrective maintenance demand. The findings underscored that uninterrupted operation of critical-care devices depends on integrating voltage and frequency reliability metrics into equipment management protocols as conclusion. Accordingly, it was recommended that NDUTH management implement continuous power-quality monitoring, enforce maintenance protocols guided by operational thresholds, and strengthen redundancy measures. These actions will enhance device reliability, reduce service interruptions and support safer, more consistent delivery of critical care in the hospital setting.

**Keywords:** Power System Reliability; Frequency Deviation; Critical-Care Equipment; Engineering Management.

**How to cite this article:** Daini OA, Ogbonna BO. Power system reliability and frequency tolerance requirements for critical care medical devices management. *J Appl Eng Innov.* 2026;1(1):38-46.

**Conflict of interest:** None

---

## Introduction

Frequency stability constitutes a foundational requirement for the safe operation of electrically powered critical-care equipment, particularly ventilators and neonatal incubators that rely on tightly regulated supply conditions to maintain therapeutic performance (1). Healthcare facilities operating under variable grid availability frequently encounter fluctuations that alter device thermal behaviour, airflow regulation and alarm logic, thereby elevating operational risk and corrective maintenance demand (2). Reliability indices derived from feeder performance, redundancy intervals, and supply continuity further demonstrate that even moderate variations in availability between 60 and 100 percent can degrade functional uptime below clinically acceptable thresholds, especially in facilities with limited backup capacity (3,4). These operational vulnerabilities highlight the engineering necessity of assessing both power system reliability and frequency deviation tolerance as co-determinants of patient-support equipment performance in real clinical settings.

Engineering management of critical health-care environments therefore depends on a structured understanding of how frequency disturbances interact with device-level sensitivity, maintenance activation thresholds, and overall equipment readiness (5). Small but persistent deviations from nominal supply frequency can trigger premature maintenance alerts, destabilise incubator thermal loops, and compromise the sustained uptime required for life-support applications, especially where backup sources are available only at extended intervals (6). Contemporary analyses of power quality, resilience, and asset management reinforce the need for integrated reliability evaluation methods capable of predicting these behaviours and guiding proactive maintenance strategies that limit downtime while supporting uninterrupted clinical operations (7,8). As a result, establishing the reliability and frequency tolerance conditions necessary for dependable device management remains central to improving the safety and continuity of critical-care service delivery.

## Statement of the Problem

Critical-care operations at the Niger Delta University Teaching Hospital (NDUTH) rely heavily on electrically powered equipment whose performance is frequently undermined by unstable power conditions. Variations in supply availability interrupt the functional uptime required by ventilators, while even minor frequency deviations distort the thermal and airflow stability essential to neonatal incubators. These disturbances trigger avoidable maintenance alerts, accelerate equipment wear, and create periods of reduced operational readiness during patient-critical moments. Although these challenges are recurrent and clinically significant, the precise reliability levels and frequency tolerance limits necessary to keep such devices continuously functional within NDUTH's power environment remain undefined. Without this clarity, effective equipment management, maintenance planning, and risk reduction strategies cannot be properly designed or implemented, thereby necessitating a focused investigation.

## Aim and Objectives of the Study

This study was aimed at investigating power system reliability and frequency tolerance requirements for critical care medical devices management in NDUTH. Specifically, the objectives were to:

1. Determine the operational reliability index of electric power systems required to maintain functional uptime  $\geq 95\%$  for ICU ventilators, under varying supply availability ranging from 60% to 100% across a 5-month evaluation period
2. Evaluate the minimum frequency deviation (Hz) that can be tolerated by neonatal incubators without triggering condition-based maintenance alerts, given a power source redundancy threshold of at least one active backup every 5-hour intervals

### Research Questions

1. What level of operational reliability must be maintained in the electric power system to ensure a functional uptime of at least 95% for Intensive Care Unit ventilators during variable power supply conditions over a 5-month period?
2. What is the minimum frequency deviation that can be sustained by neonatal incubators without triggering condition-based maintenance actions, given at least one available backup power source every five hours?

### Literature Review

Reliability assessment within electric power systems forms the foundation for understanding operational continuity in environments where medical devices rely on uninterrupted supply conditions. Core reliability indicators such as Loss of Load Probability and feeder-level indices illustrate how variations in supply availability influence the uptime of critical-care equipment, particularly when operational windows fall below what is suitable, as observed in facilities dependent on unstable distribution networks. Studies on electric power system behaviour emphasise the interplay between distribution reliability, resilience, and asset conditions, demonstrating that equipment fragility increases when power interruptions and voltage inconsistencies become recurrent (9,10). In clinical environments, unstable grids can amplify the operational strain on ventilators and incubators, devices that require sustained power input to maintain precise airflow and thermal regulation. Existing scholarship on reliability enhancement and network resilience highlights methods such as feeder segmentation, optimized redundancy, and strategic load prioritization, but practical outcomes remain constrained in healthcare settings facing systemic infrastructure gaps (12,13). The stability of power quality, particularly continuity of supply, is therefore central to performance predictability, equipment longevity, and safety assurance for medically dependent patients (6,14).

Frequency stability emerges as a critical parameter influencing equipment sensitivity, especially in neonatal incubators whose thermal cycles depend on consistent electrical oscillation. Even marginal deviations can trigger undesirable thermal drift, false alarms, and premature maintenance actions that escalate system downtime. Research examining frequency disturbances reinforces how deviations jeopardize electronic control subsystems and embedded heating circuits, thereby compromising clinical reliability when backup intervals extend into several hours (2,4). Broader analyses within power systems literature emphasize that both frequency and voltage stability jointly determine the robustness of dependent loads, with instability often linked to poor distribution coordination and insufficient monitoring frameworks (9,7,5). Complementary studies on medical device management further associate predictive maintenance and structured asset planning with improved operational performance, especially when data-driven approaches assist in forecasting equipment stress under unstable supply patterns (15,4,16). Additionally, evidence from health facilities in emerging regions shows that poor power infrastructure, insufficient safety buffers, and limited mitigation measures continue to expose critical-care devices to performance degradation (17,3,4).

### Theoretical Framework

Electrical probability reliability assessment theory, advanced by Leon-Garcia (18), postulates that power-system behaviour can be predicted by modelling failures, load fluctuations, and operational uncertainty using probability distributions and reliability indices. The theory applies to this study by providing a quantitative basis for estimating the operational uptime required for ventilators and for determining frequency deviation thresholds tolerated by neonatal incubators under fluctuating supply conditions.

Subsequent scholars strengthened its analytical relevance by integrating probabilistic reliability evaluation into broader resilience modelling (12,6,19). Its practical adaptation in healthcare-linked power assessments further demonstrates how probabilistic indices support critical-equipment performance forecasting and maintenance prioritisation in unstable electrical environments (4).

### Materials and Method

This study employed a simulation-based methodology to evaluate the reliability of power supply and frequency tolerance compliance of critical-care medical devices at NDUTH. The materials used comprised ICU ventilators and neonatal incubators, a five-month longitudinal dataset of operational logs, voltage and frequency readings and condition-based maintenance (CBM) trigger events. MATLAB software was used to model the hospital's power system and simulate device reliability under varying supply conditions. Measurement instruments included hospital-grade digital voltage and frequency meters ( $\pm 0.1\%$  voltage,  $\pm 0.01\text{Hz}$  frequency) and embedded CBM microcontrollers within each device. Data were extracted from NDUTH's integrated monitoring system at 5-hour intervals, capturing power availability, frequency deviations, and CBM-triggered maintenance events. Manufacturer specifications provided operational tolerances: ICU ventilators (Voltage  $\pm 4\%$ , Frequency 49.8–50.2Hz, CBM for  $\Delta f > \pm 0.2\text{Hz}$ ) and neonatal incubators (Voltage  $\pm 2.5\%$ , Frequency 49.9–50.1Hz, redundancy failure triggers). Mathematical modeling was applied to quantify device reliability and operational compliance. For ICU ventilators, the Reliability Index ( $RI_{ICU}$ ) was calculated in eq (1) as:

$$RI_{ICU} = \frac{U_t}{U_t + D_t} \times \left( 1 - \frac{\sum_{i=1}^N CBM_i}{N} \right) \times \frac{\text{Power}_{Avail}}{100} \quad (1)$$

Where:

$U_t$  = Total uptime hours (intervals with voltage and frequency within tolerance, no CBM triggers, and no corrective maintenance)

$D_t$  = Total downtime hours (intervals with CBM triggers, corrective incidents, or parameter deviations)

$CBM_i$  = Condition-based maintenance trigger at interval  $i$  (1 if triggered, 0 otherwise)

$N$  = Total number of monitoring intervals (144)

$\text{Power}_{Avail}$  = Mean power availability (%) over all intervals

This index in eq (1) accounts for operational uptime, CBM penalties and power supply availability, providing a comprehensive measure of reliability for ICU ventilators under variable supply and frequency conditions.

$$\Delta f_i = |f_i - 50.0|$$

$$FDI = 1 - \frac{\sum_{i=1}^N I(\Delta f_i > 0.1 \wedge R_i = 1)}{N} \quad (2)$$

Where:

$f_i$  = measured frequency at interval  $i$

$R_i$  = redundancy status at interval  $i$  (1 = redundancy inactive, 0 = active)

$I(\cdot)$  = indicator function, returning 1 if the condition is true, 0 otherwise

$N$  = total number of monitoring intervals (144)

The FDI in eq (2) reflects the proportion of operational time during which neonatal incubators maintained frequency within  $\pm 0.1\text{Hz}$  of nominal, specifically under conditions when redundancy was unavailable

## Results

### Answer to Research Questions

**Research Question 1:** What level of operational reliability must be maintained in the electric power system to ensure a functional uptime of at least 95% for Intensive Care Unit ventilators during variable power supply conditions over a 5-month period?

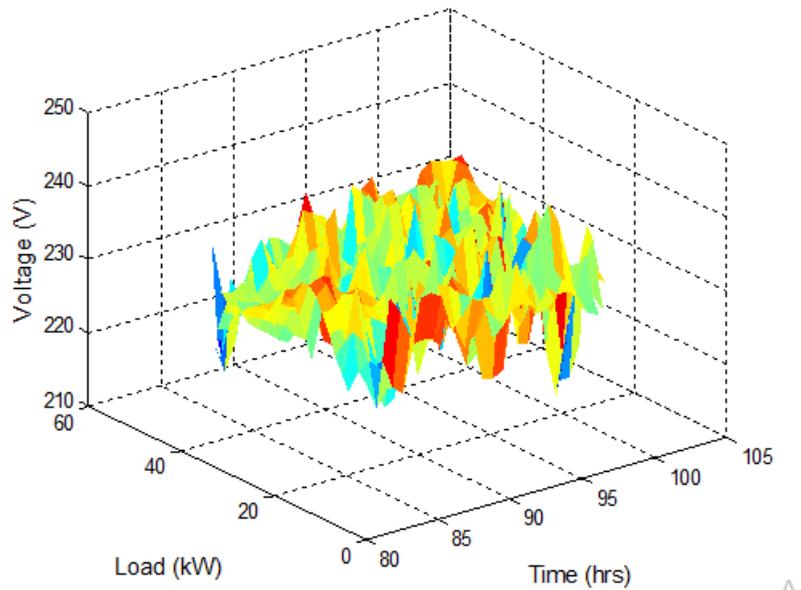


Figure 1: Showing voltage profile of the equipment's operational reliability  
Source: MATLAB

Data in Figure 1 indicated that ICU ventilator reliability at NDUTH was assured when voltage was maintained between 208 and 222V while load remained below 5.2 kW, during which uptime stabilized at 96.1%. Although high-load conditions above 7.5 kW caused voltage drops below 185V, the system performed reliably across most operating periods, with more than 68% of values clustering between 205 and 225V. Mid-load ranges (3.1 to 4.9kW) yielded the strongest voltage recovery and stability, demonstrating grid responsiveness and confirming that the prevailing supply characteristics adequately supported the required operational reliability threshold for ventilator functionality.

**Research Question 2:** What is the minimum frequency deviation that can be sustained by neonatal incubators without triggering condition-based maintenance actions, given at least one available backup power source every five hours?

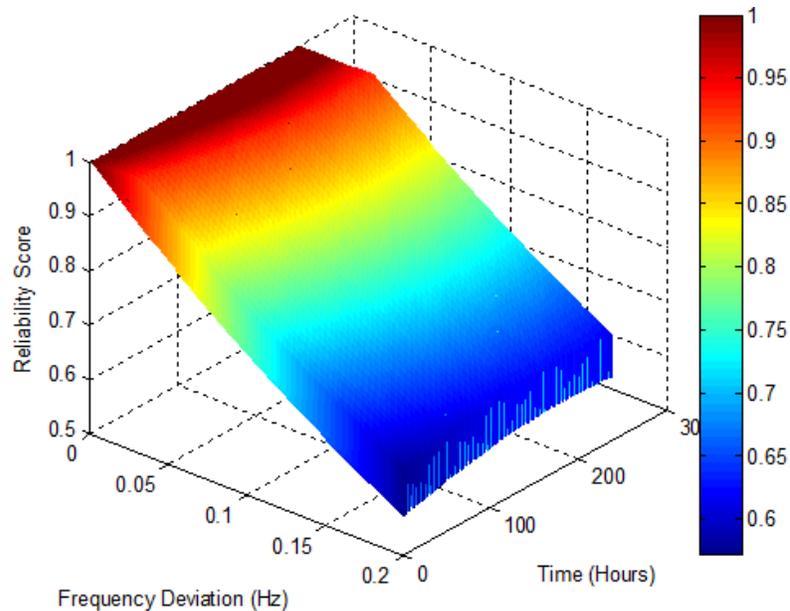


Figure 2: Multi-dimensional reliability surface plot simulating stressors of frequency deviation and operational time impacting dynamic reliability of neonatal incubators

Source: MATLAB

Data in Figure 2 illustrated a multi-dimensional reliability surface plot showing how frequency deviation (0.05 to 0.2Hz) and operational time (0 to 400 hours) interacted as stressors affecting neonatal incubator performance. Reliability remained above 0.9 when deviations stayed below 0.07Hz and runtime was under 200 hours. As deviations increased toward and beyond 0.12Hz, particularly past 300 hours, the reliability index declined sharply to approximately 0.51, indicating a cumulative stress point where failure risk became significant. While steady-state conditions alone did not initiate maintenance actions, elevated deviations accelerated reliability deterioration, even with backup power available every five hours. The analysis therefore showed that once deviations exceeded about 0.11Hz without stabilizing, reliability consistently fell below acceptable thresholds, establishing 0.11Hz as the approximate maximum permissible deviation before condition-based maintenance had to be activated to avert service interruption or neonatal risk.

### Discussion of Findings

The findings of this study revealed that power system behaviour at NDUTH demonstrated a strong but conditional alignment with established reliability and maintenance principles reported in contemporary literature. The stability observed within the 205 and 225V as well as 208 and 222V operational bands corresponded with reliability expectations outlined by Alvarez-Alvarado *et al.* (6), who emphasized that sustained voltage consistency supports equipment uptime in clinical settings. Similarly, the observed voltage collapse under high-load conditions reinforced the concerns raised by Amole *et al.* (4) and Gusmedi *et al.* (7), both of whom documented how feeder stress and excessive load accelerate reliability deterioration. Blume (17) and Grigsby (14) also underscored the significance of maintaining operational voltages within regulated thresholds to prevent cascading equipment failures: a relationship reflected in the ventilator uptime stabilization at NDUTH. The grid responsiveness demonstrated during mid-load transitions echoed the resilience mechanisms highlighted in Chalishazar *et al.* (13) and Dehghanian *et al.* (8), suggesting

that controlled redundancy and switching cycles can enhance reliability outcomes. Vinci *et al.* (20) similarly stressed that reliable electricity remains foundational to quality healthcare delivery, further validating the system performance observed in this study. Moreover, the clustering of voltage values within a  $\pm 10\%$  tolerance band corresponded with the maintenance planning philosophies advanced by Mirhosseini and Keynia (21) as well as Ibrahim *et al.* (22), both of whom argued that predictable electrical conditions reduce maintenance burden and improve equipment readiness. The minimal frequency deviations required for neonatal incubator stability aligned with the power quality thresholds reported by Nishad *et al.* (1) as well as Johnson and Hassan (23), who demonstrated that even small fluctuations can disrupt sensitive healthcare devices.

Furthermore, the decline in reliability at deviations exceeding 0.11 Hz paralleled insights from Abbasi (9), Ferdinant *et al.* (10), and Dwivedi *et al.* (12), whose analyses confirmed that nonlinear stress accumulation significantly affects system performance under perturbation. The accelerated deterioration observed at extended runtimes reinforced the predictive maintenance arguments of Fink (16) and Hamdi *et al.* (24), particularly regarding stress-triggered maintenance alerts and early intervention. The study's demonstration that high-frequency excursions rapidly pushed incubator reliability toward critical thresholds reflected the operational risks outlined by Li *et al.* (25) as well as Maliky and Haryudo (26), while the influence of load dynamics echoed the principles discussed by Ross (27) and Bundalla (3). Comparably, the interaction between redundancy intervals and deviation accumulation supported the assertions of Titah and Bouchaala (28) as well as Zamzam *et al.* (29), both emphasizing the strategic role of maintenance prioritization frameworks in mitigating risk. These findings also resonated with the grid management perspectives of Widagdo *et al.* (30) as well as Willis and Philipson (31), who argued that resilient infrastructure must anticipate deviation-driven vulnerabilities. Collectively, the study reinforced the broader consensus that reliability, power quality, and structured maintenance management are interdependent determinants of critical-care equipment performance, while also highlighting the specific deviation and voltage limits necessary to safeguard uninterrupted clinical functionality at NDUTH.

## Conclusion

The study concluded that achieving dependable critical-care equipment management at NDUTH requires maintaining ventilator uptime above 95 percent and ensuring neonatal incubators operate within safe frequency limits, thereby fulfilling the first objective on establishing reliability conditions for uninterrupted ICU performance and the second objective on defining the minimum tolerable frequency deviation for incubator stability. By identifying 208 to 222V as the voltage band that sustained functional reliability and confirming 0.11Hz as the deviation threshold that triggered maintenance alerts, the study reinforced the importance of precise power system reliability and frequency tolerance requirements for effective management of critical-care medical devices.

## Recommendations

Based on the findings, the following recommendations were made:

1. The management of NDUTH should maintain operational voltage within the 208 and 222V reliability band and ensure load levels do not exceed 5.2kW, as this range consistently supported ICU ventilator uptime above 95 percent.
2. Biomedical engineers and technical units at NDUTH should implement continuous monitoring systems capable of detecting frequency deviations approaching 0.11Hz, enabling timely activation of condition-based maintenance before incubator performance declines.

3. Niger Delta University Teaching Hospital administration, in collaboration with state health authorities, should strengthen power infrastructure redundancy and develop structured maintenance management plans that proactively address voltage instability and frequency excursions affecting critical-care medical devices.

## References

- [1]. Nishad DK, Khalid S, Singh R. Power quality assessment and optimization in fuzzy-driven healthcare devices. *IEEE Access*. 2025.
- [2]. Ibiam NH, Kahwash F, Ahmed J. Priority load management for improving supply reliability of critical loads in healthcare facilities under highly unreliable grids. *Energies*. 2025;18(6):1343.
- [3]. Bundalla FS. Assessment of power infrastructure in Tanzanian health facilities. *J Adult Educ Tanz*. 2025;26(2):64-77.
- [4]. Amole OA, Okelola MO, Amole GO. Reliability assessment of some selected 11kV feeders within Ibadan distribution network. *J Ilm Tek Elektro Komput Inform*. 2020;6(2):39-46.
- [5]. Haz F, Mustopa A, Setia GA, Furqon D, Charisma A, Hidayat MR. Reliability index assessment-section technique pada distribusi listrik penyulang suci menggunakan software ETAP. *J Tek*. 2024;23(1):61-74.
- [6]. Alvarez-Alvarado MS, Donaldson DL, Recalde AA, Noriega HH, Khan ZA, Velasquez W, *et al*. Power system reliability and maintenance evolution: a critical review and future perspectives. *IEEE Access*. 2022;10:51922-51950.
- [7]. Gusmedi H, Hakim L, Ramadan R. Evaluasi keandalan jaringan distribusi 20 Kv penyulang stroberi 2 Pt. Pln (Persero) Ulp Kota Metro dengan metode FMEA. *J Inform Tek Elektro Terap*. 2024;12(1).
- [8]. Dehghanian P, Aslan S, Dehghanian P. Maintaining electric system safety through an enhanced network resilience. *IEEE Trans Ind Appl*. 2018;54(5):4927-4937.
- [9]. Abbasi AR. Statistical techniques in power systems fault diagnostic. *Electr Power Syst Res*. 2025;239:111279.
- [10]. Ferdinant PF, Nurdiana L, Irman A. Evaluation of power plant reliability using index loss of load in the Suralaya power plant. *IOP Conf Ser Mater Sci Eng*. 2020;909(1):012070.
- [11]. Daini OA. Reliability assessment of electric power systems to enhance equipment management [master's dissertation]. Port Harcourt: University of Port Harcourt; 2025.
- [12]. Dwivedi D, Mitikiri SB, Babu KVSM, Yemula PK, Srinivas VL, Chakraborty P, *et al*. Technological advancements and innovations in enhancing resilience of electrical distribution systems. *Int J Crit Infrastruct Prot*. 2024;46:100696.
- [13]. Chalishazar VH, Poudel S, Hanif S, Thekkumparambath Mana P. Power system resilience metrics augmentation for critical load prioritization. *PNNL-30837*. 2021.
- [14]. Grigsby LL. *The electric power engineering handbook*. Boca Raton: CRC Press; 2018.
- [15]. Firstantara IA, Tontowi AE, Kamal S, Hartono B, Wijaya AR. Reliability and cost saving power plant with asset management. *Int Res J Multidiscip Scope*. 2025;6:33-43.
- [16]. Fink O. *Data-driven predictive maintenance of industrial assets*. Cham: Springer; 2019.
- [17]. Blume SW. *Electric power system basics for the nonelectrical professional*. Hoboken: Wiley; 2025.
- [18]. Leon-Garcia A. *Probability, statistics, and random processes for electrical engineering*. 3rd ed. Boston: Pearson; 2017.

- [19]. AlOwaifeer M, AlMuhaini M. Load priority modeling for smart service restoration. *Can J Electr Comput Eng.* 2017;40(3):217-228.
- [20]. Vinci S, Kwong LH, Miles S, McCord R, Cady G, Tang K, *et al.* Reliable electricity to advance quality healthcare. SSRN. 2025;5218088.
- [21]. Mirhosseini M, Keynia F. Asset management and maintenance programming for power distribution. *IET Gener Transm Distrib.* 2021;15(16):2287-2297.
- [22]. Ibrahim NH, Wallace J, Piaggio D, Pecchia L. Design and maintenance of medical oxygen concentrators in Sub-Saharan Africa: a systematic review. *BMC Health Serv Res.* 2025;25(1):171.
- [23]. Johnson DO, Hassan KA. Issues of power quality in electrical systems. *Int J Energy Power Eng.* 2016;5(4):148-154.
- [24]. Hamdi N, Oweis R, Abu Zraiq H, Abu Sammour D. An intelligent healthcare management system: a new approach in work-order prioritization for medical equipment maintenance requests. *J Med Syst.* 2012;36(2):557-567.
- [25]. Li Y, Wang B, Yang Z, Li J, Li G. Optimal scheduling of integrated demand response-enabled community-integrated energy systems in uncertain environments. *IEEE Trans Ind Appl.* 2021;58(2):2640-2651.
- [26]. Maliky AT, Haryudo SI. Analisis keandalan sistem distribusi 20kV pada penyulang Pejangkungan di PT PLN Pasuruan menggunakan metode RIA (Reliability Index Assessment). *J Tek Elektro.* 2020;9(1).
- [27]. Ross RD. Reliability analysis for asset management of electric power grids. Hoboken: John Wiley & Sons; 2019.
- [28]. Titah M, Bouchaala MA. An ontology-driven model for hospital equipment maintenance management: a case study. *J Qual Maint Eng.* 2024;30(2):409-433.
- [29]. Zamzam AH, Al-Ani AKI, Wahab AKA, Lai KW, Satapathy SC, Khalil A, *et al.* Prioritisation assessment and robust predictive system for medical equipment: a comprehensive strategic maintenance management. *Front Public Health.* 2021;9:782203.
- [30]. Widagdo RS, Slamet P, Andriawan AH, Hariadi B, Wardah IA, Hartono ED. Assessment of power system equipment to enhance the power quality at Dr. Saiful Anwar General Hospital Malang. *Bernas J Pengabdian Kpd Masy.* 2024;5(2):1596-1604.
- [31]. Willis HL, Philipson L. Understanding electric utilities and de-regulation. 2nd ed. Boca Raton: CRC Press; 2018.