Development of a full bridge series resonant radio-frequency generator for optimized RIT operation

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Abstract: For the successful operation of a radio-frequency ion thruster (RIT), an efficient energy coupling into the plasma is mandatory. Besides an optimized coil geometry, the coil current needs to be generated with the highest efficiency possible. To fulfill this requirement, a high efficiency, high performance radio-frequency generator (RFG) is crucial. Here, we propose a full-bridge series resonant RFG, which enables soft switching to maximize the efficiency of the energy conversion. The presented RFG is digitally controlled and based on gallium nitride semiconductor switches, which provide excellent switching characteristics and exhibit low conduction losses. The digital controller is implemented within a field-programmable gate array (FPGA), allowing precise timing and fast tracking of the optimal switching frequency even under alternating load conditions. Its dynamic behavior can be easily changed by adaptation of the control loop parameters. Furthermore, experimental results for a RIM10 ion source developed at the University of Giessen will be presented, to verify proper functionality of the developed RFG. The performance data of the full-bridge RFG with a modified induction coil will be compared to the conventional setup, consisting of a half-bridge inverter and a reference coil.

Nomenclature

C	= capacitance
f_{res}	= resonance frequency
f_{s}	= switching frequency
i, I	= current
i_{b}	= ion beam current
i_{res}	= resonance current
i_{zero}	= zero-crossing signal of coil current
L	= inductance
n	= number of windings
P	= electrical power
R	= resistance
$R_{\mathrm{DS(on)}}$	= drain-source on-resistance
T_{d}	= dead time
T_{Lead}	= lead time
T_{res}	= resonance period
T_{s}	= switching period
v, V	= voltage
v_1	= fundamental voltage
$v_{\mathrm{gs,T1-T3}}$	= drive signal for switches T_1 and T_3
$v_{\mathrm{gs,T2-T4}}$	= drive signal for switches T_2 and T_4

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I. Introduction

In state of the art RIT systems the RFG applies a high frequency sinusoidal current to the induction coil, in order to couple electrical energy inductively into the plasma. The optimal range of the frequencies to operate the thruster not only depends on the geometry of the ionization vessel and the coil itself, but also on the inner plasma parameters and the losses of peripheral electrical components. For established RIT systems, the optimal operating frequency lies in the high kHz- to single-digit MHz range[1,2].

The main goal of developing RFGs for space applications is to maximize the efficiency of the energy conversion. Within this frequency regime it is challenging, since switching losses are present and contribute to the overall losses significantly. To minimize the generated switching losses, resonant inverter topologies are used which implement soft switching[3]. State of the art topology for RFGs is the half-bridge series resonant inverter, which excites the series resonant tank with an unipolar rectangle voltage by switching two semiconductor switches in push pull topology. To generate the sinusoidal current with the highest efficiency possible, an analogue or digital control algorithm ensures that the switching frequency corresponds to the resonance frequency of the tank and soft switching is performed[4].

One approach to control the power transferred to the plasma and, thus, to control the output power of the thruster is to vary the RMS value of the coil current. To do so, the input voltage of the RFG is changed. The limitation of this approach arises from the maximum blocking voltage of the semiconductor switches as well as maximum available input voltage. Since the output of the half-bridge inverter is an unipolar rectangle voltage, the full capability of the DC link cannot be utilized. In the following a full-bridge series resonant inverter will be presented, which provides twice the output voltage compared to the half-bridge and thus allows to fully utilize the DC link voltage. Based on the doubled output voltage, the induction coil is modified to further increase the overall system efficiency.

II. Theory and Functional Principle

A. Full-Bridge Generator Concept

The full-bridge inverter illustrated in Fig. 1 consists of two half-bridges comprising four semiconductor switches T_1 to T_4, a DC link capacitor C_{DC}, and a series resonant tank as a load. The latter is formed by the series connection of the resonance capacitor C_{res} inside the RFG, resistance $R_{\mathrm{c+pl}}$, inductance $L_{\mathrm{c+pl}}$, and transformer L_1. Transformer L_1 is used for control purposes only and will therefore be neglected in the following explanations.

From the electrical point of view, it is desirable to describe the inner plasma processes in conjunction with the induction coil in lumped elements for analyzing and designing the circuit topology. To do so, the transformer model for inductive discharges is used[5]. As a result, changing the operating point of the thruster directly affects the parameters of $R_{\mathrm{c+pl}}$ and $L_{\mathrm{c+pl}}$. This implies that the resonance frequency f_{res} of the tank can slightly vary during the operation of the thruster. Since the transferred power of the resonant inverter depends on the ratio of switching frequency f_{s} to the tank's resonance frequency f_{res}, a closed loop system is used to ensure that $f_{\mathrm{s}} = f_{\mathrm{res}}$ to maximize the output power even under changing loads conditions[6].

The output voltage of the full-bridge inverter is compared to that of the conventional half-bridge inverter in Fig. 2. The half-bridge inverter's output is an unipolar rectangle voltage, consisting of a DC offset $V_{\mathrm{DC}}/2$ and an alternating bipolar voltage with an amplitude $V_{\mathrm{DC}}/2$. The peak value of the fundamental voltage v_1, which excites the resonant tank, is $\hat{v}_1 = 4/\pi \cdot V_{\mathrm{DC}}/2$ (Ref.6). This indicates that the full capability of the DC link cannot be utilized by using the half-bridge topology, since the DC offset does not excite the resonant tank. In the full-bridge inverter the semiconductor switches T_1 and T_4 or T_2 and T_3, respectively, can be switched simultaneously, resulting in the bipolar output voltage shown in Fig. 2. Consequently, the fundamental's peak value doubles to $\hat{v}_1 = 4/\pi \cdot V_{\mathrm{DC}}$.

As a result, the same output power can be transferred using half the input voltage. This is advantageous because the semiconductor's blocking voltage can be reduced. If switches are capable of sufficient blocking voltage, it is possible to generate a higher output voltage, thus power, using the same input voltage as in the half-bridge topology. In this case, additional operating points for the thruster become accessible.

Based on the doubled RFG output voltage, the overall system efficiency can be improved by adding more windings to the induction coil. If the number of windings is doubled starting from a coil with $n = n_1$ to $n = n_2 = 2 \cdot n_1$ windings, the equivalent plasma resistance $R_{\mathrm{c+pl}}$ and inductance $L_{\mathrm{c+pl}}$ rise[5]. To transfer the same power to the plasma, the current per winding needs to stay constant $i_{\mathrm{res},1}/n_1 = i_{\mathrm{res},2}/n_2$. Hence

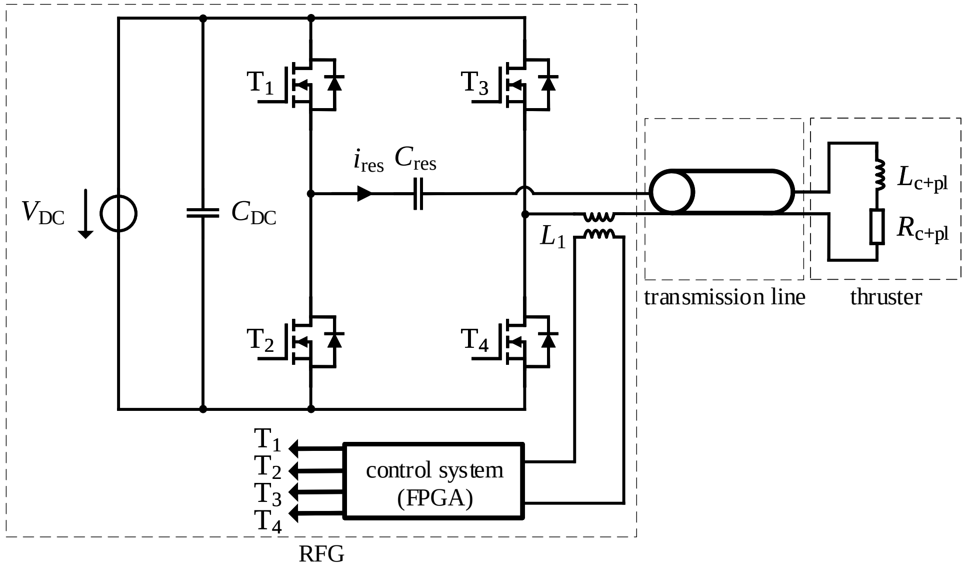


Figure 1: Simplified circuit diagram of the full-bridge series resonant RFG with digital control loop.

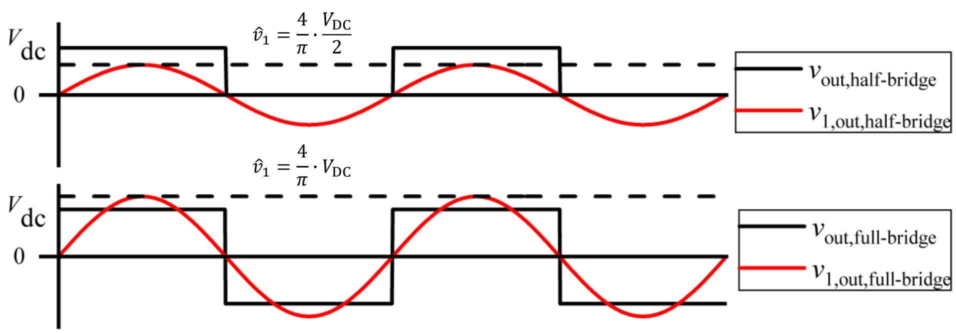


Figure 2: Output voltage of the half- and full-bridge inverter exciting the series resonant circuit.

the current $i_{\mathrm{res},2}$ is halved in comparison to the current $i_{\mathrm{res},1}$ when using a coil with the doubled number of windings. Because the inductance changes as $L \sim n^2$, the RFG's load impedance $Z_{\mathrm{c+pl}}$ approximately increases by a factor of 4. Consequently, the output voltage needs to be doubled to generate the current $i_{\mathrm{res},2}$. This requirement is compensated by the use of a full-bridge topology. As a result current related power losses are reduced. This is important for practical reasons, since long transmission lines between RFG and thruster are often mandatory and losses along the transmission line are not negligible. Nevertheless, there are considerable differences and possible challenges using a full-bridge instead of a half-bridge inverter:

- The number of semiconductor switches doubles. Therefore, the control algorithm needs to be adapted. Due to the use of four semiconductor switches, more complex modulation algorithms are feasible. Furthermore, switching losses can rise compared to the half-bridge topology.
- In half-bridge inverters one terminal of the induction coil is clamped to ground, whereas in full-bridge inverters both terminals are connected to an alternating potential. As a result, energy coupling into the plasma might occur as well by capacitive coupling. Moreover the zero-crossing detection circuit is also connected to an alternating voltage. This needs to be considered when designing the circuit, since parasitic capacitances are present for transformer L_1.
- If the induction coil is not modified, the required current capability of the DC Source V_{DC} will double compared to the conventional setup, hence energy will be transferred from the DC power supply into the DC link either when T_1 and T_4 or T_2 and T_3 are conducting.

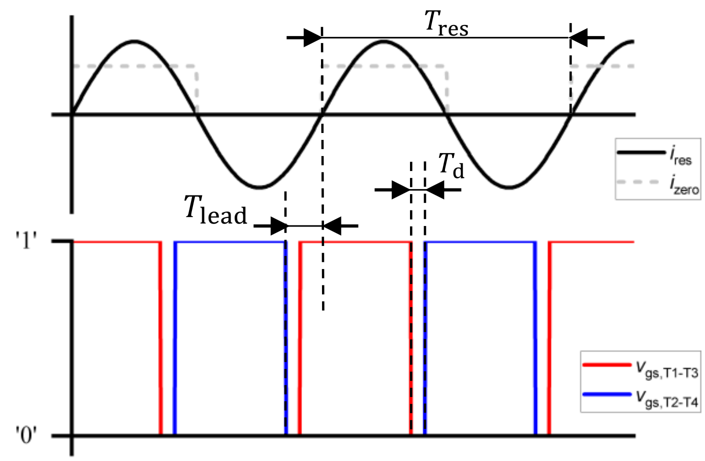
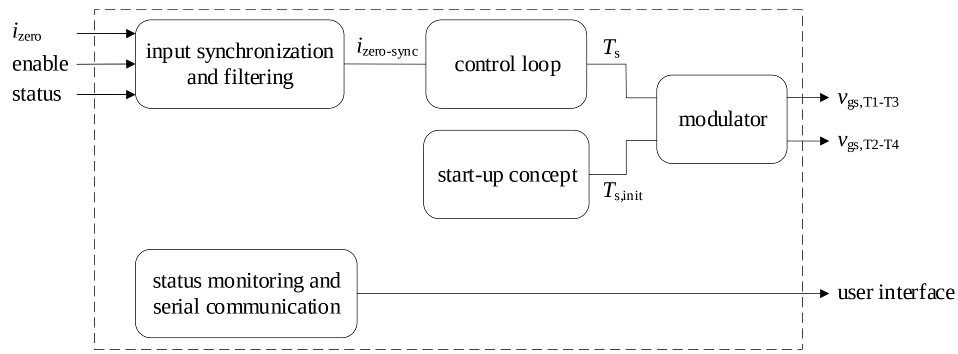


Figure 3: Oscillating coil current and corresponding control signals for steady state operation.



FPGA

Figure 4: Simplified block diagram of the implemented FPGA design.

B. Digital Control Concept

For operating the RFG and generating the appropriate gate driver signals, a digital control concept is realized on an FPGA using a hardware description language (HDL). Thus, high clock frequencies enable precise timings which are crucial to minimize the switching losses. A major advantage in choosing a digital concept instead of an analogue one is its flexibility. The dynamics can be easily adapted to adjust the transient behavior in case of varying loads by modifying the control loop parameters. Furthermore, communication interfaces can be used for real time measurement and parameterization.

Figure 3 shows the oscillating coil current i_{res}, the binary zero-crossing signal i_{zero} as well as the gate driver signals for the semiconductor switches T_1 to T_4 in steady state operation in case of an idealized current measurement. To generate the coil current i_{res} with the highest efficiency possible, the digital controller uses the zero-crossing signal i_{zero} to match the switching frequency f_{s} to the resonance frequency f_{res}. To ensure both, soft switching and safe operation, a lead time T_{Lead} between the zero-crossing signal and the gate driver signals as well as a dead time T_{d} are introduced. While lead time T_{Lead} compensates timing delays in the gate driver circuit, dead time T_{d} prevents short circuits in the half-bridges between turning T_1 and T_4 off and turning T_2 and T_3 on and vice versa.

A simplified block diagram of the implemented FPGA design is displayed in Fig. 4. First, all input signals are synchronized and filtered to prevent metastable conditions[7] as well as incorrect behavior due to electromagnetic interference (EMI). The synchronized zero crossing signal $i_{\mathrm{zero,sync}}$ is passed to the actual control loop consisting of a summing point for error detection, a digital controller, and a feedback path.

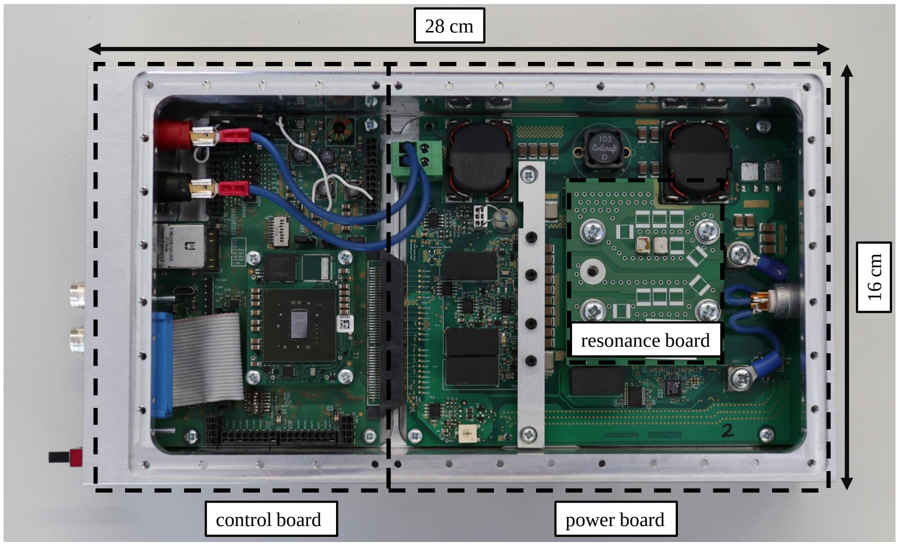


Figure 5: Hardware assembly of the developed RFG, top view

Based on the zero crossing signal the controller continuously computes the switching period T_s in order to maximize the efficiency of the RF generation. The modulator uses this switching period to generate the gate driver signals for the semiconductor switches T_1 to T_4. Since there is no energy stored in the resonant tank when the RFG is turned off, a start-up concept is required. For debugging purposes and for adapting the dynamic behavior in real time, a serial communication interface is further available on the FPGA design. Additionally the maximum coil current and temperature are monitored to ensure safe operation.

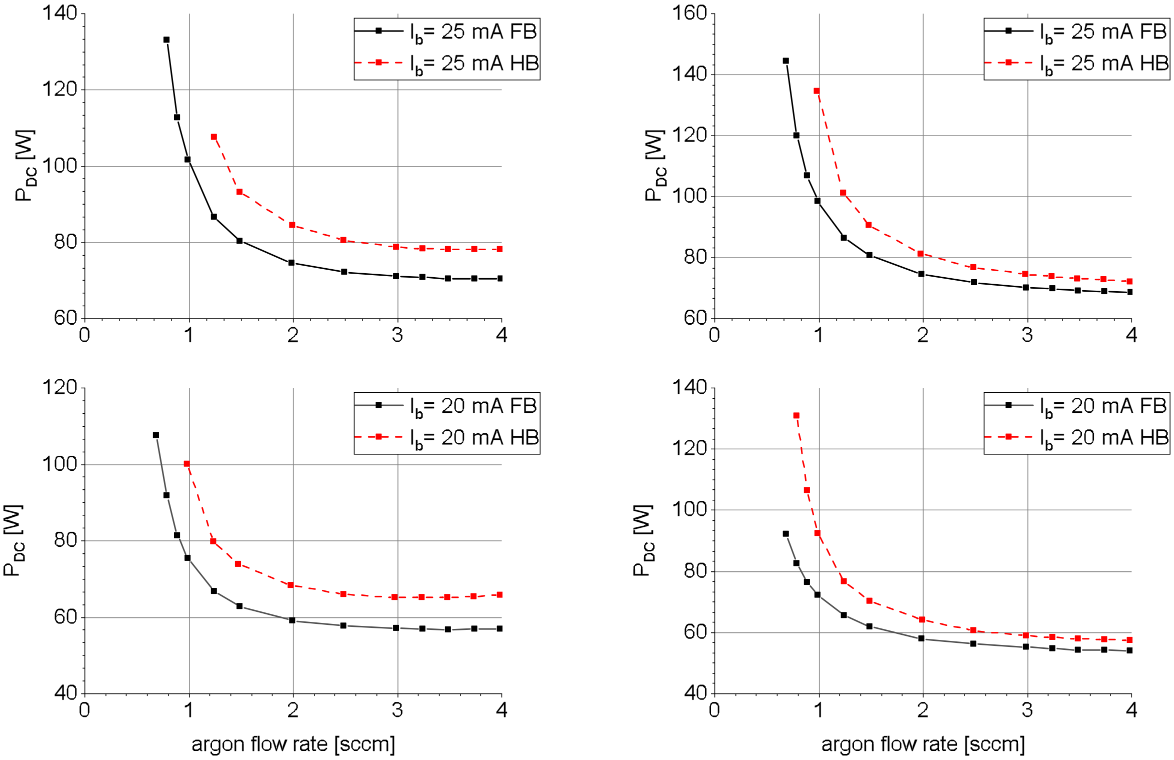
III. Hardware Assembly and Experimental Results

The hardware assembly of the developed full-bridge RFG is depicted in Fig. 5. It comprises a control board and a power board. The control board contains the FPGA, all peripheral electronics for debugging purposes as well as the user interface. Full-bridge inverter, gate driver circuits, and sensors are part of the power board.

The housing is made of aluminum and serves two purposes: It provides EMI shielding and dissipates the heat generated by the semiconductors. We employ gallium nitride semiconductor switches. They provide fast switching characteristics as well as low $R_{\mathrm{DS(on)}}$ and are capable of switching high currents at frequencies in the MHz range. The resonance board can be adjusted, to change the resonance frequency for a given thruster setup.

A performance mapping is recorded, to characterize the efficiency of the full-bridge RFG. The beam current I_b is kept constant by a beam current controller. The required RFG DC input power P_{DC} is measured and recorded as a function of mass flow. Because the output power is held constant, the performance mapping allows us to compare the efficiency of different power electronic concepts. For the performance measurements of the half-bridge RFG a coil with $n = n_1$ windings has been used. In order to take advantage of the doubled output voltage available at the full-bridge, the induction coil was modified. Here, the number of windings was doubled to $n = n_2 = 2 \cdot n_1$. All peripheral components as well as the control loop parameters were kept constant. The characterization was done at two different frequencies and two different beam currents for RIM10 with a reduced number of extraction holes.

As can be seen in Fig. 6, for all tested mass flow rates and frequencies, the full-bridge inverter with its modified induction coil requires less input power for maintaining the examined beam currents in comparison to the conventional setup. Especially at small flow rates the difference in required RFG input power P_{DC} becomes apparent. The efficiency gain can be mainly attributed to the impedance transformation, caused by the doubled number of windings. Since the power consumed on an ohmic load is proportional to ${I_{\mathrm{RMS}}}^2$, the losses along the transmission line and the conduction losses are considerably decreased due to the reduced coil current.



(a) $f_{\mathrm{RF}} = 1$ MHz (b) $f_{\mathrm{RF}} = 1.5$ MHz

Figure 6: Performance mapping measurements comparing half-bridge (HB) and full-bridge(FB) inverter for two different frequencies and beam currents.

IV. Conclusion and Outlook

In this paper, a digitally controlled full-bridge series resonant RFG has been presented. By using a resonant circuit topology and soft switching the switching losses are minimized. Employing a digital controller ensures high speed tracking of the resonance frequency with the flexibility to change the dynamics through adapting its control loop parameters. The major differences and the expected advantages in comparison to the conventional half-bridge topology have been derived. Furthermore, a simplified overview of the implemented control strategy has been given. Last, the developed hardware assembly and a performance measurement on a RIM10 have been shown. At all operating points examined, the full-bridge inverter with a modified induction coil has proved to be more efficient than the conventional setup.

Because performance mappings do not give information about the absolute efficiency of the circuit topology, but only allow relative comparisons between two different concepts, the overall efficiency of the RFG will be determined in ongoing works. While it is easy to measure the RFG's DC input power, determination of emitted AC output power is rather difficult due to phase differences close to 90°. Measuring the AC output power will allow us to implement control strategies for the output power of the thruster. Besides space applications this can be of major interest for terrestrial ion source applications, e.g. ion sources used for material processing.

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