ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-THPTS022

THE REALIZATION OF ITERATIVE LEARNING CONTROL FOR J-PARC LINAC LLRF CONTROL SYSTEM

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Abstract

In order to cope with the heavier beam loading effect, an iterative learning control (ILC) based adaptive feedforward control methods was put forward and realized in J-PARC LINAC. The experimental results show that compared with the only feedback control, the combination of ILC and feedback can improve the amplitude stability from ±4.1% to ±0.37% and phase stability is increased from ±1° to ±0.2°. In this paper, the ILC realization method will be introduced and the experimental results will be shown.

INTRODUCTION

According to the upgrade plan of J-PARC in phase II [1], the beam power from Rapid-Cycling Synchrotron (RCS) should be increase to 1.5 MW. In order to achieve this goal, both the beam current and beam pulse length in J-PARC LINAC should increase about 20%, which is 60 mA and 600 µs, respectively. The higher beam current will cause heavier beam loading effect and eventually make the waveform stability cannot meet the requirements which is ±0.5% for amplitude and ±0.5° for phase. Figure 1 shows the amplitude waveform at the flat top of ADC in SDTL (Separate-type Drift-Tube Linac) 01 station, J-PARC LINAC. The beam current here is 50 mA. Even at the beginning, by adjusting the feedforward manually, we can make the peak to peak stability of ADC amplitude almost equals to ±1%. However, due to the external disturbance especially the variation of high-power supply for klystron, after long term operation of the accelerator, the peak to peak stability of amplitude becomes ±3.62%. Figure 2 shows the phase waveform of ADC in SDTL01 station. The peak to peak stability of phase is ±1.1°, which also does not meet the requirement. In order to solve this problem, an iterative learning control (ILC) based adaptive feedforward method was put forward and realized in SDTL01 station, J-PARC LINAC. ILC is a powerful control tool for the dynamic systems with good repeatability. Its main function is to improve the transient response of system even if sometimes the information of the controlled system is incomplete. Figure 3 shows a block diagram of a typical iterative learning control loop in low-level radio frequency (LLRF) system and the rf components have been omitted for simplicity. The ILC algorithm can be given by

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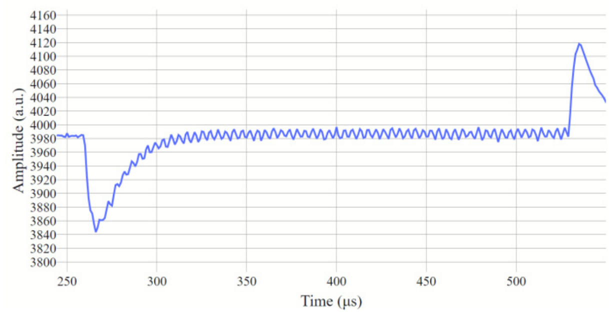

Figure 1: ADC amplitude waveform in SDTL01 station.

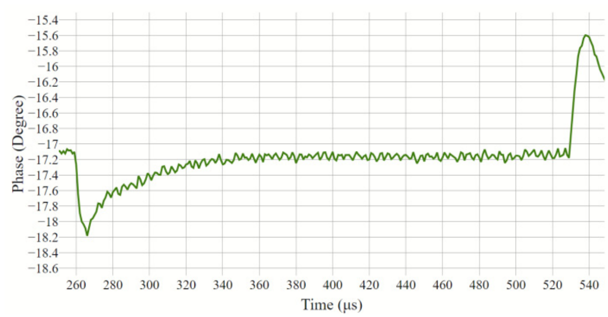

Figure 2: ADC phase waveform in SDTL01 station.

Figure 3 shows a block diagram of a typical iterative learning control loop in low-level radio frequency (LLRF) system and the rf components have been omitted for simplicity. The ILC algorithm can be given by

$$u_{j+1}(k) = Q(q)\left[u_j(k) + L(q)e_j(k+1)\right] + C(q)e_{j+1}(k) \quad (1)$$

where k is the time index, j is the iteration index, q is the forward time-shift operator $qx(k) \equiv x(k+1)$, u_j is the system input, e_j is the error, C(q), Q(q) and L(q) are defined as the feedback controller, Q-filter and learning function, respectively [2]. And Eq. (1) can be separated into two components, feedforward and feedback which are the output of ILC controller and feedback controller respectively, so we have

$$u_{j+1}(k) = w_{j+1}(k) + \mathrm{C}(\mathrm{q})e_{j+1}(k) \quad (2)$$

where feedforward component

$$w_{j+1}(k) = \mathrm{Q}(\mathrm{q})[u_j(k) + \mathrm{L}(\mathrm{q})e_j(k+1)] \quad (3)$$

Equation (3) is a widely used ILC algorithm. In our case,

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in order to shorten the development cycle, we use the simplest P-type ILC algorithm with a Q-filter, which form is

$$w_{j+1}(k) = \mathrm{Q(q)}[u_j(k) + K_p e_j(k+1)] \qquad (4)$$

where K_p is a proportional coefficient and $0 < K_p < 1$. In most instances, the Q-filter is a low pass filter. In our case, we design a simple moving average (SMA) module to replace the low pass filter in ILC Python program.

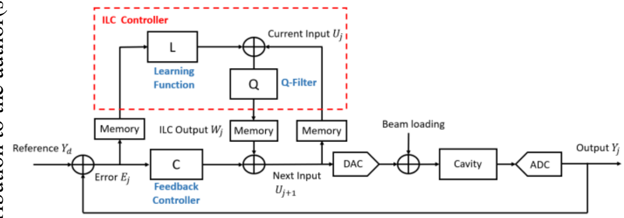

Figure 3: Block diagram of iterative learning control loop.

LLRF SYSTEM

In J-PARC LINAC, the current LLRF (Low-Level Radio Frequency) system has already been used for more than 10 years. No manufacturer continues to produce and maintain these old devices, especially the FPGA board. To ensure the normal operation of the accelerator, a new LLRF system was developed for J-PARC LINAC which core part is a MTCA-based digitizer.

Figure 4 shows the block diagram of this LLRF system. Cavity signals were down converted to 12 MHz IF (Intermediate Frequency) signals by mixer, then send into FPGA though 16 bits ADC. In FPGA, the signal will be converted to IQ (In-phase and Quadrature) components and finished feedback control. The output signals of FPGA will be sent into IQ modulator though 16 bits DAC. In IQ modulator, the IQ signal will change back to the normal signal and up convert to the 324 MHz or 972 MHz high frequency signal. Due to sometimes the output signal of IQ modulator was CW (Continuous Wave), so there is a pulse modulator to change the CW signal to Pulse signal. After that, the signal will be amplified twice by solid-state amplifier and klystron, and finally fed into the cavity.

Signals in FPGA were sampled by low & medium speed monitor with 96 MHz clock signal. Then the data of these signals or called PVs (Process Variables) will be saved in EPICS (Experimental Physics Industrial Control System) IOC (Input Output Controller) as records. These records can be called by EPICS clients, for example CSS (Control System Studio) which installed in EPICS computer. For us, we want to implement ILC with a Python program, so the PyEpics which is an interface for the Channel Access (CA) library of the Epics control system to the Python programming language was installed in our EPICS computer. Then these records can be called and use these data to do the calculation in ILC python program, and then send them back to the FPGA though IOC to finish the iteration control.

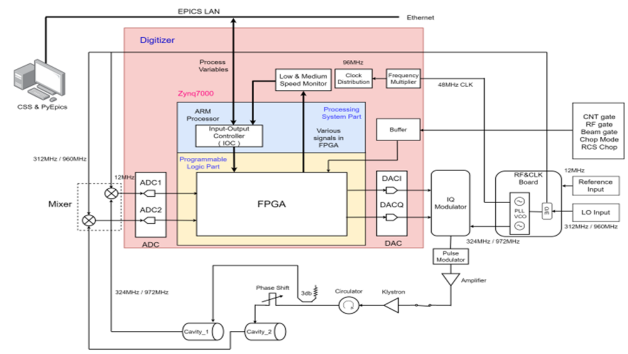

Figure 4: Block diagram of new LLRF system for J-PARC LINAC.

ILC BASED BEAM LOADING COMPENSATION EXPERIMENT

The experiment was conducted in SDTL01 station. The beam current was 50 mA. For reducing the beam losses in the RCS, there is an RF chopper between the RFQ (Radio Frequency Quadrupole) and the DTL (Drift-Tube Linac) in J-PARC LINAC. Figure 5 shows the time structure of the linac beam pulse. The chopping ratio is about 56% and the chopping frequency is 1.23 MHz in accordance with the RF frequency of the RCS [3]. For the reason of this chopped beam noise, the RF waveform at the beam position becomes similar to the sawtooth wave. In this experiment, the ILC gain K_p is set to 0.5. The alignment position of SMA algorithm is center and window length equals to 3. A shifter module was designed in the ILC program to compensate the loop delay of the system.

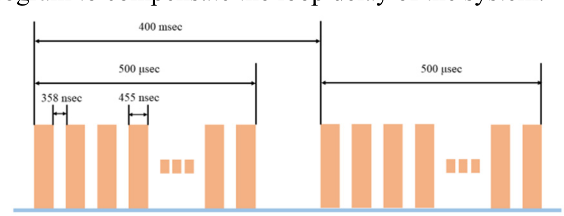

Figure 5. The time structure of the linac beam pulse.

After compensating for the loop delay well, the iteration was run 50 times. Figure 6 shows the changing process of ADC amplitude waveform at the flat top. The initial waveform corresponds to the case of only feedback control. Due to the deformation caused by the heavy beam loading was too serious, it will take so much time to compensate it if we only use the ILC. Therefore, an appropriate initial feedforward was added to the output of the ILC controller in the first iteration to shorten the convergence time. As the iteration proceeds, the waveform became flattening gradually. Compare the first and last results, the amplitude peak to peak stability was improved from ±4.1% to ±0.37%.

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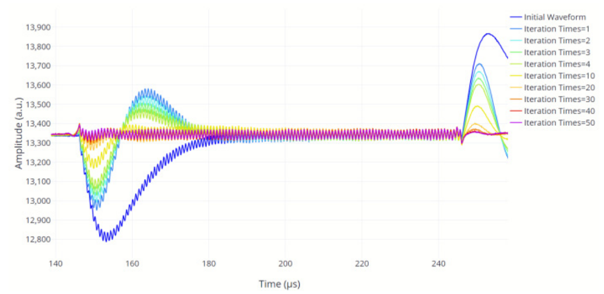

Figure 6. Changing process of ADC amplitude waveform.

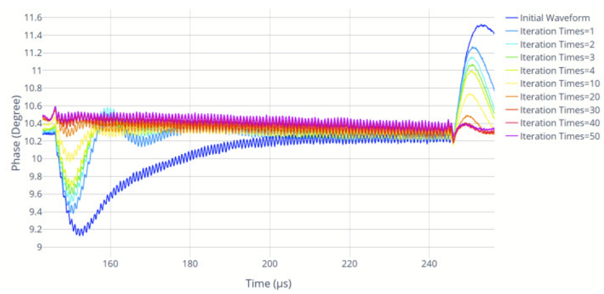

Figure 7. Changing process of ADC phase waveform.

Figure 7 shows the changing process of ADC phase waveform. As the iteration proceeds, the phase peak to peak stability was improved from ±1° to ±0.2°. After using the ILC based adaptive feedforward method, both the amplitude and phase peak to peak stability have met the requirements. However, the current ILC program still has some problems. For the long-term operation of the ILC, the program will be further optimized in the future.

CONCLUSION

In order to cope with the heavy beam loading effect, an iterative learning control based adaptive feedforward method was realized in J-PARC LINAC. The experimental results show that under 50 mA beam current, this method successfully improve the amplitude peak to peak stability from ±4.1% to ±0.37% and phase peak to peak stability from ±1° to ±0.2°. Both of them meet the requirements of J-PARC LINAC. The ILC Python program will be further optimized for the long-term operation of the ILC. And to verify the effectiveness of the ILC in the high-β section of J-PARC LINAC, the beam loading compensation experiment will be conducted in the ACS01 station in the near future.

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