RESONANCE CONTROL OF SUPERCONDUCTING CAVITIES AT HEAVY BEAM LOADING CONDITIONS*

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Abstract

The superconducting cavities operated at high Q level need to be precisely tuned to the RF frequency. Well tuned cavities assure the good field stability and require minimum level of RF power to reach the operating gradient level. The TESLA cavities at FLASH accelerator are tuned using slow (step motors tuners) and fast (piezo tuners) driven by the control system [1]. The goal of this control system is to keep the detuning of the cavity as close to zero as possible even in the presence of disturbing effects (Lorentz force detuning and microphonics). The detuning of the cavity can be determined using a few measurement methods. The most common is to measure detuning from the phase derivative at the end of the RF pulse. In order to calculate the detuning during the whole RF pulse the cavity differential equation must be solved taking into account all the driving forces (RF power delivered to the cavity and beam contribution). This is not the trivial task, particularly in the heavy beam conditions, since all signals must be precisely calibrated. This work presents the methods and algorithms to evaluate and control the detuning of the superconducting cavities in the heavy beam loading conditions.

INTRODUCTION

The accelerating gradient in the superconducting cavities depends not only on the driving force (RF power) but also on the relationship between the frequency of the RF source (f=$\omega/2\pi$) and the resonant frequency of the cavity ($f_r = \omega_r/2\pi$). Since the superconducting cavities are characterized by very high quality factor Q_L (of order of $3 \cdot 10^6$ for the TESLA cavities) the bandwidth ($\omega_{12} = \omega_r/2Q_L$) of the cavity is relatively narrow. The cavity gradient depends on the cavity detuning through the well known resonant curve (1).

$$V(\Delta\omega) = \frac{V_r}{\sqrt{1 + (\frac{\Delta\omega}{\omega_{12}})^2}} \qquad (1)$$

where: V - cavity voltage (V_r - at resonance); $\Delta\omega$ - detuning ($\Delta\omega = \omega - \omega_r$)

Therefore the cavity has to be well tuned to the RF frequency or excessive RF power is needed which is unwanted in typical applications. For TESLA cavities the detuning by 200Hz may increase the RF power required to accelerate the beam by 25% [2]. The resonant frequency of the superconducting cavities depends on the geometrical dimensions that are prone to change due to Lorentz force and microphonics (liquid helium pressure, vibrations etc.). The LFD (Lorentz Force Detuning) can change the resonant frequency of the superconducting TESLA type cavity by over 300Hz during the flattop for high gradients (over 25MV/m).

DETUNING MEASUREMENTS AND CALCULATION

The cavity detuning can be measured from derivative of the phase at the beginning of decay process. In fact, on absence of driving voltage and beam the cavity field is oscillating with resonant frequency of the cavity. The phase change relative to the reference RF signal gives exactly the detuning. This method is simple to implement and precise but it gives the detuning value at single point only - the end of the flattop. If the detuning over the whole RF pulse is needed one can scan the RF pulse length but this method affects the machine operation (pulse shortening). One can also solve the cavity differential equation (2) and calculate the detuning according to the equation (3).

$$\frac{dV}{dt} = (-\omega_{12} + i\Delta\omega)V + \omega_{12}(2V_{for} + V_b) \qquad (2)$$

where: V - cavity voltage (complex phasor); V_{for} - generator induced voltage (complex phasor); V_b - beam induced voltage (complex phasor)

$$\Delta\omega = \frac{d\angle V}{dt} - \begin{array}{l} 2\omega_{12}\frac{|V_{for}|}{|V|}\sin(\angle V_{for} - \angle V) + \\ \omega_{12}\frac{|V_b|}{|V|}\sin(\angle V_b - \angle V) \end{array} \qquad (3)$$

where: $\angle V$ - cavity voltage phase; $\angle V_{for}$ - generator induced voltage phase; $\angle V_b$ - beam induced voltage phase

The application of the equation (3) requires precise calibration of the RF signals and beam induced voltage. The cavity and forward voltage (generator induced voltage) can be calibrated using the relationship between cavity voltage, forward and reflected voltage (V_{ref}). The beam contribution is more difficult and will be discussed later. Having all the three RF signals measured ($\hat{V}, \hat{V}_{for}, \hat{V}_{ref}$) but not necessarily well calibrated one can calculate the complex coefficients a, b, c, d that well fit the equations (4). The computation procedure concerns on fitting reflected power during decay to the cavity voltage and then fitting the forward voltage to satisfy the sum of forward and reflected equal to

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cavity voltage. The calibration procedure should also take into account non-ideal characteristic of directional couplers used to measure forward and reflected voltages.

$$
\begin{aligned}
V_{for} &= a\hat{V}_{for} + b\hat{V}_{ref} \\
V_{ref} &= c\hat{V}_{for} + d\hat{V}_{ref} \\
V = \hat{V} &= V_{for} + V_{ref}
\end{aligned} \tag{4}
$$

Using the V_{for} calibrated to the cavity voltage one can calculate the detuning by equation (3). The figure 1 shows the comparison of detuning measured through shortening of RF pulse with the one calculated with equation (3)
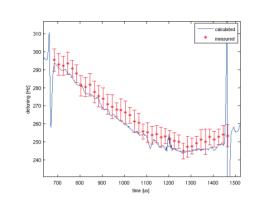

Figure 1: Detuning calculated with eg. (3) and measured with shortening RF pulse. Red bars - results of measurements (with RMS error), blue line - result of calculations.

The beam contribution is harder to calibrate. One of the methods may rely on the transient measurements from the beam. However, the classical method to measure the beam induced transients is to operate the machine in feed forward mode (for constant driving voltage). Then one can measure the drop of cavity voltage and estimate the transients. This is normal procedure used to calibrate the vector sum of the cavities feed by single klystron. Unfortunately it requires special operating conditions of the machine and limits the beam to some relatively low values. If the transients from heavy beam conditions need to be evaluated some other method is needed. If the machine is running with feedback mode (and possibly adaptive feed-forward) and the cavity voltage is stable when the beam appears and vanishes (what is assured by field controller) one can estimate the beam transients from the surplus of the forward voltage. In order to calculate the beam induced voltage let take into account the cavity equation (2). When the beam appears at time t_b the equation (2) has to be true just before the beam starts and just after that as well. Therefore one can write two equations for these two time points.

$$
\begin{aligned}
\frac{dV}{dt}\Big|_{t_b^-} &= (-\omega_{12} + i\Delta\omega)V|_{t_b^-} + \omega_{12}(2V_{for}|_{t_b^-}) \\
\frac{dV}{dt}\Big|_{t_b^+} &= (-\omega_{12} + i\Delta\omega)V|_{t_b^+} + \omega_{12}(2V_{for}|_{t_b^+} + V_b|_{t_b^+})
\end{aligned} \tag{5}
$$

where: t_b^- and t_b^+ - time just before and after beam start

One can assume that the detuning $\Delta\omega$ is constant during beam turning on since detuning changes are related to the mechanical effects of Lorentz force and microphonics and therefore it is relatively slow process. The beam transients can be found from equation (5) by detuning elimination. In practice one can also assume that the cavity voltage derivative $\frac{dV}{dt}$ is equal to 0 since the field in the cavity is well regulated by the controller and changes very slowly comparing to the changes of V_{for}. Due to the same reason one can assume also $V|_{t_b^-} = V|_{t_b^+}$ getting simple formula for beam transient (6). Numerical calculations performed on the real signals proved that neglected components are few orders of magnitude lower than the forward power transients.

$$
V_b = 2(V_{for}|_{t_b^-} - V_{for}|_{t_b^+}) \tag{6}
$$

Having the beam induced voltage and the beam current measured by toroid in the beam line one can calculate the detuning of the cavity using formula (3).

MEASUREMENTS RESULTS

FLASH [3] is (among other functions) a test bench for ILC and periodically is used to test the concepts and technology. During ILC related tests the machine is running with exceptionally high gradients and beam loading [4]. Therefore keeping cavities in resonance is one of the most important goals. During the tests in February 2011 several experiments have been performed with piezo tuners. It has occurred that the beam presence heavily affects the detuning calculations if the beam contribution is not taken into account. This is particularly important for cavities which are operated off-crest. In this papert some results obtained at ACC6 cavity 7 for beam and without beam operating conditions are presented.
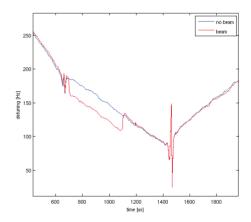

Figure 2: Detuning calculation for no beam conditions (blue) and beam condition (red) without taking into account the beam contribution. The beam current was 4.5mA with 1200 bunches (beam was present between $700\mu s$ and $1100\mu s$)

Direct application of formula (3) without beam component may lead to wrong results in detuning calculation, it is

shown in figure 2. The blue line shows the detuning for no beam conditions. The detuning with beam is expected to be very close since the gradient was kept constant for both beam conditions as a result of the controller regulation and beam loading compensation. The red line shows the detuning calculated with equation (3) without the beam component while the beam was present in the machine. The beam contribution to the detuning is clearly visible and it proves that beam must be taken into account to obtain right results.
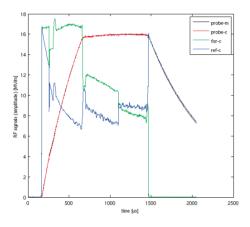

Figure 3: RF signals with beam. Both measured and calculated cavity voltage fits well that indicates the good calibration of the RF signals.

Figure 3 shows the calibrated RF signals for beam conditions. The beam contribution is clearly visible in forward and reflected voltage. The cavity voltage is kept almost constant by the field controller in spite of the beam presence. It has to be mention that the controller regulates not the individual cavities voltage but the whole vector sum of 16 cavities. Therefore the single cavity voltage do not need to be perfectly constant while the vector sum is constant. Anyway the changes are relatively small and slow.
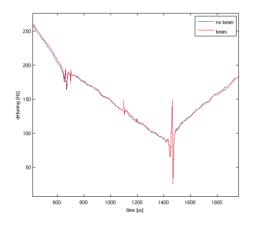

Figure 4: Detuning calculation using the formula (3) with beam contribution. Blue - no beam condition. Red - with beam

In order to apply the equation (6) one have to estimate the transients on the forward voltage. For that purpose a simple fitting procedure has been worked out. It fits the amplitude and phase of the signal to the step function. After applying the formula (3) including the beam component the results of the detuning calculation are right. The waveforms of the calculated detuning for both cases (with beam and without beam) is presented in figure 4.

As it has been expected the detuning curves overlaps showing very good agreement of the detuning calculation. The small glitches appearing during beam turning on and off are related to the signals crosstalk and numerical calculation of the derivatives. One should notice that much larger glitches appears at the end of the flattop what is related to the same effect when forward power is turned off and also at the beginning of the flattop when forward power changes significantly.

LORENTZ FORCE DETUNING COMPENSATION

In order to compensate for the cavity detuning caused by Lorentz Force one can use the piezo actuators. Piezos are fast enough, reliable and can work at cryo temperatures. They affects the cavity length changing the cavity resonant frequency in opposite direction than LFD is doing. At FLASH an automated piezo control system is used to compensate the cavity detuning. It consist of the power drivers (piezos require application of high voltage) together with multichannel digital control system. The details of the piezo control system at FLASH and the achieved performance is presented in [1].

CONCLUSION

In the paper the cavity detuning calculation is discussed, in particular for heavy beam conditions. The results of measurements and signal processing show excellent agreement with expectations. The procedure is simple and easy to implement not only in the form of computer program but in the FPGA firmware as well. It allows to precisely calculate detuning and later tune the cavities to optimum operating conditions during normal machine operation.

The analysis of the beam contribution can be used also for calibration of the vector sum. Since this procedure can be performed during normal LINAC operation (in the feedback mode) it is very useful for diagnostic purposes.

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