Investigations on Impedance Behaviour of Microwave-Plasma at Atmospheric Pressure

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Abstract – **Impedance investigations of microwave plasma at atmospheric pressure are performed using an Arduino-based PC-controlled measurement system. A simple capacitive sensor is designed to monitor the impedance of the discharge at different conditions with impedance converter AD5933 connected via Arduino microcontroller board to PC. An appropriate equivalent circuit is proposed to describe the behavior of plasma impedance. Measurements results are obtained, verifying the equivalent circuit of microwave plasma.**

Keywords – **impedance, microwave-plasma, capacitive sensor, arduino**

I. Introduction

In this study we present a new technique for investigations of a small plasma source at atmospheric pressure. Microwave plasma is produced at low power levels by means of surface wave discharge in a ceramic tube with high permittivity [1-2]. The high thermal conductivity and high working temperature of the discharge ceramic tube allow permanent work of the source cooled only by air and ensure stable plasma parameters independent on the ambient conditions for a long period. Investigations of plasma impedance behavior at different discharge conditions are performed and an appropriate equivalent circuit is verified by measurements results.

Impedance behavior is a versatile tool used to characterize the intrinsic properties of any material and its interface. It is used in many applications such as monitoring electrochemical reactions, testing batteries, geological mapping, testing coatings and many other applications [3-4]. In recent years impedance spectroscopy is especially gaining popularity for biological and medical applications. Impedance tomography as well as impedance pletismography are just two examples of this new technique in medicine. Many integrated circuit suppliers deliver already Systems on a Chip – SoC, intended to measure impedance and to analyse electric network properties. These make the realization of measurement tasks in many cases much more compact, easier and completely realizable under PC control. In this work impedance measurements are used to investigate the miniature source of microwave surface wave discharge plasma at atmospheric pressure. An appropriate capacitive sensor is designed to monitor the impedance of the discharge at different conditions. An Arduino-based PC-controlled measurement system is developed, using the impedance converter AD5933 for measuring the impedance of the capacitive sensor. The capacitive character of plasma impedance with its real and imaginary parts allow for evaluation of plasma parameters – plasma density and temperature.

II. Arduino-based Microcontroller System with AD5933 Impedance Converter

AD5933 is a high precision impedance converter system solution that combines an on-board frequency generator with a 12-bit, 1 MSPS, analog-to-digital converter (ADC). The frequency generator allows an external complex impedance to be excited with a known frequency. The response signal from the impedance is sampled by the on-board ADC and a discrete Fourier transform (DFT) is processed by an on-board DSP engine. The DFT algorithm returns a real (R) and imaginary (I) data-word at each output frequency. A DFT is calculated for each frequency point in the sweep. The result is stored in two 16-bit registers representing the real and the imaginary components R and I of the result. The data is stored in binary two's complement format. The impedance magnitude and phase are easily calculated using the following equations:

$$\text{Magnitude} = \sqrt{(R^2 + I^2)} \quad (1)$$

$$\text{Phase} = \tan^{-1}(I/R) \quad (2)$$

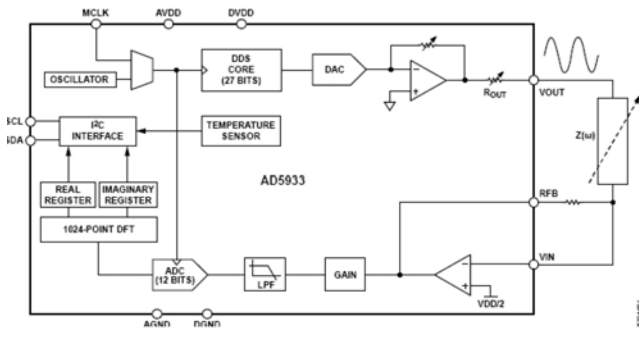

Fig.1. Impedance converter AD5933 (Analog.com)

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Once the magnitude of the impedance (|Z|) and the impedance phase angle (ZØ, in radians) are correctly calculated, it is possible to determine the magnitude of the real (resistive) and imaginary (reactive) component of the impedance (ZUNKNOWN) by the vector projection of the impedance magnitude onto the real and imaginary impedance axis using the following formulas: The real component is given by

$$|Z_{REAL}| = |Z| \times \cos (Z\emptyset) \qquad (3)$$

The imaginary component is given by

$$|Z_{IMAG}| = |Z| \times \sin (Z\emptyset) \qquad (4)$$

The system should be calibrated before measuring the unknown impedance applying known reference resistor at the input of the trans-impedance converter. Once calibrated, the magnitude of the impedance and relative phase of the impedance at each frequency point along the sweep is easily calculated. This is done off chip using the real and imaginary register contents, which can be read from the serial I2C interface.

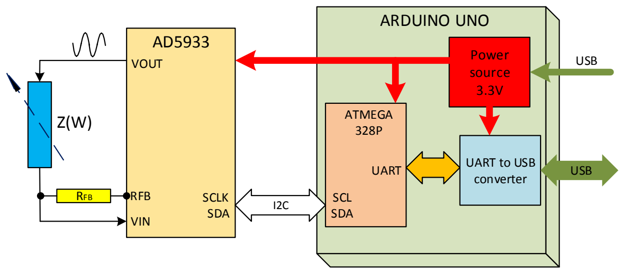

Fig. 2. Connecting Arduino to AD5933 via I2C and to PC via USB

The AD5933 permits the user to perform a frequency sweep with a user-defined start frequency, frequency resolution, and number of points in the sweep. In addition, the device allows the user to program the peak-to-peak value of the output sinusoidal signal as an excitation to the external unknown impedance connected between the VOUT and VIN pins. Control of the AD5933 is carried out via the I2C compliant serial interface protocol. The AD5933 is connected to this bus as a slave device under the control of a master device – the Arduino microcontroller board in this case. Arduino is connected via USB to a Personal Computer using open source coding for control and calculating the results [3]

III. Design of a Capacitive Sensor for Miniature Microwave Plasma Discharge at Atmospheric Pressure

To successfully investigate plasma parameters by means of the impedance converter AD5933, some constructions of an appropriate plasma impedance probe were considered [7-12], most of them based on the capacitive character of the plasma impedance. In this work a convenient capacitive sensor is designed to suite the features of the investigated microwave plasma source.

A. Miniature microwave plasma discharge at atmospheric pressure

The plasma source developed in [1] is operating at low power regime at atmospheric pressure and creates argon plasma in dielectric tube with inner diameter of 1 mm. This tube is an extension of open-ended coaxial structure. Microwave power at frequency 2.45 GHz is coupled into the source applicator at power levels 5-20 W. The plasma source operates as a plasma torch in case of plasma column longer than the dielectric tube length. The source maintains discharges over a wide range of neutral gas flow and works in continuous wave and pulse regimes of the input microwave power. The dielectric of the exciter of the surface waves is a ceramic tube with inner diameter of D= 1mm and outer of 2 mm of alumina ceramic with dielectric constant εd = 9.3, which is also used as a discharge tube. This material reduces significantly the exciter dimensions l1 to the length of 10 mm (l1~ λ0/4 d ε , λ0 – wave length in the free space).

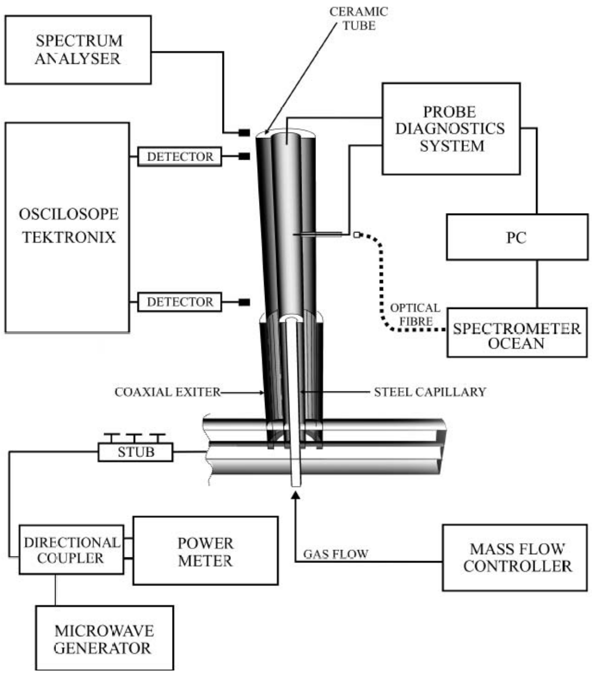

Fig. 2. Experimental set-up of microwave plasma discharge at atmospheric pressure

B. Capacitive sensor design

These small dimensions – length and diameter of the dielectric tube set specific demands on the plasma impedance probe which has to be used in our measurement system. Previously two ideas were discussed – first one about using a coax cable as a small antenna placed in the discharge torch, and second one – about a capacitive sensor built up of two rings slipped on the ceramic discharge tube. Considering the small inner diameter of the tube the usage of a coax as a capacitive sensor is not the best solution. Two thin copper wires with diameter 1mm wrapped around the ceramic tube at a distance of 5mm (fig. 3) are used as two rings of the capacitive sensor. The equivalent circuit of the sensor in absence of plasma discharge is given on figure 4. The capacitor formed of these two rings is approximately evaluated by the formulae:

$$C_o = \varepsilon\Pi(r_{out}^2 - r_{in}^2)/d, \quad (5)$$

where r_{out} is the outer radius of the ring;
and r_{in} is the inner radius of the ring.

Parallel to this capacitor in absence of plasma a resistance Rd is connected defined by isolation resistance of the dielectric tube. When however plasma discharge is excited inside the ceramic tube, the equivalent circuit is completely changed. Plasma inside the tube acts as a conductor, which is shown in the equivalent circuit in figure 5 by a resistance Rpl, added in parallel to C_o. The effect of plasma presence inside the tube is also indicated through adding of two equal capacitances C_c in series with this small plasma resistance. These capacitances are formed between each ring and the conducting plasma inside, divided not only by the wall of the dielectric tube but also by the pre-sheet at the inner side of the walls. The major change in the equivalent circuit is the emergence of an additional capacitance Cpl between the two copper rings as a result of plasma ignition which causes variation in the dielectric constant in-between the both metal rings of the capacitive sensor over the tube.

C. Equivalent circuit of the capacitive sensor

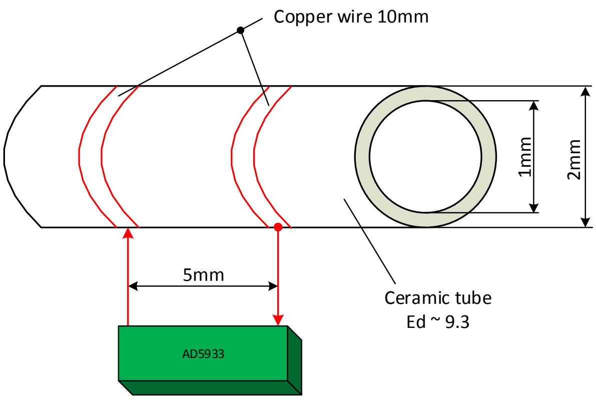

Fig. 3. Capacitive sensor over the discharge tube

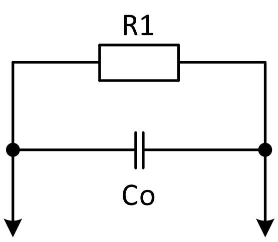

Fig. 4. Equivalent circuit of the sensor in absence of plasma

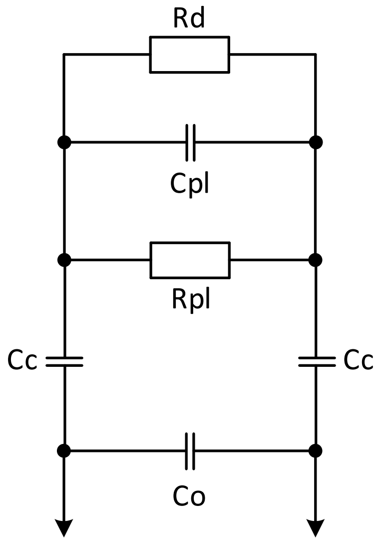

Fig. 5. Equivalent circuit of the capacitive sensor with plasma in the discharge tube

IV. EXPERIMENTAL RESULTS

Microwave plasma discharge at atmospheric pressure was investigated at three different values of discharge-sustaining power. The impedance of the plasma was measured by the impedance converter AD5933 connected to Arduino and PC according to figure 2. The level of exciting voltage was chosen 2V and the frequency set to 30Khz. Results for the |Z|-magnitude, the real and the imaginary part obtained by the measurement are shown in table 1 for 10W, 15W and 20W discharge power.

TABLE1. EXPERIMENTAL RESULTS

Power (W)	|Z| magnitude (Ohm)	Real part (Ohm)	Imaginary part (Ohm)
0 (No plasma)	74592	59673.6	44755.2
10	60988	36592.8	48790.4
15	42446	25467.6	33946.8
20	10123	6073.8	8098.4

Obviously the impedance of the sensor is changed significantly in presence of plasma. Parallel to the initial capacitance Co the series capacitances of the ring-dielectric-plasma-pre-sheet are added together with the parallel combination of plasma capacitance Cpl and plasma resistance Rpl. It is seen that increasing the power leads to significant reducing in the impedance of the plasma with reducing its real as well as its imaginary part.

V. CONCLUSION

In this work an impedance investigation of a microwave-plasma at atmospheric pressure is performed using an impedance converter AD5933 connected to Arduino platform and to PC. An appropriate equivalent circuit of the microwave plasma is proposed and verified by measurement results. The real and the imaginary part of the plasma impedance are measured and the effect of the microwave power sustaining the discharge is estimated.

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