DIGITAL LOW-LEVEL RF CONTROL SYSTEM WITH FOUR INTERMEDIATE FREQUENCIES AT STF

T. Matsumoto#, S. Fukuda, H. Katagiri, S. Michizono, T. Miura, Y. Yano, KEK, Ibaraki, Japan
Y. Okada, NEC Network and Sensor Systems, Ltd., Tokyo, Japan

Abstract

A field programmable gate array (FPGA)-based digital low-level RF (LLRF) control system is used with a feedback control system to achieve amplitude and phase stabilities of the accelerating field in superconducting accelerators. A new digital LLRF control system that uses different intermediate frequencies (IFs) has been developed to decrease the number of analog-to-digital converters (ADCs) required during the feedback operation of the RF sources.

Operation of a digital LLRF control system using four different IFs at the Superconducting RF Test Facility (STF) in KEK was commenced in December 2008, and feedback operation was performed using four superconducting cavities. The performance of this digital LLRF control system has been reported in this paper.

INTRODUCTION

The RF station at the International Linear Collider (ILC) requires stabilities of 0.07% and 0.24° in the amplitude and phase of the accelerating field, respectively, in order to achieve the desired collision luminosity [1]. The RF station at the ILC is equipped with three cryomodules (two of these are composed of nine superconducting cavities each, while the third is composed of eight cavities) and one klystron that generates RF power. In order to satisfy the stability requirements of the accelerating field, a digital LLRF control system based on a field programmable gate array (FPGA) board will be installed to control the RF field with vector-sum feedback (FB) and feedforward (FF) operations. In order to use vector-sum FB control at the ILC RF station, the amplitude and phase (or the I and Q components) of all 26 cavities must be measured to calculate the vector sum. In addition, the RF waveform of drive power and reflection power from all the cavities must be monitored to ensure stable operation of the ILC RF station.

In a typical digital LLRF control system, the RF signal is down-converted into an IF signal while the I and Q component of the RF signal are preserved, as shown in Figure 1(a). The IF signal is then sampled by an analog-to-digital converter (ADC) at a constant sampling rate (SR), and the I and Q components of the RF signal are determined by digital signal processing. The digital LLRF control system requires approximately 80 ADCs for one ILC RF station.

A digital LLRF control system using a new technique has been developed in order to decrease the number of ADCs required by the system. In this technique, the RF signals picked up from different signal sources are down-

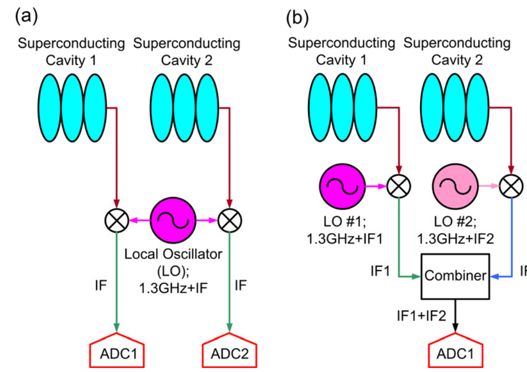

Figure 1: Schematic diagram of the digital LLRF system: (a) Typical system and (b) IF-mixture technique.

converted into different IF signals. These IF signals are then combined using a combiner and sampled by an ADC with a constant SR, as shown in Figure 1(b). The I and Q components of each IF signal are evaluated by digital signal processing (IF-mixture technique). The digital LLRF control system that employs this IF-mixture technique using four IFs has been developed and its performance has been evaluated using a superconducting cavity at the Superconducting RF Test Facility (STF) in KEK [2].

Operation of four superconducting cavities at STF was commenced in December 2008 [3]. During this operation, the performance of the digital LLRF control system equipped with four IFs was evaluated and compared with that of the conventional digital LLRF system employed for the STF.

DIGITAL LLRF SYSTEM

The digital LLRF control system at the STF consists of an FPGA board mounted on CompactPCI, a mixer unit, an IQ modulator (AD8349) unit, and a signal distribution system. The FPGA board consists of an FPGA chip (VirtexII Pro 30), ten 16-bit ADCs (LTC2204), and two 14-bit digital-to-analog converters (DACs) (AD9764). The signal distribution system comprises a clock distribution chip (AD9510) and IQ modulators (AD8346) and behaves as a generator of the timing clock (40.625 MHz) signal and local oscillators (LOs) of various frequencies to demonstrate the IF-mixture technique. The mixer unit of the digital LLRF control system comprises four mixer blocks; each mixer block stores four 6 channel active mixers (AD8343).

IQ Detection Scheme

The down-converted IF signal is expressed as follows:

$$x(t) = I(t)\cdot\cos(\omega_{IF} t + \varphi) + Q(t)\cdot\sin(\omega_{IF} t + \varphi),$$

#toshihiro.matsumoto@kek.jp

where $I(t)$, $Q(t)$, and φ are the I component, Q component, and loop phase of the cavity, respectively, and $\omega_{IF} = 2\pi \cdot IF$.

When the sampling rate of the ADC and the frequency of the IF signal satisfy the condition $M \cdot IF = N \cdot SR$ (N is an integer and M is an integer greater than 3), the sampled IF signal is expressed as follows:

$$x(n) = I \cdot \cos(\frac{2\pi \cdot N}{M} \cdot n) + Q \cdot \sin(\frac{2\pi \cdot N}{M} \cdot n) \cdot$$

For M = 4 and N = 1, the sampled IF signal contains a sequence of I, Q, –I, and –Q (direct IQ detection). This combination of the values of IF and SR is adopted for the regular digital LLRF control system at STF and the sampling rates of ADC and the FPGA clock are set at 40.625 MHz.

Another method for numerically calculating the I and Q components is to average the consecutive signal samples using the following equations [4].

$$I = \frac{2}{N}\sum_{n=1}^{N} x(n) \cdot \cos(\frac{2\pi \cdot N}{M} \cdot n) \qquad (1)$$

$$Q = \frac{2}{N}\sum_{n=1}^{N} x(n) \cdot \sin(\frac{2\pi \cdot N}{M} \cdot n)$$

This method is more time-consuming than direct IQ detection. However, averaging of the signal samples (Eq.1) helps reduce the effect of noise and jitter caused by ADC sampling and also helps in canceling the constant offset.

IF-Mixture Technique

When different IF signals that fulfill the condition $M \cdot IF = Ni \cdot SR$ are combined, the combined IF signal, after being sampled by the ADC, is expressed as follows:

$$X(n) = \sum_{i=1} x_i(n) = \sum_{i=1} \left\{ I_i \cdot \cos(\frac{2\pi \cdot N_i}{M} \cdot n) + Q_i \cdot \sin(\frac{2\pi \cdot N_i}{M} \cdot n) \right\}$$

By selecting appropriate values of Ni and M in Eq.1, a specific set of I and Q components is obtained from the combined IF signal and the remaining I and Q components are removed. In this experiment, we choose the combinations of (M, N1, N2, N3, and N4) = (9, 1, 2, 3, and 4) to perform the IF-mixture technique using four IFs.

The algorithm for this four IF-mixture technique using four ADCs was implemented in the FPGA board using VHDL.

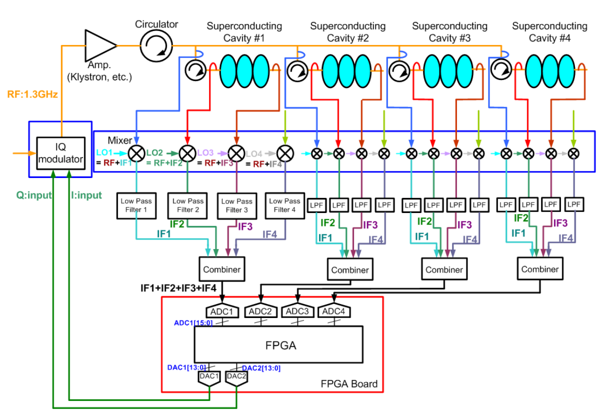

Figure 2: Schematic diagram of system configuration.

PERFORMANCE OF THE LLRF SYSTEM

The configuration of the digital LLRF control system that employs the IF-mixture technique is shown in Figure 2. The IF signals of the cavity field and the drive power and reflection power picked up from the same cavity are combined. For different IF signals, the fluctuations in amplitude and phase at flat top are calculated from Eq.1 and compared with that estimated from direct IQ detection algorithm. The amplitude and phase of the cavity field estimated with both algorithms are shown in Figure 3, and Table 1 shows the fluctuation of amplitude and phase estimated for the different IFs and direct IQ detection. The results show that the estimated IQ accuracy is almost same in both algorithms.

Table 1: The fluctuation in amplitude and phase for different IFs and direct IQ detection

	ΔA/A	Δϕ
IF1 (4.514 MHz)	7.3E–05	0.014°
IF2 (9.028 MHz)	8.8E–05	0.013°
IF3 (13.542 MHz)	1.0E–04	0.014°
IF4 (18.056 MHz)	1.0E–04	0.016°
Direct IQ (10.156 MHz)	7.1E–05	0.014°

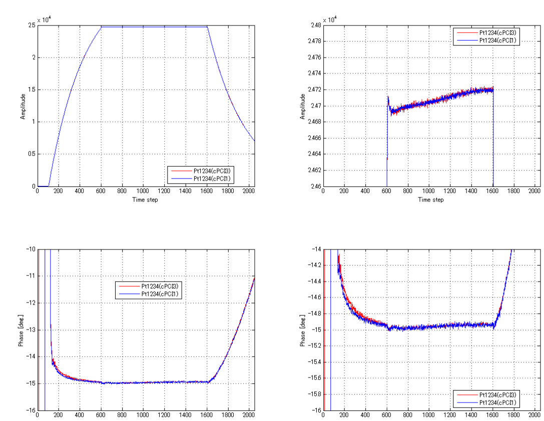

Figure 3: Measured amplitude and phase components: Blue: direct IQ, red: IF-mixture with IF2.

RF Operation with IF-Mixture Technique

The amplitude of the cavity field, drive power, and reflection power estimated by Eq. 1 for all cavities are shown in Figure 4. Each waveform estimated with the IF-mixture technique is well consistent with that calculated by direct IQ detection. This shows that the evaluation of a specific set of I and Q components from the mixed IF signal by using the IF-mixture technique is practicable.

The loaded Q (Ql) and detuning (df) of each cavity are estimated by the time decay of the cavity field by using both the algorithms. Then the corresponding values obtained by both algorithms are compared with each other. The fitting results of 150 successive pulses are listed in Tables 2 and 3. The fitting error estimated by IF-mixture

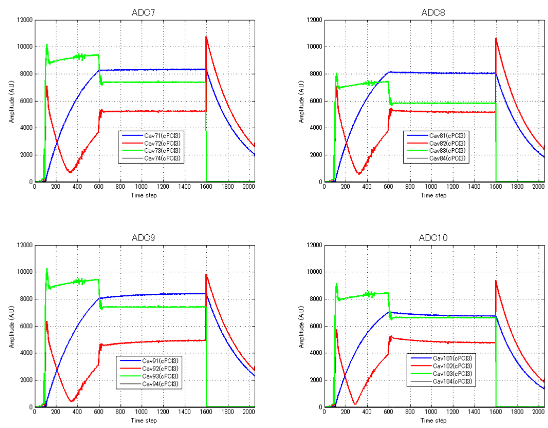

Figure 4: Amplitude of the cavity field, drive power, and reflection power estimated by Eq. 1. Blue: cavity field; green: drive power; and red: reflection power.

technique is almost twice that estimated by direct IQ detection; however, the fitted values obtained with these two algorithms are consistent with each other.

Table 2: Values of Ql estimated by the IF-mixture technique and direct IQ detection

Ql	IF-mixture	Direct IQ detection
Cavity #1	$(1.508 \pm 0.006) \times 10^6$	$(1.515 \pm 0.003) \times 10^6$
Cavity #2	$(1.358 \pm 0.004) \times 10^6$	$(1.361 \pm 0.002) \times 10^6$
Cavity #3	$(1.443 \pm 0.006) \times 10^6$	$(1.450 \pm 0.003) \times 10^6$
Cavity #4	$(1.428 \pm 0.004) \times 10^6$	$(1.432 \pm 0.002) \times 10^6$

Table 3: Values of df estimated by the IF-mixture technique and direct IQ detection

df	IF-mixture	Direct IQ detection
Cavity #1	$(42.1 \pm 3.1)°$	$(39.8 \pm 3.4)°$
Cavity #2	$(2.4 \pm 2.5)°$	$(1.2 \pm 2.4)°$
Cavity #3	$(2.8 \pm 3.7)°$	$(1.2 \pm 2.8)°$
Cavity #4	$(1.9 \pm 2.3)°$	$(1.5 \pm 2.3)°$

Feedback Performance

Figure 5 shows the relation between the proportional gain (P-gain) and the amplitude and phase stabilities at the flat top under FB operation. The P-gain is calculated from the difference between the set point and the average of the measured flat top. The FB operation becomes unstable when the P-gain exceeds 120.

In the region of stable FB operation, errors in the amplitude and phase at the flat top, which ranges from 650 μs to 1550 μs, depend on the P-gain. Figure 6 shows the observed amplitude and phase at the flat top. The amplitude and phase over the flat top become constant when an appropriate FF table is adopted. This also causes the errors in amplitude and phase to be 0.03% (RMS) and 0.03° (RMS), respectively.

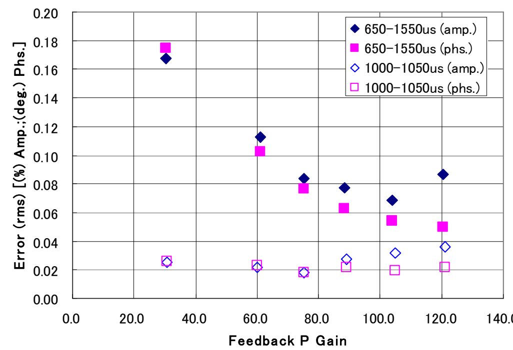

Figure 5: Errors in amplitude and phase at the flat top.

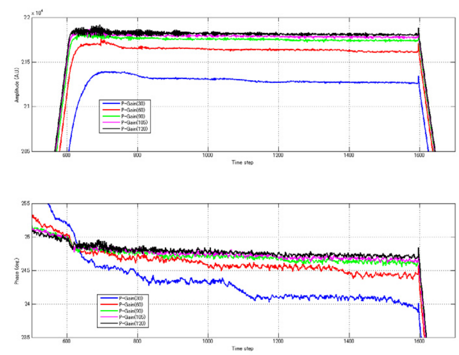

Figure 6: Amplitude and phase at the flat top with different proportional gain.

SUMMARY

Operation of a digital LLRF control system employing the IF-mixture technique for four superconducting cavities was commenced at STF in December 2008. The signal estimated using the IF-mixture technique was consistent with that of direct IQ detection. The FB performance of the system was examined for several P-gains, and the stabilities of the amplitude and phase were expected to be 0.03% (RMS) and 0.03° (RMS), respectively, when an appropriate feed-forward table was adopted.

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