2020 29th International Symposium on Discharges and Electrical Insulation in Vacuum (ISDEIV)

Book of Abstracts

C5-O3-9

The onset of the magnetized pulsed vacuum arc: a promising way for high efficiency propulsion

Content

Vacuum arcs nowadays are used in the wide range of applications including high current electronics, thin films deposition, particle accelerators and advanced plasma propulsion. Small, lightweight low-power micro-cathode arc thrusters are well-suitable for altitude control of small satellites like cubesats, and the thrust of such thrusters can be remarkably enhanced by implementing a magnetic field. However, for such applications as orbit raising or interplanetary missions, their thrust level needs to be improved even further by the adding a second acceleration stage. Recently, we proposed a possible approach for two-staged thruster – a micro cathode thruster with magneto plasma dynamical (MPD) stage with external magnetic field created by permanent magnet or magnetic coil. The concept of two-stage micro-cathode arc thruster implies the preliminary production of initial fully-ionized metal plasma by the first stage based on pulsed vacuum arc, and acceleration of this plasma by the j x B force created in the second stage. MPD approach looks promising since it allows accelerating quasi-neutral plasma without using low-transparent accelerating grids, high voltages, and additional power-consumable cathodes-neutralizers with limited lifetime. Investigating this new plasma thruster, we found that being sufficiently magnetized by a dc magnetic field having both axial and radial components, such two-stage magnetized pulsed vacuum arc discharge demonstrates a threshold behavior: such single-pulse parameters as thrust, total charge of expelling ions, and ion-to-arc charge ratio rapidly jump after certain threshold dc voltage ap-plied between the cathode of the first-stage micro-cathode arc thruster and the accelerating (MPD) electrode. Using independent experimental methods (electrical measurements and dynamic measurements with torsional thrust stand), we observed that the mentioned effect allows increasing the thrust (in several tens of times) together with thrust-to-power ratio (in several times).
This opens up the perspectives of creation of new type of miniature and low-power plasma thrusters for small satellites propulsion. The work was supported by NASA DC Space Grant Consortium and Vector Launch Inc.

Primary authors: Dr ZOLOTUKHIN, Denis (The George Washington U niversity); Mr DANIELS, Keir (George Washington University); KEIDAR, Michael (George Washington University)

Presenter: Dr ZOLOTUKHIN, Denis (The George Washington University)

Track Classification: C5. Space related technologies

C1-O11-14

Quality Assurance of Vacuum Interrupters Intended for Transmission Voltage Level Application

Content

Vacuum Interrupters (VI's) have since their first commercial introduction in the late 1950s proven to be an extremely reliable component for use in all Low- and Medium-Voltage power switching applications. Today vacuum technology dominates in the distribution voltage level markets. One of the unknowns in the early days was the expected life of these sealed devices. Sealing techniques where in their beginnings and knowledge of gasses penetrating through (tiny) leaks, out-gassing of materials and permeation of gases through the enclosure were barely understood. In those days measuring even the degree of vacuum in pumped systems was still in its infancy and limited in range and accuracy. Under these circumstances it was virtually impossible to determine the vacuum life of hermetically sealed devices which were intended to be applied in switchgear systems with a service life of 30, 40 or 50 years. However, materials and components, design, processing and quality control as also measurement techniques have greatly improved over the years and vacuum life for factory new interrupters can nowadays be determined well beyond the longest expected service life. Modern VI's for use up to and including distribution voltage levels have a design life of at least hundred years surpassing the service life of any practical switchgear system. Resent developments however, where single-break VI's are being introduced in the lower transmission voltage levels starting from 72.5kV and being applied in (high pressure) gasses other than air, raises the question if the current measurement techniques can be applied one-on-one on these substantial larger devices and maintain a sealed for life assurance for interrupters leaving the factory. The overall impact of an interrupter failure during its service life due to a poor degree of vacuum in the transmission voltage level domain could be substantial. Therefore, it is essential to have a proper vacuum measurement system in place for these new interrupter styles to ensure shipment of sealed for life devices. This paper presents the current vacuum measurement technique for VI's as also some basic design considerations like the use, selection and placement of getter materials. In the second part we will take a closer look at the current measurement technique to see if it is suitable or could be made suitable for VI's with a large free internal volume and intended for use in other gases than air, like e.g.: N2, SF6, CO2 or NovecTM and gas mixtures under elevated pressures up to about 0.8MPa. Finally, the outcome of the investigation and recommendations are being discussed.

Primary author: LEUSENKAMP, Martin (Eaton Corporation)

Presenter: LEUSENKAMP, Martin (Eaton Corporation)

Track Classification: C1. Vacuum interrupters and their applications

C1-O5-15

Discrimination of Discharge Pattern in Cut Model of Vacuum Interrupter

Content

Electrical insulation of a vacuum interrupter (VI) is a composite system composed of vacuum, metal, and solid insulator. Detection of weak points in insulation where breakdown may occur is important for insulation design of VI. In order to grasp insulation conditions inside VI, it is important to identify discharge sites and discharge patterns. On the other hand, solid insulators of VI are mostly made of opaque ceramics, and it is very difficult to directly visually observe discharge sites and patterns inside VI. Therefore, a method is needed to identify discharge patterns from outside, based on discharge waveforms and physical mechanisms of particular discharge patterns. Previously, we have proposed a discrimination method of discharge patterns in VI by extracting features and parameters of applied voltage, discharge current, and shield potential change, based on the relation between discharge type (gap breakdown or surface flashover), discharge voltage, developing time, and discharge path length. And, we confirmed the effectiveness of this method by using the simplified electrode system simulating the structure inside VI. In this study, we aim to verify that our proposing method can discriminate discharge patterns even in an actual structure of VI.

We prepared a cut model of VI, whose structure is similar to that of actual VI. Its shield electrode and alumina ceramic insulators have been partly cut for observing the discharge site. In this VI cut model, we simulated the weak points in insulation by additional needle electrodes. The VI cut model was set in a vacuum chamber at 10^{-5} Pa. We applied a negative standard lightning impulse voltage between contact electrodes in the VI cut model. We measured the applied voltage and the shield potential with voltage dividers (50 MHz) and the anode current with two high frequency current transformers (20 MHz and 200 MHz).

Still images of discharge were captured with a digital camera to check the discharge patterns. In various settings, e.g. with/without needle electrodes, different positions and lengths of needle electrodes, different gap lengths between contact electrodes, and with/without electric field relaxing electrode at the edge of alumina insulator, we verified the effectiveness of our proposing discharge discrimination method. In all settings, we almost succeeded to discriminate the initiation pattern of discharge. Even in the case that the discharge image could not be captured because the discharge would occur behind electrodes or insulators, it was estimated that the method enabled us to discriminate the discharge pattern. In the case of complex discharge pattern with gap and/or surface discharge, basically we could also discriminate the discharge pattern as well as in our previous electrode model simulating VI. In the present VI cut model similar to actual VI, we found the new discharge pattern, in which the first gap discharge induced another gap discharge due to the diffusion of particles from the first discharge. However, by modifying the discrimination method based on the above physical mech-anism of new discharge pattern, we got the prospects that the method can be applied to actual VI structure.

Primary authors: Dr KOJIMA, Hiroki (Nagoya University); Mr DONEN, Taiki (Mitsubishi Elec-tric Corporation); Mr KIMURA, Toshinori (Mitsubishi Electric Corporation); Mr KOKURA, Kentaro (Mitsubishi Electric Corporation); Prof. HAYAKAWA, Naoki (Nagoya University)

Presenter: Dr KOJIMA, Hiroki (Nagoya University)

Track Classification: C1. Vacuum interrupters and their applications

B1-O1-17

Influence of Ignition Position on the Properties of Vacuum Arc Generated by Switching RMF Contacts

Content

Radial magnetic field (RMF) contacts are widely used for the control of vacuum arcs at high currents. The self-induced magnetic field from the flow of the current through the contact structure drives the arc motion, reducing the thermal load on the contact surfaces. The initiation behavior of the drawn arc can affect the arc motion, and thereby the performance of the contacts. This contribution reports on the influence of the arc ignition position on the behavior and properties of switching arc between the RMF contacts. An AC current pulse with a peak value of about 28 kA and frequency of 50 Hz is used. Electrodes were made of Cu-Cr. Defined ignition positions were mechanically created on the cathode surface, with optical confirmation. Besides the arc cur-rent and voltage measurements, various optical diagnostics were used. Two high-speed cameras equipped with narrow-band filters characterized the arc behavior, which distinguished the emission of atomic, and ion copper lines. The anode activity was observed by an additional high-speed camera. Near infrared radiation (NIR) spectroscopy determined the anode surface temperature after current zero crossing. In addition, the density of neutral chromium vapor close to the current zero crossing was measured by means of broadband optical absorption spectroscopy. Three Cr I resonance lines at 425.43 nm, 427.78 nm, and 428.97 nm are used for the analysis. The results show clear influence of initial arc position on anode temperature and Cr density.

Primary authors: GORTSCHAKOW, Sergey (Leibniz institute for plasma science and technol-ogy); Dr GONZALEZ, Diego (Leibniz Institute for Plasma Science and Technology (INP)); METHLING, Ralf (Leibniz Institute for Plasma Science and Technology (INP Greifswald)); Dr FRANKE, Steffen (Leib-niz Institute for Plasma Science and Technology (INP)); Prof. UHRLANDT, Dirk (Leibniz Institute for Plasma Science and Technology (INP)); Mr LAWALL, Andreas (Siemens AG); Dr TAYLOR, Erik D.(Siemens AG); GRASKOWSKI, Frank (Siemens AG)

Presenter:METHLING, Ralf (Leibniz Institute for Plasma Science and Technology (INP Greifswald))

Track Classification: B1. Switching in vacuum and related phenomena

C1-P2-20

Switching of load currents with vacuum interrupters and the resulting electrical life

Content

Although a considerable amount of effort is focused on the short-circuit performance of vacuum interrupters, in practical applications these high current operations rarely or almost never occur. Instead, the bulk of operations in the field are switching load and/or capacitive currents. For load current switching, the low contact erosion and low metal vapor generation of the vacuum arc enables very long electrical life. Although this behavior is very advantageous, it does make the testing and determination of the ultimate electrical life at load currents difficult. Tests on Cu-Cr and Cu-W contacts in vacuum interrupters performed 20,000-30,000 operations at 2500-2700 A. The vacuum interrupters with both types of contacts maintained the dielectric strength, contact shape and composition, and small change in contact resistance necessary to perform all required duties even after arcing operations with total transferred charges >200 kA·s per interrupter. Contact erosion was within the parts machining and assembly tolerances of the vacuum interrupter, and of no practical significant. These results further confirm that vacuum interrupters can have a very long electrical life when switching currents where the vacuum arc is naturally diffuse.

Primary author: Dr TAYLOR, Erik D. (Siemens AG)

Co-authors: Mr EISELT, Martin (Siemens AG); Mr TSCHIESCHE, Ralf (Siemens AG); Mr SURESH, Unni (Siemens AG); Dr BRAUNER, Thomas (Siemens AG)

Presenter: Dr TAYLOR, Erik D. (Siemens AG)

Track Classification: C1. Vacuum interrupters and their applications

B3-O8-25

Study of High-Current Anode Modes for Various Electrode Materials

Content

The anode activity in switching vacuum arcs deserves special attention since this electrode is the main source of neutral metal vapour when the arc current is sufficiently high. The vapour distribution between the electrodes is arbitrary, can't be controlled by electromagnetic fields, and promotes the arc re-ignition in case of sufficient high density. However, the desired surface properties can be achieved by the choice of appropriate electrode material, which provide certain possibilities to influence the anode activity. In the frame of the present work electrodes made from CuCr alloy with the same composition, but different thermal processing has been studied under the AC current load of up to 6.5 kA. Especially, the appearance of various anode modes has been analyzed. The anode modes were distinguished by optical observation using a high-speed camera techniques (diffuse, footpoint mode, anode spot type 1), as well as by arc voltage measurements (anode spot type 2). The existence range of var-ious anode modes have been determined. Simultaneously to the optical observations, the anode surface temperature was determined by means of NIR spectroscopy. In addition, the density of neutral chromium vapor after current zero crossing was measured by means of broadband optical absorption spectroscopy. Three Cr I resonance lines in the region 425-429 nm are used for the analysis. The morphology of the anode surface after appearance of various anode modes have been analyzed by microscopy. The results show a clear influence of material properties on the anode activity and electrode erosion. The results of anode surface temperature and Cr I density measurements for various electrode materials will be presented and discussed.

Primary authors: GORTSCHAKOW, Sergey (Leibniz institute for plasma science and technology); Dr GONZALEZ, Diego (Leibniz Institute for Plasma Science and Technology (INP)); Dr FRANKE, Steffen (Leibniz Institute for Plasma Science and Technology (INP)); METHLING, Ralf (Leibniz Institute for Plasma Science and Technology (INP Greifswald)); Prof. UHRLANDT, Dirk (Leibniz Institute for Plasma Science and Technology (INP)); Dr BOENING, Sabine (PLANSEE Powertech AG); Dr BOENING, Mike (PLANSEE Powertech AG)

Presenter: Prof. UHRLANDT, Dirk (Leibniz Institute for Plasma Science and Technology (INP))

Track Classification: B3. Vacuum arc physics

A1-O6-26

A Method to Analyze Particle Induced Vacuum Breakdown with Obvious Field Emission Current

Content

To reveal vacuum breakdown mechanism is important for insulation enhancement between vacuum gap. In this experiment, impulse voltage was applied across pure copper plane electrode gap in ultra-high vacuum condition (ranging from 10-6 to 10-7 Pa). Surface analysis with XPS (X-ray photoelectron spectroscopy) was carried out in the surface analysis chamber. The circuit current and applied voltage were measured during the breakdown test. Two cameras were fixed with a right angel of 90° to capture the breakdown pictures and the breakdown location on the cathode surface was obtained. The anode and cathode electrode surfaces were both scanned under SEM. The electric field flux was also simulated. The results showed a typical kind of measured break-down waveform: obvious field emission current appeared but no breakdown occurred at the peak value of field emission current. When the field emission current decreased from the peak, a sud-den breakdown happened. Through surface analysis, the electrode surface was pure copper was confirmed. Through two cameras were fixed with a right angel of 90°, breakdown site was located. The SEM results showed no micro-protrusions existed around breakdown site and many particles covered on the center of electrode. So, the breakdown waveform was viewed as particle induced breakdown. A model how the particle induced breakdown with obvious field emission current was built to explain this phenomenon.

Primary authors: Dr LI, Shimin (Jiangsu Key Laboratory of New Energy Generation and Power Conversion, Nanjing University of Aeronautics and Astronautics); Prof. YAMANO, Yasushi (Department of Electrical and Electronics Systems, Saitama University); Prof. GENG, Yingsan (State Key Lab. of Electrical Insulation and Power Equipment, Xi'an Jiaotong University); Prof. LIU, Zhiyuan (State Key Lab. of Electrical Insulation and Power Equipment, Xi'an Jiaotong University); Prof. WANG, Jian-hua (State Key Lab. of Electrical Insulation and Power Equipment, Xi'an Jiaotong University); Prof. ZHANG, Chaohai (State Key Lab. of Electrical Insulation and Power Equipment, Xi'an Jiaotong Univer-sity)

Presenter: Dr LI, Shimin (Jiangsu Key Laboratory of New Energy Generation and Power Conversion, Nanjing University of Aeronautics and Astronautics)

Track Classification: A1. Vacuum breakdown and pre-breakdown phenomena

B3-I7-29

Electrode Processes in AMF-Contact Systems of Medium Voltage Vacuum Interrupters when Switching the Limiting Current. A Review

Content

The limiting interrupted current or breaking capacity is one of the most important characteristics of a vacuum circuit breaker (VCB). A VCB shall be able to interrupt a short-circuit current in the event of a network failure, which, depending on the power of the network, can amount to 100 kA. The main element of the VCB is the vacuum interrupter (VI). Therefore, there is a need for VIs which are able to switch off large currents and at the same time have acceptable weight and dimensional parameters. In order to create and improve such VIs, it is necessary to develop physical studies of high-current vacuum arcs and, in particular, the processes on electrodes at a current close to the limiting interrupted current. The article provides a brief overview of the results obtained in this field in the past. The concepts of the physics of the processes determining the limiting interrupted current, formed on the basis of these results, are formulated. Further, the article provides an overview of the results of modern research. Appeared in the last decade new technical tools have allowed progress in understanding processes at the electrodes during the arc burning and determination of the thermal state of the electrodes after arc extinction. The results obtained in a number of modern works allowed us to supplement and clarify the previous hypotheses. It is shown that in the process of breakdown of the gap immediately after zero current, which limits the switched current, the processes on the electrodes, namely the dynamics of the electrode melt, play an important role.

Primary author: Mr SHKOL'NIK, Sergey (Ioffe Institute)

Presenter: Mr SHKOL'NIK, Sergey (Ioffe Institute) Track

Track Classification: B3. Vacuum arc physics

B2-P3-33

Experimental Investigation of Vacuum Arc Characteristics of Four Kinds of AMF Contacts

Content

Axial magnetic field (AMF) contacts are widely used in vacuum interrupters. In this paper, the magnetic field distribution of 1/2 coil-type contact, 2/3 coil-type contact, 1/3 coil-type contact and cup-type contact are calculated and analyzed. It is found that the AMF strength of coil-type contacts is much greater than that of cup-type contact. The order of residual AMF from weak to strong is: cup-type contact, 1/3 coil-type contact, 1/2 coil-type contact and 2/3 coil-type contact. The order of phase shift from small to large is: 1/3 coil-type contact, 2/3 coil-type contact, 1/2 coil-type contact and cup-type contact. Triggered vacuum arc experiments about these contacts are carried out and the vacuum arc evolution process is recorded by high-speed camera. It is found that, under the same current, the arc constriction of the cup-type contact is the most serious and the arc of 2/3 coil-type contact has almost no constriction.

Primary author: WANG, Lijun (Xi'an Jiaotong University)

Co-authors: Prof. JIA, Shenli (Xi'an Jiaotong University); Mr SHI, Weixin (Xi'an Jiaotong Univer-sity); Mr WANG, Kai (Xi'an Jiaotong University); Mr YAN, Chao (Xi'an Jiaotong University)

Presenter: WANG, Lijun (Xi'an Jiaotong University)

Track Classification: B2. Interaction of vacuum arcs with magnetic fields

A1-P3-36

Kinetic Simulation of the Plasma Formation in the Vacuum Gap with CuCr50 Cathode

Content

In this work, an improved two-dimensional (2D) particle-in-cell/Monte Carlo collisional (PIC/MCC) model is developed to simulate the plasma initiation between planar electrodes in the vacuum break down stage. The improved model is based on the previous work. In this paper, the electric field applied to the electrode gap, which is axis-symmetric, is constant and above the critical field for the breakdown in vacuum. The field distribution is obtained by solving the Poisson's equa-tion in 2D cylindrical coordinate and the positions of charged particles, which are traced as super particles to save the calculation time and computer memory, are given by Newton's law. Vari-ous collisions between particles including elastic scattering, impact excitation and ionization are treated with MCC method. The flux of electrons emitted from the cathode is calculated by the field emission equation considering the Schottky effect and the evaporation rate of atoms is calculated according to Hertz-Knudsen equation. The grid size and time step satisfy the constraints given by the Debye length and plasma frequency, and the number of super particles per cell is above 100 to give reliable results. Results show that the plasma quickly forms from the field emission and evap-oration near the field emitter and expands in a hemispherical shape. During the discharge, an ion sheath, a quasi-neutral region and an acceleration layer can be observed in the simulation. There is a large gradient in the plasma density distribution near the field emitter. The well-pronounced potential hump near the cathode, the high ion velocity in the acceleration layer and ion charge state agree well with results in previous research works. In addition, the effect of cathode material is investigated.

Primary author: Dr WANG, DAN (State Key Laboratory of Electrical Insulation and Power Equipment, Xi'an Jiaotong University)

Co-authors: Prof. WANG, LIJUN (State Key Laboratory of Electrical Insulation and Power Equipment, Xi'an Jiaotong University); Dr LIU, JIE (State Key Laboratory of Electrical Insulation and Power Equipment, Xi'an Jiaotong University); Mr WANG, ZHIWEI (State Key Laboratory of Electrical Insulation and Power Equipment, Xi'an Jiaotong University); Prof. JIA, SHENLI (State Key Laboratory of Electrical Insulation and Power Equipment, Xi'an Jiaotong University)

Presenter: Dr WANG, DAN (State Key Laboratory of Electrical Insulation and Power Equipment, Xi'an Jiaotong University)

Track Classification: A1. Vacuum breakdown and pre-breakdown phenomena

C4-O3-38

Precision High Voltage Platform for Accelerators and Ion Mass Analysis

Content

High voltage platform are of widespread use in nuclear physics accelerators in order to provide the initial acceleration of ions. The ion source environment is particular challenging for high voltage (HV) holding, since the discharge can be energized from source radiation or secondary particles, generated by the ion beam. Moreover, the accelerator spectrometers for charge to mass ratio selection of exotic nuclei require a well defined beam energy, which fact poses challenging requests to high voltage design, rising the question of which electrode design rules are necessary for a quiet voltage operation, with tol-erable energy rms relative fluctuation in the 10^{-5} order, including contributions from all devices in a beamline (spanning a 10 m size). Need for a thick plate ground is discussed and compared to existing installations. Several components must be optimized for achieving and measuring with the required precision: the transformer and transmission line system must not couple 50 Hz ripple and harmonics larger than HV generator ones; the cooling system may offer a convenient bleeder (for safety and for proper load of the HV generator); corona free operation of large area surfaces is necessary. The acceleration and deceleration tubes (each one formed by many electrodes) should stand vacuum arcs, possibly triggered by beam accidental loss, without any damage for long peri-ods. The parameters required for stability of this nonlinear system with many degrees of freedom are discussed, with particular attention to the case of resistive voltage dividers. Such dividers, provided that inter-electrode capacitance and resis-tances are balanced and calibrated, also offer a convenient method to measure ripple voltage, to be compared with other breakdown diagnostics. The ion mass spectrometer itself offers another method, if calibrated by extensive ion orbit simulations, which can be compared with previous methods.

Primary authors: CAVENAGO, Marco (INFN-LNL); BALTADOR, Carlo (INFN-LNL); BELLAN, Luca (INFN-LNL); COMUNIAN, Michele (INFN Laboratori Nazionali di Legnaro); FAGOTTI, Enrico (INFN-LNL); PALMIERI, Antonio (INFN-LNL); PISENT, Andrea (INFN-LNL); Dr ROSSIGNOLI, Mas-simo (INFN-LNL)

Presenter: CAVENAGO, Marco (INFN-LNL)

Track Classification: C4. Accelerators and fusion reactor related issues

B1-P1-40

Evolution of Intermediate-frequency Vacuum Arc in Axial Magnetic Field

Content

Variable intermediate-frequency (360-800 Hz) power technology is widely used in aircraft power supply systems. This paper studies the appearance and evolution of vacuum arc in axial magnetic field (AMF) at 360-800 Hz. By the influence of the AMF, arc voltage and arc energy will be minimized, which is advantageous for maintaining arc diffusion. The experimental results show that when the contact separation was 3 mm, the vacuum arcs were uniformly distributed and diffused in the AMF contacts. By analyzing the dynamic volt-ampere characteristics of vacuum arc, the evolution of vacuum arc is studied. From the dynamic volt-ampere characteristic at different currents and different frequencies, a similar rule can be observed, that is, as the current and voltage change there are 3 stages in the vacuum arc evolution, which are arc free expansion stage (S1), arc transition stage (S2) and arc diffusion stage (S3). In S1, the arc is controlled by a small magnetic field, and the arc begins to expand. In S2, the main feature of vacuum arc is that the number of cathode spots increases around the rotating arc. The arc voltage increases gradually, rises to a peak and then begins to drop. The S3 of vacuum arc occurs at the peak current and continues until the current passes zero. In S3, the rapid expansion of arc is stopped, and the cathode spots occu-pied the largest area of contact surface. After the current peak, the brightness of the arc gradually decreases as the current decreases, and the number of cathode spots decreases also.

Primary authors: Dr JIANG, Yuan (University of Science and Technology Beijing); Prof. LI, Qing (University of Science and Technology Beijing); Prof. WU, Jianwen (Beihang University); Mr XIA, Shangwen (Beihang University); Mr JIA, Bowen (Beihang University); Ms XIN, Chao (ABB (China) Ltd.Beijing)

Presenter: Dr JIANG, Yuan (University of Science and Technology Beijing)

Track Classification: B1. Switching in vacuum and related phenomena

B3-P1-41

Cathode and plasma phenomena in vacuum-arc sources of deuterium ions

Content

An experimental and theoretical study of the content of deuterium ions in the arc discharge plasma was performed for deuterated zirconium cathodes. It was found experimentally that the deuterium ion percentage increased significantly with increasing arc current and decreasing arc duration, reaching 85% at kiloampere currents and few microsecond durations. In this case, a clear correlation was found between the content of deuterium ions in the arc plasma and the mean charge of zirconium ions: the higher the mean Zr ion charge, the greater the amount of deuterium ions in the plasma. A model is proposed to describe the desorption of deuterium from a deuterated cathode during the operation of the vacuum arc cathode spot. It is shown that the amount of deuterium desorbed immediately from the crater formed during the operation of the cathode spot cells is several times smaller than the total amount of desorbed deuterium. The main portion of deuterium is desorbed from the hot cathode region adjacent to the crater and from the crater at the stage of its cooling. A model was developed to describe the ionization processes that occur in the plasma of a vacuum arc with a deuterated cathode. It was shown that the relative content of deuterium ions in the plasma jet ejected from an individual cathode spot cell is not over 50%. The deuterium atoms are additionally ionized when the plasma jets of individual cells are mixed within a group cathode spot with high average current density. Conditions for additional ionization arise when the density of cells on the cathode surface is high, that is, at the initial stage of the discharge operation. The work was supported by the Russian Science Foundation (grant No. 18-19-00069).

Primary authors: BARENGOLTS, Sergey (Prohorov General Physics Institute RAS); Dr FROLOVA, Valeria (Institute of High Current Electronics, SB, RAS, Tomsk, Russia); Dr NIKOLAEV, Alexey (High Current Electronics Institute); OKS, Efim (High current electronics i nstitute); Dr SAVKIN, Konstantin (High Current Electronics Institute); Prof. SHMELEV, Dmitry L. (Institute of Electrophysics, RAS, Eka-terinburg, 620016, Russia); Dr UIMANOV, Igor (Institute of Electrophysics, UB, RAS, Ekaterinburg, Russia); YUSHKOV, Georgy (High Current Electronics Institute)

Presenter: BARENGOLTS, Sergey (Prohorov General Physics Institute RAS)

Track Classification: B3. Vacuum arc physics

A1-O6-42

Influence of Middle Gap Distance on Breakdown Characteristics of Triple Vacuum Gaps in Series

Content

As vacuum circuit breakers develop to high voltage level, the multiple floating shields are used in vacuum interrupters. The dielectric strength of the shield gaps needs to be evaluated during insulation design inside the vacuum interrupters. And the shield gaps can be regarded as multiple vacuum gaps in series. The objective of this paper is to determine the influence of gap distance on the breakdown characteristics of triple vacuum gaps in series with asymmetrical distribution under lightning impulse voltage. In the experiments, a negative standard lightning impulse volt-age was applied. A sphere-plane electrodes system was selected in the experiments, which was conducted in the vacuum interrupter with the glass bulb. The material of the electrodes was Cu. The diameter of sphere was 18 mm. The diameter of plane electrode was 50 mm. The gap distance of the sphere-plane electrodes could be adjusted. The triple vacuum gaps in our experiments was composed of three asymmetrical sphere-plane electrodes systems. The experimental researches can help to further understand the breakdown characteristics of multiple floating shields in vac-uum interrupters.
The experimental results will be presented in the full paper.

Primary authors: Mr SHEN, Jingyu (Xi'an Jiaotong University); Dr MA, Hui (Xi'an Jiaotong University); Mr MA, Xiangteng (Xi'an Jiaotong University); Prof. GENG, Yingsan (State Key Lab. of Electrical Insulation and Power Equipment, Xi'an Jiaotong University); Prof. LIU, Zhiyuan (State Key Lab. of Electrical Insulation and Power Equipment, Xi'an Jiaotong University); Prof. WANG, Jianhua (State Key Lab. of Electrical Insulation and Power Equipment, Xi'an Jiaotong University)

Presenter: Mr SHEN, Jingyu (Xi'an Jiaotong University)

Track Classification: A1. Vacuum breakdown and pre-breakdown phenomena

A1-I5-43

Identifying Critical Plastic Activity in Electrodes under Intense Electric Fields and the Link to Breakdown Nucleation

Content

The hypothesis that arc nucleation is related to plastic activity due to collective motion of dislocation in the cathode is examined via experiments and theoretical efforts over the last few years. I will summarise current theoretical and experimental observations indicating specific dislocation activity related to the applied high field. In addition I will discuss the challenges that lie ahead in trying to confirm this hypothesis as well as put it to use.

Primary authors: ASHKENAZY, Yinon (The Hebrew University of Jerusalem (IL)); ENGELBERG, Eli (Hebrew University of Jerusalem); POPOV, Inna; NACHSHON, Itay; LACHMANN, Sagy Itschak (Hebrew University of Jerusalem); Dr GAD, Raanan (Hebrew University)

Presenter: ASHKENAZY, Yinon (The Hebrew University of Jerusalem (IL))

Track Classification: A1. Vacuum breakdown and pre-breakdown phenomena

B3-P1-46

Modeling and Simulation research on the influence of metal particles on the characteristics of high-current vacuum arc

Content

In the breaking process of vacuum interrupter, the vacuum arc carries internal energy and kinetic energy into the anode surface, and the anode becomes active due to the high temperature. When the anode is active, metal particles with the same temperature as the anode surface will sputter out from the anode surface. When the metal particles enter into the arc column, the neutral atoms evaporated from the metal particle surfaces will collide with the cathodic plasma. In this paper, the microscopic physical model of the interaction between the metal particle vapor and the cathodic plasma is established, the influence of the metal particles on the plasma parameters and the ionization recombination process of the neutral atomic vapor and the cathodic plasma are studied. The results show that the neutral atomic vapor has significant cooling effect on the plasma near the metal particles, and leads to significant decrease of the ion temperature and electron temperature near the metal particles, however the ion density near the metal particle has significant increase due to the ionization of the neutral atomic vapor. The variations of ion temperature and ion den-sity near the metal particles lead to the ion pressure decrease first, then increase and then decrease (from cathode to anode). In addition, the decrease of electron temperature near the metal particle leads to the decrease of the electrical conductivity, and finally leads to the current density near the metal particle much lower than that in the arc plasma region. Due to the ionization recom-bination process, the neutral atom density near the metal particle surfaces rapidly decrease, and the ionization recombination front is formed at the place where the neutral atoms meet with the cathodic plasma. The results are beneficial to the deeper understanding of the interaction between the metal particles and the cathodic plasma.

Primary authors: Dr HUANG, Xiaolong (College of Electrical Engineering, Sichuan University, Chengdu, 610065, China); Mrs BAI, Xueyan (State Grid Meishan Power Supply Company, Meishan, 620010, China); Mr ZHU, Haiyi (College of Electrical Engineering, Sichuan University, Chengdu, 610065, China); Mr GOU, Hangyuan (College of Electrical Engineering, Sichuan University, Chengdu, 610065, China); Mrs ZHAO, Lihua (College of Electrical Engineering, Sichuan University, Chengdu, 610065, China); Dr REN, Junwen (College of Electrical Engineering, Sichuan University, Chengdu, 610065, China); Prof. WANG, Lijun (State Key Laboratory of Electrical Insulation and Power Equipment, Xi'an Jiaotong University, Xi'an, 710049, China); Dr WANG, Zhong (College of Electrical Engineer-ing, Sichuan University, Chengdu, 610065, China)

Presenter: Dr HUANG, Xiaolong (College of Electrical Engineering, Sichuan University, Chengdu, 610065, China)

Track Classification: B3. Vacuum arc physics

A1-O7-48

Pre-breakdown Markers on the Surface of Copper Cathodes of Vacuum Gaps

Content

Recently, a new view on the problem of initiation of vacuum breakdown is forming, which is, the factor of limitation of electrical strength of vacuum gaps should be seek not only on the surface, but also in the bulk of electrode material. Recent studies indicate that the initiators of the vac-uum breakdown may be defects of crystal structure of cathode material [1,2], most likely the dislocations [2–5]. In works [6–8] we suggested that the initiation of vacuum breakdown can be associated not only with dislocations arising under electric field action in the bulk of cathode material near inhomogeneities, but also with dislocations that initially exist in the material and have crops into the surface. However, so far there has been no direct experimental evidence that dislocation phenomena or dislocations themselves may be the initiators of vacuum breakdown. In this paper, a purposeful study the correlations of dislocation outcrops on the surface of single-crystal and coarse-grained particularly pure copper with positions of explosion-emission marks left subsequently by a short cathode vacuum spark was carried out. The coincidence of the cath-ode micro-explosive erosion sites with the positions of dislocation outcrops that existed before the breakdown was revealed. The appearance of extensive zones with altered crystal structure around the explosive centers is detected. Data on the nearsurface dislocation structure arising after a short-pulse spark on initially dislocation-free silicon single crystals are also presented.

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Primary authors: Dr NEFEDTSEV, Evgeny (Institute of High Current Electronics SB RAS); ONIS-CHENKO, Sergey (Institute of High Current Electronics, Tomsk, Russia)

Presenter: Dr NEFEDTSEV, Evgeny (Institute of High Current Electronics SB RAS)

Track Classification: A1. Vacuum breakdown and pre-breakdown phenomena

C4-P2-50

Experimental Results of Low-Z Materials as a High Voltage Septum Anode

Content

In the framework of the Physics Beyond Colliders study (PBC) at CERN, considerable efforts are being made to reduce the beam loss and remnant activation of the slow extraction equipment in the SPS LSS2 region. Simulations have demonstrated that changing the material of the septum anode, presently consisting of an array of WRe wires, for a low-Z alternative could reduce the overall activation of the extraction region in the order of 30%. A laboratory test set-up was built, allowing the high voltage (HV) testing of anodes using wires made of different materials. This paper outlines the operational requirements for the anode materials and presents the experimental results of HV tests with low-Z alternatives, such as CNT wires and Titanium alloy wires.

Primary author: BORBURGH, Jan (CERN)

Co-authors: BALHAN, Bruno (CERN); GODDARD, Brennan (CERN)

Presenter: BORBURGH, Jan (CERN)

Track Classification: C4. Accelerators and fusion reactor related issues

C3-P2-51

Formation of Pulsed Low-Energy Electron Beam by a Plasma-Cathode Electron Source Based on Cathodic Arc in the Forevacuum Pressure Range

Content

Wide application of glasses, ceramics and polymers, requires improvement of current methods and development of new methods of their treatment. In particular, wide range of surface modification methods of glasses, ceramics and polymers are developed. But most glasses, ceramics and polymers do not conduct electric current under normal conditions, i.e. are dielectrics, so to treat this material by electron beam at ordinary gas pressure (for electron-beam sources up to 0.1 Pa) it is required to use additional equipment to compensate negative charge on dielectrics' surface. Forevacuum plasma-cathode electron sources generating low-energy (up to 20 keV) electron beams in the forevacuum pressure range (3 - 100 Pa) provide direct treatment of dielectric materials. In particular, pulsed forevacuum plasma-cathode electron sources provide surface modification of dielectric materials. The paper presents results of research of influence of accelerating gap configuration and gas pres-sure on generation and propagation of pulsed large-radius, low-energy (up to 10 keV) electron beam by a plasma-cathode electron source in the forevacuum pressure range 4 - 30 Pa. The arc discharge with cathode spot (cathodic arc) has been used to generate emission plasma in order to provide generation of electron beam with current up to tens of amperes and pulse duration up to several milliseconds. A redistributing electrode has been mounted in the discharge gap of plasma-cathode source to improve homogeneity of arc plasma density distribution near electron extraction region (distance from the cathode is 60 mm). The accelerating gap is formed by anode mesh (emission electrode) and mesh extractor. Shape of mesh extractor and size of mesh cells affect on current density distribution across the electron beam. Varying of gas pressure causes a change in the distribution of current density of e-beam. An increase in gas pressure leads to ap-pearance of pronounced peaks in the distribution of current density of electron beam. Moreover, the use of a gas with grater ionization cross section causes a greater effect. The work was supported by the Russian Foundation for Basic Research grant No. 18-38-20044.

Primary authors: Dr KAZAKOV, Andrey (Federal State-Funded Institution of Higher Education – Tomsk State University of Control Systems and Radioelectronics); Dr MEDOVNIK, Alexander (Federal State-Funded Institution of Higher Education – Tomsk State University of Control Systems and Radioelectronics); Prof. OKS, Efim (High current electronics institute)

Presenters: Dr KAZAKOV, Andrey (Federal State-Funded Institution of Higher Education – Tomsk State University of Control Systems and Radioelectronics); Dr MEDOVNIK, Alexander (Federal State--Funded Institution of Higher Education – Tomsk State University of Control Systems and Radioelec-tronics)

Track Classification: C3. Electron, ion, neutron, X-ray and other beam and light sources

A1-P3-52

Temperature effect on the characteristics of radio frequency vacuum breakdown

Content

The report presents the results of a numerical simulation of the process of heating the microprotrusions on the cathode exposed to an radio-frequency electromagnetic fields depending on their initial temperature. The calculated model includes a self-consistent calculation of the electric field at the microprotrusion surface and the field emission characteristics of the microprotrusion using the particle-in-cell method, a calculation of the current density distribution in the microprotru-sion, and a calculation of the lattice and electron temperatures with the use of the heat equation taking into account the Joule and Nottingham effects, and also the finite rate of the heat exchange between the electrons and the lattice. As a result of the simulation, the dependences of the heating time of the microprotrusion on the cathode to a critical temperature from the enchancement factor of electric field for various initial temperatures are obtained.

Primary authors: BARENGOLTS, Sergey (Prohorov General Physics Institute RAS); Prof. SHMELEV, Dmitry L. (Institute of Electrophysics, RAS, Ekaterinburg, 620016, Russia); Dr UIMANOV, Igor (Insti-tute of Electrophysics, UB, RAS, Ekaterinburg, Russia 2 Institute High Current Electronics, SB, RAS, Tomsk, Russia)

Presenter: BARENGOLTS, Sergey (Prohorov General Physics Institute RAS)

Track Classification: A1. Vacuum breakdown and pre-breakdown phenomena

A1-P3-54

The Study of the High-Voltage Strength of the Tandem-Accelerator with Vacuum Insulation

Content

Accelerator based epithermal neutron source has been proposed and developed at BINP [1] for Boron Neutron Capture Therapy [2] - promising method for treatment of tumors. To obtain a proton beam with an energy of up to 2.3 MeV and a current of up to 10 mA, a new type of charged particle accelerator is used - an electrostatic tandem-accelerator with vacuum insulation. The accelerator has a fast ion acceleration rate, a large amount of energy stored in the gaps, a high value of the electric field strength of the vacuum gaps and a high value of the electric field strength along the surface of the insulators [3]. The dynamics of discharges and high-voltage breakdowns during accelerator training and when working with an ion beam using an ohmic voltage divider, gamma dosimeters, a thermal imager, and video cameras was studied. The accelerator training scenario has been developed, the basic features of the development of discharges and breakdowns have been determined. According to the results of the studies, the accelerator was modernized, which allowed to exclude high-voltage breakdowns of the accelerator gaps. This result is extremely important for this type of accelerator, considered as promising for the widespread adoption of BNCT in clinical practice. The report presents and discusses the results of studies and plans for further research.

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Primary authors: Mr BYKOV, Timofei (Novosibirsk State University); Mr KASATOV, Dmitrii (Bud-ker Institute of Nuclear Physics); Mr KOLESNILOV, Iaroslav (Budker Institute of Nuclear Physics); Mr KOSHKAREV, Alexei (Budker Institute of Nuclear Physics); Dr MAKAROV, Alexandr (Budker Institute of Nuclear Physics); Mr MELCHENKO, Stepan (Tomsk Polytechnic University); Mr SHCHUDLO, Ivan (Budker Indtitute of Nuclear Physics); Dr SOROKIN, Igor (Budker Institute of Nuclear Physics of SB RAS); TASKAEV, Sergey (Budker Institute of Nuclear Physics)

Presenter: TASKAEV, Sergey (Budker Institute of Nuclear Physics)

Track Classification: A1. Vacuum breakdown and pre-breakdown phenomena

B1-P1-61

Determination of Reignition Window of a Fast Vacuum Circuit Breaker Engaged in Shunt Reactors Switching

Content

When a fast vacuum circuit breaker (FVCB) is introduced into an application of fault current limiter, comprised by the FVCB and a parallel connected current limiting inductor, the short-circuit current breaking and transferring performance of the FVCB circuit branch depends on a decaying rate of short-circuit current di/dt before current zero and a rising rate of transient recovery voltage du/dt. However, there is no literatures cast light on short-circuit current breaking boundaries of the di/dt and the du/dt for a FVCB. The objective of this paper is to determine the reliable short-circuit current breaking di/dt and du/dt boundaries for a fast vacuum circuit breaker used in the fault current limiter. A synthetic test circuit is used to provide a power frequency test current, ranging from 5 kA to 40 kA, and a transient recovery voltage (TRV). The rising rate of the TRV du/dt is defined as a slope of the instant value from the 10% to the 90% of the TRV waveform. The du/dt can be adjusted both by changing the damping RC component and by changing the charging voltage of the voltage source in the synthetic test circuit. The arcing time during the test changes from 0.5 m/s to 9.5 ms. A 40.5 kV/2500 A-31.5 kA commercial vacuum interrupter is used, with the contact material is Cu50Cr50, the diameter of the contact is 68 mm, and the contact stroke is 20 mm. An electromagnetic repulsion actuator is used to provide an opening velocity for the breaking operation of the test vacuum interrupter, which ranges from 2.0 m/s to 6.0 m/s and stepped by 1.0 m/s. Details of the test result and discussion will be presented in a full paper version.

Primary authors: Dr YAO, Xiaofei (School of Electrical Engineering, Xi'an Jiaotong University); Dr DING, Jiangang (School of Electrical Engineering, Xi'an Jiaotong University); Dr GUAN, Chen (School of Electrical Engineering, Xi'an Jiaotong University); Dr RONG, Yi (School of Electrical Engineering, Xi'an Jiaotong University); Mr ZHANG, Luyang (School of Electrical Engineering, Xi'an Jiaotong Uni-versity); Mr ZHAO, Qing (School of Electrical Engineering, Xi'an Jiaotong University); Prof. LIU, Zhiyuan (School of Electrical Engineering, Xi'an Jiaotong University); Prof. WANG, Jianhua (School of Electrical Engineering, Xi'an Jiaotong University)

Presenter: Dr YAO, Xiaofei (School of Electrical Engineering, Xi'an Jiaotong University)

Track Classification: B1. Switching in vacuum and related phenomena

B1-P1-62

Computer-Aided Evaluation of Movement and Appearance of Vacuum Arcs

Content

The vacuum interrupter (VI) can perform breaking operations for rated and short circuit currents. At switching operation, the energy of the switching arc is distributed over the contact surface using magnetic fields to guarantee a constant performance over the period of service. The magnetic fields can be applied in a transversal or axial direction and interact with switching arc, which consists of metal vapor in plasma state. The visual appearance of this metal vapor or vacuum arc is classified in different modes depending on contact distance and current. Within these modes diffuse plasma or different kinds of constriction can appear. High-speed imaging is a common method to investigate these phenomena in custom vacuum chambers. Thereby the scope is mostly on the arcing behavior or the mode. The comparison of the investigations can vary between different publication due to the high complex processes and the different interpretations of the resulting visual appearances. This paper suggests a reproducible approach to automate the evaluation of images. The valuation of different modes, the tracking of the vacuum arc and the implementation are key contents. In previous publications, the required settings of high-speed cameras and the processing of images for an automated evaluation were described. With this tool, images are decomposed and used as raw data in which patterns and features can be described. These features are then used for the evaluation of the images. For the correct evaluation of images, the decisions made within the program have to be comprehensible. As object of investigation, short-circuit breaking operations with 35 Hz and 7 kA peak-currents with pin electrodes are performed. This test setup is used to generate references for different modes and gaps. Different sets of images recorded during these operations are used to show the operation of the decision algorithm for different arc modes and movement. Resulting from this evaluation is automated calculation of the arc mode and position of footpoints.

Primary author: WEBER, Benjamin (TU Braunschweig)

Co-authors: Mr MEYER, Timo (TU Braunschweig); Dr GENTSCH, Dietmar (ABB AG); Prof. KUR-RAT, Michael (TU Braunschweig)

Presenter: WEBER, Benjamin (TU Braunschweig)

Track Classification: B1. Switching in vacuum and related phenomena

B1-O1-63

Investigation of Vacuum Arcs Between with Varying Gaps up to 40 Mm

Content

As one of the most common circuit breaker technology, the vacuum interrupter (VI) is widely used in medium grid voltages. A main task is the interruption of high short circuit currents, where the VI outperforms other approaches due to low arc voltages during breaking operations. These low voltages are the result of the special kind of plasma produced as the contacts are separated. The applied current evaporates the contact surface and with the lack of a gaseous atmosphere, a metal vapor plasma is ignited. To avoid evaporation on a stationary point axial or transversal magnetic fields are applied to move the plasma over the contact surface. This plasma constricts due to the pinch effect with rising currents. The constriction behavior for gaps in the range of 20 mm gaps is well known and allows constructing VI for middle voltage level. Higher voltage levels require lager gaps to withstand dielectric stress. With growing gaps, the question of the constriction be-havior of vacuum arcs arises. To investigate this task two approaches are combined for this paper. Pin electrodes are used to create a reproducible reference for different gaps. To achieve long contacts gaps a programmable frequency converter with servo drive is used. Over a three-stage control loop, a predefined open-ing curve is implemented. Different opening curves with final gaps up to 35 mm are performed. Furthermore, the frequency of the synthetic test circuit is adjusted to 35 Hz to achieve longer arcing times. At this frequency, short circuit breaking operations with up to 7 kA peak currents are performed and observed using a high-speed camera in a rectangular arrangement. This test setup is combined with a software-based evaluation tool for reproducible analysis of arcing behav-ior. The description of the behavior with rising gaps shows the point where constricted arc is too long to be stable between the electrodes. The optimum of the arc length is essential of vacuum interrupters. This contributes to the feasibility of VIs in higher voltage levels.

Primary author: WEBER, Benjamin (TU Braunschweig)

Co-authors: Mr KÜHN, Benjamin (TU Braunschweig); Dr GENTSCH, Dietmar (ABB AG); Prof. KURRAT, Michael (TU Braunschweig)

Presenter: WEBER, Benjamin (TU Braunschweig)

Track Classification: B1. Switching in vacuum and related phenomena

C1-O5-64

Lightning impulse conditioning of a combined field grading and shielding arrangement for vacuum double break

Content

Advantages as environmentally friendly operation and relative low maintenance costs of vacuum circuit breakers (VCB) in comparison to other interrupters have established the VCB in the medium voltage range. In order to enlarge the operational voltage level the approach of double break is common. To symmetrize the voltage distribution over the series gaps the use of external grading capacitors is one possible solution. In the current work a double breaking vacuum chamber with additional field grading and shielding electrodes in a separate surrounding vacuum chamber to symmetrize the voltage distribution is presented. The purpose of this work is to investigate the shielding behaviour of the arrangement in a first step. Therefore a grounded surrounding electrode is used to disturb the symmetric field distribution over the arrangement. In a second step the dielectric behaviour in dependence of the shield preparation before and during conditioning is investigated. Complete breakdowns of the arrangement are detected using a common voltage divider. To detect partial breakdowns, the shields own capacitances are determined and used to generate a voltage divider. This approach also allows the estimation of the floating middle potential. All tests were performed with lightning impulse voltage stress (LIV). The present study combines the topic of conditioning with the topic of field shielding and delivers new approaches to symmetrize electric fields over vacuum double break arrangements for high voltage use.

Primary authors: Mr MEYER, Timo (TU Braunschweig); Mr KÜHN, Benjamin (TU Braunschweig); Dr GENTSCH, Dietmar (ABB AG); Prof. KURRAT, Michael (TU Braunschweig)

Presenter: Mr MEYER, Timo (TU Braunschweig)

Track Classification: C1. Vacuum interrupters and their applications

B3-P1-66

Thin Zr Film Deposition Using a Refractory Anode Vacuum Arc Plasma Source

Content

Zr films were deposited using plasma generated in a Hot Refractory Anode Vacuum Arc. (HRAVA). The cathode and anode were fabricated from Zr and graphite respectively and were not cooled. Both electrodes were 60 mm diameter, and 10 mm thickness. The gap distance was 8 mm, and the distance from the arc axis to the substrate was 110 mm. The arc was operated either 40 or 60 s before a glass substrate was exposed to the plasma for 15 s. The film thickness was measured by profilometry. The rate of deposition was obtained using the film thickness and exposition time. The visual radiation emitted by the plasma plume was photographed with a digital camera. The discharge started as a cathodic arc, which heated and deposited cathodic material on the anode. When the anode was sufficiently hot, all the deposited cathodic material was re-evaporated from it, and a steady state was established in which all cathodic material reaching the anode was evapo-rated from it. The arc emitted a radially expanding plasma with significantly reduced macroparticle (MP) contamination. The rate of film deposition increased from 0.44 to 0.64 m/min and 0.47 to 0.71 m/min when the arc current was increased from 150 to 225 A for times before exposure of 40 and 60 s, respectively.

Primary author: Prof. BEILIS, Isak I. (Faculty of Engineering,Tel Aviv University,)

Co-authors: Dr ARBILLY, D (Faculty of Engineering, Tel Aviv University); Dr YANKELEVICH, Y.(Faculty of Engineering, Tel Aviv University); Prof. BOXMAN, Raymond L. (Faculty of Engineering, Tel Aviv University)

Presenter: Prof. BEILIS, Isak I. (Faculty of Engineering,Tel Aviv University,)

Track Classification: B3. Vacuum arc physics

B4-P3-67

Asynchronous Discharge of Two Serial Connected Vacuum Interrupters under Lightning Impulse Voltage

Content

An asynchronous breakdown phenomenon is observed in two series connected vacuum gaps in our research. A time difference of the asynchronous breakdown instance is determined to range form several hundreds of nano-seconds to several micro-second, when a standard lightning impulse voltage is imposed. A kind of 12 kV commercial vacuum interrupter (VI) with the contact material of CuCr50 is used and connected in series. The gap distance of each VI ranges from 0.5 mm to 3 mm, stepped by 0.5 mm. Both a positive and a negative standard lightning impulse voltage are stressed across the test VIs, with an up and down method, respectively. Two voltage dividers with the same parameter are used to capture the breakdown of the gaps. The time difference of each asynchronous breakdown instance is obtained, and details of the results will be presented in the full paper version.

Primary authors: Mr LIU, Xue; Mr DING, Jian'gang; Mr YAO, Xiaofei; Mr GUAN, Chen; Mr RONG, Yi; Mr ZHANG, Jun; Mr ZHAO, Jun; Mr LIU, Zhiyuan; Mr WANG, Jianhua

Presenter: Mr YAO, Xiaofei

Track Classification: B4. Computer modeling and computer aided design

B3-P1-68

Arc spot on film cathode using kinetic approach of plasma flow

Content

A physical model of spot operation in a vacuum arc with a film cathode was developed by studying the dense kinetic plasma flow in the Knudsen layer. Transient heat conduction in a thin metal-lic film was taken into account for a moving spot, considering the cathode energy balance. The electron emission, vaporization and plasma processes including sheath formation, electron beam relaxation, atom ionization and the plasma flow in the expansion region were studied. A system of equation was derived and solved numerically for a case studied by Kesaev experimentally of Cu films of 0.017 to 0.14 m thickness deposited on glass substrates. The solution revealed at the external boundary of Knudsen layer a cathode potential drop of about 12 V, and a plasma velocity normalized by the sound speed of about 0.16. Both weakly depended on the film thickness. The power losses due to film heat conduction was comparable with the vaporization energy and both increased from 0.1 up to 1W, while the spot velocity decreased from 104 to 3 103 cm/s when the film thickness was increased from 0.017 to 0.14 m. The tract width increased with film thickness. The calculations and measurements showed comparable results.

Primary author: Prof. BEILIS, Isak I. (Faculty of Engineering, Tel Aviv University)

Presenter: Prof. BEILIS, Isak I. (Faculty of Engineering, Tel Aviv University)

Track Classification: B3. Vacuum arc physics

C1-P2-70

Behavior of vacuum interrupters during switching operations with a high rate of rise of recovery voltage (RRRV)

Content

Current interruption by circuit breakers requires the rapid restoration of the dielectric strength of the contact gap after the end of arcing. Typical short-circuit certification tests for medium volt-age (MV) circuit breakers use a transient recovery voltage (TRV) after the end of the full rated short-circuit current with a rate of rise of the recovery voltage (RRRV) in the range of 0.3-1.3kV/µs. Higher values up to 3.8kV/µs are used for tests below the full rated short-circuit current (tests T10, T30, T60 for example). Vacuum interrupters are extensively used in MV power systems in circuit breakers, reclosers, tap changers, load break switches and contactors. Occasionally special switching duties can require RRRV beyond the standard values, such as generator switching applications which require a RRRV of up to 5kV/µs. Successful tests were performed up to 10kV/µs with the full rated short-circuit current for axial magnetic field contacts (AMF), without observing a performance limit. Similar tests on transverse magnetic field contacts (TMF) were performed up to 7kV/µs with the full rated short-circuit current, again without observing a performance limit. In addition, the high RRRV values tested here demonstrate that RRRV for high-voltage (HV) system voltages ≥ 72.5kV up to 10kV/µs will not be a challenge for vacuum interrupters. Furthermore, this performance demonstrates that after the current zero, the recovery of the voltage withstand for the contact gap proceeds much faster than the solidification of the contact surface and the dispersion of the neutral metal vapor out of the contact gap.

Primary authors: VENNA, Karthik Reddy (Siemens AG); D TAYLOR, Erik; Mr LAWALL, Andreas (Siemens AG); Dr GENTSCH, Dietmar (ABB AG); Dr WETHEKAM, Stephan (Siemens AG)

Presenter: VENNA, Karthik Reddy (Siemens AG)

Track Classification: C1. Vacuum interrupters and their applications

B1-I1-82

DC Interruption Performance of Vacuum Interrupters in a Quench Protection Switch Based on Forced Current Zero

Content

In a superconducting Tokamak, superconducting coils play crucial roles in generating desired magnetic field profile and confining high-temperature plasma. When quench occurs inside superconducting magnet, tremendous energy stored in the coil has to be dissipated in time before any damage to the magnet caused by heat or electric stress. In this paper, a quench protection switch (QPS) based on forced current zero is investigated experimentally. The first current commutation process from the bypass switch (BPS) to the main circuit breaker (MCB) is presented. The second current commutation process from the MCB to the discharging resistor is mainly studied. In this stage, experimental current in the MCB, which uses vacuum interrupter, is forced to zero by a high-frequency countercurrent, which is a typical approach of DC interruption. The interruption performance and influence of contacts structure, countercurrent frequency and contacts stroke are discussed. The evolution of vacuum arc in this process is investigated as well.

Primary authors: SHI, Zongqian (Xi'an Jiaotong University); Mr LI, Sheng (Xi'an Jiaotong University); Ms ZHAO, Linyan (Xi'an Jiaotong University); Mr ZHAO, Zeliang (Xi'an Jiaotong Univer-sity); Mr LI, Jiayao (Xi'an Jiaotong University); JIA, Shenli (Xi'an Jiaotong University); WANG, Lijun (Xi'an Jiaotong University)

Presenter: SHI, Zongqian (Xi'an Jiaotong University)

Track Classification: B1. Switching in vacuum and related phenomena

B4-P3-85

The Influence of Transient Interrupting Voltage on the Residual Plasma Dissipation in a 10kV Mechanical DC Vacuum Circuit Breaker

Content

The direct current (DC) transmission systems have been developed rapidly in recent years. The vacuum circuit breaker has become a core component of the mechanical DC vacuum circuit breaker due to its excellent performance in extinguishing arc. Compared with the traditional alternating current interruption, an artificial current zero of DC interruption is created by injecting a high frequency current generated by an extra circuit into the vacuum circuit breaker. Therefore, the transient interrupting voltage TIV imposing on the mechanical DC vacuum circuit breaker should be very different from the transient recovery voltage generated by alternating current interruption. The dissipation of residual plasma under the TIV generated by DC interruption is important for post-arc dielectric recovery process and whole interruption performance. However, there are still few discussions about the influence of TIV on the dissipation of residual plasma. In this paper, the evolution of TIV is firstly studied on the basis of a 10kV mechanical DC vacuum circuit breaker. Then a one-dimensional particle-in-cell model is developed to study the influence of TIV on the dissipation of residual plasma.

Primary authors: Dr MO, Yongpeng (Xi'an Jiaotong University); JIA, Shenli (Xi'an Jiaotong Uni-versity); SHI, Zongqian (Xi'an Jiaotong University)

Presenter: Dr MO, Yongpeng (Xi'an Jiaotong University)

Track Classification: B4. Computer modeling and computer aided design

C5-P2-93

The Effect of Axial Magnetic Field on the Lifetime of Micro Cathode Arc Thruster (μ-CAT)

Content

- The micro cathode arc thruster (μ-CAT) is a propulsion device applied to micro satellites, which has the characteristics of simple structure, light weight and low power consumption relatively. At present, the key maintaining stable operation of the μ-CAT for a long time is the delicate balance between metal contamination and evaporation of the conductive coating during the process of vacuum discharge.
- In this paper, the design of μ-CAT is completed and the relevant experiment platform is established. In the condition of applied magnetic field, we use a special working mode regulating the peak discharge current dynamically, for the life testing. For comparison, the life testing was also performed in the working mode in which the peak discharge current was constant at 40 A and 10 A,respectively.
- The experiment results show that the working mode of changing peak discharge current can effectively extend the working life of the micro cathode arc thruster (μ-CAT). It demonstrates that the delicate balance between metal contamination and evaporation of conduc-tive coating material during vacuum discharge of micro cathode arc thruster (μ-CAT) can be effectively controlled macroscopically, which for the subsequent μ-CAT design and the study of microscopic mechanisms, maintaining the long working life of μ-CAT, have important implications.

Primary author: Mr WANG, Guan

Co-authors: Mr CHEN, Boyang; Dr SUN, Liqiong; Prof. WANG, Zhenxin

Presenter: Mr WANG, Guan

Track Classification: C5. Space related technologies

C1-P1-96

Application of Standard design of Vacuum Interrupter in Dual Contact Moving VCB to Withstand Higher TRV Values

Content

Use of series vacuum interrupters is known in the industry which is used to improve the dielectric performance of Vacuum interrupters to handle the higher voltages. This uses Two or more Vacuum interrupters for the said application or a specially designed Vacuum Interrupters. Which can become a little complicated, bulky. In this paper, a standard design of Vacuum interrupter is used to generate an idea of double mov-ing contact. Commercially available Single moving contact VI are mounted on existing mechanism but with modified linkage in order to pull both the contacts of VI, which results in movement of Fixed contact along with VI Bottle in one direction and Moving contact in other direction. Advantage of this method is that the opening velocity of VI is increased to around twice of original with existing spring mechanism and contact travel along with contact gap also increased, so it can be used for Higher voltages or clearing fault with higher TRV values. A detailed description of the mechanical parameters, its advantages is given.

Primary authors: Mr ALAM, MOHD SHANEY (LARSEN & TOUBRO LTD); Mr RAJHANS, Rupesh (Larsen & Toubro)

Co-author: Mr CHHAYA, Pravin (Laresen & Toubro Ltd)

Presenter: Mr ALAM, MOHD SHANEY (LARSEN & TOUBRO LTD)

Track Classification: C1. Vacuum interrupters and their applications

C1-O11-99

Prestrike Characteristics of Vacuum Circuit Breakers with Cup-type AMF Contacts and Spiral-type TMF Contacts under Capacitive Making Operations

Content

The prestrike gap of vacuum interrupters is one of the most important characteristics for the investigation of the injected energy into the contacts from the prestrike arcs during the making operations and of the dielectric strength between the electrodes in vacuum interrupters. The objective of this paper is to analyze the characteristics of the prestrike gap distribution under the influence of different amplitudes of inrush current during the capacitive current prestrike process. A commercial double-break circuit breaker with two 12 kV vacuum interrupters is used during the experimental tests. The tests are operated for 30 cycles of making operations under the inrush current of 10 kA and 20 kA separately. The displacement of the moving contact is measured with a high precision linear displacement transducer from which the prestrike gaps can be computed. Weibull distribution is used to fit the prestrike gaps and the prestrike electric field strength. The experimental results show that with the increment of the inrush current between the contacts, the prestrike gap tends to increase, indicating that the possibility of breakdown between the contacts increases. Moreover, the scattering effect of the prestrike gaps becomes stronger. Compared with the single-break circuit breaker, the double-break circuit breaker can reduce the scattering effect of the prestrike gaps under the same amplitude of the inrush current.

Primary authors: GENG, Yun (Xi'an Jiaotong University); Dr YAO, Xiaofei (School of Electrical En-gineering, Xi'an Jiaotong University); Mr DONG, Jinlong (Xi'an Jiaotong University); GENG, Yingsan (Xi'an Jiaotong University); WANG, Jianhua (Xi'an Jiaotong University); LIU, Zhiyuan (Xi'an Jiaotong University)

Presenter: GENG, Yun (Xi'an Jiaotong University)

Track Classification: C1. Vacuum interrupters and their applications

B4-O10-102

Development of a numerical model on metallic vapour behaviour in vacuum arc based on Moving Particle Semi-implicit (MPS) method and finite volume method

Content

A high voltage rated vacuum interrupter (VI) for vacuum circuit breakers (VCB) has recently been developed, because vacuum is an environmentally friendly high-voltage withstand medium com-pared to fluoride gas. Therefore, investigating arc behavior under reduced pressure is important for high voltage VCB design. In a vacuum circuit breaker, the arc plasma is maintained only by the metal vapor itself supplied from the electrodes. Metal vapor is generated by evaporation from the cathode and anode at high current densities. The emitted metal atom vapor is ionized to generate ions and electrons, forming an arc plasma. In order to simulate such an arc plasma under reduced pressure, several numerical models have been developed. One is a fluid model, which is used to simulate arc plasma dynamics under re-duced pressure during the high current phase. However, it is difficult to simulate low pressure, low current phase arc dynamics using a fluid model. Another calculation method is the particle method. Several particle methods have been developed, such as the Direct Simulation Monte Carlo (DSMC) method and the Particle-in-Cell (PIC) method. The DSMC method is often used to solve Boltzmann equations and simulate particle transport, for example, in vacuum arc deposition. The PIC method is also widely used for dynamic simulation of charged particles in low-pressure plasma. However, these methods require a long computation time to solve because of the very short time steps. In this study, we developed a unique hybrid model for the dynamic behavior of metal vapor in a vacuum arc [1]. This model is based on the Moving Particle Semi-implicit (MPS) method for hydro-dynamics of metal vapors, treated as a combination of many fluid elements with free boundaries. The original MPS method was developed to simulate incompressible flow dynamics. On the other hand, in this study, the original MPS method was modified to handle both compressible and incom-pressible flows of vapor, taking into account the vapor sound speed. This MPS method solves the Navier-Stokes equation, the Poisson's equation for pressure and the energy transport equation for dynamics of vapor elements. On the other hand, electron energy conservation for electron tem-perature and Possion's equations for electrostatic and vector potentials for electro-magnetic field were solved by Finite Volume Method (FVM). Thus, the resultant hybrid model can treat ions and atoms as heavy particles by the MPS model, whereas electrons as a fluid by the FVM method. The developed simulation model can calculate temporal evolutions in particle density for each of species, heavy particle temperature, ionization degree, current density distributions between the electrodes during vacuum arc with electromagnetic field. The calculation can be done in several hours, which is relatively shorter than those required for conventional particle models like DSMC and PIC.

[1] Y.Tanaka, et al., ICEPE-ST2017, E-O-3, 2017.10,Xian, China

Primary authors: Prof. TANAKA, Yasunori (Kanazawa University); Mr MIYAZAKI, Takamitsu (Kanazawa University); Dr NAKANO, Yusuke (Kanazawa University); Mr HATANAKA, Yuto (Kanazawa University); Prof. ISHIJIMA, Tatsuo (Kanazawa University); Mr ASANUMA, Gaku (Fuji Electric Co. Ltd); Dr ONCHI, Toshiyuki (Fuji Electric Co. Ltd)

Presenter: Prof. TANAKA, Yasunori (Kanazawa University)

Track Classification: B4. Computer modeling and computer aided design

C1-P2-105

Dependence of Short Circuit Breaking Current on its Minimum Arcing Times of a Fast Vacuum Circuit Breaker

Content

Controlled switching of a short-circuit fault can largely decrease arc erosion of the contacts in circuit breaker. However, there still no literatures cast light on controlled switching strategies of a fast vacuum circuit breaker (FVCB), especially on controlled switching of the short-circuit breaking current under different fault categories. The objective of this paper is to quantitatively determine the relationship between the short-circuit breaking current with opening velocities under different arcing durations. A 40.5 kV commercial vacuum interrupter is used, with the diameter of the contact is 68 mm, the material of the contact is Cu50Cr50. A synthetic test circuit is used to provide a test current ranging from 15 kA to 40 kA, and a transient recovery voltage TRV. The peak value of the TRV uc ranges from 50 kV to 90 kV, and the rising time of the TRV, from 10% uc to 90% uc, changes from 20 μs to 200 μs. An electromagnetic repulsion actuator is used to drive the vacuum interrupter, with an opening velocity ranging from 2.0 m/s to 6.0 m/s. Result and discussion will be presented in the full paper version.

Primary author: Mr GUAN, Chen (School of Electrical Engineering, Xi'an Jiaotong University, Xi'an, China)

Co-authors: Mr YAO, Xiaofei (School of Electrical Engineering, Xi'an Jiaotong University, Xi'an, China); Mr DING, Jiangang (School of Electrical Engineering, Xi'an Jiaotong University, Xi'an, China); RONG, Yi (School of Electrical Engineering, Xi'an Jiaotong University, Xi'an, China); Mr CHEN, Xinggui
(School of Electrical Engineering, Xi'an Jiaotong University, Xi'an, China); Mr WANG, Jianhua (School of Electrical Engineering, Xi'an Jiaotong University, Xi'an, China); Mr LIU, Zhiyuan (School of Electri-cal Engineering, Xi'an Jiaotong University, Xi'an, China); Prof. YANABU, Satoru (School of Electrical Engineering, Xi'an Jiaotong University)

Presenter: Mr GUAN, Chen (School of Electrical Engineering, Xi'an Jiaotong University, Xi'an, China)

Track Classification: C1. Vacuum interrupters and their applications

B3-P1-106

Physical characterization of the optical transmission path for digital high-speed camera observation of vacuum arcs

Content

The improvement of vacuum interrupters is an ongoing process, where arc characteristics are of special interest. Especially in case of Radial- or Transversal magnet field contacts (TMF) the rotation properties represent one interesting factor. The aim is to derive information about arc position, arc movement and, based on this, the thermal behavior of the contact surface. Therefore arc tracking approaches based on magnetic, electronic or optical recordings have been published. The improvement of these techniques is of high interest for further investigations with scientific and industrial scope. The purpose of this contribution is to investigate the influence of the optical transmission path during optical investigations using a two side angle arm over a mirror system. Both paths of the mirror system have different properties but are used in combination to derive arc information. A characterization of both optical paths to determine a correctional factor for the evaluation system is necessary. Therefore, the transmission path of the setup is characterized using a spectrometer and a calibrated radiation source. Additionally and for comparison, the optical arrangement is tested in an exemplary investigation setup with TMF contacts and short circuit currents between 5 to 15 kA. The rotation characteristics are analyzed with and without correction factor to evaluate the differences. This contribution improves the comparability of optical investigations for vacuum interrupters and helps to avoid failures in the analysis procedure.

Primary authors: KÜHN, Benjamin (Tu Braunschweig); Mr KOPP, Tobias (TU Braunschweig); Mr DORSCH, Christian (TU Darmstasdt); Prof. KURRAT, Michael (TU Braunschweig); Prof. HINRICH-SEN, Volker (Tu Darmstadt)

Presenter: KÜHN, Benjamin (Tu Braunschweig)

Track Classification: B3. Vacuum arc physics

A1-O6-107

Prebreakdown Current Characteristics of Vacuum Gaps with Various Gap Distances

Content

Mechanical shocks are long considered to be responsible for late breakdowns or non-sustained disruptive discharges of a vacuum circuit breaker, during the switching process. However, there still remains no quantitative research on this phenomenon. The objective of this paper is to determine a quantitatively relationship between the mechanical shock strength and the DC breakdown voltage under different vacuum gaps. An elaborate test equipment was developed to provide a mechanical impact force on the transmission part of the test vacuum interrupter (VI). The mechanical vibration imposed on the movable contact of the VI can be quantitatively evaluated by effect of the impact velocity on the vibration, which ranger from 1.0 m/s to 3.0 m/s, stepped by 0.5 m/s. A 40.5 kV vacuum interrupter (VI), with a couple of butt-type contacts, was used. The contact material was CuCr25 (Cu 75%wt, Cr 25%wt). The contact gap was set to range from 1 mm to 10 mm, stepped by 3 mm. DC voltages were applied across the test VI, with an up and down method. The 50% DC breakdown voltages U50 were determined, under each mechanical shock case. In each experimen-tal case, the DC voltage stressed on the test VI lasts for one second. Details of the experimental result and discussion will be presented in a full paper version.

Primary authors: Dr DING, Jian'gang (State Key Lab. of Electrical Insulation and Power Equipment, Xi'an Jiaotong University); Dr YAO, Xiaofei (State Key Lab. of Electrical Insulation and Power Equipment, Xi'an Jiaotong University); Mrs CHANG, Xiaoxue (State Key Lab. of Electrical Insulation and Power Equipment, Xi'an Jiaotong University); Mr LIU, Xue (State Key Lab. of Electrical Insulation and Power Equipment, Xi'an Jiaotong University); Dr GUAN, Chen (State Key Lab. of Electrical Insula-tion and Power Equipment, Xi'an Jiaotong University); Prof. LIU, Zhiyuan (State Key Lab. of Electrical Insulation and Power Equipment, Xi'an Jiaotong University); Prof. GENG, Yingsan (State Key Lab. of Electrical Insulation and Power Equipment, Xi'an Jiaotong University); Prof. WANG, Jianhua (State Key Lab. of Electrical Insulation and Power Equipment, Xi'an Jiaotong University)

Presenter: Dr DING, Jian'gang (State Key Lab. of Electrical Insulation and Power Equipment, Xi'an Jiaotong University)

Track Classification: C1. Vacuum interrupters and their applications

A1-I6-118

21st Century Planar Field Emission Theory and Its Role in Vacuum Breakdown Science

Content

Although field electron emission (FE) nearly always comes from sharp projections of one kind or another, the interpretation of FE measured current-voltage [Im(Vm)] data nearly always makes the theoretical assumption that emission can be treated as if from the smooth planar surface of a Sommerfeld-type free-electron conductor. In fact, this is likely to be a wildly unrealistic assumption. Other difficulties also emerge when one investigates how to put FE onto a more scientific basis, in which experiments and theory can be compared more reliably. First, current-voltage data-analysis techniques [such as Fowler-Nordheim (FN) plots] often focus exclusively on the emission process, thereby disregarding the numerous "complications" that can be (and often are) associated with device operation and with the physics and engineering of the whole FE current extraction and measurement system. Second, there have been significant developments in planar FE theory since FN's 1928 work, especially in the last ten years. These are not widely understood, but in fact this "21st Century planar field emission theory" allows the more precise extraction, from Im(Vm) data, of the so-called formal emission area. (FE literature currently uses a variety of methodologies to extract area information, based on several slightly different mathematical approximations.) Third, there are several types of entrenched error and "weak practice" in FE literature, particularly in FE technological literature. Fourth, it is long overdue that we move on to develop methodology for interpreting Im(Vm) data from so-called "point-form emitters" (i.e., emitters shaped like a needle or a rounded post), but serious research into this is only just beginning. In effect, a gap of some-thing like 90 years has opened up between (a) the most sophisticated FE theory and (b) Im(Vm) basic data-interpretation methodology as often currently used. The author's strategic viewpoint is that: (a) we need to adapt FE theory so that it focuses more on what experimentalists can measure, rather than on what theoreticians can predict; and (b) in mak-ing reforms, we need to start from where the experimentalists actually now are. My view is that three immediate strategic needs are: (a) to bring experimental/technological FE (both emission theory and data interpretation) up to the level of "best 21st Century planar emission theory"; (b) to reduce the levels of both complexity and error in existing FE literature taken as a whole; and (c) to move forwards with the development of point-form-emitter Im(Vm) data-interpretation theory. Further development of emission theory, at zero and finite temperature, and for curved emitters, are also needed, but will happen anyhow. The main issues covered in outline in this talk are as follows.

(1) Various nomenclature issues – e.g., what actually is the so-called "Fowler-Nordheim Law"?
(2) The Extended Murphy-Good FE Equation – an "experimentalist-oriented equation".
(3) Ideal FE devices/systems and the orthodoxy test.
(4) Modern developments in (zero-temperature) FE emission theory.
(5) Basic current-voltage data interpretation theory for planar emitters, and a simple improvement.
(6) Common errors and "weak practices".
(7) Future stages of development for Im(Vm) data interpretation theory.
(8) Relevance to vacuum breakdown science.

Primary author: FORBES, Richard (University of Surrey)

Presenter: FORBES, Richard (University of Surrey)

Track Classification: A1. Vacuum breakdown and pre-breakdown phenomena

B3-P1_O2-121

Influence of Floating Shield Wall on Dynamic Behavior of Metal Vapor during Arc Sustaining by Moving Particle Semi-implicit (MPS) Simulation

Content

For improvement of arc quenching performance in vacuum circuit breakers (VCBs), it is necessary to well-understand vacuum arc phenomena. Control techniques of the vacuum arc are important for enhancing its current interruption performance. In addition to experimental verification, to understand arc behaviors by numerical simulation is one of the important challenges. A Novel approach of a hybrid model using moving particle semi-implicit (MPS) method and finite volume method (FVM) [1], simulating heavy particle behavior in arcs, has been developed to investigate dynamic behavior of metal vapor in vacuum arcs. In our previous study using the above unique method, the influence of presence of floating metal shield wall was investigated on arc characteristics including the distributions of heavy particle temperature, ionization degree and current density and so on [2]. In case with floating metal shield wall, ionization degree of heavy particles between contacts was found to decrease compared to those without the wall. This is because all the particles colliding with the shield wall were neutralized and reflected toward the center. After the above calculation results, the present work focuses on the role of floating metal shield wall against arcs between the electrodes. Influence of its boundary condition was also studied on the deposition rate of metal vapor on the shield wall during arc sustaining. The developed model can calculate temporal evolutions in particle density, heavy particle tem-perature and ionization degree between the electrodes during vacuum arc sustaining. Boundary conditions of floating shield, such as reflection velocity, deposition ratio of heavy particles, were varied as a parameter to study dynamic behavior of metallic vapor between the electrodes. Cal-culation results show that the heavy particle temperature reached 7000 K between the electrodes, while it partly around cathode surface reached 12,000 K. Such heavy particle temperature increase is due to energy transfer by collisions with energetic electrons. The heavy particle temperature is also influenced by the boundary condition on floating metal shield wall because the heat exchange between vapor and the floating shield wall can contribute to decrease the heavy particle tempera-ture. A change in heavy particle behavior during collision on floating shield wall can influence the temperatures of heavy particles and electron and ionization degree between the electrodes. This influence on ionization degree and the number of existing heavy particle would also affect the electrical conductivity of arc decaying process.

[1] Y. Tanaka, et al., ICEPE-ST 2017, E-O-3, 10, 2017, Xi'an, China

[2] T. Miyazaki, et al., ICEPE-ST 2019, C-3-5, 10, 2019, Kitakyushu, Japan

Primary authors: Dr NAKANO, Yusuke (Kanazawa University); Mr MIYAZAKI, Takamitsu (Kanazawa University); Mr HATANAKA, Yuto (Kanazawa University); TANAKA, Yasunori (Kanazawa Univer-sity); ISHIJIMA, Tatsuo (Kanazawa University); Mr ASANUMA, Gaku (Fuji Electric Co. Ltd); Dr ONCHI, Toshiyuki (Fuji Electric Co. Ltd)

Presenter: Dr NAKANO, Yusuke (Kanazawa University)

Track Classification: B3. Vacuum arc physics

C1-O5-122

Small inductive current switching with high-voltage vacuum circuit breakers

Content

Circuit breakers are appropriate devices to energize and de-energize electrical circuits. The requirements for standard switching applications are typically covered by the IEC 62271-100 and IEC 62271-1. In addition to these standard applications other switching cases requires performance which is not automatically qualified by type tests in accordance to IEC 62271-100 and -1. This is explicitly the case for switching of small inductive currents. The range of requirements for these applications is extremely wide -from switching of unloaded transformers, to the quite high current of tertiary winding applications at transformers. Nowadays, gas circuit breakers are the preferred solution to cover all high-voltage applications for these inductive loads. Typically, individual pole operated circuit breakers with a point on wave switching device will be used to operate the circuit breaker in the reignition free window to ensure a safe and sustainable opera-tion. Compared to standard switching application these special configurations require a reduction in service interval for the contact system. The application of vacuum circuit breakers in high-voltage systems would cause the need, that the technology also covers these requirements. In this paper, the subject is explored to show that the application of a common operated vacuum cir-cuit breaker in combination with a filter circuit is a suitable instrument to avoid switching overvolt-ages and internal winding resonance overvoltages when small inductive loads are de-energized. The basis of this approach is the simulation of these circuits with an electromagnetic transient program with high-frequency models of the relevant grid components to evaluate appropriate dimensions and locations for filter circuits. This simulation study comprises a methodology to determine optimized parameters for the filter circuits and a subsequent verification by means of simulation of breaking operations with a vacuum circuit breaker model. The methodology is based on the long-term experience in the medium voltage range will also be applied to the high-voltage applications. On this basis also the acceptance criteria are derived from medium voltage knowhow. The simulation activities are accompanied by appropriate tests to evaluate and verify the simula-tion results.

Primary author: Dr GIERE, Stefan (Siemens AG)

Co-authors: Mr LAWALL, Andreas (Siemens AG); D TAYLOR, Erik; Dr WETHEKAM, Stephan (Siemens AG); Dr HEINZ, Thomas (Siemens A G); Mr WEISKER, Jan (Siemens A G); Mr SCHAEFER, Rene (Siemens AG); Mr TRUNK, Kai (Siemens AG); Dr STIEHLER, Christian (Siemens AG)

Presenter: Dr GIERE, Stefan (Siemens AG)

Track Classification: C1. Vacuum interrupters and their applications

A1-P3-125

Using Murphy-Good Plots to Interpret Field Emission Current-Voltage Data

Content

This presentation focuses on one small but significant part of a multistage project (outlined in a separate presentation) that aims to improve the interpretation of measured field electron emission (FE) current-voltage I(V) data. The project first stage aims to improve data interpretation within the framework of the almost universally used (but not physically realistic) “smooth planar emitter methodology”. This models a real field emitter, which is usually taken to be needle-shaped, post-shaped, or otherwise “sharp”, as if it were a smooth, planar structureless surface, with constant emission area.
Measured FE I(V) data are traditionally analysed via Fowler-Nordheim (FN) plots, as ln{I/(V*V)} vs 1/V. These have been used since 1929, because in 1928 FN predicted they would be linear. In the 1950s, a mistake in FN’s thinking was found. Corrected theory by Murphy and Good (MG) in 1956 made theoretical FN plots slightly curved. This causes difficulties when attempting to extract precise values of emission characterization parameters from straight lines fitted to experimental FN plots. Improved mathematical understanding, from 2006 onwards, has now enabled a new FE data-plot form, the “Murphy-Good plot”. This plot has the form ln{I/(V^k)} vs 1/V , where k ≈ 2–(”eta”)/6, and “eta” is a simple known function of local work function, which is itself assumed known and constant. Modern (”21st century”) FE theory predicts that a theoretical MG plot should be “almost exactly” straight. This makes precise extraction of well-defined characterization parameters from ideal I(V) data much easier. This presentation first explains the value of re-stating basic FE equations in terms of a “scaled” (or “dimensionless”) field f that is related to the usual local barrier field F by f=F/FR, where FR is the “reference field” needed to pull the top of the Schottky-Nordheim barrier (used in MG theory) down to the Fermi level. It then explains the idea that Murphy-Good-type FE equations can be expressed in various different mathematical “formats”, related to the different ways in which the FE special mathematical function v(x), where x is the Gauss variable, can be mathematically ap-proximated. FN plots and MG plots link to different forms of mathematical approximation for v(x), and our improved (since 2006) understanding of the mathematics of v(x) has led to an improved form of data plot. Relevant formulae for the interpretation of the slope and intercept of a MG plot will be presented, after their derivation has been outlined. By using spreadsheet-based simulations, it can be demon-strated that MG plots do indeed perform more precisely than FN plots. Careful use of MG plots could also help remedy other problems in FE technological literature. It will then be argued, again by means of spreadsheet simulations, that it might be possible to use formal-area values extracted from MG plots to investigate whether experimental FE current-voltage data are in fact well described by the Extended Murphy-Good FE equation. [In fact, we do not theoretically expect them to be, but it is currently unclear how easy it would be to detect discrepancies.]

Primary author: FORBES, Richard (University of Surrey)

Presenter: FORBES, Richard (University of Surrey)

Track Classification: A1. Vacuum breakdown and pre-breakdown phenomena

A2-P1_O9-126

Progress in Vacuum Flashover Mechanism: validity of ETPR Theory

Content

I.INTRODUCTION

Surface flashover is a ubiquitous insulation failure that exhibits a far lower breakdown voltage than that of volume breakdown for the same dimension[1]. It remains the primary restriction with respect to the development of high-temperature superconductivity (HTS) equipment, space-craft solar arrays, and pulse-power devices. There is little consensus regarding the intermediate discharge mechanism of surface flashover. In recent years, interfacial secondary electron emission derived from field emission has been continuously developed and achieved general acceptance[2]. Nevertheless, electron triggered polarization relaxation (ETPR) theory, a below-surface mecha-nism proposed in 1991[1], is still controversial. Less progress on flashover mechanism from the perspective of dielectrics restricts innovations in insulating materials and prevents a better under-standing of flashover. We report the flashover voltages of 5% mol Bi0.95Y0.05FeO3/epoxy composites (BY5FO/EP) with a wide range of filler contents. The polarization of composites was simulated, and the relationship with the flashover variations was established. Meanwhile, whether the ETPR theory is applicable for nanosecond flashover is discussed. Frequency and air molecular concentration are proposed which can lead the dominant flashover mechanism transition.

II.EXPERIMENTAL

A. Sample preparation

The details about how to prepare Y doped BiFeO3 and composites.

B. Characterization and Experimental test

Flashover test and detail parameter setting.

III. AVAILABILITY OF ETPR THEORY FOR DC FLASHOVER

A. Flashover sine shaped variation

The flashover voltages show sine-shaped variations. In order to better understand this variation, we define it as ‘X’ curve which explains the interaction between filler and matrix. The ‘X’ curve can be divided into a variable-frequency sine Eq. (1) f1(x) and a double exponential function Eq.(2) f2(x). Bi-exponential f2(x) can be used as a extended model to illustrate other properties which show different trends before and after percolation.

B. Simulation of polarization. We believe the variations in flashover voltage related to polarization of composites and computed the local polarization of the composites based on a well-established multi-layer core model and filler-matrix phase reversal.

C. Trap parameters. We also calculate the trap depth of composite as filler increasing which also show similar varia-tion. Simultaneous sine-variation of dielectric constant and trap depth leads to regular variation of flashover. Meanwhile, the voltage conditioning can further prove the contribution of polarization energy and trap stability.

IV. PREDICT OF APPLICATION SCOPE OF ETPR THEORY. Through dielectric property as a function of frequency, we analyze the reason for limitation of ETPR theory for nanosecond flashover. However, we proposed some methods to verify whether the ETPR theory is applicable for nanosecond impulse flashover.

V.TRANSITION OF DOMINANT MECHANISMS

We report the transition of dominant flashover mechanisms from two dimension: air pressure and frequency, and discuss two extremely cases applicable for SEEA and ETPR theory.

VI. INTERPRETATION OF CONTROVERSIAL PHENOMENA

Based on our experimental results and analysis, the controversial phenomena including the effect of impurity, surface conductivity and dielectric constant on flashover performance are explained.

[1] G. Blaise and C. L. Gressus, J. Appl. Phys. 69, 6334 (1991).
[2] R. A Anderson and J. P Brainard, J. Appl. Phys. 51, 1414 (1980).

Primary authors: Dr YIN, Kai (Aalborg University); Dr DUAN, Qijun (North China Electric Power University); Dr ZHANG, Hanchi (Aalborg Univeristy); Dr YAN, Jiyuan (North China Electric Power University); Prof. LÜ, Fangcheng (North China Electric Power University); Prof. XIE, Qing (North China Electric Power University)

Presenter: Dr YIN, Kai (Aalborg University)

Track Classification: A2. Surface discharges and flashover phenomena

B1-P1-127

Measurement of transient temperature distribution at anode surface after current zero in vacuum interrupter

Content

In vacuum interrupters, an insulation ability is degraded after high current interruption, because of thermal electrons, metal vapors, and residual plasma. Thermal electrons and metal vapors are produced from the electrode surface, which is heated by arc period by the arc between electrodes. Therefore electrode temperature is affect insulation ability. It is important to measure the tran-sient of temperature distribution at electrode surface, for explication of interruption phenomenon in vacuum. Hence, two color pyrometer method with a high-speed camera for temperature mea-surement of electrode in vacuum was developed, and temperature of Cu-Cr test electrode was measured after current zero by its method. The maximum temperature was 2300-3300 K imme-diately at 9-12 kA current interruption. Also, relationship between electrode temperature and insulation ability between electrodes after current zero was investigated.

Primary author: Mr DAIBO, Akira (Toshiba Infrastructure Systems & Solutions Corporation)

Co-authors: Dr NIWA, Yoshimitsu (Toshiba Infrastructure Systems & Solutions Corporation); Mr ASARI, Naoki (Toshiba Infrastructure Systems & Solutions Corporation); Mr SAKAGUCHI, Wataru (Toshiba Infrastructure Systems & Solutions Corporation); Mr SASAKI, Yo (Toshiba Infrastructure Sys-tems & Solutions Corporation); Mr YOSHIDA, Takeshi (Toshiba Infrastructure Systems & Solutions Corporation)

Presenter: Mr DAIBO, Akira (Toshiba Infrastructure Systems & Solutions Corporation)

Track Classification: B1. Switching in vacuum and related phenomena

B4-P3-132

Numerical simulation of vacuum arc and anode thermal process during the interruption process of HVDC vacuum switch with forced current zero

Content

It is of great significance to study the characteristics of DC vacuum arc (DCVA) and anode thermal process during the interruption process of HVDC vacuum switch with forced current zero, which have an important influence on the breaking performance of the DC vacuum circuit breaker. In this paper, based on a 3-D magneto-hydrodynamic model, DCVA and anode thermal process under DC interruption process are simulated and analyzed. Firstly, a DCVA dynamic model is established under the commercial cup-shaped electrodes. The DCVA is simulated at seven different moments during the DC breaking process with a current falling frequency of 500Hz. The distribution of arc plasma's parameters at seven different times, such as ion number density, axial current density, ion velocity and heat flux density to anode, is obtained by the simulation. Furthermore, a 2-D transient axisymmetric model of anode thermal process in DCVA is established. Heat flux densities to anode under the realistic axial magnetic field, which were obtained from the DCVA dynamic model, are considered as the boundary conditions of the anode activity model. Through the numerical simulation, anode temperature distribution along radial and axial directions can be obtained. The distributions of anode melting radius, depth, saturated vapor pressure and vapor flux also can be obtained by the simulation.

Primary authors: Mr JIANG, Jing (Xi'an Jiaotong University); Prof. WANG, Lijun (Xi'an Jiao-tong University); Mr YANG, Ze (Xi'an Jiaotong University); Mr LI, Jiagang (Xi'an Jiaotong Univer-sity); Mr LUO, Ming (Xi'an Jiaotong University); Prof. JIA, Shenli (Xi'an Jiaotong University); Prof. SHI, Zongqian (Xi'an Jiaotong University)

Presenter: Mr YANG, Ze (Xi'an Jiaotong University)

Track Classification: B4. Computer modeling and computer aided design

C1-P2-133

Research and Design of AC Contactor for Aircraft

Content

With the improvement of capacity and performance of civil aircraft, the development of variable frequency AC power supply system(360-800hz) in aircraft puts higher requirements for the breaking performance of contactor as the main power distribution equipment. Compared with the air arc extinguishing technology, the vacuum interrupter has the advantages of good arc extinguish-ing performance and strong environmental adaptability. Aiming at the design of aero AC contactor under variable frequency AC conditions, a vacuum contactor solution is proposed. First, based on the vacuum interrupter design theory, a miniaturized vacuum interrupter was designed. Then, the mechanical characteristics of the vacuum interrupter are analyzed, and an electromagnetic operating mechanism which can effectively match the load force characteristics is proposed, and the simulation experiment is carried out by using the finite element method. Finally, an engineering prototype is made for experiment. Through the comparison of experimental data and simulation results, the correctness of the design is verified, and the application of vacuum arc extinguishing technology in more-electric aircraft is promoted.

Primary authors: Mr XIA, Shangwen (Beihang University); Prof. WU, Jianwen (Beihang University); YUAN, Yang (Beihang University); LUO, Xiaowu (Beihang University); TONG, Ziang (Beihang University); Mr JIA, Bowen (Beihang University)

Presenter: Mr XIA, Shangwen (Beihang University)

Track Classification: C1. Vacuum interrupters and their applications

B1-P1-137

Investigations of arc instabilities in DC vacuum arcs

Content

Vacuum arcs have the natural tendency to interrupt currents before the natural current zero of a system, which is known as current chopping. The goal of this paper is to present the investigation of different contact materials and to evaluate their maximum current chopping. For that pure copper, CuCr and tungsten were selected. The investigations have been performed in a synthetic circuit generating high currents for 100 ms, and where over-voltages arising from the interruption on the vacuum interrupter were clipped at 1.6 kV. The results show the unstable behavior of the vacuum arc at low current, which results in current chopping up to 25 A for Cu and W, and to a maximum of 7 A for CuCr. It is also found that the arcing duration depends exponentially on the current level, as previously determined by other authors. The originality of the work is to be able to study the current chopping mechanism in a DC circuit at voltages higher than previous studies. Analogies and differences will be discussed in the paper. In particular, it is observed that the arc voltage fluctuations prior to arc extinction are depending on the contact material and DC current level. Tungsten exhibits strong voltage fluctuations up to more than 1’000 V (more than 50 times the arc voltage) before eventually chopping, while copper voltage fluctuations stay below 200 V generally at a comparable current.

Primary authors: DELACHAUX, Thierry; Dr GENTSCH, Dietmar (ABB AG)

Presenter: DELACHAUX, Thierry

Track Classification: B1. Switching in vacuum and related phenomena

A2-P3-138

Investigation on Potential of Floating Electrode in Modelled Vacuum Interrupter during AC Voltage Application

Content

The objective in this paper is grasping a charging characteristics on the floating electrode mod-eled on Vacuum Interrupters (VIs) during unipolar AC voltage application. In order to develop the higher voltage VIs, controlling surface flashover events occurred inside of VIs is one of the issues to be solved. In actual VIs, a floating electrode is attached such as an arc shield. This floating elec-trode may be charging as a precursory phenomenon before surface flashover occurs. However, there is no report concerning about the charging phenomenon formed on the floating electrode. Therefore, a charging characteristics on the floating electrode were investigated by surface poten-tial meter. Especially, this paper focused on the relationship between electric field strength inside of experimental sample and charging potential formed on the floating electrode. In this paper, two kinds of experimental samples were prepared. These sample have a floating electrode between two alumina cylinders. The inside of samples are kept under high vacuum con-dition. The difference for two samples is a constitution of the floating electrode. One sample is without anything at the floating electrode (Sample A). But another sample has shield rings at the both side of floating electrode to relax the electric field around the triple junction of floating elec-trode (Sample B). A charging potential on the floating electrode was measured by surface potential meter with high speed response not to contact the floating electrode. A probe of the potential me-ter was fixed in front of the floating electrode. As a result, when a lower voltage was applied, only a potential due to electrostatic induction de-termined by the capacitance of the sample and grounded objects around the sample was measured from the floating electrode. After that, when the higher voltage was applied, not only the induced potential but also a charging potential was observed enough to change the potential of the float-ing electrode strongly. For Sample A, the floating electrode was positively charged due to the field electron emission from the floating electrode itself and the charging potential was remained at a certain range even when high voltage is applying. On the other hand, for Sample B, it was negatively charged due to the electrons influx into the floating electrode in the early stage of high voltage application because electron emission from the floating electrode is suppressing by the shield rings. After that, with higher voltage is applied, the charging potential was changed from the negatively polarity to the positively polarity because electron emissions occur from the float-ing electrode. In addition, these charging potential were suppressed after voltage conditioning process. These results suggest that charging characteristics on the floating electrode is depending on the electric field inside of the samples including a degree of the voltage conditioning.

Primary author: Mr FUKUDA, Hideaki (MEIDENSHA CORPORATION)

Co-authors: Mr YAMAMURA, Kenta (MEIDENSHA CORPORATION); Mr KUSA, Ryutaro (Saitama University); Prof. YAMANO, Yasushi (Saitama University)

Presenter: Mr FUKUDA, Hideaki (MEIDENSHA CORPORATION)

Track Classification: A2. Surface discharges and flashover phenomena

A2-P3-139

Parameters of the Microexplosive Cathode Processes Occurring During the Initiation of a Vacuum Breakdown

Content

The report presents the results of numerical simulations of the electrical explosion of cathode microprotrusions initiated by explosive electron emission current. The behavior of the basic parameters of the cathode material (temperature, density, and pressure) during a microexplosion was investigated for tungsten and copper cathodes. The integral of specific current action has been calculated in relation to the microprotrusion geometry. The formation of a liquid metal fraction during an electrical explosion of a microprotrusion and its motion have been simulated. The parameters of microcraters left by microexplosions on the cathode surface have been calculated. This work was supported in part by the Russian Foundation for Basic Research Grant 17-08-01282 and Grant 19-08-01004, in part by the Russian Academy of Sciences (RAS) Presidium through the Basic Research Program 5P.

Primary authors: Dr ORESHKIN, Evgeny (P.N. Lebedev Physical Institute of the RAS); Prof. BARENGOLTS, Sergey (Prohorov General Physics Institute RAS); Prof. ORESHKIN, Vladimir (IHCE SB RAS); Dr KHISHCHENKO, Konstantin (JIHT); Prof. MESYATS, Gennady (P.N. Lebedev Physical Institute of the RAS)

Presenter: Dr ORESHKIN, Evgeny (P.N. Lebedev Physical Institute of the RAS)

Track Classification: A2. Surface discharges and flashover phenomena

C1-P2-141

Development of a 40.5kV Two-break Phase-controlled Vacuum Circuit Breaker for Switching Capacitor Bank and Shunt Reactor

Content

Restrike during interrupting capacitor banks and multiple reignitions during interrupting shunt reactor with vacuum circuit breakers may lead to severe switching overvoltage. In this paper, the mechanism, perniciousness and suppression of capacitor banks and shunt reactor switching overvoltage are systematicall analyzed, and then a 40.5kV two-break phase-controlled vacuum circuit breaker with very low probability of reignition and restrike was proposed. A capacitive current switching test circuit has been designed, which consists of a high frequency inrush current circuit and a power frequency circuit, to perform back-to-back capacitor banks switching test. The test result shows that a two-break vacuum circuit breaker can reduce the probability of restrike significantly. The control strategy on switching capacitor banks and shunt reactor by the phase controlled circuit breaker is described and a switching controller is designed. The two-break circuit breaker operation is controlled by high accuracy permanent magnet operating mechanism. Three phase loading test is performed further based on IEC62271-100 and IEC62271-110, the result shows that two-break and phase-controlled technique can restrain the switching overvoltage of capacitor banks and shunt reactor effctively.

Primary author: Mr PENG, Jing (Electric Power Research Institute, Yunnan Power Grid Co. Ltd.)

Co-authors: Mr WANG, Ke (Electric Power Research Institute, Yunnan Power Grid Co. Ltd.); Mr TAN, Xiangyu (Electric Power Research Institute, Yunnan Power Grid Co. Ltd.); Mr MA, Yi (Power Research Institute, Yunnan Power Grid Co. Ltd.); Dr YAN, Jing (State Key Lab. of Electrical Insulation and Power Equipment, Xi'an Jiaotong University); Prof. LIU, Zhiyuan (State Key Lab. of Electrical Insulation and Power Equipment, Xi'an Jiaotong University); Prof. GENG, Yingsan (State Key Lab. of Electrical Insulation and Power Equipment, Xi'an Jiaotong University)

Presenter: Mr PENG, Jing (Electric Power Research Institute, Yunnan Power Grid Co. Ltd.)

Track Classification: C1. Vacuum interrupters and their applications

A2-O9-142

Investigation of Electron Emission from Metal/ Insulator Interface in Vacuum and Eletric Charge on the Insulator

Content

Flashover along a surface of solid insulator (surface flashover) is one of the problems in improving insulation performance in gas, liquid and vacuum. It has been regarded that the emission of electrons from the cathode triple junction (CTJ) is a first step of initiating the surface flashover. Therefore, it is important to investigate field electron emission phenomenon around the CTJ region. In order to investigate the electron emission characteristics from the boundary region between the insulator and the metallized layer, an alumina insulator sample with a metallized layer formed by the Mo-Mn method was used. In addition, since the positive charge of alumina is possible to be related to the electron emission from CTJ, an experiment was also conducted on a sample with Cr₂O₃ coating on the surface to suppress the charge. In the experiment, the precursor current was measured and the discharge position was photographed. The experimental results showed that a several numbers of breakdown are observed around the boundary between the insulator and the metallized layer. After such experiments repeat several times, the prebreakdown pico-ampere order current was measured. The value of prebreakdown current increased slowly with the elapsed time even if the applied voltage was kept constant. It increased more than two orders of magnitude during about 3-5 minutes, finally lead to a breakdown event or saturated to a certain value. In addition, for the coated sample, the electron emission current decreased and the breakdown voltage improved. Furthermore, no current rise phenomenon was observed when the voltage was constant. Based on the above results, this phenomenon is probably due to the effect of the alumina being charged by the electrons emitted from the CTJ. Therefore, We conducted a charge measurement experiment in the next step.
In the experiment for charge distribution measurement, a sample in which CTJ was formed by alumina ceramics located on the center of a stainless steel plate was used. This sample was also experimented with a sample additionally coated with Cr₂O₃. In the experiment, a voltage was applied before the breakdown occurred, and immediately after that, the surface potential was measured. As a result of the experiment, it was observed that the alumina was negatively charged on the almost whole area while a part was positively charged. On the other hand, for the coated sample, no positive charge was observed. From the above results, it was confirmed that the electric field was locally amplified by locally positive charging, leading to an increase in current and discharge in the previous study.

Primary author: Mr ASARI, Naoki (Toshiba Infrastructure Systems & Solutions Corporation)

Co-authors: TATEYAMA, Chihiro (Toshiba Infrastructure Systems & Solutions Corporation); MIURA, Hayato (Saitama University); Prof. YAMANO, Yasushi (Saitama University)

Presenter: TATEYAMA, Chihiro (Toshiba Infrastructure Systems & Solutions Corporation)

Track Classification: A2. Surface discharges and flashover phenomena

B2-P3-143

Investigation of Vacuum Arc Behavior of TMF Contacts with CuCr and WCu Materials

Content

In this paper, the vacuum arc characteristics of TMF contacts were studied under different materials based on the experiments. Six commonly used contact materials (CuCr10, CuCr30, CuCr50, WCu10, WCu30) were compared. Each set of contacts was subjected to interruption experiment with an effective current of 5 kA, 10 kA, and 15 kA. The Rogowski coil and the high-voltage probe were used to measure the current and voltage of the contact at the same time, and the high-speed camera was used to simultaneously record the change of the arc appearance during the experi-ment. The arc produces rotation force under the influence of TMF. Combined with the measured arc voltage and current, the arc rotation movement is analyzed. The noise of arc voltage is clearly associated with the arc rotation of the CuCr contact. The arc of WCu contact hardly rotates and the arc voltage is relatively stable. The CuCr contacts hardly reignite under the same experimen-tal conditions, while the WCu contacts are easy to reignite at high currents. From the aspect of erosion, the surface of the CuCr contact is severely melted. But the bottom surface of the WCu contact has a large amount of erosion area.

Primary authors: ZHANG, Xiao; Prof. WANG, Lijun; Mr YAN, Chao; Mr LIN, Renjie; Prof. JIA, Shenli

Presenter: ZHANG, Xiao

Track Classification: B2. Interaction of vacuum arcs with magnetic fields

C4-P2-144

Characteristics of extracted ion beam of cesium-free negative ion source TPDsheet-U

Content

The use of negative-ion sources without cesium seeding is desired for neutral beam injectors used on the development of magnetic fusion reactors. In the present work, a TPD type magnetized-Sheet plasma for Negative Ion Source (TPDsheet-NIS) that produces negative ions using volume production without cesium seeding have been designed [1-3]. The developed system is experimentally tested using steady-state hydrogen plasma at the gas pressure of 0.3 Pa and the magnetic field of 0.04 T. The discharge power has a maximum value of 12 kW. The negative hydrogen ion beam is extracted using a two-grid extraction system located at the periphery of the sheet plasma. The first (plasma facing) and second grids are called the Plasma grid (PG) and the Extraction grid (EG), respectively. PG has 4 mm diameter, EG has 8 mm diameter, and the gap between the grids is 6 mm. Two different types of grid structures are used in the experiment to extract the negative-ion beam: single-aperture grids and multi-aperture grids (3×13 apertures). The negative hydrogen ions are successfully extracted from the sheet plasma using both single and multi-aperture grids. The current densities of the ion beams increases with the increasing discharge current and extraction voltage. At an extraction voltage of 9.5 kV and a discharge current of 80 A, the approximate current density of the negative hydrogen ion beam is 8.4 mA/cm2 for the case of single-aperture grids. At an extraction voltage of 9.5 kV and a discharge current of 50 A, the approximate current density of the negative hydrogen ion beam is 23 mA for the case of multi-aperture grids.

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Primary authors: Prof. TONEGAWA, Akira (Department of Physics, School of Science, Tokai Uni-versity); Mr KAMINAGA, Hiroki (Graduate School of Science and Technology, Tokai University); Mr TAKIMOTO, Toshikio (Doctor's course of science and technology, Tokai University)

Presenter: Prof. TONEGAWA, Akira (Department of Physics, School of Science, Tokai University)

Track Classification: C4. Accelerators and fusion reactor related issues

B3-O8-145

Time-Dependent 3D Reconstruction of Arc Shape in a TMF contact system

Content

It is well known that the transverse magnetic field (TMF) can drive the vacuum arc to move continuously on the contact, resulting in a non-axisymmetric characteristic of the vacuum arc. Therefore, the particle distribution of the vacuum arc is also non-uniform. And the various particles will directly affect the interaction between the vacuum arc and electrodes, which in turn influence the burning of arc and the successful interruption of interrupter. The two-dimensional information from a single direction is not sufficient to show the particle distribution of the arc.

In this paper, the CuI ions were observed by a 3D imaging system with optical filters from multiple directions, and the distribution was reconstructed by filter back-projection (FBP) and Algebra Reconstruction Technique (ART) method based on the record from those directions. A series of metal contacts with different copper and chromium contents were used in our experiment.

Through the above method, we obtained a series of 3D distribution of Cu ion under different copper and chromium contents, according to the 3D distribution, the pattern of particle generation in a vacuum arc was analyzed.

Key words—Vacuum arc, Transverse magnetic field, three-dimensional reconstruction, particle distri-bution

Primary author: Dr WANG, Zhenxing (Xi'an Jiaotong University)

Co-authors: Mr LI, Yi (Xi'an Jiaotong University); Mr PAN, Yangbo (Xi'an Jiaotong University); Mr DU, Yuwei (Xi'an Jiaotong University); Dr SUN, Liqiong (State Key Laboratory of Electrical Insulation and Power Equipment, Xi'an Jiaotong University)

Presenter: Dr WANG, Zhenxing (Xi'an Jiaotong University)

Track Classification: B3. Vacuum arc physics

C4-P2-146

Final Acceptance Testing of the CERN SPS Electrostatic Septa

Content

In the framework of the LHC Injector Upgrade (LIU) project, the high field electrostatic septa (so-called ZS) have been upgraded to comply with the new requirements. Prior to their installation in the SPS accelerator in 2020, the septa were tested to verify their final performance. This report summarises the results of these final acceptance tests, covering the vacuum acceptance test, the HV conditioning, the final beam impedance measurements together with the ZS interconnects and validation of the upgraded ion trap system.

Primary author: BALHAN, Bruno (CERN)

Co-authors: BORBURGH, Jan (CERN); PROST, Antoine (CERN); BARLOW, Roger Andrew (CERN); Mr MO, Jorgen andreas (CERN)

Presenter: BALHAN, Bruno (CERN)

Track Classification: C4. Accelerators and fusion reactor related issues

C1-P2-147

Influences of different manufacture ways on the anti-welding ability of electrical contacts

Content

The purpose of this paper is to investigate the influences of different manufacture way of CuCr30 contacts including vacuum arc melting VAM , vacuum induction melting VIM , and powder metallurgy PM on the welding properties of CuCr contacts. The electrical experiment was conducted by using pre-strike inrush current with 10 times of operation. The experiment indicate that pre-strike arcing time of contacts made by VAR and VIM are shorten than those made of PM caused by higher density of contact material and more homogeneous micro-structure with fine dispersion Cr particles in copper matrix, but contacts made by PM have lower welding force compared with VAR and VIM, so it is easier to separate when welding happened of two contacts. Pre-strike arcing time of contacts made by VIM decreased with increasing of operation time which caused by fine Cr particles of contact material in the remelting layer.

Primary author: Mr ZHANG, shisong (shaanxi sirui advanced materials co.,ltd)

Presenter: Mr ZHANG, shisong (shaanxi sirui advanced materials co.,ltd)

Track Classification: C1. Vacuum interrupters and their applications

B2-P3-149

High Speed Observation of Vacuum Arcs between Different Contact Diameter at TMF Contact Pair

Content

Vacuum interrupter especially with high short-circuit interruption ability are mostly equipped with the same diameter at the applied contact parts. Especially for short circuit current making and breaking interruption operations the contact material is based on CuCr-25…35 wt.-% in most of the cases by applying transverse magnetic field (TMF) contact systems worldwide and multipurpose application. The study is carried out on standard contact pair with both contacts having the same diameter as well as “optimized” contact pair with different contact diameter by applying the TMF principle. Furthermore, it considered the combination of TMF principle on the one hand side contact and the butt contact on the other side. The contact material is based on the well-known solid-state sintered material production technology. A huge number of interruption operations under short circuit current conditions are done to investigate the arc movement and the arc path at contact pairs applied the different contact diameter. By using a high-speed digital video camera, different contact pairs are observed during arcing under short-circuit conditions at the opening and interruption operation. The investigation is concentrated on the average and highest arc velocity, the number of possible turns at one half period at 50 Hz with T = 20 ms and movement path of the chosen polarity on its own “positive” and the “negative” wave polarity at the applied AC interruption current is being presented. The study is focused on four contact pais such as one standard contact with same diameter and three different contact diameter pair combination. The combination of TMF contact to butt contact was taken in addition under considered.

Primary authors: Dr GENTSCH, Dietmar (Research and Development); Mr GORLT, Kai (Research and Development)

Presenter: Dr GENTSCH, Dietmar (Research and Development)

Track Classification: B2. Interaction of vacuum arcs with magnetic fields

B3-P1-150

Liquid metal jet formation and droplet pinch-off dynamics in the cathode spot of a vacuum arc

Content

The explosion of the liquid-metal jets formed during the formation of a crater on the cathode of vacuum arc are considered to be the basic mechanism of the initiation of new cathode spot cells that are responsible for the self-sustainng of a vacuum discharge [1, 2]. According to this model, the appearance of new cathode spot cells is due to the interaction of a liquid-metal jet with a dense cathode spot plasma [2]. With this important part played by the liquid-metal phase in the operation of a cathode spot, a quantitative description of the hydrodynamic processes responsible for the drop formation was so far confined to estimating or very simplified calculations. In this work a two-dimensional axisymmetric model has been developed to describe the formation of liquid-metal jet and the droplet pinch-off. These processes occur during the extrusion of the melt from the crater by the pressure of the cathode spot plasma of a vacuum arc. The jet formation has been numerically simulated for a copper cathode in the “inertial” mode of the melt splashing until the first droplet pinch-off. In this case, a jet with a longitudinal velocity gradient is formed. This gradient decreases the diameter of the jet and causes its elongation, resulting in droplet pinch-off. It has been shown that the mechanism of the droplet pinch-off is based on Rayleigh–Plateau instability. The droplet pinch-off time decreases with increasing jet velocity and increases for droplets of larger diameter. The simulation of the process of the droplet pinch-off also made it possible to calculate the time dependence of the coefficient of enhancement of current density in the droplet-jet neck. Based on the obtained results and experimental data on the explosion of metal wires [3], we obtained estimates of the current density on the droplet surface at which we can expect the development of temperature runaway in the neck at the first droplet pinch-off due to Joule heating, leading to its electrical explosion. The simulation predicted the electrical explosion of the droplet-jet neck at the current density on the droplet surface 10^7 A/cm^2.

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Primary author: UIMANOV, Igor (Institute of Electrophysica UB RAS)

Co-author: Prof. MESYATS, Gennady (P.N. Lebedev Physical Institute of the RAS)

Presenter: UIMANOV, Igor (Institute of Electrophysica UB RAS)

Track Classification: B3. Vacuum arc physics

B3-O1-157

The Turbulent Nature of the Ion Flow of the Vacuum Arc

Content

The new approach to explaining of ions and electrons acceleration in the vacuum arc is presented. The ion acoustic plasma shock waves can produce the well-known shape of ion energy distribu-tion as well as the dependence of that on the ion charge state. Experimentally measured mean ion velocities dependence on cathode material properties can be explained by ion sound shock wave dependence on “hot” electron temperature and ion mass. Experimentally measured energy distribution can be formed statistically by ion acoustic waves with different amplitudes and velocities. In addition, the plasma turbulence can be the cause of several unexplained effects: The correspondence of ion flow peaks to strong discharge current falls can be explained by plasma turbulence rising which in turn causes abnormal plasma resistance. The Fourier spectra of ion flow law 1/f can be explained by Kolmogorov’s established turbulence spectra.

Primary author: Dr MUZYUKIN, Ilya (Institute of Eectrophysics UB RAS)

Presenter: Dr MUZYUKIN, Ilya (Institute of Eectrophysics UB RAS)

Track Classification: B3. Vacuum arc physics

B3-O8-159

Two-dimensional spectroscopy for vacuum arc in steady state and decaying state under free- recovery condition

Content

Vacuum circuit breaker (VCB) is attracting attention recently from the viewpoint of environmental friendliness and ease of maintenance, etc. In the VCB, a vacuum arc discharge can be maintained by metal vapor supplied from the electrodes during high current interruption process. This vacuum arc is extinguished mainly due to natural diffusion of metal vapor around current zero. To improve the arc extinction performance in VCBs and the controllability of vacuum arc behavior, it is necessary to understand the complex phenomena in the vacuum arcs. For this purpose, we have developed a numerical model with a particle method and a fluid method for vacuum arcs[1]. But, the present research focuses on experimental approach to measure dynamic behavior of metal vapor in steady state and in transient free-recovery state vacuum arcs by using two-dimensional spectroscopy. In the present paper, first, a fundamental experimental system was developed, which consists of a DC current source, a vacuum chamber with electrodes and an IGBT switch. The electrode used was made of an alloy of copper and chromium. Between the electrodes, a vacuum arc discharge was formed at currents of 30 A and 50 A. The IGBT was connected in parallel with the electrodes to commutate the arc current between the electrodes to the IGBT, which makes free-recovery state between the electrodes. Free-recovery condition is the most fundamental transient state for de-caying arcs. High speed imaging was conducted for a steady state and transient decaying arcs with a high speed video camera with frame rates of 10,000 fps for steady state and 200,000 fps for free-recovery state. Furthermore, two-dimensional spectroscopic observation was also carried out using a high speed video camera with an imaging spectrometer, especially focusing on copper and chromium atomic spectral lines and their ion lines. As the result, there were several cathode spots, which were repeatedly coupled and split. Near the cathode spots, a bright region is present involving both copper and chromium atomic spectral lines and copper ion lines. No chromium ion lines could be detected. This indicates that copper and chromium were provided from the electrode to the arc almost uniformly and the electrons originates from the ionization of copper. From the bright region, a cone-shaped light emitting area is expanded toward the anode. After current down for free-recovery condition, this bright region near the cathode spot decayed gradually with time, while the cone-shaped light emitting area disappeared rapidly within 20 μs. This result implies that vapor in the cone-region decays due to rapid diffusion.
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Primary authors: Mr HATANAKA, Yuto (Kanazawa University); Mr MIYAZAKI, Takamitsu (Kanazawa University); Prof. TANAKA, Yasunori (Kanazawa University); Dr NAKANO, Yusuke (Kanazawa University); Prof. UESUGI, Yoshihiko (Kanazawa University); Prof. ISHIJIMA, Tatsuo (Kanazawa University); Mr ASANUMA, Gaku (Fuji Electric Co., Ltd.); Dr ONCHI, Toshiyuki (Fuji Electric Co., Ltd.)

Presenter: Mr HATANAKA, Yuto (Kanazawa University)

Track Classification: B3. Vacuum arc physics

B3-P1-161

Average Charge State Variation in the Cathode Material Ion Flow from the Low Current Microsecond Vacuum Arc

Content

Different material samples were used as the vacuum arc cathode in the 4 microsecond vacuum arc discharge. Pulse source was the LC-line with quasi-rectangular pulse shape. Arc current varied from threshold current for certain material to 100 A. Charge state distribution and the average charge state of the cathode material ions were measured via the Thomson spectrometer with automated image recording and digital data processing. It was found that the ion charge state distributions were close to the classical data at the hundred-ampere currents; and the average charge state significantly decreased with the arc current decrease for all investigated materials. The decrease of the average charge was due to decrease of the high-ionized ion fractions and increase of single-ionized ion fraction. This effect, observed earlier only for copper cathodes, confirmed to be a fundamental feature of the plasma generation in low-current vacuum arcs.

Primary authors: ZEMSKOV, Yury (Institute of Electrophysics, Ural Branch, Russian Academy of Sciences); UIMANOV, Igor (Institute of Electrophysica UB RAS)

Presenter: ZEMSKOV, Yury (Institute of Electrophysics, Ural Branch, Russian Academy of Sci-ences)

Track Classification: B3. Vacuum arc physics

C4-O4-177

A GEM-based high-rate x-rays diagnostic for flux measurement during high voltage conditioning in vacuum insulated systems

Content

The MITICA experiment at Consorzio RFX Padova, within the framework of the European Magnetic Confinement Fusion effort, is a full-scale prototype of the Neutral Beam Injector (NBI) heating system envisioned for ITER, which will be required to produce 1MeV beams of deuterium with an ion current of 40 A for up to 1 hour. These specifications far exceed any current NBI devices with a compact electrostatic accelerator to operate at 1MV being double the voltage reached up to now. To achieve these conditions the entire beam source and accelerator of MITICA are insulated by a vacuum instead of the more commonly used insulating gas. This is to avoid radiation induced conductivity in the gas by radiation produced from fusion reactions. However, this serves to be an overall more complex system and vacuum insulation has its own substantial hurdles regards stability and voltage holding. The High Voltage Padova Test Facility (HVPTF) is a concurrent R&D project focused on understanding the physical processes behind breakdown and micro-discharges in high-voltage insulation, as well as developing new diagnostics, models, and operational modes to address these challenges and aid in the stable operation of MITICA. The high-resolution charac-terization of the X-ray energy spectrum during the high voltage conditioning of a multi electrode vacuum insulated system such as HVPTF could be vital to understand the fundamentals behind voltage breakdowns and which stage is causing the micro discharge onset. This technique seems particularly promising for measuring small dark currents (< 10μA), which are generally difficult to be measured with standard techniques. The X-rays produced during HV experiments are mainly due to bremsstrahlung interaction between the electrons escaping from the HV electrodes (field emission effect) and the background gas or the chamber walls. The X-rays spectrum extends from low energy (~ keV) up to several hundreds of keV depending on the maximum potential difference applied to the electrodes (up to 800 kV). During these events high photon flux (>106 photons/cm2s) is produced. This paper shows the development and preliminary results of a newly designed X-Ray diagnostic based on Gas Electron Multiplier (XR-GEM). This detector is able to stand very high rate (> MHz) in single photon counting mode and can cover the energy range from 3 - 50 keV. The XR GEM detector is equipped with anodic pads (256 pads 6x6 mm2) readout with a new data acquisition system called GEMINI, which gives the possibility to obtain a counting rate of several MHz and, thus, sub-ms time resolution together with mm spatial resolution.

Primary authors: CROCI, Gabriele (Universita & INFN, Milano-Bicocca (IT)); MCCORMACK, Oisin (INFN); MURARO, Andrea (CNR); Dr GROSSO, Giovanni (ISTP-CNR); SPAGNOLO, silvia; PI-LAN, Nicola (Consorzio RFX); DE LORENZI, Antonio (Consorzio RFX); Dr FONTANA, Cristiano Lino (Dipartimento di Fisica 'G. Galilei', Università di Padova); Dr GOBBO , Renato (Dipartimento di In-gegneria Industriale, Università di Padova, 35131 Padova, Italy); GORINI, Giuseppe (Universita & INFN, Milano-Bicocca (IT)); Mr FINCATO , Michele (Consorzio RFX (CNR, ENEA, INFN, Università di Padova, Acciaierie Venete)); Mr LOTTO, Luca (Consorzio RFX (CNR, ENEA, INFN, Università di Padova, Ac-ciaierie Venete)); MARTINES, Emilio (Consorzio RFX); Dr PINO , Felix (Dipartimento di Fisica 'G. Galilei', Università di Padova); Dr RIGAMONTI, Davide (ISTP-CNR); SPADA, Emanuele (Consorzio RFX); ZUIN, matteo; Dr ROSSETTO, Federico (Consorzio RFX); TARDOCCHI, Marco

Presenter: CROCI, Gabriele (Universita & INFN, Milano-Bicocca (IT))

Track Classification: C4. Accelerators and fusion reactor related issues

B3-O2-184

Characteristics of Vacuum Arc Voltage and Material Transfer with Different Contact Materials

Content

In this paper, the contact material transfer characteristics and contact surface micro morphology characteristics of 41mm contact diameter vacuum interrupter are analyzed. The electrode material of one contact of the vacuum interrupter is CuW80, and the electrode material of the other contact is CuCr25. When the vacuum interrupter interrupts the intermediate frequency arc of 5-15kA at a small gap distance, the morphology of different positions of the contact surface changes to different degrees, and the electrode components at different positions transfer to different degrees. In this paper, the micro morphology of contact surface in flat, crack, hole and droplet splash and the composition characteristics of contact material are analyzed, and the influence of ablation degree on contact micro morphology is obtained. The results show that for the Vacuum Interrupters with CuW80 and CuCr25 as contact materials, the transfer degree of Cu with lower melting point is the slightest, while Cr and W have different degrees of transfer after breaking large current.

Primary authors: Mr TONG, Ziang (Beihang University); Prof. WU, Jianwen (Beihang University); Mr CHEN, Jun (Guizhou Tianyi Electrical CO., Ltd.)

Presenter: Mr TONG, Ziang (Beihang University)

Track Classification: B3. Vacuum arc physics

B1-P1-185

Study on the Electrical Life Prediction of Vacuum Interrupter along Contact Erosion

Content

Vacuum circuit breaker was mainly used device in the medium voltage range. Vacuum interrupter is the core part of Vacuum Circuit Breaker. Vacuum interrupters have only one set of contacts to control the arcing and carry load currents. The contact structure comprises two parts the moving contact assembly and the fixed contact assembly. The fixed contact is stationary and held firmly in place, while the moving contact is free to move. When the circuit breaker operates, an arc is formed between the separated contacts. Due to the intense heat of the arc, the contact material melts. If the erosion of the contact reaches the limit, the vacuum interrupter will not cut off the fault current and cause an accident. Therefore, diagnosing the state of contact is very important in predicting the life of vacuum interrupter. In this paper, experiments were performed to determine the electrical life of a vacuum interrupter as a function of current. Rated short-circuit currents was using VI for 7.2kV 25kA. After the breaking test, the erosion of the contact was measured and arc energy was calculated. As a result, the relationship between the accumulated arc energy and contact erosion was analyzed. Finally, experimental results proposed a formula to evaluate the electrical life of vacuum interrupter.

Primary authors: Mr YOON, jaehun (LSIS); Dr RYU, jaeseop (LSIS); Dr BAE, chaeyoon (LSIS); Dr CHOI, jongung (LSIS)

Presenter: Mr YOON, jaehun (LSIS)

Track Classification: B1. Switching in vacuum and related phenomena

C4-P2-189

Development of vacuum RF feeder lines for front-end mirrors plasma cleaning in ITER optical diagnostics

Content

Plasma cleaning of front-end optical mirrors becomes an essential part of ITER optical and infrared diagnostics due to the risk of contamination with Be, W and their oxides as a result of First Wall and Divertor sputtering. As little as 10 nm of deposits may affect mirror performance. A capacitively coupled RF gas discharge (CCP) is considered as a candidate technology for optical surface cleaning. Due to complex design requirements, the power RF circuit components such as cables and feedthroughs have to be specially developed to provide reliable kV-range electrical insulation and to deliver necessary power to the front-end optical mirrors, in close proximity to the First Wall of the tokamak. The design foresees 5-6 m long vacuum RF cable feeds, temperatures of vacuum components up to 350 C, total RF power up to 1kW and DC-grounded water-cooled mirror electrodes connected to the vessel with coaxial pipe-lines of quarter-wavelength long. Higher RF voltage may therefore be needed to ignite and maintain plasma at 1-10 Pa pressures considered for plasma cleaning. The RF vacuum circuitry becomes inaccessible for repair and replacement once the tokamak is assembled. A service time of 10 years is expected. The RF power feeds should be compact to fit in in the duct where other diagnostic hardware and subsystems such as alignment, shutters and calibration are located. In the present report, we analyze a design approach to such RF circuit components and discuss vacuum mineral-insulated (MI) RF cables as potential power feed designs. A new compact RF air-to-vacuum high-voltage 1 kW / 3 kV interface is developed for 20-80 MHz RF. MI vacuum cables performance is compared with that of the 25 mm rigid vacuum coax line, which can be considered as an alternative solution. The results are considered for the design of mirror plasma cleaning systems in the multiple ITER tokamak optical diagnostics: Ultra-Wide Angle Viewing System (UWAVS), Visual Spectroscopy Reference System (VSRS), Edge Thomson Scattering (ETS) and Divertor Impurity Monitor (DIM) as well as in remote vacuum plasma cleaning applications in semiconductor industry.

Primary authors: Dr USHAKOV, Andrey (TNO); Dr VERLAAN, Ad (TNO); Dr STEPHAN, Ulf (FAP GmbH); Dr STEINKE, Olaff (FAP G mbH); Dr DE BOCK, Maarten (ITER-IO); Mr MANISCALCO, Matthew (TNO); Mr VERHOEFF, Peter (TNO)

Presenter: Dr USHAKOV, Andrey (TNO)

Track Classification: C4. Accelerators and fusion reactor related issues

C1-P2-190

Design of new liquid metal limiter and research on influencing factors of current limiting characteristics

Content

The liquid metal current limiter (LMCL) has the unique advantages of limiting current automatically, no moving parts, and self-healing.At present, the cavity of LMCL is an insulating material, which mainly utilizes the generated arc current limiting. The more LMCLs in series, the greater the resistance. Therefore, it is only suitable for low voltage and small current applications, and has not been developed into the field of high voltage current limiting.In order to develop LMCL into the field of high voltage current limiting, the paper adds a fast vacuum switch, current limiting reactor and other devices to design a new high voltage variable resistance current limiter topology structure.The ceramic resistor cavity is designed using ANSYS software.The current limiting exper-iment of LMCL was performed under different short circuit currents. The self-shrinking critical current of the liquid metal in the high-power ceramic resistor cavity is determined.Based on the research in this paper, LMCL can be developed into the field of high voltage current limiting. It provides a basis for future current limiter topology structure and optimization design.

Primary authors: Dr LI, Jinjin (Dalian University of Technology); Prof. HUANG, Zhihui (Dalian University of Technology); Prof. DUAN, Xiongying (Dalian University of Technology)

Presenter: Dr LI, Jinjin (Dalian University of Technology)

Track Classification: C1. Vacuum interrupters and their applications

B3-P1-192

Proposal of Time-Resolved Integral Field Spectroscopy for Vacuum Arc Observation

Content

The objective of this paper is to propose a new spectroscopic method for observing vacuum arc phenomena. Spectroscopic observation is an important method in the study of vacuum arcs. Using the spectroscopic method, one can obtain a lot of useful information, for example, the excited state of atoms and the temperature of arcs. To obtain spectral data, spectrometers and narrowband filters are mainly used. Spectrometers are usually equipped with a slit, thereby spatial information is limited to one-dimensional information along the slit. Since arcs have a spatial expansion, it is desirable to obtain two-dimensional spatial information, also in the case of spectroscopic observations. The use of a narrow band filter is able to obtain two-dimensional image information, but the wavelength is limited to a specific value of the filter.

In astronomy, a method to obtain spectroscopic data of two-dimensional images such as nebula and galaxies is used. This method is referred to as Integral Field Spectroscopy (IFS) and is used to obtain the spectroscopic information of a two-dimensional image in a single exposure.

A high-speed camera system and IFS combine to record the time variation of a two-dimensional arc image and its spectroscopic data. We named this method “Time-Resolved Integral Field Spectroscopy” (TRIFS). Equipment for TRIFS is composed of an imaging lens, fiber bundle, collimator, diffraction grating and a high-speed c amera. The arc image incident on the fiber bundle is converted into a one-dimensional image. The one-dimensional image is dispersed by the diffraction grating and recorded by the high-speed camera.

In order to verify the feasibility of TRIFS, we tested various prototype models. As a result, it became clear that TRIFS could be a useful method for the research of vacuum arcs and discharge phenomena in general. In this paper, the following items are described. First, the principle and equipment for this method. Second, an example of a vacuum arc observa-tion. Third, image data processing and perspective.

Primary author: MATSUI, Yoshihiko (MEIDENSHA CORPORATION Basic & Core Technology Research Laboratories)

Co-authors: Mr SUWA, Akihiro (MEIDENSHA CORPORATION Basic& Core Technology Research Laboratories); Mr KATO, Kazuya (MEIDENSHA CORPORATION Basic& Core Technology Research Laboratories); Mr NIWAKAWA, Makoto (MEIDENSHA CORPORATION Basic& Core Technology Re-search Laboratories)

Presenter: MATSUI, Yoshihiko (MEIDENSHA CORPORATION Basic & Core Technology Research Laboratories)

Track Classification: B3. Vacuum arc physics

B5-P3-198

Fast rotating liquid metal layer as anode for high brightness X-ray source

Content

The new generation high brilliance X-ray source based on Kα emission for semiconductor manufacturing metrology requires a brightness that is much higher than the existing technology can offer. X-ray source applications would include film characterization and CD metrology with measurement times suitable for production control. In this report, we explore the borders of the X-ray scheme containing an electron beam and a massive anode to achieve brilliance of more than 1011 photons·s-1·mm-2·mrad-2·line-1 requiring high power density in the focal spot (> 103 MW/cm2). In order to improve the source brilliance, we explore the recent development of the fast-rotating liquid-metal layer, which we use as an anode of a new compact X-ray generator to produce high intensity and high brilliance emission of Sn K-alpha line. The liquid-metal-electrode technology has recently been implemented in the high brightness 13.5 nm Extreme UV (EUV) source of the EBL-2 beamline system in TNO used for nanolithography experiments and tests [1-4]. In the EUV source, the vacuum spark is generated in Sn vapor between two rotating disk electrodes producing intense EUV emission. A cooling circuit using liquid Sn circulation capable of operating at powers of tens of kilowatts and peak powers of > 500 MW/cm2 was developed as a part of the radiation source. The successful history of the development of EBL2 and previous EUV systems using liquid Sn cooling at tens of kW dissipated power levels gives us a certain confidence that such system can also be used for a new bright X-ray source with higher power densities. In this report, we numerically and analytically analyze an opportunity to focus a high-power e-beam of up to 70-90 keV on the rotating anode layer. The focused e-beam generates intense Kα in the Bremsstrahlung spectra in the liquid Sn layer. A stable Sn surface of 20-50 μm thickness on a solid Tungsten or Molybdenum metal platform rotating with a linear speed of 10 m/s is considered achievable. The results of X-ray output simulations predict possibilities to produce an intense characteristic X-ray spectrum with a strong K-alpha component. The overall concept of a compact table-top prototype is also presented in the report.

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Primary authors: USHAKOV, Andrey (TNO); Dr TERAMOTO, Yusuke (BLV Licht GmbH); Dr VELTHUIS, Han (TNO); Dr STODLNA, Aneta (TNO); Mr JANSSEN, Jochem (TNO)

Presenter: USHAKOV, Andrey (TNO)

Track Classification: B5. Pulsed power physics and technology

C5-O3-205

Developing of Compact Plasma Thruster Based on Flashover Discharge

Content

Currently, the space industry is actively developing, and with it, the demand for different space thrusters is growing. In this work, a prototype of a small size pulsed plasma engine is described and investigated. The main idea was to make a small electric propulsion system that could be used on CubyeSat and other small satellites. It follows that the mass of the propulsion system should not exceed 250g and the power consumption of 5W. The design of the thruster is simple; it consists of a metal cathode and anode and a solid insulator between them as a propellant. Thrust is produced by plasma flow generated by pulsed vacuum flashover discharge. In this prototype planar electrode design with a gap about 1mm was used. As the material for the electrodes, Cu or Al can be used. In addition to the thruster, it was necessary to develop a Power processing unit (PPU) which could generate high voltage impulses with amplitude up to 10kV and frequency from 1 to 10кHz. With the right pulse parameters, it is possible to achieve a working mode with minimal cathode erosion, to ensure high system stability. The following system parameters were studied: thrust, reliability, ion flow velocity and their dis-tribution. To determine ion speed and spatial structure of the ion flow we used small-sized ion detectors installed at various angles and distances from thruster. We used torsional pendulum to measure trust.

Primary authors: MIKHAILOV, Pavel (The Institute of Electrophysics of the Ural Division of the Rus); MUZYUKIN, Ilya (Institute of Electrophysics UB RAS)

Presenter: MIKHAILOV, Pavel (The Institute of Electrophysics of the Ural Division of the Rus)

Track Classification: C5. Space related technologies

B3-P1-208

High-Current Pulsed Vacuum Arc in Coaxial Electrode System

Content

The pulsed vacuum discharge is seriously investigated during a long period of time [1]. It can be a source of multiply charged plasma. The results of the study of a high current pulsed vacuum arc are presented in this paper. A coaxial electrode design with 1 mm anode-cathode gap was used in this experiment. The cathode is made of copper and has a round shape with a diameter of 2 mm. The anode was in the form of a ring with an inner diameter of 3 mm. Molybdenum was used as an anode material because of its high melting temperature (2620 ℃). Anode and cathode were separated by a solid polyethylene insulator. All experiments were carried out in a vacuum chamber at a pressure of 10-5 mm Hg. To obtain a vacuum arc, a pulsed generator was used. In this experiment, we used pulses with a duration of 12 μs (FWHM) and a current amplitude up to 10.8 kA at a charging voltage up to 10 kV. In this experiment, mass and ion erosion of the electrodes were investigated. After each experiment series (several dozen pulses with the same parameters) cathode anode and insulator were weighed and then replaced with new ones. Moreover, ion plasma flow was taken using four small-sized ion collector analyzers. These analyzers were placed at the same distance but different angles from electrodes. The signal from these detectors was recorded by a multichannel oscilloscope and then it was analyzed. This method allows to measure the temporal and spatial dependence of the ion current. After collecting data from various angles (mainly from 0o to 60o), the data were averaged and integrated over time and angle. As a result, values for ion erosion were obtained.

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Primary authors: MIKHAILOV, Pavel (The Institute of Electrophysics of the Ural Division of the Rus); MUZYUKIN, Ilya (Institute of Electrophysics UB RAS); UIMANOV, Igor (Institute of Electrophysica UB RAS); Prof. SHMELEV, Dmitry L. (Institute of Electrophysics, RAS, Ekaterinburg, 620016, Russia); ZEMSKOV, Yury (Institute of Electrophysics, Ural Branch, Russian Academy of Sciences); CHAIKOVSKY, Stanislav (Institute of Electrophysics, RAS, Ekaterinburg, 620016, Russia)

Presenter: MIKHAILOV, Pavel (The Institute of Electrophysics of the Ural Division of the Rus)

Track Classification: B3. Vacuum arc physics

A1-O9-210

Dynamic Coupling Between Particle-in-Cell and Atomistic Simulations

Content

We propose a method to directly couple molecular dynamics, finite element method and particle-in-cell techniques, to simulate response of a metal surface to high electric fields. We use this method to simulate the evolution of a field emitting tip under thermal runaway, by fully including the 3D space-charge effects. We also present a comparison of the runaway process between two tip geometries of different widths. The results show with high statistical significance, that in case of sufficiently narrow field emitters, the thermal runaway occurs in cycles where intensive neutral evaporation alternates with cooling periods. The comparison with previous works shows, that the evaporation rate in the regime of intensive evaporation is sufficient to ignite a plasma arc above the simulated field emitters. The proposed method, which is under constant development, forms the basis for fully simulating the processes that lead from thermal runaway of intensively field emitting nanotips tips to full arc plasma onset. By introducing and handling new particle species such as neutrals and ions, we aspire to bridge the gap of understanding between the dark current and the vacuum arc ignition. This understanding is becoming increasingly important, in view of recent developments in the analysis of the dependence of the breakdown rate to the available electromagnetic power.

Primary authors: KYRITSAKIS, Andreas; VESKE, Mihkel; SJOBAEK, Kyrre Ness (University of Oslo (NO)); ZADIN, Vahur (University of Tartu); DJURABEKOVA, Flyura (University of Helsinki)

Presenter: KYRITSAKIS, Andreas

Track Classification: B4. Computer modeling and computer aided design

B3-O2-213

Observations of the Distortion of The Energy Distributions of Cathode Material Ions in Vacuum Arc Plasma Generated by the Microsecond LC line Discharge

Content

Low current vacuum arc discharge was investigated. Pulse source were the LC-lines with quasi-rectangular pulse shape. Pulse durations were 2 and 4 microseconds. Discharge electrodes were made of copper. Ion flow composition and ion energy spectra were obtained via the Thomson spectrometer with automated image recording and digital data processing.
Entering of the ion flow to the spectrometer was partially limited by the electrostatic gate with variable duration and delay of the closing pulse. Therefore the detection of ions depended on the ion velocity and the generation moment of the ion. It was found that the ion spectra have low energy (tens of eV) and high energy (hundreds of eV)parts. High energy ion fraction were sufficiently large; and the high energy ions were apparently generated at the discharge end at the given discharge parameters.

Primary authors: ZEMSKOV, Yury (Institute of Electrophysics, Ural Branch, Russian Academy of Sciences); UIMANOV, Igor (Institute of Electrophysica UB RAS)

Presenter: ZEMSKOV, Yury (Institute of Electrophysics, Ural Branch, Russian Academy of Sci-ences)

Track Classification: B3. Vacuum arc physics

C1-P2-217

High Endurance Capacitive Current Switching Test Station

Content

Capacitive current switching is a major requirement for circuit-breaker. The international standards as IEC or IEEE and national standard as GB require minimum 48 cycles for class C1 and 104 ones for class C2 breakers. However, on the network, operation can be daily, weekly or less frequent. Therefore, during life span of a breaker, the number of operations can be of the orders of 100's up to 10 000 operations.

In this frame, we have upgraded our capacitive current switching test station with main emphasis on high endurance and detection of restrikes. The target is to perform 10 000 cycles within a week. Due to the high number of cycles over limited time, key issues are fast operation, high precision measuring apparatus and fast acquisition system. Inrush current can be adjusted from 2 kA to 20 kA and voltages from 12 to 24 kV according to the different network applications. The test circuit is based on synthetic configuration based on a high voltage capacitors and inductors to generate the inrush current. The recovery voltage is created with voltage doubler type Latour.

The test station requires detection of transient phenomena as restrikes. The data quantity is very high and can reach more than 10 million measurements per cycles. Therefore, automatic detection of transient phenomena is required. Specific software to analyze the data has been developed. It displays restrikes events analysis according number of operation and time after breaking. In addition, it is possible to analyze and control all parameters applied during tests campaign. In this frame, vacuum circuit breaker and SF6 circuit breakers have tested and critical design parameters as contact material, can be compared.

Primary authors: Dr GODECHOT, Xavier (Schneider-Electric); ALBERTO, Diego (Schneider-Elec-tric); GAUTHIER, Jean-Pierre (Schneider-Electric); PAPILLON, Anthony (Schneider-Electric)

Presenter: Dr GODECHOT, Xavier (Schneider-Electric)

Track Classification: C1. Vacuum interrupters and their applications

B2-P2-218

Dynamics of dense vacuum arc cathode-spot plasma in magnetic field

Content

The dynamics of the plasma generated by the explosive-emission cells of the cathode spot of a vacuum arc in a magnetic field is considered [M.M. Tsventoukh, D.L. Shmelev and S.A. Barengolts 2019 Plasma Phys. Control. Fusion 61 062001]. It is shown that the expansion of the (high-density) plasma in a transverse magnetic field may cause asymmetry in the plasma density distribution at the cathode spot boundary. The asymmetry, in turn, increases the probability of the ignition of new explosive-emission cells in the region of a stronger magnetic field in the direction of B × I. The disturbed plasma density distribution estimated in the magnetohydrodynamic approximation is presented. In addition, the velocity of the 'retrograde' spot motion (ignition of new explosive-emission cells) in the stronger field region is estimated as a function of the external magnetic field strength. The velocity estimates (a few to tens of m/s/T) are shown to agree with experimental data.

Primary author: TSVENTOUKH, Mikhail (Lebedev Physical Institute RAS)

Co-authors: Prof. SHMELEV, Dmitry L. (Institute of Electrophysics, RAS, Ekaterinburg, 620016, Russia); BAREN-GOLTS, Sergey (Prohorov General Physics Institute RAS)

Presenter: TSVENTOUKH, Mikhail (Lebedev Physical Institute RAS)

Track Classification: B2. Interaction of vacuum arcs with magnetic fields

B4-I9-220

Progress in micron-scale field emission models based on nanoscale surface characterization for use in PIC-DSMC vacuum arc simulations

Content

We are developing a stochastic, micron-scale field emission model based on nanoscale characterization of real surfaces for use in Particle-In-Cell Direct Simulation Monte Carlo (PIC-DSMC) simulations of vacuum discharge. 3D PIC-DSMC simulations of cm-sized devices cannot resolve atomic-scale (nm) surface features and thus we must generate micron-scale models for an effective "local" work function, field enhancement factor, and emission area. These effective models are based on atomic-scale characterization of the as-built electrode surfaces. In the present work, representative probability density distributions of the work function and field enhancement factor (beta) for a sputter-deposited Pt surface are generated from atomic-scale surface characterization using Scanning Tunneling Microscopy (STM), Atomic Force Microscopy (AFM), and Photoemis-sion Electron Microscopy (PEEM). The atomic-scale beta distribution function is derived from the AFM/STM data by resolving the nm-scale measured surface topology with a finite element method, imposing an applied electric field, and capturing the actual local field enhancements (local normal field vs. applied field). The atomic-scale work function is sampled from nm-scale PEEM measure-ments of the same surface. In the micron-scale model, at initiation, every simulated PIC-DSMC surface element draws properties (work function and beta) for many independent "atomic emit-ters" based on the area ratio of the element to the resolution of the measured data. During the simulation the field emitted current from an element is computed by summing the contributions of the "atomic emitters". This "atomic emitters" model has reasonable agreement with measured micron-scale emitted currents across a range of electric field values. The computational cost of the model is negligible compared to the rest of the timestep (push, collide, etc.) as the majority (>99.99%) of the "local emitters" contribute less than 0.001% of the current and are ignored.

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Primary authors: MOORE, Chris (Sandia National Labs); JINDAL, Ashish (Sandia National Labora-tories); Dr BUSSMANN, Ezra (Sandia National Labs); Dr OHTA, Taisuke (Sandia National Labs); BERG, Morgann (Sandia National Laboratories); Dr THOMAS, Cherrelle (Sandia National Labs); Dr SCRYM-GEOUR, David (Sandia National Labs); CLEM, Paul (Sandia National Laboratories); HOPKINS, Matthew (Sandia National Laboratories)

Presenter: MOORE, Chris (Sandia National Labs)

Track Classification: B4. Computer modeling and computer aided design

C4-I2-222

Technological aspects the IFMIF Radio Frequency Quadrupole realization: design features and experimental results at the IFMIF prototype accelerator (LIPAc)

Content

The IFMIF prototype accelerator (LIPAc) is presently under commissioning at the Broader Approach site of Rokkasho in Japan. The project is a collaboration between Europe and Japan (coordinated by F4E and QST respectively), the main accelerator components have been designed and realized be European Institutes. In particular the RFQ, designed to accelerate a current of 125 mA deuterons from 0.1 to 5 MeV, has been realized by INFN; the acceleration of a pulsed beam with nominal current, energy and transmission has been recently demonstrated, the beam power will be gradually increased towards the nominal 625 kW during 2021. The challenges of this accelerator (that is the most powerful of his kind) are strictly related with the necessity to keep a electric high field level to accelerate and focus the beam particles. A sur-face field of about 25 MV/m (1.8 Kilpatrick field at 175 MHz) is kept on the electrodes, that need to maintain a very precise geometry in presence of high RF dissipation and high beam current. Moreover, even if beam transmission is very high (above 90%), the losses and the consequent gas load are not negligible. These technological aspects will be discussed, together with the solution adopted and the experimental results found.

Primary author: PISENT, Andrea (INFN)

Presenter: PISENT, Andrea (INFN)

Track Classification: C4. Accelerators and fusion reactor related issues

C5-P2-223

Regulation of Secondary Electron Yield Based on Microporous Array Structure Surface

Content

Electrostatic charging and discharging induced by spacecrafts interaction with space plasma is the main cause of on-orbit spacecrafts failures and anomalies, accounting for over 50% of all accidents. It has been observed that secondary electrons emission is of dominant importance in determining surface charges accumulation and multipactor discharge. Electron beam bombardment on the dielectric surface is consisted of complicated procedures of energy transfer from primary electrons to secondary electrons and internal charges transport. This paper is focused on modification of the polyimide film, a widely used spacecraft material, and its dynamic characteristics of secondary electrons emission yield (SEEY) is investigated. Surface fluorination can produce fluoride groups C-F(n) by replacement of C-H bonds. New introduction of C-F bonds changes chemical energy structure and potential barrier of materials surface, which has significant influences on SEEY. The SEEY measurement device is set up with an electron gun (energy from 50eV to 2000eV) and a hemi-spherical detector (biased to +100V positive voltage, equipped with a shielded grid). Time-resolved evolution of secondary electron emission and trapped charges accumulation in fluorinated poly-imide film is studied. The result indicates that secondary electrons emission deposits charges in the material, and the induced internal electric field affects trajectories and bombardment energies of injected electrons, resulting in dynamic attenuation of external SEEY from its initial amplitude to a self-consistent steady value. The attenuation tendency is followed by an exponential decay law, characterized by the time constant τ. Furthermore, τ defines the charging procedure rate and is influenced by incident primary currents. Modification methods of fluorination including gas proportion (N2 and F2) and applied time are discussed to optimize processing techniques of charging mitigation.

Primary authors: Dr SONG, Baipeng (Xi'an Jiaotong University); Prof. ZHANG, Guan-Jun (Xi'an Jiaotong University)

Presenter: Dr SONG, Baipeng (Xi'an Jiaotong University)

Track Classification: C5. Space related technologies

C2-P2-224

Pulsed Electron-Beam Assisted Synthesis of a Ni-Al Surface Alloy

Content

The Ni-Al multilayer system is an interesting object for research, not only because it is a “storage” of chemical energy, which can be released at high rate in the form of heat during the formation of bonds between atoms of Ni and Al [1-2]. It also provides a number of intermetallides such as Al3Ni, Al3Ni2, AlNi, AlNi3 which can be synthesized during this reaction. Of greatest important is AlNi intermetallic material, which has the highest melting point of all nickel and aluminum intermetallic compounds. Due to the combination of a high melting point and relatively high thermal and electrical conductivity, NiAl intermetallic have considered as a candidate for use as a matrix material in the manufacture of vacuum interrupter electrodes, i.e. replacements of copper used now in this quality [3-4]. The results of numerical and experimental studies on the synthesis of Ni-Al surface alloy on a steel substrate are presented. The alloy was formed by preliminary magnetron sputtering of multilayer Ni-Al coatings of two types from (1) thin ~ 0.1 and (2) thick ~ 1 μm films and their subsequent irradiation with mixing by a pulsed electron beam transported to the target in a plasma-filled diode. In the work, the optimal irradiation mode was determined by the numerical method for the formation of a Ni-Al surface alloy where intensive melting of all deposited films occurs, and there is no evaporation of the surface material. It is experimentally shown that, as a result of pulsed electron-beam heating, a Ni-Al surface alloy is formed, which is represented by NiAl high-temperature intermetallic phase. In the case of Ni-Al multilayer system made up of thin films, the surface alloy formed is homogeneous, but a network of cracks appears on the surface. In the case of Ni-Al multilayer system made up of thick films, the surface alloy formed is heterogeneous, both along the surface and along the depth of the target. Its structure is a composite, combining the alternation of strong (but brittle) and soft (but ductile) components, corresponding to NiAl high-temperature intermetallic phase and (Al, Ni) solid solution, respectively. It is precisely this structure of the Ni-Al surface alloy that makes it possible to obtain a crack-free surface with high tribological and other physical properties.

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Primary authors: MARKOV, Alexey (Tomsk Scientific C enter); Mr YAKOVLEV, Evgenii (Insti-tute of High-Current Electronics SB RAS); Mrs SHEPEL’, Daria (Tomsk Scientific Center SB R AS); Dr SOLOVJEV, Andrey (Tomsk Scientific Center SB R AS); Mr PETROV, Vsevolod (Tomsk Scientific Center SB RAS)

Presenter: MARKOV, Alexey (Tomsk Scientific Center)

Track Classification: C2. Surface modification and related technologies

A1-P3-229

Characterization of X-ray Events for a Vacuum High Voltage Holding Experiment

Content

The High Voltage Padova Test Facility (HVPTF) is an experimental device for investigating HV insulation in vacuum, in support of the realization of MITICA, the prototype of a neutral beam injector for ITER. The facility investigates the physical phenomena underlying voltage holding in vacuum, such as the mechanisms causing breakdowns and the electrode conditioning process, along with testing technical solutions to increase the breakdown threshold. Inside a high vacuum chamber, two stainless steel electrodes, separated by a few centimetres gap, can achieve HV values up to 400 kV each. The conditioning process consists of the gradual increase of the breakdown voltage in time, until the system achieves a saturation value. Between two consecutive breakdown events, current micro-discharges involving the electrodes are observed; high energy X-rays (up to hundreds of keV) and a global increase of gas emission (in particular H2 and CO2 are detected by the Residual Gas Analyser) are measured in correspondence to the current events. Three new X-rays detectors have been recently installed: a small LYSO (4 × 4 × 20 mm3), a LaBr3 (1" x 3/4") and a thin YAP (1"x 2 mm) scintillating crystals, coupled to photomultipliers. They all are small sized scintillators, with very fast pulses (40-100 ns) in order to minimize pile-up effects during the high intensity discharges. However, the high Z and densities guarantee a full energy absorption of the X-rays (they can measure up to 500 keV), with a significant probability, in spite of the small sizes. Energy resolutions are less than 9%. In this contribution we present a characterization of the micro-discharge dynamics occurring during the conditioning phase, focusing on the new details uncovered via the new diagnostics.

Primary author: SPAGNOLO, Silvia

Co-authors: PILAN, Nicola (Consorzio RFX); DE LORENZI, Antonio (Consorzio RFX); Dr FONTANA, Cristiano Lino (Dipartimento di Fisica 'G. Galilei', Universit di Padova); Dr MC CORMACK, Oisin (Istituto Nazionale di Fisica Nucleare, Sezione di Milano Bicocca, 20126 Milano); MURARO, Andrea (CNR); CROCI, Gabriele (Universita & INFN, Milano-Bicocca (IT)); Dr GOBBO , Renato (Dipartimento di Ingegneria Industriale, Universit di Padova, 35131 Padova, Italy); GORINI, Giuseppe (Universita & INFN, Milano-Bicocca (IT)); Dr GROSSO, Giovanni (ISTP-CNR); Mr FINCATO , Michele (Consorzio RFX (CNR, ENEA, INFN, Universit di Padova, Acciaierie Venete)); Mr LOTTO, Luca (Consorzio RFX (CNR, ENEA, INFN, Universit di Padova, Acciaierie Venete)); MARTINES, Emilio (Consorzio RFX); Dr PINO , Felix (Dipartimento di Fisica 'G. Galilei', Universit di Padova); Dr RIGAMONTI, Davide (IST-P-CNR); Dr ROSSETTO, Federico (Consorzio RFX); SPADA, Emanuele (Consorzio RFX); TARDOCCHI, Marco; ZUIN, matteo

Presenter: SPAGNOLO, Silvia

Track Classification: A1. Vacuum breakdown and pre-breakdown phenomena

C4-I4-230

The Importance of the Neutral Beam Test facility to ITER

Content

ITER is an international project to develop an experimental reactor as a step to realize fusion energy. To achieve ITERs objectives to operate with high fusion power, Pfus ~ 500 MW with fusion gain, Q=10 for 400 s in a baseline scenario, and Pfus > 250 MW, Q=5 operation for 3600 s in advanced scenarios ITER relies on the realisation of the auxiliary heating systems, of which one of the most important is the Neutral Beam injection system. A total power of 33 MW from the two heating neutral beam (HNB) injectors is envisaged in the present scenario. To achieve the required heating and current drive necessary from the neutral beams, the injectors are required to provide 1 MeV D0 neutral beams created by accelerating deuterium negative ions to -1 MV across 5 electrostatic grids. These stringent requirement have never been demonstrated on any existing machine to date, making them first of a kind with significant physical and technological challenges. In addition, a beam line at lower energies, 100kV is also envisaged as a diagnostic neutral beam (DNB), to realise charge exchange measurements.

One of the advantages of neutral beams as a technique for heating, current drive, and momentum input is that their coupling to the plasma is not strongly dependent upon the edge conditions of the tokamak plasma, and the interaction with the plasma takes place primarily through a relatively well-understood mechanism, two-body collisions. As a consequence, a neutral beam test facility (NBTF) can be utilized effectively to develop, test, and improve the neutral beam capabilities at a location remote from the ITER machine, with a high degree of confidence that it will function in a similar fashion when installed on the tokamak, and that it will drive effects within the confined plasma which are largely predictable. The ITER NBTF, is intended to capture these benefits for ITER, and for both the primary heating and current drive beams (HNB) and the DNB. The NBTF will consist of two complementary test facilities at Consorzio RFX in Padua, a 1 MV test bed (MITICA), which differs from an actual injector only in the diagnostic capability, and an ion source test bed (SPIDER) which is capable of testing a full size ITER ion source at full parameters, but with an higher degree of flexibility and at reduced voltage of 100 kV.

The NBTF is the centrepiece of a coordinated development effort, including subsidiary test facilities in Japan, Europe and India, that will result in the experience and information necessary to proceed with the finalization of the ITER neutral beams.

Having such a facility for the development of neutral beams allows the inherent technological and physics risks of Neutral beam injectors to be mitigated. These risks can be summarised in a few main categories, HV Holding, Optics and Ion source efficiencies. This paper will outline the importance of the NB system to ITER and highlight the importance of the NBTF in ensuring that these systems are successfully realised on the ITER machine.

Primary author: Dr BOILSON, Deirdre (ITER Organization)

Co-authors: Mr ROTTI, Chandramouli (ITER Organization); Mr TOIGO, Vanni (Conzorzio RFX); Mr BONICELLI, Tullio (Fusion for Energy); Dr VELTRI, Pierluigi (ITER Organization)

Presenter: Dr BOILSON, Deirdre (ITER Organization)

Track Classification: C4. Accelerators and fusion reactor related issues

C4-O4-235

Ceramic coatings for arc prevention between plasma facing components

Content

The design of the RFX-mod2 fusion experimental device requires a 3 mm copper shell close to the plasma to achieve improved plasma confinement properties. Such conductive structure, located around the plasma and aimed to passively stabilize the plasma, shall have an electrical discontinu-ity in both the poloidal and toroidal directions, in order to allow the penetration of electromagnetic fields into the plasma region. These gaps avoid the formation of net poloidal and toroidal eddy cur-rents during transient phases of the plasma confinement experiment. Moreover, the shell has been designed with an overlapping region at the poloidal gap in order to reduce the induced field er-rors.

During operations in Reversed Field Pinch magnetic configuration, the loop voltage, that is the externally induced electromotive force sustaining the plasma current, can reach values up to 400 V. These values can rapidly step up to 1.5 kV during fast plasma current terminations. Therefore, intense electric fields can generate between the shell flaps, only a few millimetres apart, along the overlapping region. Furthermore, taking into account that the stabilizing shell, being located inside the vacuum chamber, is exposed to low temperature plasma, the formation probability of harmful electric arcs is high. In order to avoid arc formation, different kind of insulation coating on the copper, able to with-stand the applied electric fields in the presence of plasma, are under investigation. The electrical insulation performances of ceramic coating on a copper samples are investigated. Several deposition methods have been evaluated, including magnetron sputtering, atmospheric plasma spray and detonation gun spray, which differ in the adhesion to the substrate, compact-ness, porosity and mechanical strength of the deposited material. The last two methods have the advantage of being conducted in air at atmospheric pressure, without the aid of complex vacuum systems. In order to validate the process, an experimental apparatus was prepared in laboratory, aimed to reproduce the expected conditions at the shell gap. It consists of a vacuum chamber in which a helium plasma was generated by means of a hot tungsten filament and a DC power supply. A bias voltage was applied between a copper plate and a cylindrical electrode (Ø 4 mm). The plate side facing the electrode was covered with alumina. The two electrodes were floating and biased by a small capacitor bank (0.3÷2 μF). The voltage on the electrodes was applied for 200ms, with a repetition rate of 1Hz. In this contribution, the experimental results, aiming to study the conditions for the arc formation in presence of weakly ionized plasma (ne ~ 1016 m-3), are presented. In particular, voltage pulses up to 2.7 kV were applied, with a background gas pressure between 10-3 and 10 mbar. Further-more, the electrodes were kept both in contact and spaced up to 5 mm. Furthermore, the results of similar experiments performed on a mini mock-up, simulating the RFX-mod2 overlapping shell, are presented.

Primary authors: Dr CORDARO, Luigi (Consorzio RFX); Dr CAVAZZANA, Roberto (Consorzio RFX); Dr ZUIN, Matteo (Consorzio RFX); Mr BERTON, Giovanni (Consorzio RFX); Dr PAVEI, Mauro (Consorzio RFX); SPOLAORE, Monica (Consorzio RFX, Padova, Italy); PERUZZO, Simone(ConsorzioRFX)

Presenter: Dr CORDARO, Luigi (Consorzio RFX)

Track Classification: C4. Accelerators and fusion reactor related issues

C4-P2-236

Electrode conditioning for the prevention of DC arc formation within a cold plasma

Content

In the RFX-mod2 experiment presently under construction, devoted to the study of magnetic confinement of fusion relevant plasmas, significant electric fields, in the kV/mm range, are expected to form in between in-vessel conductive plasma facing components during transient plasma current phases (start-up and termination). While such electric fields are of no concern for components in vacuum, the presence of a scrape-off plasma at the edge (electron density ne 1016 ÷1018 m-3, electron temperature Te of few eV) can create the conditions for potentially dangerous arc formation. For this reason part of the plasma facing components (in particular the graphite 'first wall' tiles covering the copper 'stabilizing shell' placed within the plasma chamber) require a proper conditioning technique capable of maintaining the insulation between conductive components even in presence of the scrape-off plasma. An experimental apparatus has been developed in order to test the conditions for the arc formation and prevention between two electrodes immersed in a plasma generated by a hot emitting filament. The results of an extensive experimental campaign will be presented, aimed at demonstrating the possibility of gaining a sufficient electrical conditioning by applying the standard conditioning technique usually employed for higher voltage ranges. It consists of a sequence of high voltage pulses applied to the pair of electrodes with current limitation, in the presence of a background cold plasma with low ionization degree. The experimental procedure is such that the voltage of the pulses is slightly increased when arcing ceases, until the final desired voltage level is achieved (2.5 kV). Different electrode materials have been tested in a variety of plasma conditions in terms of electron density and working gas pressure.

Primary authors: Dr ZUIN, Matteo (Consorzio RFX, corso Stati Uniti 4, 35127, Padova, I taly); Dr CAVAZZANA, Roberto (Consorzio RFX, corso Stati Uniti 4, 35127, Padova, Italy); Dr CORDARO, Luigi (Consorzio RFX, corso Stati Uniti 4, 35127, Padova, Italy); PERUZZO, Simone (Consorzio RFX, corso Stati Uniti 4, 35127, Padova, Italy)

Presenter: Dr ZUIN, Matteo (Consorzio RFX, corso Stati Uniti 4, 35127, Padova, Italy)

Track Classification: C4. Accelerators and fusion reactor related issues

C4-I3-237

Vacuum Insulation in Negative Ion Accelerator with Long Gap and Large Surface for Fusion Application

Content

Vacuum insulation of 1 MeV negative ion accelerators for fusion application is characterized by long gaps of 80~1000 mm and large surface areas > 2 m^2 with diameters over 2 m. In order to design such electrodes structure, the empirical scaling and the scaling technique to predict the sustainable voltage of 1/1 full-scale from that of 1/5-scale have been developed. In order to realize fusion plasmas in the ITER Project, a 5-stage electrostatic accelerator for 1 MeV, 40 A negative ion beams is being developed for plasma heating. Since the accelerator is installed in vacuum, the electrode structure to sustain a high voltage of DC -1 MV is required not only for the inside of the accelerator but also in a single gap of 1 m between the accelerator and the vacuum vessel. However, since there is no design database including the vacuum vessel, the design and its validation are critical issues for ITER. The electrode structure of the accelerator consists of a combination of plane and coaxial electrodes with corners. In order to design such electrodes, empirical scaling of the voltage holding capability has been developed so far. According to the Clump theory indicating that a breakdown occurs at a certain value of the product of voltage V and electric field E, an allowable maximum EV was experimentally investigated by using plane and coaxial electrodes with surface area < 10 m^2 for uniform electric field. In addition, the allowable EV for the breakdown due to local electric field was also experimentally investigated by using cylindrical electrodes having rounded corners with diameters R < 1 m. These results have been integrated to the empirical scaling of EV~S^-0.22 for uniform electric field and EV~exp(-1.8e-3 R) for local electric field at the corner. The empirical scal-ing has been validated in the development of a prototype accelerator and a high voltage bushing for ITER by taking into account a plane, coaxial and corner configurations. As for the validation of the design of the accelerator for ITER, a 1/5 mockup simulating the config-urations of the accelerator, the high voltage bushing and the vacuum vessel is being developed. As a first step, voltage holding tests of the 1/5 mockup only for the 5-stage high voltage bushing was carried out. As a result, the empirical scaling for coaxial electrodes agreed well with the experimen-tal value of EV in each stage. In a 5-stage test, even though the EV was limited by the breakdown between the electrode and the vacuum vessel due to the local electric field, the empirical scaling for local electric field successfully predicted the experimental result. By comparing the results in 1/5 mockup and 1/1 full scale for the high voltage bushing, the scale effect has been obtained for the first time, which was found to be a combined effect including area and gap length. By using the scale effect, voltage holding capability of the full-scale system in ITER will be predicted after the 1/5 mockup experiment by using all electrodes.

Primary author: Dr KOJIMA, Atsushi (QST)

Co-authors: Dr WATANABE, Kazuhiro (QST); Mr SHIBATA, Naoki (QST); Dr KASHIWAGI, Mieko (QST); Dr TOBARI, Hiroyuki (QST); Mr UMEDA, Naotaka (QST); Mr ICHIKAWA, Masahiro (QST); Dr HIRATSUKA, Junichi (QST); SAQUILAYAN, Glynnis (QST); Dr YAMNO, Yasushi (Saitama Univer-sity)

Presenter: Dr KOJIMA, Atsushi (QST)

Track Classification: C4. Accelerators and fusion reactor related issues

A2-P3-238

Effect of Surface Modification on Trap Distribution and Vacuum Surface Flashover of Polymeric Materials

Content

The surface trap parameter and distribution could significantly affect the surface flashover characteristic of insulation mateirials in vacuum. To further understand the influence of traps on flashover of polymeric materials, the surface trap parameters, including trap energy level and trap density, were regulated by surface modification. Firstly the atmospheric pressure plasma jets were used to treat the fluorinated ethylene propylene (FEP) film to control trap density, and electron beam irradiation was used to change surface trap energy level of polymide (PA6). Then the effect of different processing conditions on the insulation properties of material surface was studied. The trap parameters were tested and caculated by means of isothermal surface potential decay (ISPD), and space charge distribution in FEP film body was also measured by means of pulsed electro-acoustic (PEA). At last surface flashover experiment under DC and pulsed voltage in vacuum was performed using finger-type electrodes, and the relationship between surface trap parameter and flashover voltage was analyzed in diffrent treatment conditions. The results show that some inorganic groups containing silicon element are introduced on the surface of FEP, and the trap density increases in different degrees while the trap energy level changes slightly. The space charge distribution has a positive correlation with the trap density. The trap level increases after electron beam irradiation with diffrent energy and treatment time while the trap density changes slightly. The increase of trap level and trap density could improve the vacuum surface flashover voltage to a certain degree by surface modification.

Primary author: Mrs REN, Chengyan (Institute of Electrical Engineering, Chinese Academy of Sciences)

Co-authors: Mr ZHANG, Chuansheng (Institute of Electrical Engineering, Chinese Academy of Sciences); Dr KONG, Fei (Institute of Electrical Engineering, Chinese Academy of Sciences); Prof. ZHANG, Cheng (Institute of Electrical Engineering, Chinese Academy of Sciences); Prof. SHAO, Tao (Institute of Electrical Engineering, Chinese Academy of Sciences); Prof. YAN, Ping (Institute of Electrical Engi-neering, Chinese Academy of Sciences)

Presenter: Mrs REN, Chengyan (Institute of Electrical Engineering, Chinese Academy of Sciences)

Track Classification: A2. Surface discharges and flashover phenomena

C2-O3-239

Plasma Deposition Films to Improve Surface Insulation Properties in Vacuum

Content

Ceramic as an insulation material is widely used in the field of pulse power technology, due to the good mechanical and electrical properties. However, the surface flashover at the interface of vacuum-dielectric is observed frequently, which limits the development of pulse power technology. In order to satisfy the demand of industry development, the improvement of the surface insulation performance of ceramic is urgent. Therefore, in this paper, the functional films are deposited on the ceramic surface by plasma modification technology in order to suppress the surface flashover. The experimental system includes pulse power supply, reactor and electrical measurement system. The pulse power supply (CMPC-40, Institute of Electrical Engineering, CAS) has a pulse rise time of 0.5 μs, a pulse width of 8 μs, and a pulse recurrence frequency (PRF) up to 3 kHz. The ceramic samples are treated with precursor assisted by plasma for several minutes. The precursor is carried out by argon gas. Before and after the plasma modification, surface charge accumulation and dissipation characteristics are discussed, respectively. The results shows the withstanding voltage increased to 29% after plasma modification. The physical and chemical characteristics before and after modification are also discussed.

Primary author: Dr KONG, Fei (Chinese Academy of Sciences)

Co-authors: Mr DONG, Pan (China Academy of Engineering Physics); Mr YU, Weixin (Chinese Academy of Sciences); Prof. REN, Chengyan (Chinese Academy of Sciences); Prof. ZHANG, Cheng (Chinese Academy of Sciences); Prof. YAN, Ping (Chinese Academy of Sciences); Prof. SHAO, Tao (Chinese Academy of Sciences)

Presenter: Dr KONG, Fei (Chinese Academy of Sciences)

Track Classification: C2. Surface modification and related technologies

A1-P3-241

Theoretical and Experimental Study of Breakdown Delay Times in Pulsed Discharges

Content

In pulsed discharges with a frequency of 1 – 100 Hz the breakdown delay time, τd, has a stochastic nature. For example, in helium pulsed discharge experiments at 100 Torr, τd varies from 0.1 to 10 μs. Additionally, the mechanisms responsible for the evolution of the discharge current, jd, is still not clear. In PIC MCC simulations we consider the jd for different conditions at U=3.25 kV and 100 Torr. Various types of electron emission processes from the electrodes are considered. A wide distribution of τd was observed and analyzed.

Primary author: Dr SCHWEIGERT, Irina (The George Washington University)

Co-authors: Dr HOPKINS, Matthew (Sandia National Laboratories); Dr BARNAT, Edward; KEIDAR, Michael (George Washington University)

Presenter: Dr SCHWEIGERT, Irina (The George Washington University)

Track Classification: A1. Vacuum breakdown and pre-breakdown phenomena

B3-P1-243

Decay of vacuum arc plasma with composite CuCr cathodes after a discharge current break

Content

During the operation of vacuum interrupters, there is a problem of the electrical strength recovering of the discharge chamber after quenching the vacuum arc. An important factor affecting this characteristic is the presence of residual plasma in the discharge gap, which, in the absence or in the presence of a slowly growing electric field, retains its directional velocity and can cause electrical breakdown. In the present work, in the discharge system of the Mevva-5.Ru metal ion source, conditions typical for a vacuum switch were made, and ion-emission processes in the decaying plasma of a vacuum arc are investigated. Copper-chromium composites Cu1-xCrx (x = 0.25, 0.3, 0.5), used as electrode materials for standard current interrupters from Tavrida Electric, as well as pure copper and chromium were used as cathodes for the vacuum arc. It is shown that the decay time of the plasma of a vacuum arc discharge after its switching off is characterized by a nonmonotonic dependence on the external axial magnetic field with a maximum in the range from 0.3 to 0.4 T. This dependence is due to two competing processes: deceleration, as a result of the confinement of plasma electrons, and acceleration, with an increase in the temperature of plasma electrons, which is a consequence of an increase in the discharge voltage in an external magnetic field.

Primary author: Prof. OKS, Efim (High current electronics institute)

Co-authors: SAVKIN, Konstantin (Institute of High Current Electronics); YUSHKOV, Georgy (High Current Electronics Institute); Dr GUSHENETS, Vasily (High Current Electronics Institute); Dr BUGAEV, Alexey (High Current Electronics Institute); Dr NIKOLAEV, Alexey (High Current Electron-ics Institute); Dr FROLOVA, Valeria (High Current Electronics Institute)

Presenter: Prof. OKS, Efim (High current electronics institute)

Track Classification: B3. Vacuum arc physics

B1-P1-244

Experimental Investigation of Anode Activity between Spiral Slot Contacts

Content

When the vacuum switch breaks a large current, the strong arc energy causes a large amount of metal vapor to be sputtered from the anode, and the anode is obviously a latex. Vigorous anode activity may reduce the strength of the medium recovery at the time of current zero crossing and re-ignite the arc, which prevents the current from successfully breaking. Therefore, anode activity has an important impact on the arc interruption. In this paper, the experimental research on the anode activity of the spiral slot transverse magnetic contact was carried out. The equipment used in the experiment and the process of the experiment are introduced. The contact morphology after arc ablation was compared by scanning electron microscopy analysis. The anode ablation was analyzed in combination with the spraying of inter-electrode droplets and the arc energy during arcing. The influence of contact structure, contact material and contact diameter on anode melting and ablation was discussed. The results show that the increase of chromium content is beneficial to reduce the ablation of anode contacts in a certain range. At the same time, the increase of contact diameter reduces the arc energy density, which is also beneficial to reduce ablation.

Primary authors: YANG, JinWang (Xi'an JiaoTong University); Prof. XIU, Shixin (Xi'an Jiao-tong University); Mr QIN, Ke (Xi'an Jiaotong University); Mr WEI, Leming (Xi'an Jiaotong Univer-sity); WANG, Ting (Xi'an Jiaotong University)

Presenter: YANG, JinWang (Xi'an JiaoTong University)

Track Classification: B1. Switching in vacuum and related phenomena

B4-P3-245

Numerical Simulation of Anode Dynamic Behavior under Transverse Magnetic Field

Content

Severe anode activity may reduce the dielectric recovery strength of the interelectrode at zero current crossing and increase the possibility of arc reignition. On the other hand, arc motion between transverse magnetic field (TMF) contacts can avoid breaking failures caused by excessive ablation. Therefore, arc motion characteristics and the thermal change process in anode region have an important influence on the successful breaking of TMF contacts. In order to study the change process of anode activity during arc motion, based on the principle of conservation, an anode dynamic behavior model considering the deformation of anode surface under the action of TMF was established in this paper. In addition, heat transfer between arc and anode, movement of molten pool, deformation of free contact surface, and the complex physical processes in which the three were coupled to each other were involved in the model. The coexistence of gas, liquid and solid was considered in the model, and the fluid volume function was used to describe the anode surface morphology. Through the established model, the thermal variation of the anode region and the deformation of anode surface with development of arc motion were analyzed.

Primary authors: LONG, Zhisong (State Key Laboratory of Electrical Insulation and Power Equipment, Xi'an Jiaotong University); XIU, Shixin (State Key Laboratory of Electrical Insulation and Power Equipment, Xi'an Jiaotong University); LIU, Zhanpeng (State Key Laboratory of Electrical Insulation and Power Equipment, Xi'an Jiaotong University); CHU, Bo (State Key Laboratory of Electrical Insula-tion and Power Equipment, Xi'an Jiaotong University); WANG, Ting (State Key Laboratory of Electrical Insulation and Power Equipment, Xi'an Jiaotong University)

Presenter: LONG, Zhisong (State Key Laboratory of Electrical Insulation and Power Equipment, Xi'an Jiaotong University)

Track Classification: B4. Computer modeling and computer aided design

C3-P2-246

Some Features of the Vacuum Arc Ion Source Operation with Lanthanum Hexaboride Cathodes

Content

This paper concentrates on resent results related to the experimental studies of a vacuum arc ion source operation with a lanthanum hexaboride cathode. The lanthanum hexaboride cathode is a hot pressed rod with almost perfect density (4.65 g/cm3) and has small porosity. Lanthanum hexaboride, although it is considered as a refractory ceramic material, has a very low resistivity and a metallic type of conductivity under normal conditions. The behavior of the cathode spots on the LaB6 cathode surface is similar to the behavior of the spots on a pure metal cathode. Cathode spots along with vapors and charged particle flows emit a huge flow of hot droplets – macroparticles, as well as small cathode fragments. In results, the operation of this plasma generator as part of the ion source is accompanied by the accelerating gap breakdowns. The breakdowns occurred with a delay of several milliseconds after the vacuum arc extinction. Breakdowns are caused by the evaporation of incandescent macroparticles and the formation of dense plasma when macroparticles bombard the ion-optical system electrodes. To reduce the macroparticles flow, the plasma generator was supplemented with a direct-flow mechanical filter installed along the expansion of the cathode plasma. The field of a permanent magnet in the sunset region compensated the loss of the plasma flow on the filter. The vacuum arc source produces the 600-mA pulsed (100-300 μs) broad (4 cm in diameter) beam of boron and lanthanum ions with now gas.

Primary authors: Prof. OKS, Efim (High Current Electronics Institute of SB R AS); Dr BUGAEV, Alexey (High Current Electronics Institute); Dr GUSHENETS, Vasily (High Current Electronics Institute)

Presenter: Prof. OKS, Efim (High Current Electronics Institute of SB RAS)

Track Classification: C3. Electron, ion, neutron, X-ray and other beam and light sources

C3-P2-248

Current Characteristics of a High-Current Electron Gun with Multi-Gap Initiation of Explosive Emission by Dielectric Surface Flashover

Content

The present work is devoted to the study of current characteristics of a high-current, plasma-filled electron gun with multi-gap initiation of explosive emission by dielectric surface flashover. The initiation of explosive emission was performed using 69 operating in parallel arc plasma sources whose electrodes and tubular ceramic insulators are inserted to the disk explosive-emission cathode. Plasma anode was formed by high-current reflective (Penning) discharge or by hybrid discharge matching Penning discharge with vacuum arcs. Experiments have demonstrated good emissivity of a new cathode assembly, which is approximately 1.5–1.7 times higher than an emissiv-ity of traditional copper-braided explosive-emission cathode. Moreover, a new cathode assembly revealed much better stability of operation than traditional copper-braided cathode.

Primary authors: OZUR, Grigory (IHCE SB RAS); Mr PETROV, Vsevolod (Institute of High Cur-rent Electronics); Mr KIZIRIDI, Pavel (Institute of High Current Electronics, Siberian Branch, Russian Academy of Sciences)

Presenters: OZUR, Grigory (IHCE SB RAS); Mr PETROV, Vsevolod (Institute of High Current Elec-tronics); Mr KIZIRIDI, Pavel (Institute of High Current Electronics, Siberian Branch, Russian Academy of Sciences)

Track Classification: C3. Electron, ion, neutron, X-ray and other beam and light sources

C1-P2-249

Research on Improving the Success Rate of Synthesis Experiment Using Laser Triggered Vacuum Switch

Content

Vacuum circuit breaker plays an important role in the stable operation of power system. In order to test its breaking capacity, the synthetic circuit is generally selected for the synthetic experiment. Synthesis experiment requires high precision of sequential coordination. Mechanical actuators are generally adopted in the existing experimental circuit to control the input of large current generated by the current source. However, due to the accuracy of the mechanism itself, the probability of successful synthesis to meet the requirements of the IEC standard is not high, useless data are obtained, and the service life of the experimental device is wasted. To solve above problems, this paper proposes a method of using laser triggered vacuum switch instead of mechanical actuators as high current input switch. A large number of statistical studies were made on the conduction characteristics of laser triggered vacuum switches. And the comparison between the two methods was made in the experimental circuit. The results show that the experimental group using laser triggered vacuum switch can greatly improve the success rate of the synthesis experiment. The research results provide guidance for the improvement of the synthetic circuit and improve the success rate of synthetic experiment.

Primary authors: Ms TIAN, Shuyun (Wuhan NARI Limited Liability Company,State Grid Electric Power Research Institute); Dr FU, Yifan (Dalian University of Technology); Dr ZHANG, Hao (Dalian University of Technology); Prof. LIAO, Minfu (Dalian University of Technology); Mr CAI, Wei (Wuhan NARI Limited Liability Company,State Grid Electric Power Research Institute); CHENG, Lin (Wuhan NARI Limited Liability Company,State Grid Electric Power Research Institute); Mr ZHANG, Jie (Wuhan NARI Limited Liability Company,State Grid Electric Power Research Institute)

Presenter: Dr FU, Yifan (Dalian University of Technology)

Track Classification: C1. Vacuum interrupters and their applications

B1-P1-251

Experimental Research on DC Interruption Characteristics of Vacuum Interrupter by Forced Current Zero

Content

In the DC grid, the fault current rises very fast due to low impedance. Fast DC circuit breakers are needed to isolate faults and avoid a collapse of the common DC grid voltage. Based on the forced current zero technology, the vacuum interrupter equipped with fast electromagnetic repulsion mechanism is a very promising solution of fast DC interruption. This paper presents experimental research work on DC interruption characteristics of a vacuum interrupter. The post arc current and transient interruption voltage (TIV) are measured with a current zero (CZ) diagnostic system. The influence of the breaking current, di/dt and du/dt at CZ, gap distance on the post current have been analyzed.

Primary authors: TANG, Qiang (Xi'an Jiao Tong University); Prof. JIA, Shenli; Prof. SHI, Zongqian

Presenter: TANG, Qiang (Xi'an Jiao Tong University)

Track Classification: B1. Switching in vacuum and related phenomena

A1-P3-252

Study of Electron Emission Characteristics Based on Fractal Micro-Protrusions on Electrode Surface

Content

It is widely known that electron emission is one of key initiation factors of vacuum breakdown. The electron emission characteristics are considered to be related to many factors, such as micro-protrusions shape, material properties and temperature distribution. The objective of this paper is to study the emission characteristics based on fractal micro-protrusions by considering both thermal emission and field electron emission. First, the micro-protrusions on the electrode surface are modeled based on Weirstrass-Mandelbrot (W-M) fractal function. Then, the microscopic electric field distributions of the micro-protrusions are simulated by finite-element method under the typical voltages. Furthermore, the time-dependent current density and temperature distribution caused by resistance heating on the micro-protrusions are calculated iteratively with considering both thermal emission and field emission. Finally, the calculated results are compared with the results based on the traditional Fowler-Nordheim (FN) equation. The results of this paper may provide some useful information to study the vacuum breakdown initiated by electron emission.

Primary authors: Prof. ZHANG, Yingyao (Tongji University); Mr WANG, Haoyu (Tongji Univer-sity); Ms DAI, Decun (Tongji University); Mr YU, Hao (Tongji University); Prof. JIN, Lijun (Tongji University); Prof. LANG, Chenglian (Tongji University)

Presenter: Mr WANG, Haoyu (Tongji University)

Track Classification: A1. Vacuum breakdown and pre-breakdown phenomena

A1-O7-253

Temperature Distribution of Cathode Micro-protrusion Based on Smoothed Particle Hydrodynamics Method

Content

In this paper, Smoothed Particle Hydrodynamics (SPH) method is introduced into the study of the temperature distribution of the cathode micro-protrusion with the resistive heating caused by the emission current. Firstly, the partial differential governing equations for hydrodynamics with material strength are established. Then, the kernel approximation is used to approximate the field function in the partial differential equations, and the particle approximation is used to discretize the kernel approximation equations in order to obtain a series of SPH governing equations. At the same time, the thermodynamic equations are introduced into the SPH method. Based on the source code of SPH method, the mathematical model of cathode micro-protrusion is established. The SPH equations are solved by using the explicit integration method. The temperature distribution of cathode micro-protrusion with different field emission current Joule heat are simulated. The results can provide theoretical guidance for the quantitative study of the physical mechanism of vacuum discharge induced by field emission.

Primary authors: Prof. ZHANG, Yingyao (Tongji University); Ms DAI, Decun (Tongji Univer-sity); Mr WANG, Haoyu (Tongji University); Mr YU, Hao (Tongji University); Prof. JIN, Lijun (Tongji University); Prof. QIAN, Xuejun (Tongji University)

Presenter: Ms DAI, Decun (Tongji University)

Track Classification: A1. Vacuum breakdown and pre-breakdown phenomena

B4-P3-254

Kinetics of Pulsed Anodic Ion Flow in Low-Pressure Gas Discharge with Initiation by Electron Beam

Content

It has long been known that a flow of positive ions is observed in vacuum arcs. Not only do positively charged particles fly against the direction of electrostatic force, but their kinetic energy is significantly higher than the anode voltage of the arc discharge. This effect, unexpected for the first researchers, still does not have a generally accepted explanation. We can mention, for example, two alternative hypotheses such as the presence of a “hump of electric potential” in the gap and the acceleration of ions by an “electron wind”. This paper presents the original simulating results of a new electro kinetic mechanism of ion accel-eration due to the transient dynamics of the electric potential during breakdown in a low-pressure gas. The theoretical model of low-pressure gas breakdown is based on solving a system of one-dimensional Boltzmann equations for electrons and positive ions. The electric field is calculated from Poisson equations self-consistently with the kinetics of charged particles. The simulation allows us to follow in detail the evolution of the distribution function of both electrons and ions during the development of the discharge at fore-vacuum gas pressures. Simulation showed that at some stage local regions with the opposite direction of the field strength vector may appear inside the gap, and in these regions anode-directed ion flows are generated. Ion flow to the anode can occur even in a one-dimensional formulation of the kinetic problem, and one reason for their emergence is the non-monotonic distribution of the electric potential during transient mode of breakdown development. It should be noted that the kinetic equation approach, in contrast to that of describing hydrodynamic plasma, describes such situations in a natural and consistent way.

Primary authors: Prof. KOZYREV, Andrey (Institute of High Current Electronics); Prof. KOZHEVNIKOV, Vasily (Institute of High-Current Electronics.); Mrs SEMENIUK, Natalia (Institute of High-Current Elec-tronics)

Presenter: Prof. KOZYREV, Andrey (Institute of High Current Electronics)

Track Classification: B4. Computer modeling and computer aided design

A1-P1-255

Anode Material Adhesion to Cathode during Spark Conditioning Process in Vacuum

Content

This research aims to optimize the conditioning effect in vacuum for the application of vacuum circuit breakers (VCBs) in higher voltage levels. Basically, in the conditioning process, defects on cathode surface are removed by repetitive BDs (Breakdowns). However, at the same time, micro-protrusions can be generated on the cathode surface by the adhesion of melted particles of anode material. In the conditioning process, since the cathode surface condition extremely influences the initiation of BD, the adhesion of the anode material to the cathode may dominate the conditioning characteristics. For this purpose, the anode material adhesion to cathode during conditioning process is discussed in this paper from experimental approach.

We set rod-plane electrodes in a vacuum chamber. We used two electrode systems: rod (made of OFHC Cu)-plane (made of stainless steel) and rod (made stainless steel)-plane (made of OFHC Cu) electrode system. The gap distance was 1 mm, and the tip radius of the rod electrode was 2 mm. We applied negative impulse voltage to the rod electrode and conducted spark conditioning with up-down method. BD charge, which corresponds to discharge energy at BD, was controlled by limiting resistors of impulse generator circuit. In order to verify the adhesion state of the anode material, we conducted conditioning experiment on some pairs of electrodes. To one pair, the voltage was applied until the conditioning saturation. To the others, smaller number of voltages before conditioning saturation was applied. After that, we observed the surface of rod cathodes with a digital microscope.

When the voltage was applied until the conditioning saturation, the anode material was adhered to the surface of the cathode during the conditioning process, since the surface condition of the cathode has changed from the original color of the cathode material to the color of the anode material. In particular, protrusion-like adhesion was obviously confirmed. In contrast, when the voltage was applied with the smaller number than that for the saturation, no protrusions were observed, but the color of the cathode surface has changed to the color of the anode material in a coat-like adhesion. These similar results were confirmed for the different combinations of the cathode and anode materials for two electrode systems.

From the above results, it is considered that coat-like adhesion mainly occurred up to the saturation voltage, and then protrusion-like adhesion occurred due to BD at the saturation voltage level. These experimental results suggest that the protrusion-like adhesion of the anode material on the cathode surface could be a dominant factor of conditioning saturation in vacuum.

Primary author: KITA, Naoki

Co-authors: KOJIMA, Hiroki; FUKUDA, Hideaki; SAKAKI, Masayuki; HAYAKAWA, Naoki

Presenter: KITA, Naoki

Track Classification: A1. Vacuum breakdown and pre-breakdown phenomena

B4-P1_O10-256

Numerical Simulation of Transient Vacuum Arc with Active Anode Modes

Content

This work investigates the transient arc behaviors during the anode spot mode with CuCr25 electrodes. In this simulation, a 2D transient magneto-hydro-dynamic (MHD) model considering multi-components is used to calculate the arc parameters. Then the energy flux is obtained to calculate the anode temperature which is set as the temperature boundary condition of the anode side in the MHD model in next time step. Simulation results show that most conclusions are similar with those given in our previous steady model. As for the transient process, when the anode tempera-ture is lower than 1500K, the anode vapor can hardly be seen since its density is very lower. When the anode temperature is higher, the anode vapor density increases significantly. As a result, ions from the cathode are decelerated by the anode vapor when they arrive at the ionization layer, lead-ing to high ion temperature here. Then the arc current are more likely to flow to the edge of the atom vapor area instead of the anode center. Thus, the energy flux to the anode begins to heat the area around the anode spot, leading to a uniform anode temperature distribution and a larger anode spot. The maximum anode temperature occurs after the peak current due to the thermal in-ertia. Then the anode temperature begins to decrease and remains uniform. The simulation results are consistent with the experimental results.

Primary authors: YANG, Ze; WANG, Lijun (Xi'an Jiaotong University); Mr LUO, Ming (Xi'an Jiaotong University); Mr ZHANG, Zhefeng (State Key Laboratory of Electrical Insulation and Power Equipment); Mr JIANG, Jing (Xi'an Jiaotong University); JIA, Shenli (Xi'an Jiaotong University); GORTSCHAKOW, Sergey (Leibniz institute for plasma science and technology); Prof. UHRLANDT, Dirk (Leibniz Institute for Plasma Science and Technology (INP))

Presenter: YANG, Ze

Track Classification: B4. Computer modeling and computer aided design

B3-O2-257

Properties of Droplets Emitted from Vacuum Arc Cathodes Made of Copper, Tungsten and Titanium

Content

Molten droplets emitted from the cathode of vacuum arcs have been investigated by using a time-of-flight set-up along a vertical flight tube equipped with two light barriers at different distances from the cathode surface. The light scattered by particles passing the light barriers cross section was registered. The velocity was determined by the flight-time. Simultaneously, from the amount of the scattered light, the size of the passing particle was inferred applying the Mie-scattering theory. As the arrangement of the cathode could be oriented differently with respect to the flight tube, a coarse angular distribution of the parameters was obtained covering the range from almost parallel to the cathode surface (2…5°) to perpendicular. This paper extends the results presented in our former publication on copper cathodes [1] with new investigation of particles emitted by arcs on tungsten and titanium cathodes. The multi-spot arcs carry currents from 0.1kA up to 1kA maximum for a fixed duration of about 1ms. Several ten-thousand discharges have been carried out on the various cathodes at some ten different angular positions. Because of the large amount of data, electronic processing by newly developed algo-rithms was required to identify and characterize the several tens of thousands of particle peaks. As expected, the behavior of the particles emitted from the cathodes made of different materials exhibits similarities as well as differences. The number of particles per discharge depends strongly on the cathode material and varies remarkably with the angle between flight direction and cathode surface. Generally, smaller particles were found to have higher velocities and vice versa. However, a few large particles were recorded having unexpectedly high velocities. Regarding all cathode materials, several particles were observed flying close to the normal direction with respect to the cathode surface. The distribution of the particle sizes follows an exponential law restricted at small and large values by a detection limit and the statistics, respectively. The distribution of the emis-sion velocities exhibits more than one local maximum pointing to distinct particle populations having distinct typical velocities. These populations contribute differently to the overall amount of particles at various angles. The observations could be attributed to a complex size-dependent re-organization of the particle velocities possibly induced by a supplemental interaction of the fly-ing particles with the embedding cloud of arc plasma.

[1] Siemroth P., Laux M., Pursch H., Sachtleben J., Balden M., Rohde V., Neu R., IEEE Trans. Plasma Sci., 47 (2019), pp. 3470-3477

Primary authors: Dr SIEMROTH, Peter (retired from Arc Precision GmbH); Dr PURSCH, Heinz (retired from Arc Precision GmbH); Dr LAUX, Michael (ret. from Arc Precision GmbH); Mr SACHTLEBEN, Juergen (ret. from Arc Precision GmbH); Dr BALDEN, Martin (Max-Planck-Institut für Plasmaphysik, Garching); Dr ROHDE, Volker (Max-Planck-Institut für Plasmaphysik, Garching); Prof. NEU, Rudolf (Max-Planck-Institut für Plasmaphysik, Garching, Technische Universität München)

Presenter: Dr SIEMROTH, Peter (retired from Arc Precision GmbH)

Track Classification: B3. Vacuum arc physics

C2-P2-258

The Formation of Field-Induced Emission Structures on the Nanostructured Tungsten Surface

Content

Abstract. The tungsten surface coated with nano fuzz subjected by an electrical field was investigated. To measure the field emission properties of the non-excited tungsten, surface the extremely low current measurement procedure was developed. Point anode was used, with electrode gap about 0.4 – 0.8 mm. The slow rising of the electrical field in some cases led to avalanche-like emission current amplification that in turn led to the breakdown. The current amplification waveforms suggest that emission structures are formed on the cathode surface. The field-induced emission structures time was in the range of 10-100 s. The emission pictures on a phosphor screen and emission current waveforms suggest that during avalanche-like emission current rise several emission structures could be formed.

Primary authors: Dr LVOVICH MUZYUKIN, Ilya (Institute of Electrophysics UB RAS); MIKHAILOV, Pavel (The Institute of Electrophysics of the Ural Division of the Rus)

Presenter: MIKHAILOV, Pavel (The Institute of Electrophysics of the Ural Division of the Rus)

Track Classification: C2. Surface modification and related technologies

B3-P1-259

Measurements of the radiation power of a high-current vacuum arc at high current densities

Content

The radiation of a vacuum (p ~ 10-3Pa) arc was measured in the visible and ultraviolet spectral regions (200nm≤λ≤800nm). The arc burned on CuCr30 electrodes 30 mm in diameter with an interelectrode distance of 4 mm. The arc was ignited in the center of the cathode by breaking the current in the auxiliary circuit. The arc was powered by a current pulse with a duration of 10 ms in a nearly rectangular shape. The arc was stabilized by a uniform axial magnetic field (B≤0.45T), which was generated by a pair of Helmholtz coils, put on a vacuum chamber. Radiation was removed through one of the side windows of the vacuum chamber. The window was made of KU-1 quartz. The radiation detector was a silicon photodiode 1.2 mm in diameter located outside the vacuum chamber on an axis intersecting the axis of symmetry of the discharge at the center of the interelectrode gap. The signal from the photodiode was taken through an amplifier with a conversion factor of 1360V/A and recorded on an oscilloscope. The measurements were made in a wide range of currents from 10kA to 25kA, which corresponds to a current density in the developed discharge of 1.5kA/cm2≤j≤3.5kA/cm2. Considering the type of the spectral sensitivity of the diode, two series of measurements were made - measurements without a filter and through a ZhS-10 filter that cuts off radiation with λ≤400nm. The results obtained made it possible to analyze the dependence of the radiation power on the arc current at different stages of its development. The results showed that at high current densities in the developed vacuum arc with anodic activity, a significant part of the power is transferred by radiation.

Primary authors: Mr BARINOV , Yuriy (Ioffe I nstitute); ZABELLO, K onstantin; Mr LOGACHEV , Alexander (Ioffe Institute); Ms POLUYANOVA , Irina (Switchgear design bureau LTD); Mr SHERSTNEV, E (Ioffe Institute); Mr SHKOL'NIK, Sergey (Ioffe Institute)

Presenter: ZABELLO, Konstantin

Track Classification: B3. Vacuum arc physics

B1-P1-261

Influence of Different External Magnetic Field Applied Time on the Dynamic Voltage Distribution of Double-break Vacuum Gaps in Series

Content

External magnetic field configurations have an important effect on the dynamic voltage distribution of vacuum circuit breakers (VCBs) in series, but few works pay attention to it so far. The objective of this paper is to study the dynamic voltage distribution of VCBs with different exter-nal magnetic field (EMF) applied time. The simulation model of integrated vacuum chamber was built up. The capacitances of each break and stray capacitance were calculated. The test platform was set up based on integrated vacuum chamber. The dynamic voltage distributions of VCBs with different EMFs applied time were studied and analyzed. The test results prove that, different EMF applied time on two series breaks can improve the voltage distribution uniformity. When the magnetic field applied time of the upper break is fixed, the dynamic voltage distribution improved with the applied time of lower magnetic field approaching the current zero point. The works in this paper provide references for magnetic field regulation and optimization design of the series vacuum switch of multi-break VCBs.

Primary authors: Dr FU, Yifan (Dalian University of Technology); Prof. DUAN, Xiongying (Dalian University of Technology); Dr ZHANG, Hao (Dalian University of Technology); Mr ZHANG, Minjun (Dalian University of Technology); Mr MA, Xinming (Dalian University of Technology); Mr DONG, Huaqing (Dalian University of Technology); Prof. LIAO, Minfu (Dalian University of Technol-ogy)

Presenter: Dr FU, Yifan (Dalian University of Technology)

Track Classification: B1. Switching in vacuum and related phenomena

B3-P1-262

2D Kinetic Simulation of Current-Carrying Plasma Expansion

Content

A two-dimensional kinetic simulation of the expansion of the current-carrying plasma of the cathode spot of a vacuum arc is carried out. The modeling was performed by Particle-in-Cell and Direct Simulation Monte Carlo methods. The processes of ionization and recombination and Coulomb scattering were taken into account. Two fundamentally different solutions are demonstrated for an expanding plasma in an external electric field, but in contrast to [1] in a two-dimensional version. The first solution is a “quiet” expansion of the plasma at a relatively low flowing current. In which only ion-acoustic current instabilities arise, which do not lead to catastrophic consequences. In this regime, the plasma expands at a speed of ~ 10^6 cm/s, the electron temperature of the plasma reaches 5 eV, and the average charge state of ions (Cu) is ~ 2. In the second case, the current is large enough to excite the Buneman instability, after which the plasma plume decays and ions with relatively high energies scatter towards the anode and cathode.

[1] D.L. Shmelev, S.A. Barengolts and M.M. Tsventoukh, “Numerical Simulation of Plasma Near the Cathode Spot of Vacuum Arc,” IEEE Trans. Plasma Sci., vol. 45, no. 11, pp. 3046-3053, Nov. 2017, doi: 10.1109/TPS.2017.2754541.

Primary author: Dr SHMELEV, Dmitry (Institute of Electrophysics UB RAS)

Co-authors: BARENGOLTS, Sergey (Prohorov General Physics Institute RAS); TSVENTOUKH, Mikhail (Lebedev Physical Institute RAS); UIMANOV, Igor (Institute of Electrophysica UB RAS)

Presenter: Dr SHMELEV, Dmitry (Institute of Electrophysics UB RAS)

Track Classification: B3. Vacuum arc physics

B2-P3-263

Modeling of Effect of Axial Magnetic Field on Deuterium Ionization in Vacuum Arc on Deuterium-Saturated Cathode

Content

Among other things, a vacuum-arc discharge is used in neutron tubes to generate neutrons [1]. Vacuum neutron tubes are a miniature vacuum arc ion source with a cathode saturated with deuterium whose ions are accelerated in an ion optical system to form a beam, when the beam interacts with a target containing deuterium atoms, a neutron flux is produced. Neutron tubes are used for well logging. In this work, we study some issues of the generation of deuterium ions during the combustion of a vacuum arc on a deuterium-saturated zirconium cathode. Using numerical simulation, the effect of a axial external magnetic field on the dissociation and ionization of deuterium near the plasma jet of a group spot on a deuterium-saturated zirconium cathode was studied. The simulation was carried out using a hybrid model of type [2], in which the electronic subsystem is treated as a massless liquid, while ions, atoms and molecules are treated as macroparticles with the help of Particle-in-Cell and Direct Simulation Monte Carlo methods. It is shown that an increase in the axial magnetic field leads to a noticeable increase in the degree of hydrogen ionization only in the immediate vicinity of the plasma jet of the vacuum arc. The simulation results are compared with preliminary experimental results.

[1] A. A. Bitulev, S. V. Churin, N. N. Shchitov, D. I. Yurkov, S. G. Kladko, S. P. Maslennikov, D. S. Stepanov, and E. Y. Shkolnikov, “Increasing the Efficiency of Ion Sources of Vacuum Neutron Tubes,” At. Energy, vol. 118, pp. 354–359, September 2015.
[2] D. L. Shmelev, V. I. Oreshkin and I. V. Uimanov, “Hybrid Numerical Simulation of High-Current Vacuum Arc Taking Into Account Secondary Plasma Generation,” IEEE Trans. Plasma Sci., vol. 47, pp. 3478-3483, 2019, doi: 10.1109/TPS.2019.2905624.

Primary author: SHMELEV, Dmitry (Institute of Electrophysics UB RAS)

Co-authors: BARENGOLTS, Sergey (Prohorov General Physics Institute RAS); UIMANOV, Igor (Institute of Electrophysica UB RAS); Dr FROLOVA, Valeria (High Current Electronics Institute)

Presenter: SHMELEV, Dmitry (Institute of Electrophysics UB RAS)

Track Classification: B2. Interaction of vacuum arcs with magnetic fields

B1-O1-264

Neutral Atom Density at Current Zero in Interruption of Intense-Mode Vacuum Arc

Content

A large number of vacuum circuit breakers (VCBs) are installed in medium-voltage-class AC networks. Improvement of interruption capacities of the VCBs is required for the application to high-voltage (HV) AC networks as SF6-free current breaking device. The current interruption capabilities of the VCBs are highly dependent on plasma parameters such as a neutral atom density. Measuring such plasma parameters and elucidating the vacuum arc phenomena occurring in the vacuum gap is indispensable for the development of HV-VCBs. In the interruption phase of an intense-mode vacuum arc discharge, interruption failure at current zero occurs due to the ionization of neutral atoms evaporating from the anode surface, and clarifying the critical density for current interruption is essential. However, the measurement of the neutral atom density distributions is extremely difficult for conventional sensors due to the spatial non-reproducibility of the vacuum arc. This paper aims to find the critical neutral atom density for the success and failure of the current interruption. The electrodes are axial magnetic field types with a 6-mm diameter and their compositions are CuCr (Cr: 50wt%). The 50-Hz half-wave sinusoidal current is injected to a 4.5 mm-gap and the transient recovery voltage with a peak value of 25 kV is applied to the vacuum gap after current zero. The success or failure of the current interruption is controlled by varying the interruption current value; the current values for interruption success and failure are 2 kArms and 4 kArms, respectively. The neutral atom density distributions are measured by the Shack-Hartmann type laser wavefront sensors at about 20 μs before the current zero and the instantaneous current value is about 300 A. The critical neutral atom density as a determinant fac-tor for the interruption success or failure is discussed based on the comprehensive experimental results.

Primary author: Mr KIKUCHI, Ryo (The University of Tokyo)

Co-authors: Mr HIRANO, Yuichi (The University of T okyo); Mr EJIRI, Haruki (The University of Tokyo); Prof. INADA, Yuki (Saitama university); Prof. KUMADA, Akiko (The University of Tokyo); Prof. HIDAKA, Kunihiko (The University of T okyo); DAIBO, Akira (Toshiba Infrastructure Systems & So-lusions Corporation); Dr NIWA, Yoshimitsu (Toshiba Infrastructure Systems & Solutions Corpora-tion); Mr SASAKI, Yo (Toshiba Infrastructure Systems & Solutions Corporation); KONDO, Junichi (Toshiba Infrastructure Systems & Solutions Corporation); Mr ASARI, Naoki (Toshiba Infrastructure Systems & Solutions Corporation)

Presenter: Mr KIKUCHI, Ryo (The University of Tokyo)

Track Classification: B1. Switching in vacuum and related phenomena

A1-P3-265

Electrical Properties of He-induced W "fuzz" within the Pre-breakdown and Breakdown Regimes

Content

In the work presented, the investigation of the He-induced W “fuzz” electrical properties was carried out. The W “fuzz” sample was manufactured in an analogous way as the one described in [1]. For this research, an automated experimental setup was designed. The setup was based on a vacuum chamber operated under high vacuum condition (~10⁻⁷ Pa). The vac-uum diode under investigation comprised of a flat W “fuzz” field-emissive cathode with an area of about 1 cm² and a 2 mm radius cylindrical copper anode rounded with a 2 mm radius hemisphere. The cathode-anode distance was about 200 μm. A voltage applied to the diode was up to 10 kV. An HV power supply was controlled employing the DAC/ADC module “L Card E20-10” (https://en.lcard.ru/products/external/e20-10). This module allowed one to register automatically currents and voltages of interest also. As a result of the investigation, the data on the dielectrical strength of the vacuum diode with the W “fuzz” cathode were obtained. The effect of the cathode conditioning was demonstrated after the number of breakdowns. An increase in the breakdown electric field strength from about 4·10⁵ V/cm for the very first breakdown up to 9·10⁵ V/cm for the 20th breakdown was registered. In addition, the emissive characteristics of the W “fuzz” cathode were studied in accordance with the Fowler-Nordheim theory. Under the conditions described, the field-emissive current didn’t exceed several microamperes. The estimated value of the electric field enhancement factor β was found to be about 40 before the breakdown and about 70 after the breakdown. The obtained β values are somewhat smaller than the ones obtained by other research groups for the nanostructured W cathodes [2,3]. This fact should be investigated additionally.

[1] O.V. Ogorodnikova, et.al. “Deuterium and helium retention in W with and without He-induced W ‘fuzz’ exposed to pulsed high-temperature deuterium plasma,” J. of Nuclear Materials, vol. 515, pp. 150 159, 2019.

[2] D. Hwangbo, Sh. Kajita, N. Ohno, and D. Sinelnikov, “Field Emission From Metal Surfaces Irradiated With Helium Plasmas,” IEEE TPS, vol. 45, pp. 2080-2086, 2017.

[3] D. Sinelnikov, et.al. “Arc tracks on nanostructured surfaces after microbreakdowns,” J. of Phys.: Conf. Ser., vol. 748, 012012, 2016.

Primary authors: Mr MAMONTOV, Yuriy (Institute of Electrophysics UB RAS); ZEMSKOV, Yury (Institute of Electrophysics, Ural Branch, Russian Academy of Sciences); UIMANOV, Igor (Institute of Electrophysics UB RAS)

Presenter: Mr MAMONTOV, Yuriy (Institute of Electrophysics UB RAS)

Track Classification: A1. Vacuum breakdown and pre-breakdown phenomena

C1-P1-268

Characterization of the breakdown voltage of vacuum interrupters by different procedures

Content

This work compares three different procedures for the application of the Lightning Impulse Voltage Waveform (LIVW) with 1.2/50 μs front/half value times: Up & Down (UD), Always Breakdown (AwBD) and Multilevel (ML) to obtain the voltage breakdown distribution for Vacuum Interrupters (VIs). The voltage pulses were applied to several VIs for medium voltage application with both fixed and floating shield with gap lengths ranging from 4mm to 15mm. The repeatability of the results for a given procedure was investigated and the results compared. The AwBD procedure, where the peak voltage of each pulse is set and kept at the same arbitrary high level to collect a breakdown for each pulse, was thoroughly investigated. This procedure is effective to collect data on many breakdowns very quickly, due to both the speed of the voltage conditioning phase and because breakdown data are collected for each pulse. Furthermore, the memory effect due to the status of the previous pulse (BD or withstand pulse) is reset due to the random distribution of surface microprotrusions produced by the arcing occurrence at each pulse. In contrast, for the ML procedure the status of the ith-pulse depends on the status of the i-1th-pulse. On the other hand, the AwBD procedure showed a dependency of the breakdown voltage distribution curves on the set peak voltage applied. This phenomenon has been investigated and might be explained by a delay time between the breakdown onset and the voltage collapse on the rising front of the pulse, where the slope (dV/dt) of the LIVW depends on the chosen set peak voltage. However, the results suggested that after having identified the proper delay time, the results can be corrected providing a similar breakdown voltage distribution independent on the set voltage and close to that obtained with the UD procedure.

Primary author: PATTON, Tommaso (Consorzio RFX)

Co-authors: Mr LAWALL, Andreas (Siemens AG); D TAYLOR, Erik; Dr GOBBO , Renato (Diparti-mento di Ingegneria Industriale, Universit di Padova, 35131 Padova, Italy); BETTINI, paolo (Universit di Padova); MARCONATO, Nicolò (Consorzio RFX - Università di Padova)

Presenter: D TAYLOR, Erik

Track Classification: C1. Vacuum interrupters and their applications

B4-P3-269

Application of the Voltage Holding Prediction Model to floating and fixed shield vacuum interrupters

Content

The Voltage Holding Prediction Model (VHPM) is a design technique formulated at Consorzio RFX that combines numerical modelling and experimental data in order to calculate a breakdown probability curve. The cuve is based on the two parameters Weibull distribution for any multi-electrode multi-voltage vacuum insulated system under dc voltage. The progresses in employing the VHPM to predict the Lightning Impulse Voltage Waveform (LIVW) breakdown probability of medium voltage Vacuum Interrupter (VI) are the subject of the present contribution. A new experimental campaign on two Siemens VI models have been carried out at the high voltage laboratory of the Industrial Engineering Department of the Padua University. The use of a convenient methodology of experimental data acctual, called Always Breakdown method, allowed to improve the quality of the data obtaining a well fitted Weibull distribution of the voltage breakdown. This topic is described in detail in another contribution. The analysis of the two different VI models, with different key features, allowed a better under-standing of the ability of the VHPM to describe different physical arrangements and explain the resulting breakdown behavior. This contribution describes the analyses carried out on the two models, in different conditions such as electrodes gap, polarity and maximum applied LIVW volt-age, with the Weibull shape and scale parameters (m and W0) calculated by fitting the experimental data for the two tube models, in order to assess the prediction capability of the proposed method. Reason of measurement-prediction discrepancy is supposed to be sought in an arc onset-peak voltage delay time affecting the correct interpretation of the experimental measurements used to estimate m and W0. Preliminary analysis on this specific topic, as well as an assessment of the influence of the parameters adopted in the physical model are also described.

Primary authors: MARCONATO, Nicol (Consorzio RFX - Universit di Padova); PATTON, Tom-maso (Consorzio RFX)

Co-authors: BETTINI, paolo (Universit di Padova); DE LORENZI, Antonio (Consorzio RFX); Dr GOBBO , Renato (Dipartimento di Ingegneria Industriale, Universit di Padova, 35131 Padova, Italy); Mr LAWALL, Andreas (Siemens AG); D TAYLOR, Erik

Presenter: MARCONATO, Nicolò (Consorzio RFX - Università di Padova)

Track Classification: B4. Computer modeling and computer aided design

B1-P1-270

Contact Heating under Back-to-Back and Single Capacitor Inrush Current Arcs

Content

The restrike probability of vacuum interrupters during capacitive switching is in a wide sense related to the inrush current during energizing of a capacitor because of the associated contact erosion, melting and solidification, and subsequent rupture of possible welds. However, a simple relation is difficult to prove because of the random and rare occurrence of restrikes. Inrush currents of switched capacitors exhibit a wide range of peak values and frequencies. The inrush current of single capacitor banks is in the range of several kA at 400 Hz or less, whereas that of capacitors switched back-to-back are up to 20kA with frequencies around 4000 Hz. Peak inrush current and frequency determine the arc appearance. However, most experiments investigate capacitive switching on single capacitor banks. The question therefore arises whether these experiments give representative results for all possible combinations of inrush current parameters.
The current density of the pre-arc is decisive for the heating of the contact surface under the arc root. It can be evaluated from the pre-arc plasma diameter recorded by a high-speed camera. It is observed that for the low frequency arc at single bank switching, the arc spreads out with the speed of cathode spots. For the high frequency arc at back-to-back capacitor switching, the plasma expands with much higher speeds. With the time dependent current density of the pre-arc and an assumption for the arc voltage, the temperature of the contact surface at the point of preignition can be calculated. Though the temporal development of current densities and heating energies at back-to-back switching differs considerably from that at single capacitor switching, the obtained surface temperatures are in the same range.

Primary authors: Dr DULLNI, Edgar (Engineer); Dr GENTSCH, Dietmar; Mr CHEERLA, Srinivasa (Engineer)

Presenters: Dr DULLNI, Edgar (Engineer); Dr GENTSCH, Dietmar

Track Classification: B1. Switching in vacuum and related phenomena

B3-O8-271

Streak image observations of vacuum arc spots in a magnetically steered arc plasma source

Content

The physics of vacuum arc spot operation remains subject of research due to difficulties associated with short characteristic times (ns to μs) and short length scales (μm or even smaller). The advancement of modern plasma diagnostic technologies may allow us to probe arc spot plasma with higher spatial and temporal resolution than before. In this contribution, we report about of the ignition and evolution of arc spots using a steered arc plasma source which is in its construc-tion similar to a linear sputtering magnetron: the E × B field is utilized to have some control of spot locations while performing the study. Optical emission from arc spot plasma is investigated for different conditions including type of cathode material, background pressure, pulse width, and current. The main plasma diagnostics tool we employ is a streak camera with an image intensifier which allows us to observe the dynamics of arc spots and sub-cells, if present. We report on preliminary results, focus on the concept but also stress the limitations of the approach which are, apart from technical issues related to the stochastic nature of the phenomena, routed in the finite probability of spontaneous emission. This suggest that future methods may have to use external light sources.

Primary author: Mr OH, Kyunghwan (Leibniz-Institute of Surface Engineering)

Co-authors: Dr KALANOV, Dmitry (Leibniz-Institute of Surface Engineering); Prof. ANDERS, André (Leibniz-Institute of Surface Engineering)

Presenter: Mr OH, Kyunghwan (Leibniz-Institute of Surface Engineering)

Track Classification: B3. Vacuum arc physics

A1-P3-273

Prestrike Characteristics of Double-Break Vacuum Circuit Breakers with Asynchronous closing operations under DC Voltages

Content

The prestrike phenomenon in double-break vacuum circuit breakers (VCBs) is complex but significative. Previous studies mainly focused on the prestrike phenomenon in double-break VCBs with synchronous closing operations. However, experimental work on prestrike characteristics of double-break VCBs with asynchronous closing operations cannot be found in literatures. This paper aims to experimentally investigate the probabilistic characteristics of prestrike gaps, prestrike voltage distributions and prestrike electric field strengths in double-break VCBs consisting of two commercial vacuum interrupters (VIs) in series with asynchronous closing operations under direct current (DC) voltages. Four groups of closing operation tests were carried out, including the synchronous closing operation of two VIs, 1ms faster of the low-voltage side VI, 0.5ms faster of the high-voltage side VI, and 0.2ms faster of the high-voltage side VI. The experimental results show that the 50% prestrike gap d₅₀, the 50% prestrike voltage U₅₀ and 50% prestrike electric field strength E₅₀ of each VI in double-break VCBs, which is calculated by the Weibull distribution. Scatters in prestrike gaps of each VI in a double break in the case of 0.2ms faster of the high-voltage side VI were smaller than that in the case of synchronous closing operations because of the voltage-sharing effect in the double-break VCB. The Weibull distributions of prestrike voltage and prestrike electric field strength under different conditions show that asynchronous breakdown of double-break VCBs has the effect of changing the partial voltage ratio of double break.

Primary authors: CHEN, Xinggui (Xi'an Jiaotong University); GENG, Yun (Xi'an Jiaotong University); YAO, Xiaofei (School of Electrical Engineering, Xi'an Jiaotong University); ZHANG, Luyang (Xi'an Jiaotong University); HUANG, Jincai (Xi'an Jiaotong University); LIU, Zhiyuan (School of Elec-trical Engineering, Xi'an Jiaotong University); GENG, Yingsan (Xi'an Jiaotong University); WANG, Jianhua (Xi'an Jiaotong University)

Presenter: CHEN, Xinggui (Xi'an Jiaotong University)

Track Classification: A1. Vacuum breakdown and pre-breakdown phenomena

B2-P3-274

Simulation of Cathode-Spot on Hydrogen Titanium Cathode with Various Impregnation Degree

Content

In this paper, the formation process of single cathode spot arc crater on hydrogen titanium cath-ode is simulated. The influence of impregnation degree (the amount of H per metal atom) on the formation and development of crater is studied by controlling variable method. In this model, the hydrogen diffusion in cathode is calculated, and the deformation of cathode metal is simulated by hydrodynamic model. The components considered in the model include electrons, Ti atoms, H atoms, Ti ions (Ti1+, Ti2+ and Ti3+) and H+ ions. The simulation results indicate that impregna-tion degree has a great effect on the cathode spot process. On pure titanium cathode, the mean charge state is larger but on hydrogen titanium cathode, the total ion number density is larger since there are additional hydrogen ions. Low impregnated hydrogen (the impregnation degree is less than 1) can reduce the cathode surface temperature and ablation. With the increase of impreg-nation degree, the electron temperature in the arc region and the average charge state of titanium decreases and the ionization rate of evaporated and escaped atoms also decrease. At the same time, the craters become smaller. Simulation results are in agreement with the other researchers' works.

Primary authors: LI, Jiagang (Xi'an Jiaotong University); WANG, Lijun; ZHANG, Xiao

Presenter: LI, Jiagang (Xi'an Jiaotong University)

Track Classification: B2. Interaction of vacuum arcs with magnetic fields

A1-P3-275

Overheating of Nanostructured Tendril Bundles due to Thermo-Field Emission

Content

Arcing is a negative phenomenon that occurs among plasma-wall interaction processes in thermonuclear devices. Nanostructured tendril bundles (NTBs) can be formed on a plasma-facing surface of tungsten [1-2] after irradiation by helium plasma that contains impurities of neon, argon, or nitrogen. These structures can increase the probability of unipolar arcing because of significant electron emission under a relatively small applied electric field of several kV/mm [3]. The electron emission can appear due to sufficient field enhancement factor that can be up to several thousand. Furthermore, NTBs can be easily overheated, that leads to the initiation of the thermofield emission consequently triggering explosive emission because of intensive Joule heating, even without any additional external power load. Plasma irradiation experiments in NAGDIS-II (Japan) and compact plasma devices in MEPhI (Rus-sia) allow to grow samples with NTB for various geometry depending on plasma parameters, ad-ditional sources of tungsten ions and atoms in the plasma and biasing voltage. The numerical calculations, as well as experimental results obtained in vacuum diode with lumines-cent anode demonstrate that NTB structures can be destroyed due to the initiation of the explosive emission under an electric field with a magnitude of several kV/mm and even without any external power load. However, the distance between NTBs, their size and geometry play a major role in the initiation of the explosive emission. Overheating numerical model for NTBs with various aspect ratios allowed for estimation of the range of electric fields with stable emission, the range corresponding to the explosion emission, and the relatively narrow range between them corresponding to the melting of NTB without total destruction. The simulation results were compared with vacuum diode experiments for specially prepared NTB geometries. The electric field of several kV/mm can exist in linear plasma simulators as well as thermonuclear devices. Explosive electron emission is accompanied by a huge current density as well as an erosion of the PFC's surface that may lead to the initiation of unipolar arcing. Our experimental results show the possibility of erosion due to explosions of NTBs even without arcing. However, NTB can emit stable electron current for a long time without degradation making them promising as flat cold cathodes.

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Primary authors: SINELNIKOV, Dmitry (National research nuclear university MEPhI); Mr KU-LAGIN, Vladimir (National Research Nuclear University MEPhI (Moscow Engineering Physics Insti-tute)); Mr BULGADARYAN, Daniel (National Research Nuclear University MEPhI (Moscow Engineer-ing Physics Institute)); KAJITA, Shin; Prof. OHNO, Noriyasu (Graduate School of Engineering, Nagoya University); Mr HWANGBO, Dougyn (University of Tsukuba, Faculty of Pure and Applied Sciences, Ibaraki, Japan)

Presenter: SINELNIKOV, Dmitry (National research nuclear university MEPhI)

Track Classification: A1. Vacuum breakdown and pre-breakdown phenomena

B1-P1-276

Experimental Investigation of Vacuum Arc Under Quadrupolar Axial Magnetic Field Contact

Content

Abstract- Axial magnetic field (AMF) can effectively control vacuum arc by making it maintain diffuse state. In this paper, a quadrupolar contact which can generate a AMF is investigated by simulations and experiments. Experiments were carried out at circuit current from 15 to 40kA, and at least three experiments were performed for each current level. By using a high-speed digital video camera, the arc behavior was recorded, meanwhile, the arc voltage and arc current were also recorded. The magnetic field distribution was calculated and analyzed, and a three-dimensional (3D) magneto-hydro-dynamic (MHD) model was adopted to study the characteristics of the arc. As a result, the evolution process of the arc can be interpreted. Simulation results show that a quadrupolar axial magnetic field distribution was generated by the special current flow. The residual magnetic field of the quadrupolar contact at current zero is low and phase shift time is small. It was observed that cathode spots covered the contact quickly and no constricted arc existed under both low current and high current, so the arc voltage was low with little noise. Moreover, the contact melting was uniform and no local severe erosion occurred due to the AMF generated by the quadrupolar contact. The simulation results are consistent with the experimental results.

Primary authors: WANG, Hongda (Xi'an Jiaotong University); Mr WANG, Lijun; WANG, Kai; YANG, Ze

Presenter: WANG, Hongda (Xi'an Jiaotong University)

Track Classification: B1. Switching in vacuum and related phenomena

B5-P3-279

Research on Trigger Characteristics of Electrically Surface Flashover Triggered Vacuum Switch with Different Trigger Electrode Materials

Content

The trigger characteristics of surface-flashover triggered vacuum switch (TVS) are greatly influenced by its trigger electrode material's work function, ablation resistance and other physical parameters. This paper discusses the influence of work function of materials and the amounts of field emission electrons on the performance of TVS theoretically. Based on the detachable vac-uum chamber, test platform for the trigger characteristics of TVS is built. By changing the trigger electrode materials, trigger energy and other parameters, the trigger characteristics of TVS are experimentally studied. The results showed that, different trigger electrode materials have differ-ent critical trigger waveforms. When the applied trigger energy is near the critical energy, the trigger delay of the switch is longer, and the jitter is greater. As the trigger energy increases, the trigger delay and jitter of TVS will decrease at the same time. When the trigger energy is greater than 130% of the critical energy, the effect of increasing applied trigger energy on the delay and jitter will tend to be gentle. Besides, with the increase of the operating voltage of vacuum gap, the trigger delay time shows a trend that firstly increases, then reaches a peak when the undervoltage ratio is around 50%, and then decreases and tends to stabilize. Compared with metal as the trigger electrode, graphite has the advantages of low trigger applied energy, short trigger delay, low jitter, and long working life, and the jitter of its trigger delay is kept within 10ns. The switch conduction performance is stable after 200 breakdowns, and its life performance is good.

Primary author: Mr SUN, Wenhao (Dalian University of Technology)

Co-authors: Prof. LIAO, Minfu)(Mr SUN, Yijie (Dalian University of Technology); Mr CHEN, Zhanqing (Dalian University of Technology); Mr ZHANG, Ming (Dalian University of Technol-ogy); Mr ZHANG, Hubo (Dalian University of Technology); Prof. DUAN, Xiongying (Dalian University of Technology)

Presenter: Mr SUN, Wenhao (Dalian University of Technology)

Track Classification: B5. Pulsed power physics and technology

C1-P1-282

Transients in hybrid switchgear involving SF6 and vacuum interrupters

Content

Hybrid switchgear have become popular for medium voltage applications. They usually involve Vacuum Interrupters (VI) immersed in SF6 gas. The presence of SF6 as an insulating medium greatly reduces the clearance requirements, thus enabling the development of compact switchgear convenient to be installed in locations with space constraints. The insulating gas, however, modifies the dielectric characteristics of the switchgear. Hence comprehensive investigation is required to assess the behaviour of the switchgear during switching transients. This paper attempts to study the switching transients associated with hybrid switchgear and com-pare with that of air insulated switchgear. A 36kV switchgear is modelled using PSCAD/EMTDC. The vacuum interrupters are modelled using library available in PSCAD and have been suitably modified to resemble the system under study. The simulation components use Mayr/Schavemaker model for simulating the vacuum interrupters. GIS has been studied in great detail in literature for the purpose of modelling Very Fast Transient Over-voltages (VFTO). The influence of SF6 has been incorporated by using methods used in the simulation of GIS switchgear – using capacitances and surge impedances. The system behaviour is studied under various switching transients like short circuit current interruption, current chopping and capacitive current interruption. The same con-ditions are simulated for air insulated switchgear and the nature of over-voltages are compared. High Power Laboratory at CPRI, Bangalore has tested several hybrid switchgear in the recent years. The voltage and current transients including body currents have been recorded associated with the tests. Many phenomena have been observed including restrike during capacitive current switching. The paper presents the pertinent voltage and current waveforms along with the possi-ble analysis. The paper attempts to draw insights regarding hybrid switchgear, which have become numerous in the grid but have remained relatively under-investigated, through modelling and experimental means.

Primary authors: Mr V, Sreeram (CPRI, India); Mr S, Arunkumar (CPRI, India); Mr REDDY, S Sudhakara (CPRI, India); Mr T, Gurudev (CPRI, India); Mr M, Maroti (CPRI, India)

Presenter: Mr V, Sreeram (CPRI, India)

Track Classification: C1. Vacuum interrupters and their applications

B5-P3-284

Study on Free Dielectric Recovery Characteristics of Laser Triggered Vacuum Switch

Content

As a promising pulsed power switch, the interruption performances of laser triggered vacuum switch (LTVS) is affected by the ablation of electrode and target. To further study the influence of different factors on the interruption performances of LTVS at high frequency, the inherent dielectric recovery strength of LTVS is measured, that is, the dielectric recovery process with-out recovery voltage. Based on the detachable vacuum interrupter, the experimental platform of LTVS dielectric recovery characteristics is built. By changing the current amplitude, frequency and electrode spacing, the curves of LTVS dielectric strength with time under different factors are compared, and the influence of various factors on LTVS dielectric recovery strength is discussed. Experimental results show that the dielectric recovery strength of LTVS decreases with the in-crease of current amplitude and electrode spacing. With the change of frequency, the dielectric recovery strength at higher frequency is lower than that at lower frequency in the initial period of time, but then the dielectric strength recovers rapidly. All the above studies provide references for improving the repetitive interruption performances of LTVS.

Primary authors: Mr ZHANG, Hubo (Dalian University of Technology); Prof. LIAO, Minfu (Dalian University of Technology); Dr CHEN, Zhanqing (Dalian University of Technology); Mr SUN, Yijie (Dalian University of Technology); Mr SUN, Wenhao (Dalian University of Technology); Dr ZHANG, Ming (Dalian University of Technology)

Presenter: Mr ZHANG, Hubo (Dalian University of Technology)

Track Classification: B5. Pulsed power physics and technology

B5-P3-285

The influence of external axial magnetic fields on the interruption capacities of laser triggered vacuum switch

Content

Magnetic fields across vacuum gap have important effects on the interruption process of vacuum switch. To improve the repetitive operating capacity of laser triggered vacuum switch (LTVS), influences of different external axial magnetic fields (AMF) on the interruption capacities of LTVS are studied in this paper. The 3-D simulation models of vacuum gap with Cup-type axial magnetic electrode and Helmholtz coil, which is employed to generate external axial magnetic field, are built up. The magnetic field distributions in vacuum gap are calculated and compared. The test platform is set up based on a detachable vacuum chamber. The influences external AMF strength, applied moments, and directions on the interruption capacity of LTVS are studied and analyzed. The test results prove that, compared to other applied moments, the LTVS with external AMF applied at current-zero point presents larger current interruption capacity. And the interruption capacity of LTVS increases with the magnetic field strength. The LTVS with AMF under the reverse direction external AMF shows better interruption capacity compared to the same direction external AMF. Applying a 65mT reverse AMF with the frequency of 13.9KHz, which leading the current-zero point of the LTVS by 6 microseconds, can increase the breaking capacity of the LTVS at 3.9KHz from 520A to 750A. The works provide suggestions for the design of LTVS products.

Primary author: Mr SUN, Yijie (Dalian University of Technology)

Co-authors: Prof. LIAO, Minfu (Dalian University of Technology); Mr SUN, Wenhao (Dalian Uni-versity of Technology); Mr CHEN, Zhanqing (Dalian University of Technology); Mr ZHANG, Hubo (Dalian University of Technology); Mr ZHANG, Ming (Dalian University of Technology); Prof. DUAN, Xiongying (Dalian University of Technology)

Presenter: Mr SUN, Yijie (Dalian University of Technology)

Track Classification: B5. Pulsed power physics and technology

C1-O5-286

Dielectric Strength Improvement by Higher Frequency AC Conditioning

Content

To increase the dielectric strength of vacuum interrupters (VIs), spark conditioning with repetitive breakdowns (BDs) by impulse or AC voltage application is one of the effective methods. AC conditioning with the frequency of 50 Hz or 60 Hz has been widely used owing to the advantage of lower cost for conditioning completion with hundreds of BDs. However, the dielectric strength after AC conditioning is usually lower than that after impulse conditioning. This might be attributed to harmful BDs during AC conditioning, i.e. some BDs would damage the electrode surface. We confirmed that multiple BDs occurred successively in a half cycle of AC voltage application. Multiple BDs would not be caused by weak points on electrode surface, but triggered by metal vapor due to the previous BD in the same half cycle. In order to suppress such multiple or harmful BDs during AC conditioning, in this paper, AC conditioning with the higher frequencies is proposed. When a BD occurs in a half cycle with the higher frequencies, the instantaneous voltage can be quickly decreased and the subsequent or multiple BDs can be suppressed. The effects of AC conditioning with the higher frequencies on the dielectric strength are discussed in this paper.

First, we measured the increase of BD voltage by AC conditioning at two different frequencies, 120 Hz and 550 Hz. We set sphere-plane electrodes made of OFHC Cu in a vacuum chamber at 10⁻⁶ MPa. AC conditioning was conducted at each frequency with the gap distance of 1 mm under a fixed applied voltage of 32 kV_{rms} for 10 minutes. The BD voltages before and after conditioning were evaluated by negative standard lightning impulse voltage with up/down method with the enlarged gap distance of 3 mm.

Experimental results revealed that the evaluated BD voltages before and after AC conditioning at 120 Hz were 125 kV and 181 kV, respectively, which means 45 % increase. On the other hand, those at 550 Hz were 144 kV and 240 kV, corresponding to 67 % increase, which is higher than that at 120 Hz. This improvement of evaluated BD voltage and its increase ratio at 550 Hz can be regarded as the effect of higher frequency AC conditioning. The total numbers of BDs during AC conditioning were 465 times at 120 Hz and 356 times at 550 Hz, respectively, including the intermittent BDs with a long time interval (ms order) beyond the half cycle and the multiple BDs in the same half cycle. The multiple BDs were classified into the first BD and the subsequent BDs in the same half cycle. The number ratio of subsequent BDs at 550 Hz was 28.4%, which is lower than 49.9% at 120 Hz. These results suggest the feasibility of higher frequency AC conditioning for the dielectric strength improvement of VIs.

Primary authors: Mr KONAGI, Ryota (Nagoya University); Prof. KOJIMA, Hiroki (Nagoya Uni-versity); Mr IITSUKA, Shinsuke (Hitachi Industrial Equipment Systems Co., Ltd.); Mr KOBAYASHI, Masato (Hitachi Industrial Equipment Systems Co., Ltd.); Prof. HAYAKAWA, Naoki (Nagoya Univer-sity)

Presenter: Mr KONAGI, Ryota (Nagoya University)

Track Classification: C1. Vacuum interrupters and their applications

C1-P2-287

A Fast Fault Detection Method for Vacuum Controlled Fault Interruption Based on Wavelet Singularities and BP Neural Network

Content

A fast identification of a short-circuit fault within an ultimately short time interval, based on a fast short circuit fault detection (FSCFD) of the short-circuit fault, contributes to a significant promotion of the transient operating stability of the power system. From the state of art, there remains no algorithm that can determine the occurrence of short circuit fault accurately within 0.3 ms. The objective of this paper is to propose an FSCFD method. The method referred to a fusion of multiple criteria, which included a voltage wavelet transform algorithm, a current wavelet transform algorithm, a current waveform curvature algorithm, and a back-propagation (BP) neural network algorithm. Each of the algorithms was initiated to obtain a short circuit fault identification re-sult and the fault type immediately after the sampling of the fault current. A multi-information fusion technology, correlated with the Dempster/Shafer (D-S) evidence theory, was adopted to fuse the four identification results to obtain the most reliable value. The fusion process obeyed such a sequence in the following orders: 1) modification of the evidence source; 2) solutions for the similarity matrix; 3) normalization of the evidence body, and 4) implementation of the fusion treatment. The proposed FSCFD method, validated both in the simulation and experiment, proved that it can accomplish the identification of a short-circuit fault within 0.25±0.003 ms.

Primary authors: ZHANG, Luyang (Xi'an Jiaotong University); YAO, Xiaofei (School of Electrical Engineering, Xi'an Jiaotong University); Mr LI, Ziang (Xi'an Jiaotong University); CHEN, Xinggui (Xi'an Jiaotong University); DING, Jiangang (School of Electrical Engineering, Xi'an Jiaotong University, Xi'an, China); GUAN, Chen (School of Electrical Engineering, Xi'an Jiaotong University); WANG, Jianhua (Xi'an Jiaotong University); GENG, Yingsan (Xi'an Jiaotong University); LIU, Zhiyuan (School of Electrical Engineering, Xi'an Jiaotong University)

Presenter: ZHANG, Luyang (Xi'an Jiaotong University)

Track Classification: C1. Vacuum interrupters and their applications

C2-P2-288

Characterization of millisecond-scale high-power impulse magnetron discharge in helium

Content

Impulse magnetron discharges with millisecond-scale pulses—extended duration modes of technological high-power impulse magnetron sputtering (HiPIMS)—have promising applications in pulsed plasma facilities of different kinds due to high ionization degree (up to 90%), suitable duration, and scalable hardware design. Depending on operating conditions, at the same power level, two distinct diffuse regimes can be distinguished: the one with intense target sputtering—long HiPIMS (L-HiPIMS) [1],—and the non-sputtering low-voltage one (non-sputtering magnetron discharge [2–4]). The majority of existing studies of these discharge forms were made for argon working gas. For a number of prospective high-power pulsed plasma applications (pulsed plasma accelerators and thrusters), however, the option of using light gases is preferable.
The operation of millisecond-scale impulse magnetron discharges in light gases (helium and hydrogen) has been examined by electrical and optical diagnostic methods. The pulse duration was varied from 1 ms to 20 ms, and the maximum pulse energy was 6 kJ. Special probe head combining Langmuir probe and Mach probe was utilized to measure plasma parameters (electron density, electron temperature) and plasma flow velocity in a time-resolved fashion. The electrical measurements were accompanied with optical emission spectroscopy and high-speed imaging.
The use of the long pulsed modes enables achieving high plasma density (up to 1015 cm–3) and accelerating the ion flux with a peak energy distribution of 20–30 eV, which corresponds to 60–80 km/s for a hydrogen ion.

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Primary author: KAZIEV, Andrey

Presenter: KAZIEV, Andrey

Track Classification: C2. Surface modification and related technologies

A1-P3-291

Short-pulse Breakdown of Near-cathode Sheath in the Presence of a Local Magnetic Field

Content

The breakdown of ion sheath formed between the plasma and the cathode determines the functioning of plasma-filled explosion-emission sources of electron beams, and also affects the stability of the operation of plasma immersion ion implantation devices, vacuum switches, etc. The regularities breakdown initiation in the vacuum gap (VG) and in the cathode ion sheath (CIS) should have some similarity. Indeed, before the breakdown in the CIS as well as in the VP, there are no electrons and therefore there are no conditions of origin and development of avalanches and streamers, as in the gas environment. It follows that the initiation of CIS and VP breakdown is largely related to the processes occurring on the cathode surface. From the other hand, the spe-cial features of pre-breakdown conditions in the CIS are both electric field nonuniformity due to space-charge of ions and high-energy ion bombardment of cathode surface.
In present work, it is experimentally established that the local magnetic field significantly reduces the pulsed dielectric strength of both VG and CIS, initiating a breakdown at the point of the magnetic lines exit from the cathode surface at flux density of about 0.3 T and higher. According to the literature, the magnetic flux density above 0.1 T can affect dislocation paramagnetic stoppers and as sequence plastic properties of the material as a whole (the magnetoplastic effect). The reduction of the electrical strength of CIS and VG by local magnetic field can be used to increase the efficiency of the explosion-emission cathodes of vacuum and plasma-filled electron guns.

Primary authors: Mr ONISCHENKO, Sergey (Institute of High Current Electronics SB RAS); Mr PETROV, Vsevolod (Institute of High Current Electronics); Dr NEFEDTSEV, Evgeny (Institute of High Current Electronics SB RAS)

Presenter: Dr NEFEDTSEV, Evgeny (Institute of High Current Electronics SB RAS)

Track Classification: A1. Vacuum breakdown and pre-breakdown phenomena

A2-P3-292

The Effect of Microstructure on Vacuum Surface Flashover

Content

Vacuum surface flashover brings significant damage to dielectric-vacuum insulation system which is widely used in many areas, including pulsed-power devices, dielectric window, particle acceler-ator and other vacuum electronic devices. Thus, the research on flashover mitigation is needed.

It has been believed that flashover voltage is influenced by various factors, such as surface roughness, dielectric SEY, surface treatment and so on. What's more, previous work has proved that grooved surface can greatly improve surface insulation strength. However, some questions still remain unknown. Though different micro structures, for instance the rectangular and triangular groove, have been considered in previous works, a theoretical ground is lacking on how barrier shape and distribution quantitively affect electrons dynamics and the optimal shape which best mitigates the multipactor-induced avalanche is yet to be determined.

In this work, a particle-in-cell (PIC) simulation code is employed to reveal the flashover development under complex surface microstructure. The time-spatial electron distribution is proposed and the distribution during SSEE state is given. Meanwhile, the impact of groove number and depth are discussed with the average surface charge density and anode current. In addition, an optimal solution of microstructures is proposed and a theoretical explanation is given. In the end, experimental results considering the structures in the simulation are proposed and discussed.

From the simulation work described above, it's found that micro grooves can significantly suppress the surface charge accumulation. With the same applied voltage, the surface charge density of grooved surface is much lower. It's also observed that grooves increase the surface flashover voltage in vacuum as well. When it comes to the groove size and number, it's proved that deeper and more grooves have a better performance. Relevant experimental results show agreement with the simulation.

In conclusion, it's shown that groove number and depth hinder the initiation of vacuum flashover, reducing the average charge density and anode current, which in turns improves flashover threshold. It is also found that the influence of groove depth reaches saturation above certain value. The effect of groove number has also been proved by experimental work, which is consistent with simulation results. In addition, optimal surface structure for application is suggested to use grooves with optimal size mentioned before, improved groove number in line with acceptable mechanical strength is also recommended.

Primary authors: ZHANG, Shu (Xi'an Jiaotong University); Mr HUANG, Kun (State Key Laboratory of Electrical Insulation and Power Equipment, School of Electrical Engineering, Xi'an Jiaotong University); Dr SONG, Falun (Science and Technology on High Power Microwave Laboratory, Institute of Applied Electronics, CAEP); Mr CHENG, Yanlin (Institute of Electronic Engineering, China Academy of Engineering Physics); SUN, Guangyu (Xi'an Jiaotong University); Prof. MU, Haibao (Xi'an Jiaotong University); ZHANG, Guan-Jun (Xi'an Jiaotong University)

Presenter: ZHANG, Shu (Xi'an Jiaotong University)

Track Classification: A2. Surface discharges and flashover phenomena

C1-P2-295

Development of a Vacuum Arc Extinguishing Chamber for a Single-Break Vacuum Circuit Breaker for 110 kV

Content

The requirements for high-voltage vacuum circuit breakers for networks with a grounded neutral are formulated, due to the perspective of introducing vacuum circuit breakers into operation in networks with a solidly grounded neutral. Constructive solutions have been proposed for vac-uum interrupters for 110 kV voltage, which make it possible to reduce the probability of repeated breakdowns in them, reduce the negative consequences of repeated breakdowns and eliminate the possibility of reducing the electrical strength of the chambers as they deplete their electrical life. The design of a vacuum arc-extinguishing chamber for a 110 kV single-break vacuum circuit breaker has been developed, taking into account the presence of repeated breakdowns. The de-sign of the screen system excludes metallization of the ceramic body, which reduces the electrical strength of the vacuum chamber.

Primary authors: SCHNEIDER, Anton (IHCE SB RAS); Prof. LAVRINOVICH, Valery; Dr RYL-SKAYA, Lidiya; POPOV, Sergey (IHCE SB RAS)

Presenter: SCHNEIDER, Anton (IHCE SB RAS)

Track Classification: C1. Vacuum interrupters and their applications

C4-P1_O4-299

RF induced discharges in vacuum in the SPIDER experiment

Content

SPIDER is the full-size prototype of ITER Neutral Beam Injector ion source, in operation since June 2018 as part of the ITER Neutral Beam Test Facility located in Padova, Italy. The ion source of SPIDER is composed of eight Radio Frequency drivers operated in low hydrogen gas pressure, 0.3 Pa, driven at 1 MHz with a total nominal power of 800 kW, an extraction and acceleration system is used to produce a negative ion beam with an energy up to 100 keV.
RF breakdowns outside the ion source beset the SPIDER experimentation since the beginning of the operations. Such breakdowns could be sustained by the power supplies but in many cases cause the plasma pulses to stop and might cause source damages. The scope of this work is to summarize the experimental pieces of evidence, classify the type of breakdowns and describe the electrical model for these events. Three classes of diagnostics have been used to investigate the RF breakdowns: electrical measure-ments from the Ion Source and Extraction Power Supply, visible cameras (both fast and slow) and optical fibers which collect lights from the rear of the SPIDER experiment. Each of these signals is somehow affected by the RF breakdowns; their comparative analysis allows improving the un-derstanding of this issue and helped the identifications of different types of breakdowns that can occur outside the SPIDER Ion Source.
A discussion of the reasons behind the occurrence of the discharges, induced by the Radio Frequency, concludes the work.

Primary authors: DAN, Mattia (RFX); Dr ZAMENGO, Andrea (Consorzio R FX); Dr AGOSTINI, Matteo (Consorzio RFX)

Presenter: DAN, Mattia (RFX)

Track Classification: C4. Accelerators and fusion reactor related issues

C1-P1_O11-302

The Impact of Particles on Post-arc breakdowns in Capacitive Interruptions

Content

The advantage of long electrical life make vacuum circuit breakers suitable for clearing the capacitive loads. However, the high probability of post-arc breakdowns threatens the safety and reliability of the power system potentially. It is believed that particles generated in the inter-ruption processes are responsible for triggering the breakdowns. The objective of this paper is experimentally observing the generation and dynamics of particles in capacitive interruptions as well as their resultant effects on post-arc breakdown, to further reveal possible mechanisms for particle-induced breakdown. An optical diagnostic platform based on a laser-shadow technique was constructed to detect the particles generated by different electrodes materials. Meanwhile, a 12 kV synthetic test circuit which contained an inrush current source was set up. Particles genera-tion was observed to be closely related to the contact materials and inrush Currents. Additionally, under the influence of the recovery voltage, particles showed complex and diverse dynamic behav-iors, such as bouncing, oscillating, levitating, lifting, and rotating. Besides, particles generated in capacitive interruption were inclined to wander for a longer time in the vacuum gap, lasting 200 ms after arc extinction. More importantly, it was found that post-arc re-breakdowns were more likely to occur when particles were close to the electrode at higher recovery voltages. Based on particles behaviors, breakdown moment and recovery voltage, particles were primarily responsi-ble for the long delayed restrikes. Key words: Vacuum circuit breakers, free particles, capacitive interruptions, restrikes, inrush cur-rent.

Primary authors: YAN, Wenlong (Xi'an Jiaotong University); WANG, Zhenxing (Xi'an Jiaotong University); Mr CHEN, Boyang (State Key Laboratory of Electrical Insulation and Power Equipment Xi'an Jiaotong University); Dr SUN, Liqiong (State Key Laboratory of Electrical Insulation and Power Equipment Xi'an Jiaotong University); GENG, Yingsan (Xi'an Jiaotong University); LIU, Zhiyuan (Xi'an Jiaotong University); WANG, Jianhua (Xi'an Jiaotong University)

Presenters: YAN, Wenlong (Xi'an Jiaotong University); WANG, Zhenxing (Xi'an Jiaotong Univer-sity)

Track Classification: C1. Vacuum interrupters and their applications

C1-P2-304

Numerical Simulation and Analysis of Post Arc Breakdown Process of Vacuum Circuit Breaker

Content

Sheath development is affected by many factors, and its initial and process parameters directly affect the dielectric recovery and breaking performance. This paper focuses on the development of post arc sheath of 12kV / 20KA vacuum circuit breaker. Based on the drift-diffusion equation, the influence of initial parameters on the sheath breakdown process is analyzed, and the distribution and variation of micro parameters such as electron density, ion density, electric field potential and post arc current are studied. In order to analyze the formation of breakdown channel and the change of micro parameter dis-tribution during sheath development, a simulation model of breakdown process is established. According to the breakdown theory, the background metal vapor density is increased to reflect the collision ionization effect, the TRV slope is increased to reflect the cathode surface emission, and the secondary electron emission coefficient is set. According to the simulation results, the breakdown process is analyzed, and the distribution of electron and ion density, the distribution of electron density and spatio-temporal variation are ob-tained. The distribution of electric potential and electric field intensity, the change law of spatio-temporal variation and post arc current, and the change trend of ion velocity and mode value are analyzed. Based on Thomson discharge theory, the influence factors of post arc breakdown are analyzed, and the effects of metal vapor density, initial plasma density, TRV slope and secondary emission coefficient of electrode surface on the electron density multiplication process of metal vapor from weak ionization to strong ionization after breakdown are discussed. In this paper, the micro explanation of sheath development, channel formation and breakdown process of arc reignition, the changing trend of electric field intensity on cathode surface, current density after arcing and ion velocity on cathode surface with time, and the influence mechanism of parameters on the formation speed of breakdown channel are obtained.

Primary authors: CHEN , Hai (State Key Laboratory of Reliability and Intelligence of Electrical Equipment,Hebei University of Technology); LIU, Xiaoming (State Key Laboratory of Reliability and Intelligence of Electrical Equipment, Hebei University of Technology); GENG, Yuxiang (Tianjin Key Laboratory of Advanced Technology of Electrical Engineering and Energy, Tiangong University); Mr LI, Peiyuan (State Key Laboratory of Reliability and Intelligence of Electrical Equipment, Hebei University of Technology); JIANG, Wentao (School of Mechanical Engineering, Tiangong University, Tianjin Key Labora-tory of Advanced Technology of Electrical Engineering and Energy)

Presenter: CHEN , Hai (State Key Laboratory of Reliability and Intelligence of Electrical Equipment,Hebei University of Technology)

Track Classification: C1. Vacuum interrupters and their applications

B4-P3-305

Design and motion characteristics analysis of permanent magnet repulsion mechanism for vacuum circuit breaker

Content

In this paper, the fast operating mechanism of mechanical low-voltage DC vacuum circuit breaker is taken as the research object, the structure optimization design and motion characteristics anal-ysis of bistable permanent magnet repulsion mechanism are carried out, and the electromagnetic mechanical system model and design method of vacuum interrupter and mechanism are studied. The topology and parameter group design method of bistable permanent magnet repulsive mech-anism is studied. Based on finite element electromagnetic calculation and quantitative analysis of reaction force and reaction force work, the topology and parameter design scheme of external cir-cuit of repulsive mechanism is proposed. The physical mathematical model of coil repulsive disk structure and the equivalent second-order circuit model of mutual inductance coupling circuit are established, and the field circuit coupling analysis is carried out to obtain the working state of "RLC" series second-order circuit. Taking the external circuit parameters of repulsive structure as optimization variables, the short-est time for electromagnetic repulsive force to reach its peak value and the maximum work done by electromagnetic repulsive force in its action time is as optimization objectives, and the work-ing state of external circuit under damping is as constraint conditions, the self-adaptive mesh multi-objective particle swarm optimization algorithm is adopted to realize the parameters group optimization design of the mechanism, the combination of the parameters which can satisfy the design requirements is obtained. Combined with the system parameters of the fast operating mechanism, the finite element method is used to simulate the motion characteristics, and the feasibility of the design method is verified. Through the simulation analysis of the influence of coil housing material and housing structure on the magnetic circuit, the control method of energy conversion efficiency of fast operating mech-anism is proposed. In order to reduce the bouncing of the moving parts at the end of opening, the electromagnetic buffer is used to reduce the speed at the end of opening to meet the design requirements of motion characteristics.

Primary authors: CHEN , Hai (State Key Laboratory of Reliability and Intelligence of Electrical Equipment, Hebei University of Technology); LIU, Xiaoming (State Key Laboratory of Reliability and Intelligence of Electrical Equipment, Hebei University of Technology); ZHANG, Yi (Tianjin Key Lab-oratory of Advanced Technology of Electrical Engineering and Energy, Tiangong University); JIANG, Wentao (School of Mechanical Engineering, Tiangong University, Tianjin Key Labora-tory of Advanced Technology of Electrical Engineering and Energy); LI, Peiyuan (State Key Laboratory of Reliability and Intelligence of Electrical Equipment, Hebei University of Technology)

Presenter: CHEN , Hai (State Key Laboratory of Reliability and Intelligence of Electrical Equipment, Hebei University of Technology)

Track Classification: B4. Computer modeling and computer aided design

A1-P3-307

Pre-Breakdown Phenomena between Electrodes in Vacuum: the Role of Accumulation Points in the Onset of Microdischarges

Content

The reliability of HV insulation across a single gap, in vacuum and low-pressure gas, is known to be a critical issue to be addressed in the development and realization of the electrostatic accelerator for the ITER Neutral Beam Injector (NBI). This paper describes recent experimental results obtained at the High Voltage Padova Test Facility (HVPTF) with the aim of developing an adequate high-voltage insulation system for the MITICA accelerator, the prototype for the ITER NBI. The experiments were carried out on a double-polarity configuration, using sphere-to-sphere electrodes, separated by 30 mm gap. The results showed that the onset of microdischarges is not solely dependent on the cathodic electric field, but also depends on the applied voltage, which determines the energy of the emitted electrons hitting the anode. Furthermore, this phenomenon seems to be dependent on a mutual exchange of charged particles between specific accumulation points on both electrode surfaces. The outcome of these experiments is reported and analyzed with both analytical and numerical models

Primary authors: PILAN, Nicola (Consorzio RFX); Dr CAVENAGO, Marco (INFN/LNL Italy); Prof. CHITARIN , Giuseppe (Consorzio RFX); Dr DE LORENZI, Antonio; Dr FONTANA , Cristiano Lino (Università di Padova); Dr OISIN , Mc Cormack (CNR-IFP, Milano); Dr GOBBO, Renato (Università di Padova); Mr FINCATO , Michele (Consorzio RFX, Padova , Italy); Mr LOTTO, Luca (Università di Padova); Prof. PESAVENTO , Giancarlo (Università di Padova); Dr PINO, Felix (Università di Padova); Dr SPADA, Emanuele (Consorzio RFX , Padova, Italy); Dr SPAGNOLO , Silvia (Consorzio RFX, Padova , Italy); Dr ZUIN, Matteo (Consorzio RFX, Padova , Italy)

Presenter: PILAN, Nicola (Consorzio RFX)

Track Classification: A1. Vacuum breakdown and pre-breakdown phenomena

A1-O6-308

Investigation of Vacuum Breakdown in Pulsed DC Systems

Content

Vacuum breakdown in the pulsed DC experiment at CERN was investigated by means of electrical measurements, SEM imaging, Focused Ion Beam technique (cross sectioning), and numerical modelling. The breakdown sites comprise one or more craters. There is plastic deformation beneath the craters. The craters are surrounded by a 'wave pool', which could be from 70 nm up to 1 μm thick.

The crater(s) represent the epicenter of the breakdown, where electron emission and vaporization of the metal occur, and the plasma ball is formed. The only possible mechanism of ionization of neutral vapor seems to be ionization by the emitted electrons. The pressure exerted by the plasma ball is responsible for the formation of the crater. This physical picture is generally similar to what was seen in simulations of formation of cathode spots in vacuum arcs under conditions typical for, e.g., circuit breakers and unipolar arcs in fusion devices. There is, however, a very important difference. There are external factors provoking the formation of cathode spots in vacuum arcs (the plasma cloud left over from an (extinct) spot that previously existed in the vicinity of the (new) spot being ignited), and the ignition of unipolar arcs (plasma instabilities which deliver high energy and particle fluxes to the plasma-facing components). There is no such external agent which would facilitate the breakdown in the CERN experiment. Therefore, the breakdown voltage is by orders of magnitude higher than in vacuum and unipolar arcs. Moreover, the breakdown is dominated by field electron emission, which is irrelevant in vacuum and unipolar arcs and enhancement of the field on cathode microprotrusions must be a decisive effect.

Simulations have been conducted with the aim to describe the mechanisms of vacuum breakdown, from the initiation of field emission and heating of the protrusion, to vaporization of the cathode material, production of plasma by ionization of the metal vapor and destruction of the protrusion by melting. The model comprises the Navier-Stokes equations describing the motion of the molten metal of the cathode, in conjunction with the heat transfer equation and current continuity equations in the cathode (including both the molten and solid parts). The Laplace equation is used to compute the electric potential and field in the gap between electrodes in the initial phase of the breakdown; switching to a model with a thin near-cathode plasma layer will occur in the course of the development of the breakdown.

First results show that the heating due to electron emission (i.e., Nottingham effect) is a very important mechanism, resulting in rapid increase of the protrusion temperatures; this may be indicative of a microexplosion. Further results will be presented on the evolution of voltage and current in the gap, destruction of the microprotrusion and crater formation.

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Primary authors: Dr KAUFMANN, Helena (University of Madeira); PROFATILOVA, Iaroslava; POPOV, Inna; BENILOV, Mikhail; WUENSCH, Walter (CERN)

Presenter: Dr KAUFMANN, Helena (University of Madeira)

Track Classification: A1. Vacuum breakdown and pre-breakdown phenomena

A1-O7-309

Pulsed Breakdown Behaviors across Microgaps at Various Atmospheres

Content

With the rapid miniaturization and integration of electronic and electromechanical devices, especially for vacuum micro devices, it is urgent to study the electrical breakdown behaviors of pulsed breakdown at microscale and explore its underlying principle. In this paper, the influence of atmospheric pressure and electrode geometries on pulsed breakdown at microscale was studied by the home-built electro-optical measuring system. Results show that when the gap width is less than 5 μm, the role of gas molecules density or gas pressure inside the gap could be eliminated which means that the breakdown process is similar as the vacuum breakdown. For different electrode geometries, when the gap width is larger than 15 μm, the breakdown voltage remains the same regardless of the electrode geometries, whereas difference behaviors can be observed when the gap width is less than 15 μm, and these results can be analyzed from different breakdown mechanism such as field electron emission, ion-enhanced field emission and Townsend avalanche. The results presented in this paper would be of a great help for better understanding the physical mechanism of pulsed breakdown at microscale.

Primary authors: MENG, Guodong (Xi'an jiaotong university); LI, Yimeng (Xi'an jiaotong university); SHE, Junyi (Xi'an Jiaotong University); XIA, Linghan (Xi'an Jiaotong University)

Presenter: LI, Yimeng (Xi'an jiaotong university)

Track Classification: A1. Vacuum breakdown and pre-breakdown phenomena

A1-I8-311

Atomic dynamics of metal surface under applied strong electric fields

Content

Until recently the dynamics of atoms under high electric fields has been largely overlooked due to the common belief that electric forces, which can possibly be exerted by the field on a surface atom are too small to affect its motion in any significant manner. However, the recently developed technique known as Atom Probe Tomography showed that increasing the absolute value of the field at the surface may lead to its direct removal from the surface. Moreover, the atoms were found to migrate (visibly change their positions on the surface) towards the regions where the field can be enhanced. The originally proposed model by Tsong and Kellog considered an adatom as the polarized dipole on the surface which can interact with a surface field gradient. It did not receive sufficient recognition in the community as the assumptions used in the model were insufficiently justified. In our recent work [1], we have re-visited this approach using the density functional theory calculations of W surfaces under strong electric fields in order to shed the light on redistribution of electron densities around a surface defect in order to determine the origin and nature of surface charges from the dipole moment viewpoint. We found out that the dipole moment of an adatom results not only from the electric field as in the case of a free-standing atom, but also influenced by the interatomic forces which bind the adatom to the surface. Hence, it is important to consider the entire system to find out the polarization characteristics of it. This becomes particularly important if we want to follow the kinetics of atomic rearrangement on the surface under the field due to diffusional transitions. The effect of surface charge (polarization of the surface) affects interatomic interactions, causing ef-fect of a tensile Maxwell stress on its surface. Apart from the surface kinetics of the atoms, we look at the defect dynamics under the surface. Previously we showed that it is possible that dislocations can emit from near-surface voids bringing layers of atoms to the surface. In the recent experiment we observed formation of similar protrusion on the surface loaded with hydrogen atoms under applied electric field. The pressure of the hydrogen gas in the forming bubbles is not too high, yet, the shear stress in the direction of the open surface is sufficient to emit dislocations in the form of prismatic loops. These prismatic loops contribute to formation of surface protrusions of similar diamond-like shapes as those that we predicted earlier. The protrusions formed by the hydrogen bubbles are much larger and are easily visible in SEM images of micron resolution. This result confirms indirectly that the surface does not require very high stress values to initiate the dislo-cation motion under the surface. Some of these are attracted to the surface forming atomic steps and protrusions sharpening surface rough features, in turn, increasing further field enhancements, which may affect surface atomic dynamics on the surface.

[1] A. Kyritsakis et al ., Phys. Rev. B 99, 205418 (2019)

Primary authors: DJURABEKOVA, Flyura (University of Helsinki); KYRITSAKIS, Andreas; BAIBUZ, Ekaterina (University of Helsinki); Dr JANSSON, Ville (University of Helsinki); KIMARI, Jyri; SARES-SALO, Anton (Helsinki Institute of Physics (FI)); LOPEZ CAZALILLA, Alvaro (University of Helsinki)

Presenter: DJURABEKOVA, Flyura (University of Helsinki)

Track Classification: B3. Vacuum arc physics

A1-O7-313

New Development of BIRD Model

Content

The possibility that the flow of electrons emitted by a cathode at high dc voltage is essentially due to local emission of a covering dielectric layer is at the basis of the BIRD (Breakdown Induced by Rupture of Dielectric) model. This model assumes that, in presence of sufficient electric field, the electrons trapped in polarization structures of the dielectric layer are extracted by quantum tunnel-ing effect. As a consequence of the layer electron depletion, the electric field inside the dielectric layer increases and the rupture (breakdown) of the layer itself can occur, provided certain condi-tions are met. To investigate experimentally the features of this model the High Voltage Short Gap Test Facility (HVSGTF) has recently been built in Padua. The experimental dark current measured at different electrode configurations permits us to test the correctness of the model predictions. In particular, we consider the trend of the current as a function of time and its dependence on the characteristic properties of the dielectric layer. From the theoretical side, we investigate the consistency between a semi-classical model and a simple quantum model

Primary author: Dr SPADA, Emanuele (Consorzio RFX)

Co-authors: Dr DE LORENZI , Antonio; Mr LOTTO, Luca; PILAN, Nicola; SPAGNOLO, Sil-via; ZUIN, Matteo

Presenter: Dr SPADA, Emanuele (Consorzio RFX)

Track Classification: A1. Vacuum breakdown and pre-breakdown phenomena

C4-O4-314

Preparation of the vacuum insulation tests on the MITICA 1 MV electrostatic Accelerator

Content

MITICA is the prototype of the ITER Heating Neutral Beam Injector (NBI), which is designed to generate a 40 A beam of Hydrogen/Deuterium negative ions, to accelerate the ions up to an energy of 1MeV and then to neutralize them, producing a neutral beam of about 16.6 MW power. The design of MITICA is as far as pos- sible identical to the design of the ITER HNB, except that in the ITER NBI, the neutral beam will be directed to the plasma in the Tokamak vessel via a duct, whereas in MITICA the neutral beam will be directed to a water-cooled calorimeter. The NBI system will consist of a Vacuum Vessel (AISI304L, overall dimensions 15 × 5 × 5 m3), where the negative ion Beam Source, which is the most complex component of the NBI system, will be installed, together with other components (i.e. gas-cell Neutralizer, residual Ion Dump and Cryo-Pumps). The negative ion Beam Source includes a Plasma Chamber (with a gas injection system and auxiliaries for the production of negative Hydrogen/Deuterium ions) and a multi-stage Electrostatic Accelerator, constituted by a series of 7 metallic grids each having 1280 apertures. The Plasma Chamber and the metallic grids of the multistage electrostatic Accelerator will be kept at different electric potentials ranging from about - 1MV (Plasma Chamber, Plasma Grid and Extraction Grid) to ground potential (Grounded Grid) in steps of 200 kV. The Vacuum Vessel will be grounded. The insulation between electrodes having different electric potential will be provided by gaps in vacuum (filled with low pressure Hydrogen during operation) and by alumina post insulators. The voltage holding capability of the MITICA Beam Source at 1 MV is a very challenging issue, which could not be fully addressed so far on the basis of the theoretical models and experimental results available in literature. This paper describes a specific HV test campaign to be implemented in the MITICA Vacuum Vessel using a mock-up of the Beam Source. The tests have been designed with the aim of incorporating the essential features both of the single-gap and of the multi-stage insulation, so as to obtain reliable data on voltage holding at 1 MV and, if necessary, to focus on the most effective solutions. The tests shall be performed in the MITICA Vessel (already available in the NBTF site) both in vacuum and in low-pressure gas, using a specific Test Power Supply, in parallel with the construction and assembly of the MITICA Beam Source. In the paper, the test objectives and requirements are first introduced. Then the strategy and test configurations are defined. Finally, some design solutions for the electrode realization are described and preliminary plan together with a list of test equipment is given.

Primary author: Dr CHITARIN, Giuseppe (University of Padova and Consorzio RFX)

Co-authors: KOJIMA, Atsushi (National Institutes for Quantum and Radiological Science and Technology); LUCHETTA, Adriano Francesco (CNR - Istituto per la Scienza e Tecnologia dei Plasmi, Con-sorzio RFX); MARCUZZI, Diego (Consorzio RFX); Dr ZACCARIA, Pierluigi (CNR - Istituto per la Scienza e Tecnologia dei Plasmi, Consorzio RFX); TOIGO, Vanni (CNR - Istituto per la Scienza e Tec-nologia dei Plasmi and Consorzio RFX); APRILE, Daniele (INFN-LNL); Dr MARCONATO, Nicolò (Uni-versità di Padova and Consorzio RFX); PATTON, Tommaso (Consorzio RFX); PILAN, Nicola (Con-sorzio RFX); BATTISTELLA, Manuela (Consorzio RFX); BERTON, Giovanni (Consorzio RFX); BREDA, Mauro (Consorzio RFX); DAN, Mattia (RFX); FINCATO , Michele (Consorzio RFX, Padova , Italy);

GRANDO, Luca; VALENTE, Matteo (Consorzio R FX); RIGONI GAROLA, Andrea (RFX); DE LORENZI, Antonio (Consorzio RFX); TOBARI, Hiroyuki (QST); UMEDA, Naotaka (QST); WATANABE, Kazuhiro (QST); KASHIWAGI, Mieko (National Institutes for Quantum and Radiological Science and Te)

Presenter: Dr CHITARIN, Giuseppe (University of Padova and Consorzio RFX)

Track Classification: C4. Accelerators and fusion reactor related issues