DESIGN OF RAPID TUNING SYSTEM FOR A FERRITE-LOADED CAVITY WITH HEAVY BEAM LOADING

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Abstract

A high power, broadband and rapid frequency sweeping RF system was developed to satisfy the demand of China Spallation Neutron source (CSNS)/ Rapid Cycling Synchrotron (RCS). The cavity tuning is the key issue which has great impact on the performance of the whole RF system. In order to satisfy the requirement of cavity dynamic tuning caused by the nonlinear characteristics of ferrite, some new technologies were developed and applied. In this paper, the overall design of the tuning system will be introduced. The ensuing discussion will be focused on the comparison between different types of bias supplies, the control algorithm of low level RF (LLRF) system and the beam loading compensation issues.

INTRODUCTION

In a rapid cycling synchrotron (RCS), cavity tuning is the key issue to maintain the stability and efficiency of RF system. The wide frequency range, the short acceleration time and the heavy beam loading effect poses great challenge to the dynamic performance of tuning system. In this article, the design of tuning system of China Spallation Neutron Source (CSNS)/RCS RF system will be introduced, and the related new technologies and methods will also be discussed.

CSNS/RCS RF SYSTEM

CSNS is a multidisciplinary research facility under construction, which is composed of an H- linac, a proton RCS, two transport lines, a target station, and several instruments. The project plan to be built in two or three phases. In the first phase, the RCS is designed to accelerate proton beam from 80MeV to 1.6 GeV with a repetition rate of 25 Hz and a beam power of 100 kW.

In the first phase, a total of 8 fundamental RF systems are used to provide a peak RF voltage of 165 kV. The RF systems operate on the harmonic number h=2, and the frequency sweeps from 1.022 MHz at injection to 2.444 MHz at extraction with a repetition rate of 25 Hz.

The RF system is mainly composed of a cavity, a bias supply, a high power RF amplifier and a digital low level RF (LLRF) system. The cavity used is a ferrite-loaded coaxial resonator with two accelerating gaps and is single ended. Corresponding to the bias current varying range of 200-2800 A, the resonant frequency of cavity can sweep from 1.02 to 2.44 MHz with the cavity gap capacitance of 3nF. For one gap, a nominal peak RF gap voltage of more than 11.8 kV is required. The RF amplifier consists of a three stage amplifiers chain. The final stage amplifier uses a tetrode TH558. The maximum plate dissipation of the tube is 500 kW. The tetrode is driven by a feedback (FB) amplifier of 800W located in the rack of the final stage amplifier adjacent to the cavity. The RF drive signal from a wide-band solid-state preamplifier of 500 W will be combined with an RF signal extracted from the cavity which has a proper amplitude and delay to drive the FB amplifier.

DESIGN OF TUNING SYSTEM

For a typical tuning system, the load voltage should be in anti-phase to the grid voltage. In this way, the load presents purely resistive and the RF system is most efficient. The optimized tuning condition is guaranteed by the tuning control loop in LLRF system through changing the additional biasing magnetic field. Based on above principle, the CSNS/RCS RF tuning system is mainly composed of two subsystems in the function. One is the tetrode grid tuning system, and the other is the cavity tuning system. Both of two subsystems have a similar control flow. Firstly the input and output signals of the RF amplifier are sampled respectively, then the phase between two signals is compared and the tuning error is calculated , lastly through related control algorithm the control loop corrects the resonant

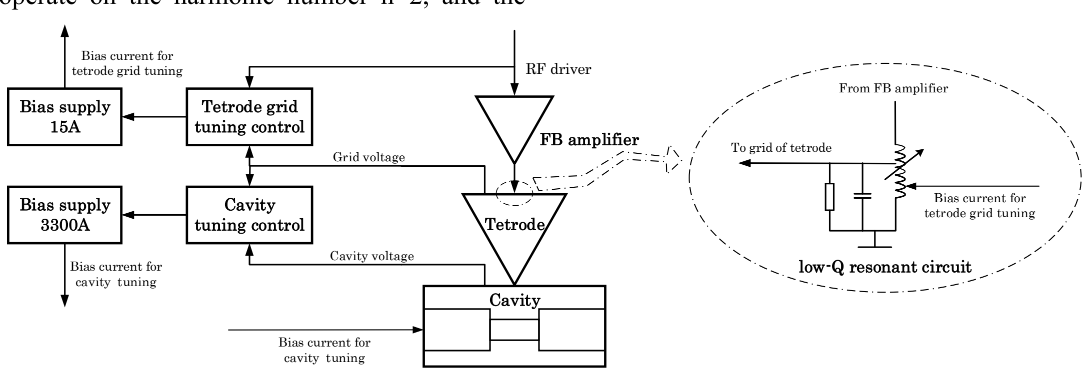

Figure 1: CSNS/RCS RF tuning system configuration.

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condition of the load by adjusting the bias current. Fig.1 shows the configuration of the CSNS/RCS RF tuning system.

Other than the common design, there is a tetrode grid tuning system with servo control to compensate the parasitic capacitance of the tetrode grid in the operating frequency range. As shown in the right part of Fig.1, a low-Q resonant circuit is located at the tetrode grid with an impedance matching network with the ratio 4 to 1. The network is also ferrite-loaded, so the inductance can be verified in accordance with the parasitic capacitance value. One of the major function of the tetrode grid tuning system is to ensure the gain and stability of RF power source during widely frequency sweeping operation. The other is to ensure the phase shift in the RF feedback control system which is adopted to reduce transient beam loading and enhance the dynamic performance on account of the characteristics of low latency and high bandwidth.

For the cavity tuning system, due to the bandwidth limit of bias supply with large current, some new technologies are used to improve the dynamic performance of RF system with heavy beam loading, and will be presented in the following sections.

PRINCIPLE AND STRUCTURE OF BIAS SUPPLY

The bias supply is used to correct the resonant condition by providing an additional biasing magnetic field. Due to such nonlinear characteristic as magnetic hysteresis and dynamic loss, the bandwidth actually needed is much higher than the repetition rate and the ability of fast and fine adjustment is the key performance indicator. In practice, the tuning system bandwidth should be greater than 10 kHz to obtain an ideal result with the detuning phase less than 5 degree. Generally speaking, the bandwidth of digital control system can achieve the level of dozens of kHz, and the analog system could be even higher. The bandwidth of tuning system actually is limited by the bias supply. So the performance of tuning system largely depends on the small signal bandwidth (SSWB) of bias supply. In CSNS/RCS, the RF system operates in a pulse mode. Fig. 2 shows a typical working pattern of bias supply in one cycle. The maximum current is about 3300A. After the beam extraction, the current rapidly decreases to a low value (~150A) in about 1 ms.

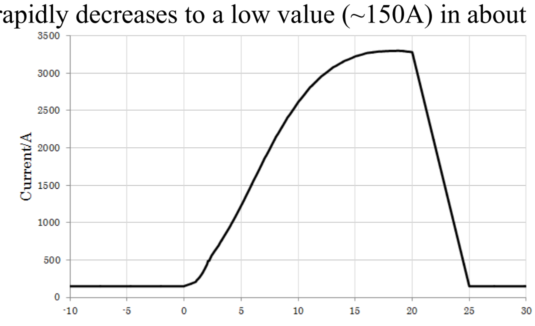

Figure 2: A typical working pattern of bias supply.

The screen grid modulation is used to reduce power dissipation of the final stage tetrode. Based on the same consideration, the switch type of bias supply was chosen and developed in the original design with a 4 modules output-parallel scheme. The main part of the bias supply is a DC-DC converter with pulse width modulation (PWM). Balancing the power dissipation with the bandwidth, the operating frequency of converter power tube is 20 kHz. For a single module with frequency doubling, the operating frequency is 40 kHz, and the equivalent switching frequency with 4 modules current sharing is 160 kHz. But even with the optimized hardware structure and inner control parameters, the actual measurement showed that the bandwidth of switch type of bias supply was about 3 kHz, which cannot satisfy the demand of tuning system. , which cannot satisfy the demand of tuning system. To improve the bandwidth of bias supply, 2 upgrading schemes were proposed. In the first, a brand new linear type of scheme was adopted, and in the second, a small linear subcircuit would be added into the existing switch type of bias supply. At last, both of these 2 schemes were implemented, just in case.

The linear type of bias supply adopts a classical Darlington circuit scheme with 3 stages. One transistor in the first stage drives 2 transistors in the second stage, and one transistor in the second stage drives 13 transistors in the third stage. There are 48 transistors in first stage, and 1248 transistors in total. The maximum current for one transistor is 16 A, and the maximum power dissipation is 250 W. In theory, the linear type of bias supply should have the highest bandwidth. But limited by the distributed parameter and current sharing of so many transistors, the actual bandwidth is about 23 kHz.

The second upgrading scheme is called combined type of bias supply. A small linear type of modulator with a maximum 180A output is added into the switch type of bias supply, as shown in Fig. 3. In this case, the major part of bias current which is also the low frequency component will be provided by the switch type, and the low current with high frequency which is used to fast adjustment will be provided by the linear type. In this way, the power dissipation and bandwidth of bias supply is balanced, and the stability is also improved. The bandwidth of combined type of bias supply is above 30 kHz, which is the highest among the 3 different types of bias supplies.

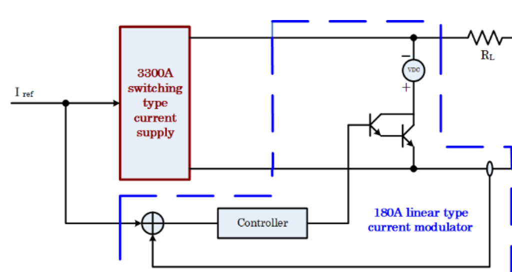

Figure 3: The schematic of combined type of bias supply.

At last, the combined type of bias supply was chosen for the formal technical scheme. Fig. 4 shows the bandwidth comparison in the condition of 1000A DC plus 10A AC.

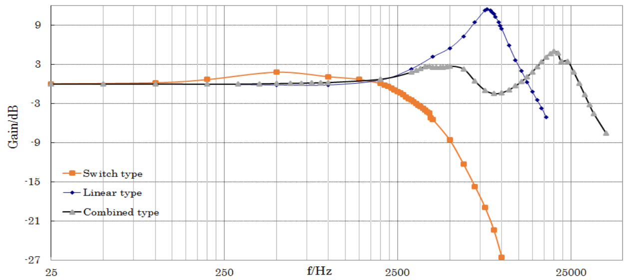

Figure 4: The bandwidth comparison of 3 different types of bias supply.

In practice, as mentioned above, SSWB is the most important technical indicator to the tuning system. In order to achieve higher performance, some other indicators may be affected. First, the requirement of tracking precision could be relaxed. Not like the power supply used in magnet system, the actually needed current is guaranteed by the tuning system instead of the inner controller of bias supply. Second, the requirement of voltage ripple could be also relaxed. Lower voltage ripple means bigger filtering capacitance, which will lead to decline of the bandwidth. In CSNS/RCS RF system, the actual requirement of voltage ripple is lower than 0.5% of output voltage, and the consequence sideband component is lower than 70 dB. Besides, due to the existing of bypass capacitor, part of the bias current with high frequency will pass through this path. Because this part of current will not change the tuning condition of the cavity, so the linear modulator should generate much higher current than actually needed.

TUNING CONTROL ALGORITHM

The tuning control algorithm in LLRF is designed to minimize the detuning phase by adjusting the resonate frequency of cavity. In general case, a feedback loop based on the proportional-integral-derivative (PID) controller is commonly used. Usually through adequate approximation and simplification, the PID controller can be applied in a nonlinear time-varying RF system. But in the case of tuning system with a wide dynamic range, and due to the severe nonlinear characteristics of ferrite under high RF power, the use of PID controller is quite limited. How to choose an appropriate set of control parameters is in a dilemma. Either the control precision cannot be guaranteed or the risk of system oscillation and instability significantly increases. To solve this problem, an adaptive feedforward module is implemented as shown in Fig. 5.

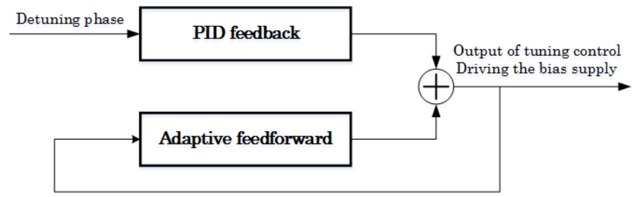

Figure 5: The principle of tuning control algorithm.

The adaptive feedforward module is operated in a self-regulating mechanism. Generally speaking, the feedforward control measures the disturbances and responses to the driving signal in a pre-defined way. In fact, the pre-defined way is the transfer function of controlled system. To the tuning system, it's difficult to directly measure the real-time transfer function. However, the system characteristic can be obtained in an indirect way. With the PID controller, the driving signal should be modified to make sure the cavity is tuned. That is, the relation between the driving signal and the resonant frequency of cavity indicates the real-time system characteristic at a specific point. That means the driving signal can be used to adjust the 'pre-defined way' of feedforward control.

SUMMARY AND DISCUSSION

In the high power integrated test of RF system, the detuning phase of cavity tuning is less than ±5 degree, and the detuning phase of grid tuning is less than ±2 degree. It seems higher bandwidth and bigger bias current is needed to obtain a smaller detuning phase. But because of higher bandwidth of amplitude and phase control system, the disturbance induced by the tuning systems can be eliminated. The control precision of cavity voltage is less than ±0.1% and phase to the reference signal is less than ±0.2 degree.

Due to the bandwidth limit, the RF feedback is recommended to compensate the heavy beam loading effect. In this case, the tetrode gird is necessary to maintain the phase margin. The tuned condition should be carefully measured with the action of RF feedback. Besides, the CSNS/RCS RF system uses a similar beam loading compensation scheme as ISIS. In the beginning of injection, sudden appearance of beam will cause a big disturb to the tuning system. Consider the bandwidth, the detuning phase will be compared by the cavity voltage and the grid voltage subtracts the beam loading compensation driver to maintain the stability. In fact, the subtracted part is the beam loading compensation driver multiplying a coefficient which is 1 at injection. After injection, the beam circulating current will smoothly increase, and then the coefficient will gradually decrease to 0. That means the tuning system is back to the classical way in which the power consumption is optimized. Of course, the coefficient can keep 0, if through relevant test and proving the system could maintain stable. There is another idea. If the global timing system works well and the cycle by cycle repetition of the beam condition is good, the adaptive feedforward module mentioned in the tuning control algorithm is hoped to replace the function of beam loading compensation.

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