OPERATIONAL EXPERIENCE WITH THE RF CONTROL FOR THE TESLA TEST FACILITY

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1 ABSTRACT

In the rf system for the TESLA Test Facility each klystron supplies rf power to 16 cavities. The superconducting cavities are operated in pulsed mode and at high accelerating gradients. The control of significant Lorentz force detuning and precise measurement of the vector sum are the main issues to be solved. Presently two control systems are under development with the goal to compare the performance of analog versus digital feedback systems. A common feature of both systems is the use of feed forward to minimize power needs and control effort. Prototypes have been evaluated during operation of a single cavity at gradients up to 25 MV/m. The nominal beam loading of 8 mA is simulated by reduction of the incident power to 25% at the time of beam injection. The resonance frequency of the cavity at the beginning of a pulse is adjusted for minimum power requirements. Feedback loop gains are selected for minimum residual amplitude and phase error. Next the feed forward tables are adjusted to minimize the control effort of the feedback loop. The cavity parameters which are used to describe the dynamics of the lorentz force detuning have been determined. Quantitative and qualitative agreement has been achieved between measurements and simulation results.

2 INTRODUCTION

RF control systems for superconducting accelerators usually employ analog circuits in the feedback loops for amplitude and phase control. While digital control systems are widely used for control of slow processes, cost and technological limitations have prohibited the application of digital feedback in fast control loops in the past. Most recently data acquisition rates of 1 MHz at 14 bit resolution and processing times of a few µs - assuming a simple algorithm - are possible with commercially available boards at a cost comparable to that of analog systems.

The design of the control system for the TTF is challenging for the following reasons:

- the Lorentz force will detune the cavity by more than one cavity bandwidth during a 1.3 ms rf pulse. Therefore additional power is needed for rf control,
- microphonics will modulate the pre-detuning of the cavity at the begin of the pulse and increase peak power requirements necessary for control,
- the vector-sum must be calibrated to better than ±10% for the gradient and ±1° in phase for each cavity to achieve an rms energy gain stability of 2.7×10^{-4} assuming a microphonic noise level of ±10°,
- the vector-sum of 16 cavity probe signals must be regulated to an amplitude stability of the order of $\sigma_A/A \le 2\cdot10^{-3}$, and a phase stability of $\sigma_\phi \le 0.5°$,
- beam loading transients of $\Delta A/A = 1.4\cdot10^{-3}$ with TTF Injector II: the bunch charge is $5\cdot10^{10}\ e^-$, and the repetition rate is 1 MHz which corresponds to an average beam current during the beam pulse of 8 mA.

3 RF SYSTEM DYNAMICS

Due to the pulsed nature of rf and beam and the fact that the electrical time constant of the cavity is comparable to the pulse length, it is necessary to understand the dynamics of the rf system. The rf pulse length is 1.3 ms, and the repetition rate is 10 Hz. With an incident power of 200 kW (=8mA×25MV/m×1m) for cavity filling and beam acceleration, the cavity filling time is 500 µs ($Q_L = 3\cdot10^6$) for a gradient of 25 MV/m. The pulsed cavity field consists of three segments (see fig. 1 and fig. 2):

- cavity filling time (500 µs)
- beam-on (flat-top) time (800 µs)
- cavity field decay ($\tau_c = 700\ \mu s$).

The incident power of 200 kW would result in a steady state gradient of 50 MVm. An average beam current of 8 mA will induce a cavity voltage of -25MV/m, i.e., steady state is reached when the beam is injected at time $t_{beam} = \ln 2\cdot\tau_c$.

The dynamics of the pulsed system can be easily understood for a cavity operated on resonance in absence of microphonics and lorentz force detuning. The Lorentz force [1] detunes the cavity according to $\Delta f = 2\cdot\pi\cdot K\cdot E_{acc}^2$ where $K = -1\ Hz/(MV/m)^2$ is the steady state Lorentz force detuning constant for the stiffened TESLA cavity. This Lorentz force detuning leads to nonlinear terms in the system model [2] and cannot be solved analytically. An intuitive understanding of the dynamics of the pulsed system can be developed from numerically solved study cases. The rf system parameters of interest are:

- cavity gradient (E_{acc})
- cavity phase (φ_{cav})
- cavity detuning ($\Delta f = f_0 - f_{rf}$)
- amplitude and phase of incident wave (V_{inc} and φ_{inc}).

The open loop response of the cavity field is shown in Figure 1. The amplitude of the incident wave is reduced to 50% at the time of beam injection to simulate the injection of the beam current. This would result in a perfectly flat top in absence of lorentz force detuning and microphonics. The actual measured response shows the effect of the lorentz force. If the cavity is pre-detuned such that operating frequency and resonance frequency of the cavity are equal in about the middle of the beam pulse, one obtains a reasonably flat top with only a few percent gradient fluctuation and about 10° phase change. Therefore a moderate gain of 20 dB for amplitude and phase loop are sufficient to obtain the desired amplitude and phase stability.

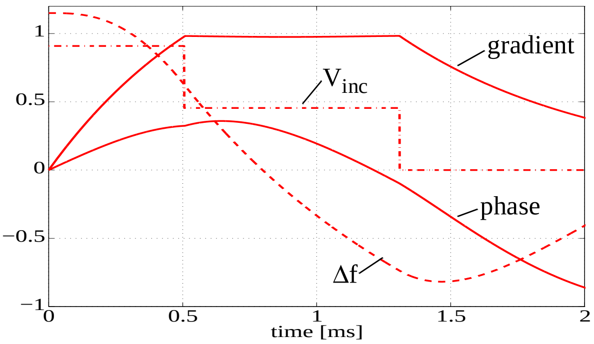

Figure 1 : Open loop response. No beam. Incident power reduced to 25% at time of beam injection.

The closed loop response of the same parameters is shown in Figure 2. Here amplitude and phase are regulated during the beam-on time. As a result, some additional forward power is necessary to maintain the gradient while the cavity is detuned. The forward power reaches a minimum close to zero detuning. It should be noted that the accelerating field is close to steady state conditions during the beam pulse. In closed loop it is necessary that the rf frequency tracks the resonance frequency of the cavity to ensure minimum power requirements during cavity filling. This is indicated by the time varying generator phase during filling. In the presence of microphonics it is only possible to follow the average Δf(t) curve. The amplitude of the microphonics determines the amount of available peak power required for control

4 ANALOG VS DIGITAL FEEDBACK

The designer of an rf control system has several choices for the design of the low level rf control. For feedback one can choose the traditional amplitude and phase control system,

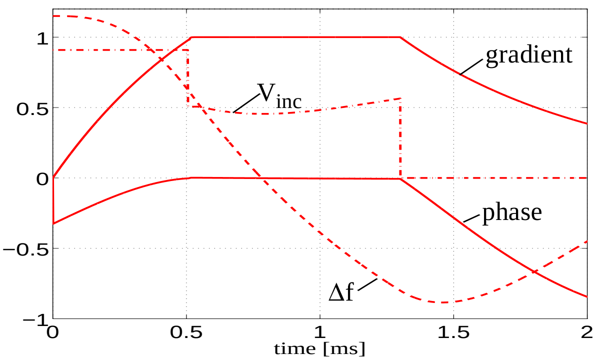

Figure 2 : Closed loop response with simulated beam. Amplitude and phase are constant during beam acceleration. The forward power is time dependent due to time varying cavity detuning.

one can apply feedback to in-phase (I) and quadrature (Q) component of the cavity field, or use direct rf feedback where the cavity probe signal is compared to an rf reference. The cavity itself can be operated in a self-excited loop configuration or can be driven by a fixed frequency generator. All systems have in common an electrical signal which represents the cavity field that is compared to a reference signal. The resulting error signal is amplified and drives the modulator for the incident wave to the cavity. These can be amplitude and phase controllers, I/Q controllers, or other means to control the incident wave.

4.1 Analog Feedback Design

The analog feedback system employs I/Q detection for the cavity field and an I/Q controller for the incident wave.

The main features of the analog feedback system are:

- I/Q detectors for cavity field
- I/Q control during filling and flat top
- time varying I/Q setpoint during filling, exponential time dependence with variable start-time, start voltage and time constant
- 800 kHz notch filter in the feedback loops to suppress the excitation of the 8/9 π-mode

4.2 Digital Feedback Design

A detailed description of the digital feedback design can be found elsewhere [2]. Here only the main features are described:

- 1 MHz (14 bit) sampling rate of the cavity field
- digital I/Q detection
- DSP board (TMS320C40 at 50 MHz) for data processing. This allows for 25-50 instructions per µs since multiply and add can be done simultaneously in a 40 ns cycle
- data processing includes multiplication of I/Q vector with rotation matrix, calculation of the vector-sum and the feedback algorithm
- 1 MHz update rate of DACs (16 bit) for I/Q control
- tables for setpoints, gains, and feed forward. Each table contains separate values for I and Q and is 2048 points (1 per µs) long
- computational delay including ADC and DAC conversion is on the order of 2.5µs

5 OPERATIONAL EXPERIENCE

For monitoring purposes of the cavity field, incident wave, reflected wave, and the rf reference signal, the digital I/Q detection has been proven a valuable tool. It guarantees a linearity for the amplitude and phase measurement of better than 1% and 0.3° respectively. The calibration of gradient, power, and relative phase therefore requires only one reference point for each signal.

The analog and digital feedback systems have been evaluated with simulated beam to ensure that the open loop conditions are similar to the operating conditions under nominal beam loading. For simplicity, the drive frequency has been varied to adjust the pre-detuning instead of the mechanical frequency tuner which must be used in routine linac operation.

5.1 Operation of the Analog System

Initially open loop operation with simulated beam is established. The in-phase component of the incident wave is pulsed while the quadrature component is set to zero. The cavity loaded Q is adjusted to the design value of $Q_L = 3 \cdot 10^6$. The loaded Q is verified by a measurement of the field decay time, the initial pre-detuning is adjusted using the slope of the measured cavity phase $\varphi_{cav}(\ )$ during the field decay, and the incident power is raised until the desired gradient is reached after 500 μs filling time. At the time of beam injection the incident power is lowered to a value which corresponds to the steady state conditions at the time of beam injection.

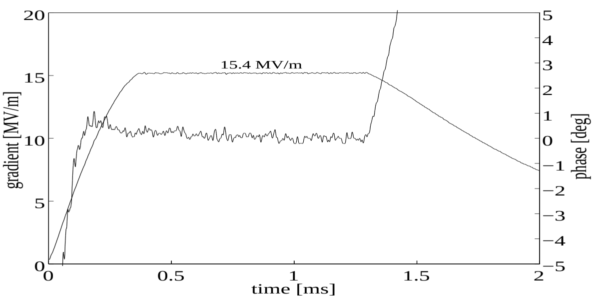

Figure 3: Analog feedback closed loop performance: cavity gradient and phase.

The pre-detuning is then adjusted for field flatness during the beam-on time. Next the loop phase shifter is adjusted such that the measured field transient vector points in the direction of the in-quadrature field component at the beginning of the pulse. This procedure guarantees that I and Q feedback loops are decoupled. The loops are now closed and the feedback gain is increased until the residual errors are minimized. The pre-detuning is finally adjusted to minimize the peak power needed for control.

The performance of the analog I/Q controller for a single cavity operated at 15.4 MV/m is shown in Figure 3. With feedback loop gains of 40 dB, the amplitude and phase are regulated to 0.3% and 0.4° respectively thereby exceeding the requirements. This degree of regulation has been maintained for some period of time demonstrating the operability of the system.

5.2 Operation of the Digital System

The operation of the digital feedback is similar to that of the analog version. The availability of arbitrary feed forward tables and an adjustable digital filter provides additional error suppression.

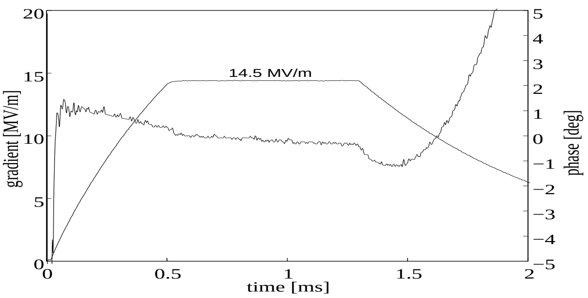

Figure 4: Digital feedback closed loop performance: cavity gradient and phase.

The feed forward tables must be scaled in amplitude and phase with the setpoints for gradient and cavity phase. Due to aliasing effects there is no necessity for a notch filter to suppress the 8/9 π-mode. The quality of regulation is comparable to that of the analog feedback despite the additional loop delay of 2.5 μs which reduces the phase margin by 20° at a loop gain of 40 dB. The residual errors are systematic and can therefore be compensated using fine adjustment of the feed forward tables.

6 CONCLUSION

We have demonstrated that it is possible to control a superconducting cavity operated at high gradients and in pulsed mode. The field regulation of the analog and digital rf control systems meets the requirements when operating a single cavity at 15 MV/m in presence of microphonics and Lorentz force detuning. It has, however, to be demonstrated that the operation of 16 cavities driven by one klystron yields similar results.

7 ACKNOWLEDGEMENTS

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8 REFERENCES

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