CONTROL PERFORMANCE IMPROVEMENT BY USING FEEDFORWARD IN LLRF

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Abstract

The LLRF design is ongoing at ESS. One major task of LLRF is to overcome a variety of perturbations such as klystron droop and ripple, Lorentz detuning and beam loading. These perturbations can be well suppressed by classical PI (proportional-integral) controller in feedback loop, but at a cost of raising risk of instability and consuming power overhead for overshoot. Since ESS is a green project focusing on energy efficiency, we will hence investigate in this paper some feedforward and advanced adaptive algorithms to deal with these perturbations, so as to improve the control performance and reduce the power overhead.

INTRODUCTION

The European Spallation Source (ESS) is a planned neutron source to be built in Lund, Sweden, which is planned to produce the first neutrons in 2019. At ESS, around 200 LLRF stations are expected to be built by the year 2019 for a variety of RF cavities such as RFQ, DTL, spoke and elliptical superconducting cavities. ESS is to built as a green plant, placing very high demands on powers efficiency and operational availability. It is therefore essential for ESS LLRF system to minimize the RF power overhead for the regulation and increase the system robustness and flexibility. Traditional PI feedback alone can well suppress the perturbations in the loop, but at a cost of increasing potential risk of instability and consuming more power overhead for overshoot. Feed-forward and other advanced control methods are therefore investigated and expected to be employed together with feedback at ESS to achieve required high demands in this large facility.

FEEDFORWARD

Feedforward control is an effective way to deal with the repetitive perturbations that can be measured before it affects the output. A typical feedforward control in LLRF system is shown in Figure 1. Ideally, feedforward control can completely eliminate the effects of the measured perturbations on the system output. Some possible feedforward solution for the main perturbations in cavity accelerating field are investigated.

Lorentz Force Detuning Compensation

The superconducting cavity operating in pulse mode with high accelerating field suffers from Lorentz force detuning (LFD) which causes a dynamic shift of cavity resonance frequency and consequently leads to a significant distortion in cavity field. LFD effect can be compensated

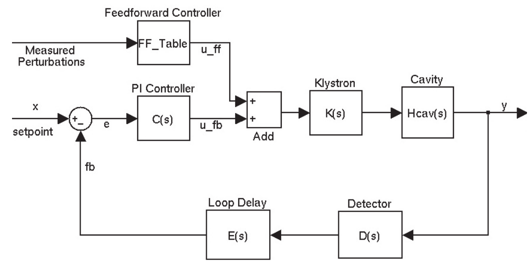

Figure 1: Feedforward control in LLRF system

by applying a piezo tuner, but it can also be compensated by feedback or feedforward with some power overhead. One way to compensate LFD effect in feedforward is to calculate required drive signal for the next pulse according to cavity detuning measured at the current pulse[1].

In a RLC cavity model, the cavity voltage has the following relation with the total input current at steady state[2]:

$$\mathbf{V_{cav}} = \frac{R_L}{1 - itan\varphi_D} \cdot \mathbf{I_{total}} \tag{1}$$

where, $R_L = \frac{1}{2}(R/Q)\,Q_L$, $tan\varphi_D = Q_L\left(\frac{\omega_0}{\omega} - \frac{\omega}{\omega_0}\right)$, $\mathbf{I_{total}} = \mathbf{I_g} - \mathbf{I_b}$, $\mathbf{I_g} = 2\mathbf{I_{for}}$, $\mathbf{I_b} = 2\mathbf{I_{b0}}$. $\mathbf{I_{for}}$ is equivalent klystron forward current seen from cavity side while $\mathbf{I_{b0}}$ is the average DC beam current.

If we take the cavity voltage as the reference, i.e.,$\mathbf{V_{cav}} = V_{cav} + i \cdot 0$, and correspondingly write the current with the complex form:

$$\begin{aligned} \mathbf{I_g} &= I_{gr} + iI_{gi} \\ \mathbf{I_b} &= I_{br} + iI_{bi} \end{aligned} \tag{2}$$

giving the known V_{cav} and the detuning of the cavity, we can conclude the required **Ig** as follows:

$$I_{gr} = \frac{V_{cav}}{R_L} + I_b cos\varphi_b \tag{3}$$

$$I_{gi} = -\frac{V_{cav}}{R_L} tan\varphi_D - I_b sin\varphi_b \tag{4}$$

In superconducting cavity, $tan\varphi_D \approx \frac{\Delta\omega}{\omega_{1/2}}$, $\Delta\omega = \Delta\omega_P + \Delta\omega_L(t)$, $\Delta\omega_P$ is the pre-detuning to compensate the synchronous phase operation while $\Delta\omega_L(t)$ is due to LFD effect. When Q_L is optimized and appropriate pre-detuning is chosen to completely cancel the synchronous phase effect, the generator power can be written as[1]:

$$P_g = \frac{1}{8}\frac{V_{cav}^2}{R_L}\left(4 + \left(\frac{\Delta\omega_L(t)}{\omega_{1/2}}\right)^2\right) \tag{5}$$

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Simulations on LFD compensation by feedforward have been done and the required power for compensation is shown clearly in left of Figure 2 . To make a comparison, a feedback with loop gain 100 and loop delay of 2 µs is also introduced for LFD compensation which is shown in the right of Figure 2. There is obvious overshoot and more power consumption during the region of beam start and it gets worse as the loop gain and loop delay increase. It might help if we apply a lower loop gain feedback together with feedforward at the beginning of beam injection since feedforward can keep a flat field as well.

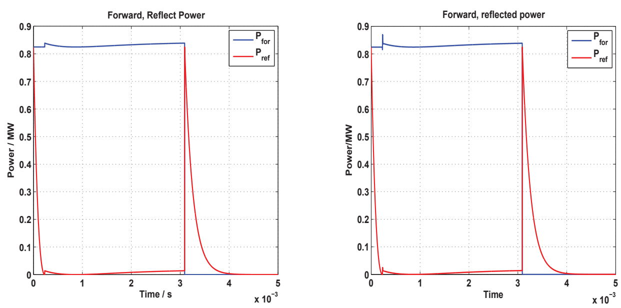

Figure 2: Cavity field control simulation: (a) with feedforward only, (b) with feedback and feedforward.

Klystron Ripple Compensation

Some calculation and measurement shows that the klystron high cathode voltage droop and ripple of 1% induces more than 10° in klystron output phase and 1.25% in amplitude. At ESS, there might be potentially serious droop and ripple because of long RF pulse of more than 3 ms.The PI feedback loop can not well suppress the ripples with high amplitude and high frequency in klystron output, and it gets worse in normal conducting cavity[3]. The strict requirement on modulator output voltage variation thus needs to be applied to keep less ripple in klystron output, however, it might increase the design complexity and the cost of modulator. Feedforward is therefore under consideration to try to improve the performance, thereby relaxing the limits.

A straightforward and effective way to compensate the ripple by feedforward is to add the counteractive signal to the feedforward table, which has the same frequency but the counter-phase (180° phase difference) with the ripple. The counteractive feedforward signal can be calculated by measuring the variations of the high voltage, and applying it in a klystron model. Figure 3 shows a simple block diagram of feedforward compensation for klystron ripple. As ESS has a high demand on efficiency, we probably cannot run the klystron far away from the saturation point. It is important to obtain an accurate klystron model from real measurement data as klystron will have non-linear characteristics in amplitude and phase saturation curves.

The result of the klystron ripple compensation at CESR shows that feedforward control reduces the ripple by more

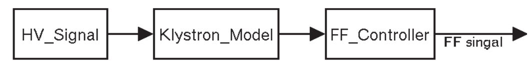

Figure 3: Feedforward control for klystron ripple

than one order of magnitude[4].

Klystron Linearization

Klystrons in most accelerators are typically run far below saturation in a linear region of operation in order to facilitate the feedback regulation of the phase and the amplitude of the fields in the cavities, but at a cost of reduced efficiency. Within the ESS project which emphasizes the power efficiency, we will look into and test the use of linearization techniques to reduce power overhead for LLRF control. There are various kinds of methods to implement linearization for klystron, but the digital predistortion method appears to be the most promising linearization technique for the accelerator cavity application with narrow bandwidth and high gain requirement.

Predistortion linearization technique to some extent is a kind of feedforward method. Figure 4 shows a typical predistortion linearization technique for power amplifier in communication system. It is realized by introducing a predistorter block having the inverse nonlinear characteristics of the klystron to compensate the non-linearization. Digital predistortion method is of high flexibility and precise linearization, but needs careful and adequate measurements of the characteristics of the klystron in order to calculate the accurate coefficients of the linearization table.

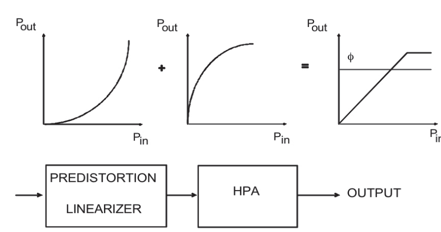

Figure 4: Typical predistortion linearization scheme[5]

Beam Loading Compensation

Feedforward control is not only used for improving the system performance such as decreasing the power overhead for overshoot and reducing potential instability in feedback loop, but a necessary tool in some case to eliminate the repetitive perturbation which is caused due to feedback or can not be suppressed by feedback. An common perturbation of this kind can be seen at the first several ten microseconds of beam loading in pulsed mode operation, where obvious error or even oscillation is caused due to the delay and high gain in feedback loop .

A straightforward way for this repetitive error is to generate an opposite error signal $-e(t)$ from proper feedforward input signal $u_{ff}(t)$ to cancel the original error $e(t)$ in

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feedback loop. To obtain the proper feedforward input signal $u_{ff}(t)$, measurement of the system characteristics has to be done by giving known stimulus signal at feedforward input, and observing the corresponding response at error output. The constant system response matrix from $u_{ff}(t)$ to $e(t)$ is then obtained. At last the required feedforward input signal $u_{ff}(t)$ can be calculated from the inverse of system response matrix and error signal[6].

However, the constant response system matrix obtained in this way might not be accurate enough if operating point changes. It is necessary to update the system response matrix and feedforward table continually, which is the case in adaptive feedforward in next section.

ADAPTIVE FEEDFORWARD

Feedforward is effective for the repetitive perturbations. However, the repetitive perturbations and the system properties may vary slowly with the time due to the slow variations or operating point changes. Thus, it is crucial to introduce adaptive algorithm to compensate these possible changes and variations. A typical adaptive feedforward control in LLRF is given in Figure 5. Accurate measurement for the specific perturbation is not no longer necessary. Instead the error signal between cavity output and setpoint is measured and appropriate adaptation algorithm is applied to update the followed feedforward table. The new output is produced and new error signal is calculated for next iteration. This procedure is repeated until the error signal is small enough to reach the desired performance.

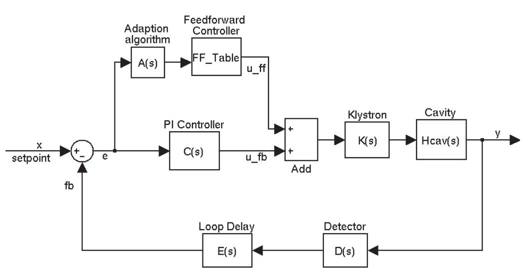

Figure 5: Typical adaptive feedforward control in LLRF

The early implemented adaptive feedforward controls in pulsed machine are mainly to deal with the beam loading transient phenomenon under feedback. An example of this adaptive control method is the one applied in Tesla Test Facility (TTF), which is similar with the way showed in beam loading feedforward compensation in last section. The approach in TTF is to measure the responses of a set of step functions stimulus and obtain the system-response matrix. To deal with the slow variations and drift in system, step responses are measured continually to maintain a continuous updated system model and feedforward table[7].

Adaption algorithm in TTF works and shows a significant improvement on system performance. However, the system response matrix measurement and feedforward table update could not be fast enough. At SNS, an iterative learning control algorithm with a simple form and efficient computation is proposed for superconducting cavity. A special self-learning L-filter is the key factor in this method, which filters the error signal and yields a new feedforward table for next iteration in order to make the new error smaller. The learning filter needs to be carefully designed so that it satisfies the condition for convergence and avoid any unstable behaviour in the system[8].

In recent years, a novel reverse-lowpass feedforward is developed at FLASH, which is simple but efficient to adaptively update the feedforward table. In this algorithm, the signal of the feedback-contributed part in drive signal is identified, time reversed, and filtered. The filtered signal is then time reversed, time shifted and finally used to update the current feedforward table. It is easy to implement and even fast enough to adapt within $1 \sim 2$ pulses[9].

CONCLUSION

Feedforward is essential for the repetitive perturbations with less power consumption and flexibility. Some possible proposals of feedforward control for different perturbations are given in this paper and several adaptive feedforward control methods are introduced. We should look into theses control schemes and find appropriate solutions to achieve required high demands in RF field control at ESS.

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