Amplitude and Phase Control of the Accelerating Field in the ESS Spoke Cavity

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Abstract

We report about numerical simulations of the accelerating field dynamics in the ESS spoke cavity in the presence of the beam loading and Lorentz detuning. A slow feedforward is used to cure the Lorentz detuning whereas a fast feedback through a signal oscillator and cavity predetuning technique are applied to eliminate the beam loading effect. An analysis performed with a Simulink model shows that a combination of feedforward, feedback and cavity pre-detuning result in a substantially shorter stabilization time of the field voltage and phase on a required level as compared to a control method using only the feedforward and feedback. The latter allows one to obtain smaller magnitude but longer duration deviations of the input dynamically. At the same time, when a perturbation can be foreseen like the Lorentz detuning, it is useful to prepare it to a desired setpoint and feeding the error back to the controller. The idea is to control a system’s output by comparing it to a desired setpoint and feeding the error back to the controller. The most widely used control technique is the negative feedback based on a PID controller. The idea is to control a system’s output by comparing it to a desired setpoint and feeding the error back to the input dynamically. At the same time, when a perturbation can be foreseen like the Lorentz detuning, it is useful to use a feed-forward technique to prevent such a perturbation. Combined feedback and feed-forward control can significantly improve performance over simple feedback architectures when there is a major disturbance to the system that can be measured beforehand [2]. In the present paper we apply aforementioned techniques of the control to stabilize the spoke cavity voltage magnitude and phase.

INTRODUCTION

To obtain the beam of a high quality in terms of the energy spread and emittance the cavity voltage magnitude and phase should be controlled very accurately. According to the ESS design [1], the voltage magnitude deviation must be below 0.1% of the total value and its phase deviation must not exceed 0.5 degrees. This can be achieved by means of an appropriate control. The most widely used control technique is the negative feedback based on a PID controller. The idea is to control a system’s output by comparing it to a desired setpoint and feeding the error back to the input dynamically. At the same time, when a perturbation can be foreseen like the Lorentz detuning, it is useful to use a feed-forward technique to prevent such a perturbation. Combined feedback and feed-forward control can significantly improve performance over simple feedback architectures when there is a major disturbance to the system that can be measured beforehand [2]. In the present paper we apply aforementioned techniques of the control to stabilize the spoke cavity voltage magnitude and phase.

THE BEAM-CAVITY INTERACTION: FEEDBACK AND FEED-FORWARD

To study the evolution of the accelerating field in a spoke cavity we will adopt the traditional model [3], in which the cavity is presented by the lumped RLC circuit, the coupler

![Circuit Diagram](image)

Figure 1: The lumped model: cavity modeled by an RLC circuit, the coupler by a connected transmission line of impedance \(Z_T\) and the beam by a current source.

by the transmission line with impedance \(Z_T\) on which we have the incident (generator) wave current \(I_s\) and the reflected wave current \(I_r\). The latter is assumed to disappear without re-reflection. The beam is modeled as a current source \(I_{RF}^b\), where \(I_{RF}^b\) is the RF beam current that is twice of the DC beam current, \(I_{RF}^b = 2I_{DC}^b\). The cavity characterized by the resonant frequency \(\omega_0\) is excited to voltage \(V_c\) under these conditions.

We will assume that variations of the generator and beam currents as well as external perturbations are slow as compared to the RF period such that a dynamic quantity may be represented as a product of a slow varying envelope multiplied by \(\exp(i\omega t)\) (in general case \(\omega\) is not identical to \(\omega_0\), e.g. \(V_c(t) = \text{Re}(A(t) \exp(i\omega t))\) and \(\omega^{-1} \ln A/\omega \ll 1\). Impedances of the loaded cavity and transmission line can be expresses in terms of the shunt cavity resistance \(R_c\) and three quality factors: \(Q_0\) is the quality factor of the bare cavity, \(Q_{ext}\) is the quality factor of the cavity with the coupler, \(Q_L = (Q_0^{-1} + Q_{ext}^{-1})^{-1}\) is the total quality factor. For a superconducting cavity the loaded quality factor is mainly determined by the external Q-factor, \(Q_{ext} \approx Q_{ext}\). Then, using the slow varying approximation we arrive at a first order differential equation for the complex cavity voltage amplitude [3]

\[
t_F \frac{dA}{dt} + A(1 - 2i\delta Q_L) = 2Q_L \frac{R}{Q} [I_s(t) - I_{DC}^b(t) F_b e^{-i\phi_e}],
\]

where \(\delta = (\omega_0 - \omega)/\omega\) is the normalized detuning, \(\phi_e\) is the synchronous phase defined according to the electron linac convention (the energy transfer from the field to the beam is maximal when \(\phi_e = 0\)), \(F_b\) is the beam form-factor, \(t\) and \(t_F\) are the observation and filling time, respectively.

The current reflected by the cavity reads

\[
I_r(t) = \frac{1}{2Q_L(R/Q)} \left[ A(1 + 2i\delta Q_L) - t_F \frac{dA}{dt} \right] - I_{DC}^b(t) F_b e^{-i\phi_e}.
\]

and the power coming to the cavity from the coupler (incident power) and the power reflected by the cavity to the

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The cavity voltage evolution in the presence of the beam loading and Lorentz detuning with applied feed-forward and feedback controls was performed with a model developed in the Simulink MatLab in a way similar to that realized in [2]. A typical diagram of the control system is shown in Fig. 2.

**SIMULATION RESULTS**

We performed simulations of the spoke cavity using Eqs. (1)-(8) for the following set of parameters: \( I_{b,DC} = 50 \text{ mA} \), the nominal power ought to be transferred to the beam \( P_0 = 240 \text{ kW} \), \( F_b = 1 \), \( \phi_c = 15.2^\circ \), \( Q_0 = 1.2 \cdot 10^{30} \), \( R/Q = 426 \), frequency \( f = 351.8 \text{ MHz} \), optimal initial detuning \( \Delta f^{opt} = -395 \text{ Hz} \), \( V_c = 4.974 \text{ MV} \), \( Q^{opt}_{ext} = 1.21 \cdot 10^6 \), \( t_F = 72 \mu s \).

The beam during its passage through the cavity induces the voltage that adds to the voltage induced by the incident (from coupler) current so that the magnitude and phase of the total induced voltage changes during the interaction of the beam with the cavity, see dashed black curves in Fig. 3 representing the cavity voltage magnitude and phase as a function of time. Filling of the cavity with the electromagnetic field is also accompanied by the Lorentz detuning.
Figure 4: Dynamic detuning of the frequency caused by the electromagnetic pressure vs. time. The red solid curve and the black dashed curve stand for the cavity with and without control, respectively.

Figure 5: The voltage magnitude and phase of the controlled cavity with (red solid curve) and without (blue dotted curve) the cavity predetuning vs. time. Note that the time scales are different.

shown by the dashed black curve in Fig. 4. One can see that the cavity voltage and phase deviate substantially from the required nominal values. As we mentioned the cavity voltage can be controlled by means of a fast feedback to cure the beam loading and by a slow feed-forward to cure the Lorentz detuning. The results for the controlled cavity are shown at the same Figs. 3, 4 by solid red curves. In addition, in Fig. 5 the voltage magnitude and phase are shown in detail. It turns out that using the cavity predetuning defined by Eq. (6) one can stabilize the voltage magnitude and phase on the nominal level within 10 µs whereas without the cavity predetuning the phase stabilization can not be achieved. An additional required incident power from the coupler and the reflected power are shown in Fig. 6.

Figure 6: The extra incident power $P_i(t)$ required to compensate the beam loading and the reflected power $P_r(t)$ vs. time. Note that the time scales are different.

CONCLUSION

We found that that a combination of feedforward, feedback and cavity pre-detuning allows one to stabilize the ESS spoke cavity voltage and phase within 10 µs on the nominal level such that the voltage magnitude error and phase error are 0.5% do not exceed 0.2°, respectively. The maximal required additional power is around 4.2%.

ACKNOWLEDGMENT

One of the authors (V.A.) is thankful to Dr. Joachim Tückmantel for explaining some elements of the theory of the beam-wave interaction in a cavity.

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