A DIFFERENTIATED RELIABILITY MODEL FOR INDUSTRIAL POWER SUPPLY SYSTEMS CONSIDERING THREE TYPES OF EQUIPMENT FAILURES

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Abstract

The reliability of power supply systems is a critical factor influencing the operational continuity and safety of industrial enterprises. Conventional reliability assessments often treat all failures uniformly, neglecting the unique characteristics of failure mechanisms such as short circuits, open circuits, and non-actuation of protection devices. This paper proposes a differentiated reliability evaluation model based on non-stationary failure rate functions that reflect the time-dependent nature of each failure type. Using a piecewise failure rate model across three operational phases—burn-in, steady-state, and aging—the methodology accounts for individual failure flows and their cumulative impact on system reliability. A numerical case study demonstrates the application of the model to a transformer, showing a more accurate prediction of failure-free probability compared to traditional models. The results confirm that short circuits dominate risk during aging, while non-actuation and open circuits also contribute significantly. The model enhances diagnostic precision, supports targeted maintenance planning, and can be extended to system-level reliability assessment for complex industrial energy infrastructures.

Keywords: industrial power supply systems; reliability modeling; short circuits; open circuits; protection failure; non-stationary failure rate; differentiated failure flows; preventive maintenance

I. Introduction

The reliability of power supply systems is a fundamental indicator of the resilience and safety of industrial enterprises. According to ISO 14224 and GOST 27.002–2015, reliability is defined as the ability of a system or component to perform its required functions under stated conditions for a specified period of time.

In the context of increasing energy demands, digital control, and stricter continuity requirements (as defined by ISO 55000 and EN 50160), the role of reliability becomes even more critical. In energy-intensive industries such as metallurgy, petrochemicals, and heavy manufacturing, even a short-term power interruption can result in production downtime, equipment damage, or process disruption [1-3].

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Traditional reliability assessments use general indicators such as:
– probability of failure-free operation P(t),
– mean time between failures (MTBF),
– availability factor Kg,
– failure rate λ(t) [1,2].

However, most models treat all failures uniformly, without accounting for the underlying failure mechanisms. In practice, three major types of failures occur in industrial power systems:

1. Short circuits (SC) – sudden overcurrent events leading to immediate disconnection and potential equipment destruction.
2. Open circuits (OC) – typically caused by conductor breakage or terminal degradation, disrupting the flow of power.
3. Malfunctions or equipment non-response (ENR) – failure of automatic circuit breakers or protection devices to activate under fault conditions.

Figure 1 illustrates a typical industrial power supply scheme, indicating critical nodes and the most probable locations for each type of failure.

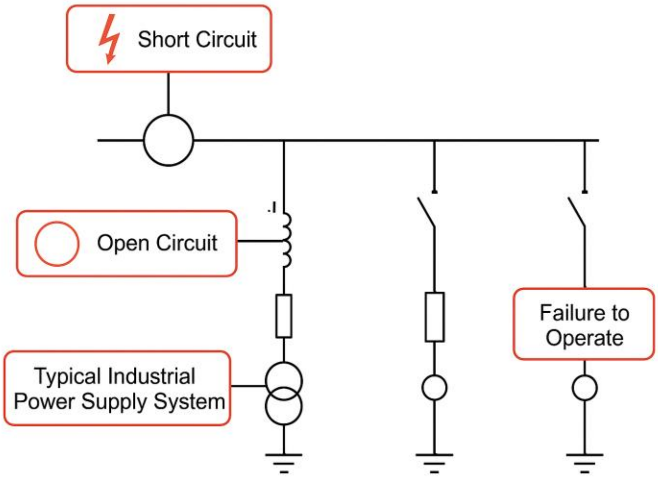

Figure 1. *Typical layout of an industrial power supply system, annotated with locations of three main types of failures: short circuit, open circuit, and equipment malfunction.*

Ignoring the nature and probability of each failure type often results in an inaccurate reliability forecast and may lead to inefficient maintenance or protection strategies. While current standards such as IEC 60300 and local regulations (e.g., SP 256.1325800.2016) require reliability assessment, they rarely mandate differentiation by failure type [4].

The objective of this paper is to develop a comprehensive reliability evaluation model that incorporates three distinct failure types. The proposed model enhances accuracy and provides more realistic diagnostics for system design, modernization, and risk mitigation planning.

II. Problem statement

Modern industrial power supply systems are characterized by high structural complexity and strict requirements for uninterrupted operation. Accurate reliability assessment is essential at all levels—from individual components to the overall network. One of the key aspects of such analysis is the proper classification of failures, accounting for their nature, dynamics, and impact on system behavior.

In practice, failures in power systems differ significantly in their physical origin and functional consequences. The most common types include:

- Short circuits (SC) – sudden insulation breakdowns accompanied by fault currents, resulting in the immediate disconnection of affected components by protection systems.
- Open-circuit faults – caused by mechanical wear, thermal degradation, or connector failure, these lead to power interruption without necessarily triggering protective devices.
- Failure to operate (non-actuation) – malfunctions of protective or switching devices that fail to respond under abnormal or emergency conditions.

Each of these failure types exhibits distinct statistical characteristics and impacts system reliability in different ways. For example, short circuits typically occur in aging power transformers, while open-circuit faults are more prevalent in overhead lines, and non-actuation failures often affect complex control and protection devices [5-7]. Therefore, using a generalized failure representation, as in many conventional models, does not reflect the true reliability behavior of industrial power systems.

To accurately represent the failure process, the authors propose a three-phase model of failure rate variation over time:

$$\lambda(t) = \begin{cases} \lambda_1, 0 \le t < T_1 & (burn - in\ phase) \\ \lambda_2, T_1 \le t < T_2 & (normal\ operation) \\ \lambda_3, t \ge T_2 & (aging\ phase) \end{cases}$$

This time-dependent, non-stationary model enables more accurate predictions of failure likelihood across an asset's life cycle. Each failure type (SC, open circuit, non-actuation) is represented by a separate failure flow $\lambda_i(t)$, reflecting its unique behavior and operational risk.

However, traditional reliability assessment models often ignore such distinctions and use a single aggregated failure rate λ, typically assuming a constant hazard function. This simplification introduces significant limitations:

- Underestimation of critical failure probabilities, such as the increased likelihood of short circuits in aging transformers;
- Incorrect prioritization of maintenance resources, where components with low failure risk are overserved while vulnerable nodes remain unprotected;
- Improper redundancy allocation, based on averaged reliability indicators rather than failure-specific analysis;
- Neglect of hidden or latent failures, especially in protective relay systems, where non-actuation may go undetected until a critical event occurs.

These shortcomings can result in operational planning errors, reduced system availability, and elevated risk of outages or equipment damage [8]. For industrial enterprises, where downtime can lead to substantial economic loss, ensuring high accuracy in failure modeling is particularly important.

Therefore, there is a clear need for a differentiated reliability assessment methodology that:

- Separately models short circuits, open circuits, and non-actuations;
- Applies non-stationary failure rate models $\lambda(t)$;
- Supports system-level integration of component-specific risk profiles.

This approach forms the basis for the methodology proposed in the following section, aimed at enhancing the reliability and risk awareness of industrial power supply systems.

III. Solution to the problem

To improve the accuracy of reliability analysis in industrial power supply systems, it is essential to separately account for the three dominant types of equipment failures: short circuits, open circuits, and failures of switching or protection devices. Each failure type has its own occurrence probability, intensity, and impact on system availability [9]. The proposed methodology is based on the construction of a generalized reliability model incorporating multiple independent failure flows, each described by a non-stationary failure rate function.

The overall failure process of each system component is modeled as a nonhomogeneous Poisson process with a time-dependent failure intensity. For each failure type j∈{1,2,3}, where:

- j=1 corresponds to short circuits (SC),
- j=2 to open circuits (OC),
- j=3 to failure to operate (non-actuation),

the failure rate is expressed in a piecewise form:

$$\lambda_j(t) = \begin{cases} \lambda_{j1}, 0 \le t < T_1 \\ \lambda_{j2}, T_1 \le t < T_2 \\ \lambda_{j3}, t \ge T_2 \end{cases}$$

where T_1 and T_2 represent the transition points between the burn-in, stable operation, and wear-out phases, respectively.

The cumulative probability of failure-free operation for a single component over the interval [0, t], considering all three types of failures, is then:

$$P(t) = exp\left(-\int_0^t \sum_{j=1}^{3} \lambda_j(\tau)\, d\tau\right)$$

This formulation allows failure intensities to evolve over time and differ by failure type.

For example, in the case of a transformer, the following numerical parameters were used in the source study (in failures/hour):

- Short circuits: λ_{11}=1.2×10⁻⁵, λ_{12}=1.8×10⁻⁵, λ_{13}=3.0×10⁻⁵
- Open circuits: λ_{21}=0.6×10⁻⁵, λ_{22}=0.9×10⁻⁵, λ_{23}=1.5×10⁻⁵
- Non-actuation: λ_{31}=1.0×10⁻⁶, λ_{32}=1.5×10⁻⁶, λ_{33}=2.5×10⁻⁶

With time thresholds set at T_1=1000 hours and T_2=4000 hours, the integral in the exponential can be explicitly calculated piecewise over the interval of operation (e.g., 5000 hours). As a result, the overall reliability function becomes:

$$P(5000) = exp\left(-\sum_{j=1}^{3}\left[\lambda_{j1}\cdot T_1 + \lambda_{j1}\cdot (T_2 - T_1) + \lambda_{j3}\cdot (5000 - T_2)\right]\right)$$

Substituting the values:

$$\begin{aligned} P(5000) &= exp(-[(1.2 + 0.6 + 0.1)\cdot 10^{-5}\cdot 1000 + (1.8 + 0.9 + 0.15)\cdot 10^{-5}\cdot 3000 \\ &+ (3.0 + 1.5 + 0.25)\cdot 10^{-5}\cdot 1000]) = exp(-[0.019 + 0.0855 + 0.0475]) \\ &= exp(-0.152) \approx 0.859 \end{aligned}$$

This result demonstrates that even for a single transformer, the probability of failure-free operation over 5000 hours is only ~85.9%, reflecting the compounded effect of all three failure types. If only one failure type (e.g., short circuits) were considered, the calculated reliability would be overestimated—often by 10–20%, depending on the element and operating time.

The methodology can be extended to evaluate system-level reliability by using appropriate structural models (series, parallel, or hybrid configurations) and combining component reliabilities accordingly. For series-connected components, the total system reliability is the product of individual Pi(t) values; for parallel redundancy, the complement rule is applied:

$$P_{parallel}(t) = 1 - \prod_{i=1}^{n}(1 - P_i(t))$$

This enables modeling of complex power supply systems with redundancy and load transfer schemes. Additionally, mean time to failure (MTTF) and average number of failures in time t can be derived as:

$$N_j(t) = \int_0^t \lambda_j(\tau)d\tau$$

$$MTTF_j = \int_0^\propto P_i(t)dt$$

The application of this model in the article allowed the authors to identify the most vulnerable components in a test configuration of a power supply system, to optimize maintenance intervals, and to justify targeted redundancy for the most failure-prone paths.

In summary, the proposed model addresses the key limitations of traditional reliability assessments by integrating differentiated failure flows, time-dependent intensities, and failure-type-specific risks, thereby enabling more realistic and actionable evaluations of industrial power supply reliability.

IV. Results and discussion

To validate the proposed reliability assessment methodology, a numerical case study was performed for a representative component of an industrial power supply system, such as a power transformer. The analysis incorporates three independent failure flows—short circuits (SC), open circuits (OC), and failures to actuate (NA)—each modeled using a piecewise failure rate function across three distinct operational phases: burn-in, steady-state operation, and aging.

The time-dependent reliability function P(t) was computed over an operating horizon of 5000 hours using failure rate values taken from real-world industrial data (as referenced in the original study). Each failure type was represented by a different set of failure intensities λj(t), and the overall system reliability was determined by integrating these rates into the exponential failure-free operation model:

$$P(t) = exp\left(-\int_0^t \sum_{j=1}^{3} \lambda_j(\tau)\, d\tau\right)$$

The results are presented in Figure 2, which shows a continuously decreasing reliability curve. The slope of the curve increases over time due to the compounding effects of aging and the nonlinear accumulation of risks from all three failure types.

Probability of failure-free operation P(t) over time, calculated for a representative power system component (e.g., transformer), accounting for three distinct failure flows: short circuits (SC), open circuits (OC), and non-actuation (NA). Each failure type is modeled using a time-dependent piecewise failure rate function λj(t) across three operational phases: burn-in, stable operation, and aging. The exponential degradation trend illustrates the cumulative effect of all failure types over 5000 hours.

To further interpret these results, cumulative failure intensities and corresponding reliability values were calculated at selected time intervals. The values are summarized in Table 1.

Cumulative integrals of failure intensities and corresponding reliability values P(t)P(t)P(t) over the equipment's life cycle, with individual contributions from short circuit, open circuit, and non-actuation failure types. The results clearly demonstrate the additive effect of multiple failure mechanisms and the importance of differentiated modeling.

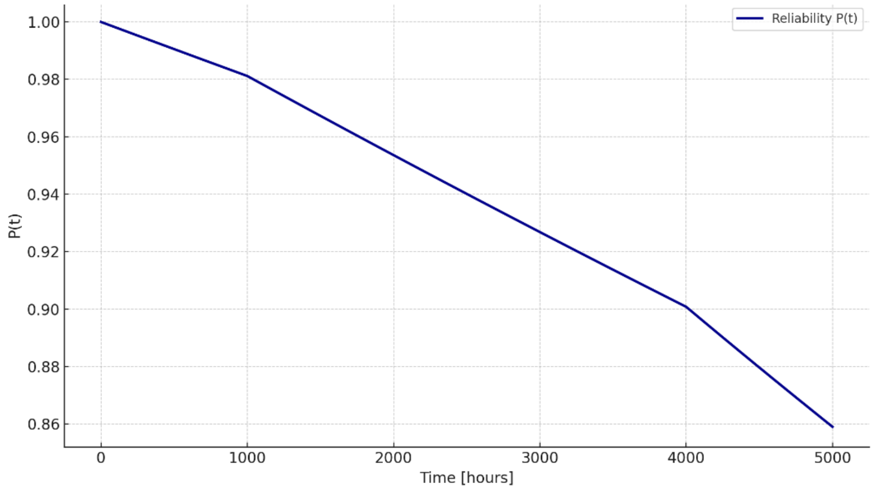

Figure 2.: *Reliability function of power supply equipment considering three failure types*

Table 1. *Cumulative failure intensities and reliability values for a typical power system component*

Time (h)	$\int_0^t \lambda_{SC}(t)dt$	$\int_0^t \lambda_{OC}(t)dt$	$\int_0^t \lambda_{NA}(t)dt$	$\int_0^t \lambda dt$	P(t)
1000	0.01200	0.00600	0.00100	0.01900	0.98118
2000	0.03000	0.01500	0.00250	0.04750	0.95361
3000	0.04800	0.02400	0.00400	0.07600	0.92682
4000	0.06600	0.03300	0.00550	0.10450	0.90077
5000	0.09600	0.04800	0.00800	0.15200	0.85899

The results presented in Figure 2 and Table 1 highlight two critical insights:

1. The non-linearity of reliability degradation becomes pronounced in the aging phase, where failure rates increase significantly. For example, after 5000 hours of operation, the probability of failure-free functioning drops to approximately 85.9%, even though all individual failure rates appear low at first glance.

2. Each failure mechanism contributes differently over time. Short circuits contribute the most to reliability degradation, especially in later phases, while open circuits have a moderate and more evenly distributed impact. Non-actuation failures, though less frequent, remain critical due to their hidden nature and potential to compromise protection systems.

Compared to traditional single-failure-type models, the proposed approach provides a more realistic representation of operational risks. It enables:

- Identification of critical components based on differentiated failure patterns,
- Optimization of preventive maintenance schedules by targeting phase-specific vulnerabilities,
- Justification of redundancy strategies based on the dominant failure mechanisms.

This methodology can be integrated into existing SCADA or maintenance planning systems to enhance the predictive capabilities and risk awareness of industrial power engineers.

V. Conclusion

This paper proposed an advanced methodology for assessing the reliability of industrial power supply systems by explicitly accounting for three major types of equipment failures: short circuits, open circuits, and non-actuation of switching and protection devices. Unlike traditional approaches that rely on a single average failure rate, the presented model incorporates distinct failure flows with time-dependent intensities, structured across three operational phases: burn-in, steady-state, and aging.

The analytical expressions derived and the numerical case study demonstrated the tangible impact of differentiated modeling. Over a 5000-hour operation interval, failure-free probability declined to approximately 86%, revealing a significant underestimation when using conventional methods. The results emphasized that:

- Short circuits dominate the failure risk during aging,
- Hidden failures (non-actuation) require special attention due to their low visibility and high potential impact.

By applying this approach, reliability engineers can obtain a more realistic and granular understanding of system behavior, allowing for:

- More targeted maintenance scheduling,
- Risk-informed redundancy planning,
- Improved decision-making in the design and operation of power supply infrastructures.

The methodology is scalable and can be extended to complex multi-element power systems, integrating seamlessly into digital asset management platforms and reliability-centered maintenance (RCM) frameworks. Future research may focus on incorporating failure dependencies, repair dynamics, and real-time condition monitoring data to further enhance the model's applicability in adaptive and self-healing power networks.

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