# On Improving Reliability of Shipboard Power System

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***Abstract*—Distribution system reliability, defined by the expected frequency and duration of load service interruptions caused by component failures, is shown to be dependent on the topology of the distribution network, as well as on the relative placement of loads and generators within the system. In a shipboard electrical distribution system, a network topology based on the breaker-and-a-half scheme is shown to confer greater reliability than equivalent distribution topologies based on the ring bus and double bus, double breaker designs. The overall service interruption rate in the breaker-and-a-half topology is 17.8% less than that in the ring bus topology and 40.0% less than that in the double bus, double breaker topology. Further, an optimized equipment placement configuration is algorithmically identified for the loads and generators within the breaker-and-a-half distribution network, further increasing reliability. The optimal equipment placement decreases the overall system interruption rate by 0.54%. The paper also determines an optimal location for additional in-feeds that should be connected to the ship's most critical loads so that maximum benefits to service reliability are obtained.**

***Index Terms*—Power distribution, power system reliability, shipboard power system.**

## I. Introduction

IN an electric naval vessel, the proper functioning of equipment loads, such as radar, weapons, and propulsion motors, is of paramount importance to both mission success and personnel wellbeing. One key component to ensuring continuity of service for a ship's equipment is the shipboard electrical distribution system. A failure of the distribution system can result in vital equipment being left without power until repairs can be performed, potentially posing serious threats to the crew and to the mission. Therefore, it is necessary to ensure that shipboard electrical distribution systems are designed to be as robust as possible in order to minimize the frequency of service interruptions.

During peacetime operations, service interruptions are most often caused by failures of individual components within the distribution system. The probability that service to an equipment load might be interrupted depends upon two factors: the overall topology of the distribution system and the relative placement of loads and generation units within the system. Previous work has been performed to establish metrics for calculating peacetime quality of service (QOS) in shipboard power distribution systems (SPS) [1]. This QOS metric has been applied to shipboard power system design with primary focus on equipment design choices such as generator size and control interfaces [2], [3]. The approach to quantify distribution system reliability as a function of system topology has also been explored in the context of terrestrial power systems [4]–[6].

This work evaluates system reliability from the perspective of the overall distribution network topology, that is, the relationship between the reliability of a distribution circuit and the high-level topology of its connections. The method is specifically applied to the distribution system of an electric naval vessel, but the approaches described here can apply to most small-scale distribution systems, such as substations or microgrids. Notional shipboard distribution systems based on the ring bus and breaker-and-a-half (BAAH) topologies found in terrestrial utility substations have been previously evaluated for reliability [6]. Additionally, a distribution system based on the double bus, double breaker (DBDB) design is added to the evaluation in this work. It is concluded that, although DBDB contains more circuit breakers, BAAH topology outperforms both DBDB and ring bus topologies.

Another way of improving SPS reliability is by optimally placing the equipment loads within a given ship-board distribution topology. Therefore, having established the BAAH topology as superior, the work is extended to understand the relationship between system reliability and the relative placement of equipment loads and generators within a given SPS laid out in BAAH topology. In literature, the reliability gains obtained by optimally placing the equipment loads within a given SPS topology has not been widely studied. Instead, system reconfiguration problems, which aim to reconfigure the power path in a SPS to serve the critical loads in an event of fault or damage, have been extensively studied [7]–[11]. For example, [7] proposes a multi-agent system (MAS) to reconfigure the ship's electric propulsion system in an event of fault. In [8], the SPS reconfiguration problem is formulated as a network flow problem in order to restore service to unfaulted sections of the system. An equipment placement problem is different from the system reconfiguration problem, as the latter is concerned with finding an optimal power path for a given SPS topology and equipment placement configuration.

The paper proposes an algorithm based on particle swarm optimization (PSO) to obtain an optimal equipment arrangement in a given SPS topology which will confer the highest level of system reliability, i.e., the smallest overall service interruption rate. The proposed algorithm simulates several candidate solutions, each candidate solution representing a particular equipment configuration. Next, the algorithm updates each candidate configuration, according to the candidate best and the global best solutions. The algorithm eventually converges to the global

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optimized solution, representing the optimal equipment configuration.

The proposed algorithm is implemented for BAAH topology and the results confirm that the proposed algorithm is able to improve the service reliability indices for the ship-board power system. However, the improvement in the system reliability indices due to optimal equipment placement are not very significant, implying that the base case SPS in BAAH topology was close to optimal to begin with. Furthermore, the paper also aims to improve the service reliability of a critical load, e.g., a pulsed load, by providing an additional in-feed to it. The optimal location for the additional in-feed to which the pulsed load should be connected, is also determined. The results conclude that, on providing only one additional in-feed to the critical load, the overall system interruption rate decreases by 37.5%.

## II. Reliability Calculation Method

### A. Reliability Concepts

Reliability analysis is, in general, the evaluation of how often systems or pieces of equipment are expected to fail, and how long such a failure is expected to persist before being repaired and returning to service. In the context of distribution systems, reliability is split into two related concepts: component reliability and system reliability.

*1) Component Reliability:* Component reliability analysis assesses the expected frequency and duration of physical failures of distribution system components, such as circuit breakers, buses, and power converters. In this study, component failures are grouped into three types: passive failures, active failures, and stuck breakers. Passive failures cause the failed component to act as an open circuit, preventing power from flowing through the component. Active failures disable the failed component and cause all adjacent circuit breakers to trip and isolate the fault. A stuck breaker fails to isolate a fault.

*2) System Reliability:* System reliability analysis assesses the expected frequency and duration of service interruptions, caused by component failures, to equipment loads served by the distribution system. Here, a service interruption to an equipment load is defined as the load being electrically isolated from all generation units. A shipboard distribution system serves five equipment systems: propulsion, energy storage, radar, pulsed loads (e.g., weapons systems), and zonal load centers (encompassing lighting, refrigeration, etc.). The reliability of each equipment system is evaluated separately.

### B. Component Reliability Indices

Component reliability is quantified through two indices: failure rate $(\lambda)$ and mean time to repair (MTTR). The failure rate is defined as the expected number of failures a given component will experience over the course of one year. The MTTR is defined as the expected length of time, in hours, that the component failure will persist before it is repaired. The inverse of MTTR is called the repair rate, denoted $\pi$. With the exception of stuck breakers, which by definition must occur as the result of an adjacent active failure, component failures are assumed independent of one another. The values for the component failure reliability indices used in this analysis are shown in Table I, taken either from manufacturer data or from independent testing [13]–[15]. Note that the failure rate of stuck breaker failures is modeled differently than other failures. This is explained in further detail in Section II-C.

TABLE I
Component Failure Reliability Indices

| Component Failure | λ (failures per year) | MTTR (hours) |
|---|---|---|
| Circuit Breaker – Passive | 0.01 | 4 |
| Circuit Breaker – Active | 0.01 | 4 |
| Bus – Active | 0.01 | 8 |
| Converter – Passive | 0.006 | 1 |
| Converter – Active | 0.006 | 1 |
| Circuit Breaker – Stuck | 5% | 1 |

### C. System Reliability Indices

Equipment system reliability is quantified through two indices: the service interruption rate, denoted $\mu$, and the system MTTR. The service interruption rate is defined as the expected number of service interruptions that the equipment system will experience due to component failures over the course of a year. The system MTTR is defined as the expected number of hours that a service interruption will persist before service is restored through repairs to failed components. A third index, total expected downtime, is the product of the interruption rate and MTTR, defined as the expected number of hours per year that the equipment system will spend in an interrupted state.

The calculation of the system reliability indices for each equipment load is accomplished using a two-part process. First, fault-tree analysis is used to identify a complete list of interruption scenarios for a given equipment load [12]. Here, an interruption scenario is a minimal set of one or more concurrent component failures that disconnects the equipment load from all generators. The number of individual component failures involved in an interruption scenario is called the scenario's order. Interruption scenarios up to second-order are considered, as third- and higher-order failures are exceptionally rare and therefore do not greatly affect reliability indices [4], [5].

Next, reliability indices are derived for the equipment load using Markov models [12]. The load's reliability indices are derived from the component reliability indices ($\lambda$ and MTTR) shown in Table I. Each interruption scenario is simulated in a Markov model, with each state of the model representing a combination of working and failed components. Through each scenario's Markov model, equations used for calculating scenario interruption rates and MTTRs are derived. A more detailed derivation of these equations can be found in [6].

For example, for a first-order interruption scenario involving a component failure with failure rate $\lambda$ and repair rate $\pi$, $\mu_{\text{scenario}}$ and $\text{MTTR}_{\text{scenario}}$ are calculated as follows:

$$\mu_{scenario} = \lambda \quad (1)$$
$$MTTR_{scenario} = \pi^{-1}. \quad (2)$$

Note that $\mu_{\text{scenario}}$ and $\text{MTTR}_{\text{scenario}}$ in (1) and (2) represent reliability indices for any first-order interruption scenario.

Similarly, for a second-order interruption scenario involving two component failures, neither of which is a stuck breaker failure, with failure rates $\lambda_1$ and $\lambda_2$ and repair rates