博士論文(要約)

Non-Sustained Disruptive Discharge in Vacuum Circuit Breaker

(真空遮断器における非持続性破壊放電現象)

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Non-Sustained disruptive discharge (NSDD), according to the definition of IEC and IEEE, which is disruptive discharge in the Vacuum Circuit Breaker (VCB) after the interruption of large current. But, this discharge does not induce further power frequency current flow into the shielded electrical element.

In this research, the proper simulation circuit is constructed in order to research the discharge in the VCB. The test circuit is named as Synthetic Circuit. This circuit consists of high voltage circuit for the insulation test; and the large current circuit to generate large current in the circuit. An optical fiber control system has been developed while the test of the VCB, because the electromagnetic noise in the test field is so large that the electrical wire does not working accordingly.

Using the constructed Synthetic Circuit, the behavior of the NSDD is researched from the real circuit. The roadmap of this research is to research NSDD from the related phenomena to the theory background, which will enable us to understand the discharge from the behaviors to the essence.

As previously reported, NSDD is considered to be related to the conducting particles generated in the arcing time. The direct observation of the particles in the VCB is confirmed through the optical method. Through record the diffraction pattern, the movement of the particles can be tracked and confirmed directly.

Through the observation of the conducting particles in the VCB, the particle phenomena are confirmed. The size of the particle is confirmed to be within 200 microns in diameter. And the lifetime of the particle is generally less than 1/4 cycle of the power frequency, which indicates that the particle have relative short time to induce further discharge in the VCB; through the confirmation of the bouncing time interval, two types of particles are confirmed. One type is the loosely contacted particle on the electrode surface. These particles will move through the voltage pass zeros. While voltage pass zero, the electric force act on the particle will be changed, thus the particle will be lifted by the electric force; the other type is that the welded particles in the VCB, while the voltage goes to the peak value of the waveform, the strong electric force will act onto the particles.

If the electric stress act on the particle is large enough to pull break the welded neck, the particle will be released into the inter-electrodes space of the VCB.

Through the observation results, the particles have relatively large size, relatively slow speed. These entire reasons make the particle cannot carry large enough current as the observed discharge current in the VCB. The discharge current is generally larger than tens of Amperes, but the current carried by the observed particles is in the order of micro-Ampere.

For further confirmation, some particles are introduced onto the electrode surface. And, high voltage with step waveform is applied to the electrodes. If the discharge is related to the particle movement, the discharge and bouncing of particles should be observed at the same time. But, the results show that the discharge take place before any movement of the particles. Thus, the conclusion of the particle observation is that: Particle cannot directly lead to the observed discharge current.

According to the research roadmap, the surface condition of the electrodes tends to be of interest. The surface scan and microscope observation results show that: the surfaces of the electrodes are modified seriously after the arc. Before arc, the electrode surface has very low surface roughness, which is less than 5 micron. However, after arc, the surface roughness goes up to 50 micron for 4kA arc current; and up to 170 micron for 10kA arc current. For 10kA arc current, the arc left some craters on the surfaces of the electrodes.

Thus these surface changes must be responsible for the later discharge, i.e. NSDD. As known, the surface roughness change on the electrodes acts like protrusion on the surface. While withstanding high voltage, the protrusions are under strong Field Emission. The Joule heating of this current will heat the protrusion to high temperature to release vapor. This vapor will be the possible reason for the NSDD.

The first observation result is that, the vapor is observed while the strong field emission disappears, which implies that that local protrusion on the point electrode surface is polished by the current. The second result is that the particles are generated on the point electrode surface, which confirmed that particle phenomenon is an intrinsic phenomenon in the vacuum insulation. Through the analysis of the field emission waveform, the Fowler-Nordheim plot shows that the field emission on the point electrode is under a triangle cycle, if the field emission waveform is enclosed by the cooling part, viz, the non-field emission time. While in the voltage increase side, the field emission have relative high field enhancement factor than that of the voltage falling side. On the voltage rising side the field enhancement factor is several thousands, but in the voltage falling side, the value is only several hundreds. That means the discharge will be relatively easy on the voltage rising side, this is the same behavior in partial discharge.

After the experiment, the Field emission based joule heating model is constructed in the VCB to research the critical condition of the breakdown. The applied voltage is addressed on to the protrusion on the electrode surface, which is under strong field emission. After the joule heating takes place in the protrusion, the temperature of the protrusion is raised, thus the metal vapor density is getting dense. To some critical value, the discharge is enabled in the metal vapor. This model shows that the critical temperature for the protrusion is only the melting temperature. But the result is coincident with the experiment done by previous experiment. Thus the initiation of the discharge is understood as the Joule Heating from the Field emission.

The research of the discharge in NSDD is the same condition as the research of the discharge suing the arced electrodes in the vacuum chamber. on the other hand, the discharge in VCB after arc while withstanding high voltage is a very fast process, which is in the order of 0.5micro-second. Thus, the use of AC waveform is not necessary for the research of NSDD, because the key point is the discharge itself.

The first test of the arced electrode is the dielectric strength. The test result shows that the insulation level gets higher and higher as the test number increases. This indicates the same result with the point-to-plane electrode. As the protrusion is conditioned descending, the insulation level gets higher accordingly. And, the anode electrodes while arcing time always have the higher insulation level than that of the cathode electrode, this indicates that the cathode surface is modified more seriously than the anode electrodes.

The second test result shows that the predischarge current is in the order of mA. And according to the Child Langmuir equation, the field emission results lead to the voltage-current relationship for the predischarge. Thus, for application, under a specific voltage, if a critical current is observed, the discharge will be expected.

For a third observation is that the discharge process. Using the high speed video camera, the discharge is observed. The discharge is a very fast process. The discharge initiated as a ball shape, and then develops as a bridge to shorten the gap of the VCB. After the source power is exhausted, the discharge begins to extinguish. The discharge contracts again to the cathode local area. At the same process, the particles are observed.

As the discharge process is very fast, even high resolution is in need. While using exposure time at the order of ns, the discharge process is observed. the result shows that the discharge is in the order of 300ns.

In order to confirm the sustainability of the discharge, current limiting resistor is used to limit the current of the discharge. As 100Mohm resistor is used, the discharge extinguished very fast, the voltage on the electrodes recover according to the resistor. But, the resistor goes to 100kohm, the current will flow for a while after the breakdown induced by the breakdown. Thus, the conclusion is that: the discharge is always going to be disruptive. And the discharge can be self-restorable at very small current from the power source.

The theory analysis of the NSDD is performed in the last section. The paschen curve of a discharge is revisited briefly, in order to confirm the discharge details. The analysis shows that the pashchen discharge core is based on the balance of the ion generation and the electron generation. And, the key assumption of the discharge is that the Boltzmann distribution of the electron energy. But, in vacuum, the discharge should not only maintain the electron generation through the ion-cathode impaction, but also maintain the discharge environment through the ion sputtering process through the collision with cathode. Based on this idea, the general form of the Paschen Curve for a discharge is derived.

Furthermore, the discharge in the vacuum shows that the mean free path of the electron is very large, thus the electron energy is not obeying the Boltzmann distribution. For barely collision in vacuum, the single point distribution of the electron energy is used to replace the Boltzmann distribution. As the analysis results show, the discharge is not so strongly depend on the metal vapor density, but strongly dependent on the ionization cross section of the material. The self-sustainable condition for the discharge is in the order of tens volts. This condition can be easily maintained near the cathode for the working condition of VCB. Thus, the discharge in vacuum is always disruptive. At the end, the discharge extinction condition is that the voltage goes to low enough to disable the sputtering, or the current is low enough to make to discharge ionization not strong enough. After this condition fulfilled, the metal vapor will diffuse to the vacuum, the insulation level will be recovered, thus the discharge is turned to be non-sustained, as termed NSDD.

For the future research on this topic should focus on the diagnosis of the plasma while the NSDD takes place. Since the discharge current is as low as tens amperes, which makes most of the measurement method void. Proper method should be carefully chosen. Another research on this topic should focus on the simulation research, since the discharge is on the critical condition of the fluid. This condition makes the fluid equation for general plasma void in vacuum. Monte Carlo method would be possible solution to this problem, with consideration of the discharge strongly dependent on the electron energy distribution.