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# NO-LOAD RESONANCE OF LOW-FREQUENCY CAPACITIVE ELECTRIC DISCHARGE

Diliana GOSPODINOVA, Peter DINEFF

*Technical University of Sofia, Department of Electrical Apparatus, 1000 Sofia, Bulgaria,
E-mail: dineff_pd@abv.bg; dilianang@abv.bg.

**Abstract.** Creating conditions for electric resonance of voltages in the electric circuit of low-frequency capacitive discharge allows realizing regimes with maximal active power. On the other hand, the active power is a measure for the effectiveness of plasma-chemical processes going on in the working gap of discharge. This determines the practical value of such an investigation. Resonance adjustment is carried out by adding a capacitance connected in series in the electric circuit.

**Keywords**: external (volt-ampere) static characteristic, high-pressure low-frequency discharge, plasma-chemical surface modification, surface power density, voltage or serial resonance.

## INTRODUCTION

The high-pressure low-frequency capacitive (*LF-CD*) discharge is an autonomous electric discharge that exists owing to the presence of a series capacitive ballast reactance introduced in the external electric circuit of the discharge in order to limit the electric current of the discharge [1].

The electric resonance is the frequency-based response of an electrical oscillatory system to an external periodical force action, which is expressed by the abrupt increase of the amplitude of steady-state oscillations. Such a response is observed when the frequency of external force action is approaching a definite frequency value, characteristic for the electrical system. Linear oscillatory systems are characterized by reactive and dissipative parameters, which do not depend on the magnitude of the external force action. The number of resonance frequencies corresponds to the number of degrees of freedom of the linear system. Resonance frequencies coincide with the frequencies of natural oscillations of the system [2].

The variety of elementary plasma-chemical processes that define the existence of *LF-CD* discharge at high pressure and low frequency (50/60 Hz) is very great and presupposes the existence of an electrical oscillatory system with many degrees of freedom or many frequencies of its natural oscillations.

**THE TASK** of the present work consists in examining the conditions, at which there exists a resonance of voltages in the electric circuit of the *LF-CD* discharge at high pressure.

These conditions should be used as a basis for investigating the possibilities of utilizing the technologically effective electrical regimes of discharge burning, characterized by high values of the surface density of active electric power.

## CONDITIONS FOR THE OCCURRENCE AND EXISTENCE OF AN ELECTRIC RESONANCE

The *LF-CD* discharge is an autonomous electric discharge characterized by the fact that the electric current is limited by connecting a capacitive ballast reactance in the external circuit of the discharge. The dynamic regime of burning provides a large value of *Debye*'s radius, which determines the existence of ideal classic plasma in relatively big technological volumes. This plasma is of low temperature due to the worsened impact interaction and exchange of kinetic energy between the light and heavy components of the cold plasma. The low-frequency capacitive discharge is the only electric discharge that produces cold technological plasma at high or atmospheric pressure.

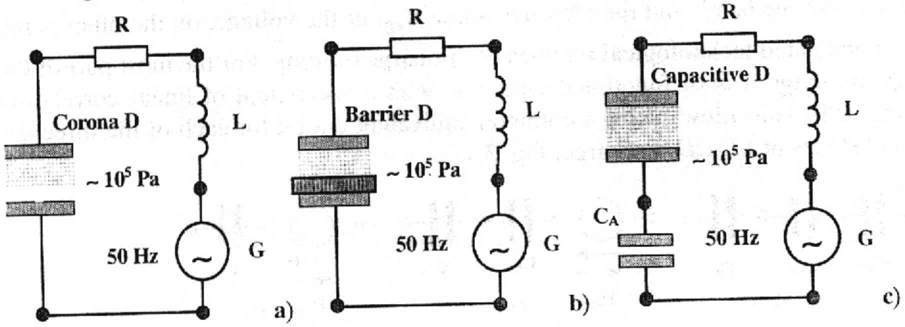



**Figure 1.** Types of *LF-CD* discharges at high pressure:
**a** – corona discharge; **b** - barrier discharge; **c** - capacitive discharge.

In the practice the *LF-CD* discharge is used under the forms of barrier, corona or capacitive electric discharges, Fig. 1.

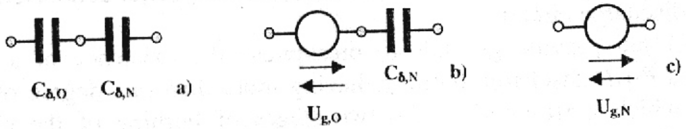



**Figure 2.** Equivalent circuit of the discharge region of *LF-CD* discharge for various stages of development: **a** – pre-discharge stage; **b** - discharge stage of plasma-chemical processes based on the oxygen in the air; **c** - discharge stage of plasma-chemical processes based on the nitrogen in the air. $U_{g,O}$ and $U_{g,N}$ are characteristic voltages of discharge burning.

The difference between the capacitive discharge and the other two types of discharges consists in the fact that in the latter two cases the capacitor is integrated by design into the discharge gap. The difference between the corona and barrier discharge consists in the fact that the barrier for the barrier discharge is made of hard insulation material, while in the corona discharge it is of the air that fills up that part of the air gap, which is free of electric discharge. A partial electric discharge in the air gap is present, Fig. 1.

Our investigations as well as those of other researchers allow proposing the use of an equivalent circuit of the discharge gap of *LF-CD* discharge of serial type. This equivalent circuit is different for each of the various stages of discharge development as a function of the voltage applied, Fig. 2.

The existence of two discharge burning voltages $U_{g,O}$ and $U_{g,N}$, that are specific for each *LF-CD* discharge depending on pressure, size of working gap, capacitance or barrier thickness, is experimentally confirmed. Each of the voltages of burning characterizes the *LF-CD* discharge in one of the two possible technological regimes of plasma-chemical modifications: *the first* of them produces ozone- and oxygen-containing cold plasma, and *the second* one plasma rich in nitrogen oxides, Fig. 2.

Our investigations confirm the existence of a linear relationship between the quantity of electricity $Q$, respectively the average value of electric current $I_{av}$ or its density $J_{av}$, on one hand, and the effective value $U_{eff}$ of the voltage, on the other hand, in the two indicated technological regimes of discharge burning. For the most part of the investigation range it is of functional type, i. e. with a coefficient of linear correlation exceeding 0.99. This allows using a common equivalent circuit for each of the three development stages of *LF-CD* discharge, Fig. 3.

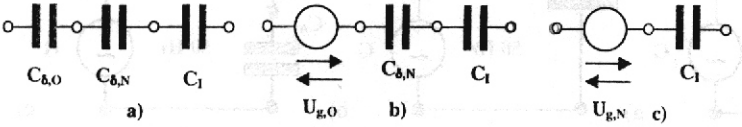



**Figure 3.** Common equivalent circuit for the various development stages of *LF-CD* discharge: **a** – pre-discharge stage; **b** - discharge stage based on the plasma-chemical behavior of the air oxygen; **c** - discharge stage based on the plasma-chemical behavior of the air nitrogen.

$C_I$ is the capacitance of the "sound" air gap of corona discharge, capacitance of the barrier located in the air gap, or capacitance of the ballast capacitor connected in series into the electric discharge circuit.

The facts disclosed provide grounds to presuppose the existence of a linear resonance system in *LF-CD* discharge burning, having more than one degree of freedom, two at least, which correspond to the two stages of burning of the electric discharge. The linearity is defined by the fact that the discharge burning voltage does not depend on parameters of the external electric field (force), i. e. on voltage $U_{eff}$ applied with a constant frequency of 50 Hz. The external force action is performed by the external source of voltage in the serial resonance, namely the electric resonance of voltages.

In a linear resonance system it is possible to use the principle of superposition, i. e. the response of the system to external force action consists of the responses of a multitude of oscillators that constitute it. In this situation, adjusting the oscillatory system into one of the multiple existing natural resonances leads to effective transfer of energy solely at the frequency characterizing namely this resonance. Although the rest of the oscillators do not work efficiently, they also consume energy.

So, the total energy-related parameters for this resonance are not at their possible maximum; for instance, the power factor is not at its maximal value, i. e. $cos\varphi = 1$. The total current is not of the form characteristic for the resonance with one degree of freedom. The curve shows the superposition of the current from the resonance maximum with the other currents. The so-called enveloping curve of the current with expressed local maximum is experimentally obtained. However, this maximum may be "swallowed" into the enveloping curve and will not be clearly expressed, [2].

Multiplicity of the resonance in the time-frequency range of investigation may be expected as the high sensitivity of the process should "bring to the light" a more detailed picture of processes, which go on in the discharge gap, and of their relation to the external force action, i. e. that resulting from voltage $U_{eff}$ applied across the discharge. At a constant frequency of the external force action (50 Hz) the susceptibility of discharge system may be modified by changing their parameters, and it will adjust itself into resonance through the change in the additional capacitance $C_A$ connected in series into the circuit.

This approach to investigation permits revealing all degrees of freedom in a linear resonance system like the *LF-CD* discharge. Introducing an additional capacitor and adjusting the discharge contour into electric resonance allows finding that discharge regime, which is the maximally effective one from the energy-related and technological viewpoints in each of the two technological regions of existence of the *LF-CD* technological discharge.

Due to the considerable amount of presented experimental characteristics, the examination is focused on a concrete *barrier discharge*. This barrier discharge is burning in the space between two plane electrodes for constant thickness $\delta = 3$ mm of the barrier - made of alkaline glass, located in the inter-electrode space, and for constant size $b = 3$ mm of the working air gap.

The plasma generator operates at no load, or the working gap is simply an air gap, i. e. no materials for surface plasma-chemical modification, that could influence the discharge electric characteristics, are placed into it. Non-influenced or electric resonance characteristics of the *LF-CD* discharge at no load are involved.

## EXPERIMENTAL RESULTS AND DISCUSSION

The external static volt-ampere characteristic of the *LF-CD* discharge investigated is plotted experimentally as a function of the values of additional capacitor $C_A$ connected in series or of the variation of natural resonance frequency $\omega_0$.

Each of the two operating regions of the external characteristic may be presented by a linear regression relationship of the form:

(1) $$I_{av} = B\,U_{eff} + A, \text{ for } U_g = |A|/B \text{ at } \delta, b = Const.$$

The variation of the basic parameters of the external volt-ampere characteristic as well as of several of the electric characteristics of discharge as functions of the natural resonance frequency changed by varying the capacitance value of additional capacitor $C_A$ is shown in Fig. 4.

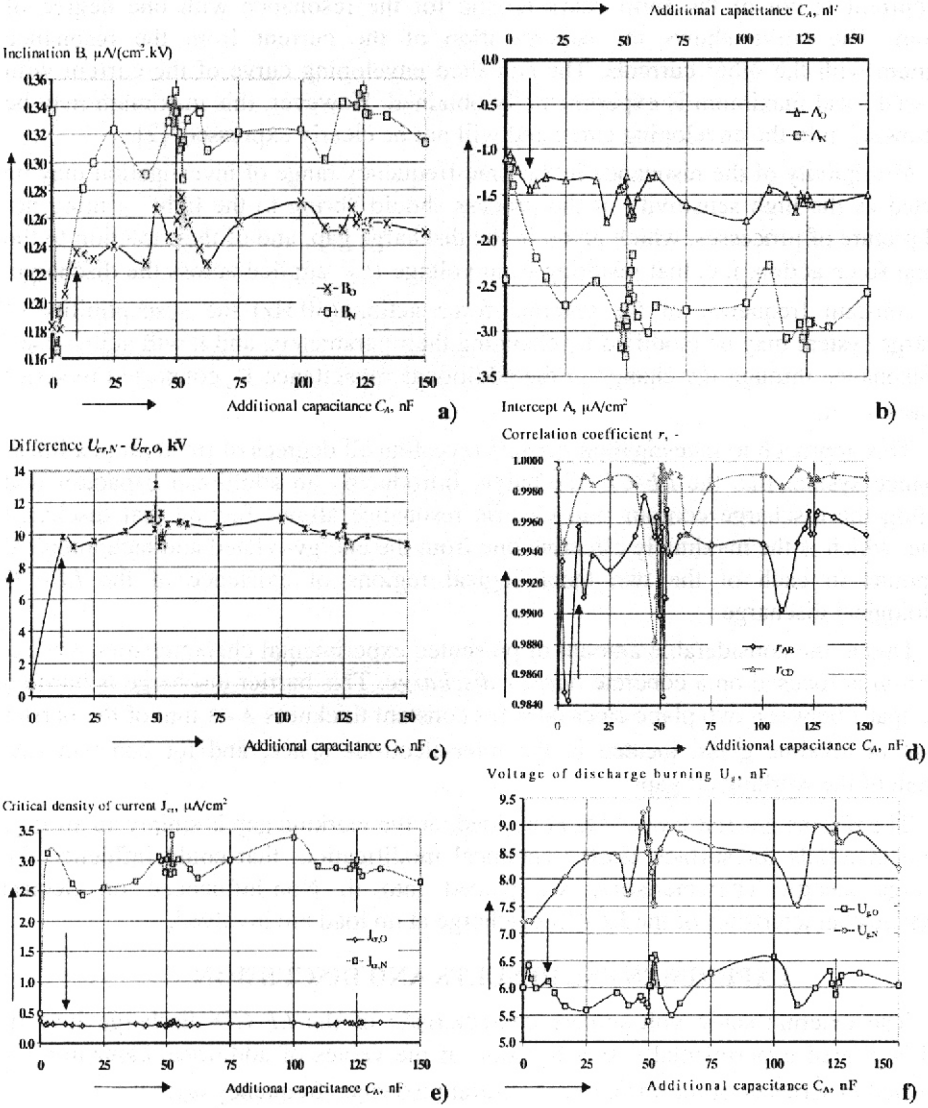
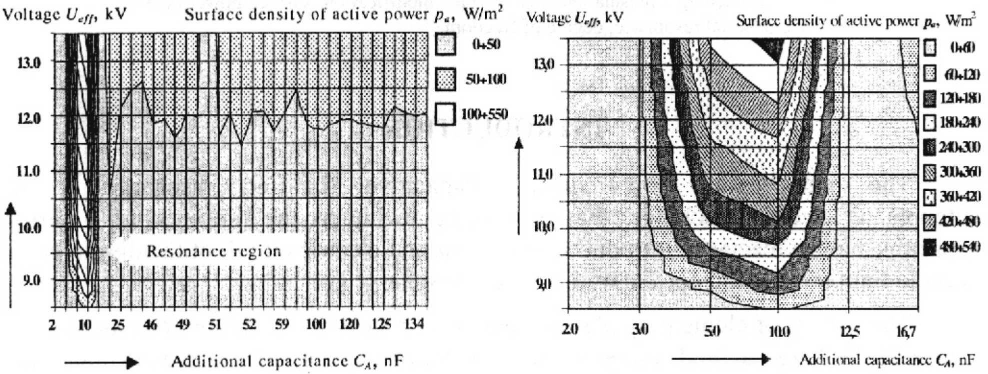



**Figure 4.** Variation of the parameters of the external volt-ampere characteristic of *LF-CD* discharge: inclination $B$ (**a**), intercept $A$ (**b**) and correlation coefficient $r$ (**c**), and of basic parameters: width of the first operating region $U_{cr,N} - U_{cr,O}$ (**d**), critical current density $I_{cr}$ (**e**) and discharge burning voltage $U_g$ (**f**), as functions of the value of additional capacitance $C_A$ for constant geometrical parameters: barrier thickness $\delta = 3$ mm and size $b = 3$ mm of working air gap.

In the same time the surface density of the active power $p_a$ of discharge is determined in order to find out that frequency of the multitude of natural resonance frequencies in the first operating region of the *LF-CD* discharge, which defines the maximal value of the surface density of active power $p_a$ or the maximal power that is transferred from outside the discharge. The natural resonance frequency that corresponds to additional capacitance $C_A$ = 10 nF defines an active power of discharge, which is about four times higher under these conditions, Fig. 5.

Comparing results of Figs. 5 and 4 indicates that the variation of either of the electric parameters of discharge relating to the first operating sector does not show in a doubtless way the place of the most effective resonance regime of discharge burning, that corresponds to the highest active power transferred from the mains to the electric discharge.

The effective burning of *LF-CD* discharge in conditions of serial electric resonance may be revealed solely through the characteristic $p_a = \varphi(U_{eff})$ as this is not allowed by the enveloping characteristic of the curves of remaining relationships in fig. 4.




a) b)

**Figure 5.** Investigation of the region of serial resonance (**a**) through the surface density of active power $p_a = \varphi(C_A)$ in the first operating region of the *LF-CD* discharge: an increase of the region (**b**) of resonance with a maximal value of $p_a$. In the region of local maximum $C_A$ = 10 nF the active power $p_a$ is about four times higher.

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