DESIGN OF THE DIGITAL RF CONTROL SYSTEM FOR THE TESLA TEST FACILITY

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1 ABSTRACT

The cavities in the TESLA Test Facility are operated in pulsed mode at gradients of up to 25 MV/m with each klystron driving multiple cavities. Significant Lorentz force detuning and control of the vector-sum are the main issues for the low level rf controls. A digital feedback system has been developed to provide flexibility in the control algorithms, precise calibration of the vector-sum, and extensive diagnostics and exception handling. The main features are a sampling rate of 1 MHz for the individual cavity signals, digital in-phase and quadrature detection, calculation of the vector-sum which includes gradient calibration and the correction of phase offsets, and feedback algorithm. The algorithm includes time-optimal control and a Kalman filter to correct for loop delays on the order of several µs and provide an optimal state estimate in presence of detector noise. An attempt is made to optimize the complexity of the feedback algorithm versus the computational delay.

2 INTRODUCTION

With the advent of reasonably priced high speed data conversion devices and digital signal processors which combine tremendous computing power and I/O capability, the design of rf control circuits will assume a new direction. The concept of digital control provides enormous flexibility in the control algorithms, diagnostics, and exception handling, but also has it's drawbacks. Sophisticated algorithms demand significant computation time and the designer of a digital system faces the challenge of optimizing the control algorithm versus computational delay.

The rf system of the TESLA Test Facility requires extensive diagnostics and a high degree of automation to control the 16 cavities which are driven by one klystron. Fortunately, the electrical time constant ($\tau_c = 700\mu s$) of the superconducting cavities is large compared to the sampling period ($T_s = 1\mu s$) of the rf field. This allows for a fairly accurate modelling of the system dynamics over several µs and ensures that fast noise fluctuation are suppressed by the low pass characteristics of the cavity. The estimate of the cavity field is therefore more accurate than the “noisy” measurement signal.

3 REQUIREMENTS FOR RF CONTROL

Usually the requirements for an rf system are stated in terms of achieved amplitude and phase stability. It is also important to include operational issues such as turn on of the rf system, calibration of gradient and phase, and control of the frequency tuner.

3.1 Amplitude and Phase Stability

The requirements for amplitude and phase stability of the vector-sum of 16 cavities are driven by the maximum tolerable energy spread for the TESLA Test Facility. The goal is an rms energy spread of $\sigma_E / E = 2 \cdot 10^{-3}$. The requirements for gradient and phase stability are therefore of the order of $5 \cdot 10^{-3}$ and $0.5°$ respectively. In addition to meeting the field regulation requirements, the rf system must be reliable, robust, operable, and well understood.

3.2 Operational Requirements

The turn on procedure for the rf system is fairly complex [1] due to the large number of cavities driven by the same klystron. It is therefore important to fully or semi-automate procedures for the calibration of the vector-sum, phasing of cavities, and operation of the frequency tuner. Also gradient or phase changes should be controlled by a single knob as well as the rf system be turned on and off with a single button. In case of operational problems the control system must provide the operator guidance for trouble shooting and allow for complete manual operation.

4 RF CONTROL DESIGN

4.1 RF Control Considerations

The amplitude and phase errors to be controlled are of the order of 5% and 20 degrees respectively as a result of Lorentz force detuning and microphonics. These errors must be suppressed by a factor of at least 10 which implies that the loop gain must be adequate to meet this goal. Fortunately, the dominant source of errors is repetitive (Lorentz force) and can be reduced by use of feed forward significantly. It should be noted that bunch-to-bunch fluctuations of the beam current cannot be suppressed by the rf system since the gain bandwidth product cannot exceed 1 MHz due to the low-pass characteristics of the cavity, bandwidth limitations of electronics and klystron, and cable delay.

4.2 Principle of RF Control

The first step in the design of an rf control system is to determine available sensor and actuator locations in the sys-

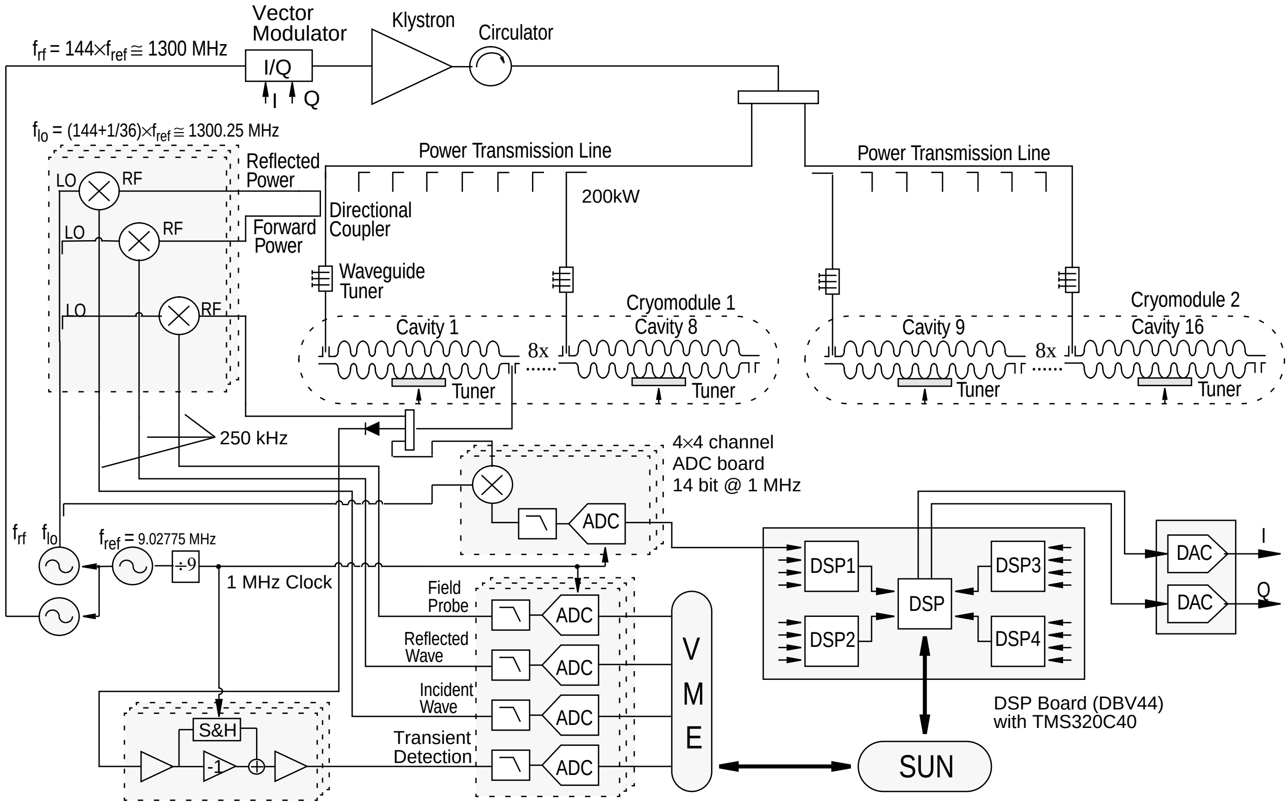

Figure 1 : Schematic of the Digital RF System for the TESLA Test Facility

tem. For the rf system for the TTF the following sensor signals have been chosen:

- 16x amplitude and phase of the cavity field
- 16x amplitude and phase of incident wave
- 16x amplitude and phase of the reflected wave
- 1x total incident and reflected wave

The actuators are:

- 1x amplitude and phase control of incident wave
- 16x cavity frequency control (motor activated tuner)
- 16x manual adjustment for loaded Q and phase of incident wave using three stub waveguide tuners

Fast amplitude and phase control can only be accomplished by modulation of the incident wave which is common to 16 cavities. Therefore fast control of an individual cavity field is not possible. The modulator for the incident wave is designed as an I/Q modulator to control the in-phase (I) and quadrature (Q) component of the cavity field instead of the traditional amplitude and phase modulators. The coupling between the loops is therefore minimized and control in all four quadrants is guaranteed.

The detectors for cavity field, and incident and reflected wave are implemented as digital I/Q detectors. The rf signals are converted to an IF frequency of 250 kHz and sampled at a rate of 1 MHz, i.e., two subsequent data points describe I and Q of the cavity field. The I and Q component which describe the cavity field vector are multiplied by 2x2 rotation matrices to correct the phase offsets and to calibrate the gradients of the individual cavity probe signals. The vector-sum is calculated and a Kalman filter is applied. The Kalman filter provides an optimal state (cavity field) estimate by correcting for delay in the feedback loop and by taking stochastic sensor and process noise into account. Finally the set point is subtracted and a time optimal gain matrix is applied to calculate the new actuator setting (I and Q control inputs to a vector modulator). Feed forward is added from a table in order to minimize the control effort. The feed forward tables are adaptively updated to reflect slowly changing parameters such as average detuning angle, microphonic noise level, and phase shift in the feed forward path.

4.3 Fast Feedback Hardware

The hardware of the digital feedback consists of 14-bit, 2 MHz ADCs (AD929 from Datel), the interface circuit to the input of the digital signal processors (DSP), the 6 DSPs (TMS320C40 from Texas Instruments), and two 16-bit, 10 MHz DACs which drive the vector modulator. Five DSPs are used to acquire the probe signals of the 16 cavities and perform the matrix multiplication while one DSP is calculating the vector-sum and performing the feedback algorithm. The clock frequency of the DSPs is 50 MHz which allows for 25 instructions per microsecond. An additional DSP may be required to perform a more complex algorithm. The overall data processing time will be on the order of 2-3 µs. A cable delay of 600 ns, ADC conversion of 500 ns, and DAC conversion of 200 ns increases the total delay to 3-4 μs thereby adding more than 100 degrees phase shift at 100 kHz.

With the addition of the digital I/Q detectors for incident and reflected wave which are read by the controls computer - these signals are not used in the feedback algorithm - the complete information about each cavity is available. Graphs of the individual signals are displayed for monitoring, optimization, and trouble shooting purposes. The tuner control is derived from the time dependence of the gradient signal.

The calibration of the vector-sum and the phasing of the cavities is based on beam loading. The beam induced transients are observed at zero crossing and phase offsets are determined by nulling of the average transients. Dedicated hardware for transient detections allow for precise calibration of the vector-sum [2].

4.4 Feedback Algorithm

The non-linear dynamics of a single cavity are described by the state space equation:

$$\begin{bmatrix} \dot{v}_r \\ \dot{v}_i \\ \dot{\Delta\omega} \end{bmatrix} = \begin{bmatrix} -\omega_{1/2} & -(\Delta\omega + \Delta\omega_T) & 0 \\ \Delta\omega + \Delta\omega_T & -\omega_{1/2} & 0 \\ -\frac{2\pi \cdot K}{\tau_m} v_r & -\frac{2\pi \cdot K}{\tau_m} v_i & -\frac{1}{\tau_m} \end{bmatrix} \cdot \begin{bmatrix} v_r \\ v_i \\ \Delta\omega \end{bmatrix} + \frac{R\omega_{rf}}{2Q} \cdot \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} I_r \\ I_i \end{bmatrix}$$

where v_r , v_i : real and imaginary component of the cavity voltage ,

I_r , I_i : real and imaginary component of the total current (generator + beam)

$\Delta\omega + \Delta\omega_T = \omega_0 - \omega_{rf}$, $\omega_0 = \omega_0(t)$: resonance frequency of the cavity ,

ω_{rf} : operating frequency , $\omega_{1/2} = \frac{\omega_{rf}}{2Q}$: half width of resonance ,

$\Delta\omega_T$: detuning by frequency tuner , τ_m : mechanical time constant ,

K : Lorentz force detuning constant .

Linear and time invariant systems of the form $\dot{x}(t) = A \cdot x(t) + B \cdot u(t)$ are well understood in modern control theory and solutions for an optimum controller can be found in textbooks. For the above non-linear system which describes the cavity dynamics one can also find various solutions for a controller. It is, however, critical to keep the computational delay as small as possible to allow for sufficient gain bandwidth product and avoid instabilities due to delay. Since the data processing time (few μs) will be short compared to the time constant of the cavity (700 μs), it is possible to correct for these delays and reach significantly higher feedback loop gains than in analog systems with the same delay.

The computational delay is minimized by treating the ensemble of 16 cavities like one cavity and applying the feedback algorithm only to the vector-sum. Simulations with realistic spreads in system parameters such as loaded Q_L , mechanical time constant τ_m , Lorentz force detuning constant K , power and phase of incident wave, errors in vector-sum, and initial detuning angle have demonstrated that the ensemble of 16 cavities is well described by the dynamics of a single cavity.

The present feedback algorithm applies proportional gain to the error signal and uses a digital low-pass filter to reduce the sensor noise. More sophisticated algorithms such as time varying Kalman filter and time-optimal control are planned to be used in the near future.

The design of a feed forward algorithm is as important as the feedback algorithm. The Lorentz force induced gradient and phase fluctuations result in a repetitive error signal which can be compensated by feed forward which adds a fixed and negligible amount of cpu time. The feed forward tables are optimized by measurement of the average correction signal from the feedback loop and adjustment of the feed forward tables such that the average feedback signals are close to zero.

4.5 Application Software

The application software will assist the operator with startup and operation of the rf system. This includes automated operation of the frequency tuners, calibration of the vectorsum, phasing of cavities, and adjustment of various control system parameters such as feedback gains, feed forward tables, and setpoint correction during cavity filling. Extensive diagnostics inform the operator about cavity quenches, cavities requiring manual tuning, and an excessive increase in control power.

5 CONCLUSION

A digital rf control system has been developed for the TESLA Test Facility. The prototype hardware has been installed and successfully tested with a single cavity and a simple feedback algorithm. The quality of amplitude and phase control is similar to that of the analog system even without applying sophisticated feed forward algorithms. With the implementation of adaptive feedback, it is expected that the digital feedback will out perform a purely analog solution. The major advantage of the digital feedback are the built in diagnostics which are essential for the operation of 16 cavities driven by one klystron.

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7 REFERENCES

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