Effect of an external electrode on the characteristics of a low frequency discharge

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(Received: 1 September 2008 / Accepted: 24 December 2008)

The variation of the breakdown voltage of a low frequency electrical pulsed discharge due to an external electrode is reported. The discharge tube consists of a thin glass tube having two internal hollow electrodes. A thin copper foil wrapped around the glass tube forms the external electrode. The internal electrodes of the discharge tube are supplied by a flyback converter. Its operating point is self-adjusted being matched to the operating regime of the discharge. In this way the flyback converter has two functions, namely, to supply the discharge and to detect the discharge changes. The pulsed electrical discharge was achieved including the discharge tube and flyback converter in a relaxation oscillator circuit. The modifications of the relaxation oscillations threshold voltages if the external electrode is connected to the ground by means of a resistor are evidenced. The discharge tube is intended to be used as a plasma antenna. Because at low frequencies the RF excitation circuit is equivalent to a low impedance connection to the ground, the purpose of the work is to evaluate the RF excitation circuit influence on the characteristics of the discharge plasma. Measurements revealed that breakdown voltage decreases as effect of the external electrode.

Keywords: plasma antenna, hollow electrode, flyback converter, pulsed discharge, relaxation oscillator

1. Introduction

Plasma antenna technology represents a novel approach in the field of the wireless communications. Conventional antennas employ the various structures of metallic conductors in order to transmit or to receive rf signals. In the case of the plasma antennas the metallic conductors are replaced by the ionized gas columns. The purpose of the work is to evaluate the radiofrequency (RF) excitation circuit effect on the characteristics of a low frequency pulsed electrical discharge which is intended to be used as a plasma antenna. As will be described bellow the external electrode is a short metallic cylinder surrounding the discharge tube and connected electrically by means of a resistor to the ground. The shape of the external electrode is similar to that of the metallic sleeves used to excite plasma antennas [1]. This study has been suggested by the experimental observation reported in our previous work [2] regarding the frequency drift of a relaxation oscillator equipped with a gas filled voltage regulator tube owing to an external electrode. At low frequencies the RF excitation circuit is equivalent to a low impedance connected to the ground. This impedance is equal to zero if the metallic sleeve is connected to a tuned circuit or is equal to 50 Ω if the metallic sleeve is excited by a standard RF generator.

2. Experimental setup

The discharge tube DT consists of a thin glass tube, with an inner diameter of about 1.5 mm and an outer diameter of 5 mm, filled with Ne at few torr pressure, having two internal hollow electrodes, E1 and E2, which are separated by 150 mm (Fig. 1a).

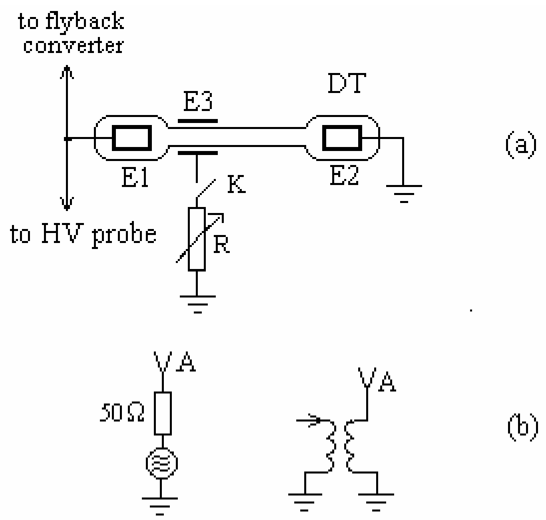

Fig.1 (a) Discharge tube (b)Two possible RF excitation circuits simulated by the resistor R.

The two internal electrodes are connected to the output of a flyback converter. A thin copper foil, with length of 30 mm, wrapped around the discharge tube, similarly to a metallic sleeve, forms the external electrode E3. The external electrode is connected by means of the variable resistor R to the ground. The switch K allows isolating the external electrode from the ground. The electrode E3 simulates the presence of a RF excitation circuit (Fig 1b). The flyback converter accomplishes two functions,

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namely, to supply the discharge and to detect the discharge changes. The method was inspired by the electronic lamp ballast technique. Electronic lamp ballast uses the switch mode power supplies to achieve the proper starting and operating electrical conditions for the fluorescent lamps [3-5]. A high voltage probe connected to the electrode E1 allows to measure the voltage across the discharge tube. The output of the high voltage probe is connected to a digital oscilloscope which records the voltage waveform.

3. Flyback converter operation

The electrical diagram of the circuit used to supply discharge tube electrodes is shown in Fig. 2.

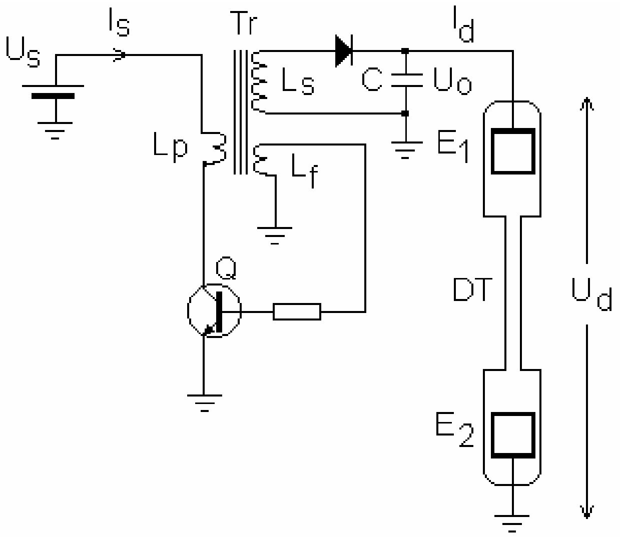

Fig.2 Electrical diagram of the flyback converter.

The electronic circuit represents a self oscillating flyback converter without output voltage control. The bipolar junction transistor Q operates as an electronic switch which interrupts periodically the electrical current through the primary winding. When the switch is on the energy provided by the dc power supply is stored in the magnetic field of the transformer ferromagnetic core. The voltage polarity across the secondary winding is negative, so that the secondary winding and the capacitor C are isolated by diode D. When the switch is off the voltage polarity across the secondary winding becomes positive and the stored energy is transferred to the capacitor C. The positive feedback necessary to switch the transistor Q is provided by the winding Lf. The load consisting of the discharge tube is connected directly to its output. No resistor ballast is necessary to be inserted into the load circuit. Accurate descriptions of the flyback converter operation on the flyback converter operation can be found in various papers (*e.g.* [6-8]). Here will be presented only general relations derived from charge and energy conservation laws which are necessary to understand the principle of the experiment. Generally, output dc voltage U_0, duty cycle δ, operating frequency f and dc supply current I_s of a flyback converter depend on the load. In the ideal case, without any losses, the period T of the flyback converter oscillations can be written as :

$$T = f^{-1} = \frac{N_p B_{sat} S}{U_s} + \frac{N_s B_{sat} S}{U_0} \tag{1}$$

where B_{sat} is core saturation flux density (usually ~0,3 T), U_s and U_0 are dc supply voltage and flyback converter respectively, while N_p and N_s are turns number for transformer Tr primary and secondary windings, respectively. Output dc voltage U_0 is given by:

$$U_0 = \frac{\delta}{1-\delta} \frac{N_s}{N_p} U_s \tag{2}$$

where δ represents duty cycle. The average power P_0 delivered to the load is:

$$P_0 = f\Delta W_0 = \frac{B_{sat}^2 S^2 f}{2A_L} \tag{3}$$

where ΔW_0 is the amount of energy transferred during a single period to the capacitor C, while S and A_L are, core effective cross-sectional area and core effective inductance of the transformer Tr, respectively. An important feature of the flyback converter is that the amount of energy transferred to the load during a single period depends only on the dimensions and magnetic properties of the transformer core. Due to the internal loses only a part of energy $\Delta W < \Delta W_0$ is transferred to the capacitor C. Consequently the capacitor C is charged progressively, time t_c taken for the voltage across its terminals to grow from zero to its steady state value U_0 being:

$$t_c = \left(\frac{CU_0^2}{2} \cdot \frac{1}{\Delta W} \right) \frac{1}{f} \tag{4}$$

In analogy to the charging of a capacitor series connected to a resistor, it may be considered that the output circuit of the flyback converter is equivalent to an ideal voltage source connected to the capacitor C through a non-linear circuit element conventionally designed as R_N in Fig.3. The output voltage U_0 is maxim when the output is open circuit (no discharge). By connecting a load the output voltage U_0 decreases. By an appropriate design the open circuit output voltage can achieve several kilovolts and initiate discharge. Once the plasma has been ignited, the operating parameters of the flyback converter (supply current, duty cycle and operating frequency) are self-adjusted so that the output voltage is matched to the operating regime of the discharge. The flyback converter used in our experiments is supplied by a low voltage dc source (Us=10-25V), operates at frequencies from 5 to 15 kHz and is able to deliver high voltages up to 5kV.

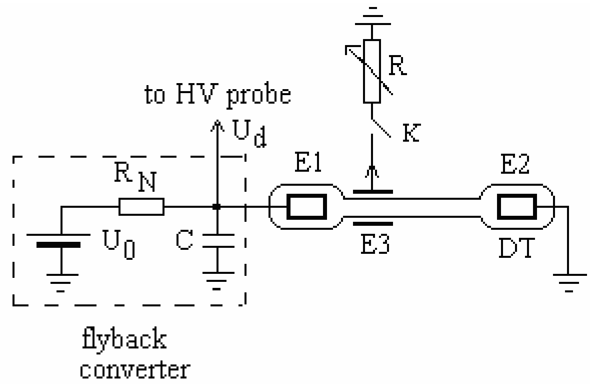

Fig.3 Equivalent electrical diagram of the experimental setup

The flyback converter can be also used to detect the discharge changes. Because the ballast resistor is missing the output voltage U_0 is forced to be equal to U_d. Accordingly to (2), any changes of plasma parameters yielding variations of the voltage $U_d \cong U_0$ lead automatically to the variations of the duty cycle δ. Consequently, according to (1) and (3), operating frequency f and dc supply current I_s, which is related to the power delivered to the load P_0, are modified. These variations can be easily detected and recorded.

4. Generation of relaxation oscillations

Using the experimental setup described above, under certain conditions, the relaxation oscillations can be started. The relaxation oscillations have been employed both to obtain a low frequency pulsed discharge and to evaluate the effect of the external electrode E3 on the breakdown voltage of the discharge tube. The topology of the equivalent electrical diagram of the experimental setup (Fig. 3) is similar to that of a relaxation oscillator. Basically, a relaxation oscillator is a circuit where a capacitor is charged progressively and then discharged rapidly (Fig.4).

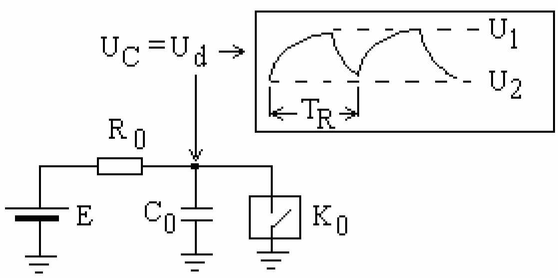

Fig.4 Basic diagram of a relaxation oscillator. Inset shows the waveform of the voltage across capacitor C_0.

According to Fig. 4, the progressive charging and discharging of the capacitor C_0 are performed by the device designed as R_0 and nonlinear switch K_0, respectively. The nonlinear switch K_0 is characterized by two treshold voltages U_1 and U_2. The state of the nonlinear switch depends on the voltage $U_K = U_C$ across its terminals. The nonlinear switch is on if $U_C > U_1$ and off if $U_C < U_2$. For $U_1 < U_C < U_2$ the state of the nonlinear switch depends on its previous state. The circuit can oscillate only if the dc supply voltage $E > U_1 > U_2$. The voltage U_c varies between the values U_1 and U_2 , the its waveform being similar to a so called "sawtooth wave". In the simplest case the capacitor C_0 is charged through a resistor while nonlinear switch consists of a discharge tube. The thresholds voltages will be $U_1 = U_b$ and $U_2 = U_m$, where U_b and U_m are discharge breakdown voltage and minimum voltage necessary to maintain the discharge, respectively. Voltages U_b and U_m represent two important parameters of an electrical discharge. By inserting the discharge tube in the relaxation oscillator circuit and by analyzing the waveform of the relaxation oscillations, U_b and U_m can be measured. In our case, as explained above, the capacitor C is charged gradually, receiving an amount of energy equal to ΔW during each period. If all the conditions necessary to occur relaxation oscillations are fulfilled and if the discharge time of capacitor C is neglected, then the relaxation oscillations period T_R for the circuit above considered is given by:

$$T_R = \left(\frac{CU_b^2}{2} - \frac{CU_m^2}{2} \right) \frac{1}{f\Delta W} \tag{5}$$

5. Experimental results and discussions

The breakdown voltage U_b and minimum voltage necessary to maintain the discharge U_m, have been measured for several values of the resistor R inserted between the external electrode E3 and the ground. For this purpose the dc supply voltage U_s of the flyback converter was settled to obtain relaxation oscillations. Therefore a pulsed discharge is obtained, electrical current flowing through discharge tube only during the rapid discharging of the capacitor C. The voltages U_b and U_m have been evaluated using the waveforms of the discharge voltage U_d recorded by a digital oscilloscope. A typical waveform, corresponding to U_s=19V, f=8.56kHz, R=0, C=6.2nF, open circuit output voltage for flyback converter U_0=3kV, is shown in Fig. 5. From experimental voltage waveform presented in Fig. 5 parameters U_b= 1.5 kV, U_m= 1.2 kV, T_R = 9.1 ms were determined. Note that if switch K is open (*i.e.* $R=\infty$) and $U_s \leq$ 19V then flyback converter output voltage is not enough to ignite electrical discharge.

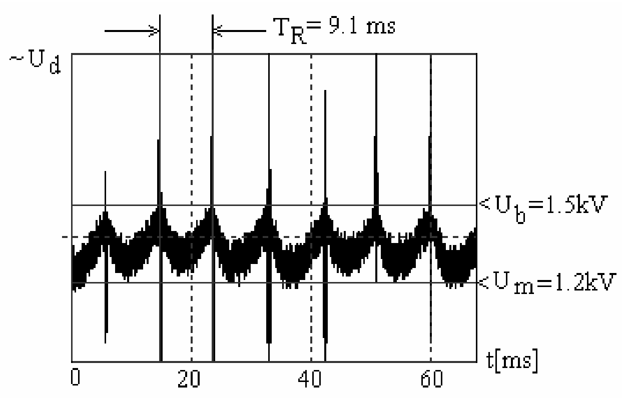

Fig. 5 Waveform of the voltage U_d across the discharge tube for $U_s=19V$, f=8.56kHz, $R=0$.

The voltages U_b and U_m versus resistance R are shown in Fig. 6.

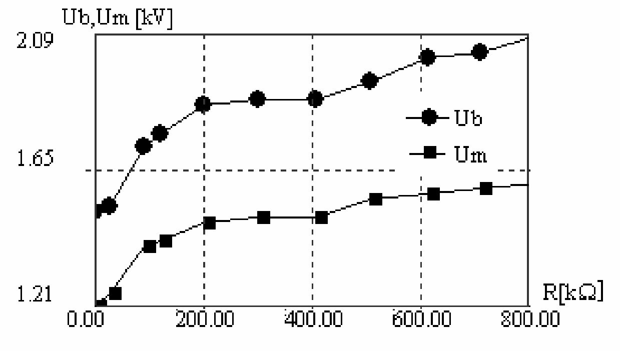

Fig. 6 Variation of the voltages U_b and U_m as a function of resistance R.

As can be seen from Fig. 6 both voltages U_b and U_m decrease if the external electrode E3 is connected to the ground. Magnitude of the effect decreases with increasing of the electrical resistance R between this electrode and ground. By varying the resistance R between the two extreme values, namely R=0 (electrode E3 connected directly to the ground) and $R=\infty$ (switch K open) the breakdown voltage U_b can be significantly changed. Let U_{bmin} be the breakdown voltage when external electrode is connected to the ground and U_{bmax} otherwise. If the flyback converter output voltage U_0 satisfies the condition $U_{b\min} < U_0 < U_{b\max}$, by closing switch K the discharge can be ignited even if the supply voltages is less than breakdown voltage $U_b = U_{b\max}$ of the discharge tube in absence of the external electrode. By opening switch K the discharge ceases to exist because, in this case $U_0 < U_b = U_{b\max}$. Therefore, if the discharge tube is used as a plasma antenna, the external electrode could have simultaneously two functions. The first is to perform RF excitation of the antenna and the second is to act as a control element for antenna operation. According to Eq. (5) and taking into account that ΔW depends only on the transformer ferromagnetic core characteristics and that frequency f remains practically constant, then the following relation must be satisfied:

$$\frac{1}{T_R}\left(\frac{CU_b^2}{2} - \frac{CU_m^2}{2}\right) = f\Delta W = P_D \approx const. \qquad (6)$$

The constant P_D may be interpreted as the average power transferred to the electric discharge by the flyback converter.

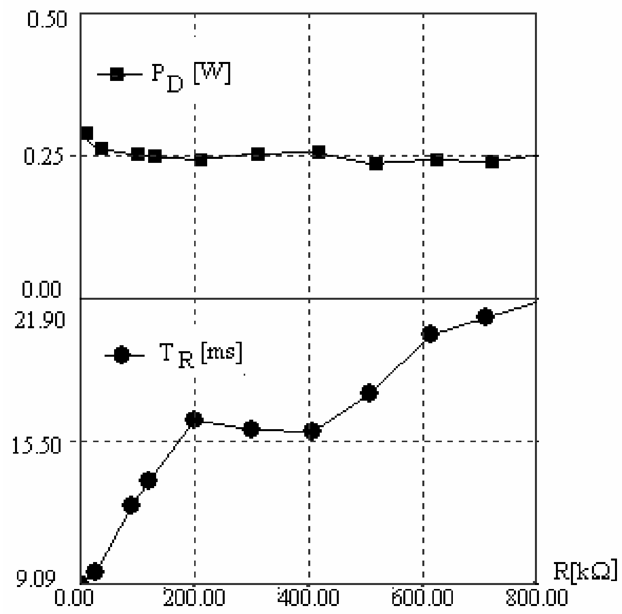

Fig. 7 The variations of the relaxation oscillations period T_R (bottom) and parameter P_D (top) as a function of the resistance R.

In Fig. 7 are shown the variations of the relaxation oscillations period T_R and parameter P_D as a function of the resistance R. The parameter P_D remains practically constant, around 0.25W. The variation of the dc supply current after the relaxation oscillations start was: $\Delta I_s \cong 0.02A$ which is equivalent to a supplementary electric power provided by dc power supply: $\Delta P_s = U_s \Delta I_s \cong 0.38W$. These results are in good agreement with the physical interpretation of the parameter P_D and with theoretical considerations.

6. Conclusion

We investigated the effect of an external electrode, placed outside of a glass discharge tube, on the properties of a low frequency pulsed electrical discharge. It was studied the case of a thin cylindrical glass tube having two hollow electrodes. A flyback converter has been used both to supply discharge tube and to study the discharge properties. The pulsed discharge is achieved including the discharge tube in a relaxation oscillator scheme. The modifications of the relaxation oscillations threshold voltages if the external electrode is connected to the ground by means of a resistor have been observed. The experimental arrangement was intended to simulate the presence of the rf excitation circuit when the discharge tube is used as a plasma antenna. Experimental results shown that, for this kind of geometry, a proper biased external electrode modifies significantly the properties of the electrical discharge. It has been experimentally demonstrated that, using an external electrode, the breakdown voltage of the tube discharge can be decreased. In this way it is possible to turn on and off, a plasma antenna only connecting and disconnecting, respectively, the rf excitation circuit. This work is done in the framework of the project PRET (2-Cex 06-11-7) and is supported by the National Authority for Scientific Research (ANCS) -Romania.

References:

[1] G. Borg *et al*. *Appl. Phys. Lett*., **74**, 3272 (1999).

[2] O. S. Stoican, *8th International Balkan Workshop on Applied Physics*, Constanta,Romania, July 5-7, 2007, Paper No. S2 P19.

[3] D. M. Vasiljevic, *IEEE Trans. on Industrial Electronics*, **36**, 499 (1989)

[4] G T Palmer *et al* , *Meas. Sci. Technol.* **6,** 1634 (1995)

[5] S. Chan et al. H. Chung, S. Y. Hui, *IEEE Trans.on Power Electronics*, **20,** 1450-1458 (2005)

[6] B. T. Irving, M. M. Jovanovic, *IEEE Applied Power Electronics Conf. and Exposition*, *2002 (APEC2002) Proc.*, **2,** 897 (2002).

[7] T. Suntio, , IEEE Trans. On Power Electronics, **21**,479 (2006)

[8] A. I. Pressman, *Switching Power Supply Design* (McGraw-Hill Professional, New York .1998) pp.105-141