RESEARCH ARTICLE

Experimental Comparative Analysis of Electromechanical, Static and Microprocessor Relay Protection Technologies

Miloš J. Milovanović[1,*], **Jordan N. Radosavljević**[1] and **Bojan D. Perović**[1]

[1] Faculty of Technical Sciences, University of Pristina in Kosovska Mitrovica, RS-38220 Kosovska Mitrovica, Serbia

Abstract

This paper presents an experimental comparative analysis of electromechanical, static, and microprocessor-based protective relays using the secondary injection testing method. The study evaluates key performance indicators, including pickup current, dropout current, and operating time, under controlled laboratory conditions. The results show that electromechanical relays exhibit pickup current deviations below 5%, accompanied by relatively high variability in operating time (up to 0.2 s), mainly due to inherent mechanical limitations. Static relays demonstrate improved performance, with enhanced stability, reduced deviations, and limited time variation within ±0.1 s. Microprocessor-based relays achieve the highest level of performance, characterized by minimal deviations, negligible hysteresis, and fast response times of approximately 30 ms. The findings confirm that the technological evolution of protective relays leads to significant improvements in accuracy, response speed, and operational stability. Nevertheless, electromechanical and static relays can still ensure reliable operation when properly maintained and correctly applied. The presented results provide a realistic assessment of relay performance across different technological generations and offer a useful basis for decision-making in the modernization and upgrade of protection systems.

Keywords: electromechanical, static and microprocessor relays, experimental analysis, relay protection, secondary injection testing.

1 Introduction

The reliable operation of modern power systems largely depends on the performance of protection systems, whose primary function is the fast and selective isolation of faults. Protective relays, as key components of secondary equipment, enable efficient system monitoring and control, while ensuring the protection of primary assets and limiting the impact of disturbances. Accordingly, modern protection systems are required to meet high standards in terms of accuracy, selectivity, and operating speed. The evolution of power systems has been accompanied by significant advancements in protection technologies, transitioning from electromechanical to static and, more recently, to microprocessor-based (digital) relays. Modern microprocessor-based relays

Submitted: 11 April 2026
Accepted: 22 May 2026
Published: 03 June 2026

Vol. 2, **No.** 2, 2026.
10.62762/TEPNS.2026.788018

***Corresponding author:**
✉ Miloš J. Milovanović
milos.milovanovic@pr.ac.rs

Citation
Milovanović, M. J., Radosavljević, J. N., & Perović, B. D. (2026). Experimental Comparative Analysis of Electromechanical, Static and Microprocessor Relay Protection Technologies. *ICCK Transactions on Electric Power Networks and Systems*, 2(2), 79–88.

provide advanced functionalities, such as adaptive settings, communication capabilities, and integration into information and communication systems, thereby enhancing flexibility and overall protection performance. The reliability of such protection devices is a critical concern that can be evaluated through methods including fault injection and fault tree analysis [1].

With the increasing penetration of distributed generation and renewable energy sources, power systems are becoming more complex. This is reflected in bidirectional power flows, variations in short-circuit levels, increased harmonic distortion, and dynamic changes in network topology and operating conditions. These factors significantly affect protection system performance, including the detrimental impact of harmonic distortion on digital relay operation [5], and require the implementation of advanced and adaptive protection schemes [3, 4]. Traditional protection approaches based on fixed settings often fail to ensure adequate selectivity and sensitivity under such conditions. One of the fundamental challenges in protection system design is achieving optimal coordination between primary and backup relays while satisfying selectivity, reliability, and speed requirements. These requirements are formalized in relevant IEEE standards and technical guidelines [2, 6], and are frequently formulated as optimization problems [7, 8].

Although relay protection has been extensively studied, the majority of existing research focuses on algorithm development, optimization techniques, and simulation-based analyses, including tools for modeling and simulation of protection systems for educational and research purposes [9], as well as metaheuristic optimization approaches [7, 8, 10]. Particular attention has been given to adaptive protection schemes and relay coordination in networks with variable topology and distributed energy resources [7, 8, 11]. In addition, some studies employ fault record data and machine learning techniques to evaluate relay performance under real operating conditions [12], while others combine simulation models and data-driven approaches to improve fault detection and classification [13]. From an economic perspective, several studies have shown that replacing electromechanical relays with microprocessor-based devices can significantly reduce operational and maintenance costs, with relatively short payback periods (2–3 years) [14]. However, despite the extensive body of theoretical and simulation-based research, there is a noticeable lack of studies based on experimental validation under laboratory or real operating conditions. Practical evaluation of relay performance requires specialized equipment and infrastructure, and is therefore typically limited to research institutes, manufacturers, and large utility companies, which reduces its availability in open scientific literature. Furthermore, modern microprocessor-based relays introduce additional challenges related to system complexity, reliability, and sensitivity to external influences, highlighting the need for their experimental verification. In this context, a clear gap can be identified between theoretical and simulation-based studies on one side and experimental validation on the other, which represents the main motivation of this work.

The main contribution of this work lies in the direct experimental comparison of electromechanical, static, and microprocessor-based protection relays under consistent laboratory conditions using the same testing methodology and comparative performance indicators. Unlike many previous studies focused primarily on simulation-based analyses, optimization approaches, or individual relay technologies, the presented investigation provides a unified experimental evaluation of three technological generations of relay protection systems.

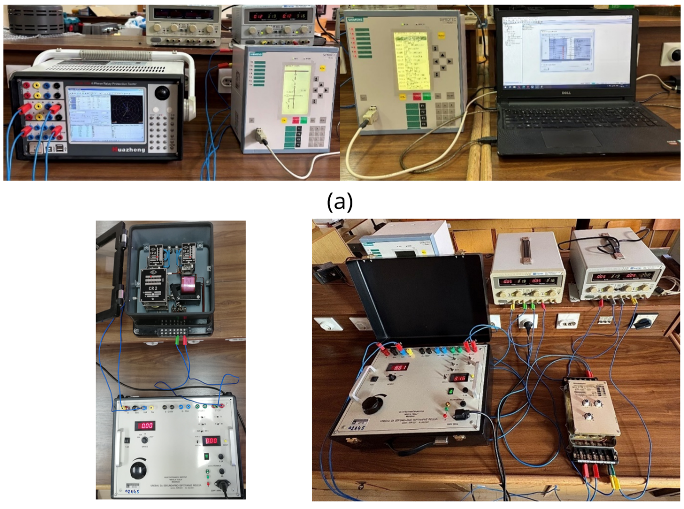
This paper presents a comparative experimental analysis of different relay technologies, with particular emphasis on their dynamic characteristics and operating time. The results contribute to a better understanding of the behavior of electromechanical, static, and microprocessor-based relays and their application in modern power systems. The experimental investigation was conducted using the secondary injection testing method, which enables precise evaluation of relay performance under controlled laboratory conditions. Three generations of protection devices were analyzed: electromechanical relays (2×IR-2 + CR-2), static relays (INO 240A), and modern microprocessor-based relays (SIPROTEC 7SJ62). The study includes the assessment of their operating characteristics, response times, and behavior under different fault conditions.

Test signals were generated using specialized relay testing equipment (SIR-2 and HZJB-1200), capable of simulating real operating conditions through precise control of current, voltage, phase angles, and timing parameters. This approach enables a direct comparative analysis of different relay technologies, with a focus on dynamic performance, operating time, and deviations from set values under simulated fault conditions.

2 Methodology

The research methodology is based on the experimental evaluation of protective relays using the secondary injection testing method, which represents a standard approach for verifying relay performance in power systems. This method enables the assessment of relay functionality under controlled laboratory conditions, without direct connection to the primary power system.

The tests were conducted using specialized relay testing equipment for secondary injection (SIR-2 [15], developed in cooperation between the Nikola Tesla Electrical Engineering Institute and the Instrument Transformer Factory in Zaječar, and HZJB-1200 [16], Huazheng Electric Manufacturing Co., Ltd.). These devices enable the generation of precisely defined current and voltage signals, as well as accurate measurement of time-related parameters. According to the manufacturer specifications, both test systems provide high measurement accuracy and adequate temporal resolution for laboratory verification of protective relay characteristics. For the HZJB-1200 relay test system, the manufacturer specifies current and voltage output accuracy of ±0.2% and timing measurement accuracy better than 0.1 ms. Such equipment is widely used in practice for factory acceptance testing, commissioning, and periodic verification of protection systems in substations and industrial installations. The experimental setup and the tested relay devices are shown in Figure 1.


(a)

(b) (c)

Figure 1. Experimental setup and relay devices under test: (a) SIPROTEC 7SJ62 microprocessor-based relay with HZJB-1200 test set, (b) electromechanical relay (IR-2 + CR-2), and (c) static relay INO 240A tested using the SIR-2 system.

2.1 Tested relay types and practical application

The experimental investigation was conducted on three types of protective relays: electromechanical relays (2×IR-2 + CR-2), static relays (INO 240A), and microprocessor-based relays (SIPROTEC 7SJ62), which are commonly used in transmission and distribution systems depending on the level of system modernization. These devices represent three distinct technological generations of protection systems that are still present in practical applications. Electromechanical and static relays are typically found in legacy protection schemes, particularly in systems that have not been fully modernized, whereas microprocessor-based relays are widely deployed in modern installations requiring higher accuracy, selectivity, and communication capabilities [2].

In practice, these relays are predominantly used for overcurrent protection of lines, transformers, generators, and motors, where their coordination is defined by time–current characteristics and selectivity requirements [7]. The problem of optimal relay coordination is commonly formulated as a complex optimization task, and various solution approaches have been proposed in the literature, including metaheuristic and intelligent optimization techniques [7–13]. Differences in operating principles among these relay types directly affect their operating characteristics, response times, and overall protection performance. Therefore, experimental validation under controlled laboratory conditions is important for objective comparative evaluation of different relay technologies.

2.2 Testing Procedure

The tests were performed using the secondary injection method, where simulated current and/or voltage signals corresponding to fault conditions in power systems were applied to the relay inputs. The testing procedure was carried out by gradually increasing the current from values below the pickup threshold to values exceeding the set pickup level, while recording the relay operating time. The investigation focused on overcurrent protection with one or two operating stages (stage 1 and stage 2), where the pickup current

Table 1. Measured pickup and dropout current values for the IR-2 relay.

Set current, I_{set} (A)	4	5	6	7	8	9	10
Pickup current, I_{pickup} (A)	3.96	5.00	6.05	6.96	7.95	9.11	10.28
Dropout current, I_{dropout} (A)	3.50	4.20	5.00	6.00	6.95	7.96	8.70
Dropout ratio, $a = I_{\text{dropout}}/I_{\text{pickup}}$	0.88	0.84	0.83	0.86	0.87	0.87	0.85
Deviation (%)	-1.00	0.00	0.83	-0.57	-0.62	1.22	2.80

and operating time were determined independently for each stage.

Particular attention was given to the following performance indicators:

- pickup current,
- operating time,
- stability near threshold conditions,
- relay response under sudden current variations.

The operating time was measured using the internal timing functions of the test equipment, ensuring high temporal resolution. To improve result reliability and reduce random errors, the tests were repeated for multiple fault current levels. Additionally, the measurements were conducted using two different relay test devices (SIR-2 and HZJB-1200), enabling cross-validation of the obtained results. A high level of agreement between the results obtained using the SIR-2 and HZJB-1200 systems was observed, with differences in measured operating times within a few milliseconds for the investigated operating conditions, confirming the reliability and consistency of the applied methodology. For clarity, the results presented in this paper correspond to measurements obtained using the HZJB-1200 test system [16]. The collected data were processed and used for comparative evaluation of different relay types based on the measured operating times under different current levels.

For each operating condition, the measurements were repeated three times, and the presented results correspond to the average values. The experiments were conducted under stable laboratory conditions at approximately constant ambient temperature and supply conditions, without significant external disturbances or fluctuations affecting relay operation. Timing measurements for all relay types were obtained using the internal timing functions of the applied relay test systems, based on the interval between current injection and activation of the relay output contact. Particular attention was given to measurement repeatability, especially for electromechanical relays whose operating characteristics may be influenced by mechanical condition and environmental factors.

3 Results and Discussion

This section presents the experimental results obtained for electromechanical, static, and microprocessor-based relays, together with a comparative discussion of their operating characteristics and performance.

Table 2. Measured inherent operating times of the IR-2 relay at a set pickup current of 5 A.

I_{test} (A)	5	7	9
t_1 (ms)	66	42	20
t_2 (ms)	85	45	23
t_3 (ms)	77	39	18
t_{mean} (ms)	76	42	20.33

Table 3. Total operating times of the IR-2 + CR-2 relay at a test current 30% higher than the set current.

t_{set} (s)	1	2	3	4	5
t_1 (s)	1.05	1.95	2.85	3.94	4.94
t_2 (s)	1.12	1.93	2.92	3.76	4.86
t_3 (s)	1.18	1.91	2.91	3.78	4.78
t_{mean} (s)	1.12	1.93	2.89	3.83	4.86
Deviation (%)	11.67	-3.50	-3.56	-4.33	-2.80

3.1 Electromechanical relay

The tested electromechanical protection scheme consists of a current-operated relay (IR-2) and a time-delay relay (CR-2) connected in series. The IR-2 relay acts as an instantaneous overcurrent element that initiates the operation of the CR-2 unit, which provides an adjustable time delay in the range of 0.5–5 s. The pickup current range of the IR-2 relay is 4–10 A. The experimental procedure included the determination of pickup and dropout currents, as well as the analysis of operating characteristics. The connection scheme used during testing is shown in Figure 2, while the obtained results are presented in Tables 1, 2 and 3.

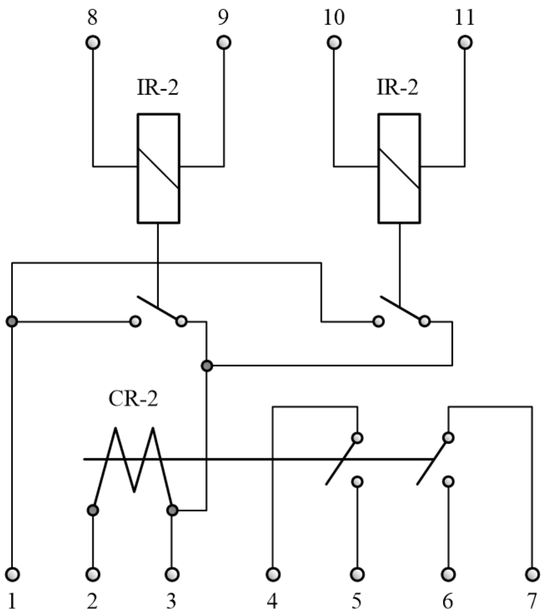


Figure 2. Connection diagram of the electromechanical relay used during the experimental secondary injection testing procedure.

Based on the results presented in Table 1, it can be observed that an increase in the set current results in a corresponding increase in the measured pickup current, with relatively small deviations from the set values. The measured deviations range from -1% to 2.8%, indicating satisfactory accuracy consistent with typical characteristics of electromechanical overcurrent relays. The dropout ratio (a), shown in the fourth row of Table 1, ranges from 0.83 to 0.88, which falls within the expected range for electromechanical relays. These values indicate acceptable stability and proper release behavior without undesirable contact oscillations.

The inherent operating time of the relay, presented in Table 2, decreases with increasing current, which is consistent with theoretical expectations for overcurrent electromechanical relays. The average operating time decreases from approximately 76 ms at lower current levels to about 20 ms at higher currents, indicating improved response speed under higher fault currents. The total operating time represents the sum of the response time of the IR-2 element and the time delay introduced by the CR-2 element. As shown in Table 3, deviations between the set and measured times exceed ±0.1 s in certain cases, reflecting the limited precision of mechanical timing mechanisms. Although the obtained results demonstrate acceptable accuracy and stability under laboratory conditions, the observed deviations and hysteresis effects are directly related to the relay's mechanical design. The performance of electromechanical relays is influenced by contact condition, spring characteristics, and magnetic system properties, which are subject to aging, wear, and contamination. Consequently, their long-term stability and repeatability remain limited compared to modern digital solutions.

3.2 Static Relay

The tested static relay INO 240A is a two-phase overcurrent relay with a definite-time characteristic, comprising a time-delayed element (l>) and an instantaneous element (l>>), intended for overload and short-circuit protection. The time-delay element is electronically implemented and adjustable via a front-panel potentiometer, while the pickup currents are set as multiples of the nominal current, $I_n = 5\,\text{A}$. The relay requires a 110 V DC auxiliary supply, provided by laboratory sources, as shown in Figure 1(c). The connection scheme is presented in Figure 3, while the experimental results are given in Tables 4 and 5.

Table 5. Operating times of the INO 240A relay at a test current 30% higher than the set current.

t_{set} (s)	1	2	3	4	5
t_1 (s)	0.92	1.92	2.93	3.94	4.97
t_2 (s)	0.94	1.96	2.95	3.97	5.02
t_3 (s)	0.93	1.94	2.94	3.95	4.98
t_{mean} (s)	0.93	1.94	2.94	3.95	4.99
Deviation (%)	-7.00	-3.00	-2.00	-1.17	-0.20

Table 4. Measured pickup and dropout current values for the INO 240A relay (phase A).

Set current, I_{set} (A)	$0.7 \cdot I_n$	$0.8 \cdot I_n$	I_n	$1.2 \cdot I_n$	$1.4 \cdot I_n$	$1.8 \cdot I_n$
Pickup current, I_{pickup} (A)	3.55	4.02	5.05	6.08	7.02	9.07
Dropout current, I_{dropout} (A)	3.20	3.61	4.54	5.52	6.38	8.37
Dropout ratio, $a = \frac{I_{\text{dropout}}}{I_{\text{pickup}}}$	0.90	0.90	0.90	0.91	0.91	0.92
Deviation (%)	1.43	0.50	1.00	1.33	0.29	0.78

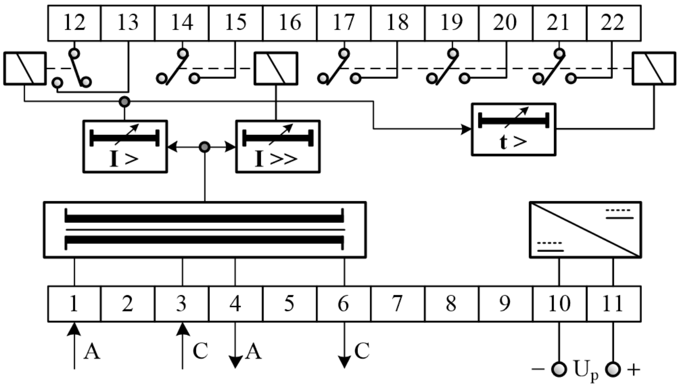


Figure 3. Connection diagram of the static relay used during the experimental secondary injection testing procedure.

The results presented in Table 4 indicate that the static relay INO 240A exhibits high accuracy in determining the pickup current, with small and uniformly distributed deviations across the entire setting range. Particular attention is drawn to the dropout ratio values a, which fall within a narrow range of 0.90 to 0.92, indicating high operational stability and minimal hysteresis compared to electromechanical relays. Such behaviour ensures reliable relay dropout without instability or oscillations near threshold current values.

The analysis of the time-delay element, shown in Table 5, demonstrates very good agreement between the set and measured operating times. The deviations are within ± 0.07 s, with no observable nonlinearities or systematic errors, confirming the high precision of the electronic implementation. In contrast to electromechanical relays, where deviations are larger and influenced by mechanical limitations, the static relay exhibits stable and reproducible behaviour across the entire setting range. Overall, the results show that the static relay provides improved accuracy, reduced deviations, and enhanced reliability compared to electromechanical relays, both in terms of current and time characteristics. This makes it suitable for application in power systems with more stringent requirements regarding selectivity, operating speed, and stability. However, despite these advantages, static relays have limited functionality compared to modern microprocessor-based relays. In particular, they lack advanced communication capabilities, integration into SCADA systems, remote monitoring and control, and flexibility in adaptive parameter settings. These features are generally recognized in the literature as important for modern power systems characterized by complex network topologies and the integration of distributed energy resources. Consequently, static relays can be considered an intermediate technological solution between electromechanical and microprocessor-based protection systems, combining improved measurement and timing performance with limited capabilities in terms of automation and communication.

3.3 Microprocessor relay

The tested microprocessor-based relay SIPROTEC 7SJ62 is a multifunctional protection device intended for applications in medium- and high-voltage power systems, including the protection of lines, transformers, and motors. The device belongs to the fourth generation of the SIPROTEC family and is characterized by the integration of protection, control, and diagnostic functions, as well as advanced communication interfaces (IEC 61850, PROFIBUS, DNP3), which, according to manufacturer documentation, enables integration into modern SCADA systems [17]. The relay was tested using the DIGSI 4 software environment in combination with the secondary injection method, where the test device was directly connected to the relay current inputs. The generated current signal was applied to the selected phase, while the relay output contact was used to register the operating instant and determine the response time, as shown in Figure 1(a). This experimental setup enables precise control of input quantities and reliable determination of relay performance parameters. The applied approach allows not only the verification of static characteristics but also a detailed analysis of dynamic behaviour, operating logic, and recorded events, representing an important functional capability of modern microprocessor-based relay.

The SIPROTEC 7SJ62 relay includes a wide range of protection and auxiliary functions, classifying it as a modern multifunctional protection device. Its core functions include overcurrent protection with both time-dependent and time-independent characteristics, as well as directional overcurrent protection. In addition, the device provides voltage protection (under- and overvoltage), frequency protection, current unbalance protection, and thermal overload protection. Further functionalities include earth-fault protection, autoreclosing, circuit breaker failure protection, and advanced features such as fault location and supervision of measurement and control circuits. In addition to protection functions, the relay integrates advanced monitoring and diagnostic capabilities, including supervision of instrument transformers, output circuits, and event and fault recording with high time resolution. Although this study focuses primarily on overcurrent and short-circuit characteristics, the selected functions represent key processes of fault detection, digital signal processing, and time coordination in modern protection systems [17]. The connection scheme used during the experimental testing of the SIPROTEC 7SJ62 relay is presented in Figure 4.

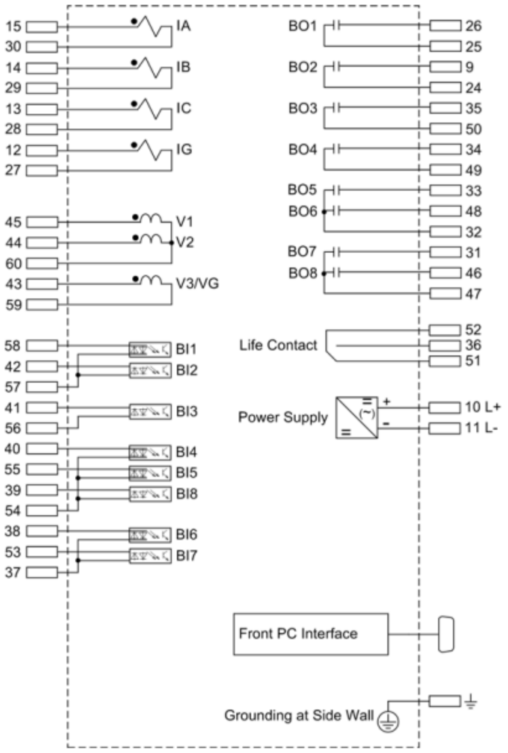


Figure 4. Part of the connection diagram of the SIPROTEC 7SJ62 relay used during secondary injection testing [17].

Initial functional testing was performed in the DIGSI 4 environment without the use of a test set, relying exclusively on software-based tools. This step enabled verification of correct relay operation under controlled conditions, including validation of protection functions, signalling, and response to predefined commands. As a standard preliminary procedure, this approach allows rapid identification of potential issues prior to detailed experimental testing. The visual signalling functionality was also verified by activating LED indicators via software, first individually and then sequentially, confirming the proper operation of the indication system, which is essential for monitoring, diagnostics, and operational reliability. Following the initial functional verification, experimental testing was carried out using a relay test set. The relay was configured with a pickup current of 5 A, and the test current was applied to phase A, gradually increased from 0 to 6 A in steps of 0.05 A with a time interval of 1 s. The measured pickup current was 5.05 A, while the dropout current was 4.75 A, indicating stable and reliable operation of the protection function. The obtained results also demonstrated highly stable and repeatable operation of the investigated relay under all considered test conditions, with only minimal deviations of the measured quantities. The dropout ratio of approximately 0.94 confirms very low hysteresis and high operational stability. Unlike electromechanical relays, where mechanical effects such as friction and inertia significantly influence dropout behaviour, these effects are minimized in microprocessor-based relays, enabling more precise definition of operating thresholds.

Further analysis of time characteristics showed that for a set operating time of 0.5 s, the measured value was 0.502 s, while for a setting of 1 s, the measured operating time was 1.015 s, confirming high timing accuracy. Testing of the short-circuit protection (instantaneous element) resulted in a measured response time of approximately 31 ms, indicating fast signal processing and minimal delay in the output circuit. The fast and stable response characteristics of the investigated SIPROTEC 7SJ62 relay are associated with digital signal processing and algorithm-based evaluation of measured quantities implemented within the protection device. Compared to conventional relay technologies, such implementation reduces the influence of mechanical inertia and contributes to improved operating consistency and repeatability. The reported operating times correspond to local protection function operation during secondary injection testing and were not influenced by external communication functions or IEC 61850 communication processes.

In parallel with experimental measurements, the DIGSI 4 environment enabled detailed visualization and analysis of recorded events, including fault occurrence, protection activation, and switching operations. The analysis of time-stamped event records provides a high level of operational transparency, allowing precise diagnostics, identification of potential irregularities, and optimization of relay settings.

The comparative summary presented in Table 6 clearly illustrates the progressive improvement in operating accuracy, repeatability, and stability

Table 6. Comparative summary of the main performance characteristics of the investigated relay types.

Characteristic	Electromechanical relay	Static relay	Microprocessor-based relay
Tested device	IR-2 + CR-2	INO 240A	SIPROTEC 7SJ62
Pickup current deviation	up to 2.8%	below 1.5%	approximately 1%
Dropout ratio	0.83–0.88	0.90–0.92	approximately 0.94
Operating time deviation	up to ±0.2 s	below ±0.1 s	below ±0.05 s
Inherent operating time	20–76 ms	electronic	approximately 30 ms
Repeatability	Moderate	Good	Very high
Hysteresis effects	Pronounced	Low	Very low
Communication capabilities	None	Limited	Advanced
Sensitivity to mechanical wear	High	Low	Negligible

from electromechanical to microprocessor-based relay technologies. In particular, the tested microprocessor-based relay exhibited the smallest deviations, the lowest hysteresis effects, and the highest operational consistency among the investigated devices.

The presented experimental observations complement previously published studies focused on relay coordination optimization, adaptive protection, and simulation-based analysis of protection systems [7–13]. In particular, the obtained results experimentally confirm the improved operating stability, reduced operating time deviations, and enhanced repeatability of modern microprocessor-based relay technologies reported in previous simulation-oriented and optimization-based investigations. Unlike many previously published studies primarily focused on coordination algorithms, adaptive protection concepts, or simulation models, the present work provides direct laboratory verification of pickup characteristics, operating times, hysteresis effects, and repeatability for different relay technologies under controlled operating conditions.

4 Conclusion

The conducted experimental study enabled a comparative evaluation of electromechanical, static, and microprocessor-based protective relays under controlled laboratory conditions. The results show that all three relay generations can provide satisfactory accuracy and reliability in terms of pickup current and basic protection functions when properly configured and applied.

The tested electromechanical relay exhibited pickup current deviations below 5%, with dropout ratios in the range of 0.83–0.88. Their inherent operating times ranged from approximately 20 ms to 76 ms, while deviations in total operating time, caused by the mechanical time-delay element, reached up to 0.2 s. These findings confirm their functional capability but also highlight limitations related to mechanical design, including higher variability and sensitivity to contact condition and maintenance level. Static relays demonstrated improved performance, with pickup current deviations generally below 2% and dropout ratios within a narrow range of 0.90–0.92. Their operating times were stable, with deviations limited to approximately ±0.1 s and no observable nonlinearities. This behavior confirms higher accuracy and reproducibility compared to electromechanical devices, although with limited functionality in terms of communication and flexibility. The tested microprocessor-based relay achieved the highest level of performance among the investigated devices, with a measured pickup current of 5.05 A for a set value of 5 A and a dropout current of 4.75 A (dropout ratio $\approx$ 0.94). The deviations in operating time for the first protection stage were below 0.02 s, while the short-circuit protection exhibited a response time on the order of several tens of milliseconds. These results confirm high accuracy, fast response, and stable operation, as well as the advantages of digital signal processing and algorithm-based implementation of protection functions.

The comparative analysis clearly demonstrates distinct differences in performance among the three relay technologies. Electromechanical relays exhibit the highest variability in both operating time and dropout characteristics, primarily due to inherent mechanical limitations. Static relays provide improved accuracy and significantly reduced deviations, with stable and reproducible behavior across the entire operating range. Microprocessor-based relays achieve the best overall performance, characterized by minimal deviations, very low hysteresis, and fast response times, along with advanced functional capabilities. Despite these differences, electromechanical relays can still provide reliable operation when properly maintained and applied under suitable conditions, while static relays represent an intermediate technological solution between traditional and modern protection systems. The selection of relay technology should therefore be based on system requirements, including accuracy, operating speed, functional capabilities, and maintenance conditions. The presented experimental results contribute to a comparative assessment of relay performance across different technological generations and may provide useful supporting information for protection system modernization studies. It should be noted that the presented investigation was conducted using one representative relay device from each considered technological category under controlled laboratory conditions. Therefore, the obtained results should be interpreted as a comparative experimental case-study of the tested devices and operating conditions, rather than as universally applicable conclusions for all relay designs and manufacturers. Furthermore, the present study was limited to steady-state laboratory conditions and did not consider several factors characteristic of modern power systems, including harmonic distortion and dynamic network behavior.

Future research will focus on the influence of harmonic distortion in current and voltage signals on relay performance, particularly under conditions of increasing penetration of renewable energy sources, energy storage systems, and electric vehicle charging infrastructure. Special attention will be given to the impact of harmonics on measurement accuracy, pickup thresholds, and operating times, as well as to the capabilities of modern microprocessor-based relays in signal filtering and processing. In addition, future studies will investigate relay performance under dynamic network conditions, including topology changes, bidirectional power flows, and variations in short-circuit levels, which are essential for the development of adaptive and intelligent protection systems.

Data Availability Statement

Data will be made available on request.

Funding

This work was supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia under Contract No. 451-03-34/2026-03/200155.

Conflicts of Interest

Miloš Milovanović served as an Associate Editor of the *ICCK Transactions on Electric Power Networks and Systems* at the time of manuscript submission. To ensure the integrity of the peer-review process, Miloš Milovanović was not involved in the editorial handling, peer review, or decision-making process for this manuscript, which was handled independently by another editor. The remaining authors declare no conflicts of interest.

AI Use Statement

The authors declare that no generative AI was used in the preparation of this manuscript.

Ethical Approval and Consent to Participate

Not applicable.

References

[1] Zhou, H., Yu, H., Zou, Z., Su, Z., Xu, Z., Yang, W., & He, C. (2025). Relay protection device reliability assessment through radiation, fault injection and fault tree analysis. *Micromachines, 16*(1), 69. [CrossRef]

[2] Institute of Electrical and Electronics Engineers. (2025). *PC37.113/D5.1, May 2025 - IEEE approved draft guide for protective relay applications to transmission lines*. IEEE. https://ieeexplore.ieee.org/document/11130712

[3] Banerjee, G., Hachmann, C., Lipphardt, J., Wiese, N., & Braun, M. (2024). Adaptive hybrid overcurrent protection scheme with high shares of distributed energy resources. *Energies, 17*, 6422. [CrossRef]

[4] Barranco-Carlos, A., Orozco-Henao, C., Marín-Quintero, J., Mora-Flórez, J., & Herrera-Orozco, A. (2023). Adaptive protection for active distribution networks: An approach based on fuses and relays with multiple setting groups. *IEEE Access, 11*, 31075–31091. [CrossRef]

[5] Wannous, K., & Toman, P. (2018). Evaluation of harmonics impact on digital relays. *Energies, 11*(4), 893. [CrossRef]

[6] Institute of Electrical and Electronics Engineers. (2015). *IEEE Std C37.113-2015 - IEEE Guide for Protective Relay Applications to Transmission Lines*. IEEE. [CrossRef]

[7] Radosavljević, J., & Jevtić, M. (2016). Hybrid GSA-SQP algorithm for optimal coordination of directional overcurrent relays. *IET Generation, Transmission & Distribution, 10*(8), 1928–1937. [CrossRef]

[8] Korashy, A., Kamel, S., Jurado, F., & Youssef, A.-R. (2019). Hybrid whale optimization algorithm and grey wolf optimizer algorithm for optimal coordination of directional overcurrent relays. *Electric Power Components and Systems, 47*(7–8), 644–658. [CrossRef]

[9] Ren, J., & Kezunovic, M. (2010, September). Modeling and simulation tools for teaching protective relaying design and application for the smart grid. In *2010 Modern Electric Power Systems* (pp. 1-6). IEEE.

[10] Štefko, R., Šárpataky, M., Šárpataky, Ľ., Kohan, V., Havran, P., & Kolcun, M. (2022). Modeling of protection relays and renewable energy sources for microgrid systems. *Acta Electrotechnica et Informatica, 22*(3), 9-17. [CrossRef]

[11] Godwal, S. D., Pandya, K. S., Vora, S. C., Mehta, C. R., & Rajput, V. R. (2023). Optimal overcurrent relay coordination for interconnected power systems: A proper approach and improved technique. *e-Prime – Advances in Electrical Engineering, Electronics and Energy, 5*, 100248. [CrossRef]

[12] Acharya, D., & Das, D. K. (2022). An efficient optimizer for optimal overcurrent relay coordination in power distribution system. *Expert Systems with Applications, 199*, 116858. [CrossRef]

[13] Kulikov, A., Loskutov, A., & Bezdushniy, D. (2022). Relay protection and automation algorithms of electrical networks based on simulation and machine learning methods. *Energies, 15*(18), 6525. [CrossRef]

[14] Perović, B., Milovanović, M., Vukašinović, J., Jovanović, A., Gajić, M., & Vulović, M. (2024). A simple procedure for evaluating the economic justification of replacing electromechanical relay protection in power plants with microprocessor protection. *23rd International Symposium INFOTEH-JAHORINA*, 20–22 March 2024. [CrossRef]

[15] Milosavljević, S., & Milosavljević, R. (1999). Secondary relay testing device – SIR 3. *Zbornik radova Elektrotehničkog instituta "Nikola Tesla"* (in Serbian), 14, 117-122.

[16] Huazheng Electric Manufacturing (Baoding) Co., Ltd. (n.d.). *HZJB-1200 6 phase relay protection tester - User manual*. Huazheng Electric Manufacturing (Baoding) Co., Ltd., Baoding, China. Retrieved from https://www.huazhengelectric.com

[17] Siemens AG. (2016). *SIPROTEC 4 7SJ62/7SJ63/7SJ64 multifunctional protective relay with local control: Manual*. Retrieved from https://support.industry.siemens.com/cs/document/109743375/

Miloš J. Milovanović received his B.Sc., M.Sc., and Ph.D. degrees in Electrical and Computer Engineering from the Faculty of Technical Sciences, University of Priština in Kosovska Mitrovica, in 2013, 2015, and 2021, respectively. He is currently an Assistant Professor in the Department of Power Engineering at the same faculty. His research interests include power system analysis and optimization, power quality, electrical measurements, and distributed power generation. He has authored or co-authored over 50 journal and conference papers, with more than 450 citations and an h-index of 12. (Email: milos.milovanovic@pr.ac.rs)

Jordan N. Radosavljević received his M.Sc. degree from the Faculty of Electrical Engineering, University of Priština, in 1998, postgraduate M.Sc. degree from the Faculty of Electrical Engineering, University of Belgrade, in 2003, and Ph.D. degree from the Faculty of Technical Sciences, University of Priština in Kosovska Mitrovica, in 2009. He is currently a Full Professor at the same faculty. His research interests include power system analysis and control, power system optimization, as well as the application of metaheuristic optimization algorithms. He has authored and co-authored three university textbooks, two textbook chapters, more than 50 journal papers, and 45 conference papers, with over 1200 citations and an h-index of 16. He is also the author of one international scientific monograph published by the IET and one national scientific monograph. (Email: jordan.radosavljevic@pr.ac.rs)

Bojan D. Perović received his B.Sc., M.Sc., and Ph.D. degrees in Electrical and Computer Engineering from the Faculty of Technical Sciences, University of Priština in Kosovska Mitrovica, in 2011, 2012, and 2018, respectively. He is currently an Associate Professor in the Department of Power Engineering at the same faculty. His research interests include renewable energy sources and power cable systems. He has authored or co-authored over 50 journal and conference papers, with more than 250 citations and an h-index of 10. (Email: bojan.perovic@pr.ac.rs)