Abstracts of Contributions Presented at the 21st Symposium on Physics of Switching Arc, Nove Mesto na Morave, Czech Republic, 7. – 11. 9. 2015:

Application Important Characteristics of Diffuse Coplanar Surface Barrier Discharge – Plasma Layer Thickness and Humidity Influence

Čech J.[1], St'ahel P.[1], Buček A.[1], Černák M.[1]

[1]*Masaryk University, CEPLANT - R&D Center for Low-Cost Plasma and Nanotechnology Surface Modification, Kotlářská 2, 611 37 Brno, Czech Republic, cech@physics.muni.cz*

Diffuse coplanar surface barrier discharge (DCSBD) is a type of dielectric barrier discharge operated at atmospheric-pressure capable to generate diffuse „cold“ atmospheric-pressure plasmas in ambient air, oxygen and other standard plasma gases. Here the two characteristics of DCSBD are discussed, that have the direct influence on the industrial applicability of DCSBD.
The first, intrinsic, characteristic of DCSBD is the fact, that the plasma is generated in the form of very thin plasma layer above dielectric surface. On one hand this puts the limits on the optimum distance of treated materials and their surface roughness; on the other hand this is of the great benefit of DCSBD, due to the extremely high power density of more than 100 W/cm^3, which leads to high throughput of plasma treatment. The thickness of the plasma layer in air was precisely spectroscopically measured using high resolution optical stage. Measured plasma thickness of 0.20±0.08 mm is in agreement with the plasma treatment studies utilizing the DCSBD.
Second parameter important to real industrial applications of DCSBD is the influence of air humidity on the parameters of the discharge. The measurement in broad range of absolute humidity of air was performed. It was found that the highly humid air leads to the self-organization of microdischarges to dense filament patterns accompanied with slight increase of rotational temperature of OH (approx. 50 K), while the vibrational temperature of N_2 remains practically the same, i.e., 2700±600 K. The OH radical emission, with respect to the emission of N_2, increases with the humidity even though the slight saturation of the emission occurs above the level of approx. 30 g_{H2O}/m^3, which corresponds to approx. 60% relative humidity (RH) at 40°C.

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Optimization of Tripping Force in the Low Voltage Circuit Breaker

Chorovský P.[1]

[1]*Brno University of Technology, Technická 12, 616 00 Brno, Czech Republic, xchoro00@stud.feec.vutbr.cz*

Circuit breakers are electrical devices which protect electrical equipment and installation against overcurrents and short-circuit currents. Their role is to extinguish an electrical arc as fast as possible. There are several options. One of them is a proper reaction of the circuit breaker mechanism. The article deals with optimization of tripping force in the low voltage circuit breaker. The basic principles of circuit breakers functions are described in the first part of the article. A method of optimization with details is described in the second part.

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Peculiarities of Utilization for Liquids Decontamination Purposes Electrical Discharges, Initiated in Nozzle-Shape Electrode Structures

Emelianov A.I., Azizov E.A., Rodionov N.B., Yagnov V.A.

Joint-stock company State Research Centre of Russian Federation "Troitsk Institute for Innovation and Fusion Research", Pushkovykh str., possession 12, city district Troitsk, Moscow, 142190, Russian Federation

Possibilities of bactericidal effect of phenomena which are following electric discharges in liquid initiated by a different ways are analyzed. The results of this work are: 1. Development of methodology, based on application of discharges in still liquid and electrical discharges with a large surface of radiation, formed along an envelope area of mixing of a submerged stream during one operating cycle of decontamination. 2. Steady discharge ignition in liquid under abnormally low electric field strength of E = (0,45 – 0,7) kV/cm, minor energy input level and wide range of initial liquid conductivity. 3. Discharge with easily variable surface of radiation in UV wavelength range ignition and formation in liquid. 4. Demonstration of capabilities of electric discharge at small depth for liquid decontamination purposes.

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Numerical Study on the Influence of Design Parameters on the Hot Gas Flow inside the High Voltage Circuit Breakers

Ha M.J.[1], Park J.H.[1], Byeon J.Y.[2]

[1]*Power & Industrial Systems R&D Center, Hyosung Corporation, Anyang-Si, Korea, manjuny@hyosung.com*
[2]*School of Mechanical and Aerospace Engineering, Seoul National University, Seoul, Korea*

In the present study, numerical simulation program was developed based on CFD taking into account physical phenomena such as arc, radiation, nozzle ablation, contact moving. Due to high temperature during current interruption, heat transfer is dominated by radiation. Radiative heat transfer was calculated with DOM (Discrete Ordinate Method) radiation model. Influence of design parameters – geometries of nozzle, expansion chamber – was investigated with numerical simulation. Pressure build-up in the expansion chamber and flow of hot gas inside the circuit breaker were investigated with different design parameters. Numerical results were compared with experimental data to validate the simulation results.

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Diagnostics of Plasma Jet Generated in Water/Argon DC Arc Torch

Hurba O.[1,2], Hlína M.[1], Hrabovský M.[1]

[1] *Institute of Plasma Physics AS CR, v.v.i., Za Slovankou 1782/3, 182 00 Prague 8, Czech Republic, ipp@ipp.cas.cz*
[2] *Charles University in Prague, Faculty of Mathematics and Physics, Ke Karlovu 3, 121 16 Praha 2, Czech Republic, www@mff.cuni.cz*

Thermal plasma jet generated by the torch with water/argon stabilized arc was investigated. Plasma torches of this type have been used for plasma spraying, waste treatment and gasification of organic materials. Electric probes and schlieren photography were used for diagnostics of the

jet in the region downstream of the torch exit. Information about structure and shape of plasma jet was evaluated from the measured data. Large extent of radial plasma spread and high level of turbulence were found from both the schlieren and the probe diagnostics. Profiles of floating plasma potential and ion saturation currents were derived from probe measurements. Plasma temperature corresponding to measured ion saturation currents was determined using calculated composition of plasma assuming existence of local thermodynamic equilibrium.

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Preliminary Study of Mixing of Plasma Species in a Hybrid-Stabilized Argon-Water Electric Arc

Jeništa J.[1], Takana H.[2], Uehara S.[2], Nishiyama H.[2], Murphy A. B.[3], Bartlová M.[4], Aubrecht V.[4]

[1]*Institute of Plasma Physics AS CR, v.v.i., Za Slovankou 3, 182 00 Praha 8, Czech Republic, jenista@ipp.cas.cz*
[2] *Institute of Fluid Science, Tohoku University, 2-1-1 Katahira, Aoba-ku, Sendai, Miyagi, 980-8577, Japan, nishiyama@ifs.tohoku.ac.jp*
[3]*CSIRO Materials Science and Engineering, PO Box 218, Lindfield NSW 2070, Australia, Tony.Murphy@csiro.au*
[4]*Brno University of Technology, Technická 8, 616 00 Brno, Czech Republic, bartlova@feec.vutbr.cz*

This paper focuses on numerical simulation of mixing of plasma chemical species in the discharge region and upstream from a rotating disc anode in the worldwide unique type of thermal plasma generator with combined stabilization of electric arc by axial argon flow and tangential water vortex. This kind of arc has been used for plasma spraying and for production of syngas (a mixture of CO and hydrogen) from biomass.
We assume two-dimensional, axisymmetric, unsteady, compressible and turbulent plasma flow with inhomogeneous mixing of water and argon species, calculated by the combined diffusion coefficients method. Turbulence is treated by Large-Eddy Simulation with the Smagorinsky subgrid-scale model. Radiation losses from the plasma are employed by the partial characteristics method. The complete set of conservation equations is being solved numerically with the plasma properties dependent on temperature and pressure.
Results of simulation for 300-600 A and argon mass flow rates of 22.5-40 slm indicate inhomogeneous mixing of argon and oxygen-hydrogen species. The higher content of argon species in the central region of the arc occurs for higher currents. The argon diffusion mass flux is driven mainly by the concentration and temperature space gradients.

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Investigation of Arc-Anode Attachment Area by using High-Speed Camera

Ondáč P.[1,2], Mašláni A.[1] ,Hrabovský M.[1]

[1]*Institute of Plasma Physics AS CR, Za Slovankou 1782/3, 182 00 Prague 8, Czech Republic, ondac@ipp.cas.cz*
[2]*Department of Surface and Plasma science, Faculty of Mathematics and Physics, Charles University, V Holešovičkách 2, 180 00 Prague 8, Czech Republic*

We have experimentally investigated arc-anode attachment in dc plasma arc, stabilized by water vortex, by using a high-speed camera (maximum 1080 000 fps). The arc-anode interaction influences power distribution in the plasma, a flow structure of the plasma jet, and also lifetime of the anode. The anode is external copper disk located downstream of the exit nozzle, therefore direct observation of anode attachment region was possible. More than one attachment was observed in one frame with exposure time 0.25 μs or 0.29 μs . A width of the visible bright part of the attachments is not stable and changes with time. We have measured velocities of these attachments as well as the velocity of the plasma flow. During the whole period of motion of the attachment, its velocity is approximately constant and smaller than the flow velocity. The movement of the attachments corresponds with measured time dependence of the saw-tooth like voltage between cathode and anode, shown in previous publications.

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Investigation of Plasma Properties in a Narrow Gap for Short Time Current

Runge T.[1], Kopp T.[1], Kurrat M.[1]

[1]*Technische Universität Braunschweig, Institute for High-Voltage Technology and Electrical Power Sytems, Schleinitzstrasse 23, 38106 Braunschweig, Germany, t.runge@tu-braunschweig.de*

The investigation of plasma properties is needed for developing new surge arresters. To understand the behavior of the plasma it is important to identify its properties. Previous investigations of plasma properties are mostly limited at a current frequency 50 Hz. In the current study the plasma properties are investigated at short time current.

The investigations were carried out in a self-developed experimental model which is quenching the plasma in a defined narrow gap. This model is equipped with an outlet duct of different cross sectional areas. The model spark gap was tested according to the 8/20 μs impulse current with different amplitudes up to 23 kA. The measured properties such as the arc voltage and current during the impulse give an exposure about the plasma. The measured data have been implemented into a mathematical model in order to make it possible to calculate the plasma properties like the electrical conductivity, temperature and pressure over simplified relations at different points during the impulse current.

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Abstracts of Invited Lectures Presented at the 21st Symposium on Physics of Switching Arc, Nove Mesto na Morave, Czech Republic, 7. – 11. 9. 2015:

The Problem of Chemically Active Plasma Nonequilibrium. Review

Chernyak V.[1], Nedybaliuk O., Martysh E., Solomenko O., Fedirchik I., Iukhymenko V., Prysiazhnevych I., Veremii Iu.

[1] *Taras Shevchenko National University of Kyiv, Faculty of Radio Physics, Electronics and Computer Systems, Kyiv, Ukraine, chernyak_v@ukr.net*
[2] *A.J. Drexel Plasma Institute Drexel University 3141 Chestnut Street Philadelphia, PA 19104, USA*

The relationship of physical and chemical processes in complex plasma-chemical systems will be discussed in detail. Particular attention will be paid to the influence of chemical processes activated plasma on the properties of the plasma.
The physical and chemical processes in quasi-equilibrium and non-equilibrium plasmas are multi-channel. It is connected with the fact that they pass through a large number of vibrational or electron-vibrational levels with formation of excited states and excited intermediate products in different quantum states. Such multichannel nature of physico-chemical processes in the presence of deviations from thermodynamic equilibrium leads to the fact that the direct and inverse processes are often pass through different quantum states.
So, the question remains: how to change the level of the non-equilibrium state in plasma systems when reactive components are injected in it. We believe that a great importance it should have in the case of exothermic processes. This paper investigates some aspects of this problem.
Today, mutual consideration of chemical and physical processes allowed to increase the energy efficiency of the hybrid plasma - catalytic reforming of liquid hydrocarbons in several times. The features of the ethanol reforming with the influence of exothermic chemical reactions on the level of non-equilibrium gas-discharge plasma are discussed. It is shown that effect of chemical reactions on the level of non-isothermality plasma itself can be extremely high and aimed at reducing the difference between translational and vibrational temperatures of plasma. The coefficient of transformation of electric energy into the chemical energy of the produced syngas has substantial increase when plasma activation of both components of the fuel mixture is transited to the activation of the oxidizer only in the hybrid plasma-**c**atalysis partially-oxidation reformer system.

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Future Proof and Low Carbon Footprint Insulation for Switchgear

Kosse S.[1], Hammer T.[2]

[1]*Siemens AG, Corporate Technology, Erlangen, Germany, sylvio.kosse@siemens.com*
[2]*Siemens AG, Corporate Technology, Erlangen, Germany, thomas.hammer@siemens.com*

Gases with high dielectric strength are the major insulation medium in modern gas insulated switchgear (GIS). This contribution gives a short historical review of electrical insulation concepts in circuit breakers and switchgear. On this basis, today's status of GIS in terms of the amount of insulating gas used and its leakage rate is presented to deduce the technical requirements for new insulation concepts. Further on, taking into account environmental aspects and regulations, we discuss a minimal set of requirements which have to be fulfilled by future insulation gases and concepts.

The CO2 footprint of available modern switchgear will be shown and reflected on the given set of requirements.

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Understanding the Mechanisms of Capillary Arc Discharge Plasma and the Interactions between Plasma Jet and Propellants Used for Electrothermal-chemical Launcher

Li X.[1], Hang Y.[1], Jia S.[1]

[1] *State Key Laboratory of Electrical Insulation and Power Equipment, Xi'an Jiaotong University, Xi'an, Shaanxi, China, xwli@mail.xjtu.edu.cn*

In this work, a two-dimensional time dependent magneto-hydrodynamic (MHD) model of capillary arc discharge plasma is presented. A modified kinetic ablation model and a revised deposition model are applied in this model. The surface temperature of the capillary's inner wall which dominates ablation/deposition characteristics is studied and calculated by the successive approximation method. By solving this model, the transient radial distribution of capillary arc discharge plasma parameters is acquired. Then, the influence of the radial distribution of the plasma jet in the plasma-propellant interactions (PPI) is investigated and a two-dimensional model of this process is developed. The capillary model is verified by comparing calculated ablation radius and mass with experimental results and the PPI model is verified by radiation experiments. It is shown that the radial distribution of the plasma jet is important in the plasma-propellant interactions.

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Why the Arc, and its Interactions with the Electrodes, are Important in Predictive Modelling of Arc Welding

Murphy A. B.

CSIRO Manufacturing Flagship, PO Box 218, Lindfield NSW 2070, Australia, tony.murphy@csiro.au

Computational models of arc welding can be divided into two groups: those that focus on the workpiece (i.e., the metal parts being welded together), and those that focus on the arc. The great majority of models fall into the first group; they represent the arc through a two- or three-dimensional heat source, and predict properties of the workpiece such as the shape and depth of the fusion zone and heat-affected zone, residual stress and deformation, and microstructure.

Models that focus on the arc have gradually increased in sophistication over the years. Whereas they initially predicted only the properties of the arc, they now in many cases include the workpiece in the computational domain.

In this paper, I will show that models that including the arc and workpiece in the computational domain have very significant advantages over models that represent the arc as a heat source. This is because the interactions of the arc and the workpiece and electrode involve two-way coupling. The deformation of the workpiece, for example due to melting or the transfer of molten metal, affects the location of the arc–workpiece attachment, and therefore the heat transfer to the workpiece. Metal vapour formed by vaporization of the weld pool affects the properties of the arc and therefore the heat transfer to the workpiece. Only by modelling the arc and its interactions with the workpiece can the heat transfer be accurately predicted. If the model

is approximated by a heat source, measurements (for example of the temperature at several points in the workpiece) are required to calibrate the heat source properties.
A computational model of metal–inert-gas welding of aluminium has been developed that includes the arc, electrode and workpiece self-consistently. The model predicts the depth and shape of the weld pool, the fusion zone and the heat-affected zone for a wide parameter range. The model also predicts the thermal history at every point in the workpiece. This is the information that is required as input for finite element models that predict residual stress and deformation, and microstructure, of the workpiece. Combining the arc model with such finite element models promises to deliver a model that will predict all important properties of the weld without the need for calibration against measurements.

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Numerical Challenges of Arc Simulations and the Path towards a Perfect Code

Nordborg H.

HSR University of Allied Sciences, 8640 Rapperswil, Switzerland, henrik.nordborg@hsr.ch

The simulation of electrical arcs and other forms of gas discharges in industrial applications continues to be challenge. We argue that there are two sides to this problem. One has to do with the complexity of the physical processes involved. The other is related to numerical methods and high-performance computing. These two aspects are strongly interlinked. Just as it is impossible to write a good simulation code without knowledge about the physical models, it is also not possible to make progress with the physical modeling without access to a fast simulation code. Validation of complex numerical simulations requires a large number of parameter studies, which are only possible if each simulation is fast, robust, and converges towards a unique solution.
We argue that a more systematic effort to develop and optimize the simulation tools for arc discharges is required in order to accelerate research in this field and to make the results more useful for industrial applications. In particular, we need massively parallel and scalable simulation codes which solve the flow equations and the equations for the electromagnetic fields on a common mesh in a strongly coupled fashion. The tools should also support moving and deforming meshes in order to handle the opening of contacts and mesh adaption to reduce the computational effort. Although no tool satisfying all of these requirements exists on the market today, it could be developed rather quickly using available knowledge and known numerical algorithms. Only the solver for the Maxwell equations requires significant improvements in order to be suitable for gas discharge simulations. Here we present a path towards a vastly improved solver for electrical arcs, which can be built on existing simulation codes and commercial tools. We also discuss some of the research challenges involved and present some recent results.

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Development of Long Flashover and Multi-Chamber Arresters and Insulator-Arresters for Lightning Protection of Overhead Distribution and Transmission Lines

Podporkin G. V.

Streamer Electric Company, 195220 Saint-Petersburg, Russia, georgij.podporkin@streamer.ru

Long Flashover Arresters (LFAs) were suggested and developed for lightning protection of Medium voltage lines 3-35 kV against induced overvoltages and direct lightning strokes. Main feature of LFAs is increased length of lightning flashover path. The LFA's length may be several times greater than that of an insulator (string, etc.). Due to a special inner structure the LFA impulse flashover voltage is lower than that of the insulator and when subjected to lightning overvoltage the LFA flashovers before the insulator. Increased length of flashover insures quenching of power arc follow when current crosses zero. This phenomena can be called "zero quenching". Main advantage of LFAs is that current and energy pass outside the arresters.

Reported also are results of research and development of multi-chamber arresters (MCA) and insulators (MCIA) that combine characteristics of insulators and arresters. The base of multi-chamber arresters (MCA), including MCIA, is the multi – chamber system MCS.

MCS of first generation comprises a large number of electrodes mounted in a silicon rubber length. Holes drilled between the electrodes and going through the length act as miniature gas discharge chambers. MCS of this type insures power arc quenching when follow current crosses zero ("zero guenching").

MCS of second generation has more complicated chamber design but it quenches impulse arcs without a follow power arc ("impulse quenching"). The devices permit protection of overhead power lines rated at 10 to 220 kV and above against induced overvoltages and direct lightning strokes without using a shield wire.

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Pulsed Plasma Spraying of Liquid Feedstock for Coating Elaboration

Rat V., Mavier F., Bienia M., Lejeune M, Coudert J.F.

CNRS, University of Limoges, ENSCI, SPCTS UMR7315, European Ceramic Centre
12 rue Atlantis 87068 Limoges cedex, France, vincent.rat@unilim.fr

Growing needs in energy demand from industrialized and emerging nations compel many researches to improve the efficiency of energy management by focusing on the development of renewable energy sources and by tackling ecological concerns. For example, fuel cells, thermal barrier coatings in gas turbine industry or photo-catalytic coatings require advanced elaboration processes capable to manufacture nanostructured ceramic coatings. These materials must have specific service properties, like finely structured architectures and graded properties (porosity/chemical composition). Such refractory materials are deposited by cost-effective plasma spraying techniques possessing the advantage to treat materials with high rates (>kg/h) in high enthalpy medium (>10 MJ/kg). Ceramic nanostructured coatings can be now achieved whether nanopowders dispersed in a liquid are injected into an arc plasma jet. Controlling electric arc instabilities confined in non-transferred arc plasma torch is therefore a key issue to get reproducible coating properties. Consequently, self-sustained pulsed arc plasma jet is under study associated with a synchronous injection of droplets containing nanopowders. By adjusting the injection timing relatively to time-dependent enthalpy variations, heat and momentum transfers from plasma to materials are expected to be efficiently controlled. The electrical features of such a pulsed arc are presented and the enthalpy modulation is studied by means of optical emission spectroscopy. The plasma treatment of droplets is also shown to be dependent on the injection timing. Samples of in-flight nanopowders and coatings are also analyzed.

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Arc Modelling Challenges

Rümpler Ch.

Eaton Corporate Research & Technology, 1000 Cherrington Parkway, Moon Township, PA 15108, USA, ChristianRuempler@Eaton.com

Modeling of arcing phenomena is commonly used in the electrical industry nowadays, supporting the design process of equipment for low-, medium-, and high-voltage. In different applications arc discharges are used either as main interruption elements, e.g. in case of switching devices, or arcs can occur as fault events, e.g. as an arc flash in switchgear applications. In both cases a better understanding of the physical processes within the devices is needed in order to enhance product performance and mitigate risks in the development cycle. In this contribution some modeling challenges associated with these applications are discussed.

For low-voltage molded case circuit breakers (MCCB's), the interruption of high short-circuit currents causes large thermal and mechanical stresses. Due to device miniaturization and increasing demands for higher performance, a precise prediction of the interruption process is needed to enable design optimization. Therefore a modeling approach has been developed that covers the main physical processes during high-current arc interruption in low-voltage circuit breakers. The set of partial differential equations that describes the fluid flow, electromagnetic field, and radiation transport, respectively, are solved in a code-coupling approach which is based on customized commercial solvers. Splitting the calculation problem into separate tasks for fluid flow and electromagnetics enables a high performance solution.

Beside the challenges that come along with this complex setup, the opening motion of the contact arm due to magnetic forces has to be modeled, since it significantly influences the interruption performance. Because two codes are involved in the calculation, the mesh changes to represent different contact arm positions have to be managed and synchronized between the codes.

As a second example illustrating modeling challenges, the application of an arc modeling approach for the prediction of arc flash events in medium-voltage switchgear is discussed. Using a simplified setup, test data and modeling results are compared and analyzed. One major challenge that was identified is associated with the high numerical effort due to the large switchgear volume and the long arcing time of up to 1 s.

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Future Perspectives on High Voltage Circuit Breaker Research

Seeger M.[1]

[1]*ABB Switzerland Ltd, Corporate Research, Segelhofstrasse 1, CH-5405 Baden-Dättwil, Switzerland e-mail: martin.seeger@ch.abb.com*

The research on high voltage circuit breakers using SF_6 is addressed. An overview of current state of research in this field will be given and possible future research directions will be discussed on examples. Such directions are, for example, the radiative energy transport, the understanding and description of ablation processes at the nozzle and contact surfaces, the influence

of ablated vapors on pressure build up and interruption capability, the electric breakdown processes, departures from equilibrium, turbulence and the importance of magnetic fields and 3D modelling.

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Extended Methods of Emission Spectroscopy for the Analysis of Arc Dynamics and Arc Interaction with Walls

Uhrlandt D., Methling R., Franke St., Gorchakov S., Baeva M., Khakpour A., Brüser V.

Leibniz Institute for Plasma Science and Technology (INP Greifswald), Felix-Hausdorff-Str. 2, 17489 Greifswald, Germany, uhrlandt@inp-greifswald.de

Recently, a number of improved methods of optical emission spectroscopy have been proposed for the study of high-current arcs with special emphasis on the treatment of optical thick arc radiation and analysis of the arc dynamics. The paper gives a short review on these methods focusing on the determination of plasma properties by means of comparison of measured and simulated emission spectra and the use of high-speed video spectroscopy. The application of these methods is demonstrated for a specific example; the study of the interaction of arcs with side walls and the impact of ceramic coatings on the wall's protection. For that purpose, a free burning arc experiment with CuW electrodes is used. The strong electrode erosion causes the arc operation in copper vapour with high stability and reproducibility. The arc temperature profile is obtained from measurements of copper line radiation complemented with radiation transport simulations. The impact of the arc radiation on the evaporation of different ceramic coatings of side walls is studied by video spectroscopy. The resulting impact on the heat load of the walls is derived from thermographic measurements.

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Modelling of Turbulent SF_6 Switching Arcs

Zhang Q.[1], Yan J. D.[1], Yan G.[2]

[1]*Department of Electrical Engineering and Electronics, the University of Liverpool, Brownlow Hill, Liverpool, L69 3GJ, UK, yaneee@liverpool.ac.uk*
[2]*Henan Pinggao Group Co., Ltd. Nanhuandong Road, Pingdingshan City, 467001, China*

There is an overwhelming experimental and theoretical evidence indicating SF_6 arc burning in a supersonic nozzle (known as the switching arc) is turbulent and in local thermodynamic equilibrium (LTE). Such an arcing arrangement is commonly used as the interrupter in high voltage circuit breakers (HVCB). In order to reduce the development cost of HVCB, it is highly desirable to predict the arc behavior under the operational conditions encountered in a power system. The major difficulty in achieving full computer aided predictive design of HVCB is the satisfactory prediction of the thermal interruption capability of an arc under turbulent conditions. Mathematical modelling of turbulent arc thus forms the subject matter of the present investigation.
The present work aims at a comparative study of the performance of relevant turbulence models in predicting the behaviour of SF_6 switching arcs during the current zero period. Turbulence models studied include the Prandtl mixing length model, the standard k-ε model and its two variants, i.e. the Chen-Kim model and the RNG model. In order to demonstrate the effects of turbulence, a laminar flow case is also modelled. Based on the computational results, a detailed analysis of the physical mechanisms encompassed in each flow model is given to show the adequacy

of each model in describing the rapidly varying arcing process during the current zero period. The computed values of the critical rate of rise of recovery voltage (RRRV) are subject to verification by experimental results covering a wide range of discharge conditions. The relative merits of the flow models are discussed.

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