Simple and Efficient Circuit for the Initiation Process of an Ablative Pulsed Plasma Thruster (APPT)

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A simple and highly efficient circuit for the initiation process of an APPT to be used for propulsion of microsatellites orbit and/or attitude control is presented. The circuit optimizes the weight-power ratio, the shot pulse voltage-time ratio, and the pulse repetition frequency. Experimental tests and simulation results are presented to validate the proposed circuit.

Introduction

Presently, there is a renewed interest in APPTs for a wide range of space missions. Ablative PPT is a device that takes power from the satellite bus to ionize and accelerate plasma electromagnetically with high velocity exhaust (10 to 20 km/s). This specific impulse permits an appreciable reduction of the propellant mass requirements, compared to a monopropellant and cool gas feed system.

These kinds of motors are utilized to execute orbital maneuvers for satellites up to 50 kg, to allow speed variations between 0 to 200 m/s.

The main advantages of the APPT are:

1. A high specific thrust let a reduction of up to 30 times in the mass of necessary thruster for a given maneuver.
2. Great thrust-to-volume and thrust-to-mass ratio let with respect to other types of electric propellers, to obtain better efficiency with compact designs.
3. High thrust-to-power ratio determines a reduced impact about the energy balance of the vehicle on which the propeller acts.

Two Argentine institutions are presently engaged in electric propulsion activities: Instituto Universitario Aeronáutico (I.U.A.), of Córdoba, and the College of Engineering of National University of Río Cuarto (U.N.R.C.). They are jointly developing an Ablative Pulsed Plasma Thruster (APPT) for micro satellites propulsion. IUA is mainly responsible for the system concept study, manufacturing and testing activities; U.N.R.C. is devoted to develop design and prototyping the high voltage power supply modules and a low thrust stand.

A simple and highly efficient circuit for the initiation process of an APPT for propulsion of microsatellites orbit and/or attitude control is developed. Trying to optimize the weight-power ratio, the voltage-time of the shot pulse ratio, as well as the pulse repetition frequency.

An inverter is designed and constructed to charge a capacitor of a resonant circuit. This resonant circuit is in its rest condition activated by a tiristor, producing a pulse on the primary coil of a transformer. The secondary coil of the transformer is connected to the initiation electrodes.

The circuit features include, frequency variation, tap charge, several resonant frequencies in order to obtain a better optimization.

In this paper, first materials and methods are described, them the power supply with their energy storage capacitor for field electrodes and the initiation process circuit is described, after that the results and finally the conclusions are presented.
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Materials and methods

The PPT consists on a bar of Teflon, which is the propellant source, firmly pressed between two annular electrodes by a spring. Which is the only mobile part of the system.

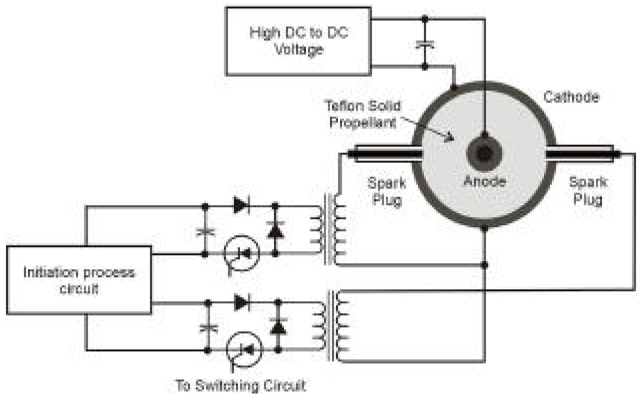

Figure. 1. Major components of the PPT.

Figure 2. APPT on the test stand

This motor conforms an ideal system for these small satellites because it is compact, it uses an inert propellant, it is easy to integrate and the mass is small (less than 5 Kg). Its low consumption (1 to 150 watts) can produce an impulse sufficient to enable great maneuver capacity that includes attitude control, orbit maintenance, or to pass to superior or inferior orbits.

Power supply

The APPT takes power from the unregulated power supply. A DC-to-DC converter charges a capacitor (3µF/4500V) to a regulated voltage between 2500V and 4000V. This converter is based on the CA3524 integrated circuit. An alternate voltage at 150KHz is obtained, through a ferrite core transformer and a rectifier, the capacitor is charged. To fix the capacitor voltage a feedback circuit is designed.

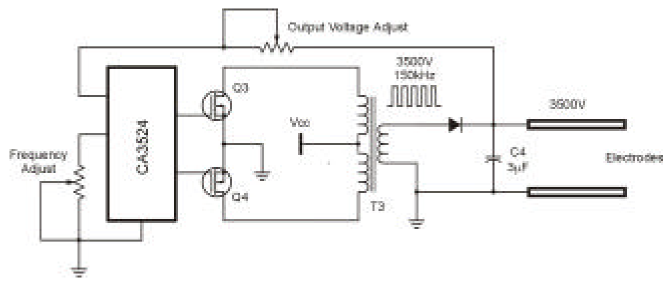

Figure 3. High voltage power supply scheme.

Energy storage Capacitor for field electrodes

In general it has been used in experiences the energy stored in a capacitor from 17µF to a voltage of 1500V, taking place in the discharge a current pick of 20kA with duration of 12µS. The consumed power is approximately 25W for a frequency of 1Hz.

This capacitor bank of 17µF is made in alternative layers of aluminum, mylar, paper and mylar with oil ONOCLOR 1016 sheets. They are in a cylindrical shape with a diameter of 12,7 cm, 8,9 cm of height and 1,93 Kg of mass, and they present a smaller parasitical inductance to 15 nH.

Initiation process circuit

Another converter designed in the same way that the previous one, charges two capacitors (8µF) to a regulated tension of 500V. Each capacitor has its own initiation process on an APPT circuit. The stored energy (1 to 2 Joules) in the capacitor, through a SCR and the coil, with a 50µS resonance frequency is discharged. This coil is magnetically coupled to another one (turns rate = 6); and generates a high voltage that produces a high intensity of electric field on a spark plug to let the initiation process of the APPT.

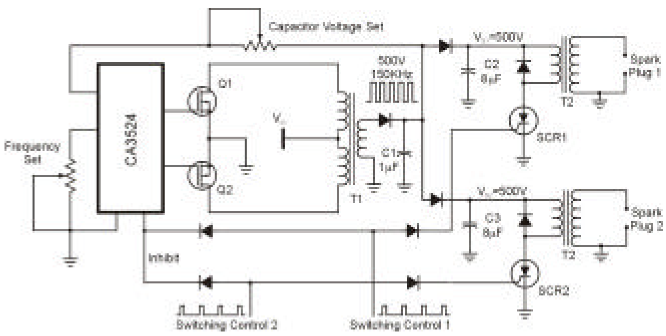

Figure 4. Power supply for Initiation process.

This discharge ablates a part of the Teflon bar and then is accelerated by electromagnet field to a high exhaust speed (10 to 20Km/s) producing the corresponding orbital maneuvers. After that, as the propellant is consumed the system spring-positionator, it relocates permanently to the bar among each shot.

Pulse transformer

The output voltage of the inverter is rectified by the diode D1 charging the capacitor C1 to a voltage of 500V.

When the SCR1 is fired, the capacitor C1 discharges their electrostatic energy into magnetic energy, and assuming that the circuit has no losses, the voltage oscillates and the current is senoidal. After the first positive semi cycle the current is cut off, because an inverse current cannot circulate through the SCR1 causing the opening of the SCR as a result.

The current that circulates for the primary coil L1 induces a voltage with a amplitude of 500V and T/2 of duration, being T the oscillation period. With an appropriate transformation relationship it is possible to obtain the 3500V necessary for the spark plugs.

The equivalent circuit of figure 5 is analyzed, I_{l0}=0 and V_{c0}=0, corresponding to t_0^+ are considered as the initial conditions.

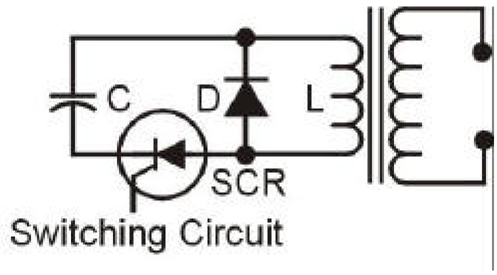

Figure 5: Proposed LC resonant circuit.

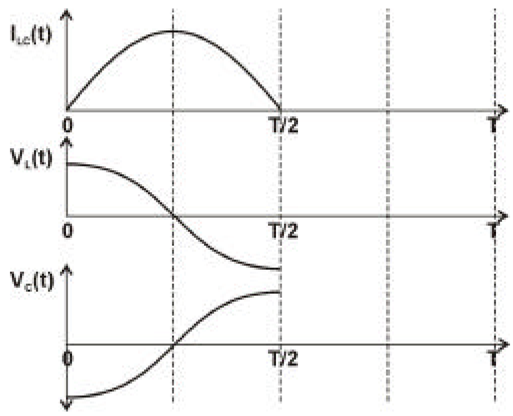

Figure 6: Waveforms of LC resonant circuit.

The equations of the circuit are:

$$v(t) = L\frac{di}{dt} + \frac{1}{C}\int i \cdot dt \qquad (1.)$$

Applying Laplace:

$$L\left(v(t)\right) = \frac{V}{P} = P \cdot L \cdot I(P) + \frac{1}{C} \cdot I(P) \qquad (2.)$$

$$I(P) = \frac{V}{P\left[P \cdot L + \frac{1}{PC}\right]} = \frac{V/L}{P^2 + \frac{1}{L \cdot C}} \qquad (3.)$$

Being P_1 and P_2 the roots of the denominator:

$$P_1 = -\frac{j}{\sqrt{L\cdot C}} \quad ; \quad P_2 = +\frac{j}{\sqrt{L\cdot C}} \qquad (4.)$$

Solving the equations:

$$I(P) = \frac{\dfrac{V\cdot\sqrt{L\cdot C}}{2\cdot j\cdot L}}{\left(P-\dfrac{j}{\sqrt{L\cdot C}}\right)} - \frac{\dfrac{V\cdot\sqrt{L\cdot C}}{2\cdot j\cdot L}}{\left(P+\dfrac{j}{\sqrt{L\cdot C}}\right)} \qquad (5.)$$

$$I(P) = \frac{V\cdot\sqrt{L\cdot C}}{2\cdot j\cdot L}\left(\frac{1}{P+\dfrac{j}{\sqrt{L\cdot C}}} - \frac{1}{P-\dfrac{j}{\sqrt{L\cdot C}}}\right) \qquad (6.)$$

$$L^{-1}\left[I(P)\right] = i(t) = \frac{V}{2\cdot j\cdot\sqrt{\dfrac{L}{C}}}\left(e^{-\frac{j}{\sqrt{L\cdot C}}t} - e^{+\frac{j}{\sqrt{L\cdot C}}t}\right) \qquad (7.)$$

$$i(t) = \frac{V}{\sqrt{\dfrac{L}{C}}}\left(\frac{e^{-\frac{j}{\sqrt{L\cdot C}}t} - e^{+\frac{j}{\sqrt{L\cdot C}}t}}{2\cdot j}\right) = \frac{V}{\sqrt{\dfrac{L}{C}}}\, sen\left(\frac{t}{\sqrt{L\cdot C}}\right) \qquad (8.)$$

$$v_L(t) = L\frac{di(t)}{dt} = V\cdot\cos\left(\frac{1}{\sqrt{L\cdot C}}t\right) \qquad (9.)$$

$$v_C(t) = \frac{1}{C}\int i(t)\cdot dt = -V\cdot\cos\left(\frac{1}{\sqrt{L\cdot C}}t\right) \qquad (10.)$$

Capacitor

Data: Energy = 1 Joule and Voltage = 500V

$$E = \frac{1}{2}C\cdot V^2 \qquad (11.)$$

$$C = \frac{2}{(500)^2} = 8mF \qquad (12.)$$

Inductor

$$p\sqrt{L\cdot C}\rangle 5\cdot t_{off} \qquad (13.)$$

$$t_{off} = 50mS \text{ (of SCR)} \qquad (14.)$$

Them:

$$L\cdot C = \left[\frac{\left(50\cdot 10^{-6}\right)\cdot 5}{p}\right]^2 = 15.92\cdot 10^{-12} \qquad (15.)$$

$$L = \frac{15.92\cdot 10^{-12}}{8\cdot 10^{-6}} = 3.166mHy \qquad (16.)$$

Maximum current

$$\hat{I}_p = \frac{V}{\sqrt{\dfrac{L}{C}}} = \frac{500}{\sqrt{\dfrac{3.166\cdot 10^{-6}}{8\cdot 10^{-6}}}} = 25.13A \qquad (17.)$$

Results

In this section details of the experimental procedure and performance data are presented and are described in detail.

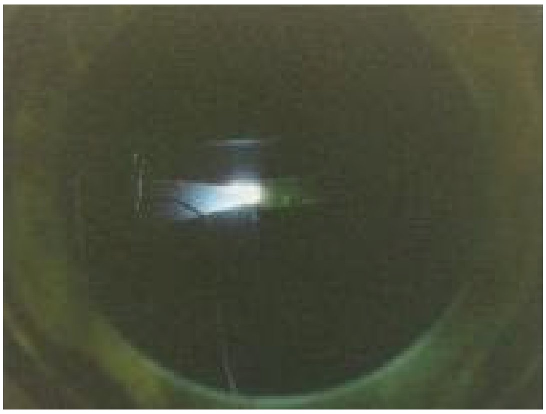

Figure 7. APPT firing in the vacuum chamber.

The pulse generated for the initiation process of the thruster is included between 2500V and 3000V with an approximate duration of 27μs and provides the sufficient energy to spark plugs for ablate the plasma.

Figure 7 shows the ablative pulsed plasma thruster operation and the generation of plasma inside a vacuum chamber, available in the Aeronautical University Institute.

Figure 8 shows the test equipment.

Figure 8. Equipment used in the test.

A capacitors bank of 3μF/4500V obtaining a current discharge of 10kA and 10μs of duration generates the field electrodes voltage.

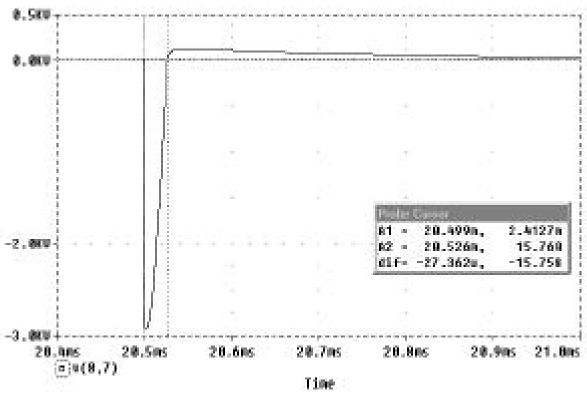

Figure 9. Result of the simulated model.

Figure 9 show the simulated model results, figure 10 shows the experimental results.

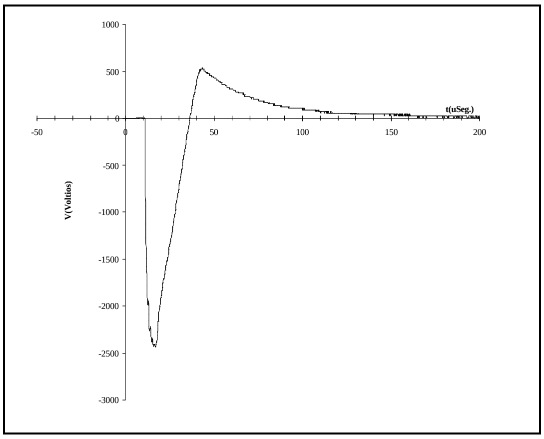

Figure 10. Experimental results.

The compression results between experimental and simulation shown the accuracy of the circuit.

Conclusions

It can be summarized saying that Erwin Marx's generator for the obtaining of high voltage is a viable option whenever one can obtain the enough capacity of the electronic switch and of the ceramic capacitors, that which would take to an investigation on the same ones.

Because the bank of capacitors of the field electrodes, used in the experiments, it is formed by electrolytic capacitors, which are not considered appropriate for flight; it is experiencing with a bank with ceramic capacitors of low capacity value but the appropriate ones are not yet gotten by being of special production. These last ones are extremely resistant to the radiations, and they also have an excellent behavior low condition of operation of discharges average and high repetitive voltages.

In order to improve the circuit design, the search is testing a new prototype with several improvements such as: Dimensions (cm), Mass (Kg), Volume (cm^3) Capacity (μF), Nominal Voltage (Volts) Energy (Joule), Density of Energy (Joule/Kg) Energy-volume (Joule/cm^3) and Mass-volume with the purpose of make the final model for flight.

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