Impulse Three Phase Power Supply Used for a Gliding Plasma Discharge

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Abstract. Power sources used for generating plasma have different configurations depending on the particular application; the aim here comprises the maximum energy transfer to the plasma discharge reaching. This work shows the performance and versatility of a simple impulse phase power source, applied to gliding arc plasma discharge. It is capable of changing the operating frequency from 5 kHz up to 150 kHz and the duty cycle from 1% to 33 % in all three phases, each one connected to three divergent tungsten electrodes. This allows a soft start plasma ignition until the full load is reached. This converter uses a sequential logic circuits composed by flip-flops, gates drivers, IGBT's and high voltage ferrite transformers. These features facilitate the maximum energy transfer to the plasma without using more complex electronic structures. The effect of frequency, duty cycle, voltage and current wave form signals is here described. This power supply has the adaptability to work whit different type of gas such as Argon, Helium, Air and Nitrogen. A Matlab Simulink simulation validates the experimental results. The main features and advantages of this configuration are also defined.

1. Introduction

One of the most important elements in a plasma discharge application is indubitably the power supply, since it must be capable to provide the necessary energy to ionize the gas leading the plasma discharge, in addition to guarantee the maximal power transfer to the load. There are several different power supply configurations, some of them use inverters, resonant circuits, and electronic converters supported by complex systems [1-4]. The impulse power supply here presented, unlike other systems, is able to modify the duty cycle in three or more phases providing a soft start plasma ignition. The operation principle is based in a sequential logic circuits which drives three IGB Transistors connected in common emitter configuration, which in turn drives three high frequency high voltage transformers. The gliding arc starts at the shortest gap (1.5mm) between divergent tungsten electrodes. In this region, due to thermal ionization of neutral particles, a thermal equilibrium between ions and electrons is obtained. Because of the axial gas flux entering into the plasma reactor, the electric arc glides along the electrodes and the discharge length grows until a critical length, determined by the power supply and gas flux; as the arc length expands, the heat dissipation increases. This results in a lowered temperature, and the plasma tends to be in non-thermal plasma discharge [5]. Beyond this point, the

energy provided by the electrical supply can no longer sustain the equilibrium phase in the gliding arc and the electrical conductivity of plasma channel decreases until the discharge extinction; then, a restrike appears in the shortest gap, leading to a new periodic cycle, therefore, the discharge regime changes alternatively from thermal to a non-thermal equilibrium medium. Both regions exist in the same chamber reactor, but depending on the location, different kinetics schemes can interact. As an example, according to several authors non-thermal regions were more appropriated for greenhouse-gas treatment [6]. In a sequential process, the gliding arcs have lifetime's ranges from 1to 250ms depending on the gas flow, gas nature and on the electrical field applied in diverging electrodes. Since the arc discharge incessantly glides, neither electrode deterioration nor erosion exists, increasing the electrodes lifetime. This phenomenon has been exploited and has been used for the treatment of pollutants [7-8] and greenhouse gases [9-10]. Recently, the power supply here described has been used for acid gas (H_2S and CO_2) degradation, obtaining high conversion rates and selectivity as well as the specific energy (SE) required during decomposition processes required to generate a mole of CO and H_2 (syngas). Another important factor is the specific energy consumption (SEC) applied to the gas mixture entering to the plasma reactor (H_2S and CO_2), the experimental results of SE (17.62 kJ mol^{-1} and SEC (30.02 kJmol^{-1}), as well as the CO_2 and H_2S conversion (29.41 % and 80.44% respectively) and finally the reforming system effectiveness (ECE = 59.05%) were reported elsewhere in [11]. Taking this into consideration, the SE, SEC, and ECE results obtained, place the high frequency pulse gliding arc discharge as one of the most efficient methods for the syngas production.

2. Experimental Setup

The general experimental setup is shown in Figure 1, it consists mainly of four sections: the first section is constituted by the working gas used (helium, argon, air or nitrogen) and the control gas instrumentation, as gas flow controller, mixer, and control valves required for the gas ministration into the plasma reactor. The second section is precisely the gliding arc reactor, composed by a quartz tube of 6cm diameter and 25cm length, inside the quartz tube laid three divergent tungsten electrodes connected to the output high voltage transformer. These transformers (third section) generate the voltage needed to reach the breakdown voltage aforementioned. The fourth section is composed by digital instrumentation to record the necessary experimental data.
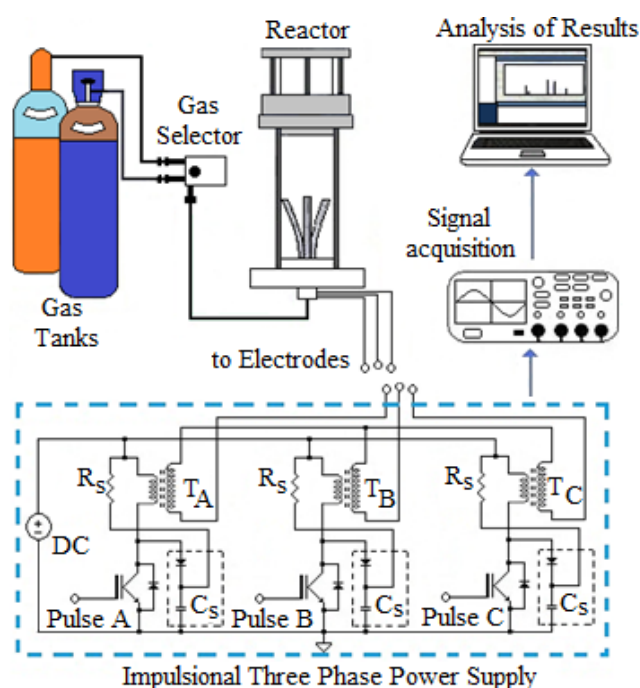

Figure 1. Experimental Setup.

The voltage required for generation of a gliding arc discharge depends on several factors, the nature of gas treated, the electrode material (tungsten), the distance between electrodes and the pressure at which it works. The breakdown voltage of the gas or gases involved in the discharge, can be calculated using the equation of Paschen's law [12] as follows:

$$V_{pd} = \frac{Bpd}{\ln(Apd) - \ln\left[\ln\left(1+\frac{1}{\gamma}\right)\right]}$$

(1)

Where V_{pd} is the breakdown voltage, p is the pressure, d is the distance between the tungsten electrodes; A and B are constants that depend on the gas composition and finally γ is the emission coefficient rate of electrons [13].

According the physical disposition of tungsten electrodes (Figure 2a) the electric field could be obtained (Figure 2b) by using equation (1), the tungsten emission coefficient Van der Wall constants can be obtained in references [13] and [14] respectively.

The experimental Paschen curves are described in figure 2c for the different gas used. In the case of He gas, the work area shows the region were plasma ignition arises, compared with the other gases (Ar, Air and N_2), helium has the lowest V_{pd} (circa 1kV), once the arc electric strikes, it glides along the electrodes and the arc voltage increases to a level that is not more sufficient to sustain the discharge (more than 4kV) and the arc blows-down, a new cycle recommences in the shortest distance between electrodes. Even if the air and N_2 need a most high breakdown voltage, the impulse power supplied is designed to work with these gases.
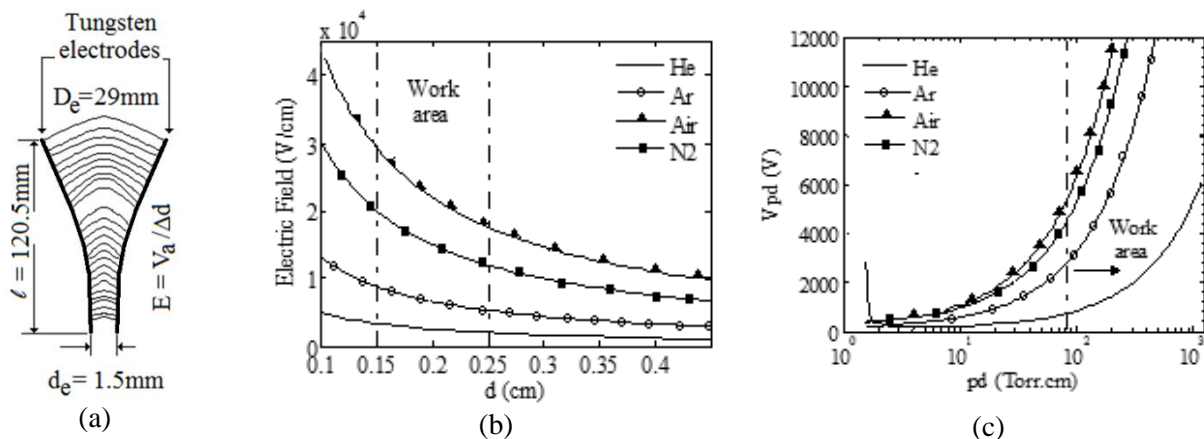

Figure 2. Experimental results: (a) physical specifications, (b) Electric field, (c) Breakdown voltage.

3. Impulse power supply- detailed description

The impulse three phase supply is illustrated in figure 3 just for a single phase; it is mainly composed of four stages: oscillator, sequential logic section, isolation section and power section. The PWM IC TL598 oscillator is responsible for generating the clock pulses, it can also varying the frequency in the order of 15 to 450 KHz and modify the duty cycle of 1% to 33%.

The second stage is a sequential logic circuit composed by a frequency divider (CI 74LS76 JK Flip-Flops) working in MOD8 to generate symmetrical and synchronized three signal pulses with a phase of 120° relative to one other. The next section is an isolation stage ensuring to minimize the possible noise interference from the power stage to the control stage. It consists of three optocouplers TLP250 IC and three Drivers (CI TC4422A) to ensure the required current to the pulse of each IGBT's gate. The fourth and final stage is the power section; composed by three IGBTs (SKM300GA123D) linked in common emitter configuration, and three high-gain (1:150) high frequency power

transformers connected in delta configuration to the converged tungsten electrodes. Each transformer has 5KVA of power capacity.
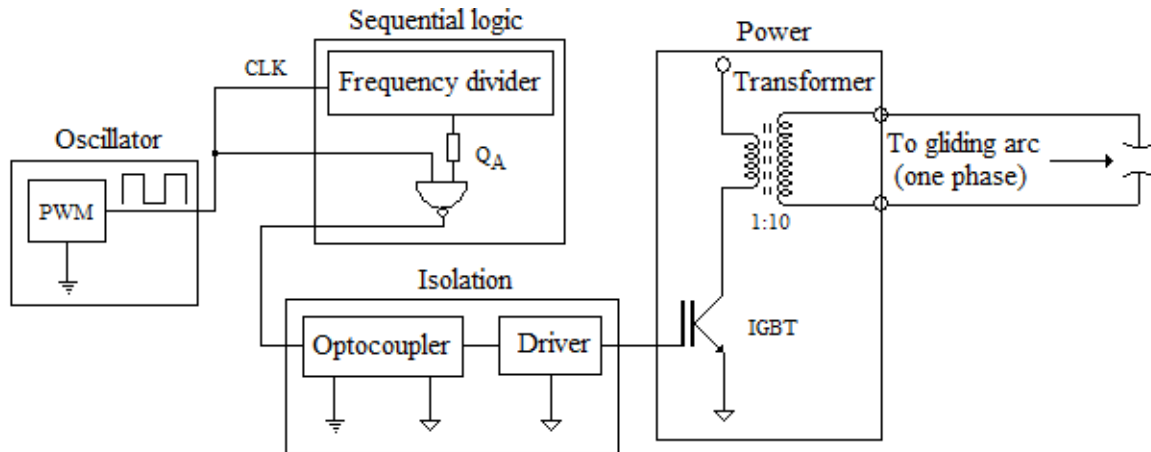

Figure 3. Diagram of the stages of digital control impulse for a single phase.

4. Analysis and results

In the oscillograme of figure 4 it can be seen that the pulses obtained at the gate of the IGBT 's, are shifted 120° relative to one other. Fig 4(a) shows 1% of duty cycle, while figure 4(b) has 33% of Duty Cycle. It is worth to mention that some dead time exist between each signal commutation, to avoid short circuit between phases. The control section works whit 15VDC.
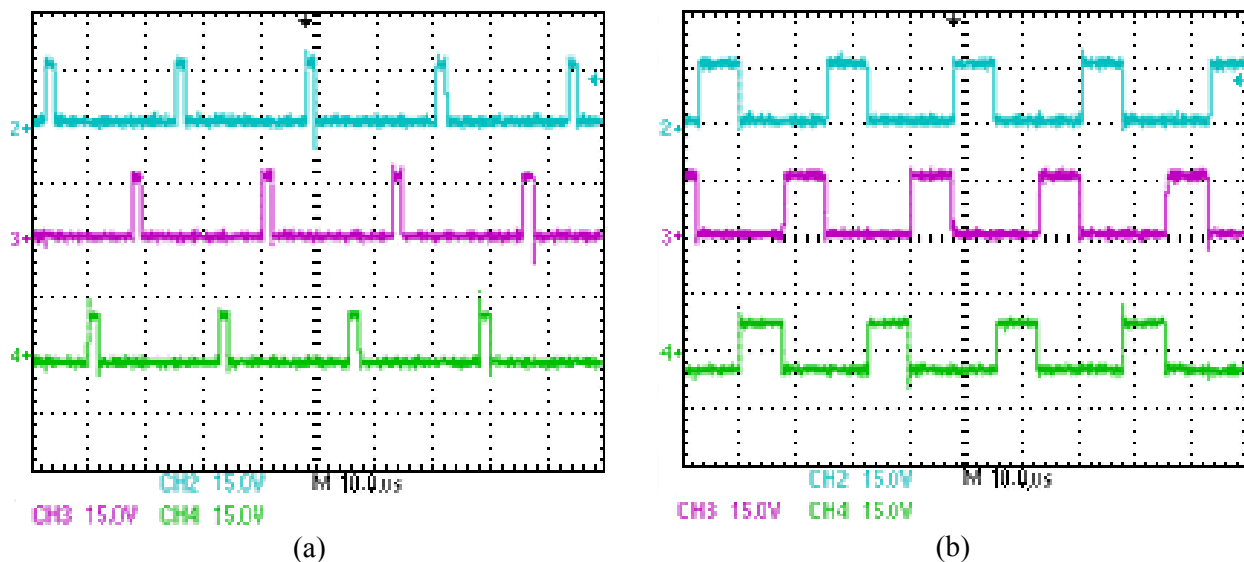

Figure 4. 15VDC gate pulses to (a) 1%,(b) 33%.

In the figure 5 shows the result of this experiment, where both the input power and the output power is measured to determine which ranges of frequency is optimized for maximum efficiency of the system in Helium and Argon plasma discharges.

In the case of Argon discharge (Figure 5a), the optimal frequency correspond to range from 5 kHz to 10 kHz. Note that after this range, the input power P_{in}, is increased considerably whit a relatively low output power P_{out}, consequently the efficiency decreases, therefore after this range it is not

adequate to work in the case of argon discharge. Similarly, in the case of Helium discharge the most adequate operation range lies between 5kHz to about 27kHz.
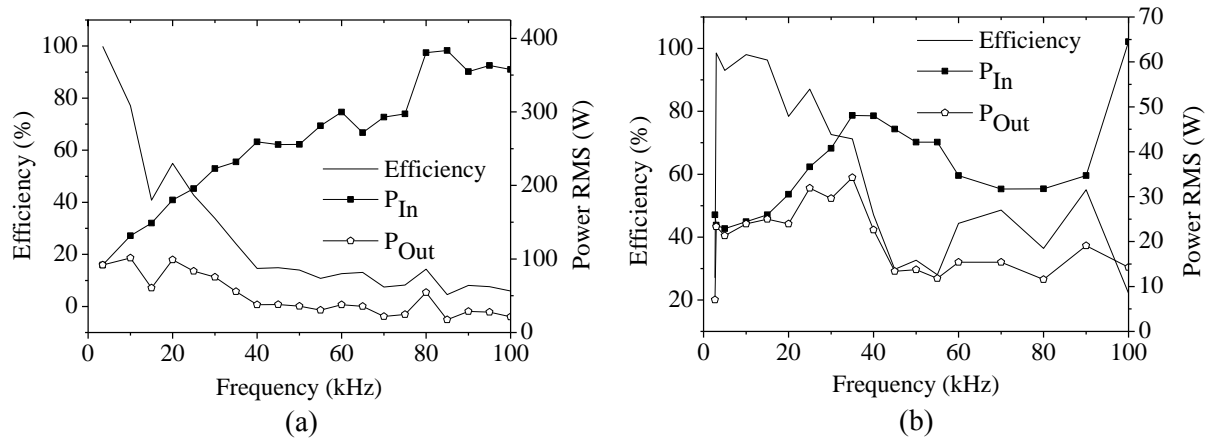

Figure 5. Effect of the frequency in: (a) Argon discharge, (b) Helium discharge

Figure 6 shows the electrical signals of instantaneous and RMS power derived from voltage and current which were obtained experimentally for different working gases: Figure 6a for Helium, Figure 6b for Argon, Figure 6c for Air, and Figure 6d for Nitrogen. In the same order, it can be observed that Helium needs only 75W of RMS power, while Argon needs 120W, Air requires 230W and Nitrogen involves 400W to work in stable conditions, this corresponds precisely for each gas conductance as was foreseen in Paschen curves in Figures 2b and 2c. Being precisely the nitrogen gas having the highest impedance and observing in the center column of Figure 6, it can be appreciated the evolution of the instantaneous change in impedance as the electric arc slides along the electrodes, in all cases the impedance shows a reduced value just when the discharge is well established, after that, the impedance has an exponential increase as the arc length grows until the electric arc extinction occurs and a new cycle begins. The nitrogen presents a more nonlinear behavior because some impedance variations are observed (from 29 to 38 µs) before the arc extinction, this is very possibly due to the nitrogen heat conductivity, which also varies depending on the electric arc temperature. From the instantaneous electrical signals it is possible to characterize the electrical behavior and to determine the impedance discharge for each gas analytical validated by using Matlab Simulink Algorithm in the forward section. This algorithm determines the impedance value, taking into account the resistive, capacitive, and inductive behavior of the plasma simply deduced by the electrical instantaneous signals *V(t)* and *i(t)*, according the following mathematical expressions:

$$R_d = \frac{\int_0^T V(t)i(t)dt}{\int_0^T \left(i(t)\right)^2 dt} \tag{2}$$

$$L_d = \frac{\int_0^T V(t)\frac{di}{dt}dt}{\int_0^T \left(\frac{di}{dt}\right)^2 dt} \tag{3}$$
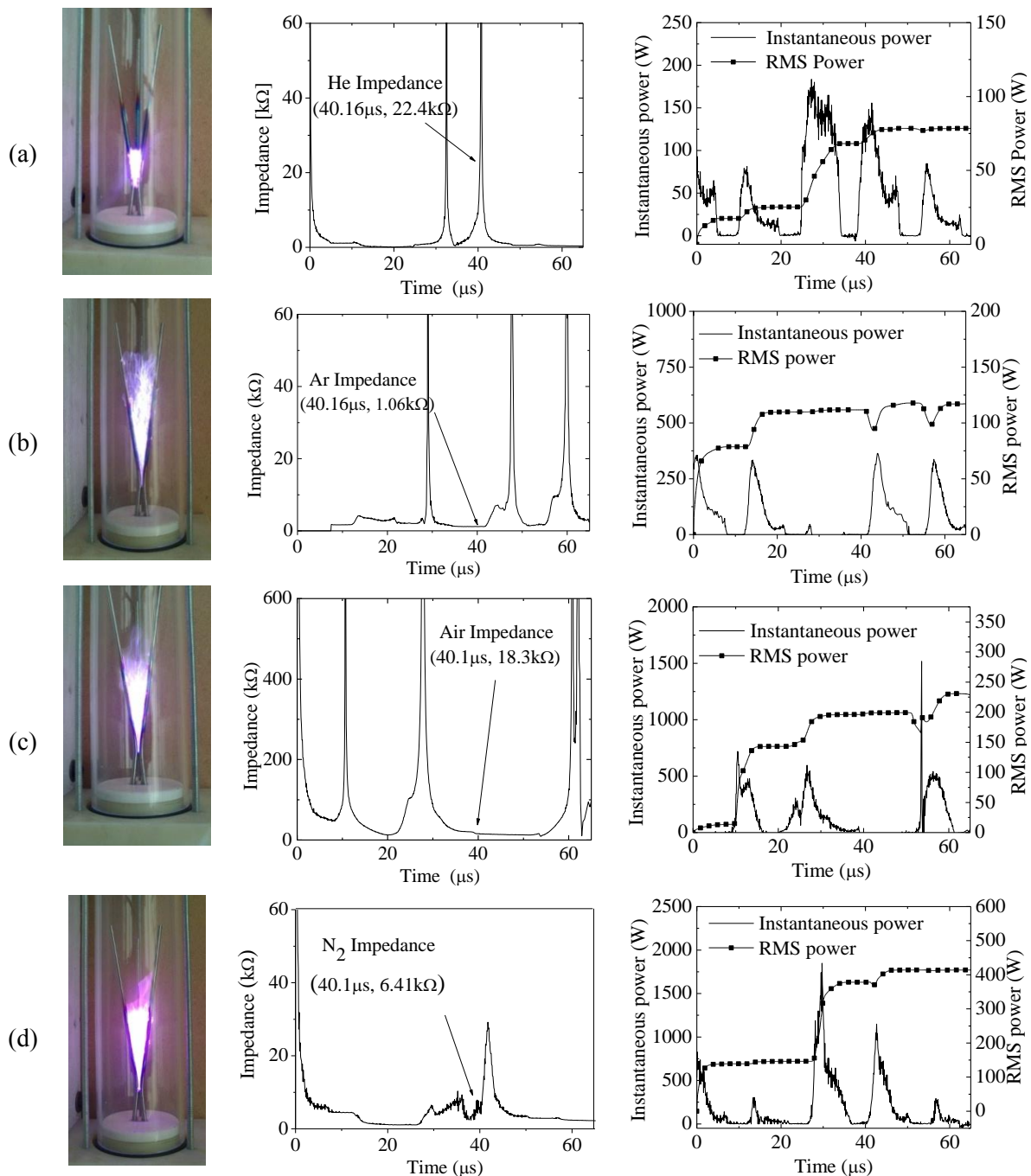
$$C_d = \frac{\int_0^T i(t)dt}{V(t)} \tag{4}$$

Figure 6. Electric signals and shock characteristics of hybrid plasma with different gases: (a) helium, (b) argon, (c) air and (d) nitrogen

Where R_d is the discharge resistance, L_d is the discharge inductance and C_d is the discharge capacitance, being $V(t)$ the instantaneous voltage applied to the discharge and $i(t)$ the instantaneous discharge current, which in turn correspond to the vectors of the experimentally obtained data voltage and the discharge current respectively.

After obtaining values expressed in equations 2, 3 and 4 one can next to determine the inductive reactance (X_{Ld}) and reactance capacitive (X_{Cd}) to finally find plasma impedance (Z_p), so, we have:

$$X_d = \sqrt{\left(X_{Cd}\right)^2 + \left(X_{Ld}\right)^2} = \sqrt{\left(-\frac{1}{2\pi f_s C_d}\right)^2 + \left(2\pi f_s L_d\right)^2} \tag{5}$$

Such that:

$$Z_p = \sqrt{\left(R_d\right)^2 + \left(jX_d\right)^2} \tag{6}$$

Being X_d extremely small, compared with respect to R_d, then, the plasma discharge impedance (Z_p), is purely resistive. In Figure 7, the algorithm which contains the aforementioned mathematical expressions is shown.

Also the power consumption is different, with nitrogen being the more power it consumes, but showing a better sliding, this according to the waveform of the instantaneous power of Figure 6d, where micro manifest -discharges that characterize this behaviour
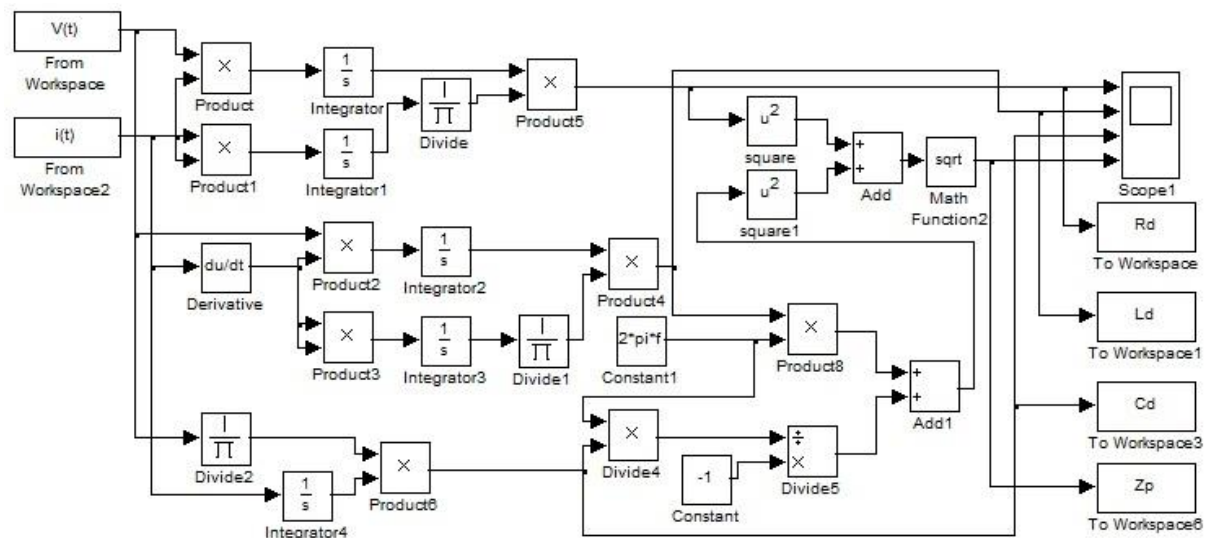

Figure 7. Algorithm in Simulink to calculate the impedance of the plasma.

5. Conclusions

This work shows the performance and versatility of a simple impulse power source, applied to gliding arc plasma discharge. It is capable of changing the operating frequency in a wide range, from 5 kHz up to 150 kHz. As well the duty cycle can be varied from 1% to 33 % in all three phases, besides; a dead time between impulsions avoids short circuit operation in power semiconductors.

Also, the paper describes a very versatile impulsion power supply, adequate to work in plasma discharges for different kind of gases; their principal features were exposed being the wide range of a frequency operation and duty cycle variation for soft start plasma discharge ignition. The gradual soft start avoids components damage in the power supply.

Moreover, this work defines the different impedance in plasma discharge according the gas used. By obtaining the instantaneous current and voltage signals, a data base can be constructed, subsequently, by the Matlab Algorithm application, the determination of the capacitance, inductance, resistance, and consequently impedance plasma discharge can be obtained.

The experimental system can be easily adapted to work with three or more electrodes, and the energy supplied is reduced to the required plasma value, depending on the kind of toxic gases treating. Finally it is found that the frequency and duty cycle are crucial for discharges with high efficiency.

Acknowledgments

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