Design of Vacuum Arc Measurement System Based on Rogowski Coil

Hui Song Shunxin Liu

Zhengzhou University of Aeronautics, Zhengzhou ,China

e-mail:lsxcj@126.com

Keywords:Rogowski Coil; volt-ampere characteristic; power system; vacuum switch; equivalent circuit; electromagnetic parameter

Abstract: A novel method is presented to detect the volt-ampere characteristic of vacuum arc in this paper. Highlights of this paper can be concluded that: the basic structure, computation models, designing principles and procedure, and selection criterions of materiel and electromagnetic parameters of the coil are analyzed respectively. The main clue of this paper is the operating principles of the Rogowski Coil. Also, there is an experiment to measure the arc ampere and acquire the volt-ampere characteristic of vacuum arc by using some experiment devices. The method for choosing the sampling resistance and integral circuit that is give in this paper are valuable for arc current measurement using Rogowski coil.

Introduction

As the control and protection equipment, vacuum switch in power system plays an important role. In the vacuum switching technologies, the most critical is the characteristics of vacuum arc. Volt-ampere characteristic is one of important characteristics of arc, which in essence reflect the physical processes of the arc. To obtain required voltage characteristic of the vacuum arc current and voltage should be checked and researched.

As a great high impulse current, Vacuum arc current can be measured by a low voltage shunt and Rogiwski coil. Rogiwski coil is a special structure of the hollow coil, non-core, so there is no need to consider the advantages and disadvantages of the coil with core. At the same time as a large current measurement sensor, Rogiwski coil has low-power output, simple structure, good linearity and other excellent features, so it is chosen as an arc current sensor in this paper.

Testing System

The measurement system consist of the vacuum system, trigger circuit, current and voltage testing device, and main circuit which is shown in Figure 1.

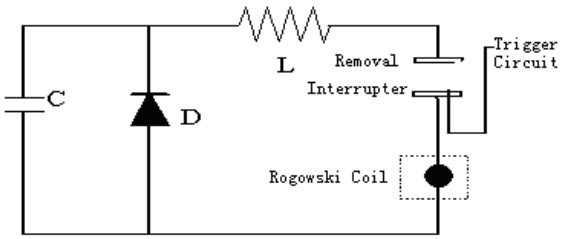

Fig.1 Main experimental Circuit

Because of replacing frequently contact, and the need for image observation in the experiment, it is not possible in the vacuum switch, so the removable arc chamber is designed to facilitate the replacement of different types of contact in this research.

In this study a stainless steel vacuum chamber of a diameter of 30cm, about 29cm high is designed. The vacuum chamber can be adjusted in a large range distance to suit the different characteristics of vacuum arc. There are the two electrodes with high conductivity copper alloy material in interrupter. The lower contact is called the cathode which is connected to porcelain by the bellows and fixed in conductive rod. By adjusting the bellows the contacts can meet different open distance. Trigger pole is directly connected to the removable insulation terminal in the cathode.

There are five mutually insulated terminals, respectively, with the outside of the ignition electrode, probe connected. Anode contact is directly mounted on the top cover of removable arc chamber by porcelain. The vacuum arc shape can be directly observed by two directions at right angles to the observation window in the interrupter. Vacuum can be measured by the vacuometer in the terminal next to the installation of the insulation.

In the primary circuit there is a diode D, to prevent reverse capacitor current, protect the capacitor, and provide a vacuum arc current freewheeling circuit

Rogiwski Coil Design

Rogiwski coil performance decides the whole measurement system accuracy and stability, so developing a high-precision Rogiwski coil is even more important. Rogiwski coil is constituted by a plastic stick uniform circular cross section core framework, shown in Figure 2. The frame is wire wound and connected to the terminal resistor at both ends of the coil. Rogiwski coil should be wrapped from the end to the start point. Rogiwski coil used to measure the steady state current, usually do not adopt hollow core framework, but ferromagnetic material to increase the sensor signal. The common is characterized by "wrapping" the structure. Material of the core is depended on the measurement object, applications and measurement requirement. In this study the impact of the vacuum arc current is strong current, so the skeleton core should be chosen.

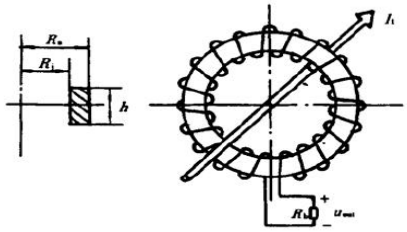

Fig. 2 Structure of Rogowski Coil

Selecting Frame Material

Some of the parameters of the material have a great impact on the entire system. The frame plays the role of support and insulation and decides Mutual inductance of the coils by the skeleton size. Selecting frame material working temperature stability, thermal expansion coefficient, mechanical strength, moisture absorption rate and other parameters, are in general considered. At the same time the dielectric constant, electric strength and dielectric loss tangent parameters are followed by further considering.

At present, quartz glass, rubber, glass, PF laminates, ceramic are suitable for Rogiwski coil frame material. Quartz glass have high softening temperature, hardness, good chemical stability, however, it is eroded by alkali and alkaline salts. The electrical property of pure rubber is easily changed due to impurities, so the drawback is not high heat resistance. When the temperature is higher than 100 ˚C, rubber will rapidly aging, and even becomes brittle or crack. At the meantime it has not resistant to light (especially UV), oxygen (especially ozone), and oil, so under the effect of gasoline and transformer oil, it will swell and become brittle. Because of the above shortcomings, it makes use of rubber by certain restrictions.

- PMMA has very good mechanical properties. Its asymmetric molecular structure is a dipole of the dielectric. Its electrical insulation performance is not high, so it is not used generally as the dielectric.
- PF resin has good Temperature characteristics, high heat distortion temperature, stripping when small deformation, low price, but its relatively large brittleness, shrinkage rate, alkali-poor, easily absorbing moisture, poor electrical properties.
- Ceramics have very good mechanical strength, excellent heat resistance, orders of magnitude in the 10^{-6} of temperature coefficient in thermal expansion so it can be considered a thermal shock stability of the material. It has also the good heat conductivity, a high degree of

chemical stability. In the general electric field it will not be aging, no permanent deformation under long-term effect of mechanical load, and zero water absorption.

From the point of use and ease of processing, fiber material (plastic) is chosen for the skeleton. It can be -20 ~ +70 ˚C temperature range of coil output error control within ± 0.05%.

Winding material selection

Enameled wire of coil is a kind of insulating layer of conductive metal. When the current flows through the wire, the magnetic field will be produced. Because it can accomplish the mutual conversion between power and magnetic energy, it is also known as magnet wire. The conductive wire core is made of round, flat, strip, foil, etc. Usually copper, aluminum or other metal wire are used for conductive wire core. Taking into the material cost performance, copper should be chosen. Copper has high thermal conductivity and electrical conductivity, adequate mechanical strength, good corrosion resistance, no low-temperature brittleness, and easy welding process, so copper is the most widely used conductive material.

Design of Structural Parameters

Rogiwski is essentially a current transformer. Measuring high current multi-hollow structure is chosen. Whenever the conductive line with the current flows through the coil, the induced electromotive force is developed. By a small-signal resistance R in the exit of the coil, the current can be measured. Designing Rogiwski coil these parameters should be based on the current wave of frequency distribution within the coil, the satisfy the self-integration, sensitivity (the value of coil cut area, and so, where is the coil turns) requirements, small resistance.

Based on the actual size, the inner radius and housing radius are determined. By the single-turn the wire length and l inductance the thickness of the coil is designed. The set of equations needed to compute the performance is listed below.

$$l = 2n(b - a + h + d), S_1 = p\,d^2 / 4, r = r\,l / S_1, \quad (1)$$

$$S_c = (h + d)(b - a + d) \quad (2)$$

Note the two equations are modified to account for the length of line and sectional area of coil.

Where n and a are number of windings and the inner radius. B and h are the housing radius and the thickness of coil. D and *p* are the diameter and resistivity of line respectively.

Derived by the theory of electromagnetic field coil, the L and M can be calculated. To make r as small as possible, the value *p* should be small. At the same time the value d should be large. By the self-integration condition and correlated condition, the high and low limiting frequency can be computed.

$$f_1 = (r + R) / 2p\,L$$

$$f_2 = L / 2p\,C_0 R \quad (3)$$

Where f_1 and f_2 are high and low limiting frequency. In this case, the frequency is determined by the coil. After simulation and trial, the real design parameter is chosen.

Experimental Result

This experiment uses the Rogowski coil, adopted LR integrator, and digital oscilloscope to measure the coil current, while another probe with a digital oscilloscope should be directly added to the static contact removable interrupter outlet ends to gain the arc voltage waveform and arc voltage characteristics. A small-signal resistance R_a should be linked to the two termination of a coil, and measuring system equivalent circuit shown in Fig.3. L,r,C_0 showed in Fig.3 are coil inductance[11], resistance and stray capacitance respectively, and the R_a is signals resistance of coil outlet end of two. From Figure 3, circuit equation can be listed as follows:

$$e = M\mathrm{d}i / \mathrm{dt} = L\mathrm{d}i_2 / \mathrm{dt} + ri_2 + i_R R_a \quad (4)$$

when $1/wC_0 >> R_a$, $i_c \approx 0$, $i_2 \approx i_R$, equation (4) becomes

$$e = L\mathrm{d}i_2/\mathrm{d}t + (r + R_a)i_2 \quad (5)$$

The turns of Rogowski coil is 650, and the port resistance R is 3.3 ohms. At the same time the current theoretical value will reach several thousand amperes in theory. Tektronix TDS-2024 digital oscilloscope with high voltage probe is used to measure voltage U_m.

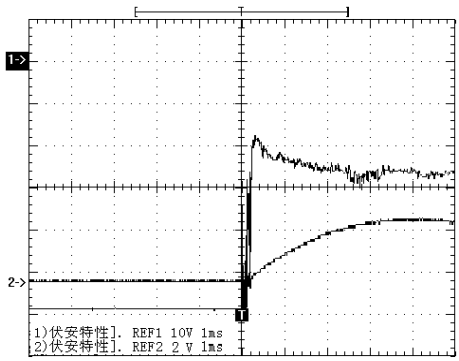

Fig.3voltage-current characteristic

Voltage characteristics of high-pressure arc is negative characteristics, but the characteristics of vacuum arc is positive characteristics. With the current increasing, the arc voltage is rising, meanwhile, experiments validate them.

Conclusion

The skeleton and line material of the coil are selected, and its equivalent circuit and how to improve the accuracy are analyzed. The vacuum arc measurement system of voltage characteristics is established adopting the designed Rogowski coil, and a positive voltage characteristics of vacuum arc is obtained; The results of the experiment shows it was to be a good choice for measuring impulse current adopting the coil.

Acknowledgments

The authors would like to thank the technical staff of the XUJI Power Group for the support given. Special thanks to L.S. Pan for his technical support in the equipment usage and software installation

Project supported by 122102210431 (hnkjt) and zzia youth fund (2013061002)

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