Development of digital twin of high frequency generator with self-excitation in Simulink

Iu Murashov*, S Zverev, V Smorodinov and S Grachev

Peter the Great St.Petersburg Polytechnic University, St.Petersburg, Polytechnicheskaya 29, 195251, Russia

* E-mail: iuriimurashov@gmail.com

Abstract. The article presents the numerical simulation results of the high frequency generator (electron tube type) with self-excitation in the Simulink. The main structural element of this generator is an electron tube GU-66A. Digitization characteristics of the electron tube is made. A mathematical model of the HF generator, taking into account the anode and grid characteristics of GU-66A according to the passport data of the product, has been developed. The parameters of the HF generator circuit are determined. A plasma-chemical reactor and its equivalent electrical parameters (set in a wide range of accepted values) are used as a load oscillation circuit. The developed model allows to determine the optimal parameters of the HF generator, as well as to predict operating modes, providing continuous supply of HF power for a long time (more than 20 hours). The equivalent electrical parameters of the plasma-chemical reactor are designed to ignite plasma discharges in argon and gas mixtures based on argon at atmospheric pressure.

1. Introduction

Modern plasma-generating devices according to the type of power sources can be divided into two main groups: direct and alternating current [1, 2]. Among the plasma-generating devices of alternating current, HF Inductively Coupled Plasma can be distinguish, which one traditionally used in plasma chemistry, as well as for producing nanostructured materials of a given dimension [1, 3]. One of the main elements of the technological installation (in addition to the plasma torch) is the power source [1–7]. Determination of optimal conditions and modes of the process with minimization of financial investments is possible when performing preliminary simulation and creation of digital twin of the HF generator and studying its coordination with non-stationary oscillatory systems, where a plasma-chemical reactor is used as a non-stationary oscillatory system (load characteristics can vary during the technological operation).

Not only pure argon can be used, but also its mixtures with hydrogen, nitrogen or air as a plasma-forming gas. In addition, both gaseous and powdered chemical reagents can be added to the plasma-generating gas mixture, which can lead to a mismatch of the output oscillating circuit of the HF generator due to the irregularity of their supply. Therefore, it is necessary to automatically coordination during the full cycle of the technological operation.

HF autogenerators (generators with self-excitation) are used as power sources of electrothermal installations designed for smelting, heating and hardening various metallic materials and parts. They are produced by the industry at the standard frequencies: 66, 440, 880 kHz, 1.76; 5.28; 13.26; 27.12 MHz and standard power line: 4, 10, 25, 40, 60, 100, 160, 250, 400, 600, 1000 kW, etc. [1, 2, 8]. The
voltage on the grid of the generator electron tube is formed using a grid feedback circuit in HF generators, which is connected to a load oscillating circuit [3]. The electrical circuit diagram of a single-circuit HF generator is shown in Figure 1.

![Electrical circuit diagram of a single-circuit HF generator](image)

**Figure 1.** The electrical circuit diagram of a single-circuit HF generator.

Creating new technological processes requires software control of power sources [9–11], increasing their power and expanding the frequency range, which leads to obtain more accurate information about the processes occurring in generators. Previously, the calculation and optimization of circuit elements was carried out using reference data provided in reference books and for stationary modes, typical designs. The development of modern computer technology allows us to develop digital twins and at the development stage to perform an assessment of the power source efficiency [12–13]. Thus, the creation of a mathematical model of the autogenerator is an urgent task, which this study is aimed at solving. It should be noted that despite the rapid development of computer technology and numerical simulation capabilities, integrated simulation of processes in a power source (HF generator) with a non-stationary oscillator loading circuit has not yet been performed.

2. **Model of the high frequency generator with self-excitation**

The HF generator (electron tube type) is a compound of a complex oscillatory system and an electron tube. Usually, an oscillating system can be described by a system of high-order linear differential equations, and an electron tube, which is a non-linear element, must be represented by a model [3]. Numerical simulation of HF generators, based on the numerical integration of a system of differential equations describing electromagnetic processes in them, allows us to solve optimization problems and to develop control algorithms, etc.

The aim of this study is identification of the HF generator parameters for coordination with the non-stationary oscillatory system and to determine the optimal modes of its operation under the conditions described above based on the developed digital twin.

2.1. **Electron tube model and its parameters**

The electron tube is a nonlinear element for which anodic and grid characteristics are given in reference [3]. In this regard, it is the most simple and natural to represent an electron tube model as two nonlinear current sources, the values of which are determined by the combination of voltages on its electrodes (see. Figure 2). The main difficulty is reduced to the exact definition of an electron tube currents. The use of interpolation polynomials of 3 and 4 orders of the table-set characteristics of the electron tube makes it possible to solve this problem.

The third-degree polynomial was used to describe the anode characteristics in this study. The polynomial coefficients were obtained using the MATLAB software with the possibility of subsequent
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integration of the obtained data into the electron tube model when simulating an HF generator in Simulink. The coefficients of the 4th degree polynomial for the grid characteristics of the electron tube (GU-66A) were obtained by analogy with the anode characteristics.

The proposed approach also makes it possible to estimate the error of the developed mathematical model of electron tube model which does not exceed 2% (in this case).

The digitized characteristics of the electron tube (GU-66A) were integrated into the Simulink environment using the "2-D Lookup Table" block. The model of the electron tube in the Simulink software is shown in Figure 2.

![Figure 2. The electron tube model in Simulink.](image)

2.2. Numerical simulation of HF generator with self-excitation
Digital twin of HF generator (based on the electrical circuit diagram of the single-circuit HF generator) was developed in Simulink (see Figure. 3). The plasma-chemical reactor and its equivalent electrical parameters (set in a wide range of accepted values [4, 14]) are used as load oscillation circuit "HF Plasma torch".
Figure 3. Model of HF generator with self-excitation in Simulink.

The equivalent electrical circuit of the plasma-chemical reactor is a series connection of active and inductive resistances at the preliminary stage. This model is implemented with the possibility of subsequent integration of the simulation results of the HF plasma torch operation.

The time dependent characteristic of load voltage as simulation result is presented in Figure 4. The transition time to the steady-state is 12 μs from the presented characteristic.

Figure 4. The time dependent characteristic of load voltage (simulation data).
3. Analysis of the simulation results
The optimum frequency (5.28 MHz) for the implementation of the technological process was determined based on a preliminary calculation of the circuit parameters and the developed mathematical model of HF autogenerator (electron tube type).

Analysis of the obtained simulation results was carried out using Fast Fourier Transform algorithm (FFT Analysis) for characteristics of the load voltage. The base frequency is the optimum generator frequency of 5.28 MHz. Analysis is performed for steady-state generator operation. The studied period is ten periods of the investigated signal oscillations with the frequency of 5.28 MHz. Time dependent characteristic (load voltage) and studied period (highlighted in red), and the results of the study using FFT algorithm are presented in Figure 5.

THD coefficient is 7%, the constant component of the signal is 0% and the higher harmonics do not exceed 6% of the base frequency signal amplitude according to the results of the analysis.

4. Conclusion
Model of HF autogenerator with self-excitation is presented in the article. The equivalent electrical parameters are used as a load oscillation circuit. The passport data of the generator electron tube GU-66A were digitized, polynomial dependencies were obtained for the anode and grid characteristics, and the parameters of the HF generator circuit with self-excitation were calculated according to the results of the study. It is recommended to use the frequency of 5.28 MHz according to the analysis of the developed model for the implementation of the technological process. The digital twin of the HF generator is designed to take into account the non-stationarity parameters of oscillatory systems. The developed model allows to determine the optimal parameters of the HF generator with self-excitation and to predict the modes of the technological process operation. The equivalent electrical parameters of the plasma-chemical reactor are designed to ignite plasma discharges in argon and argon/hydrogen mixture at atmospheric pressure.

Figure 5. FFT Analysis of load voltage.
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