MAGNETRON NONLINEARITY EFFECT ON ACCELERATOR OUTPUT ENERGY STABILITY

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Summary

The magnetron is in common use in microtron and electron linac as a RF power resource. In order to regulate the accelerator output energy, it is a feasible method to change the magnetron RF output power. It has been observed that there exists a unstable area while RF power is regulated by means of changing applied pulse voltage, which is generated with a line-type modulator. In the unstable region, the RF output power, frequency and accelerator output energy are variable (or unstable). Obviously it is not allowable for accelerator operation.

The qualitative and quantitative analysis is described about the unstable area. The cause leading to the above-mentioned phenomenon is the highly nonlinear relationship between the applied voltage and the current drawn by the magnetron, that is, the magnetron nonlinearity.

Some practical methods for solving the problem are given and experimentally proved effective.

Introduction

The magnetron is an oscillator that is charactered by small size, light weight, reasonable operating voltage, good efficiency, simple service and low price. It is still rather widely utilized in high-power pulsed radar and small-sized electron accelerator — microtron and electron linac as an oscillator today.

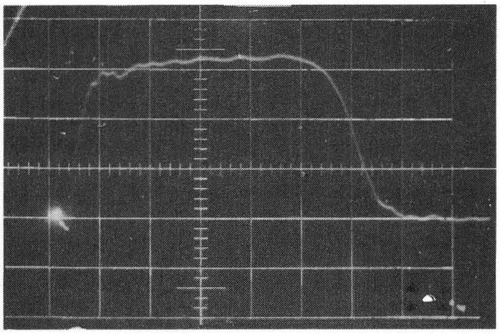
Because of the highly nonlinear relationship between the applied voltage and the current drawn by the magnetron, of particular important is the effect of the line-type pulser on the magnetron as well as the effect of the magnetron on the pulser. In order to eliminate or decrease the interaction, some satisfactory mesures are used, for instance, a despiking RC-cicuit for improving the match condition at the leading edge of a pulse.

In fact, we observed that the magnetron as a nonlinear device have another type of effect on the line-type modulator which provide a HV pulse, resulting in unstable pulse amplitude, which cause instability in RF power and frequency. It is not allowable for radar or accelerator operation.

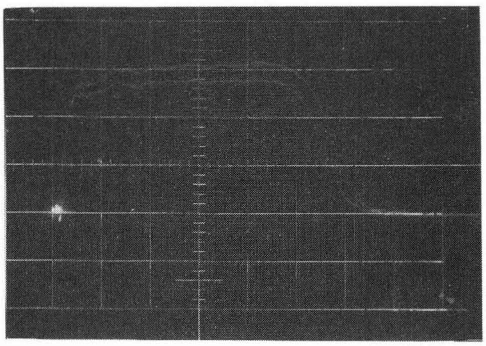
Dual envelope of the RF pulse

In order to regulate the accelerator output energy it is a feasible method to change the HV pulse amplitude of a modulator. As a pulse modulator, the line-type modulator has been widely used because of its relatively small size and weight and good efficiency. However, it has some serious disadvantages, among them a greater mismatch between the pulser and the load causes the over-all pulser operation to become unsatisfactory. If the load is a magnetron, the over-all pulser operation become more complex.

The dual envelope of the RF pulse is a unstable phenomenon because of the nonlinear mismatch between the line-type modulator and the magnetron. When occuring the phenomenon, a microwave envelope is given in Fig. 1(b) and a PFN (pulse-forming network) voltage charging waveform in Figure 2(b). Fig. 1(a) and 2(a) are the normal waveforms.

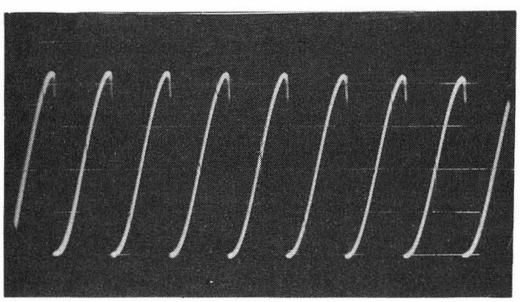


(a) the normal

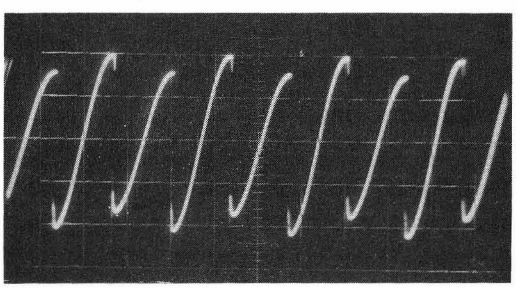


(b) the dual

Fig.1 the envelope waveforms of the RF pulse



(a) the normal



(b) the abnormal

Fig.2 the PFN voltage charging waveforms

The experiments show that this unstable phenomenon appears in low power level operation.

What are the causes leading to this difficulty?

As we know, most magnetrons can be represented by a biased diode, which current-voltage characteristic can be represented by Fig.3. For any point A along the current-voltage characteristic of the magnetron the instantaneous static impedance can be expressed as

$$R_l = \frac{V_l}{I_l} = \frac{V_s + I_l \, tg\alpha}{I_l} = \frac{V_s + I_l r_l}{I_l}$$

where V_l is the load voltage, I_l the load current, R_l the load resistance, the dynamic impedance, V_s the biased voltage.

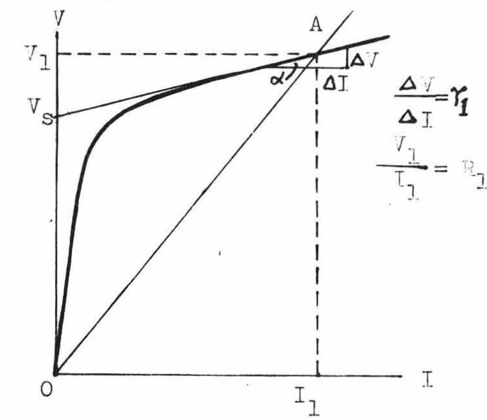


Fig.3 voltage-current relationships for a microwave magnetron, including definition of magnetron static and dynamic impedance

The line-type modulator derives its name from the similarity of the behavior of its energy storage element PFN to that of an open-circuited transmission line. If the load impedance R_l matches with the characteristic impedance Zn of the PFN, then a rectangular output pulse will be obtained. It is customary to mismatch the load slightly ($R_l < Z_n$) in order to promote formation of a slight negative voltage on the switching device in order to enhance recovery of the switch. If the switch is unidirectional (this is most common for a magnetron transmitter), a rectangular output pulse still will be obtained even though $R_l < Z_n$. When operating in low power level, there is positive mismatch ($R_l > Z_n$) between the load and the PFN, resulting in the reflected pulses following the principal pulse, which are successive descendent steps with same polarity. The future trouble from positive mismatch is to make main switch (such as a thyratron) difficult to hold off. Whereby it is preferable for main switch to have a certain amount of holding current so as to improve the operating stability of whole facility. However, while the holding current is larger, there is a rather high remain voltage $V_n(0)$ in the PFN at the beginning of next charging. In that case, for DC subresonant charging with a charging diode the expression[1] for the network voltage is

$$E_n(t)=E_b(1-\cos\omega_c t)+E_n(0)\cos\omega_c t \qquad (1)$$

$$E_{n\ max} = 2E_b-E_n(0)$$

where supposing there are no circuit losses and E_b is the DC power-supply voltage, ω_c is the resonant charging frequency, given by $\frac{1}{2\pi\sqrt{L_c C_N}}$. From equation (1), The maximum charging voltage $E_{n\ max}$ obtained in the PFN is less than $2E_b$.

It should be noted that low levels of RF output power may be generated by the magnetron even below the Hartree voltage[2]. If the first step following the principal pulse (operating point A in Fig.4) gives rise to RF output power, the remain voltage $E_{n1}(0)$ in the PFN will be lower than that $E_n(0)$ in the condition of no RF output power for first step. The network voltage $E_{n1}(t)$ of the next charging becomes

$$E_{n1}(t)=E_b(1-\cos\omega_c t)+E_{n1}(0)\cos\omega_c t \qquad (2)$$

$$E_{n1\ max}=2E_b-E_{n1}(0)$$

Because $E_{n1}(0)<E_n(0)$, the voltage of the following closely principal pulse will be higher than that of the proceding principal pulse, as a result the static resistance of the magnetron will decrease to R_1, corresponding to operating point A_1, as in Fig.4.

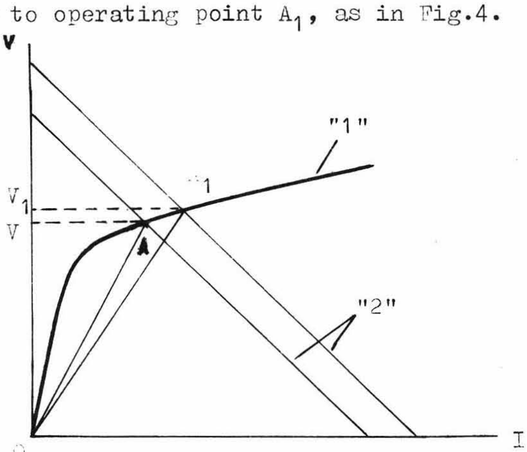


Fig.4 Graph for determining the operating point of the magnetron with the pulser load line: "1"-V/I characteristic curve of the magnetron; "2"-load line of the line-type modulator

If the following unequal relationship (3) is tenable

$$\frac{R_1-Z_n}{R_1+Z_n}\,\frac{R_1}{R_1+Z_n}E_{n1\ max}<\frac{R-Z_n}{R+Z_n}\,\frac{R}{R+Z_n}E_{n\ max} \qquad (3)$$

and if for the next cycle, the first step following the principal pulse does not give rise to RF output power, there will exist a larger remain voltage $E_n(0)$ in the PFN and from equation (1), $E_{n\ max}$ will be less than $E_{n1\ max}$, hence, under the identical power supply voltage E_b, there will exist two different $E_{n\ max}$ leading to dual envelope (see Fig.1 and Fig.2).

Equation (3) can be written as

$$\frac{R_1-Z_n}{R_1+Z_n}V_1<\frac{R-Z_n}{R+Z_n}V \qquad (4)$$

where V_1 and V are the amplitude of the principal pulse (see Fig.4). Introducing the reflecting coefficients

$$K=\frac{R-Z_n}{R+Z_n}\ ,\qquad K_1=\frac{R_1-Z_n}{R_1+Z_n}$$

$$\Delta K_1=K-K_1\ ,\qquad \Delta V=V_1-V$$

equation (4) becomes

$$\frac{\Delta V}{V}<\frac{\Delta K_1}{K_1} \qquad (5)$$

For a linear load, such as a pure resistance, the inequality (5) or (3) can not be tenable because $\Delta K_1=0$, $\Delta V>0$. The experimental studies have proved this conclusion.

Perhaps without exception, a high-power pulse transformer is used in the line-type modulator to transform the energy in a pulse from the pulse modulator to the impedance level of an RF oscillator. For simplicity, it has been assumed in our discussions that the pulse transformer introduced in the circuit have a voltage step-up ratio of n and that Z_n is reffered to the secondary side of the pulse transformer.

Generally speaking, with a well-designed modulator we can make the dual line area locate in the low power level, which does not affect normal operation for whole machine. However, if the impedance match between the PFN and the magnetron is unsuitable (such as the positive mismatch is too high in the low power level), and if the primary inductance of the pulse transformer is quite large, and if the holding current of the switch is very high, it is possible to arise the unstable area near the operating point.

The approaches to overcoming the dual line difficulty

In the unstable area, the RF output power, RF frequency and the accelerator output energy are all variable. Obviously, this type of operation is highly undesirable for a number of reasons.

We have made a lot of experiments, which are valid for controlling or eliminating the unstable phenomenon.

These approaches may be summarized as follows

1. to devise a good cut-tail circuit in the line-type modulator to cut off the steps after the principal pulse[3]. The unstable area can completely be eliminated by means of this approach.

2. to correctly design and construct the HV pulse transformer to improve the match condition between the line-type modulator and the magnetron. It is useful to decrease the primary inductance of the pulse transformer in order to decline the remain voltage in the PFN at the beginning of the charging cycle. One of them is to reasonably decrease the primary turns of the pulse transformer without influence on the pulse waveform. Another approach, which is no alternative but to be utilized, is to add a DC bias current, which direction is the same as the principal pulse, into the primary side of the pulse transformer.

3. to select the switch with small holding current, which we should ensure against continuously coducting.

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