

# ENHANCING THE RELIABILITY OF RELAY-CONTACTOR CONTROL SYSTEMS IN INDUSTRIAL AND ENERGY APPLICATIONS

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## Abstract

*Relay-contactor systems remain essential components in power control and automation circuits, particularly in critical industrial and energy infrastructure. Despite the increasing use of solid-state and programmable devices, electromechanical relays and contactors are still widely employed due to their robustness, electromagnetic isolation, and high switching capabilities. However, their reliability is subject to various failure mechanisms including contact wear, coil overheating, and mechanical degradation. This paper presents a systematic analysis of these reliability challenges, supported by statistical modeling, environmental correction factors, and empirical data. Advanced diagnostic techniques and predictive maintenance strategies are discussed, including the integration of intelligent monitoring systems capable of tracking temperature, contact resistance, and response time. The study also explores architectural solutions for improving the redundancy and resilience of DC auxiliary power systems, focusing on protection automation. The technical and economic benefits of intelligent relay systems over conventional ones are demonstrated. Results indicate that adopting adaptive reliability management and smart diagnostics significantly reduces failure rates and improves system availability.*

**Keywords:** relay-contactor systems, reliability modeling, electromechanical switching devices, failure analysis

## I. Introduction

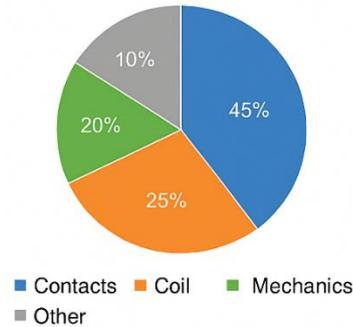
Relay-contactor systems continue to play a key role in automatic control and power supply circuits at industrial enterprises and in the energy sector. Despite the growing use of solid-state and programmable devices, electromechanical contactors and relays remain irreplaceable components in situations that require high switching capacity, electromagnetic isolation, or operation under harsh environmental conditions [1]. Their reliability directly affects the safety, stability, and continuity of technological processes, especially in critical systems such as drive control circuits, protection, redundancy, and emergency shutdown systems.

The reliability of relay-contactor devices is determined by a combination of electrical, thermal, mechanical, and environmental factors. Failures in these components often occur suddenly and can lead to the malfunctioning of the entire control system, production line shutdowns, or even accidents with significant technical and economic consequences. Therefore, improving the reliability of these elements is a relevant engineering task that requires a comprehensive approach.

Recent studies on relay-contactor equipment have focused on the wear mechanisms of contact surfaces, thermal aging of coils, contact sticking, and the estimation of residual life under different switching conditions. Despite the existence of numerous empirical models and regulatory standards (including GOST and IEC), the actual operating conditions, load characteristics, and

usage patterns are often not adequately considered in the design and maintenance process, which reduces the effectiveness of failure prevention strategies.

Figure 1 presents a generalized distribution of the causes of relay-contactor failures based on industry reports and technical assessments from field inspections.



**Figure 1.:** Structure of causes of failures in relay-contactor control systems (based on aggregated data from energy and engineering enterprises)

As shown in the diagram, the largest share of failures—approximately 45%—is due to contact wear, highlighting the importance of detailed analysis of switching conditions and the selection of appropriate contact materials. Significant contributions also come from coil overheating (25%) and mechanical wear of moving parts (20%).

The objective of this article is to conduct a systematic analysis of the factors affecting the reliability of relay-contactor control systems and to propose technical and organizational measures to improve it. The study considers reliability modeling methods, condition monitoring technologies, contact material selection, circuit design strategies, and economic evaluation of the proposed solutions.

## II. Problem statement

Relay-contactor control systems have traditionally played a key role in ensuring switching, protection, and load management in industrial electrical installations. However, despite their simple design and wide usage, they remain among the most vulnerable components in terms of failures, especially under intensive operation and external influences.

Typical failures of relays and contactors include:

- Contact sticking, which occurs due to welding caused by overload and inrush currents;
- Contact surface burning as a result of multiple switching operations in the presence of an arc, especially when disconnecting inductive loads;
- Mechanical wear of moving parts, actuators, and springs;
- Insulation degradation, accelerated by elevated temperature, humidity, and dust presence.

A critical factor affecting reliability is the nature of the switching load. Inductive loads (e.g., electric motors) produce significant current surges and arc processes, which accelerate contact erosion [2-4]. Capacitive loads cause sharp pulses during closure. Combined load modes result in cumulative effects that exacerbate degradation.

Many existing reliability assessment models are simplified: they do not take into account actual operating modes, climatic and mechanical impacts, nor the specifics of switching. In particular, they assume exponential failure time distribution, consider the structure as series-connected, and introduce environmental effects formally without adapting to specific conditions.

An example is the calculation of failure rate and reliability probability of a control and protection unit (CPU) containing contactors and relays. Without considering operating conditions, a simple model is used:

$$\lambda_S = \sum_{i=1}^n \lambda_i$$

$$P(t) = \exp(-\lambda_S \cdot t)$$

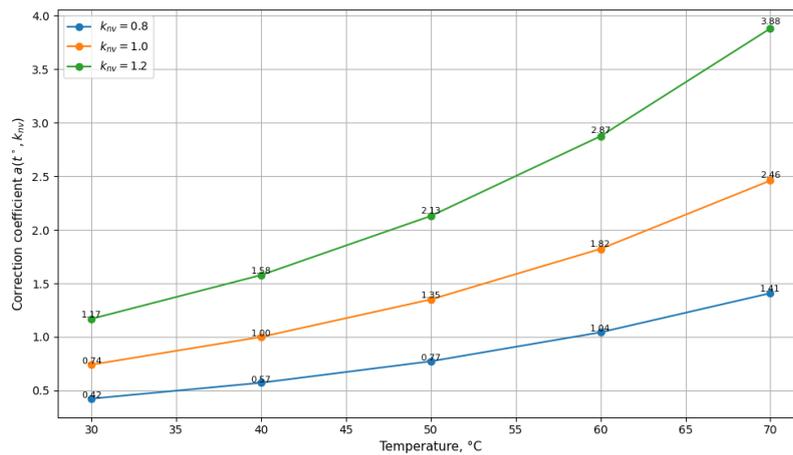
where:  $\lambda_S$  – total failure rate;  $t$  – operating time.

However, in operational conditions, reliability is significantly affected by temperature, load factor, and environmental conditions. A refined model uses:

$$\lambda_{ej} = \lambda_j \cdot a(t^\circ, k_{nv})$$

where:  $\lambda_j$  – base failure rate of the element;  $a(t^\circ, k_{nv})$  – correction factor accounting for temperature and load;  $k_{nv} = \frac{U_i}{U_n}$  – voltage load factor.

This figure (figure 2) illustrates the influence of ambient temperature and voltage load coefficient ( $k_{nv}=U_{actual}/U_{nominal}$ ) on the correction multiplier used in reliability calculations of relay-contactor systems. As temperature increases from 30 °C to 70 °C, the value of  $a(t^\circ, k_{nv})$  grows exponentially, indicating a sharp rise in the failure rate.



**Figure 2.:** Dependence of the correction coefficient  $a(t^\circ, k_{nv})$  on temperature and voltage load factor for relays and contactors

The curves also show that systems operating under overvoltage conditions ( $k_{nv}=1.2$ ) are significantly more sensitive to temperature, leading to accelerated contact wear and a reduction in mean time between failures (MTBF). This confirms the necessity of incorporating real operational conditions into reliability models for electromechanical switching devices.

The resulting probability of failure-free operation within a temperature range of 40–60 °C shows a sharp decrease (table 1):

**Table 1.:** Dependence of reliability and mean time to failure (MTTF) of relay-contactor systems on ambient temperature.

Temperature	$P(t=5800 \text{ h})$	Mean time to failure $T_{av}, \text{h}$
40 °C	0.33	5236
50 °C	0.19	3509
60 °C	0.072	2208

This demonstrates that even under nominal operating conditions, an increase in temperature by 20 °C reduces the failure-free probability by more than 4.5 times.

Despite this, in the maintenance practice of relay-contactor systems, there are no comprehensive monitoring systems capable of tracking key parameters such as switching current, response time, housing temperature, and contact resistance [5-7]. Visual inspections and periodic checks do not allow early detection of degradation processes.

Hence, there is a need to implement:

- Adequate statistical-analytical models considering actual operating modes;
- Diagnostic and predictive analysis tools based on sensor data;
- An adaptive approach to reliability management, accounting for external environment dynamics and switching intensity.

Thus, the urgent task is to transition from a traditional approach to a comprehensive reliability management model, where the relay-contactor system is regarded as an adaptive object operating in stochastically changing conditions, requiring consideration of individual operational profiles and residual life forecasting.

### III. Problem solution

Improving the reliability of relay-contactor systems requires the use of adequate mathematical models capable of capturing the probabilistic nature of failures. As a foundation, models based on continuous-time Markov chains and batch Monte Carlo methods are often employed, allowing for statistical simulation of system element states over time.

The key parameters for constructing such models include electrical switching conditions: current, voltage, and switching frequency. These factors directly influence the degradation of contact surfaces and thereby determine reliability characteristics such as the Mean Time Between Failures (MTBF) and failure rate ( $\lambda$ ).

$$MTBF = \frac{1}{\lambda}, \quad \lambda = \frac{N_{failures}}{T_{observation}}$$

The figure below shows the cumulative probability of failure as a function of operational time for conventional and intelligent relays (figure 3).

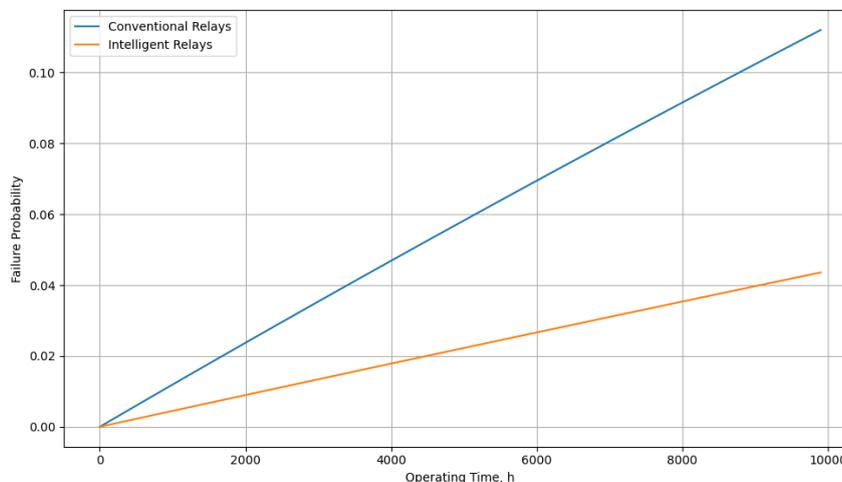


Figure 3. Cumulative probability of failure versus operating time

As shown, intelligent relays demonstrate significantly more stable performance throughout their lifecycle, reducing the probability of failure by nearly three times under identical operating conditions [8].

The reliability of relay-contactor systems can be enhanced through the implementation of the following technical measures:

- Use of arc-suppression devices (such as arc chambers and RC-snubber circuits), which reduce thermal damage to contact surfaces during switching operations.
- Anti-stick circuitry and auxiliary relays that prevent contact sticking under fault or overload conditions.
- Improved contact materials — for instance, AgSnO<sub>2</sub> or AgNi offer superior arc resistance and wear characteristics compared to conventional materials.
- Redundancy of critical components increases overall system reliability by ensuring continued operation in the event of a single-point failure.
- Regular diagnostics, including thermographic inspections, vibration analysis, and contact resistance measurements, enable early detection of degradation and preventative maintenance planning.

Ensuring the high reliability of relay-contactor circuits and protective relay automation (PRA) systems is a fundamental requirement for the stable operation of substations and power plants. Failures in these circuits can lead to incorrect or missed responses of protection devices, resulting in equipment damage or large-scale outages [9-11]. Therefore, reliability improvement must be approached comprehensively, combining optimal component selection with thoughtful system-level architectural design.

One of the key strategies involves the integration of intelligent monitoring within the relay-contactor circuits. As shown in Figure 4, typical contactor-based configurations can be enhanced by embedding smart diagnostic nodes that track key operational parameters:

- Temperature is a critical variable that reflects thermal stress due to overload conditions or inadequate heat dissipation. Elevated coil or contact temperatures may indicate early signs of degradation.
- Operating Time provides insight into the mechanical health of the relay. An increase in response delay is often associated with mechanical wear, aging springs, or contamination in the moving parts.
- Contact Resistance serves as a real-time indicator of contact surface condition. A gradual increase may point to oxidation, wear, or particulate contamination, all of which degrade electrical conductivity.

These parameters are gathered by smart relay modules, enabling the creation of a digital performance profile and facilitating predictive maintenance through real-time analysis and residual life estimation of critical components. Such monitoring helps to avoid unexpected failures and supports the scheduling of preventive actions without interrupting service.

In addition to monitoring, the architecture of the auxiliary DC power supply plays a vital role in the overall reliability of PRA systems. DC auxiliary power systems (DAPS) are responsible for powering essential control, protection, and automation equipment (figure 5). A widely adopted solution for enhancing redundancy in DAPS is a dual-channel configuration, which typically includes:

- Two independent battery banks, each equipped with its own charger,
- Two isolated DC buses (DC1 and DC2),
- Isolation diodes or automatic transfer switching (ATS) mechanisms for load switchover.

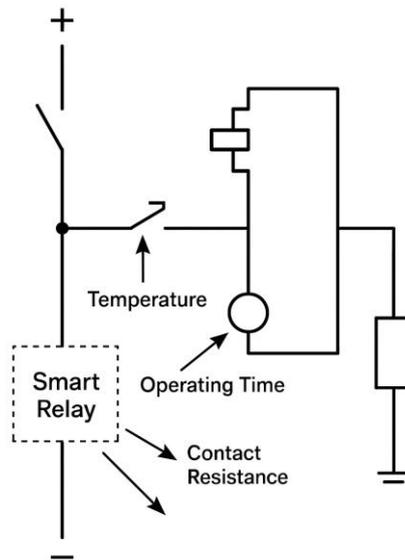


Figure 4.: Relay-contactor system with intelligent monitoring

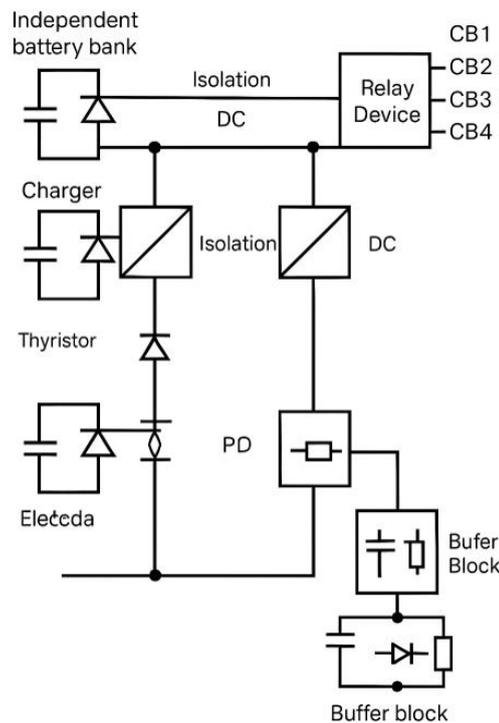


Figure 5.: Dual-channel architecture of the DC auxiliary power system with protection device (PD) and optional ATS-based redundancy.

While such systems provide redundancy, they also introduce specific technical challenges. In particular, under certain conditions—such as insulation failures, commissioning errors, or misconfigured diodes—voltage summation can occur through the isolation diodes, potentially producing voltages of up to 450 V at the input terminals of microprocessor-based relay devices (MURZ). These overvoltages can lead to catastrophic failures of logic inputs and power supplies, especially in systems relying on varistor-only protection.

To mitigate this risk, a dedicated overvoltage protection device (PD) can be employed. A simple yet effective circuit based on a thyristor (e.g., MCO 100-12io1) and a TVS diode (e.g., 1.5KE300A) can:

- Clamp and limit the surge voltage to a safe level,
- Interrupt the fault current path by turning off the thyristor,
- Trigger the disconnection of circuit breakers (e.g., CB1–CB4) before the PRA devices sustain irreversible damage.

However, an even more robust and modern solution is to eliminate isolation diodes entirely and adopt a design based on two independent buses supported by an automatic transfer switch using relays and an intermediate buffer block composed of a capacitor, diode, and resistor.

This alternative architecture offers several advantages:

- It maintains power continuity for 40–60 ms, which is sufficient to bridge short-term dips during transfer events,
- It avoids momentary voltage collapses that could deactivate intermediate relays or logic circuits,
- It is fully compatible with all standard-compliant PRA units, many of which tolerate power interruptions up to 500 ms or longer.

In conclusion, enhancing the reliability of relay-contactor and protective relay systems requires more than just robust components—it demands a system-level view that includes intelligent diagnostics, redundancy-aware architecture, and proactive protection strategies. By combining smart monitoring with well-engineered auxiliary power supply schemes, power system operators can significantly improve the availability, safety, and resilience of critical protection infrastructure.

Modern technologies enable not only the monitoring of the current condition of equipment but also the prediction of its future behavior. Machine learning methods such as XGBoost and recurrent neural networks (RNN) process operational data (response time, temperature, contact resistance) and build models capable of accurately estimating the residual life of relays.

Sensors embedded in smart devices provide continuous monitoring, and the collected data is integrated into predictive maintenance systems, which is especially effective in continuous production environments.

The implementation of more reliable and “smart” solutions must be economically justified. Below is a comparative table presenting key technical and economic parameters of conventional and intelligent relays (table 2).

**Table 2.:** Comparison of technical and economic parameters of conventional and intelligent relays

Parameter	Conventional Relays	Intelligent Relays
MTBF (hours)	83,333	222,222
Failure rate $\lambda$ (1/hour)	0.000012	0.000005
Device cost (\$)	35	120
Expected failure losses (\$/year)	7,000	2,500

The table shows that despite the higher cost of intelligent relays, they significantly reduce annual losses due to failures while providing a higher level of reliability and technical predictability.

## IV. Conclusion

This study provides a comprehensive analysis of the reliability issues associated with relay-contactor systems used in industrial automation and energy infrastructure. Through detailed examination of typical failure modes—including contact wear, coil overheating, and mechanical degradation—the paper highlights the critical role that operating conditions, load characteristics, and environmental factors play in determining system longevity.

Analytical models incorporating correction factors for temperature and voltage stress were introduced to improve the accuracy of reliability estimation. These models demonstrated a significant decrease in failure-free probability under elevated thermal and electrical loads, emphasizing the necessity of real-condition-based reliability assessment.

To address these challenges, the implementation of intelligent monitoring systems was proposed. These systems enable real-time tracking of key performance indicators such as contact resistance, operating temperature, and response delay, providing the basis for predictive diagnostics and timely maintenance. In addition, improvements in circuit architecture, including redundancy in DC auxiliary power systems and overvoltage protection, were discussed as vital strategies for enhancing operational safety and continuity.

The comparative analysis showed that intelligent relay solutions, despite their higher initial cost, offer substantial economic and technical advantages by reducing annual failure-related losses and increasing mean time between failures (MTBF).

In conclusion, enhancing the reliability of relay-contactor systems requires a multidimensional approach combining advanced modeling, smart diagnostics, improved material and design choices, and system-level architectural resilience. Future work should focus on integrating machine learning-based predictive tools and expanding sensor networks to build fully adaptive and self-diagnosing control systems.

## References

- [1] McLaren, P. G. (2007). Reliability of electromechanical relays in protection systems. *IEEE Transactions on Power Delivery*, 22(4), 2312–2318.
- [2] Singh, A. K., & Tiwari, M. (2011). Modeling and reliability analysis of electromechanical relay contacts. *Reliability Engineering & System Safety*, 96(6), 777–783.
- [3] Nakagome, M., Kajiwara, T., & Ogawa, H. (2019). Predictive maintenance of protective relays using machine learning techniques. *Electric Power Systems Research*, 172, 142–151.
- [4] Rzayeva, S. V., Piriyeva, N. M., & Guseynova, I. A. (2024). Analysis of reliability of typical power supply circuits. *Reliability: Theory & Applications*, 19(3), 173–178.
- [5] Rzayeva, S. V., & Guseynova, I. A. (2024). Application of automatic monitoring and control systems for reliability of power transmission lines. *Reliability: Theory & Applications*, 19(2), 64–69.
- [6] Rzayeva, S. V., Ganiyeva, N. A., & Piriyeva, N. M. (2024). Modern approaches to electrical equipment diagnostics. *International Journal on Technical and Physical Problems of Engineering (IJTPE)*, 58.
- [7] Rzayeva, S. V., Piriyeva, N. M., & Ismayilova, S. I. (2025). High and low voltage coordination in electrical power systems. *International Journal on Technical and Physical Problems of Engineering (IJTPE)*, 17(1), 19–31.
- [8] Piriyeva, N. M., Ganiyeva, N. A., & Karimova, R. K. (2025). Innovative approaches to selective automatic reclosing on overhead cable lines. *International Journal on Technical and Physical Problems of Engineering (IJTPE)*, 17(1), 32–34.

- [9] Piriyeva, N. M., Mammadov, N. S., & Rzayeva, S. V. (2025). Development of new methods for protecting substation and overhead lines from overvoltages. *Reliability Theory and Applications*, 20(1), 683–689.
- [10] Ahmedov, E. N., Rzayeva, S. V., Mukhtarova, K. M., & Aliyev, N. A. (2025). Innovative enhancements in ground wire configurations for superior lightning protection of overhead power lines. *International Journal on Technical and Physical Problems of Engineering (IJTPE)*, 17(1), 45–48.
- [11] Zhang, Y., Sun, Z., & Wang, X. (2019). A condition monitoring and diagnostics method for electromechanical relays based on contact resistance measurement. *IEEE Transactions on Instrumentation and Measurement*, 68(5), 1460–1468.