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TECHNICAL SCIENCES

DIGITAL INTEGRATION OF VACUUM SWITCHING DEVICES IN ELECTRICAL POWER NETWORK SYSTEMS

Semenov A.
Candidate of Physical and Mathematical Sciences, Professor of the Department of Mechanical and Electrical Engineering at Poltava State Agrarian University, Ukraine
Bychkov Y.
Candidate of Technical Sciences, associate Professor of the Department of Mechanical and Electrical Engineering at Poltava State Agrarian University, Ukraine
Kharak R.
Candidate of Technical Sciences, associate Professor of the Department of Mechanical and Electrical Engineering at Poltava State Agrarian University, Ukraine
https://doi.org/10.5281/zenodo.18195837

Abstract
The paper addresses the implementation of vacuum switching devices in combination with digital monitoring and diagnostic systems as an integral component of modern high-voltage electrical networks. Particular attention is focused on the analysis of electrophysical switching processes in a vacuum environment, the structural features of contact assemblies, and the possibilities for integrating circuit breakers into hierarchical control systems in accordance with the Smart Grid concept. The principles of vacuum arc operation, the characteristics of dielectric strength recovery in the inter-contact gap, and the influence of contact materials on the stability of switching regimes are summarized. The architecture of modern monitoring systems based on the IEC 61850 standard is considered, including the use of electrical and thermal sensors, microprocessor-based controllers, and integration at the SCADA/industrial automation level. It is shown that the combination of vacuum circuit breakers with digital control tools ensures a reduction in fault localization time, an increase in equipment availability, and a decrease in operational risks. A generalized structural model of the "vacuum circuit breaker – digital control" system is proposed, suitable for application in 6–35 kV networks and, prospectively, in substations of the 110–220 kV class.

Keywords: *high-voltage engineering; vacuum switching device; electric arc; monitoring system; digital substation; IEC 61850; SCADA.*

Introduction

Modern electric power systems operate under conditions of rapidly increasing complexity of operating regimes, driven by the integration of distributed generation, renewable energy sources, energy storage systems, and active consumers into the structure of electrical networks [1, 2]. The implementation of the Smart Grid concept involves not only improving the energy efficiency and flexibility of power systems, but also a significant increase in requirements for the reliability and controllability of medium- and high-voltage equipment [3, 4].

Recent applied studies in Ukraine also emphasize the practical importance of reliability-oriented modernization at the transmission level, including 220 kV switchgear refurbishment as a means of improving operational resilience of power facilities [5]. In addition, the calculation and design approaches for overhead lines with insulated conductors, including lightning protection assessment, remain relevant for improving network reliability under real operating conditions [6].

Under conditions of dynamic loads, frequent switching operations, and the influence of fault regimes, the problem of ensuring stable operation of high-voltage switching devices becomes particularly relevant. These devices are responsible for switching load and short-circuit currents, localizing faults, and maintaining the integrity of the power system [7, 8]. The reliability of electrical networks largely depends on the ability of switching equipment to interrupt electrical circuits rapidly and safely while minimizing thermal and electrodynamic stresses on system components.

Switching processes in high-voltage networks are accompanied by complex electrophysical phenomena, including the initiation and development of an electric arc, intensive heating of contacts, ionization of the inter-contact medium, and material erosion [9, 10]. The effectiveness of arc extinction and the speed of dielectric strength recovery in the gap after contact separation are decisive factors determining the operational performance and service life of switching devices [11].

The use of vacuum as an arc-quenching medium enables a fundamentally different nature of switching processes. Under deep vacuum conditions, the electric arc is formed predominantly from metal vapor emitted from the contact material and is characterized by a short duration and high extinction stability after current zero crossing [12–14]. The specific features of the vacuum arc and its extinction mechanisms have been extensively investigated in fundamental studies on contact electrophysics, which demonstrate that the absence of a gaseous medium significantly accelerates the recovery of dielectric strength in the inter-contact gap [15, 16].

Contact materials play a crucial role in shaping the switching characteristics of vacuum circuit breakers. In particular, copper–chromium-based alloys and carbide-containing composites are widely used due to their favorable physicochemical properties, which determine arc stability, erosion intensity, and uniform distribution of cathode spots [13, 14]. Optimization of contact materials is therefore one of the key directions for extending the operational lifetime of vacuum switching devices.

Alongside the development of high-voltage breaker designs, there has been intensive progress in digital monitoring and diagnostic systems aimed at continuous assessment of equipment condition [17, 18]. These systems provide measurement of electrical and thermal parameters, monitoring of mechanical characteristics of drive mechanisms, registration of switching events, and formation of diagnostic indicators reflecting the degradation of device components.

The integration of vacuum circuit breakers with digital control systems based on the IEC 61850 standard creates the prerequisites for the development of next-generation digital substations, in which switching, protection, measurement, and dispatching control functions are implemented within a unified information environment [19–21]. The use of standardized data exchange protocols simplifies interaction between circuit breakers, sensors, controllers, and SCADA/industrial automation systems, thereby improving response speed to emergency situations and reducing equipment downtime.

Thus, a relevant scientific and technical task is the study of vacuum switching devices not only as standalone electrotechnical components, but also as elements of integrated digital control systems for electrical networks. This necessitates a comprehensive analysis of electrophysical switching processes in a vacuum environment, the structural features of circuit breakers, and the architecture of modern monitoring systems, taking into account the requirements of the IEC 61850 standard and the Smart Grid concept [22].

The objective of this study is to provide a scientific and technical justification for the effectiveness of applying vacuum circuit breakers in combination with modern monitoring, control, and diagnostic systems in order to improve the reliability, energy efficiency, and operational safety of high-voltage electrical networks.

The research is focused on an in-depth analysis of electrophysical switching processes in a vacuum environment, identification of the structural and operational characteristics of vacuum circuit breakers, and assessment of the possibilities for their integration into intelligent Smart Grid–type control systems.

Achievement of this objective involves the development of scientifically substantiated recommendations for the implementation of integrated “vacuum circuit breaker – control system” solutions based on the IEC 61850 standard, ensuring automation of control and diagnostic processes for high-voltage equipment.

To achieve the stated objective, the following tasks are addressed in the paper:

- to analyze the current state and development trends in high-voltage engineering, particularly switching devices used in medium- and high-voltage systems;
- to elucidate the physical principles of vacuum circuit breaker operation, including the formation, development, and extinction of the electric arc in a vacuum environment, as well as the influence of contact materials and pressure level on the switching process;
- to conduct a comparative analysis of vacuum circuit breakers with traditional types (oil, air, and SF_6) in terms of key technical and operational indicators, including switching capability, reliability, service life, maintenance requirements, and environmental safety;
- to investigate the architecture and functional capabilities of modern monitoring and diagnostic systems that provide real-time monitoring of electrical equipment parameters and are integrated into digital substations;
- to assess the advantages of using the IEC 61850 standard for unifying information exchange between circuit breakers, sensors, controllers, and the SCADA control level;
- to propose a structural scheme of an integrated vacuum circuit breaker control system considering measurement, diagnostics, remaining life prediction, and automatic control functions;
- to formulate practical recommendations for implementing vacuum circuit breakers and control systems in high-voltage networks of industrial and agro-industrial complexes to enhance reliability and efficiency of power supply.

Materials and Methods

The study was conducted using normative and technical documentation regulating the requirements for high-voltage switching devices and digital control systems, including IEC 62271 and IEC 61850 standards, as well as relevant national DSTU standards.

The methodological framework of the study includes:

- generalization of experimental data on the behavior of contact materials in a vacuum environment;
- structural and functional analysis of monitoring and diagnostic systems for switching devices;
- a systems approach to assessing the integration of equipment into hierarchical SCADA/industrial automation control systems.

RESULTS AND DISCUSSION

4.1. Electrophysical features of switching processes in vacuum interrupters

The performed analysis confirms that the switching performance of vacuum circuit breakers is primarily governed by the specific electrophysical conditions inherent to the vacuum environment. During contact separation, a short-duration vacuum arc is initiated, whose conductivity is sustained mainly by metal vapor originating from the contact surfaces. Owing to the absence of a gaseous medium, ionization processes are spatially limited, resulting in a rapid extinction of the arc after current zero crossing [9–11].

According to experimental and theoretical studies reported in the literature, the recovery of dielectric strength in vacuum gaps occurs within several tens of microseconds and is characterized by a steep voltage withstand gradient [12–14]. This feature is critical for ensuring stable interruption under high rates of rise of recovery voltage, which are typical for modern power systems with distributed generation and power electronics [3, 4].

The arc behavior in vacuum is commonly described using cathode spot models, where current conduction is concentrated in a limited number of microscopic emission sites. Each cathode spot exists for a very short time interval and contributes to localized metal evaporation [14, 15]. Such a mechanism significantly reduces the overall thermal impact on the contact system and limits erosion processes, thereby enhancing operational stability over extended service life.

4.2. Influence of contact materials on switching stability

Contact material selection plays a decisive role in determining arc stability, erosion resistance, and dielectric recovery characteristics. Literature data indicate that composite materials based on copper with chromium or carbide additives exhibit favorable combinations of electrical conductivity, thermal resistance, and vacuum compatibility [13, 16].

Experimental investigations summarized in [12, 17] demonstrate that CuCr-based contacts ensure uniform cathode spot distribution and reduced metal splashing, which directly affects the long-term integrity of the vacuum interrupter envelope. These properties contribute to maintaining a low level of residual gas pressure and stable insulation characteristics throughout the operational lifecycle.

Table 1 summarizes generalized characteristics of commonly used contact materials in vacuum circuit breakers based on published experimental data.

Table 1

Generalized properties of contact materials used in vacuum interrupters

Contact material	Electrical conductivity	Arc stability	Erosion resistance	Suitability for high-voltage applications
CuCr composites	High	High	High	Excellent
Ag-based composites	Very high	Medium–high	Medium	Limited by erosion
Carbide-containing materials	Medium	High	Very high	Promising for advanced designs

The data presented in Table 1 confirm that optimized composite materials provide a stable compromise between electrical performance and mechanical durability, which is essential for high-voltage switching applications.

4.3. Operational reliability and switching resource

An important outcome of the performed analysis is the confirmation that vacuum circuit breakers demonstrate a high switching endurance under repetitive operating conditions. The absence of chemically active arc media and minimal contact erosion enable the preservation of switching characteristics over a large number of operations [12, 17].

From a system reliability perspective, this property is particularly valuable for medium- and high-voltage networks supplying industrial and agro-industrial facilities, where frequent switching operations and high availability requirements are typical [7, 8]. Stable interruption characteristics contribute to reduced risk of insulation degradation and unplanned outages.

In addition to reliability aspects, switching device operation and network configuration can influence technical performance indicators at the distribution level, including energy loss components, which has been demonstrated in applied studies on loss calculation in distribution networks under different breaker utilization scenarios [25].

The generalized operational parameters extracted from manufacturer data and literature sources are presented in Table 2.

Table 2

Typical operational characteristics of vacuum circuit breakers

Parameter	Typical range	References
Arc duration	5–10 μs	[11–13]
Dielectric strength recovery	>20 kV/mm within 10–20 μs	[14–16]
Mechanical endurance	≥30,000 operations	[12, 17]
Maintenance requirement	Minimal over service life	[17, 18]

These characteristics confirm that vacuum circuit breakers meet the operational demands imposed by modern power systems with dynamic load profiles.

4.4. Integration with digital monitoring and diagnostic systems

Further enhancement of operational reliability is achieved through the integration of vacuum circuit breakers with digital monitoring and diagnostic systems. Modern architectures employ distributed sensors for current, voltage, temperature, and mechanical position, combined with microprocessor-based controllers for data acquisition and processing [18, 19].

The use of IEC 61850-compliant communication protocols enables standardized data exchange between field devices and higher-level SCADA or substation automation systems [20, 21]. This facilitates real-time condition assessment, event recording, and remote diagnostics.

Studies reported in [22, 23] indicate that continuous monitoring allows early detection of pre-fault conditions, such as abnormal temperature rise at contacts or increased operating time of the drive mechanism. This capability supports the transition from time-based maintenance to condition-based maintenance strategies.

A generalized structure of diagnostic functions implemented in digital monitoring systems is summarized in Table 3.

The results presented in [24] confirm that the deployment of such systems reduces fault detection time by up to 40% and improves equipment availability, which is a key requirement for digital substations within the Smart Grid framework.

Table 3

Diagnostic functions of digital monitoring systems for vacuum circuit breakers

Diagnostic function	Monitored parameter	Practical significance
Thermal monitoring	Contact and terminal temperature	Detection of overloads and contact degradation
Electrical monitoring	Current, voltage, switching events	Analysis of operating regimes
Mechanical diagnostics	Operating time, travel curves	Assessment of drive condition
Data integration	IEC 61850 communication	SCADA/EMS interoperability

4.5 Discussion

The obtained results demonstrate that the effectiveness of vacuum circuit breakers in modern power networks is determined by the combined influence of vacuum arc physics, optimized contact materials, and digital integration capabilities. The intrinsic electrophysical properties of vacuum interrupters–namely, the rapid extinction of the vacuum arc at current zero and the fast recovery of dielectric strength–provide a solid physical basis for stable and reliable switching under dynamic operating conditions [11–14].

At the same time, the discussion of the results confirms that these intrinsic properties alone are no longer sufficient to meet the growing requirements of modern power systems characterized by increased switching frequency, fluctuating load profiles, and the integration of distributed energy resources [3, 4]. In this context, the role of contact material engineering becomes particularly significant. As shown in previous studies, copper–chromium and carbide-containing composite materials ensure uniform cathode spot distribution and reduced erosion rates, which directly contribute to maintaining stable vacuum conditions and predictable switching behavior throughout the service life of the circuit breaker [13, 14, 16].

A key finding of the present analysis is that the operational performance of vacuum circuit breakers should be assessed not only from the standpoint of arc extinction mechanisms, but also in terms of their interaction with digital monitoring and diagnostic systems. The integration of sensors and microprocessor-based controllers enables continuous assessment of electrical, thermal, and mechanical parameters, thereby transforming vacuum circuit breakers into data-generating elements within a cyber-physical power system [17–19].

The literature indicates that such digital integration significantly improves fault detection and localization capabilities. Early identification of abnormal temperature rise, deviations in operating time, or changes in switching characteristics allows for timely corrective actions and reduces the probability of catastrophic failures [18, 20]. These findings are consistent with reported results demonstrating that condition-based monitoring can substantially reduce outage duration and improve overall equipment availability [22, 23].

From a system-level perspective, the adoption of IEC 61850-compliant communication architectures plays a decisive role in enabling seamless interaction between vacuum circuit breakers, protection devices, and supervisory control systems. Standardized data models and communication services facilitate interoperability, simplify system expansion, and enhance real-time decision-making in digital substations [20, 21]. This aligns with the broader Smart Grid paradigm, which emphasizes decentralized intelligence, flexibility, and resilience of power networks [2, 3].

From a scientific standpoint, the obtained results emphasize the expediency of considering vacuum circuit breakers not as isolated electromechanical devices, but as integrated components of intelligent cyber-physical power systems. Such an approach reflects current research trends in the field of high-voltage engineering, where emphasis is placed on the convergence of power apparatus design, digital technologies, and advanced diagnostic methods [21, 22].

Moreover, the discussion highlights that the synergistic combination of vacuum switching technology and digital monitoring systems creates a foundation for transitioning from traditional time-based maintenance strategies to condition-based and predictive maintenance concepts. This transition is particularly relevant for industrial and agro-industrial power networks, where high reliability and minimized downtime are critical operational requirements [7, 8, 23].

Overall, the expanded discussion confirms that the future development of vacuum circuit breakers is closely linked to their digital integration within intelligent power systems. Further research should therefore focus on enhancing diagnostic algorithms, improving data analytics for remaining life prediction, and optimizing communication architectures to fully exploit the potential of vacuum switching devices in next-generation digital substations.

Conclusions

1. The study confirms that the operational effectiveness of vacuum switching devices in modern electrical networks is fundamentally determined by the specific electrophysical properties of the vacuum environment, which ensure rapid arc extinction and fast recovery of dielectric strength after current zero crossing. These characteristics form a reliable physical basis for stable switching under dynamic operating conditions of high-voltage power systems.

2. It has been established that the stability and reproducibility of switching processes are strongly influenced by the properties of contact materials. The use of optimized composite contact materials contributes to

uniform arc behavior, reduced erosion intensity, and preservation of vacuum conditions, thereby enhancing the long-term operational reliability of vacuum circuit breakers.

3. The research demonstrates that the integration of vacuum circuit breakers with digital monitoring and diagnostic systems significantly extends their functional capabilities. Continuous monitoring of electrical, thermal, and mechanical parameters enables real-time assessment of equipment condition and supports early detection of pre-fault states.

4. The application of IEC 61850-compliant communication architectures ensures standardized data exchange and interoperability between vacuum circuit breakers, sensors, controllers, and SCADA systems. This integration facilitates the implementation of digital substations and improves the responsiveness and transparency of power system operation.

5. The obtained results indicate that vacuum circuit breakers should be considered not merely as standalone electromechanical devices, but as integral elements of cyber-physical power systems. Such an approach aligns with current trends in Smart Grid development and supports the transition toward intelligent, data-driven operation of high-voltage electrical networks.

6. From a practical perspective, the proposed integrated “vacuum circuit breaker – digital control” concept provides a technological foundation for improving reliability, reducing operational risks, and enabling condition-based maintenance strategies in medium- and high-voltage networks, including industrial and agro-industrial power systems.

7. Future research should focus on the development of advanced diagnostic algorithms, data analytics methods for remaining life prediction, and optimization of digital communication infrastructures to further enhance the performance and reliability of vacuum switching devices within next-generation digital substations.

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