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VACUUM TUBE OPERATION ANALYSIS UNDER A POSITIVE GRID BIASING IN J-PARC RCS

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Abstract

Tetrode vacuum tubes are used under the positive grid voltage region to accelerate a high intensity beam in the RCS. A tube amplifier is operated in push-pull mode and two tubes are installed in the amplifier. Although each control grid should be driven in counterphase for the push-pull operation, the waveform becomes asymmetric by the effect of the positive grid voltage. The vacuum tube operation analysis should include such an effect caused by the effect of the positive grid voltage. The analysis becomes complicated because the anode current and the control grid voltage waveforms interact with each other, and it should be solved with self-consistency. We will describe the analysis result under the effect of the positive grid voltage.

INTRODUCTION

The Japan Proton Accelerator Research Complex (J-PARC) Rapid Cycling Synchrotron (RCS) has been conducting beam commissioning to minimize beam loss at the design beam power of 1 MW [1]. One of the most important issues for stable beam acceleration is compensating the heavy beam loading at the rf system. A beam loading compensation system based on the rf feedback method has been successfully commissioned [2, 3].

Tetrode vacuum tubes are used in a final-stage amplifier to drive an rf cavity. An anode power supply provides an electric power to the tubes, and the required current for the power supply is obtained by a vacuum tube operation analysis [4]. Under the ordinary condition, the anode current is almost always determined by the waveform of the control grid voltage. Two tubes are used to operate the amplifier in push-pull mode. The acceleration voltage signal is divided by an rf power splitter and delivered to each control grid circuit. The voltage waveform on each control grid becomes symmetric without the effect of the positive grid voltage.

On the other hand, the RCS rf system utilizes a multi-harmonic rf driving. This means that the waveform of the control grid voltage is not purely sinusoidal. Furthermore, a large amplitude of the anode current is needed in the RCS to compensate the heavy beam loading, and the control grid voltage then enters into the positive voltage region. A part of the anode current flows into the control grid circuit, and it deforms the waveform of the control grid voltage. Consequently, the waveforms on each control grid become asymmetric under the positive grid voltage region [5].

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Previous vacuum tube operation analysis does not treat the effect of the positive grid voltage. There is a difference in the calculation result of the required current for the anode power supply because the waveform of the control grid voltage almost always determined the anode current. We will describe the vacuum tube operation analysis under the condition of the positive grid voltage.

CONTROL GRID CURRENT

In general, the anode current I_a of the tetrode tube [6] is obtained from

$$I_a = k\left(V_{cg} + \frac{V_{sg}}{\mu_{sg}} + \frac{V_a}{\mu_a}\right)^n , \tag{1}$$

where V_a, V_{cg}, and V_{sg} are an anode voltage, a control grid voltage, and a screen grid voltage, respectively. μ_a is an amplification factor for the anode, and μ_{sg} is an amplification factor for the screen grid. k is called "Perveance" of the tube and n is a constant near 1.5. The detailed calculation method of the anode current is described in [4].

In the positive grid voltage region, a part of the anode current flows into the control grid. The current division ratio between the anode and control grid [7] is described as

$$\frac{I_a}{I_{cg}} = \delta\sqrt{\frac{V_a}{V_{cg}}} , \tag{2}$$

where I_{cg} is a current on the control grid. δ is a constant of the tube called "current-division factor". The factor depends on the characteristics of each tube, and it is defined according to the measurement result of the control grid.

Two tetrode tubes are used at the final-stage amplifier, and they are operated in push-pull mode. When the current flows into the control grid circuit in the positive grid voltage region, the control grid power supply provides the DC component of the current as shown in Fig. 1. The black line and red lines denote the case of one tube (named VT1) and the other tube (named VT2), respectively. The DC component is measured over the whole acceleration period.

On the other hand, the instant voltage waveforms of the control grid and the anode at a certain time are measured as shown in the upper and middle graph of Fig. 2. Figure 2 shows the case at the 10 ms during the acceleration. The anode current waveform is calculated from the anode and control grid waveforms by Eq. (1) as shown in the bottom graph of Fig. 2.

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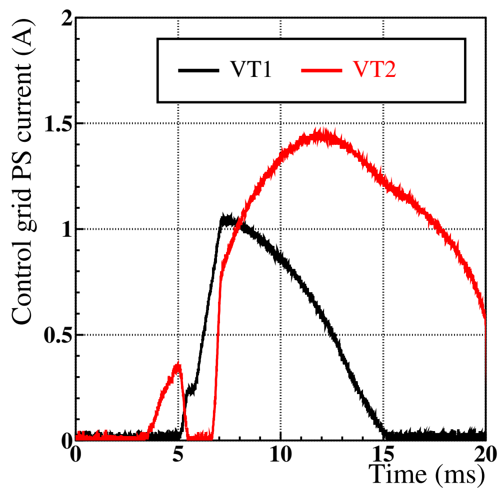

Figure 1: Measurement results of the DC power supply current of the control grid during the acceleration.

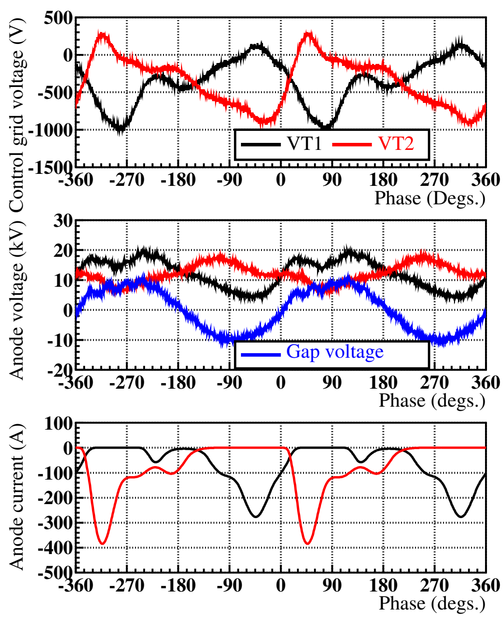

Figure 2: Measured waveform of the control grid voltage and anode voltage and the calculation result of the anode current.

Assuming a value in δ, the control grid current waveform is estimated by Eq. (2) as shown in Fig. 3. The DC component of the waveform should be equal to the control grid power supply current as shown in Fig. 1. δ can be determined by repeated calculations, which is around 4 in the RCS case. Once the δ value is determined, the control grid current waveform can be calculated by Eq. (2).

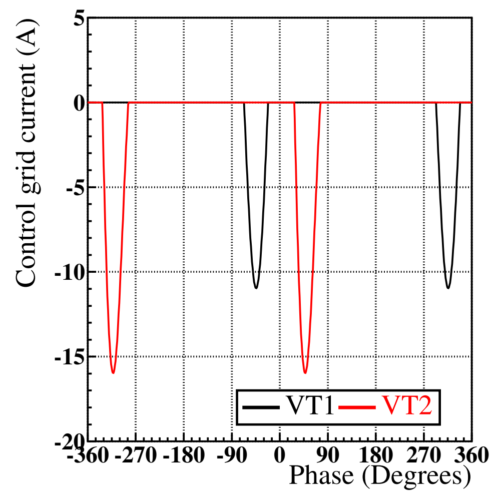

Figure 3: Calculation result of the control grid current.

ANALYSIS WITH POSITIVE GRID BIASING

A deformation of the waveform for the control grid voltage depends on the control grid current. The RCS utilizes a bridged-T type all-pass network for the control grid circuit [5] as shown in Fig. 4. Z_{cg} is an impedance of the control grid itself, Z_L and Z_C are impedances to realize the all-pass characteristics, and R is a resistor. V_d is a driving voltage from a solid-state amplifier. The all-pass conditions that the input impedance is always constant value R are

$$Z_L = \frac{R^2}{2Z_{cg}}, \quad Z_C = 4Z_{cg} \ . \tag{3}$$

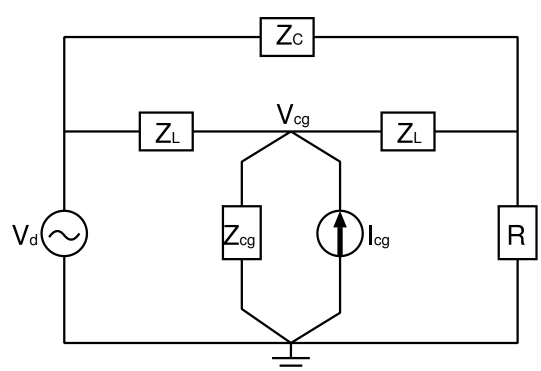

Figure 4: Bridged-T type all-pass network for the control grid circuit.

The control grid voltage V_{cg} is deformed by the control grid current I_{cg} as

$$V_{cg} = (1 - Z_L Z_{L11})V_d + Z_L Z_{L12} I_{cg} \ , \tag{4}$$

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where

$$Z_{L11} = \frac{1 + \dfrac{Z_{cg}}{Z_L + R + \frac{Z_L}{Z_C} R}}{Z_L + Z_{cg} + \dfrac{Z_{cg}\left(Z_L - R + \frac{Z_L + Z_C}{Z_C} R\right)}{Z_L + R + \frac{Z_L}{Z_C R}}} \quad (5)$$

$$Z_{L12} = \frac{Z_{cg}}{Z_L + Z_{cg} + \dfrac{Z_{cg}\left(Z_L - R + \frac{Z_L + Z_C}{Z_C} R\right)}{Z_L + R + \frac{Z_L}{Z_C R}}} \quad . \quad (6)$$

When the control grid voltage is deformed, the anode current is changed by Eq. (1), which causes change in the control grid current by Eq. (2). Eventually, the calculations are repeated until these voltages and currents are self-consistent and approach their true values.

Figure 5 shows the analysis results without the effect of the positive grid voltage. The analysis condition is that the beam loading up to the third harmonic is compensated at the 1 MW beam acceleration in the RCS. The waveform of the control grid voltage is symmetric on each control grid as shown in the top graph. The bottom graph shows the calculation result of the anode current waveform, and its DC component is equal to the anode power supply current. In this case, the anode power supply provides the current of around 140 A to the tubes.

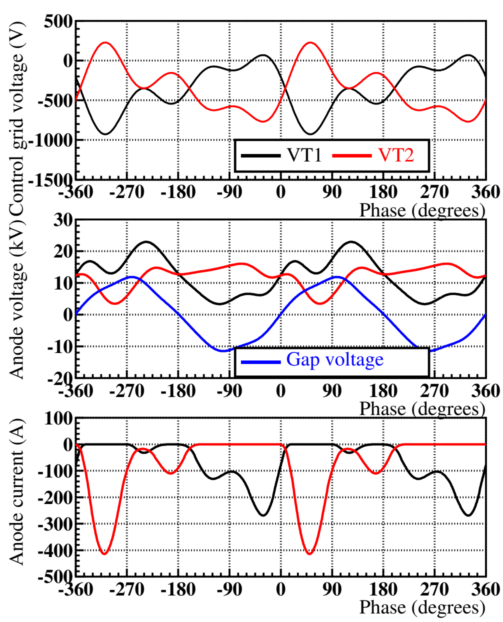

Figure 5: Analysis result without the effect of the positive grid voltage.

Figure 6 shows the analysis results with the effect of the positive grid voltage. The analysis condition is the same as Fig. 5; however, the waveform of the control grid voltage is not symmetric on each control grid because of the deformation by the control grid current. Consequently, the waveform of the anode current is different from the case without the effect of the positive grid voltage, and the anode power supply provides the current of around 160 A to the tubes. Since the difference between with and without the effect of the positive control grid voltage affects the requirement for the anode power supply, it is important to analyze the tube operation considering the effect of the positive grid voltage.

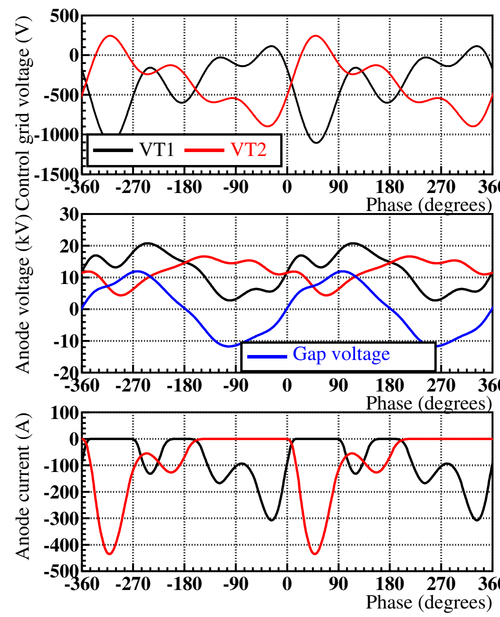

Figure 6: Analysis result with the control grid voltage effect.

SUMMARY

We have investigated the influence at the positive grid voltage region for the vacuum tube operation analysis. The part of the anode current flows into the control grid circuit in the positive grid voltage region, causing the deformation of the control grid voltage waveform. The operation analysis should be solved self-consistently because the deformation of the control grid voltage promotes the change of the anode current. The comparison between with and without the effect of the positive grid voltage reveals the difference in the calculated anode current.

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