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—self-monitoring, self-diagnosis, and self-control capabilities—this paper designs an online monitoring device for electrical wear of the contact system during the intelligentization process of vacuum circuit breakers. The wear calculation of the contact system in this device employs an improved cumulative weighting method for breaking current, where the selection of weight values and calculation of total wear are obtained by fitting the electrical life curve using the least squares method. This approach is universal and can be applied to different types of vacuum circuit breakers. The weighting 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 employed to acquire arcing time, and the installation position of the arcing time sensor and the shielding measures adopted 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 acquired using a Rogowski coil, and a current processing circuit is designed, with the 2812AD sampling correction method presented. Finally, the software flow for online monitoring of contact system wear and key technologies that should be noted during design are presented.

Full Text

Study on On-Line Monitoring System for Electrical Wear of Vacuum Circuit Breaker Contacts

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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—namely self-monitoring, self-diagnosis, and self-control capabilities—this paper designs an online monitoring device for the electrical wear of contact systems during the intelligentization process of vacuum circuit breakers. The device employs an improved cumulative weighted method for calculating contact system wear, where the selection of weighting factors and calculation of total wear are derived from electrical life curves using least squares fitting. 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 selection of K values more consistent with engineering practice. An arc duration sensor is employed to acquire arcing time, and the installation position and shielding measures for this sensor are specified. The hardware processing core utilizes the TMS320F2812 microprocessor chip, which is primarily responsible for algorithm processing, host computer communication, and CAN-BUS controller area network communication. Short-circuit currents are collected using a Rogowski coil, and a current processing circuit is designed along with a 2812 AD sampling correction method. Finally, the software flowchart for online monitoring of contact system wear and key technical considerations in the design are presented.

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 affects grid safety and stable operation. Vacuum circuit breakers (VCBs), with their excellent interruption performance and environmentally friendly characteristics, are widely used in medium- and low-voltage power systems and have achieved certain successes in expanding into high- and ultra-high-voltage domains [1-2]. In high- and ultra-high-voltage applications, 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], indicating that vacuum circuit breakers will see even broader application in the future.

The contact system is the core component of a vacuum circuit breaker, and its lifespan directly determines the overall lifespan of the VCB. Particularly with the development of smart grids and reliability-based power equipment monitoring, lifespan assessment and online monitoring of contact systems have become critically important. The evaluation and online monitoring of contact systems have evolved through three stages: First, rough estimation of wear degree through markings on the moving conducting rod, which is highly imprecise [3]. Second, assessment and monitoring through cumulative current interruption weighting, which fails to account for differences in current magnitude and arcing time among phases during actual operation, leading to significant errors between fault and non-fault phases [3]. Third, online monitoring and prediction using an improved cumulative current interruption weighting method. While this third stage addresses the conditions ignored in the second stage and can be applied to engineering practice for contact system electrical lifespan assessment, it lacks a systematic and unified method for determining the required parameters, making parameter determination difficult [3-4].

This paper focuses on systematic research into the parameter determination methods for the third stage. Inspired by the SF contact wear equivalent law obtained by the French Electric Power Group (EDF) and Italian engineering guidance company (ENEL) [5-6], and referencing the VCB electrical lifespan conversion formula from literature [7], this paper employs extensive mathematical experimentation and verification analysis. Based on electrical lifespan curves, the least squares method is used to select and analyze the current exponent and theoretical wear total in the improved cumulative current weighting method.

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

2.1 Selection of Current Exponent and Calculation of Total Wear

According to the calculation method for theoretical wear total presented in literature [3-4], the functional relationship between weighting values and their corresponding parameters can be obtained. Taking the rated current I = 1,600 A shown in [Figure 1: see original paper] as an example, the relationship between total wear Qg and weighting values is given by:

N(I) = N(I) = N(I) = N(I) = ( ) ( ) ( ) ( )
1.93 1,600 A
2.07 2,000 A

2.33 2,500 A
2.46 3,150 A

By substituting a certain quantity of interruption current values into the above equation, the relationship diagram between theoretical wear total Qg and weighting factor shown in [Figure 3: see original paper] is obtained. Analysis of [Figure 3: see original paper] reveals that after the contact material, structure, and arc extinguishing method are determined, the theoretical wear total and weighting factor are uniquely correlated. In the diagram, Qg = 50,500 and = 1.93. Using the method proposed in this paper, the relationship between theoretical wear total Qg and weighting factor for the electrical lifespan curve in literature [4] can be calculated, as shown in [Figure 3: see original paper].

In literature [4], = 1.91 and Qg = 87,300 were selected. From the curve in [Figure 3: see original paper], we obtain = 1.918 and Qg = 89,979. Comparative analysis shows Δ = 0.418% and ΔQg = 3.07%. These results demonstrate that the design method proposed in this paper is feasible and can be applied to different types of vacuum circuit breakers.

2.2 Characteristics and Selection Method of Integral Current Coefficient

Literature [4] proposes an improved cumulative current weighting method based on electrical contact theory and provides a calculation method for the integral current coefficient K. This K value calculation method evaluates based on ideal interruption according to electrical lifespan curves. The calculation process assumes uniform distribution of arcing time within the arcing interval, whereas actual interruption involves three-phase non-uniformity in arcing time. This results in calculated K values that tend to be conservative [4]. Building upon the research for calculating K values in literature [4], this paper considers the influence of arcing time differences and interruption counts, analyzes the distribution characteristics of K values, and performs dynamic analysis.

Through theoretical calculation and experimental verification, the distribution pattern of K values shown in [Figure 4: see original paper] is obtained. The curves in the diagram represent the relationship between arcing time of the first interrupting phase and K value at different interruption currents, where t represents the minimum arcing time, i represents the interruption count, and N represents the permissible interruption count. Point A represents the K value corresponding to the average arcing time, which is consistent with the selection result in literature [4]. Research indicates that after contact material and structure are determined, K is a physical quantity that dynamically varies with three-phase interruption current, three-phase arcing time, and three-phase interruption count. Its variation pattern forms an envelope zone 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 changes in arcing time summarized from actual interruption processes. The specific process of constructing the neural network model is analyzed and discussed in depth by the authors elsewhere and will not be elaborated here.

3 Design and Simulation of Arc Duration Initial Moment Detection Device

Applying the improved cumulative current weighting method to evaluate the remaining lifespan of contacts requires determination of the key parameters discussed above, as well as the arcing time t . The arc extinguishing time can be determined based on the interruption current waveform, while the arc initiation time is determined by the designed detection device. The design principle of the arc initiation time detection device is based on the fact that when a vacuum circuit breaker interrupts short-circuit current, an arc occurs between the contacts, generating strong electromagnetic radiation signals in space. The arc initiation moment is determined based on the variation characteristics of these electromagnetic signals. The specific design structure and shielding measures are shown in [Figure 5: see original paper].

In the diagram: 1 serves as insulation support; 2 is the electromagnetic shielding layer, which shields interference from electromagnetic signals of other phases on the local phase electromagnetic signal when two or more phases interrupt current simultaneously, ensuring each phase' s arcing time sensor can accurately acquire the corresponding arc initiation time and arcing duration; 3 is the induction coil for receiving and identifying electromagnetic signals during the interruption 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 the arcing time sensor has universality and good anti-interference performance; 6 is induction coil output terminal II, the arcing time signal output terminal connected to subsequent processing and sampling circuits; 7 is the magnetic core skeleton material for increasing inductance; 8 is the epoxy resin casting area for fixing the induction coil and providing 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 operations. The wear amount for each interruption is calculated through the improved cumulative current weighting algorithm. [Figure 6: see original paper] shows the simulation results of the post-stage processing circuit of the detection device, characterizing the device' s response sensitivity and response time.

4 Overall System Structure and Software Design

The monitoring device uses three-phase interruption current, output from three-phase circuit breaker arcing time sensors, and three-phase switch status signals as inputs. The system control and algorithm chip adopts the TMS320F2812 produced by TI Company, which integrates 16 channels of 12-bit ADC internally and is a 32-bit fixed-point digital signal processor capable of completing 32-bit × 32-bit multiplication operations in a single cycle, featuring powerful digital signal processing and control capabilities. The detection device system structure is shown in [Figure 7: see original paper], where CT represents current transformers for collecting interruption current.

The arcing time detection devices are installed in groups of three near the three-phase arc extinguishing chambers using insulation supports. The detected three-phase arc initiation moment variations are processed and sent to the DSP for processing and calculation. Multiple sets of online electrical lifespan monitoring devices are connected on the CAN bus to achieve information and data sharing; monitored data is uploaded to the host computer via Ethernet to enable data storage and provide data support for improving online monitoring methods.

The main flowchart of the TMS320F2812 electrical wear online monitoring system is shown in [Figure 8: see original paper]. At system startup, the system first determines whether there is a tripping signal or reclosing signal in the power grid system. When no interruption signal exists, data information is transmitted through Ethernet. When an interruption signal is detected, information acquisition begins: collecting three-phase current signals, capturing three-phase arcing time signals, and capturing three-phase switch status. The acquired information is then processed and sent to the LM-BP algorithm for core algorithmic processing [10] to dynamically calculate the K value based on field information. Finally, the K value and   value are called upon for weighted cumulative integration to obtain the monitored wear amount Qz, which is compared with the theoretical wear total Qg to evaluate the electrical lifespan of the VCB contact system.

6 Conclusion

This paper focuses on researching the characteristics of vacuum circuit breaker electrical lifespan curves and designs a VCB contact electrical lifespan online monitoring system using the improved cumulative current weighting 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 vacuum circuit breaker contact electrical lifespan online monitoring system is researched and designed, with comprehensive hardware and software design and core parameter selection methods presented to form a practically applicable engineering method. The paper emphasizes research on methods for calculating current exponent, wear total, and current coefficient, making them universal and concise for practical engineering application. Based on electromagnetic field variations around the arc extinguishing chamber at the moment of interruption, an arc duration initial moment detection device is designed, and its working principle and electromagnetic shielding measures are presented. This research provides beneficial exploration and reference for online monitoring of contact electrical lifespan in high-voltage vacuum switches.

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 circuit breaker interruption in the laboratory and processed them through the arcing time detection device. The field test results are shown in [Figure 9: see original paper], where Figure 9a shows the output waveform of the detection device (curve 1: detection device output waveform; curve 2: waveform across the induction coil), and Figure 9b shows the local detailed view of the detection device’s rising jump process (curve 1), characterizing the time from signal trigger to step jump and reflecting the detection device’ s sensitivity.

Analysis of the figures reveals that when high-frequency signals are generated during interruption, the detection device produces a pulse signal with a rising jump time of approximately 40 s, which is consistent with the simulation results shown in [Figure 6: see original paper]. Compared with arcing durations lasting several to tens of milliseconds, this clearly demonstrates rapid and sensitive detection of the arcing time initial moment with significantly higher precision than conventional auxiliary contacts.

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Note: Figure translations are in progress. See original paper for figures.