COMPUTER SIMULATION OF POWER VACUUM TUBE OSCILATORS

Assoc.Prof. Evgeni Ivanov Popov , Ph.D.
Department of Power Electronics, Technical University - Sofia

Abstract - A versatile vacuum tube model for computer simulation of power vacuum tube oscilator circuits is presented. Then based on this model the state-variable approach is applied for steady-state and transient (particularly excitation) analysis of a typical feedback Meissner oscilator to demonstrate the good applicability of the model and the technique proposed for computer simulation of power vacuum tube oscilators.

I. Introduction.

The rapid development of power electronic circuits for technology applications has created a need for numerical simulation of power electronic converters in order to facilitate their design by computer aided analysis. A number of programs and models are available for use in power electronics simulation [2], [3], [4], [5], [6], [7]. All these versatile programs, accompanied with devices models are suitable for simulation of semiconductor power electronic systems.

The computer simulation of power vacuum tube oscilators for electronic technology poses unique problems for the design engineers. The chief element in these circuits is the power oscilator vacuum tube, which has in general nonlinear V-A characteristics [1]. In some cases when the vacuum tube operates in switch mode and its operating point leaps from blocked condition to strenuous condition the versatile programs, which in principle simulate power semiconductor converters can be applied for computer simulation of the electromagnetic processes taking place in the power vacuum tube oscilators.

In most practical cases of the power vacuum tube oscilators the operating point passes from blocked condition to strenuous condition and conversely, staying for a certain amount of time which cannot be neglected, in the active region. Then the power vacuum tube has to be modelled taking into consideration its nonlinear V-A characteristics. This would allow the processes in the power vacuum tube oscilator to be simulated when the oscilator vacuum tube operates in class C, class B or class A.

II. Power Oscilator Vacuum Tube Model.

A computer simulation model of power vacuum tube is proposed, taking into account its V-A characteristics

$$i_a = F_a(v_a, v_g) \tag{1}$$

$$i_g = F_g(v_a, v_g) \tag{2}$$

where v_a is the anode-cathode voltage and v_g is the grid-cathode voltage. The vacuum tube can be considerred as a nonlinear element and can be modelled with two voltage-controlled current sources $J_a = F_a(v_a, v_g)$ and $J_g = F_g(v_a, v_g)$, as is shown in Fig.1. J_a represents the anode current of the vacuum tube and J_g represents the grid current of the vacuum tube. J_a and J_g depend on the anode-cathode voltage v_a and the grid-cathode voltage v_g .The functions F_a and F_g are determined with accordance with the vacuum tube V-A characteristics. Table I represents in tabular form the V-A characteristics (Fig.2) of the Russian manufacturred transmitting triode GU-5A.

III. State Equations of a Power Vacuum Tube Oscilator

State-variable approach can be applied for the analysis of the electromagnetic processes in the power circuit of a vacuum tube oscilator. Its matrix form is given in [8]. For instance, a vacuum tube feedback Meissner oscilator , whose ciruit diagram is shown in Fig.3, is considerred. The vaccum tube is replaced by its model (Fig.1) and the circuit normal tree is determined. The obtained equivalent circuit of the oscilator is shown in Fig.4. The state variables are v_{Cl} , v_{Ca} , v_{Cg} , i_{Ll} , i_{La} . The state equations are as follows:

$$\begin{aligned}
\frac{dv_{Cl}}{dt} &= -\frac{1}{R_l C_l} v_{Cl} + \frac{1}{C_l} i_{Ll} + \frac{1}{C_l} i_{La} - \frac{1}{C_l} J_a \\
\frac{dv_{Ca}}{dt} &= \frac{1}{C_a} i_{La} - \frac{1}{C_a} J_a \\
\frac{dv_{Cg}}{dt} &= -\frac{1}{R_g C_g} v_{Cg} - \frac{1}{C_g} J_g \\
\frac{di_{Ll}}{dt} &= \frac{1}{L_l} v_{Cl} - \frac{M}{L_l} \cdot \frac{dJ_g}{dt} \\
\frac{di_{La}}{dt} &= -\frac{1}{L_a} v_{Cl} - \frac{1}{L_a} v_{Ca} + \frac{1}{L_a} E_a
\end{aligned} \tag{3}$$

IV. State and Other Variables Determination.

The state variables v_{Cl} , v_{Ca} , v_{Cg} , i_{Ll} , i_{La} are determined by integration of the state equations system. This is done by applying the fourth order Runge-Kutta numerical integration procedure [9] or the numerical integration procedure for stiff differential equations proposed in [10]. The time step is very small, at least ten times less than the smallest time constant of the system (3), because each time step the values of the anode-cathode (v_a) and grid-cathode (v_g) voltages are specified and the values of the of the voltage dependent current sources J_a and J_g , representing the anode and grid currents of the vacuum tube are modified accordingly to v_a and v_g . The J_a and J_g values definition is done by interpolation of the tabular values given in TABLE I. The dJ_g /dt value is determined as the difference between the present and the previous value of J_g divided by the time step. Each time step as a result of the numerical integration procedure, the values of the state variables v_{Cl} , v_{Ca} , v_{Cg} , i_{Ll} , i_{La} are determined.

The variables which are not included in the state variable list are determined in the following manner

$$v_{Lg} = \frac{M}{L_l} v_{Cl} + (L_g - \frac{M^2}{L_l}) \frac{dJ_g}{dt} \quad (4)$$

$$i_{Rl} = \frac{v_{Cl}}{R_l} \quad (5)$$

$$i_{Rg} = \frac{v_{Cg}}{R_g} \quad (6)$$

$$i_{Ea} = -i_{La} \quad (7)$$

$$i_{Cl} = -i_{Rl} - i_{Ll} + i_{La} - J_a \quad (8)$$

$$i_{Ca} = i_{La} - J_a \quad (9)$$

$$i_{Cg} = -i_{Rg} - J_g \quad (10)$$

$$i_{Lg} = J_g \quad (11)$$

$$v_{Rl} = v_{Cl} \quad (12)$$

$$v_{Rg} = v_{Cg} \quad (13)$$

$$v_{Ll} = v_{Cl} \quad (14)$$

$$v_{La} = E_a - v_{Cl} - v_{Ca} \quad (15)$$

$$v_{Ja} = v_a = v_{Cl} + v_{Ca} \quad (16)$$

$$v_{Jg} = v_g = v_{Cg} - v_{Lg} \quad (17)$$

The node potentials, providing the number one node potential is zero ($v_1 = 0$), are

$$v_2 = E_a \quad (18)$$

$$v_3 = v_{Cl} \quad (19)$$

$$v_4 = v_{Cg} - v_{Lg} \quad (20)$$

$$v_5 = v_{Cl} + v_{Ca} \quad (21)$$

$$v_6 = v_{Cg} \quad (22)$$

V. Simulation Results.

The electromagnetic processes taking place in a vacuum tube feedback Meissner oscilator circuit have been simulated in accordance with the previously described manner by a program specially designed for vacuum tube oscilator circuit simulation. The input data for the analysis are as follows:

$E_a = 4000$V; $C_l = 0.54933$ mF; $C_a = 1$ mF; $C_g = 1$ mF; $R_l = 2551\ \Omega$;
$R_g = 744.7\ \Omega$; $L_l = 7.394$ mH; $L_g = 0.1915$ mH; $M = 1.1663$ mH; $L_a = 1.476\ \mu$H

The vacuum tube as has been already mentioned is GU-5A.

The results from the computer simulation for the steady-state solution after passing the transient excitation process are given in Fig.5, where the time diagrams of the vacuum tube anode-cathode voltage v_a, its anode current i_a, grid-cathode voltage v_g, grid current i_g, and the load voltage v_l for one period are shown. The same oscilator circuit with the same data has been analyzed by analytical methods [1]. The main results are: output power P=3000 W; output frequency f=2500 Hz; maximum anode current i_{amax} =4.11 A; amplitude of the load voltage V_{Clm} =3729 V; amplitude of the grid voltage 600 V; duration of the anode current 60° ; duration of the grid current 53° . The simulation results for the steady-state solution show that they are in good agreement with the results from the analytical procedure. The process of the oscilator excitation is given in Fig.6, where the time diagrams of v_a , i_a , v_g ,i_g ,v_l are shown for the transient start-up solution.

V. Conclusion.

A new vacuum tube model for numerical simulation of power oscilators has been developed. The model incorporates the nonlinear V-A characteristics of the vacuum tube. Then the state-variable approach has been applied for steady-state and transient analysis of a Meissner vacuum tube feedback oscilator, based on the newly developed vacuum tube model. The results demonstrate the good applicability of the vacuum tube model and the state-variable approach for the computer simulation of power vacuum tube oscilators for electronic technology.

VI. References.

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TABLE I

V-A characteristics of the transmitting triode GU-5A.

$J_a=F_a(v_a,v_g)$

v_a[V] \ v_g [V]	0	100	200	300	400
0	0	0	0	0	0
250	0	1.2	2.5	3.8	4.5
500	0	1.35	2.7	4.05	5.0
1000	0	1.5	3.1	4.55	5.5
1500	0	1.65	3.4	4.95	6.0
2000	0.11	1.8	3.7	5.3	6.5
2500	0.21	1.95	4.0	5.65	6.95
3000	0.31	2.1	4.3	5.95	7.3
3500	0.41	2.3	4.55	6.25	7.65
4000	0.51	2.5	4.8	6.55	7.95
4500	0.61	2.7	5.0	6.8	8.2
5000	0.71	2.9	5.15	7.05	8.45

$J_g=F_g(v_a,v_g)$

v_a[V] \ v_g[V]	0	100	200	300	400
0	0	0	0	0	0
250	0	0.7	2.0	3.25	4.2
500	0	0.6	1.75	2.9	3.8
1000	0	0.4	1.4	2.25	3.24
1500	0	0.3	1.2	1.9	2.8
2000	0	0.25	1.0	1.72	2.45
2500	0	0.24	0.85	1.55	2.21
3000	0	0.23	0.78	1.4	2.0
3500	0	0.22	0.75	1.3	1.8
4000	0	0.21	0.73	1.22	1.57
4500	0	0.2	0.7	1.15	1.45
5000	0	0.19	0.67	1.08	1.3

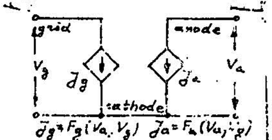


Fig.1. Vacuum tube model

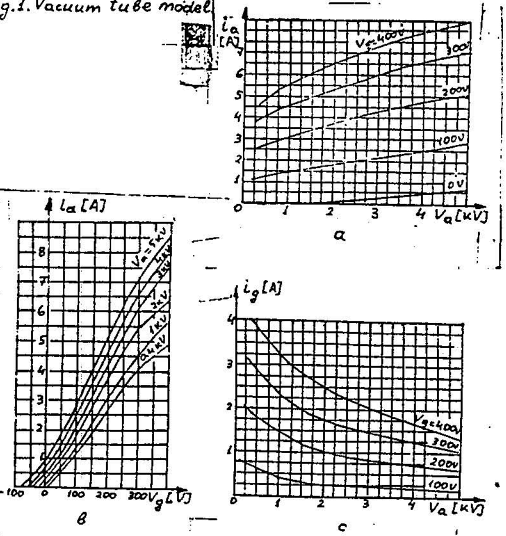


Fig.2. V-A characteristics of the transmitting triode GU-5A.

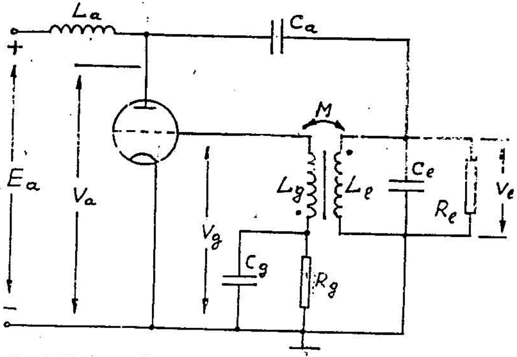


Fig.3. Vacuum tube feedback Meissner oscilator.

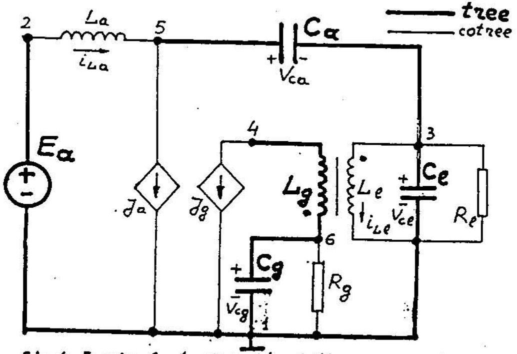
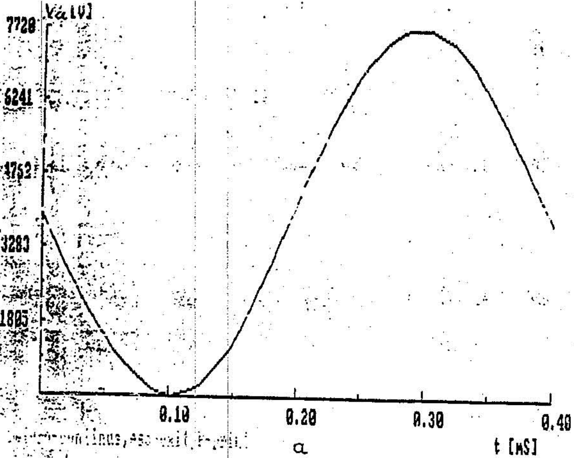
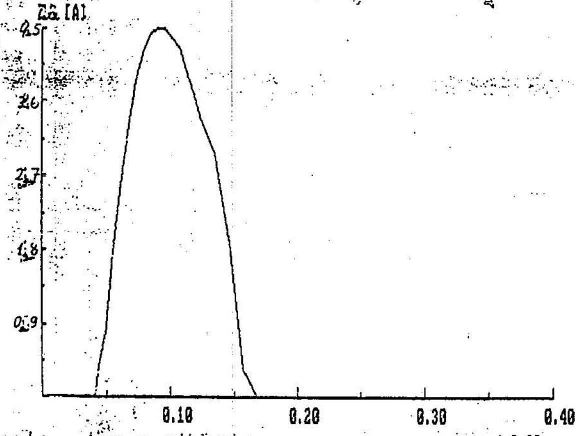


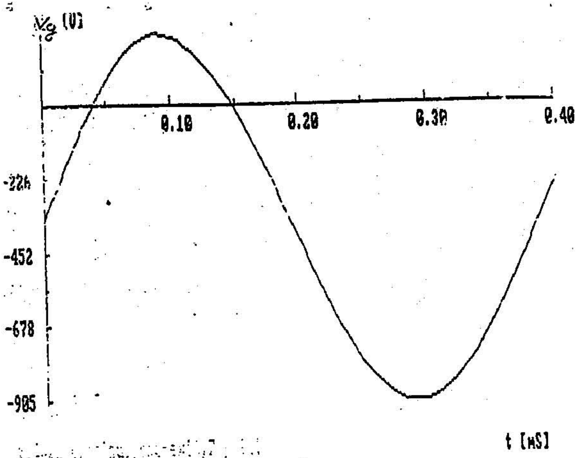
Fig.4. Equivalent circuit of the vacuum tube feedback Meissner oscilator


Va [V]
7728
6241
4752
3283
1805
0.10
0.20
0.30
0.40
t [mS]

a

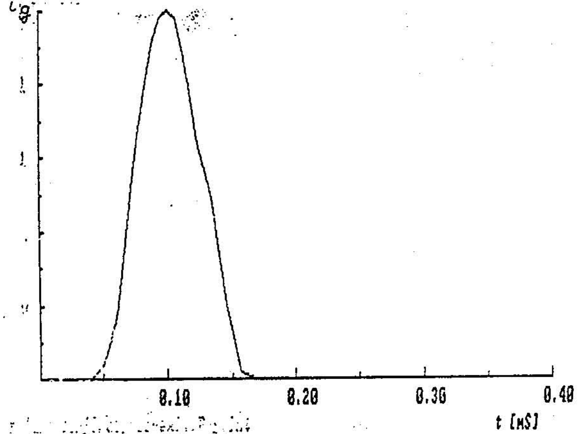
Fig.5

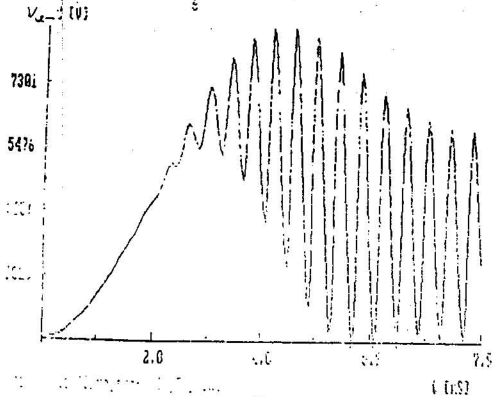

Ia [A]
4,5
3,6
2,7
1,8
0,9
0.10
0.20
0.30
0.40


Vg (V)
-226
-452
-678
-905
0.10
0.20
0.30
0.40
t [mS]

c

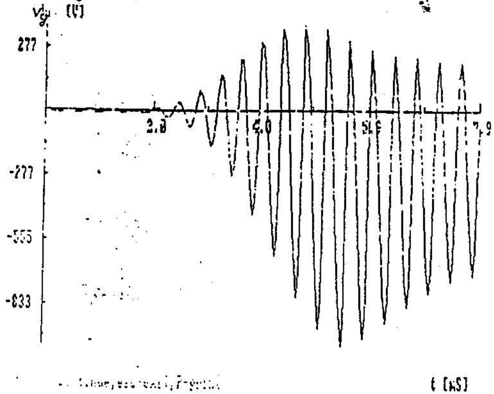
Fig.5.


ig
0.10
0.20
0.30
0.40
t [mS]



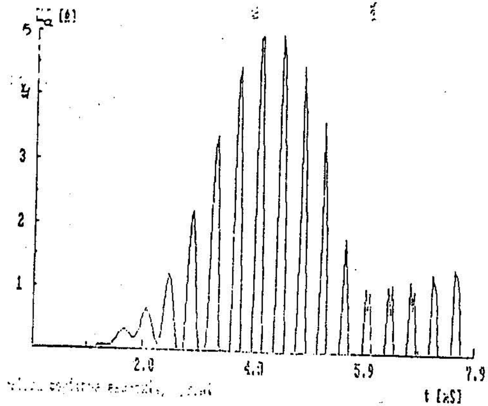
a

Fig 6.

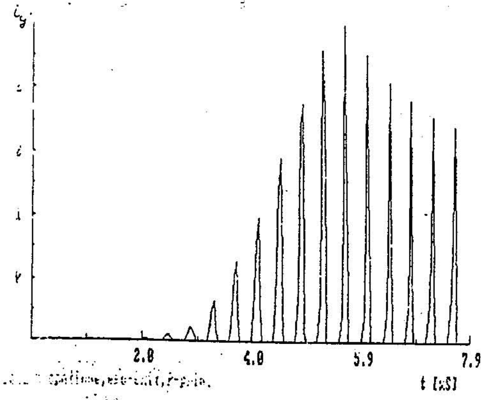


c

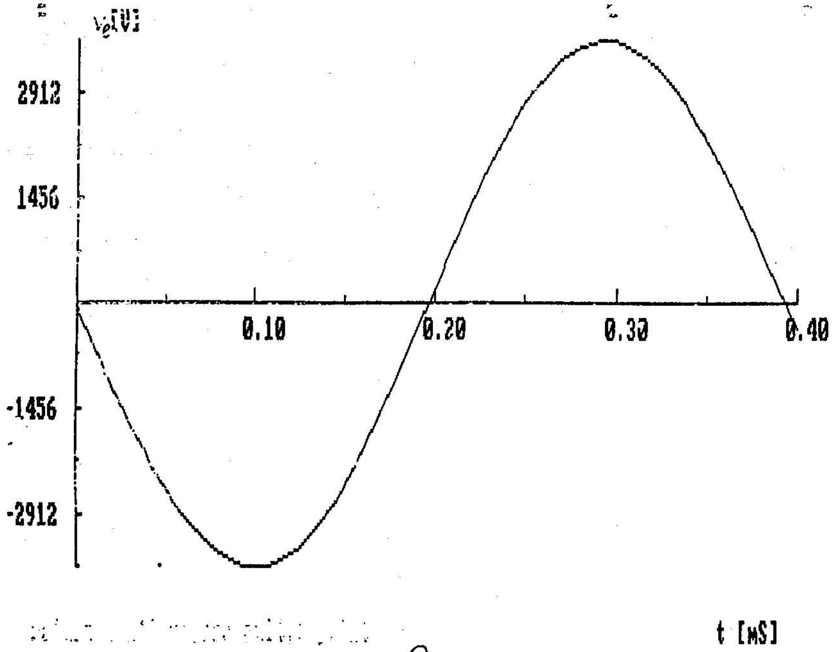
Fig 6.



б

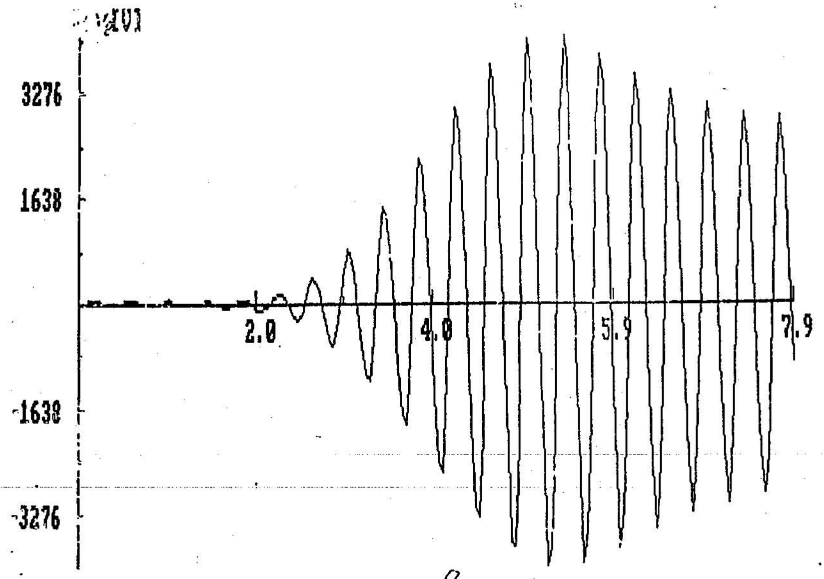


d


V_e[V]
2912
1456
-1456
-2912
0.10
0.20
0.30
0.40
t [mS]

e

Fig. 5.


V_e[V]
3276
1638
-1638
-3276
2.0
4.0
5.9
7.9
t [mS]

e

Fig. 6