AMPLITUDE AND PHASE CONTROL OF THE ACCELERATING FIELD IN THE ESS SPOKE CAVITY

V.A. Goryashko *, V. Ziemann, R. Yogi, R. Ruber, Uppsala University

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 pre-detuning 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 instantaneous voltage and phase from the required nominal values. As a result, a series of cavities only with feedforward and feedback needs an extra control technique to mitigate a cumulative systematic error rising in each cavity. In addition, a technique of adiabatic turning off of the RF power in order to prevent a high reflected power in the case of a sudden beam loss is studied.

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

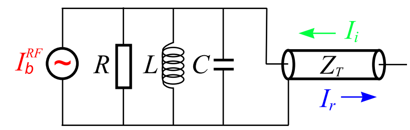

Figure 1: The lumped model: cavity modeled by an RLC circuit, the coupler by a connected transmission line of impedance Z_T and the beam by a current source.

by the transmission line with impedance Z_T on which we have the incident (generator) wave current I_i 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_b^{RF}, where I_b^{RF} is the RF beam current that is twice of the DC beam current, $I_b^{RF} = 2I_b^{DC}$. The cavity characterized by the resonant frequency ω_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 ω is not identical to ω_0), e.g. $V_c(t) = \mathrm{Re}\{A(t)\exp(i\omega t)\}$ and $\omega^{-1}\mathrm{d}\ln A/\mathrm{d}t \ll 1$. Impedances of the loaded cavity and transmission line can be expresses in terms of the shunt cavity resistance R, 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, $Q_L \approx Q_{ext}$. Then, using the slow varying approximation we arrive at a first order differential equation for the complex cavity voltage amplitude [3]

$$t_F\frac{\mathrm{d}A}{\mathrm{d}t} + A(1-2i\delta Q_L) = 2Q_L\frac{R}{Q}\left[I_i(t) - I_b^{DC}(t)F_b\mathrm{e}^{-i\phi_e}\right], \quad (1)$$

where $\delta = (\omega_0 - \omega)/\omega$ is the normalized detuning, ϕ_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 $t_F = 2Q_L/\omega$ are the observation and filling time, respectively.

The current reflected by the cavity reads

$$I_r(t) = \frac{1}{2Q_L(R/Q)}\left[A(1+2i\delta Q_L) - t_F\frac{\mathrm{d}A}{\mathrm{d}t}\right] - I_b^{DC}(t)F_b\mathrm{e}^{-i\phi_e}. \quad (2)$$

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

* vitaliy.goryashko@physics.uu.se

coupler are

$$P_{i,r} = \frac{R/Q}{2} Q_{ext} |I_{i,r}|^2. \quad (3)$$

The energy conservation low reads

$$\frac{1}{t_F}\frac{\mathrm{d}U_{st}}{\mathrm{d}\tau} = P_g - P_r - P_b, \quad (4)$$

where $U_{st} = |A|^2/2\omega Q_L$ is the energy stored in the cavity and

$$P_b = \mathrm{Re}\{A I^*_{b,DC}\, \mathrm{e}^{i\phi_e}\} \quad (5)$$

is the power transferred to the beam.

Within the steady-state limit ($A(t)$ = const) one can minimize the reflected power by tuning the cavity, the so-called 'reactive beam loding compensation',

$$\frac{\Delta\omega^{opt}}{\omega} = \frac{(R/Q) I_b^{DC} F_b \cos\phi}{V_c} \quad (6)$$

and the reflected power completely disappears if the coupler is also adapted such that

$$Q_{ext}^{opt} = \frac{V_c}{2(R/Q) I_b^{DC} F_b \sin\phi}. \quad (7)$$

For a high Q resonator such as superconducting cavities, the narrow electromagnetic bandwidth makes the coupling between the cavity and the RF feeding source sensitive to rather small amount of detuning. As a result, small mechanical deformations due to, for example, the surronding vibration noise (microphonics) or Lorentz forces (due to the radiation pressure), are a source of concern. Whereas microphonics are usually critical for CW operation, the dynamic detuning associated to Lorentz forces is the main issue for pulsed operation as in the SNS [4]. Then, one can also expect the Lorentz detuning to be especially relevant to the ESS spoke cavity. In the case of the static field pressure the frequency deviation is proportional to the negative square of the accelerating field $\Delta f = -|K_L| E_{acc}^2$, where $K_L < 0$ is referred to as the Lorentz detuning factor in Hz/(MV/m)^2. If we now take into account only the main mechanical mode, then the frequency deviation may be approximately described by a 1st order differential equation

$$\tau_m \frac{d\Delta\omega}{dt} = -[\Delta\omega(t) - \Delta\omega_T(t)] + 2\pi K_L E_{acc}^2, \quad (8)$$

where $E_{acc}^2 = |A|^2/L_{acc}^2$ and $L_{acc} = (n+1)\beta\lambda/2$ are the accelerating electric field and length, respectively, β is the velocity factor, n is the number of spoke bars, λ is the wavelength of the accelerating field, τ_m is the mechanical damping time constant and $\Delta\omega_T(t)$ is a frequency shit due to an external mechanical excitation (such as a piezo-electric tuner).

Analysis of 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.

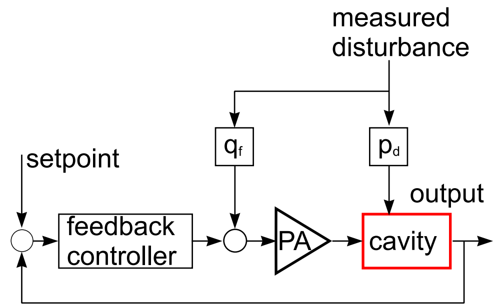

Figure 2: Feedback and feed-forward control of the accelerating voltage of a cavity fed by a power amplifier (PA).

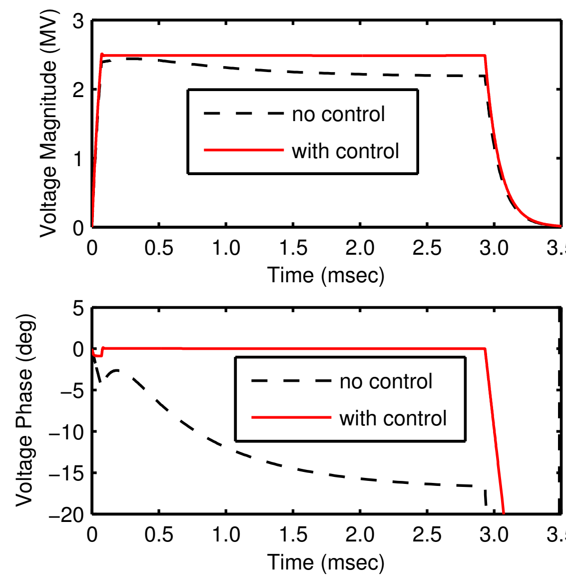

Figure 3: The cavity voltage magnitude and phase vs. time. The solid red curves stand for the spoke cavity with the implemented feedback and feed-forward control whereas the dashed black curves stand for the case with no control.

SIMULATION RESULTS

We performed simulations of the spoke cavity using Eqs. (1)-(8) for the following set of parameters: I_b^{DC} = 50 mA, the nominal power ought to be transferred to the beam P_{b0} is 240 kW, $F_b = 1$, $\phi_e = 15.2^o$, $Q_0 = 1.2 \cdot 10^{10}$, $R/Q = 426\Omega$, frequency $f = 351.8$ MHz, optimal initial detuning $\Delta f^{opt} = -395$ Hz, $V_c = 4.974$ MV, $Q_{ext}^{opt} = 1.21 \cdot 10^5$, $t_F = 72\mu$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

ISBN 978-3-95450-122-9

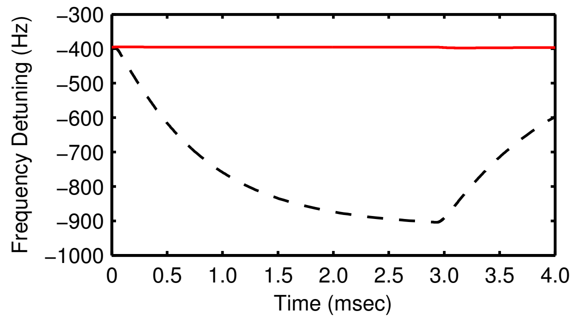

Figure 4: Dynamic detuning of the frequency caused by the electromagnetic pressure vs. time. The red solid curve and the black dashed curve stand for the cavity with and without control, respectively.

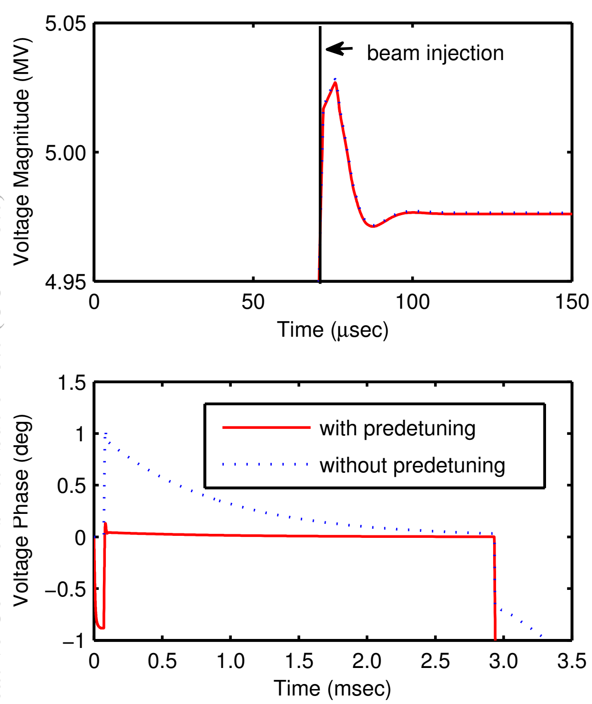

Figure 5: The voltage magnitude and phase of the controlled cavity with (red solid curve) and without (blue dotted curve) the cavity predetuning vs. time. Note that the time scales are different.

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

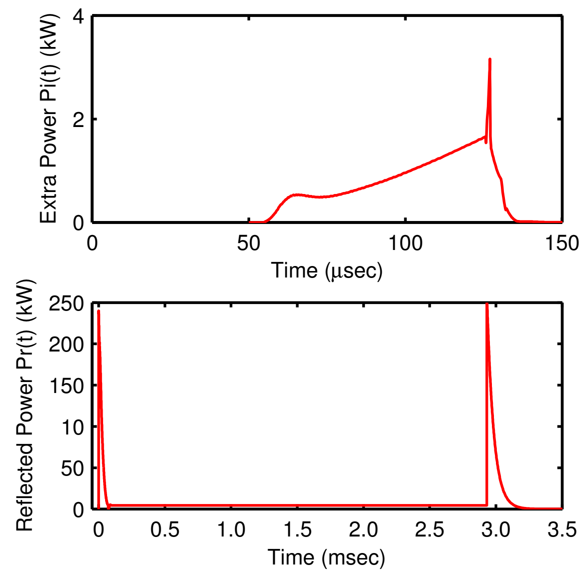

Figure 6: The extra incident power $P_i(t)$ required to compensate the beam loading and the reflected power $P_r(t)$ vs. time. Note that the time scales are different.

in detail. It turns out that using the cavity predetining 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.

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^o, 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.

REFERENCES

[1] S. Pegg, "Conceptual Design Report," ESS-2012-001, 2012.

[2] M. Hermandez, W. Höfle, sLHC Project Report 0054, CERN, April 2001.

[3] J. Tuckmantel, Internal Note, CERN-ATS-NOTE-2011-002 TECH.

[4] M. Doleans, "Studies in reduced-beta elliptical superconducting cavities," PhD, 2003.