Modeling of the RF system for the normal conducting linac

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Abstract To study the new RF control methods, a mathematic model of the RF system for the normal conducting linac is built and implemented with the software of Matlab. The model contains some typical units of the RF system, such as the klystron, the SLED and the traveling wave accelerating tube. Finally, the model is used to study the working point of the SLED and the adaptive feed forward algorithm for the RF control system. Simulation shows that the model works well as expected.

Key words RF system, mathematic model, normal conducting linac, feed forward

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1 Introduction

The normal conducting linac was widely used during the last several decades. Though the superconducting linac becomes more and more popular, many new projects still employ the normal conducting structure, for example, the injector of the synchronized radiation source or the XFEL.

The new applications require more strict stability for the RF phase and amplitude. To meet these requirements, digital technologies such as FPGA and DSP are used to implement the RF control system, which can perform fast and flexible feedback and feed forward control[1].

A proper control algorithm is very important for a digital control system, and to study the control algorithm, an effective way is to build a mathematic model and make simulation. So, for the RF control system, a mathematic model[2] of the RF system including the klystron, the SLED and the accelerating tube is built with the software of Matlab, which is a powerful tool for control system modeling. With this model, the responses of the RF system under different inputs are studied. And the new control algorithms such as the adaptive feed forward control are also studied and tested on it.

2 Modeling of the RF system

2.1 Structure of the RF system

The typical RF system of the normal conducting linac is shown in Fig. 1. The RF signal is generated by a stable oscillator and controlled by an RF modulator, which is used to change the phase and amplitude of the RF signal. The modulated RF signal is amplified and used to drive the klystron. After the klystron, a SLED is used to compress the RF pulse in order to increase the peak RF power. Finally, the RF power is fed into the traveling wave accelerating tube, where the electron beam is accelerated.

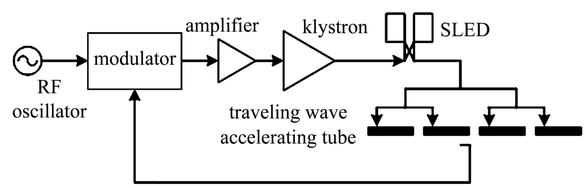

Fig. 1. Structure of the RF system.

2.2 Modeling of the klystron

The klystron is used to amplify the RF power to a level of MW. Because it has a specified band width, the klystron can be modeled as a band pass filter, which corresponds to a low pass filter in the base band. The transfer function of the klystron can be written as

$$H_{\mathrm{kly}}(s)=k_{\mathrm{kly}}\cdot\frac{\omega_{\mathrm{c,kly}}}{s+\omega_{\mathrm{c,kly}}}\,, \tag{1}$$

where $\omega_{\mathrm{c,kly}}$ is the band width of the klystron, k_{kly} is the gain factor of the klystron.

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For a real klystron, the gain factor is not a constant value. When the input power is high enough, the gain factor will decrease, that is, the klystron will be saturated. The feature of the power saturation can be modeled by a look-up table.

The model of the klystron consists of a band pass filter and a look-up table, which is shown in Fig. 2. In the klystron model, the random noise is used to simulate the high voltage ripple of the klystron modulator, which will influence both the phase and the amplitude of the RF output signal.

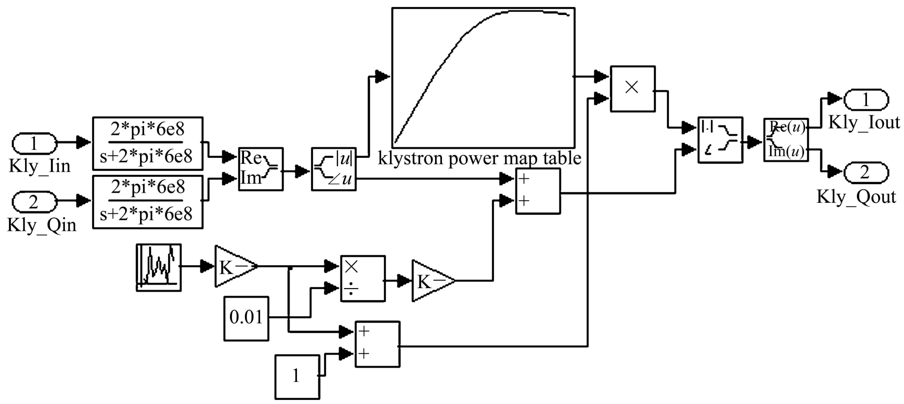

Fig. 2. The klystron model.

2.3 Modeling of the SLED

The SLED is formed by a 3 dB hybrid and two resonance cavities, which is driven by the RF power from the klystron. The structure of the SLED is shown in Fig. 3.

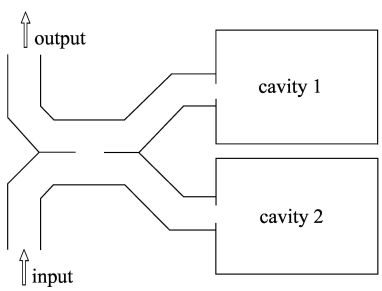

Fig. 3. The structure of the SLED.

The cavities will store the RF power and then radiate it to the output port of the SLED. For a single cavity, the cavity voltage equation[3] can be written as

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{bmatrix} V_r' \\ V_i' \end{bmatrix} = \begin{bmatrix} -\omega_h & -\Delta\omega \\ \Delta\omega & -\omega_h \end{bmatrix}\begin{bmatrix} V_r' \\ V_i' \end{bmatrix} + \frac{2\beta_{\mathrm{in}}\omega_h}{\beta_{\mathrm{in}}+1}\begin{bmatrix} V_{\mathrm{for},r}' \\ V_{\mathrm{for},i}' \end{bmatrix}, \tag{2}$$

where V_r' and V_i' are the real and image parts of the cavity voltage, $V_{\mathrm{for},r}'$ and $V_{\mathrm{for},i}'$ are the real and image parts of the driven voltage, and the other symbols are the parameters of the cavity.

The output signal of the SLED is formed by the reflected signals of the two cavities, so the SLED model can be built as Fig. 4.

Because there is a phase shift between the input and output signals of the SLED, the transfer function of the SLED should be written as a matrix

$$H_{\mathrm{sled}}(s) = \begin{bmatrix} 0 & \dfrac{s-(k_{\mathrm{sled}}-1)\omega_h}{s+\omega_h} \\ \dfrac{-s+(k_{\mathrm{sled}}-1)\omega_h}{s+\omega_h} & 0 \end{bmatrix}, \tag{3}$$

where k_{sled} is the gain factor of the SLED.

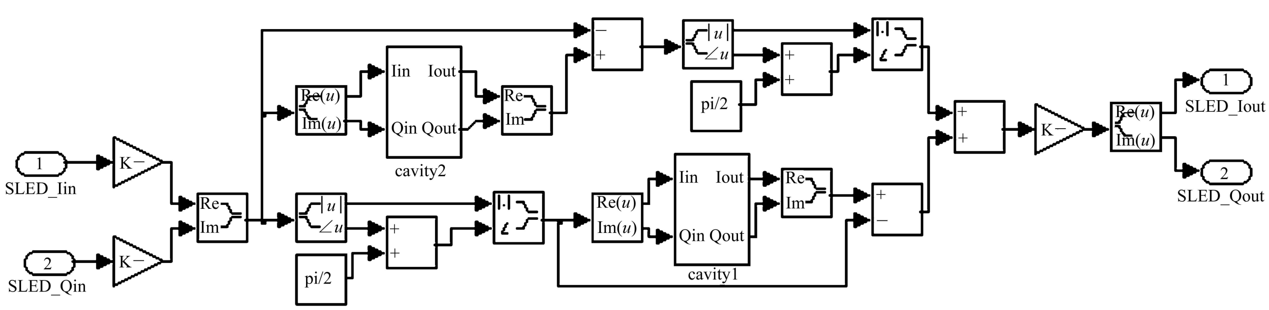

Fig. 4. The SLED model.

2.4 Modeling of the traveling wave accelerating tube

The disk loaded waveguide is the most popular accelerating structure for the normal conducting linac.

The accelerating tube can be modeled as a band pass filter with a certain attenuation during the pass band. The transfer function of the accelerating tube can be written as

$$H_{\text{acc}}(s)=k_{\text{acc}}\cdot\frac{\omega_{\text{c,acc}}}{s+\omega_{\text{c,acc}}}\,, \tag{4}$$

where $\omega_{\text{c,acc}}$ is the band width of the accelerating tube, and k_{acc} is the attenuation factor of the accelerating tube.

The RF group velocity in the accelerating tube is so slow that there is a big delay between the input and output signals. The delay time is defined as the filling time of the accelerating tube.

Consider the whole RF system including the klystron, the SLED and the accelerating tube, the transfer function is

$$H(s)=\begin{bmatrix} 0 & \frac{k_{\text{acc}}\omega_{\text{c,acc}}}{s+\omega_{\text{c,acc}}}\frac{s-(k_{\text{sled}}-1)\omega_h}{s+\omega_h}\frac{k_{\text{kly}}\omega_{\text{c,kly}}}{s+\omega_{\text{c,kly}}} \\ -\frac{k_{\text{acc}}\omega_{\text{c,acc}}}{s+\omega_{\text{c,acc}}}\frac{s-(k_{\text{sled}}-1)\omega_h}{s+\omega_h}\frac{k_{\text{kly}}\omega_{\text{c,kly}}}{s+\omega_{\text{c,kly}}} & 0 \end{bmatrix}. \tag{5}$$

The typical input and output waveforms of the RF system are shown in Fig. 5.

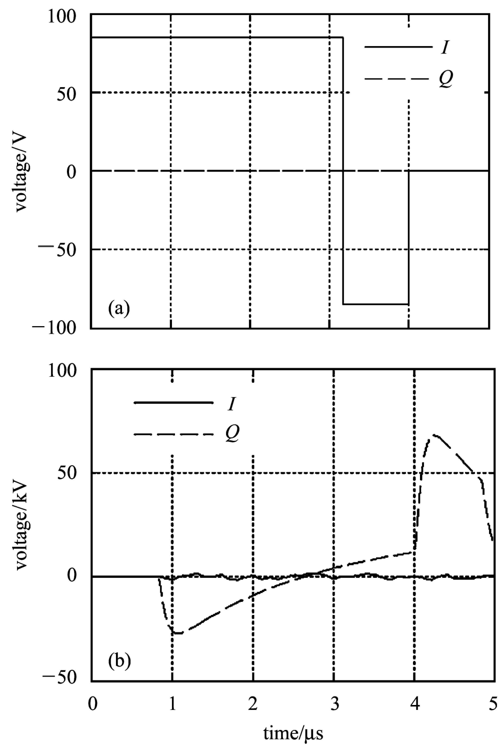

Fig. 5. The input (a) and output (b) waveforms of the RF system.

3 Application examples of the RF model

3.1 Study of the working point of the SLED

When the RF power is fed to the SLED, the two cavities of the SLED will start to store energy. After filling for some time, the phase of the input RF signal will be changed by 180 degrees. The radiation signal from the cavities and the phase inversed input signal will be added in-phase at the output port of the SLED[4].

The pulse compress effect of the SLED strongly depends on the phase inverse time of the input RF signal. With the RF model, the SLED responses under different phase inverse time are studied. Fig. 6(a) shows the output of the SLED under different input signals, while Fig. 6(b) shows the corresponding energy gain factor.

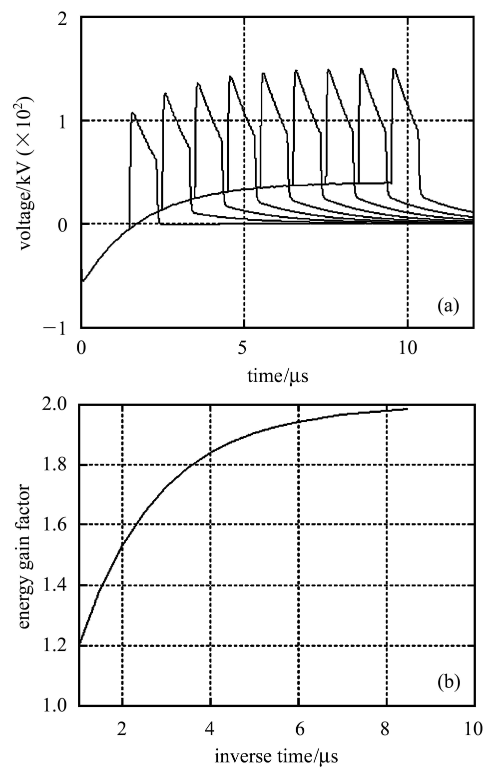

Fig. 6. Study of the working point of the SLED. (a) SLED response under different input; (b) energy gain factor.

For the SLED of BEPC Ⅱ Linac, the phase inverse time is 3.17 μs, so the energy gain factor is about 1.7.

3.2 Adaptive feed forward control system

In the RF system of the normal conducting linac, the accelerating tube has a too large delay to perform a real time feedback control. So, the adaptive feed forward control algorithm[5] can be used to control the phase and amplitude during the RF pulse. A precise model of the RF system is the base of the adaptive feed forward control system.

Figure 7 shows the structure of the adaptive feed forward control system based on the RF model established above.

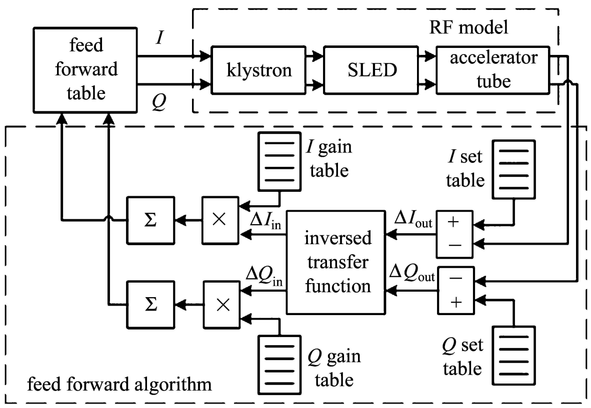

Fig. 7. The adaptive feed forward control system.

The error of the RF output signal is generated by the comparison with a set point table. The corresponding input error can be calculated by the inversed transfer function of the RF model, which can be obtained from Eq. (5). The input error calculated is added to the feed forward table in order to compensate the output error.

The waveforms of the RF output signal before and after the adaptive feed forward control are shown in Fig. 8. It is shown that the adaptive feed forward control algorithm is effective to compensate the fluctuation inside the RF pulse.

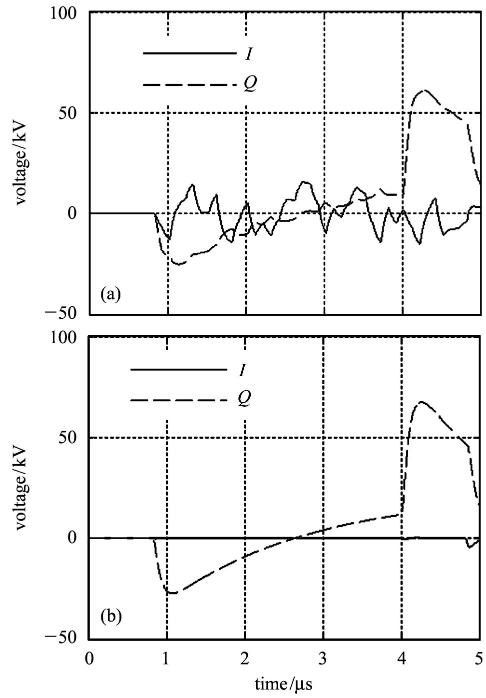

Fig. 8. RF output signals before (a) and after (b) feed forward control.

4 Summary

To study the new control algorithm for the digital RF control system, a mathematic model is built for the RF system of the normal conducting linac. The model of some typical RF units such as the klystron, the SLED and the traveling wave accelerating tube is built with the software of Matlab. Two application examples of the RF model are described and give good results.

The RF model can be used to make further study of the RF system and the new control algorithms.

References

1 Michizono S, Anami S et al. Digital Feedback System for J-PARC Linac RF Source. In: DESY. Proceedings of LINAC 2004. Hamburg: DESY, 2004. 742—744

2 Sungil K, Yiming W, Amy R. SNS LLRF Control System Model Design. IEEE PAC99 Proceedings. New York: IEEE, 1999. 1067—1069

3 Schilcher T. Vector Sum Control of Pulsed Accelerating Fields in Lorentz Force Detuned Superconducting Cavities. Ph. D. Thesis of DESY, 1998

4 GU Peng-Da. Research on New Type RF Pulse Compressro. IHEP Ph. D. Thesis, 1999 (in Chinese)

5 Liepe M, Simrock S N. Adaptive Feed Forward for the Digital RF Control System at the TESLA Test Facility. Proceedings of EPAC'98. Stockholm: Institute of Physics Publishing, 1998. 1735—1737