PERFORMANCE OF FERRITE VECTOR MODULATORS IN THE LLRF SYSTEM OF THE FERMILAB HINS 6-CAVITY TEST*

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Abstract

The High Intensity Neutrino Source (HINS) 6-cavity test is a part of the Fermilab HINS Linac R&D program for a low energy, high intensity proton/H- linear accelerator. One of the objectives of the 6-cavity test is to demonstrate the use of high power RF Ferrite Vector Modulators(FVM) for independent control of multiple cavities driven by a single klystron. The beamline includes an RFQ and six cavities. The LLRF system provides a primary feedback loop around the RFQ and the distribution of the regulated klystron output is controlled by secondary learning feed-forward loops on the FVMs for each of the six cavities. The feed-forward loops provide pulse to pulse correction to the current waveform profiles of the FVM power supplies to compensate for beam-loading and other disturbances. The learning feed-forward loops are shown to successfully control the amplitude and phase settings for the cavities well within the 1% and 1° requirements specified for the system.

INTRODUCTION

The use of FVMs to regulate the phase and amplitude of individual cavities in a multi-cavity system driven by a single klystron helps to reduce the cost of the RF system for linear accelerators[1]. High power waveguide FVMs have been developed and the dynamic range of their phase shifting and amplitude attenuating capabilities have been studied[2]. Modeling and simulation of RF control systems with FVMs have shown their potential for field control of individual cavities in a multi-cavity system[3]. A learning feed-forward[LFF] control for the HINS six cavity test accelerator was integrated into the LLRF system. All RF components are driven by a single 325 MHz, 2.5MW pulsed klystron. The LFF algorithm is described and the results of its performance with beam are presented .

LLRF SYSTEM

The RF control block diagram for the 6-cavity test is shown in Fig.1. The LLRF control system regulates the phase and amplitude of the RF field vectors of the RFQ and the six room temperature copper cavities. There is a traditional wide-band proportional and integral feedback control loop around the klystron and the RFQ. Because the RFQ is a low Q device, it behaves much like a resistive load. Therefore, by regulating the RFQ field, the klystron output to the six cavities is effectively regulated as well. This RFQ control loop greatly reduces errors from klystron modulator voltage variations and from changing beam current. There are several disturbances to the six cavities that must be corrected by the FVM controllers. These are static amplitude and phase errors, drifts in cavity resonance frequency, differences in cavity Qs, and variations in cavity beam loading. Field errors in the cavities are corrected by an adaptive feed-forward system.

The primary feed-back loop is implemented as a PI controller in a FPGA with a sampling frequency of 56 MHz. The 325Mhz RF is downconverted to a 13 MHz IF which is sampled and downconverted to baseband. A 2.1 MSPS DAQ system acquires baseband I,Q signals for pulses up-to 4ms wide. The data from all channels is uploaded to the slot0 controller between pulses and is available for processing in the CPU or for transmittal through an ethernet port to both the Fermilab ACNET control system and Labview user interfaces, for waveform display and parameter control.

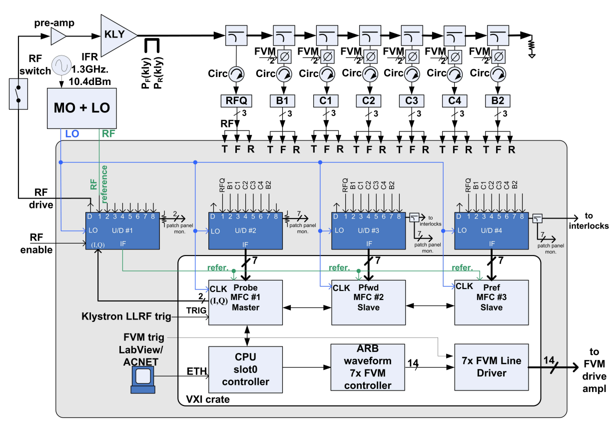

Figure 1: LLRF system configuration

LEARNING ALGORITHM

The learning feed-forward algorithm implementation for one cavity is shown in Fig.2. The wideband RFQ/klystron primary control loop is processed at the full 56 MHz sample rate of A/D converters, while the FVM control loops decimate the data to a 100 kHz rate, where it is processed and the feed-forward controller output is written to a VXI 16 channel arbitrary waveform generator module. Regulation waveforms are recalculated at the machine repetition rate of 0.5 Hz. Decimating the DAQ data by 21 brings the sample rate close to the 100 kHz sampling rate of the output DACs to the FVM. With 1024 points in the FVM waveform, the maximum width of the FVM profile is 10ms

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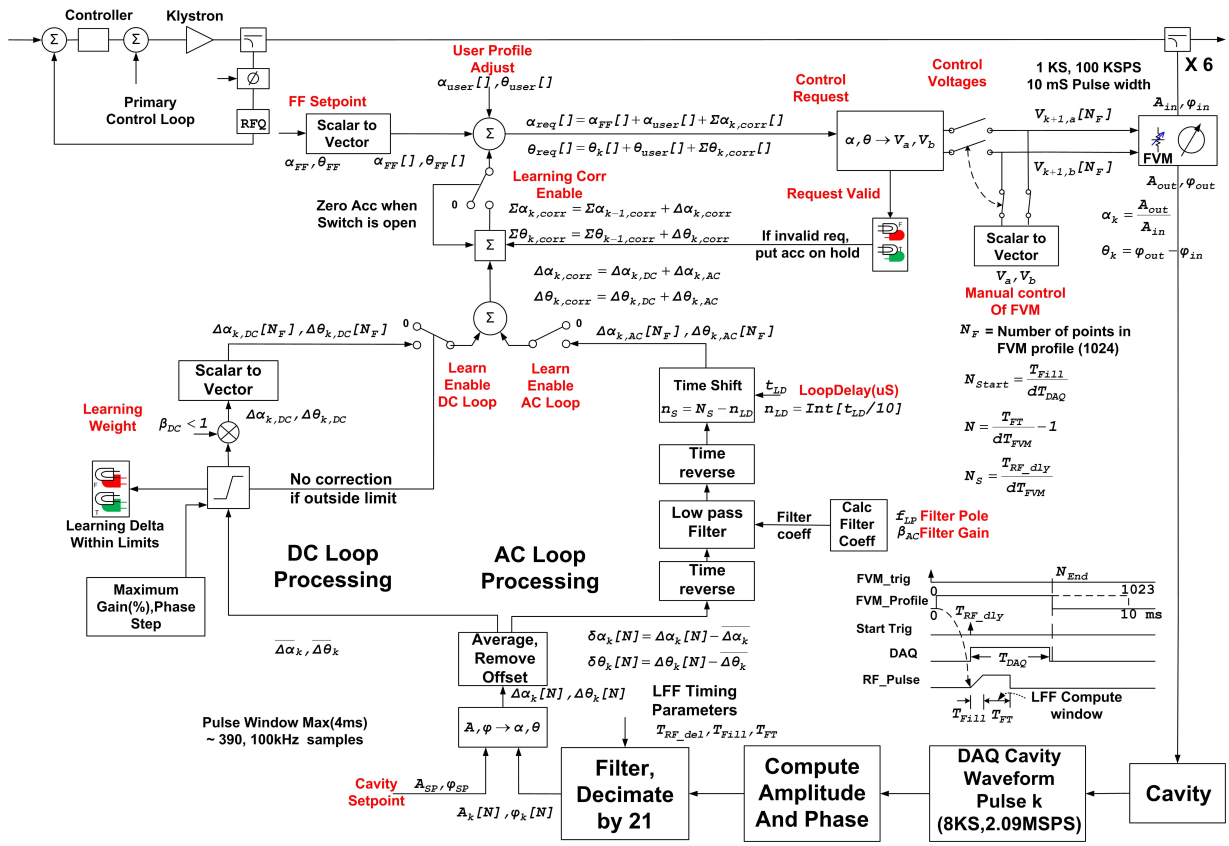

Figure 2: Learning Feedforward Algorithm

which allows for the 4ms RF pulse to be completely included within the FVM pulse. The FVM trigger starts the play-out of the waveform which is 2.5 ms before the start of the RF pulse. This allows the FVM to settle well before the arrival of the RF pulse and beam. The error in the cavity field amplitude and phase is transformed into a correction in the attenuation and phase shift parameter inputs to the FVM. The corrections are computed, based on zeroing the error in the next pulse. They can be computed exactly with an amplitude and phase computation of the cavity field read-back from the DAQ.

$$\Delta\alpha_k = \alpha_k \times (\frac{A_{SP}}{A_k} - 1) \qquad (1)$$

$$\Delta\theta_k = \phi_{SP} - \phi_k \qquad (2)$$

They can also be approximated with formulas based on the I,Q values by a linearization around the operating point as follows. With $I_e = I_{SP} - I_{cav}, Q_e = Q_{SP} - Q_{cav}$. the correction formulas are given by

$$\Delta\alpha_k = \alpha_k \times \frac{I_{cav}I_e + Q_{cav}Q_e}{I_{cav}^2 + Q_{cav}^2} \qquad (3)$$

$$\Delta\theta_k = \frac{Q_e I_{cav} - I_e Q_{cav}}{I_{cav}^2 + Q_{cav}^2} \qquad (4)$$

The approach taken in this design is to split the error into a DC component and an AC component with separate control loops. The DC loop is intended to correct offsets due to drift and parameter variations and the AC loop corrects for errors only in the flattop portion of the RF pulse to compensate for beam loading and other disturbances associated with the beam. The correction from the DC loop is an offset that is combined with the AC loop correction to add to the FVM output for the next pulse. A fault detection scheme detects large fluctuations in correction and places the learning on hold till the field recovers.

The transformation of the control request to the voltages to the FVM current coil power supplies is done using a lookup table and interpolation. Due to the highly non-linear and restricted mapping from the α and θ domain to the Va , Vb domain, the operating point of the FVM needs to be chosen carefully to provide maximum headroom for the closed loop operation[2],[3]. There are large regions where there are no valid solutions which must be kept clear of. Motorized trombones allowed the tuning of the phase and waveguide distribution taps were adjusted to obtain the desired attenuation, to bring the FVM operating point to regions with the required dynamic range.

Treating the AC error as a disturbance input as shown in Fig.3 helps to understand the correction scheme. Since the FVM input profile for pulse k+1 is calculated based on the complete cavity field waveform acquired during pulse k, anti-causal time-reversal filters can be used for disturbance detection[4]. If the transfer function of the combined FVM

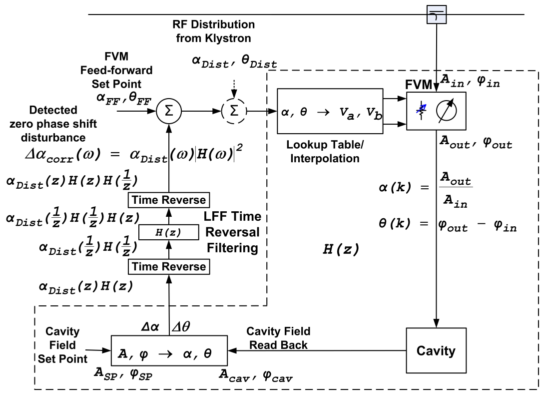

Figure 3: Time reversal filtering for FVM error detection

and the cavity system is represented by H(z), then passing the error through the anti-causal filtering shown in Fig.3, produces a zero phase shift, detected disturbance to which the appropriate gain and time advance (to account for the loop delay) can be added to cancel out the disturbance. The transfer function H(z) is modeled as a first order IIR filter whose pole and the loop delay parameter become the key tuning parameters to correct the disturbance input.

RESULTS

The learning feed-forward algorithm was tested under beam loading conditions. Fig.4 and Fig.5 show magnitude and phase plots for the cavity field with a 300 μS beam pulse with and without the LFF control. The convergence of the DC loop is determined mainly by the gain parameter. The AC loop needs to be tuned primarily with the filter pole and the loop delay parameter.

The regulation during beam was $< 0.2\%$ for amplitude and $< 0.21°$ for phase. Cavity 1 shows only a partial suppression of the disturbance because its FVM request parameters overshot the valid region and the FVM inputs are held at the last valid value.

CONCLUSION

The application of a learning feed-forward loop for FVMs showed that they are capable of regulating cavity field and phase within specifications in applications with one klystron driving multiple cavities. Tuning the AC loop was critical to the stability of the system. It was shown that with a DC loop alone, it is not possible to accurately compensate for the beam-loading disturbances. The six cavity test was specified with a longer pulse width of 1ms. Due to technical issues with the RFQ, the RF pulse widths were limited to < 500 μS.

The feasibility of using FVMs in a single klystron multiple cavity application was demonstrated in the Hins 6-cavity test. The learning feed-forward loops around the FVMs provided independent control for cavities with differing characteristics and set-points.

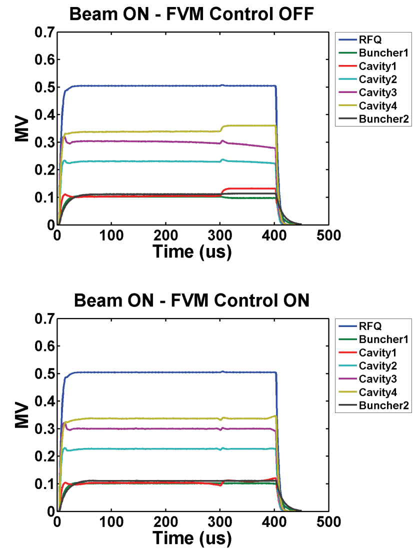

Figure 4: Cavity Magnitude with FVM LFF loops OFF/ON

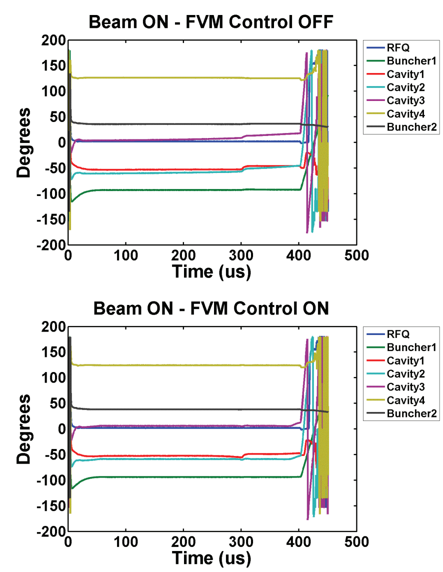

Figure 5: Cavity Phase with FVM LFF loops OFF/ON

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