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CONTENTS

Albena Asenova and Peter Dineff Bulgaria
High-voltage glow discharge in the plasma-chemical technology of high-porous media 9

Albena Asenova, Peter Dineff and Margarita Neznakomova Bulgaria
High voltage glow discharge in plasma-chemical surface modification technology 15

Genadiy Antonov Bulgaria
An induced EMF in the copper plate moving between electromagnet poles 21

Genadiy Antonov Bulgaria
About the electromagnetic field in moving bodies 27

Atanas Chervenkov and Todorka Chervenkova Bulgaria
An optimal loop shape, moving in a non-sinusoidal magnetic field, ensuring maximum repulsive force 34

Atanas Chervenkov and Todorka Chervenkova Bulgaria
Influence of the velocity on the optimal loop shape, ensuring maximum magnetic flux 40

Todorka Chervenkova and Atanas Chervenkov Bulgaria
Determination of induced eddy currents in linear parametric motor 46

Dimitar Dimitrov and Svetlozar Zahariev Bulgaria
Electronic device for control signal formation at a certain algorithm 52

Peter Dineff and Dilyana Gospodinova Bulgaria
√ **Characteristics of the low-frequency capacitive discharge** 57

Georgi Ganev and George Todorov Bulgaria
Influence of the harmonics on the step-down transformer core losses in the case of nonlinear loads 63

Georgi Ganev and Kostadin Iliev Bulgaria
Problems of EMC between the nonlinear loads and supply grids 70

Georgi Ganev and Georgi Hristov Bulgaria
Determination of the step-down transformer winding losses in the case of nonlinear loads 75

Marin Genchev, Antoaneta Todorova and Stoyan Petkov Bulgaria
Electrical characteristics of glass-filled high-viscous polyamide 80

Nikola Georgiev and Valentin Kirchev Bulgaria
Piezomotor 86

Nikola Georgiev and Margarita Georgieva Bulgaria
Piezotransformer of voltage 90

Dilyana Gospodinova and Peter Dineff Bulgaria
Low-frequency technological discharge at atmospheric pressure 94

Dilyana Gospodinova and Peter Dineff Bulgaria
No-load resonance of low-frequency capacitive electric discharge 100

Dilyana Gospodinova and Peter Dineff Bulgaria
Conditions for an electric resonance in various technological regimes of the low-frequency capacitive discharge 106

Vultchan Gueorgiev, Ivan Yatchev and Alexander Alexandrov Bulgaria
Experimental study of dynamics of solenoid electromagnet with ferromagnetic disc in the coil 112

K. Hinov, S. Shishkova, D. Boyadzhiev and I. Maslarov Bulgaria
Dynamics of polarized magnetic system supplied by discharging capacitor 118

Krastyo Hinov, Ivan Yatchev and Nikola Trifonov Bulgaria
Study of linear actuator with axially magnetised moving permanent magnet 124

Ivan Kostov and Alexander Alexandrov Bulgaria
Linear positioning of an electromagnet armature with a proportional action 131

Marin Marinov Bulgaria
Research of the conditions of work of a cast iron electrical heating plate 135

Iliana Marinova, Zaharinka Gergova and Alexander Alexandrov Bulgaria
Electrodynamic forces between conductors of arbitrary cross-section 142

Ivan Maslarov, Evgeni Sokolov and Krastyo Hinov Bulgaria
Polarized electromagnet with impact action 148

Ivan Maslarov, Evgeni Sokolov and Krastyo Hinov Bulgaria
Polarized proportional electromagnet 153

Kostadin Milanov and Mintcho Mintchev Bulgaria
Inrush current investigation in PWM converters 157

Radoslav Miltchev and Stanislav Bratkov Bulgaria
Internet-based system for controlling and monitoring rectifiers 163

Radoslav Miltchev and Stanislav Bratkov Bulgaria
Approach and technologies for development of embedded systems in electrical apparatus 169

Mihaela Slavkova and Mintcho Mintchev Bulgaria
Error of current transformers with half-wave rectified primary current 175

Mihaela Slavkova and Mintcho Mintchev Bulgaria
Influence of magnetic core material on error of current transformers with half-wave rectified primary current 181

Valerii Sudakov and Ivan Yatchev Bulgaria
Computer program for simulation of transient recovery voltage 187

George Todorov and Teodora Damyanova Bulgaria
Analytical model of a surface mounted permanent magnet synchronous generator*

George Todorov and Teodora Damyanova Bulgaria
Effect of the rotor configuration on the performance of permanent magnet synchronous generators*

I. Valkov, A. Arnaudov, V. Chincheva, T. Dimitrov Bulgaria
Solar water pump, powered by a 70Wp PV panel 193

* In additional appendix to volume II.

CHARACTERISTICS OF THE LOW-FREQUENCY CAPACITIVE DISCHARGE

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Abstract. The low-frequency electric discharge that burns at atmospheric pressure and industrial frequency (50/60 Hz) is represents a good technological alternative of the *RF*- and glow discharges at low pressure. Based on the external static characteristic of the discharge, basic electrical parameters are proposed, which are suitable for investigating and controlling the technological process of surface plasma-chemical modification.

Keywords: external (volt-ampere) static characteristic, high-pressure low-frequency discharge, plasma-chemical surface modification, surface current density, surface power density.

INTRODUCTION

The low-frequency capacitive discharge (*LF-CD*) at atmospheric pressure and industrial frequency (50/60 Hz) is the more and more frequently used alternative of glow and *RF*-electrical discharges in the technology of plasma-chemical surface treatment of polymers and polymer materials.

Burning of *LF-CD* discharge in air at atmospheric pressure is determined in the first place by the dissociation and ionization of oxygen and nitrogen i. e. by the production of ozone and the chemical active products resulting from its decomposition, and of the nitrogen oxides and their active oxidation. The variety of plasma-chemical processes is too much considerable and is an essential obstacle not only to accomplishing a general description of the technological process, but also to controlling the plasma-chemical modification.

Plasma-chemical processes going on in the *LF-CD* discharge are unambiguously connected with the development of electrical processes in the discharge. The external static characteristic of the *LF-CD* discharge that expresses the relationship between the average value of the electric current and the effective of the voltage applied can be used for explaining the electrical and plasma-chemical processes in the discharge.

Two characteristic operating sectors are observed on the external static characteristic of the *LF-CD* discharge. These operating sectors correspond to the behavior patterns of oxygen and nitrogen. We have shown the possibility to model these sectors by using a linear regression relationship.

THE TASK of the present work consists in the illustration of an original approach that allows describing and controlling the technological regimes of plasma-chemical modification through basic electrical characteristics of the *LF-CD* discharge.

THEORETICAL AND EXPERIMENTAL INVESTIGATIONS

The general view of the external static volt-ampere characteristic and straight-line operating sectors *AB* and *CD* are shown in Fig. 1a.

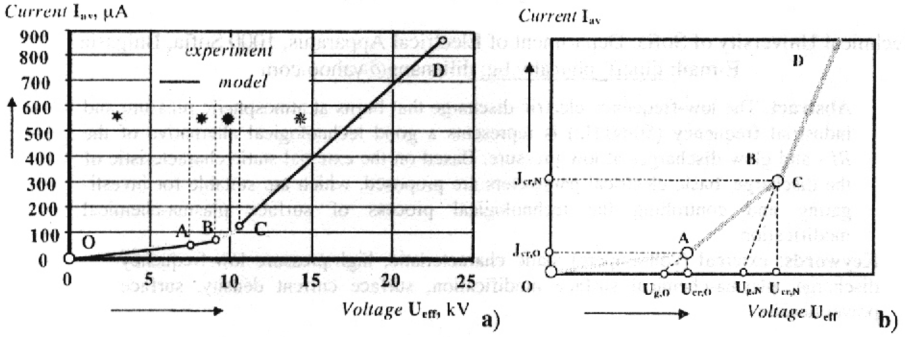

Figure 1. Characteristic sectors of the external volt-ampere characteristic of the *LF-CD* discharge, i. e. the relationship between the average current value I_{av} and the effective value of applied voltage U_{eff} (a): **OA** – non-operating sector; **AB** – first operating sector responsible for the electrical and chemical processes going on with the participation of oxygen; **CD** – second operating sector responsible for the electrical and chemical processes that go on with the participation of nitrogen; **BC** - transient region. Linear model of the external characteristic and critical electrical parameters (**b**) of the two transitions to the first (**A-B**) and second (**C-D**, point **B** ≡ point **C**) operating sectors.

Burning of *LV-CD* discharge is characterized by a constant voltage applied to the discharge or by a constant burning voltage U_g for the whole operating sector, irrespective of the values of supplied voltage U_{eff} and current I_{av}. Each operating sector is characterized by its own voltage of discharge burning, i. e. $U_{g,O}$ and $U_{g,N}$, respectively. The two voltages are represented by their effective values in the same way as they take part in the volt-ampere characteristic. Actually, after discharge ignition they should be represented by their maximal values, $\sqrt{2}\,.U_{g,O}$ and $\sqrt{2}\,.U_{g,N}$, respectively, for the effective value is meaningless under these conditions.

The equivalent electric circuits of the *LV-CD* discharge for different stages of burning may be presented by using corresponding voltage sources substituting for the discharge gap. The air gap is substituted by two capacitors, $C_{\delta}O$ and $C_{\delta N}$, connected in series in such a way that at the first non-operating stage of discharge development the equivalent circuit consists of three capacitors connected in series, Fig. 2a. At the second stage, the discharge gap is substituted by the in-series connection of a source of voltage equal to the burning voltage $U_{g,O}$ and capacitor $C_{\delta N}$, Fig. 2b. At the third stage, the discharge gap is substituted by only one voltage source $U_{g,N}$, Fig. 2c.

All subsequent considerations are made by using the demonstrated three equivalent circuits of the discharge and the plasma generator, Fig. 2.

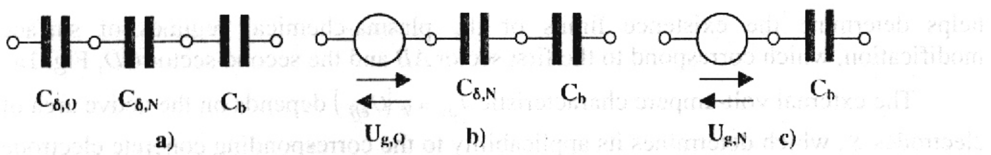

Figure 2. Equivalent electric circuits of a *LF-CD* discharge at the different stages of its development: **a** – non-operating stage, i. e. the electric discharge has not been ignited yet, the air gap is represented by the two capacitors, $C_{\Delta O}$ and $C_{\Delta N}$; connected in series; **b** – first operating stage corresponding to the active participation of oxygen; **c** – second operating stage corresponding to the active participation of nitrogen. These circuits reflect the model created for the elementary processes going on in the discharge, taking into account the participation of the two gases, oxygen and nitrogen.

The inclination of straight-line sectors in the external characteristic is determined by the capacitive reactances as follows, Fig. 2:

❑ for sector *OA*:

(1) $$C_{OA} = \frac{C_{\delta,O}\, C_{\delta,N}\, C_b}{C_{\delta,O} + C_{\delta,N} + C_b};\; C_{air} = \frac{C_{\delta,O}\, C_{\delta,N}}{C_{\delta,O} + C_{\delta,N}};\; C_{OA} = \frac{C_{air}\, C_b}{C_{air} + C_b}$$

❑ for sector *AB*:

(2) $$C_{AB} = \frac{C_{\delta,N}\, C_b}{C_{\delta,N} + C_b}$$

❑ for sector *CD*:

(3) $$C_{CD} = C_b\,.$$

The basic electrical characteristics for sector *AB* and the critical parameters, namely the critical current I_{cr} and critical voltage U_{cr}, may be wholly presented by the voltage of discharge burning $U_{g,O}$:

(4) $$I_{av} = \omega\, C_{AB} \left(U_{eff} - U_{g,O}\right);$$

(5) $$J_{av} = \frac{\omega\, C_{AB}}{S}\left(U_{eff} - U_{g,O}\right) = \frac{\omega\, C_{AB}}{S}\, U_{eff} - \frac{\omega\, C_{AB}\, U_{g,O}}{S} = B\, U_{eff} - A\,;$$

(6) $$P = U_{g,O}\left(I_{av} - I_{cr}\right);$$

(7) $$p_a = \frac{U_{g,O}}{S}\left(J_{av} - J_{cr}\right) = \frac{\omega\, C_{AB}\, U_{g,O}}{S}\, U_{eff} - \frac{\omega\left(C_{air} + C_{AB}\right) U_{g,O}^2}{S} = D\, U_{eff} - C\,;$$

(8) $$U_{cr,O} = \frac{C_{air} + C_{AB}}{C_{AB}}\, U_{g,O}\,;$$

(9) $$I_{cr,O} = \omega\; C_{air}\, U_{g,O}\,.$$

The external volt-ampere characteristic $I_{av} = \varphi\left(U_{eff}\right)$ is presented as a polygon of three straight-line sectors, each of which corresponding to a different stage of the development of the *LF-CD* discharge, Fig. 1b. In such a way, the variation of voltage applied helps determine the existence limits of the plasma-chemical regimes of surface helps determine the existence limits of the plasma-chemical regimes of surface modification, which correspond to the first sector *AB* and the second sector *CD*, Fig. 1a.

The external volt-ampere characteristic $I_{av} = \varphi(U_{eff})$ depends on the active area of electrodes S, which determines its applicability to the corresponding concrete electrode systems only. It is used with a scale change, namely $J_{av} = I_{av}/S$, for plotting the new characteristic $J_{av} = \xi(U_{eff})$ that does not depend on the active electrode area S any more and has a universal character as concerns the electrical processes, for it takes into account the intensity of elementary processes going on in the discharge itself, equation 5.

The processes of dissociation and ionization as well as the plasma-chemical processes that depend on the foregoing ones have a threshold-like character. For instance, the plasma-chemical treatment in ozone- and oxygen-containing cold plasma starts only after the *LF-CD* discharge has ignited, i. e. upon attaining the critical parameters of current and voltage, $J_{cr,O}$ and $U_{cr,O}$, respectively, which are responsible for the first operating sector *AB*, equations 8 and 9. The treatment in cold plasma containing nitrogen oxides, which is characteristic for the second sector *CD*, starts only after reaching the critical electrical parameters corresponding to the new transition: $J_{cr,N}$ and $U_{cr,N}$.

The technological effect of the modification depends not on the value of current density J_{av} at a given time, but on the difference $J_{av} - J_{cr,O}$. The specific quantity of electricity $q_S = J_{av} - J_{cr}$, carried over by the discharge per a unit of time through a unit of active area of the electrodes, represents a measure for technological effectiveness of emerging plasma-chemical changes in the air and on the polymer surface treated.

The variation of the specific quantity of electricity $q_{S,O}$ for the first operating sector *AB* may be described as a function of the voltage applied to the electrode system $U_{cr,O} < U_{eff} < U_{cr,N}$ and the discharge burning voltage $U_{g,O}$:

(10) $$q_{S,O} = J_{av} - J_{cr,O} = \frac{\omega\, C_{AB}}{S}\left(U_{eff} - U_{g,O}\right) - \frac{\omega\, C_{air}}{S} U_{g,O} \text{ or}$$

(11) $$q_{S,O} = \frac{\omega\, C_{AB}}{S} U_{eff} - \frac{\omega\, (C_{air} + C_{AB})}{S} U_{g,O} = B\, U_{eff} - \frac{C}{U_{g,O}}.$$

The technologically effective specific quantity of electricity $q_{S,O}$ may be also expressed by the surface density of active power p_a, equation 7:

(12) $$q_{S,O} = \frac{p_a}{U_{g,O}} = \frac{1}{U_{g,O}} p_a = k\, p_a,\ k = Const,$$

i. e. the variation of technologically effective specific quantity of electricity $q_{S,O}$ is proportional to the surface density of active electric power p_a.

Burning voltage $U_{g,O}$ has the meaning of a specific surface density of the active power of the *LF-CD* discharge, which is assigned to the technologically effective quantity of electricity carried over by the discharge per a unit of time through a unit of active area of the electrodes, or the burning voltage is an ***intensive characteristic*** of the technological process:

(13) $$U_{g,O} = \frac{p_a}{q_{S,O}} = \frac{p_a}{J_{av} - J_{cr,O}}.$$

The low voltage of burning $U_{g,O}$ defines a large quantity of electricity $q_{S,O}$ carried over by the discharge through a unit of active area of the electrodes:

(14) $$k = \frac{q_{S,O}}{p_a} = \frac{1}{U_{g,O}} = Const.$$

Four constants define the basic electrical and technological characteristics J_{av}, p_a, and $q_{S,O}$. These are *A, B, C,* and *D*. Constants *A* and *B* are determined on the basis of the experimentally obtained external static volt-ampere characteristic, while the rest of them are obtained from *A* and *B* by using the following basic relations in accordance with equations 5, 7, and 11:

(15) $$\frac{A}{D} = 1; \qquad \frac{A}{B} = \frac{D}{B} = U_{g,O}; \qquad \frac{C}{D} = \frac{C}{A} = U_{cr,O} = \left(1 + \frac{C_{air}}{C_{AB}}\right) U_{g,O}$$

It is sufficient to know four quantities *A, B,* $U_{g,O}$, and $U_{cr,O}$, in order to plot the basic electrical and technological characteristics of the *LF-CD* discharge for the first operating sector of the discharge's external static characteristic.

Analogous considerations are applied to describing the second operating sector of the external static characteristic.with the only differences that there exist different coefficients A* and B*, different critical voltage $U_{cr,N}$ and different burning voltage $U_{g,N}$ of the *LF-CD* discharge.

Fig. 3 illustrates the variation of burning voltage $U_{g,O}$ of the *LF-CD* discharge, which is characteristic for the first operating sector *AB*, with the variation of the parameters assumed, namely the thickness δ of the glass (alkaline glass) barrier and the size *b* of the air gap. The discharge is burning between two rectangular electrodes placed in a flat-parallel manner in a virtually uniform field.

Discharge burning voltage $U_{g,O}$ varies within rather wide limits, remaining between 2.5 and 10.0 kV in a rather large region of the factor space. There are, however, two regions, in which the burning voltage attains up to 20 kV, Fig. 3.

CONCLUSIONS

The present investigation demonstrates the importance of the basic electrical characteristics, namely discharge burning voltages $U_{g,O}$ and $U_{g,N}$, for the integral characterization of its technological behavior in the two main technological regimes.

The specific quantities of electricity $q_{S,O}$ and $q_{S,N}$ together with the surface density of active power p_a may be considered electrical parameters suitable for describing the technological behavior of the *LF-CD* discharge in the corresponding regime of burning.

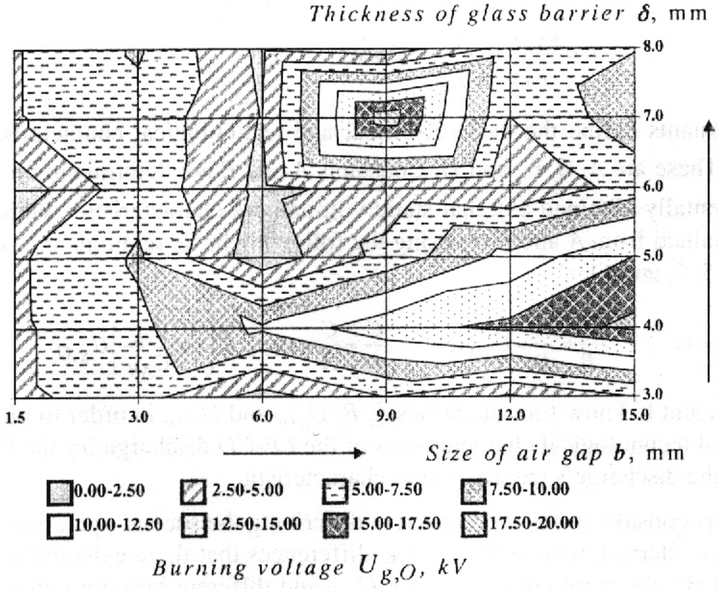

Figure 3. Variation of burning voltage $U_{g,O}$ for first operating sector *AB* of the external static characteristic of *LF-CD* discharge with the variation of barrier thickness δ and size b of the gap between electrodes.

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