Chaos Control in Virtual Cathode Oscillator by Cathode Structural Optimization

Seyed Morad Ali Hashemi[1], **Ali Pirmoradi**[2], **and Erfan Zabeh**[2]

[1]Electromagnetics Research Laboratory, Sharif University of Technology, Tehran, Iran
[2]Department of Electrical Engineering, Sharif University of Technology, Tehran, Iran

Abstract— In this paper, Virtual Cathode Oscillator as a microwave generator is studied concentrating on the nonlinear behavior of the microwave-plasma interaction that introduces chaos to the output voltage and power of the generator. It is shown that periodic oscillations of the electron beam strictly depend on the two most critical characteristics of the VCO, the input maximum voltage and the cathode radius. The chaos caused by the critical values of these two parameters, could restrict the maximum possible values of the input parameters, reducing the overall maximum output values. The effects of these two parameters are studied trough PIC-code simulations. The simulation results were used to extract the bifurcation diagrams and analyze the chaos patterns accurately. Chaos, as a serious cause for overall efficiency and output power reduction, is decreased applying a new method which is proposed considering the study results.

1. INTRODUCTION

Virtual cathode oscillator (VCO), as one of the simplest vacuum tube microwave generators considering its geometrical and constructional simplicity, has one of the most complex dynamical behaviors. Nonlinear phenomena, present in microwave-plasma interaction in the active region of the VCO, are the most important sources of the complexity of the electron beam dynamics and microwave generation process in the device. Chaos, as one of the most important phenomena appearing in the nonlinear dynamical systems, has been studied in the VCO performance [1–3]. Deeply nonlinear process of the microwave generation in VCO, considered as a dynamism governed by a complicated system of nonlinear partial differential equations (PDEs) with boundary values given by the geometry, materials and the other structural properties of the tube and initial conditions defined by the input driving pulses, is an appropriate source for the chaos build up. It has been shown that input anode-cathode voltage is one of the most important parameters in the formation of the chaos in the considered system of nonlinear boundary value PDEs.

PIC-code simulation of the system has been used extensively to study the various aspects of the chaotic behavior of a designed VCO. It has been shown that increasing input voltage pushes the system towards the appearance of more and more periodic oscillations with different periods leading finally to a completely chaotic performance. Bifurcation diagram showing this procedure has been derived via numerical processing of the PIC-code results and has confirmed the results of the time and frequency domain diagrams showing the deeply chaotic behavior of the system [4, 5]. The same has been done applying the PIC-code simulation of VCO for studying the effects of the cathode radius on the chaotic behavior of the system and it has been shown that this parameter deeply affects the chaotic performance of the designed system. Increasing cathode radius results in increased irregularities in the generated microwave parameters. Bifurcation diagram has been extracted considering the variations of the generated microwave parameters via changing cathode radius.

This diagram elegantly shows the chaos formation process through the cathode radius variations. Analyzing the simulation results, authors suggest a novel design for the cathode structure to improve the system performance and control the chaotic behavior of the system. It has been shown that the proposed cathode structure is capable of delivering higher current flows and beam powers to the interaction region of the vacuum tube avoiding the chaos occurrence compared to the conventional cathodes used in the similar systems.

2. SIMULATION AND ANALYSIS

Designed VCO diode structure has three main parts as shown by Figure 1. Shank the first part, is made by a conductor material. Parts 2 and 3 are cathode and anode, respectively. The anode-cathode voltage being increased enough the electric field on the cathode surface will go over the threshold value required for electrons to be emitted from the cathode surface. Electrons emitted from the cathode will be accelerated up to the relativistic velocities in the region between cathode and foil. Foil is used as an anode that lets electrons to pass through it. The electrons passing through the foil are decelerated due to the presence of a large amount of previously emitted electrons that are gathered at a distance from the foil that is almost equal to the anode-cathode gap distance. Electrons coming later are forced back by the potential well produced by this bunch of electrons. For this effect, the bunch of electrons is called virtual cathode. The back-scattered electrons will again forced to change their direction getting enough close to the cathode surface. The oscillating electrons together with the oscillating virtual cathode are the two origins of the generated microwave. It can be shown that the less the acceleration of the moving electrons, the more the number density of the electrons. Virtual cathode dynamics is the most important origin of the nonlinear behavior of the VCO [3, 6, 7].

To avoid runtime problems in simulating progress, we use a 2D PIC-code. Number density of the electrons is about 10^{14} particle/cm^3 with about any 4000 adjacent electrons being considered as a macroparticle to reduce the program running cost without any considerable error. Final 2D simulation results are acceptable compared to the 3D simulation results because of the cylindrical symmetry.

In all of the performed simulations we keep unchanged the device length of 50 cm device radius of 4.8 cm and foil gap of 0.5 cm.

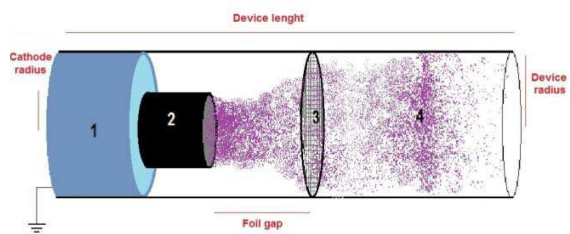

Figure 1: Schematic diagram of a VCO.

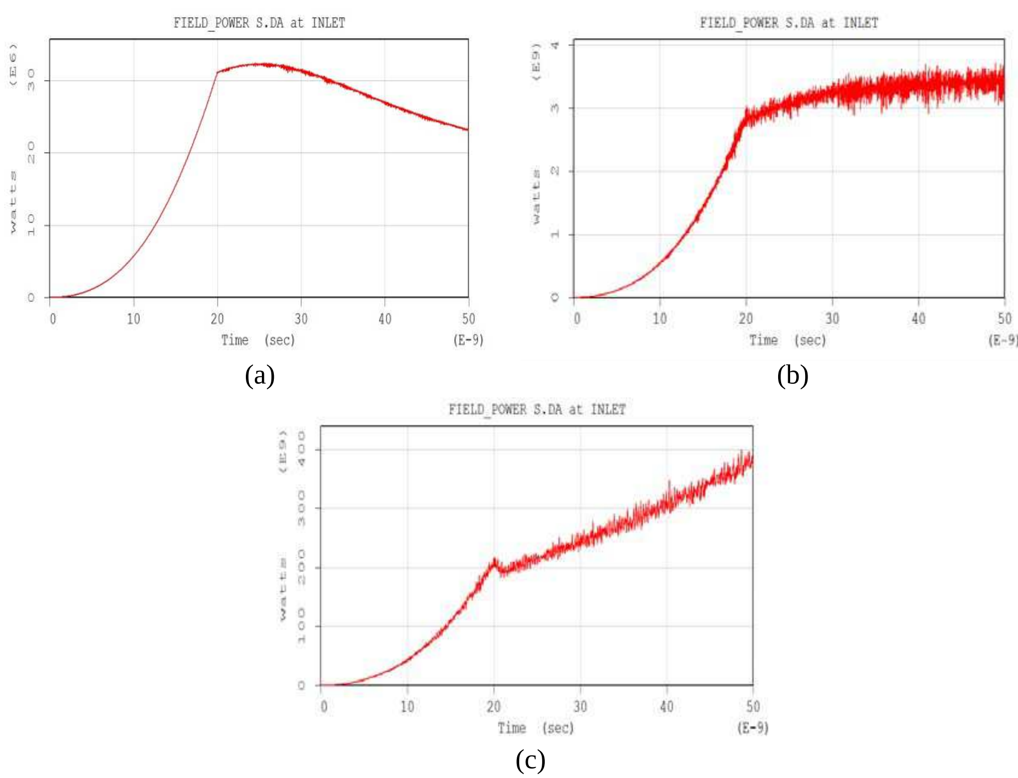

Figure 2: Power diagrams obtained for several input voltage values: (a) $V = 20\,\text{kV}$, (b) $V = 200\,\text{kV}$, and (c) $V = 2000\,\text{kV}$.

2.1. Anodecathode Voltage

Anode-cathode voltage was found out to considerably affect the chaotic behavior of the system. This was done considering the power at the input port which is the point for applying the initial condition for the system of the PDEs governing the microwave generator operation. By changing the maximum input voltage, chaos was obviously appeared in the power time diagram as shown in Figure 2. Transient time passed, power variations become vastly tolerating indicating the chaotic patterns in the system. In a future work the exact relation between the tolerations and the chaos will be explained. Another way to find the chaotic regions of the system operation is extracting bifurcation diagrams of the system. Both methods were used to analyze the system chaotic performance. Bifurcation diagram of the power is shown in Figure 3. The cone shape of the bifurcation diagram shows that the number of extra periodic signals being introduced to the system increases rapidly which is the clear characteristic of the chaos. For each analysis, we simulated the behavior of the system for over 200 times, each time with a different anode-cathode voltage with all other system parameters kept unchanged.

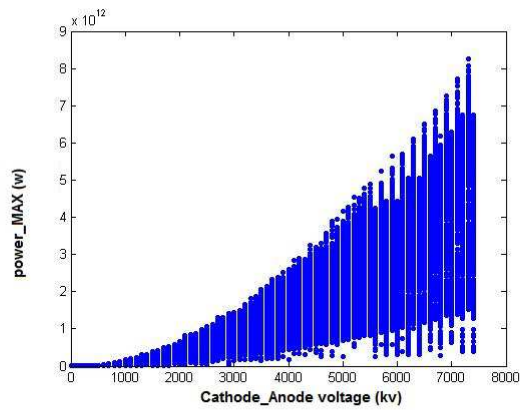

Figure 3: Bifurcation diagram extracted from simulations for system power due to the increasing anode-cathode voltage.

It is clear from the diagrams that the more anode-cathode voltage is, the more toleration is produced in the power at the input port which will be shown in a future work that is an indication of the chaos build up in the system. It is due to the increasing number of the unwanted periodic signals appearing in the system parameters. The system enters the chaotic region after 20 nanoseconds. First figure has almost no toleration, while in the second figure power variations are approximately 10^8 watts. And in the third figure in which the voltage is 2000 kV, the power toleration amplitude is almost 10^{10} watts.

2.2. Cathode Radius

In order to analyze the undesirable effects of this particular system parameter on its output parameters, bifurcation diagrams of these parameters with respect to the variations of the cathode radius was extracted.

The behavior of the system was simulated for over 200 times with increasing cathode radius while all other characteristics kept unvaried. In each simulation, system behavior in time domain was studied considering time diagrams of several system parameters one typical example being shown in Figure 4. The tolerance in amplitude in these diagrams depicts the undesirable chaotic behavior of the system that we are seeking for, as explained for the anode-cathode results.

Bifurcation diagrams show that cathode radius has considerable effects on the chaotic behavior of the system. This is done by the same PIC-code simulation as explained before. The bifurcation diagram as depicted in Figure 5, shows that the larger the cathode radius, the more chaos would occur in the system. Increasing the radius of the VCO cathode results in the injection of higher current flows into the system and chaos appearance in the measured system power, considered as a typical system parameter.

It can be seen that when the cathode radius is about 0.8 cm, the system is not quite chaotic while at radii 1 cm and 4 cm, there are almost 10^8 watts tolerations in the power. It must be noted that there are fluctuations in the bifurcation diagrams which will be explained in a complementary future work.

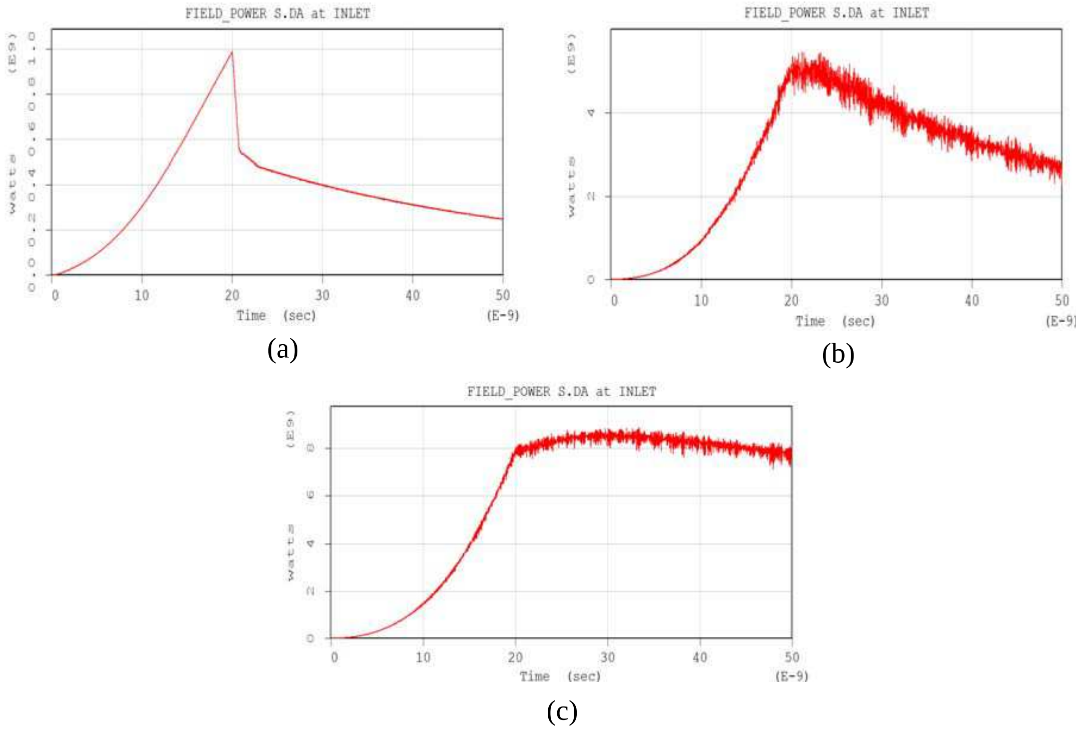

Figure 4: Power diagrams obtained for several cathode radii: (a) $R = 0.8\,\mathrm{cm}$, (b) $R = 1\,\mathrm{cm}$, and (c) $R = 4\,\mathrm{cm}$.

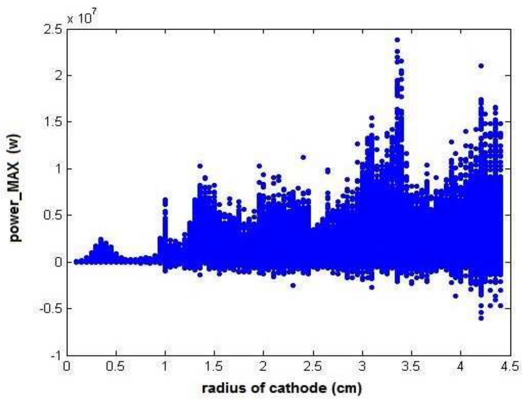

Figure 5: Bifurcation diagram extracted through simulations for the system power due to the increasing cathode radius.

3. RESULTS AND CONCLUSIONS

Small changes in anode-cathode voltage and cathode radius could make undesirable variations in the output parameters, meaning that we have potentially unstable system causing problems when getting enough close to the forbidden limits of the studied parameters. At this conditions final efficiency will be reduced considerably. To solve this problem there is two main approaches. In the first approach, being the most common way, the structure of the oscillator is changed to increase the permitted limit of the parameters variations, achieving upper efficiencies and upper allowable input powers. In the second method, the oscillator is fully redesigned to hold the all parameters variations under their forbidden limits. Some novel structural optimizations are also introduced by the authors to achieve higher efficiencies. The method will be expressed by details in the upcoming reports.

REFERENCES

1. Khramov, A. E., "Oscillations of a system of coupled oscillators with a virtod-type virtual cathode," *J. of Communications Technology and Electronics*, Vol. 44, No. 2, 1999.

2. Trubetskov, D. I. and A. E. Khramov, “Synchronization of chaotic self-oscillations,” *J. of Communications Technology and Electronics*, Vol. 48, No. 1, 2003
3. Khramov, A. E., “Chaos and formation of the structures in an electron flow with a virtual cathode in the bounded drift tube,” *J. of Communication Technology and Electronics*, Vol. 44, No. 5, 1999.
4. Khramov, A. E., “The effect of feedback on complex dynamics in the hydrodynamic model of the pierce diode,” *J. of Communications Technology and Electronics*, Vol. 47, No. 6, 2002.
5. Anfinogentov, V. G. and A. E. Hramov, “Vircator with delay feedback and beam modulation,” *IEEE Journal*, College of Applied Science, Saratov State University, 1999.
6. Anfinogentov, V. G. and A. E. Hramov,, “Chaotic dynamics and coherent structure in electron beam with virtual cathode in the diode with local neutralization,” College of Applied Science, Saratov State University. 1998.
7. Li, D., Y. Alfadhl, and X. Chen, “Nonlinear dynamics and chaos in a circuitry model of magnetron,” *IET Journal*, School of Electrical Engineering, University of London, Queen Mary, 2009.