Research on Online Detection System for Electrical Wear of Vacuum Circuit Breaker Contacts: Postprint

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Abstract

The development of smart grid technology has posed new requirements and challenges for the intelligentization of high-voltage switchgear. Based on the intelligentization requirements of high-voltage switchgear—namely self-monitoring, self-diagnosis, and self-control capabilities—this paper designs an online monitoring device for electrical wear of the contact system in the intelligentization process of vacuum circuit breakers. The wear calculation of the contact system for this device employs an improved cumulative weighted method for breaking current, wherein the selection of weight values and calculation of total wear are obtained by fitting the electrical life curve using the least squares method. This method is universal and can be applied to different types of vacuum circuit breakers. The weighted integral coefficient K is dynamically predicted using a trained LM-BP neural network, making the selection of K values more consistent with engineering practice. An arcing time sensor is utilized to acquire arcing time, and the installation position of the arcing time sensor along with the adopted shielding measures are presented. The hardware processing core adopts the TMS320F2812 microprocessor chip, which is primarily responsible for algorithm processing, host computer communication, and CAN-BUS controller area network communication. Short-circuit current is collected using a Rogowski coil, and a current processing circuit is designed, with the 2812AD sampling correction method provided. Finally, the software flow for online monitoring of contact system wear and key technologies that should be noted during design are presented.

Full Text

Preamble

The On-Line Monitoring Application Study of Vacuum Circuit Breaker Contact Electrical Wear

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Abstract

The development of smart grid technology has introduced new requirements and challenges for the intelligentization of high-voltage switching equipment. Based on the intelligentization requirements for high-voltage switches—specifically self-monitoring, self-diagnosis, and self-control capabilities—this paper designs an online monitoring device for the electrical wear of vacuum circuit breaker contact systems during their intelligentization process. The device employs an improved cumulative weighted method for breaking current to calculate contact system wear, where the weight selection and total wear calculation are derived through least squares fitting based on electrical life curves. This approach offers universality and can be applied to different vacuum circuit breaker models. The weighted integral coefficient K is dynamically predicted using a trained LM-BP neural network, making the K-value selection more consistent with engineering practice. An arcing time sensor is utilized to acquire arcing duration, with detailed specifications for its installation position and shielding measures. The hardware processing core adopts the TMS320F2812 microprocessor chip, primarily responsible for algorithm processing, host computer communication, and CAN-BUS controller area network communication. Short-circuit current is collected using a Rogowski coil, with a designed current processing circuit and a 2812 AD sampling correction method presented. Finally, the software flow for online monitoring of contact system wear and key technologies for design implementation are discussed.

Keywords: Vacuum circuit breaker, electrical wear, online monitoring, contact system

1 Introduction

Circuit breakers serve critical protection and control functions in power grids, and their performance directly impacts grid safety and stable operation. Vacuum circuit breakers (VCBs), with their excellent breaking performance and environmentally friendly characteristics, are widely used in medium- and low-voltage power systems and have achieved certain successes in advancing toward high- and ultra-high-voltage domains [1-2]. In high- and ultra-high-voltage fields, SF gas has a global warming potential 24,900 times that of CO and a lifespan of 3,200 years [1]. According to the Kyoto Protocol, SF gas will be completely banned by 2030 [2], foreshadowing broader future applications for vacuum circuit breakers.

The contact system represents the core component of vacuum circuit breakers, and its lifespan directly affects the overall breaker lifespan. Particularly with the development of smart grids and reliability-based power equipment monitoring, lifespan assessment and online monitoring have become critically important. This evolution has progressed through three stages: First, visual marks on the moving conducting rod indicated wear degree. Second, assessment and monitoring through weighted cumulative breaking current. Third, online monitoring and prediction using improved weighted cumulative methods. Stage one provides only rough estimates with poor accuracy [3]. Stage two fails to consider practical operational factors such as current magnitude differences between phases and variations in arcing time, leading to significant errors between fault and non-fault phases [3]. Stage three addresses the conditions ignored in stage two and can be applied for engineering evaluation of contact system electrical life, though it lacks systematic and unified methods for determining required parameters, making parameter identification difficult [3-4].

This paper systematically investigates the parameter determination methods for stage three. Inspired by the SF contact wear equivalent law obtained by Électricité de France (EDF) and Italian engineering guidance companies (ENEL) [5-6], and referencing the VCB electrical life conversion formula from literature [7], this study employs extensive mathematical experimentation and verification analysis. Based on electrical life curves, the least squares method is applied to select and analyze the current exponent and theoretical wear total in the improved cumulative weighted breaking current method.

[Figure 1: see original paper] illustrates a typical set of electrical life curves, whose mathematical analysis yields the fitted curve shown in [Figure 2: see original paper] depicting the relationship between breaking current and breaking times. The curve represents the relationship between breaking current magnitude and breaking count, with the corresponding fitting formula. Research results demonstrate that the curve exhibits certain smoothness characteristics, and breakers with higher rated currents achieve greater breaking counts at the same breaking current.

2.1 Selection of Current Exponent and Calculation of Wear Total

Following the calculation method for theoretical wear total presented in literature [3-4], the functional relationship between weight values and their corresponding parameters can be obtained. Using the example of a rated current In = 1,600A shown in [Figure 1: see original paper], the relationship between wear total Qg and weight value is derived. The analysis yields N(I) expressions for different rated currents. By substituting a certain quantity of breaking current values into these equations, [Figure 3: see original paper] illustrates the relationship between theoretical wear total Qg and weight value for different breaking currents.

Analysis of [Figure 3: see original paper] reveals that after determining contact material, structure, and arc extinguishing method, the theoretical wear total and weight value become uniquely determined. For the 1,600A case, the graph identifies Qg = 50,500 and = 1.93. Applying this method to the electrical life curve from literature [4] yields the relationship between theoretical wear total Qg and weight value shown in [Figure 3: see original paper]. Literature [4] selected = 1.91 and Qg = 87,300, while this method calculates = 1.918 and Qg = 89,979. Comparative analysis shows Δ = 0.418% and ΔQg = 3.07%, demonstrating that the proposed design method is both accurate and universally applicable.

2.2 Characteristics and Selection Method of Integral Current Coefficient

Literature [4] proposed an improved cumulative weighted breaking current method and presented a calculation approach for the integral current coefficient K, evaluating it based on ideal breaking conditions according to electrical life curves. The calculation assumes uniform distribution of arcing time within the arcing interval, whereas actual breaking operations exhibit three-phase arcing time non-uniformity, resulting in conservative K-value calculations [4]. Building upon the K-value calculation research in literature [4], this study considers the influence of arcing time differences and breaking count, analyzing the distribution characteristics of K-values and performing dynamic analysis.

Theoretical calculations and experimental verification produce the K-value distribution pattern shown in [Figure 4: see original paper], where curves represent the relationship between first-breaking-phase arcing time and K-value at different breaking currents. Here, tmin denotes minimum arcing time, i represents breaking count, and N indicates allowable breaking count. Point A corresponds to the K-value at average arcing time, consistent with literature [4] selection results. Research indicates that after determining contact material and structure, the K-value becomes a dynamic physical quantity that varies with three-phase breaking current, three-phase arcing time, and three-phase breaking count. Its variation pattern forms an envelope band that cannot be predicted or determined using conventional numerical equations. Therefore, the LM-BP neural network algorithm is introduced to dynamically predict and analyze the integral current coefficient K based on actual arcing time variations during the breaking process. The detailed neural network model construction is thoroughly analyzed and discussed separately and will not be elaborated here.

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3 Design and Simulation of Arcing Time Initiation Detection Device

Applying the improved cumulative weighted breaking current method to assess contact remaining lifespan requires determination of key parameters including arcing time tarc. While extinction time can be determined from breaking current waveforms, arcing initiation time must be determined by a dedicated detection device. The design principle is based on the strong electromagnetic radiation signals generated in space when arcs occur between contacts during VCB short-circuit current interruption, with arcing initiation moments determined according to electromagnetic signal variation characteristics. The specific structural design and shielding measures are illustrated in [Figure 5: see original paper].

In the diagram: (1) provides insulation support; (2) is the electromagnetic shielding layer that eliminates interference from other phase electromagnetic signals during multi-phase breaking current interruption, ensuring each phase' s arcing time sensor can accurately acquire the corresponding arcing initiation and duration; (3) is the induction coil for receiving and identifying electromagnetic signals during the breaking process; (4) is induction coil output terminal I, connected to the BNC metal shell (grounded output); (5) is the standard BNC interface output terminal, ensuring sensor universality and excellent anti-interference performance; (6) is induction coil output terminal II, the arcing time signal output connected to subsequent processing and sampling circuits; (7) is the magnetic core skeleton material for increasing inductance; and (8) is the epoxy resin casting area for coil fixation and protection [9].

After the arcing time initiation signal is output through the BNC terminal, it is sent to subsequent filtering and multi-stage amplification before being processed by the microprocessor for algorithmic computation. The wear amount for each breaking operation is calculated through the improved cumulative weighted breaking current algorithm. [Figure 6: see original paper] presents the simulation results of the detection device' s post-processing circuit, demonstrating the device' s response sensitivity and response time.

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4 Overall System Architecture and Software Design

The monitoring device uses three-phase breaking current, three-phase breaker arcing time sensor outputs, and three-phase switch status signals as inputs. The system control and algorithm chip employs the TMS320F2812, a 32-bit fixed-point digital signal processor produced by TI, integrating 16 channels of 12-bit ADC and capable of completing 32-bit × 32-bit multiplication in a single cycle, featuring powerful digital signal processing and control capabilities. The monitoring device system architecture is shown in [Figure 7: see original paper], where CT represents current transformers for breaking current collection.

Arcing time detection devices are installed in groups of three near the three-phase arc extinguishing chambers using insulated supports. Detected three-phase arcing initiation variations are processed and sent to the DSP for processing and calculation. Multiple online electrical lifespan monitoring devices are connected via CAN bus to achieve information and data sharing. Monitored data is uploaded to the host computer through Ethernet, enabling data storage and supporting improvements to online monitoring methods.

The main program flowchart for the TMS320F2812 electrical wear online monitoring system is shown in [Figure 8: see original paper]. Upon system startup, the program first checks for trip signals and reclosing signals in the grid system. When no breaking signal is present, data transmission occurs via Ethernet. Upon detecting a breaking signal, information acquisition begins: collecting three-phase current signals, capturing three-phase arcing time signals, and recording three-phase switch status. The acquired information is then processed and sent to the LM-BP algorithm for core computational processing [10], dynamically calculating K-values based on field information. Finally, the K-value and -value are invoked for weighted cumulative integration to obtain the monitored wear amount Qz, which is compared with the theoretical wear total Qg to assess the VCB contact system' s electrical lifespan.

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6 Conclusion

This paper focuses on analyzing VCB electrical life curve characteristics and designs a VCB contact electrical lifespan online monitoring system using the improved cumulative weighted breaking current method. The study establishes selection methods and specific implementations for key parameters in the improved algorithm. Based on theoretical analysis, the implementation method for the VCB contact electrical lifespan online monitoring system is researched and designed, with comprehensive hardware and software designs and core parameter selection methods presented to form a practical engineering application approach. The paper emphasizes research on calculating current exponent, wear total, and current coefficient methods to ensure universality and simplicity for practical engineering applications. Based on electromagnetic field variations around the arc extinguishing chamber during breaking, an arcing time initiation detection device is designed, with its working principle and electromagnetic shielding measures detailed. This research provides beneficial exploration and reference for online monitoring of electrical lifespan in high-voltage vacuum switch contacts.

To verify the response characteristics of the online monitoring device, particularly the designed arcing time detection device, the authors simulated high-frequency electromagnetic signals generated during breaker breaking in the laboratory. The field test results are shown in [Figure 9: see original paper]. [Figure 9a: see original paper] displays the detection device output waveform, where curve 1 represents the detection device output and curve 2 shows the waveform across the induction coil. [Figure 9b: see original paper] presents a detailed view of the detection device' s rising jump process, where curve 1 characterizes the signal' s transition from trigger to step jump, reflecting the device' s sensitivity.

Analysis of the figure reveals that when high-frequency signals are generated during breaking, the detection device produces a pulse signal with a rising jump time of approximately 40 s, consistent with the simulation results shown in [Figure 6: see original paper]. Compared with actual arcing times lasting several to tens of milliseconds, this response time demonstrates that the device can rapidly and sensitively detect arcing initiation moments with significantly higher precision than conventional auxiliary contacts.

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