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New method for capturing arc of moving on switching apparatus*

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Abstract: The switching arc that occurs in contact gap when contact of low voltage apparatus closes or breaks in electric circuit is harmful to the contacts, insulation, and reliability of electrical gear because of its very high temperature. As arcing time is very short in switching gear, it is very difficult to observe arc phenomena directly for researchers. Therefore, visualization of switching arc is important for understanding arc phenomena, to analyze the arc features, and to improve the design and reliability of switching gear. Based on analyzing the visualization methods proposed by researchers, a new switching arc capturing approach is introduced in this paper. Arc image acquisition, and image processing techniques were studied. A switching arc image acquisition and visual simulation software based on high speed CCD camera hard ware system was designed and implemented to yield enhanced arc image with good visual effect.

Key words: Low voltage apparatus, Switching arc, Image acquisition, Visual simulation
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INTRODUCTION

Much research on visual simulation of swithing arc was conducted by scholars here and abroad. A chain arc model was set up for magnetic field driven arc chamber of low voltage circuit breaker in (Zhang *et al*., 1999). 2D models for numerical simulation of evolution of arc plasma was set up and relevant computing outcome was given in (Rachard *et al*., 1999). Simulation of static and dynamic arc was done and the dynamic characters in the medium condition of close-break arc were introduced. The electrode edge current density is the index of the distribution about the 2D electrode surface and has nothing to do with electrodes temperature and interrupter, and electrodes temperature kept stable in (Swierczynski *et al*., 2004). And visual simulation of arc has been introduced but without showing dynamic arc characteristics under different conditions in (Karetta and Lindmayer, 1998).

Research on the moving arc may improve the design of electrical apparatus and enhance its function. But the time of arc burning is so short that it is difficult to capture the movement of the arc. Image sampling system of the arc motion on optic fiber can reflect the arc movement (Li *et al*., 2003), but it has low spatial resolution. Acquiring system based on CCD of arc dynamic image for low voltage apparatus has been presented in (Liu, 1998). Based on arc image sampling, the arc character is analyzed and research on the models of visual simulation was conducted; 3D animated simulation system on arc burning was designed so that it can make the changes of arc in the close-break process of electrical apparatus specific and vivid.

The occurence of arc lies basically in the contact of switching apparatus and the particles among the media around the contact. When the space of broken contacts meets with high voltage and the current reaches the minimum amount required to produce the arc current, it may produce ionization and form arc. It has advantages and disadvantages. On one hand, the electromagnetic energy in the circuit will be dis-

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charged through the arc so that it lessens the overall voltage. On the other hand, arc delays the close-break of circuit, because its heat may burn up the contacts and can even damage the insulation, and what is more, might cause explosion and fires in apparatus and lead to serious result. So the aim to do research on arc is mainly to extinguish the arc as soon as possible.

PRINCIPLE OF ARC

Arc is one form of gas discharge and its temperature in the discharged channel may be as high as 6000 K, its current density may be several thousand A/cm^2, negative electrode pressure drop may be scores of volts. The switching arc will appear. Ionization in the arc column is mainly in the form of thermal ionization. The temperature of the arc column is usually regarded to be as high as 6000~20000 K. Below 3000~4000 K, arc discharge stops. At this time the temperature in the arc column can be higher than that of its surface. The changes in the temperature arc column lag behind the changes of current. The diameter of the arc column will be enlarged with the arc current increasing and decreased with the medium's pressure and the increasing speed of the arc. The arc discharge between the electrodes of the apparatus is often regarded as a physical phenomenon. Because of its brightness and heat, high pressure and density in the gap of discharge, arc is the key factor affecting the arc reliability and span. The process of burning and extinguishing of arc is one of the main contents of the research on switching apparatus.

Occurrence of the electrical arc

In the switching arc research, the occurrence of the electrical arc accross a few main paths are as follows:

(1) The electrical arc occurs when the electric circuit turns on-off. As contacts start separating, the contact pressure between them reduces, and the contact area also contracts, and the current density with contact enlarges gradually, so that the electric resistance and the heat coming from the contact increase. At the moment when the contacts separate, the calories concentration is in the maximal physical volume, so that the heated metal melts. The liquid metal bridge forms between the contacts, and in the end it is drawn back, so that a great deal of electrons get into the contact's cleft. With the function of the electric field, they make contact through the electric field ionization, producing more electrons and positive ions in the cleft. Among them, a part of the positive ions and electrons are compounded again, the ejective energy radiates in the form of light.

(2) Electrical arc occurs during closing of contact. Before closing the link to the electric voltage source of the two contacts, electric breakdown will occur. The lowest value of breakdown voltage in the silver contact is about 15 V, when usual arc discharge can occur.

(3) Breakdown is between vacuum and gaseous gaps. Arc produced between two vacuum metal electrodes, is vacuum arc. But electrical arc actually is not at absolute vacuum but is the burning in the metals fume, and electrical arc discharge turns from the spark discharge. The formation of spark generates electricity when the gap between two electrodes is broken, electricity conductance channels in the gaps are formed, energy increases, the electric current rises gradually.

Physical nature of arc

V-A property is one of the most important arc characteristics. The function relation between arc electric voltage and electric current is first decided by the physical process of the arc gap. The arc column physical state is not static, but is always in a process of producing and eliminating ionization.

1. Potential gradient of arc column

The arc column consists of plasma. When current flows, pressure coming from the magnetic field by the function of arc current pushes down the center of the arc column. Suppose the arc column has the form of a symmetric cylinder, the potential gradient is decided as follows:

$$E \approx [U_{\text{arc}} - (U_{\text{a}} + U_{\text{c}})]/l, \tag{1}$$

where U_{a} is the anode voltage drop, U_{c} is the cathode voltage drop, U_{arc} is the arc column pressure drop, l is electrical arc length.

According to Eq.(2), the relationship of arc column potential gradient E and arc current I_{arc} can be shown to be:

$$I_{\text{arc}}=\pi r^2 b_{\text{e}} Ene, \tag{2}$$

where r is the radius of arc column channels, n is electron density, b_e is the electron transference ratio, e is electric charge.

In addition to electric current, potential gradient of the arc column has something to do with many factors, for example, arc moving speed, gas mobility, gas thermal conductivity, gas pressure, gap or channel diameter of arc, etc.

As arc is a phenomenon of electricity and heat, so arc heat influences its electricity characteristic seriously. If the spreading of heat is better, the arc column's ionization elimination is strong, the potential gradient degree of the arc column rises. Experiment indicates that the increase of gas thermal conductivity can enhance gradually the arc column's potential gradient. The contact by arc and insulating material increases greatly the potential gradient. If electricity arc is forced to burn in the insulate gap or small diameter piping, the potential gradient of the arc column can be made to increase several times.

2. Arc temperature

When arc's temperature is higher, its measure uses indirect methods, such as optics. And because experiment conditions are different, measure methods are also different. The data acquisition of arc temperature has very big difference between each other. The arc temperatures values can all be changed in a very wide scope in various different types and in different aspects of the electricity arc. People can select 6000~20000 K data as arcing, and 3000~4000 K data as extinguishing in switching apparatus.

Temperature and electric current have important relation, in that we observe that the arc temperature gradually rises with increasing current. For example, when current is 10 A, the axes temperature of the arc column is a little higher than 6000 K. While current increases to 200 A, the axes temperature of the arc column rises to 1100 K. The rising of temperature will increase the arc column conductance, then potential gradient decreases. When cooling electrical arc, current density of the arc will be increased by cooling, so the electrical arc's axes temperature rises. Temperature of arc in all regions rises along with increasing gas pressure. As discharge shrinks with increasing pressure, power transformation in unit volume is enhanced observably.

3. Arc diameter

Generally speaking, we observe that arc has very bright boundary, with the diameter taking cylindrical form while the values of the arc's current are given. The middle bright part of arc is arc column and is also the widest electric part of arc, and the broader surrounding of lower brightness is the aperture which surrounds the arc column. But the temperature is not sufficient to generate conductance. Obviously, the arc diameter should be taken as the middle bright part in the arc.

The arc diameter has relation with contact material, current, sorts of gas medium and air pressure, the function degree of the gas and the arc column as well.

The arc column does not always of cylindrical shape. When the electrical arc is in the vertical position, the heated air rises by convection. The upper part of the arc column will become wide, then shaped as a converse cone. When the arc is in the fissure of the insulation material, because of the restriction of the insulation, the section of the arc column is close to an elliptical plane. So taking the arc column as a fluid is much more vivid.

DETERMINING THE POSITION OF ELECTRIC ARC

Under the control of software, the collection of image data transfers to the host from DSP. Store arc image in the proper image way, for display, analysis and disposal.

If radiation with the arc plasma in each tiny section of arc image is enhanced and edge features of arc image are acquired, image of contact is segmented, and contact area of the apparatus is obtained. The linkage of the edges of dynamic and static contacts will form the area of the shape like column in the gap of contacts. Because the arc burning centers on the area between the dynamic contact and static contact, or taking the column area as a center, the arc can use the three optical paths to collect the arc images correctly, then it can get the main information of energy radiation in the arc burning process.

The edge of the image is the basic feature of the images, which refers to the groups of pixels including changes of Step-Index and of the Housetop. The edge can show the outline of the target and contains plenty of information, such as direction, the property of

Step-Index, shape, and so on. The edge will be reflected by the inconsistency of gray-scale. The method of edge-finding is to test the changes happening in each pixel of gray-scale. It depends on the rules of changes of the first stage directional derivative and the second directional derivative and make up the differential operation which is sensitive to the changes of gray-scale and can be used to test the edge of objects in the images. This method can be called the partial edge-testing-operation method.

CAPTURE OF SWITCHING ARC AND VISUAL SIMULATION

Hardware structure

In order to improve the whole test system, we should better improve the resolution and grey scale under the high speed transmission. This system uses the 256 level gray scale CCD of 64×64 pixels.

For shooting in the small low voltage contacts more conveniently, the top of CCD adopts straight fiberscope. Its diameter only has ∅2 mm (or ∅4 mm), and the visual angle is about 60°. Straight fiberscope is connected with prism. We use the prism so that the observers could see the object visually, to revise the focal length to get clearer arc images. Meanwhile, the light which is not influenced by prism is transferred to the CCD chip, in order to make an image.

After receiving the arc light signal from the CCD chip, it changes the 2D optical signal into 1D video frequency signal, and then it outputs the digital signal by RS-422 through the high speed A/D converter. Because of the high output rate of CCD image data, when shooting the arc image at the highest rate, the data rate from the bus cannot catch the data rate from CCD. To make full use of CCD property, we designed buffer interface unit of image data.

The design of buffer interface unit should satisfy the following requirments: storing real-time data of arc dynamic image with high speed; and using PCI to communicate. We choose the TMS320C40 DSP chip as CPU of buffer interface unit. Its instruction cycle may be less than 50 ns, process data would be 32 bit, 16 bit or 8 bit, it could also communicate via DMA.

During the whole process of testing arc, we must ensure the computer control of the CCD to synchronize shooting. It means that when the arc burning begins, CCD must shoot in synchronization, otherwise, the arc image information may be lost. So we should better design the synchrotron contact circuit.

CCD acquisition system of arc dynamic image is shown in Fig.1.

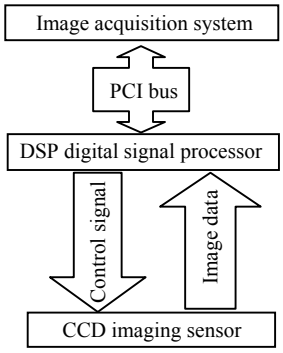

Fig.1 Data flow chart

System performance targets: DC mains: ±15 V; +5 V; Space resolution: 64×64 doc matrix; Current: I≤1.5 A; Time resolution: 3000~10000 frames/s; Power: P≤250 W; gray scale: δ=256 gray-scale; DSP storage capacity: 1~64 MB.

It is clear, this test system has many good features, such as: high resolution of images, high speed, large data storage capacity, DSP buffer unit and good performance of the whole test.

Image acquisition

The control unit of arc image acquisition can communicate with DSP interface, hardware and software would work in coordination. CCD finishes the task of arc image acquisition under DSP. The whole acquisition process is shown in Fig.2.

The steps of the algorithm of image acquisition are:

Input the parameters of image: sample speed (the exposure time of CCD), image frames, the delay time and ways of software (Wang and Wang, 2004; Wang and Liu, 2006)

Step 1: Initialize the DSP;

Step 2: Allocate the CCD parameter;

Step 3: Establish the CCD parameter structure according to the input values;

Step 4: Initialize hardware, prepare for the image sampling;

Step 5: Delay with the multimedia time-clock, output the software synch on the basis of the delaying methods;

Step 6: Sample image to the DSP;
Step 7: Go to the main program.

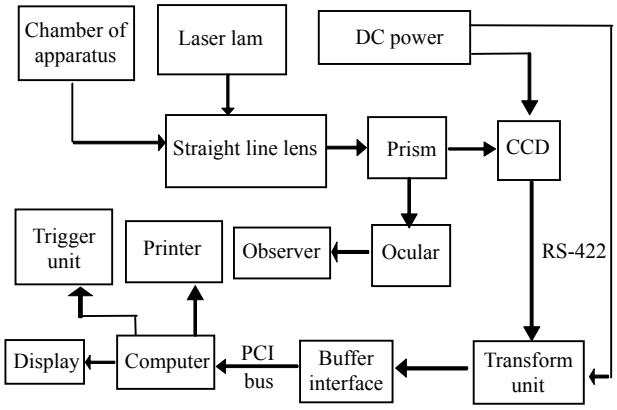

Fig.2 Switching arc image acquisition hard-system

During the process of dynamic acquisition of switching arc image, because of its high speed, the quite short exposure time of CCD, the strong electromagnetic radiation existing in the switching apparatus, the arc image acquisition and transmission are influenced by many factors. For example: the arc image is polluted by noise. Besides, because of the strong ray radiation feature of arcing, electrical contact system, and the weak reflecting feature of the chamber to the arc column, it is hard to observe the contacts and chamber from the images. The analysis of the arc image totally focuses on the motion and direction of the arc, even the function of the segmented arc is extinguished by the interrupter. For this purpose, study of the image process technique is required, and then extract useful information from the arc image for observation and analysis. To set up an exact visual arc model, it is better to extract the arc column characteristics from the arc image. Therefore, first study the edge detection algorithm of the arc image and the techniques to enhance the weak feature, then apply them to sampling and processing of switching arc dynamic image for low voltage apparatus, and visual simulation system.

Experiment for capturing arc of moving

Based on high frame rate CCD, the experiment for capturing arc of moving is shown in Fig.3, whose pictures mean a series of arcing images. From the arcing to the extinguishing of the arc, we can clearly see that the images record the whole process exactly. We also notice that the arc has a definite boundary, although it is difficult to observe the weak features of contacts and the interrupter directly. After many experiments, the system works steadily, synchronization is reliable. The control module of the arc acquisition can control the CCD arc image acquisition parameters properly and also controls the transmission and storage of the image data. We can browse the arc image conveniently and dynamically, and display the process of arcing. These lay a good foundation for disposal, analysis, and visual simulation of switching arc on low voltage apparatus.

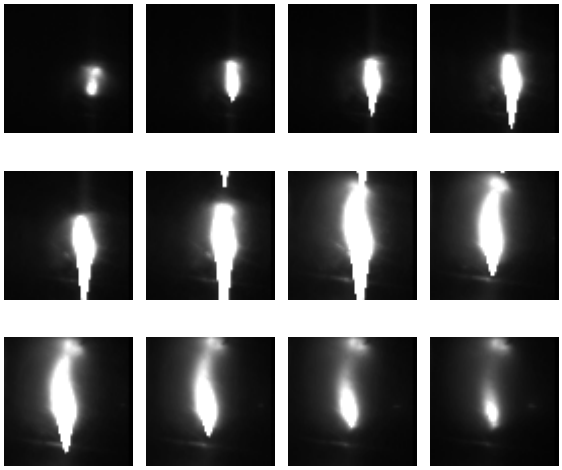

Fig.3 Capturing image arc of moving

CONCLUSION

Based on analyzing the visualization methods proposed by other researchers, a new switching arc visual approach is introduced in this paper, adopting the tool for Visual C++ software. A switching arc image acquisition and visual simulation software based on high speed CCD camera hard ware system is designed and implemented.

Arc of moving on the switching apparatus is a complex physical and chemical process. It refers to the formation of substance and the changes of properties, the flow of compressible fluid, the distribution of electromagnetic field, heat dissipation and absorption. It is also the process of space distribution and fast time-varying. Moreover many parameters are highly nonlinear. So the current models of all kinds of electric arc are only simplified and qualitative models, whose computing outcomes cannot be grounded for designing an interrupter. But it is meaningful for

analysis of the phenomenon of electric arc close-break.

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