Development of a compact high efficiency RF generator for inductive coupled plasma sources.

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Abstract: As satellite systems tend to commercialize, it imposes new demands on the design of their propulsion systems. The main goal now is its low cost, high efficiency and compact size. Nowadays “Avant-Space Systems” is developing GT-50 propulsion system based on a radiofrequency (RF) ion thruster and intends to satisfy that demands.

An inherent part of an RF ion thruster is a plasma source. It comprises an RF antenna and a RF generator (RFG). This paper presents a topology and an operating algorithm of a compact, high efficiency RFG with adjustable output power. The RFG utilizes a LC-series resonant topology with a phase-locked loop operating in a zero-current switching (ZCS) mode. The generator can operate in either a continuous (CP) or a discontinuous power (DP) mode. The DP mode enables to regulate the output power by insertion of pauses in a half-bridge switching process with the ZCS mode keeping. Thus, there is no need to have an additional power supply to regulate the RFG supply voltage.

The RFG utilizing that concept was created. Its frequency range is 1 to 6 MHz. The maximum output power is 120W. The power efficiency is up to 95%. The dimensions of the device are 100x100x15 mm, which enables to install it in a standard 1U PCB slot.

The generator was tested in operation with a 50 mm RF ion thruster in a vacuum chamber. Beam current vs RF power was measured using a Faraday probe. Regulation characteristic for DP mode and power losses are presented.

Presented topology will be employed in the GT-50 power and processing unit.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tbody>
<tr>
<td>β</td>
<td>damping factor</td>
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<tr>
<td>Cr</td>
<td>resonant capacitance</td>
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<tr>
<td>CP</td>
<td>continuous power</td>
</tr>
<tr>
<td>DP</td>
<td>discontinuous power</td>
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<tr>
<td>i_{ind}</td>
<td>inductor current</td>
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<tr>
<td>i_{phs1}</td>
<td>first phase inductor current</td>
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<tr>
<td>i_{phs2}</td>
<td>second phase inductor current</td>
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<tr>
<td>L_e</td>
<td>equivalent inductance</td>
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<tr>
<td>n_{off}</td>
<td>period number in a first phase</td>
</tr>
<tr>
<td>n_{on}</td>
<td>period number in a second phase</td>
</tr>
<tr>
<td>PPU</td>
<td>power and processing unit</td>
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<td>R_e</td>
<td>equivalent resistance</td>
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<tr>
<td>RFG</td>
<td>radiofrequency generator</td>
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<tr>
<td>u_{out}</td>
<td>output voltage</td>
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<tr>
<td>ω_r</td>
<td>resonant radial frequency</td>
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<tr>
<td>Z_T</td>
<td>oscillatory tank impedance</td>
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<td>ZCS</td>
<td>zero-current switching</td>
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I. Introduction

For the last decades, the number of small commercial spacecrafts increases rapidly. A known peculiarity of modern ambitious missions, such as large-scale satellite constellations, satellite swarms, and deep space exploration, is their tight delta-v requirements. This sparks a significant interest in compact electric propulsion systems with high specific impulse for smallsats.

Nowadays “Avant-Space Systems” is developing a compact high efficiency propulsion system named GT-50. The GT-50 is a self-sufficient easily integrated system comprising RF ion thruster, power and processing unit (PPU) and other inherent subsystems. It is designed to fit wide range of modern space missions where power consumption and dimensions are critical, and precise thrust regulation is needed. The project was started in 2016. At present, the thruster is being tested in a vacuum chamber.

GT-50 is based on RF ion thruster with inductive coupled plasma discharge. Its plasma source comprises an inductor wrapped around gas discharge chamber and an RF generator (RFG). RFG is intended to ignite and then sustain plasma discharge in accordance with required parameters. Plasma discharge is sustained by alternating circular electric field. The more optimal way to create that field is sinusoidal inductor current. It is optimal in terms of hardware realization and load matching process.

In recent literature, Simon and Probst have presented an RF generator concept utilizing a resonant converter topology. It is a high efficiency power converter operating in zero-current switching (ZCS) mode. ZCS mode allows to reduce the current switching losses dramatically. The proposed concept utilizes equivalent plasma discharge inductance as resonant tank inductance. Thus, by operating in resonant mode discharge inductance is compensated and inductor sinusoidal current is generated with high efficiency.

The previous paper did not address the problem of regulation of the output RF power. The regulation is needed if the RF thruster operates in different modes. Each mode has its own optimal RF power value. The conventional way to control the RF output power is an additional power supply unit intended to regulate the RFG supply voltage. This way increases power and processing unit’s (PPU) weight and lowers its reliability. Also, it entails additional power losses and increases the cost.

GT-50 propulsion system is intended to operate in the thrust range from 1mN to 9mN with precision thrust regulation. To satisfy PPU dimensions requirements and reduce power losses new RFG was designed. The RFG is based on resonant topology and operates in ZCS mode. The generator can operate in either a continuous (CP) or a discontinuous power (DP) mode. The DP power mode enables to regulate the output power by inserting pauses in a half-bridge switching process with the ZCS mode keeping. Thus, to control RF power there is no need to have an additional power supply.

The next section describes the construction and operation principles of the RFG unit for GT-50 propulsion system. The unit assembly view and tests results are presented in section III.

II. Design Description

The RFG operation principles utilizes the inductive coupled plasma discharge equivalent model. As known, to the first approximation an inductively coupled plasma discharge can be replaced by an equivalent series LR circuit. $L_e$ – equivalent discharge inductance. $R_e$ – equivalent discharge resistance. By adding a capacitor in series with the inductor an oscillatory tank is formed as shown in Fig. 1.

![Figure 1. Plasma source model](image)

The oscillatory tank impedance can be expressed in complex domain by the Eq. (1):

$$Z_f(S) = L_e S^2 + 2 \beta \omega S + \omega^2$$

$$\frac{2}{S}$$

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Where damping factor $\beta$ and resonant radial frequency $\omega_r$ can be expressed by Eq. (2).

$$\beta = \frac{R}{2} \sqrt{\frac{C_r}{L_r}}; \quad \omega_r = \frac{1}{\sqrt{L_r C_r}} \quad (2)$$

If the oscillatory tank input voltage frequency is equal to $\omega_r$ the impedance imaginary part becomes zero. Hence, there is no phase shift between input voltage $u_{out}$ and inductor current $i_{ind}$.

If the capacitor value $C_r$ is low enough the tank has a low damping factor and realizes narrow passband current filter passing only frequencies lying near the resonant frequency. An example of impedance vs frequency characteristics is shown in Fig. 2.

Utilizing a current filter property, it is possible to generate a sinusoidal current in the inductor by a square wave voltage source. If the wave frequency is equal $\omega_r$ and $\{\beta \ll 1\}$ only the first signal harmonic is worth to be considered. The spectrum of unipolar 1 V square wave is shown on Fig. 1.

A. Topology and Continuous Power Mode

The RFG is based on a resonant LC-series topology. Its simplified structure is presented in Fig.3.

The FET half-bridge supplies square wave voltage on the oscillatory tank. To achieve ZCS mode output current must be in phase with output voltage. The digital control unit detects edges of output voltage by $VE$ signal and output current zero-crossing by $CE$ signal. According with phase shift between $VE$ and $CE$ the control unit adjusts the gate driver enable signal $GE$ in such a way to make frequency and phase of $VE$ and $CE$ are equal. $GE$ signal is not always 50% duty since there is some offset between turn-on and turn-off half-bridge time. When $VE$ and $CE$ are matched ZCS is achieved. Signals diagram are shown in Fig.4.

The generator can operate in either continuous (CP) or discontinuous power (DP) mode. In CP mode the half-bridge switching occurs every time when output current is crossing zero as shown in Fig. 4. By
assumption that $\beta \ll 1$ and considering only first harmonic of $u_{out}$ the output RF power in CP mode can be calculated using Eq. (3).

$$W_{CP} = \frac{1}{R_e} 2^{\pi} \left( \frac{2}{\pi} U_{PRW} \sin x \right)^2 dx = \frac{2U_{PRW}^2}{\pi^2 R_e}$$

The RFG comprises high-speed precision rectifier which enables to measure RMS value of RF output current. By knowing RMS value, the output power can be calculated using Eq. (4).

$$W_{CP} = I_{RMS}^2 R_e$$

B. Discontinuous Power Mode

The conventional way to control output RF power is an additional power supply to regulate half-bridge supply voltage $U_{PRW}$. This paper proposes output RF power control technique based on insertion of pauses in half-bridge switching process with ZCS mode keeping. Since there are intervals when the RFG does not supply power to oscillatory tank this mode is called the discontinuous power mode. Signals diagram in DP mode is shown in Fig. 5.

Figure 5. The RFG signals diagram in DP mode

The operation process is split into two phases. In the first phase the half-bridge is switching every time when output current is crossing zero thus energy is pumped into oscillatory tank. In the second phase the oscillatory tank is short and oscillation process is decaying. Since inductor current oscillations are present during both phases, RF power is supplied to plasma discharge constantly.

If equivalent discharge parameters are known and constant it is possible to calculate the output RF power. This paper does not produce any derivation of equations due to available volume. Only results are presented. Assumption that $\beta \ll 1$ and considering only first harmonic of $u_{out}$ the inductor current can be expressed using Eq. (5).

$$i_{Ph1}(t) = \frac{2U_{PRW}}{\pi R_e} \left( 1 - \frac{1 - e^{-\beta2\pi n_{on}}}{1 - e^{-\beta2\pi(n_{on}+n_{off})}} \right) e^{-\beta0t} \sin \omega t$$

$$i_{Ph2}(t) = \frac{2U_{PRW}}{\pi R_e} \left( \frac{1 - e^{-\beta2\pi n_{on}}}{1 - e^{-\beta2\pi(n_{on}+n_{off})}} \right) e^{-\beta0t} \sin \omega t$$

Where $n_{on}, n_{off}$ - number of current periods in the first phase and the second phase respectively.

The RMS value of output RF power can be expressed using Eq. (6).

$$W_{RF} = \frac{2U_{PRW}^2}{R_e \pi^2 (n_{on} + n_{off})} \left( \frac{1}{2\pi \beta} \left( 1 - e^{-\beta2\pi n_{on}} \right) \left( 1 - e^{-\beta2\pi n_{off}} \right) \right)$$
By varying the ratio between $n_{on}$ and $n_{off}$ it is possible to regulate the RMS value of output RF power. It is important to notice that a real oscillation frequency in phase 1 and phase 2 is slightly different from $\omega_r$ due to damping factor. The digital control unit must track oscillation frequency permanently and correct half-bridge switching timing.

III. Hardware implementation and Measurement

The RFG unit technical requirements were derived from the GT-50 propulsion system target characteristics. Firstly, an analytical model of GT-50 plasma discharge was designed. It gave an estimate of the plasma parameters which will occur in the gas discharge chamber for all thruster modes. After mathematical conversions equivalent discharge parameters were obtained. These parameters formed the RFG load requirements. Additional requirements were imposed by available PPU dimensions and thrust regulation need. To reach a precise thrust control and provide optimal power consumption in all GT-50 modes a regulation of output RF power is necessary. It was decided to design the RFG unit with an ability to operate in DP mode and to reach an RF power step regulation of 1 %. The GT-50 and the RFG unit requirements are summarized in table 1.

<table>
<thead>
<tr>
<th>Table 1. Technical requirements</th>
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<tbody>
<tr>
<td><strong>GT-50 propulsion system</strong></td>
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<tr>
<td>Thrust rating</td>
</tr>
<tr>
<td>Power rating</td>
</tr>
<tr>
<td>Specific impulse</td>
</tr>
<tr>
<td>Regulation range</td>
</tr>
<tr>
<td>Propellant</td>
</tr>
<tr>
<td>Flow rate</td>
</tr>
<tr>
<td>Dimensions</td>
</tr>
<tr>
<td>PPU dimensions</td>
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<tr>
<td>Mass</td>
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Figure 6. The RFG unit view
According to the target characteristics the RFG unit prototype was successfully developed. Its view is shown in Fig. 6. The dimensions are only 100x100x15 which enables to install it into a standard 1U PCB slot. The power supply range is from 16 to 42 V. It is possible to use on-board accumulator to supply the RFG. There is no need to have intermediate power supply to regulate the output RF power.

A. Tests on equivalent load

Firstly, the RFG was tested with loads imitating plasma discharge parameters. It included a test on LR series circuit load and test on a quartz bulb filled with xenon. Figure 7 shows test benches view.

![LR series circuit load](image1.png) ![Bulb with xenon load](image2.png)

*Figure 7. Test bench on equivalent load*

The resonant operation and ZCS mode were checked using oscilloscope probe and inductive coupled current probe. Figure 8 shows oscilloscope screenshots for different power modes. Maximum phase shift between output voltage and inductor current is lower than 5 ns.

![CP mode](image3.png) ![DP mode](image4.png)

*Figure 8. The RFG output voltage (yellow) and inductor current (purple) traces.*

The RFG efficiency at maximum output power was measured for various frequencies and loads. The results are shown in Fig. 9. The higher the load resistance the lower the efficiency. A rise in losses is caused by transistors output capacitance switching losses. The capacitance switching losses are proportional to the square of the power supply voltage $U_{pwr}$ and capacitance value. To provide 120 W at 1 Ohm $U_{pwr}$ is equal to 24 V, in case of 3 Ohm $U_{pwr}$ is 42 V.

To increase the total efficiency, full-bridge could be used instead of a half-bridge. Using full-bridge would allow to reduce $U_{pwr}$ in half providing the same RF power.
B. Tests on the thruster

The RFG was successfully tested in operation with the GT-50 ion thruster. To measure generator characteristics a testbed including vacuum chamber was made. Figure 10 shows the testbed structure. The RFG was mounted on the chamber flange in immediate vicinity of the inductor which is necessary to minimize power reflection.

The testbed included an automatic registration and control system to verify GT-50 and the RFG operation process in various modes. By using Faraday probe ion beam properties was studied. Figure 11 shows testbed view and ion beam photo. The beam current is 120 mA.

Firstly, by using an oscilloscope probe and a current sensor inductor current and voltage were measured in CP mode. It enabled to verify equivalent plasma parameters. Figure 12 shows the equivalent discharge resistance vs RF power dependency. The results match to estimated parameters from table 1.

The next experiment included verification of a dynamic changes of the equivalent discharge resistance. The experiment purpose was to estimate how much the equivalent resistance is undulating during DP mode operation and to test Eq.5 on reality. Since DP mode includes periods when the inductor current is decaying plasma parameters are

![Figure 9. The RFG efficiency at 120 W output power](image)

![Figure 10. The GT-50 – RFG testbed structure](image)
also have some periodic changes. In the experiment inductor current oscillations was measured for different ratio between $n_{on}$ and $n_{off}$. Figure 13(a) shows inductor current oscillogram for $n_{on} = 1$ and $n_{off} = 4$. The RFG supply voltage and output power were 32V and 14W respectively. Figure 13(b) shows current behavior in spice simulation. Simulation model is based on series LR discharge model shown in Fig. 1.(c). $R_e$ is 0.6 Ohm, $L_e$ is 1.5 uH. Values were matched to get maximum similarity.

It is a matter of fact that real inductor current is decaying slower, then in spice simulation. Thus, series LR model of inductive coupled plasma discharge cannot be used to describe the inductor current when the RFG unit operates in...
DP mode. The transformer model shown in Fig. 1(b) must be addressed. Nevertheless, applied model has functional similarity with experiment results and do not contradict DP mode concept.

To verify output RF power control and the ability to regulate plasma parameters by DP technique a regulation characteristic of GT-50 thruster was measured. Faraday probe was installed in front of the ion beam. The probe area is 38 mm$^2$. A distance between the probe and grid surface was 140 mm. RMS value of output RF power was measured using an inductor voltage probe and an inductor current sensor. By varying the ratio between $n_{on}$ and $n_{off}$ the ion beam current density and the output RF power were measured. The regulation characteristics for different flow rates Results are shown in figure 14.

![Figure 14. GT-50 regulation characteristics](image)

### IV. Conclusion and outlook

In this paper, the RFG unit prototype for the GT-50 propulsion system was presented. The RFG utilizes a LC-series resonant topology with a phase-locked loop operating in a ZCS mode. ZCS mode enables to minimize current switching losses. The generator can operate in either a continuous (CP) or a discontinuous power (DP) mode. The DP mode enables to regulate an output power by insertion a pause in a half-bridge switching process with the ZCS mode keeping.

The paper produced DP mode equations which enables to calculate inductor current and RMS value of active power dissipated in inductor. Operating in DP mode it is possible to regulate output RF power by varying the ratio between $n_{on}$ and $n_{off}$ values. Thus, there is no need to have an additional power supply to regulate the RFG supply voltage.

The RFG unit prototype was designed and successfully tested with GT-50 ion thruster. The DP mode concept was verified and its ability to regulate plasma parameters was proven. Experiment on regulation of thruster beam current by DP technique was executed and results was presented.

The presented topology has been taken as the basis for the design of the GT-50 PPU RFG unit. The nearest plan is to carry out direct thrust measurement of the GT-50 in a big volume vacuum chamber to verify the thrust regulation property.

In further works we plan to address applying transformer model to accurately describe inductor current behavior and output RF power when RFG operates in DP mode.

### V. Acknowledgments

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References