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# Comparative Reliability Analysis of a Microgrid versus Zonal Nanogrids

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***Abstract*—Nanogrids are small-scale power distribution systems that can operate independently or integrated with the grid like microgrids. These nanogrids can interconnect in a network and have built-in redundancy. This paper investigates the potential of bringing zonal shipboard power ashore with zonal nanogrids to enhance energy reliability at industrial facilities which addresses the limitations of current microgrid systems and emergency backup generators. A reliability analysis is conducted by using the reliability block diagram method to compare microgrid and zonal nanogrid configurations with various control architectures to identify the most reliable solution. The two common types of control strategies are centralized and decentralized. The results indicate that decentralized zonal nanogrids offer higher reliability over a 14-day grid power outage. Furthermore, a sensitivity analysis is conducted to identify the most impactful component in the reliability of zonal nanogrids which is the power transmission lines and fiber optic cables.**

***Index Terms*—microgrid, zonal nanogrids, reliability analysis, reliability block diagrams, distributed energy resources, centralized control, decentralized control**

## I. Introduction

Energy reliability in critical facilities, such as hospitals and military installations, can be achieved using local power systems isolated from the utility grid and powered by emergency backup generators. These generators are not reliable due to required maintenance of refueling and they have about a 10% failure rate when they are needed for backup power [1]. Thus, this energy infrastructure has no redundancies if the local power system has a failure during a natural disaster and refueling is not an option for diesel generators. Nanogrids offer a flexible and reliable solution to enhance energy reliability at military installations. This approach draws inspiration from naval vessels such as DDG-1000 and LPD-17 which employ a zonal power distribution system. This zonal shipboard power concept can be adapted for shore bases as zonal nanogrids, which can enhance energy reliability.

Microgrids are systems comprising interconnected loads and distributed energy resources (DER) within defined electrical boundaries, functioning as a single controllable entity with respect to the grid [2]. They also have the ability to disconnect from the main grid and operate independently in island mode. Nanogrids are essentially smaller microgrids, typically providing power of between 10-500 kW compared to a microgrid's nominal range of 5-100 MW [3], [4]. A nanogrid is composed of distributed energy resources, energy storage, and a controller system, utilizing either AC or DC distribution. Like microgrids, nanogrids can disconnect and operate in island mode, and can connect to other nanogrids [5]. A network of interconnected nanogrids can form a microgrid [6]. These nanogrids can be arranged in a zonal bus structure similar to shipboard zonal power distribution systems.

On naval vessels, zonal power systems supply power to all onboard systems by dividing the network of loads into distinct zones. The zones are aligned with the physical bulkheads of the vessel. Each zone connects to one of two buses: port and starboard [7]. This design provides redundancy; in the event of a fault, the system isolates the affected zone and transfers its critical loads to the other bus, ensuring an uninterrupted power supply. Inspired by the enhanced energy reliability observed in ships using zonal distribution, this concept can be adapted for nanogrids as zonal nanogrids. In a zonal nanogrid configuration, each building or cluster of buildings has its own zonal nanogrid which is connected to neighboring zonal nanogrids. All zonal nanogrids are interconnected via a bus, which allows them to provide mutual support if one zonal nanogrid experiences a failure so that others can compensate by supplying power to the critical loads of the failed nanogrid, thereby maintaining energy reliability. The zonal nanogrid concept has proved to increase energy resilience [4]. Zonal nanogrids also can offer other advantages such as flexibility

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and scalability. They can be scaled up or down based on the community's energy needs and customized to meet specific requirements and local conditions. Implementing zonal nanogrids can potentially enhance energy reliability.

Currently, there is limited research on zonal nanogrid reliability and no comparative studies between the reliability of nanogrids and microgrids. However, there is nanogrid reliability research that used the Markov model and the metric loss of load expectation (LOLE) [8]. While studies on nanogrid reliability are scarce, numerous research efforts have utilized the reliability block diagram (RBD) method to analyze the reliability of microgrids [9]–[13]. Most of the reliability research did not incorporate control strategies, but Bani-Ahmed et al. [10] conducted a reliability analysis of a decentralized and centralized microgrid, integrated the RBD method with Markov Chain Modeling, while Julian et al. [14] pioneered reliability analysis of redundant controllers for power electronics.

The research presented in this paper utilizes the RBD method as it concentrates on the reliability of individual components that make up the zonal nanogrids. Markov Chain modeling is better suited for smaller systems, while the zonal nanogrids are more complex and contain more components than a microgrid. In [9], [13], they presented a hybrid approach by implementing the RBD method and the Fault Tree Analysis (FTA) method. The FTA method is not used in the research in this paper because it focuses on identifying the causes of system failures which is not the objective of this study. The RBD of the microgrid in [9] serves as a foundation for this research RBD modeling, but the number of components is different.

Much of the existing research lacks comparisons of control architectures and does not investigate the reliability of a group of zonal nanogrids against a microgrid. The research presented in this paper addresses these shortcomings by integrating various control architectures into the reliability analysis and compares the results of a single microgrid with multiple zonal nanogrids. The goal of this paper is to provide a reliability analysis that compares a microgrid against two zonal nanogrid configurations with each using different control strategies to determine the most reliable configuration for industrial facilities. The contributions of the paper are as follows:

- A framework of the reliability analysis for microgrids and zonal nanogrids
- Formulation of the RBD for the microgrid and zonal nanogrid systems

The paper is organized as follows: Section II describes the control strategies used for zonal nanogrids. Section III discusses the reliability and RBD theory. Section IV shows the reliability analysis method. Section V presents the method through a case study. Section VI draws conclusions and points the way for future work.

## II. Control Strategies

The successful implementation of zonal nanogrids relies on the effective use of controllers and control strategies to manage the power distribution and maintain stability. The controller plays a critical role in the zonal nanogrid or group of zonal nanogrids by coordinating the power production, distribution, and flow. It ensures efficient energy management by balancing supply and demand, optimizing energy storage, and integrating renewable energy sources [6]. Additionally, the controller monitors real-time data, adjusts settings to maintain stability, and communicates with other controllers to facilitate seamless energy transfer across different zones. There are broad studies on various control strategies, mostly categorized as centralized and decentralized microgrids [5], [6], [10], [15]. In the following sections we apply and adapt these control methods to zonal nanogrids.

### A. Centralized Control

In the centralized control method, a central controller manages the power flow for the zonal nanogrids and serves as the hub of the communication network, receiving information from various loads and DER [10]. Each DER has its local controller and feeds information directly to the central controller. This controller processes real-time data from energy generation sources, storage systems, and loads, including power consumption and production levels. These local controllers relay information to the central controller but they cannot communicate with each other or operate independently. One advantage of having a central controller is its ability to quickly and precisely connect with all DER and loads without external boundaries [5], [15]. However, the central control strategy requires a high bandwidth communication channel, which has the disadvantage that any faults in the communication link can lead to the failure of the entire grid and it can be quite expensive [15]. Having a single central controller creates a single point of failure in the system.

To implement the central control strategy in a group of zonal nanogrids, a central controller oversees all the zonal nanogrids. Each zonal nanogrid has its own controller, and there are local controllers for each DER and load, all connected via a high-bandwidth communications link. There are disadvantages to the central control strategy and they are addressed by an alternative control method known as decentralized control, which resolves these issues.

### B. Decentralized Control

For a decentralized control, the central controller is removed, allowing the local controllers more autonomy over their respective DERS or loads. Each local controller regulates the reference voltage and impacts the output current of the units [10]. In this control strategy, the local controllers do not communicate with their neighboring controllers. Another variant is distributed control where local controllers can exchange updates with each other and only require a low-bandwidth communication link [10]. Since local controllers can exchange status information with each other, they can assist one another with power sharing and voltage regulation. This control strategy can be implemented in the zonal nanogrids configuration. The central controller and the controllers for each zonal nanogrid are removed. The local controllers of the DER and loads have control over its unit. These two strategies are tested in the comparative reliability analysis of a single microgrid and zonal nanogrid configurations.

## III. Reliability Basics

Reliability can be defined as the probability that the system performs its required function successfully in a specific duration under certain operating conditions [16]. This research analyzes reliability through the failure rates of each component of the zonal nanogrids and microgrid by using Reliability Block Diagrams (RBD). The RBD method is a visual representation of the relationships between the system's components and can be used to calculate the overall system reliability.

Assuming that the component failure is exponentially distributed, the reliability equation is shown in (1), where $\lambda$ is the component's failure rate and $t$ is the time in hours. The equations to solve for reliability for a series and parallel connections in a RBD are shown in (2) and (3).

$$R(t) = e^{-\lambda t} \tag{1}$$

$$R = \prod_{i=1}^{C} R(i) \tag{2}$$

$$R = 1 - \prod_{i=1}^{C} (1 - R_i) \tag{3}$$

Failure rates are estimated in handbooks with historical data such as the Military Handbook Reliability Prediction of Electronic Equipment (MIL-HDBK-217). This military handbook is extensively used in the civilian sector, but its data is outdated regarding new technologies [17]. For the analysis presented in this paper we use failure rates gathered from recently published literature.

## IV. Reliability Analysis Method

The reliability function and RBD equations presented in the previous section are used to calculate the reliability of zonal nanogrids versus a single microgrid. The steps for the comparative reliability analysis are described here and summarized in Fig. 1.

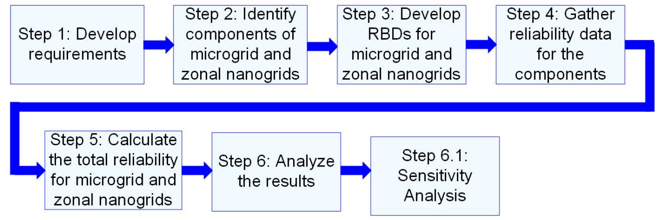


Fig. 1. Flowchart of Reliability Analysis

**Step 1: Develop requirements**. Requirements must be established to identify the constraints and clarify the objectives of the reliability analysis.

**Step 2: Identify components of the microgrid and zonal nanogrids**. Before developing RBDs, the components of the microgrid and zonal nanogrids needs to be identified. These local power systems also need to have the same components such as DER, backup generators, and controller systems. These systems also need to be using the same type of distribution, AC or DC. Diagrams are a useful tool to design the microgrid and zonal nanogrid configurations. Understanding the composition of these systems is important for analyzing their reliability and identifying the relationships necessary to construct the RBDs.

**Step 3: Develop RBDs for microgrid and zonal nanogrids**. The diagrams are used to identify the series and parallel connections of each component in the microgrid and zonal nanogrids. RBDs can be designed by hand or in commercial software tools.

**Step 4: Gather reliability data for the components**. Failure rate data can be found in manufacturer handbooks, industry databases, and academic literature. Once the failure rates are collected, they can be used to solve for the reliabilities of the microgrid and zonal nanogrids.

**Step 5: Calculate the total reliability for the microgrid and zonal nanogrids**. The reliability principles are applied to calculate the total reliability for the electrical power system configurations.

**Step 6: Analyze the results**. Observations are drawn and conclusions are formulated.

**Step 6.1: Sensitivity Analysis**. Conduct an analysis to observe which system component has the most influence on the system reliability by altering the failure rate of individual components and keeping the rest the same.

## V. Case Study

This paper investigates the potential of zonal nanogrids to enhance energy reliability at industrial facilities through a case study of a hypothetical scenario. In this scenario, the main grid of an industrial facility fails, and the zonal nanogrids must supply power to all critical loads for 14 days until the main grid is restored [18]. The facility's main grid is connected to three interconnected zonal nanogrids, each serving different zones of the facility. Reliability is assessed for both single microgrid and two zonal nanogrid configurations, utilizing either centralized or decentralized control strategies. The success criteria for the zonal nanogrids is at least one zonal nanogrid is up and providing power to the critical loads. The success criteria for the microgrid is for the whole system must be up and providing power.

### A. *Step 1: Develop Requirements*

The top-level requirement was to compare the reliability of different local power system architectures to identify the most reliable and effective energy solution for industrial facilities. The other requirements were:

1) Analyze the reliability of the microgrid and zonal nanogrid's internal components.
2) Define specific reliability metrics such as mean time between failure (MTBF), availability, and failure rates.

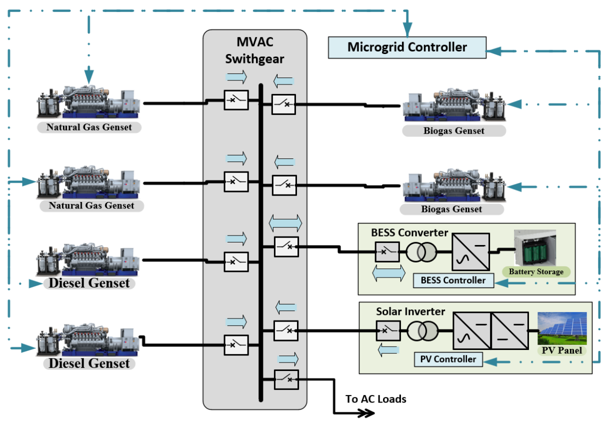


Fig. 2. Centralized Microgrid

3) Compare the different control strategies within the microgrid or zonal nanogrids.

*B. Step 2: Identify components of the microgrid and zonal nanogrids*

Designing the RBDs for the microgrid and zonal nanogrids required identifying their key components and connections from available literature. Typical devices included natural gas, biogas, and diesel generators, solar panels, battery storage, and controllers along with other components such as converters, inverters, circuit breakers, switchgears, transmission power lines, and transformers. Another component that was considered in this analysis is the communication system which includes network switches and fiber optic cables. The controller system is divided into its individual components, including the CPU, chassis, power supply, ethernet/IP module, and analog I/O module. The microgrid and zonal nanogrids are assumed to be using AC power.

Two diagrams were created outlining the connections in a microgrid and a zonal nanogrid configuration. For the two diagrams, the microgrid and zonal nanogrids are both using the centralized control strategy and are shown in Fig. 2 and Fig. 3, respectively. The zonal nanogrids configurations use the same components as the microgrid. The decentralized zonal nanogrids has the central controllers removed and the controllers for DER remain. These diagrams are used as a guide to develop the RBDs.

*C. Step 3: Develop RBDs for microgrid and zonal nanogrids*

The RBDs were built on a commercial software called Relyence by using the diagrams of the microgrid and zonal nanogrids mentioned earlier. RBDs for subsystems were made for the controller, gensets, battery and PV systems are shown in Fig. 4. These form building blocks used in RBDs for the microgrid, and zonal nanogrid comparisons. The controller RBD consists of components listed in Section V-B. The gensets are in a cold standby redundancy configuration where two gensets connect to the AC bus in parallel. One out of the two gensets are required for the subsystem to operate. Automatic transfer switches (ATS) and circuit breakers are added where necessary to the genset's subsystem (Fig. 4b). The RBDs for the PV system and battery energy storage systems (BESS) include DC/DC converter and DC/AC inverters, interfacing transformers and breakers, and local controllers (Fig. 4c). The RBD subsystems are highlighted in green when used in higher-level RBDs.

The microgrid RBD is shown in Fig. 5. The central controller, medium voltage switchgear, power lines, fiber optic cable, and network switch are arranged in series at the start of the RBD. Then, the different DERs are connected in parallel. The load center was not considered in the RBDs.

The next two RBDs to be developed are the zonal nanogrid configurations which use a centralized and decentralized strategy, respectively. These RBDs have the same parallel and series connections as the microgrid's RBD for its power generation sources. The zonal nanogrids are arranged in parallel to ensure redundancy and satisfy the success criteria. The centralized zonal nanogrids have one central controller and then each zonal nanogrid has its own controller, and each solar panel and battery storage has a local controller. The decentralized zonal nanogrid architecture has local controllers for each solar panel and battery storage and the central controllers are removed. There are network switches attached to each zonal nanogrid which are connected to a primary network switch. The power line and fiber optic cable are arranged in series with the primary network switch similar to the microgrid RBD. The RBD for the centralized zonal nanogrids is shown in Fig. 6 and the RBD for the decentralized zonal nanogrids is shown in Fig. 7.

*D. Step 4: Gather reliability data for the components*

Failure rate data is gathered from handbooks such as the IEEE-493, as well as academic literature. The power ratings for each of the power generation sources are 2 MW PV panel, 320 kWh lithium battery storage, 1.5 MW diesel generator, 1.5 MW natural gas generator, and 1.5 MW biogas generator. Several assumptions are made regarding the component failure rates. The type of generator is assumed the same for both natural gas and biogas, so the failure rates are identical. Additionally, it is assumed that the microgrid and zonal nanogrids utilize the same components, resulting in the using the same failure rates in the reliability calculations. Each component's failure rate and its sources are shown in Table I.

The total length of the power lines and fiber optic cables needs to be considered in the failure rates. The reliability of the system can be impacted by the length of the power lines and communication cables, as the transmission of power and data over long distances introduces potential vulnerabilities. A microgrid can cover a large geographic area; numerous power lines and fiber optic cables interconnect each energy generation source and load across the industrial facility. Assuming the industrial facility spans approximately 6-10 km, the power lines and fiber optic cables are assumed to extend 9 km. The failure rate for the power lines and fiber optic cables

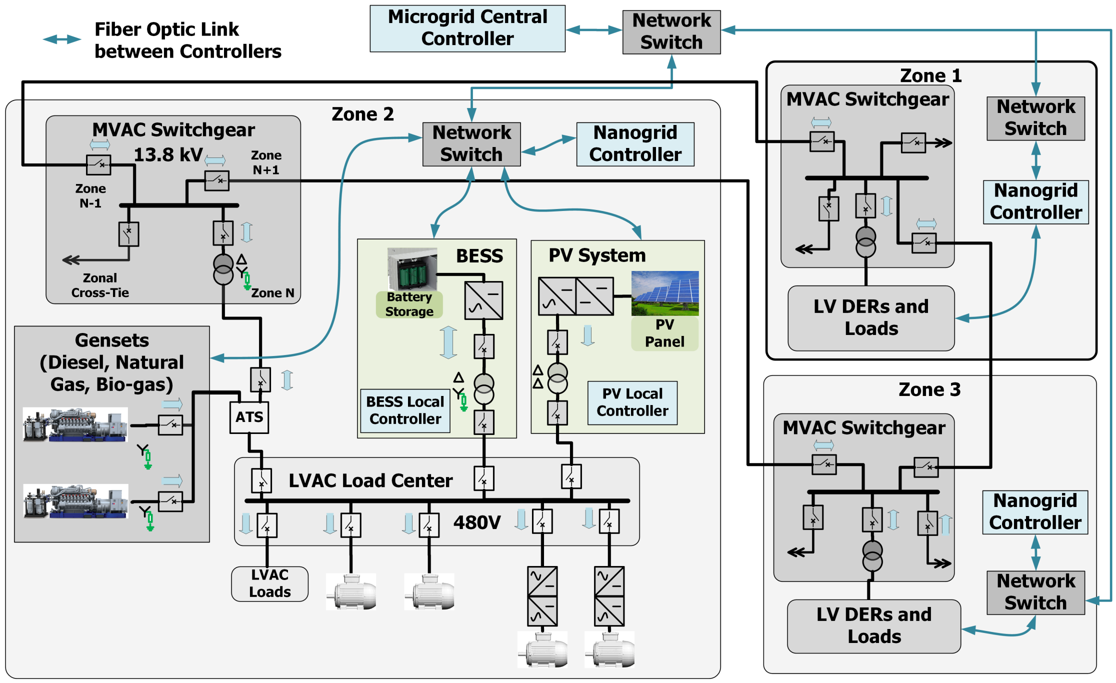


Fig. 3. Three Zonal nanogrids connected in ring structure.

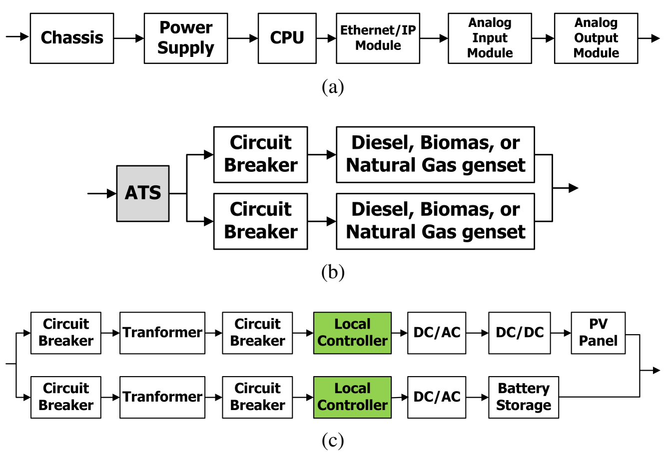


Fig. 4. RBD subsystems: (a) controller, (b) gensets, (c) battery and PV systems. The ATS in (b) is present in the nanogrid RBDs, but not the centralized microgrid RBD.

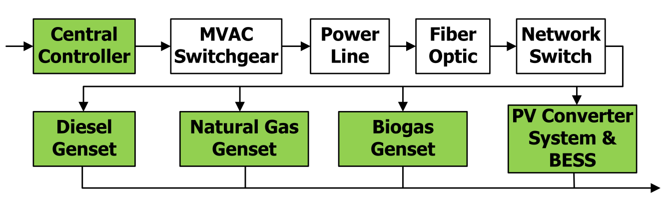


Fig. 5. RBD for the Centralized Microgrid.

is multiplied by this length, resulting in new failure rates of 93.51 failures per million hours for power lines and 4.1094 failures per million hours for fiber optic cables.

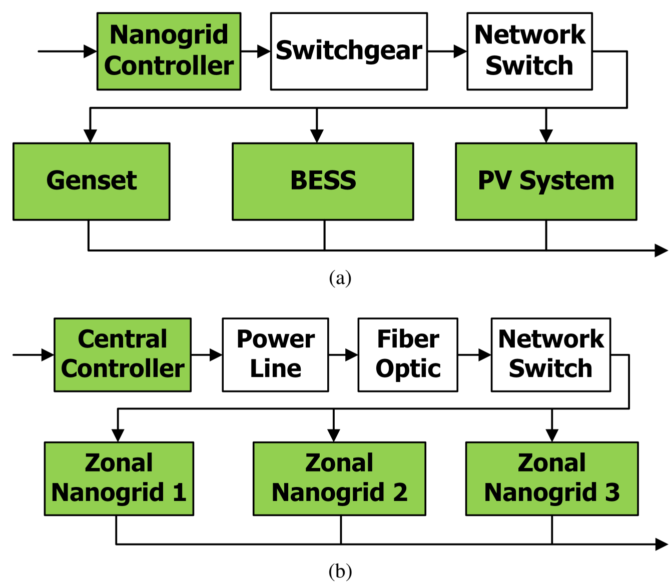


Fig. 6. RBD for centralized zonal nanogrids: (a) an individual zonal nanogrid, (b) the three zonal nanogrid system.

Failure rate calculations are performed again for zonal nanogrids; however, this configuration would use a shorter amount of fiber optic cables and power lines than the microgrid. The assumed length of power lines and fiber optic cables for each zonal nanogrid is 500 m, resulting in a total of 1.5 km for all three zonal nanogrids. The new failure rates for power lines is 15.585 failures per million hours and 0.6849 failures per million hours.

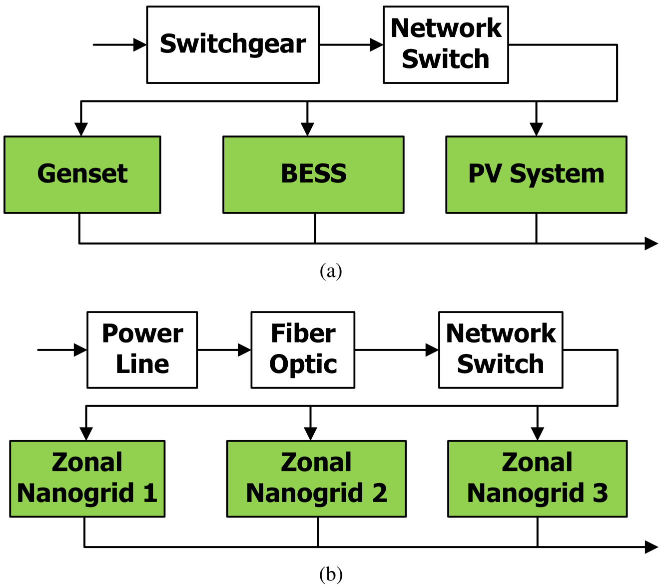


Fig. 7. RBD for decentralized zonal nanogrids: (a) an individual zonal nanogrid, (b) the three zonal nanogrid system.

TABLE I
COMPONENT FAILURE RATES

| Component | Failure Rate (failures/10ˆ6 hours) | Source |
|---|---|---|
| PV Panel | 4.56 | [19], [20] |
| Lithium Battery Storage | 5.1 | [21] |
| Diesel Generator | 1833 | [22] |
| DC/DC | 1.79 | [23] |
| DC/AC | 20.7 | [24] |
| Circuit Breaker | 1.32 | [25] |
| Transformer | 0.324 | [26] |
| Automatic Transfer Switch | 9.79 | [26] |
| Natural Gas Generator | 176 | [27] |
| Biogas Generator | 176 | [27] |
| Switchgear | 1.1632 | [26] |
| Power Line (1 km) | 10.39 | [28] |
| Fiber Optic (1 km) | 0.4566 | [28] |
| Network Switch | 2.28 | [28] |
| CPU | 2.86 | [29] |
| Chassis | 0.0362 | [29] |
| Power Supply | 0.0535 | [29] |
| Ethernet/IP Module | 0.27 | [29] |
| Analog Input Module | 0.943 | [29] |
| Analog Output Module | 1.03 | [29] |

### *E. Step 5: Calculate the total reliability for the microgrid and zonal nanogrids*

The system component failure rates obtained in the previous step were used to calculate the reliability of the microgrid and zonal nanogrid configurations using the principles of RBD and the Relyence software. A period of 14 days, or 336 hours, after a main grid outage was simulated as previously described. The reliability results for the centralized microgrid, centralized zonal nanogrids, and decentralized zonal nanogrids were: 0.964928, 0.992054, and 0.993787, respectively. Fig. 8 plots each system's reliability across the 14-day period.

### *F. Step 6: Analyze the results*

The results show decentralized zonal nanogrids exhibit the highest reliability among all grid configurations over a 14-day period, albeit by a narrow margin. As shown in Fig. 8, zonal nanogrids demonstrate higher reliability over time compared to a microgrid due to their increased redundancy. Also, the absence of the central controllers in a decentralized strategy give higher reliability as the single point of failure is removed. The reliability of the microgrid declines more rapidly over time compared to that of the zonal nanogrids. The RBDs show that diesel generators have the lowest reliability, which could mean it impacted the whole system's reliability. The length of the power lines and fiber optic cable has impacted the reliability of all grid configurations due to its higher failure rate. The results reveal that the longer the conduits, the lower the reliability of the microgrid. This finding highlights the advantage of implementing zonal nanogrids, which use shorter segments of power lines and fiber optic cables, thus enhancing reliability. Additionally, examining the outcomes suggests the importance of evaluating how variations in the failure rates of individual components affect the system's overall reliability. Conducting a sensitivity analysis could offer critical insights into zonal nanogrids' robustness and inform optimization strategies.

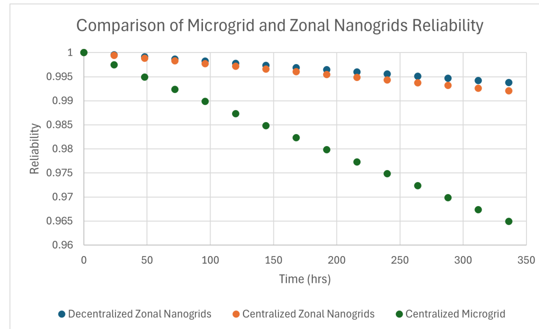


Fig. 8. Reliability Results

### *G. Step 6.1: Sensitivity Analysis*

This analysis is performed for the two zonal nanogrid configurations as this power system is the main focus of this research. The failure rates of each component are altered by +/- 25% up to 200% while the other components remain the same in the RBD analysis. The reliability calculations are calculated in the Relyence software and the results for centralized zonal nanogrids and decentralized zonal nanogrids are plotted in Figs. 9 and 10, respectively.

The components depicted in Figs. 9 and 10 have a significant impact on reliability, whereas the other components show a negligible effect. Upon examining the outcomes, it is evident that power lines significantly influence the reliability of both zonal nanogrid configurations. In the sensitivity analysis of centralized zonal nanogrids, the primary controller stands out as the second most impactful factor affecting system reliability. When the zonal nanogrids operate in island mode, power lines, central controller and fiber optic cables act as the single points of failure. Therefore, enhancing the reliability of these

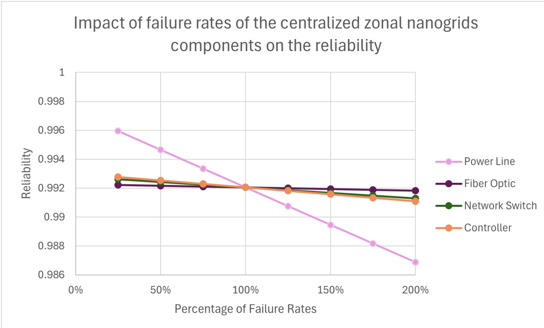


Fig. 9. Sensitivity analysis results of centralized zonal nanogrids

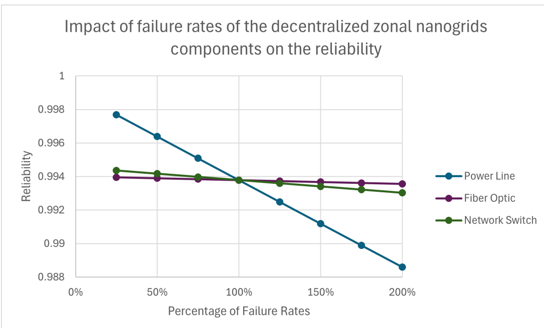


Fig. 10. Sensitivity analysis results of decentralized zonal nanogrids

components is essential to ensure a sustained power supply during main grid failures. Efforts to strengthen the reliability of these components are crucial for the overall reliability enhancement of zonal nanogrid systems.

## VI. Conclusions and Future work

This paper presents a comparative reliability analysis of different microgrid and zonal nanogrid architectures. The results show that decentralized zonal nanogrids have a marginally higher reliability than the other configurations. The advantage of employing zonal nanogrids lies in their built-in redundancy which provides a critical fallback in scenarios where a microgrid might fail without an alternate power source. Also, the length of the power lines and fiber optic cable has a significant impact on the reliability of the grid systems which shows shorter conduits equal higher reliability.

This research demonstrates that the new zonal nanogrid architecture has the potential to deliver reliable energy to critical loads and provides the capability to manage power locally. Facilities can scale down from a large microgrid to a network of zonal nanogrids, allowing them to prioritize critical loads during a power outage and achieve faster recovery from failures. This research also provides a reliability method that is useful in identifying reliable components to design zonal nanogrid power systems.

Future work opportunities include the identification of more accurate failure rates, possibly from the component manufacturers and adding the maintainability analysis. Also, validating these results with a hardware or control hardware-in-the-loop experiments will give additional support to the results presented in this paper.

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