INVESTIGATION TO REDUCE POWER OVERHEAD REQUIRED IN SUPERCONDUCTING RF CAVITY FIELD CONTROL

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Abstract

A power overhead of more than 25% is usually required in RF field control of klystron driven superconducting cavity, since it is much easier to implement field control in a linear region of klystron where it is far below saturation. It however results in a reduced efficiency and more power consumption. Within ESS project it places very high demands on energy efficiency, which leads to stringent requirements on power overhead required in RF field control. Investigation on power overhead reduction in RF field control has been carried out at ESS and related simulation has been done. In this paper we will look at how close we can implement field control to the klystron saturation and discuss if it is possible to make RF field control the RF field with 10% overhead.

INTRODUCTION

The motivation to reserve adequate power overhead in RF cavity field control is generally based on the following two considerations. First, power overhead is required to compensate the perturbations to accelerating field caused by environment or inherent error sources, such as Lorentz force detuning, microphonics, beam current instabilities, klystron ripple and Q_L variations. Second, it is safer to run the operation point in a linear region much below the saturation of power amplifiers. Due to the severe input-output non-linearities near saturation for power amplifiers especially for klystrons, in the vicinity of saturation, feedback loop performance to suppress errors is reduced due to gain compression, large feedback loop gain change occurs even with small output power variations, and considerable output phase changes happens. These factors result in poor feedback performance, and increase the risk of instabilities. The situation might get worse when the transient overshoot of feedback control is too big, bringing the klystron input power to saturation point or beyond. The following sections will present the power overhead consumed in feedback control by these issues and discuss the possible methods to reduce it.

ERROR COMPENSATION

The error sources existing in accelerator cavities lead to perturbation and distortion of cavity accelerator field, thereby affecting the final beam energy spread and beam qualities. Power overhead is then required to compensate these errors and maintain a constant cavity field. Lorentz force detuning, beam current instabilities, klystron ripple and Q_L variations are expected to be the main error sources and will be discussed in this paper. Microphonics is a big issue in some superconducting cavities with very high Q_L, but it is expected to be relatively small at ESS with higher bandwidth cavities and the use of 2K superfluid helium. The Lorentz force detuning and microphonics will become larger if there are mechanical resonances exited either by cavity pulsed operating mode or by dominant frequencies in microphonics spectrum. Therefore, the peizo tuner will be employed at ESS to compensate Lorentz force detuning effect, but the details will not be discussed in this paper.

Lorentz Force Detuning

When Q_L is optimized for the cavity and appropriate pre-detuning is chosen to completely cancel the synchronous phase effect, the power needed P_g for the cavity to maintain a desired accelerating field V_{cav} can be calculated as follows[1]:

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

where $\Delta\omega_L(t)$ is the dynamic cavity resonance frequency offset due to LFD, and $\omega_{1/2}$ is the cavity half bandwidth.

Table 1: Overhead estimation under different K for high beta cavity ($E_{acc} = 18MV/m$) at ESS

K (Hz/ $(MV/m)^2$)	Δf (Hz)	$f_{1/2}$ (Hz)	$\Delta f/f_{1/2}$	Power Overhead
1	324	447	0.7	3.3%
1.5	486	447	1.1	7.4%
2	648	447	1.4	13.1%
2.5	810	447	1.8	20.5%
3	972	447	2.2	29.5%

At ESS with very long beam pulse up to 3 ms, the dynamic frequency offset can be roughly considered as that it changes from 0 to $K \cdot E_{acc}^2$ assuming there is no badly mechanical oscillation with the cavity. If we define the power overhead with the ratio of the maximum extra power compensating the LFD to the required generator power in the case without LFD, then the power overhead can be estimated as $\left(\frac{K \cdot E_{acc}^2}{f_{1/2}}\right)^2$. The overhead can be reduced by a factor of 4 if we manage to adjust the pre-detuning for

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LFD right into the middle of the dynamic frequency offset range during beam pulse. Table 1 lists the estimated power overhead for high beta cavities under different LFD coefficient K, in which optimal pre-detuning for LFD is assumed($Q_L = 7.878 \times 10^5$ for high beta cavities)[2].

Klystron Ripple

In accelerator, the klystron suffer the droop and ripple effect resulting from the modulator (klystron cathode voltage supplier), which leads to a phase and amplitude modulation on klystron output. At ESS, there might be potentially serious droop and ripple because of long RF pulse more than 3 ms. Some calculation and measurement data indicate that 1 % change in cathode voltage results in a phase variation of more than 10 °and an amplitude variation of 1.25 % (2.5% in Power)[3].

The droop and ripple with lower frequencies (<1KHz) could be compensated PI feedback controller, and higher frequencies with high magnitude is expected to better compensated via feedforward by measuring the droop and ripple of klystron cathode voltage. Both feedback and feedforward compensate the errors by adjusting the klystron input power to generate counteractive signals to eliminate the errors. Under this context, without considering other errors such as Lorentz force detuning, the klystron will output fixed power level under feedback or feedforward control to maintain constant field in the cavity. As a result, no power overhead is needed in theory to compensate the droop and ripple caused by klystron cathode voltage variation.

Beam Current Instability

The error of ±2% droop and low frequency ripple in beam current is expected at ESS due to beam current instability in ion source. The power overhead 2% is then needed to compensate this amount of beam current instability, due to that generator current induced voltage is twice as the forward current in superconducting cavities[4].

Q_L Variations

The power coupler at ESS feeding power to cavity is not adjustable during operation and Q_L is designed to be the same for all high beta cavities. Q_L is no longer the optimal value for the beam-loaded cavities at non-optimal beam velocities. The mechanical installing errors and other uncertainties might also lead to Q_L deviating from optimal value. As a result, reflection power for the cavities with Q_L variations cannot be held zero any more and thus the power overhead is required to compensate this error.

Multiple Errors

Combining all the errors mentioned above, power overhead calculation is made for high beta cavities at ESS to see how much extra power is needed to maintain a constant field under these perturbations. Figure 1 shows the maintained cavity field and power consumed under these errors by using feedforward and feedback control. The errors used in the simulation are: Klystron cathode voltage ripple of ±1% at 1KHz, beam instability with ±2% droop and ±2% random noise, -30% Ql variation, Lorentz force detuning factor K=1Hz/MV and mechanical constant τ=1ms. The feedback loop gain is 50 and loop delay is set to 2μs, pre-detuning and feedforward are used for LFD and synchronous phase operation. The results show that around 7% power overhead is required for these errors[4]. More power will be consumed if the Lorentz force detuning factor is higher or there are any mechanical resonances, but the peizo tuner is expected to use to reduce the power consumption. Power consumption for all errors mentioned above will be reduced to less than 5% if piezo tuner is applied and works well to reduce the detuning to less than $1/4$ cavity bandwidth (~ 100Hz).

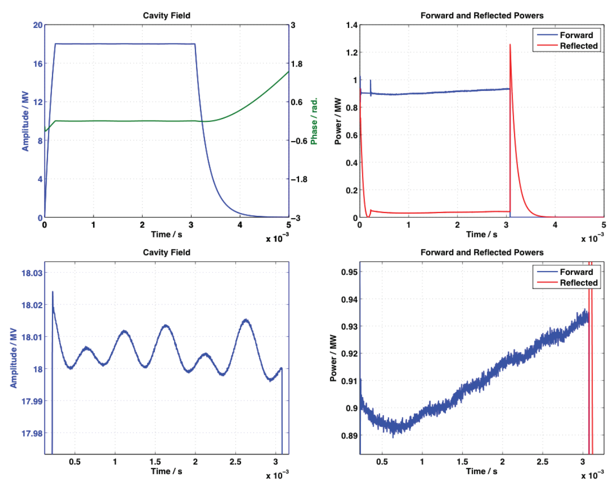

Figure 1: Cavity field and power consumption under feedback and feedforward control for multiple errors (upper) and zoomed-in for concerned areas (bottom).

BEAM COMMISSIONING

Situation is more complicated when it comes to the beam commissioning, since it is expected to deal with different beam modes with different beam currents, pulse lengths, and arrival times. While careful adjustment for beam injection time can be made in nominal beam to reduce most of the beam loading errors, it works no longer for different beam modes with different arrival time.

To see how much difference power overhead is required for different beam modes, two types of beam mode sets are considered: (a) beam modes with the same pulse length but different peak currents, (b) beam modes with the same beam peak currents but different pulse lengths. While the beam-loading perturbations caused by the former modes grow along different curves, the perturbations caused by the latter modes grow along the same curve, which is shown in the upper of Figure 2. There exists a straightforward relationship between errors and corresponding power consumption under proportional-feedback controller: P=error · G, where G is loop gain. This means the maximum peak power consumed under feedback is dependent only on the error at the peak time when system transient response reaches the first peak of the overshoot. It therefore results in different behaviours of power consumption for the two types of beam modes mentioned above. For the beam modes with different peak currents, the maximum peak power goes up as beam peak current increases, while for the beam modes with the same peak current, the maximum peak power keeps almost the same for different beam pulse lengths (pulse lengths > $10\mu s$), which is shown in the bottom of Figure 2[5].

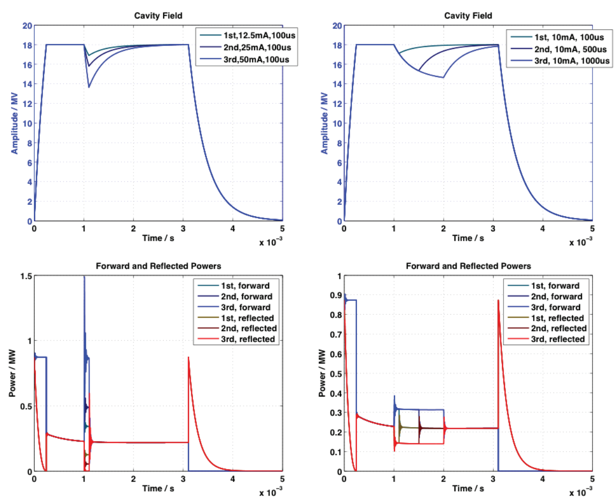

Figure 2: Perturbations to cavity field caused by different beam modes and corresponding power consumption.

There are two possible methods to improve the situation. One possible solution is to apply a perfect limiter after PI controller. Due to the difficulties to determine a amplitude lower limit threshold and phase limiter in dealing with a variety of beam modes, only has amplitude upper limit threshold been used in simulation. As a consequence, feedback induced oscillations in both power consumption and controlled cavity field still exist at the end of beam pulse and lower beam current pulses, as shown in left of Figure 3.

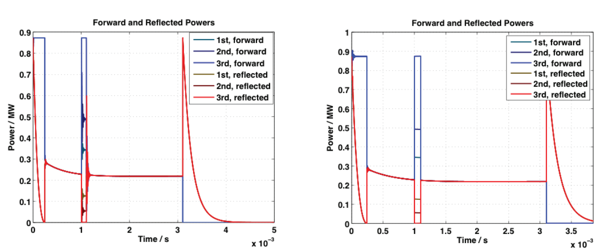

Figure 3: Comparison of power consumption improvements by perfect limiter (left) and by individual feedforward (right) at beam modes with same pulse length.

The other possible solution to improve this situation is to apply individual feedforward compensation for each beam mode by knowing related beam parameters such as beam peak current, beam pulse length, and beam arrival time[6]. The right of Figure 3 shows consumed powers for the case with individual feedforward for each beam mode, and it can be seen clearly that there is significant improvement after applying feedforward.

KLYSTRON LINEARISATION

The calculation of power overhead for error compensation and beam commissioning is based on that there is constant klystron gain in the control loop. However, in reality, severe klystron input-output non-linearities near saturation reduce available loop gain, increase the sensitivity of gain change to output power, and cause bigger phase changes. Thus, the feedback loop cannot work very well close to saturation. To deal with this problem, klystron linearisation both for magnitude and phase compensation will be put forward at ESS by adequate and accurate measurement. Four high speed ADC channels to measure the forward and reflected powers for pre-amplifier and klystron will be included in LLRF prototype and DC channel to measure the droop and ripple of klystron cathode voltage is applied as well. More investigation on klystron linearisation is still undergoing at ESS.

CONCLUSION

Calculation on power overhead for error compensation indicates that less than 10% power overhead is adequate for most errors without mechanical resonances, and this number can be further reduced to 5% if piezo tuner works well. Furthermore, power overshoot in beam commissioning can be well reduced by using individual feedforward for each beam mode. In additional, many effort has put forward at ESS to carry out klystron linearisation. It is expected to be a key factor to keep system robust running close to klystron saturation and make great contribution for power overhead reduction in cavity field control.

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