DESIGN OF A VACUUM CONTACT PAIR FOR 660/1140 V SWITCHGEARS USED IN UNDERGROUND MINE POWER NETWORKS

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ABSTRACT

The vacuum contact pair located in interruption chamber (The vacuum contact pair) is the core component of switchgears used in mining power systems. The design and evaluation process of the vacuum contact pair are often influenced by empirical parameters. With the advancement of modern technology, the application of numerical simulation tools in vacuum contact pair design has significantly improved reliability and shortened the design time. This paper presents the analysis and design of a vacuum contact pair using the finite element method (FEM) implemented in ANSYS software. Experimental validation was conducted on a physical prototype to verify the theoretical results. The findings of this study provide a solid scientific basis for domestic manufacturers to develop and produce vacuum switchgears, contributing to the replacement of imported equipment for mining power systems.

Keywords: *Arc-quenching chamber, Finite Element Analysis (FEA), Vacuum Circuit Breaker-VCB, Vacuum contact pair.*

1. INTRODUCTION

Vacuum circuit breakers (VCBs) are critical components in electrical distribution systems. Especially in underground coal mines, the VCB with 1140 VAC designed to interrupt high voltage and currents resulting from short circuits or other faults such as overcurrent or voltage also. The interruption process involves the generation of an electrical arc within the arcquenching chamber, which must be extinguished rapidly to prevent damage and ensure reliability. The behavior of the arc, particularly under high currents, is complex and often leads to arc constriction, resulting in electrode melting and reduced interruption capacity. To mitigate these effects, axial magnetic felds (AMF) are employed to diffuse the arc, enhancing the VCB's performance. The arc-quenching chamber has been designed to avoid sparking or deforming copper contactors [1].

The main design requirements for the vacuum arc-interruption chamber in 660/1140 V mining switchgear are summarized as follows:

a) Dielectric Withstand Voltage: The insulation level must comply with the rated voltage of 1140 V, with appropriate creepage and clearance distances designed according to applicable IEC/EN insulation coordination standards. The design shall ensure sufficient dielectric margins under high humidity and dust conditions typically found in mining environments;

b) Breaking and Short-Circuit Currents: The vacuum contact pair located in interruption chamber and its mechanical components must withstand the arc energy generated during current interruption. The design shall be verified according to the rated breaking capacity and short-circuit current values specified for the switchgear system and the vacuum interrupter manufacturer's data;

c) Operating Vacuum Level in chamber: The internal vacuum pressure shall be maintained within the limits recommended by the vacuum interrupter manufacturer (typically $10^{-4} - 10^{-6}$ Torr);

d) The sealing and enclosure design must ensure long-term vacuum retention throughout the operational lifespan of the equipment;

e) Materials Selection: All materials used in the chamber shall be chemically resistant, corrosion-proof, and mechanically stable under mining conditions;

f) The inner surfaces should minimize dust adhesion;

g) Seals and gaskets must withstand temperature variations, chemical exposure, and repeated mechanical operations (closing/opening cycles) without degradation;

h) Thermal Management: The design must evaluate the heat losses due to current conduction and arcing, and provide adequate cooling mechanisms — either natural convection or forced ventilation with dust-filtered air. The maximum operating temperature must remain within safe limits for both the vacuum interrupter and the conductive terminals to prevent performance degradation.

Finite Element Analysis (FEA) has emerged as a powerful tool for modeling multiphysics phenomena in vacuum circuit breakers (VCBs), including the coupling effects of electromagnetic, thermal, and fluid dynamic fields. This paper employs the commercial FEA software ANSYS to simulate the arc-quenching chamber of a VSm-type VCB. The analysis focuses on the distribution of electric fields and potentials within the contact pair chamber. The objective of this study is to provide a quantitative understanding of arc behavior and to propose design improvements aimed at enhancing the operational reliability and arc-quenching performance of vacuum circuit breakers [2], [3].

2. MATERIALS AND METHODS

2.1. Finite Element Method (FEM)

The magnetic field distribution in the magnetic circuit and the surrounding space of the electromagnetic mechanism is the solution of the Poisson equation formulated for the electromagnetic field of the motor model. This model is developed based on Maxwell–Ampere's law. According to Maxwell–Faraday's equation, for the steady-state condition of the electrical machine, it can be expressed as follows [4]:

$$\nabla \times \vec{H} = \vec{J} \quad (1)$$

where: $\vec{J}$ - DC current density flowing in the electromagnet coil, A/m^2; $\vec{H}$ - magnetic field strength, H/m.

magnetic field strength $\vec{H}$ related to magnetic flux density $\vec{B}$.

$$\vec{B} = \mu_0 \mu_r \vec{H} \quad (2)$$

where: μ_0 - permeability of vacuum; μ_r- relative permeability of the conducting medium.

Magnetic flux density $\vec{B}$ calculated via vector quantities from the potential $\vec{A}$:

$$\vec{B} = \nabla \times \vec{A} \quad (3)$$

Substitute (2) and (3) into (1), we get equation.

$$\nabla \times \left(\frac{1}{\mu_0 \mu_r} \nabla \times \vec{A}\right) = \vec{J} \quad (4)$$

Equation (4) has the general form of Poisson's equation, which can be interpreted in the analytical model corresponding to the Oxyz coordinate system as follows:

$$\frac{1}{\mu_0 \mu_r}\left(\frac{\partial^2 A}{\partial x^2} + \frac{\partial^2 A}{\partial y^2} + \frac{\partial^2 A}{\partial z^2}\right) + J = 0 \quad (5)$$

Solve (5), find $\vec{A}$, then based on (2) and (3) to calculate the magnetic flux density B and magnetic field strength H as follows:

$$\vec{B} = B_x\vec{\imath} + B_y\vec{\jmath} + B_z\vec{k} = \left(\frac{\partial A_z}{\partial y} - \frac{\partial A_y}{\partial z}\right)\vec{\imath} + \left(\frac{\partial A_x}{\partial z} - \frac{\partial A_z}{\partial x}\right)\vec{\jmath} + \left(\frac{\partial A_y}{\partial x} - \frac{\partial A_x}{\partial y}\right)\vec{k} \quad (6)$$

Given the applied voltage across the coil terminals and the DC resistance of the winding, the current density can be determined from the following equations:

$$U = R_{dc} i + L\frac{di}{dt};\ I_{dc} = \frac{U}{R_{dc}} \quad (7)$$

where: U - voltage applied to the two poles of the coil; R_{dc} - coil resistance; L- coil inductance; I_{dc} - current in the coil; S_{dq} - coil cross section.

The Finite Element Method (FEM) is a numerical technique used to solve equation (5) to determine the magnetic vector potential $\vec{A}$, t from which the magnetic flux density $\vec{B}$ and magnetic field intensity $\vec{H}$ can be calculated using equations (3) and (2), respectively. This enables accurate determination of the magnetic field distribution in space, providing valuable insights for designers and operators in adjusting the parameters of the electromagnetic mechanism in magnetic separators to optimize the field distribution and improve machine performance. The FEM procedure consists of the following four fundamental steps:

a) Discretize the analysis domain into subdomains (elements). These elements are interconnected to form a computational mesh;

b) Select the interpolation (shape) functions and approximate the solution within each element;

c) Assemble all elements within the analysis domain to obtain the global system matrix;

d) Solve the global matrix equation using an iterative numerical method.

To perform computations using the Finite Element Method (FEM), digital computers and specialized software programs based on the mathematical foundations of FEM are required.

2.2. FEM model for vacuum circuit breaker

A finite element model (FEM) of the vacuum contact assembly was developed to simulate and evaluate its operating characteristics. The FEM configuration shows the vacuum contact assembly in VCB (Fig. 1) and the magnetic actuator that generates the attraction force (Fig. 2) [5]. In the ANSYS model, a dense mesh is applied around the electrode region to accurately determine the electric potential gradient, thereby enabling simulation of the formation of the cathode spot—the initial stage of the vacuum arc discharge. These simulation results provide a quantitative foundation for understanding arc behavior during the initial phase of the switching process.

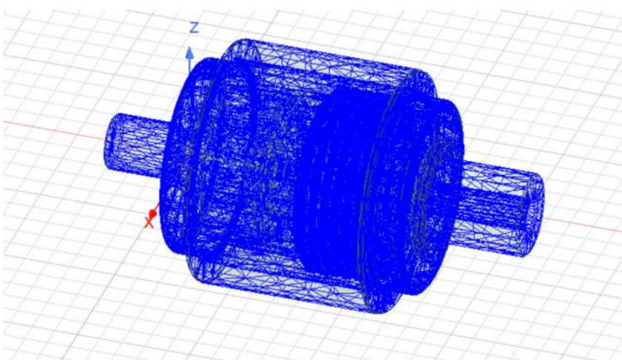

Figure 1. Vacuum contact assembly in VCB

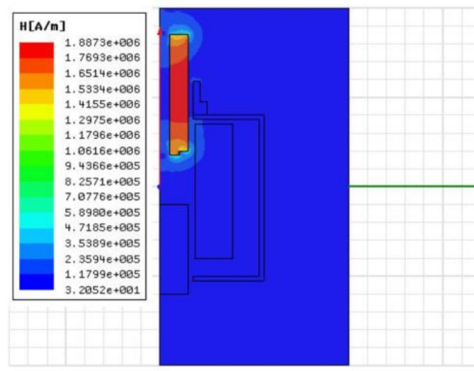

Figure 2. Electromagnet and the attraction force

Based on the established FEM model, the force characteristics of the vacuum contact assembly were analyzed under varying excitation currents supplied to the electromagnetic coil. The resulting electromagnetic attraction force is illustrated in Fig. 3.

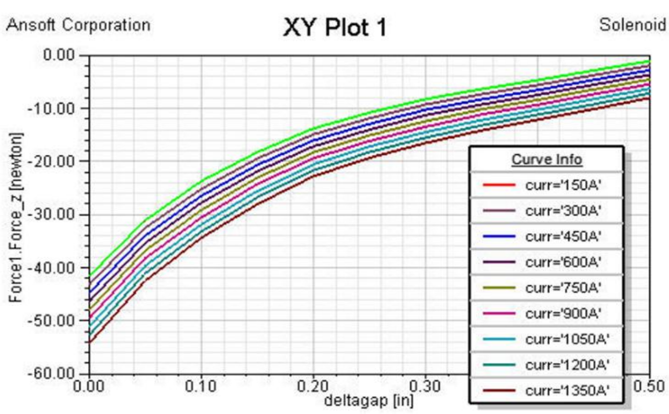

Figure 3. Relationship between electromagnetic force and electric current

Figure 4. Prototype Vacuum contact assembly

Thermal–electromagnetic analysis reveals that the maximum temperature region is concentrated at the center of the electrode, reaching approximately 12,000–15,000 K, while the boundary region maintains a lower range of 4,000–6,000 K. This temperature gradient is consistent with spectroscopic camera observations in practical arc-quenching chambers, confirming the high reliability of the simulation model. The combined results from ANSYS enable the development of a coupled-field model integrating electric, thermal, and electromagnetic interactions, providing a solid foundation for optimizing the design of AMF-type vacuum arc-quenching chambers.

The Lorentz force distribution within the model clearly illustrates two opposite action regions: at the cathode, the force is directed inward, leading to arc constriction; whereas at the anode, the force is directed outward, promoting plasma diffusion. Consequently, the model demonstrates the dynamic equilibrium mechanism of the arc column, facilitating arc stabilization and faster extinction as the current passes through the zero point.

2.3. Vacuum contact assembly in -VCB test evaluation

To mitigate contact erosion and enhance arc stability, this study proposes replacing pure copper contacts with copper–chromium (Cu–Cr) and tungsten–copper (W–Cu) alloys. These alloys exhibit superior thermal resistance, reduced material evaporation rates, and maintain electrical conductivity comparable to that of pure copper. Several international experimental investigations (conducted in Russia, Germany, and China) have demonstrated that CuCr30 and W–Cu alloys can reduce contact erosion rates by approximately 60–70% and extend the electrical lifetime by a factor of 2–3 compared with conventional copper contacts [6], [7]. To validate these findings, the research team fabricated a prototype vacuum contact assembly rated at 400 A and operating voltage of 660/1140 V, as illustrated in Fig. 4.

The model consists of five main components: the fixed contact, moving contact, bellows, vapor shield, and ceramic insulator, which are modeled with axial symmetry (Z-axis as the symmetry axis). All geometric dimensions are defined in millimeters to accurately represent the VSm-type configuration. The bellows are made of stainless steel, the ceramic insulator is composed of Al_2O_3, and the remaining parts are manufactured from high-purity copper. The prototype vacuum contact assembly was experimentally tested in the laboratory using the experimental setup illustrated in Fig. 5.

Figure 5. Vacuum contact assembly in VCB, Test Evaluation

Figure 6. High-voltage generator of 13.6 kVAC

The insulation test of the vacuum contact was conducted at an applied voltage of 13.6 kVAC using a high-voltage generator, as shown in Fig. 6.

According to the experimental results obtained, during a single current interruption cycle at 30 kA, the temperature of the copper contact increased by approximately 1200 K, approaching the melting threshold. A slight melting phenomenon was observed at the cathode center, accompanied by material evaporation at the arc periphery. These phenomena are consistent with simulation results, where the central electrode region exhibits maximum current density and Lorentz force, leading to the highest energy concentration.

3. CONCLUSIONS

This study has demonstrated the effectiveness and high accuracy of the finite element analysis (FEA) method in simulating, analyzing, and optimizing the arc-quenching performance of contact pair in vacuum circuit breakers (VCBs). By combining ANSYS tools, a coupled multiphysics model (electromagnetic–thermal–fluid) was developed to accurately represent the complex physical phenomena occurring within the vacuum interrupter. The results confirm that optimizing the axial magnetic field and selecting appropriate contact materials are the two most critical factors in preventing arc constriction and enhancing the interruption capability of VCBs under high short-circuit current conditions ❐

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THIẾT KẾ CỤM TIẾP ĐIỂM CHÂN KHÔNG CHO CÁC THIẾT BỊ ĐÓNG CẮT 660/1140V SỬ DỤNG TRONG MẠNG ĐIỆN MỎ HẦM LÒ

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TÓM TẮT

Cụm tiếp điểm chân không là bộ phận lõi của các thiết bị đóng cắt được sử dụng trong hệ thống điện mỏ. Quá trình thiết kế và đánh giá cụm tiếp điểm chân không thường bị chi phối bởi các tham số kinh nghiệm. Với sự phát triển của công nghệ hiện đại, việc ứng dụng các công cụ mô phỏng số trong thiết kế cụm tiếp điểm chân không đã góp phần nâng cao độ tin cậy và rút ngắn thời gian thiết kế. Bài báo này trình bày quá trình phân tích và thiết kế cụm tiếp điểm chân không bằng phương pháp phần tử hữu hạn (FEM) được triển khai trong phần mềm ANSYS. Việc thử nghiệm đã được tiến hành trên mẫu nguyên mẫu vật lý nhằm kiểm chứng các kết quả lý thuyết. Kết quả nghiên cứu này cung cấp cơ sở khoa học vững chắc cho các nhà sản xuất trong nước trong việc phát triển và chế tạo cụm tiếp điểm chân không sử dụng trong các máy đóng cắt, góp phần thay thế thiết bị nhập khẩu phục vụ cho hệ thống điện mỏ.

Từ khóa: *Buồng dập hồ quang, phân tích phần tử hữu hạn (FEA), máy cắt chân không-VCB, Cụm tiếp điểm chân không*