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COMPENSATION STRATEGIES FOR RAMPING WAVEFORM OF TPS BOOSTER SYNCHROTRON MAIN POWER SUPPLIES

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Abstract

Booster synchrotron for the Taiwan photon source project which is a 3 GeV synchrotron light source constructed at NSRRC had been commissioning successfully when the electron beam was accelerated to 3 GeV on December 16 2014. The booster is designed to ramp electron beams from 150 MeV to 3 GeV in 3 Hz therefore the large main power supplies have features of waveform play with trigger functionalities. However, due to the limited bandwidth of power supplies, different magnet loading will result in quite different phase lag for dipoles and four quadrupoles families and the relative err of input and output of dipole and quadrupoles would be quite different. To improve the relative error between the output readings and reference, several strategies are developed and will be summarized in this report.

INTRODUCTION

The TPS is a state-of-the-art synchrotron radiation facility featuring ultra-high photon brightness with extremely low emittance [1]. The 3 GeV stored electron beam with 5 mA was achieved and the first synchrotron light was observed in December 31. It consists of a 150 MeV electron Linac, a 3 GeV booster synchrotron, and a 3 GeV storage ring. The EPICS (Experimental Physics and Industrial Control System) was chosen for the TPS accelerator control.

The booster main power supplies are composed of one dipole power supply with maximum current 1200 Ampere and four family quadrupole power supplies with maximum current of 120/150 Ampere. At first, these power supplies supported external trigger and internal waveform generator for booster power supply ramping. However, the reproducibility of power supply itself was unsatisfactory at injection due to non-synchronize and asynchronous internal clock of power supply regulator and external trigger. Therefore, the original digital regulation loop was modified to analogue and control interface was also revised so that all of power supplies could be driven by synchronized current waveform reference with common clock source and trigger. It effectively improved the reproducibility more than 1/5 [2, 3].

Figure 1 shows the overall booster ring power supplies control interface. One dedicated EPICS IOC equipped with one CPU blade, one EVR fanout and ADC/DAC modules is built to serve synchronous control and monitor of main booster power supply. Serial to Ethernet adapter are used to interface with On/Off control and status monitor. Moreover, the DT8837 which has 24 bits ADC provide extra high more precision monitoring than ADC modules and also support the external clock for synchronization.

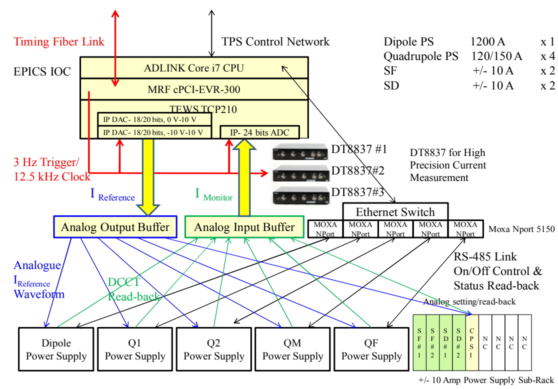

Figure 1: Control infrastructure of TPS booster ring power supplies.

POWER SUPPLY CHARACTERIZATION

Power supply for booster dipole and quadrupoles were contracted and delivered by Eaton. Figure 2 shows the step response of dipole and four quadrupole power supplies at first arrival. It exhibited quite different frequency response which would result in unacceptable tracking error difference between dipole and quadrupole power supplies at injection during ramping as Fig. 3. Adjusting loop gain of power supply analogue regulator by changing resistors could improve the difference but ineffective, imprecise and time-consuming. When one of power supply fails and the spared is necessary, the characterization of the spared would be required re-calibrated, this will cost much man-power and time. It will be quite a burden from maintenance points of view.

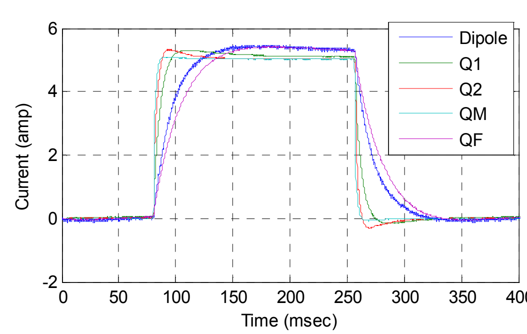

Figure 2: Step response of dipole and four quadrupole power supplies. Dipole and QF had slower response due to larger magnet loading.

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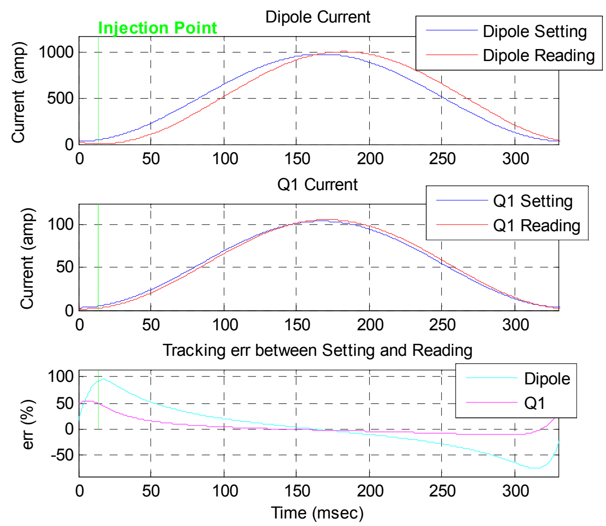

Figure 3: Ramping waveform of Dipole and Q1. Different phase delay will cause different tracking err between setting and reading.

Therefore, it is decided to modify waveforms iteratively so that output current could fit the desired reference currents of themselves rather than changing resistors and loop gain. In the next section, we will demonstrate several strategies of modifying waveforms.

STRATEGIES TO MODIFY POWER SUPPLY WAVEFORM

There are three strategies developed to compensate these errs between output and reference waveform: (1) Proportional compensation (2) System response matrix calculation (3) Proportional and time shift compensation as Fig. 4. Scheme (1) has NRE (Normalized Relative Err respective to reference) ~1% for the worst case of QF. Scheme (2) NRE could achieve 0.5%; Scheme (3) is around 0.2%.

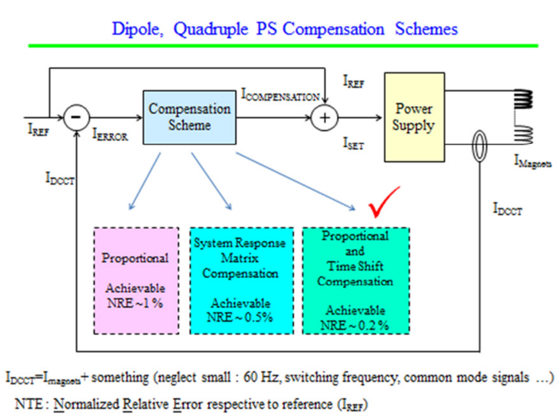

Figure 4: Three Compensation schemes.

Proportional Compensation

The formula of the proportional compensation is as Eq. 1 For Q1, Q2 and QM power supply with faster frequency response, NRE could achieve ~ 0.2% after two or three iterations. However, for dipole and QF with slower response, the NRE could not be lower than 1%.

$$setWf_{n+1} = setWf_n + (refWf - getWf_n) \quad (1)$$

System Response Matrix Calculation

For dipole and QF power supply with slower response, the system response matrix calculation is applied to infer the input from output. The impulse response is measured from as Eq. 2 and the system response matrix is constructed from impulse response as Eq. 3. The compensation for the next step is calculated as Eq. 4. Inverse matrix calculation is by SVD method. The number of how many eigenmodes should be corrected must be evaluated carefully to avoid instability. Normally, the first 20 to 30 eigenmodes is suggested in our QF case.

$$\mathrm{h(t)} = h_0\delta(t) + h_1\delta(t-1) + h_2\delta(t-2) + \cdots \quad (2)$$

$$RM = \begin{bmatrix} h_0 & 0 & 0 & \dots & 0 \\ h_1 & h_0 & 0 & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ h_n & h_{n-1} & \dots & 0 & 0 \\ 0 & h_n & h_{n-1} & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \dots & h_n & h_{n-1} \\ 0 & 0 & \dots & 0 & h_n \end{bmatrix} \quad (3)$$

$$setWf_{n+1} = setWf_n + RM^{-1}(refWf - getWf_n) \quad (4)$$

This scheme a little improves NRE of dipole and QF to 0.5% compared to the first scheme but it doesn't fall into tolerance. Besides, inverse matrix calculation and file load with the dimension of 3000*3000 takes much time. Latter it's observed that the major difference of output and input of the inverse matrix is only time delay or phase lag as Fig. 5. Therefore, the third scheme is thus developed.

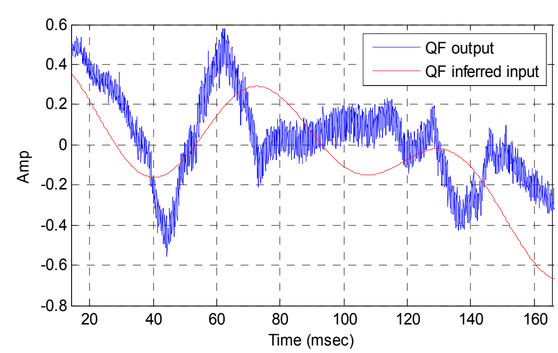

Figure 5: The inferred input (red) from output (blue).

Proportional and Time Shift Compensation

The formula of this scheme is as Eq. 5. The time delay parameter τ could be measured by response of each power supply respectively. It could achieve NRE around 0.2% after two to three iterations. Compared to the second scheme, it has better NRE, less calculation time and no instability problem caused by SVD computation. Moreover, the low pass filter is also applied to filter measurement err.

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$$setWf_{(n+1)}(t) = setWf_{(n)}(t) + refWf(t-\tau) - getWf_{(n)}(t-\tau) \quad (5)$$

The Figs. 6 & 7 shows the NRE is gradually decreased during three iterations of correction for Dipole and Q1 respectively. At injection point, the NRE could achieve 0.2 % as require.

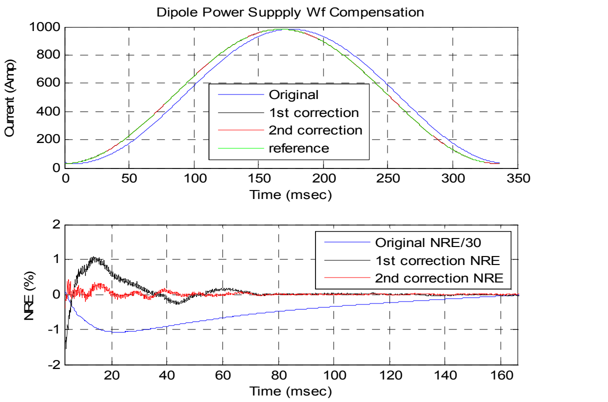

Figure 6: The upper plot is output waveform gradually closed to reference and the lower plot is NRE gradually decreased during three iterations of correction for Dipole.

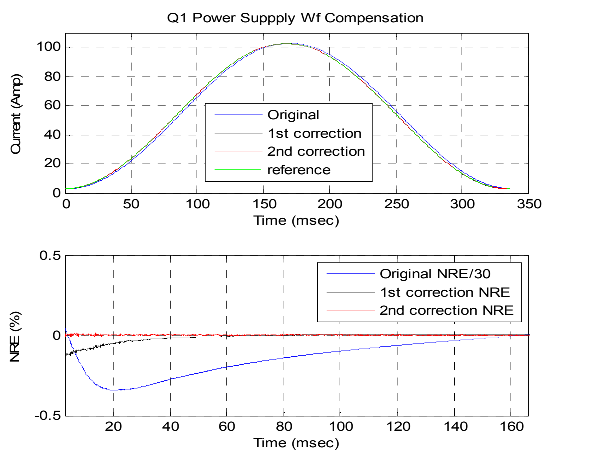

Figure 7: The upper plot is output waveform and the lower plot is NRE during three iterations of correction for Q1. It only required ones correction to achieve 0.2 % NRE.

BOOSTER RAMPING AND TUNE COMPENSATION

At Booster DC mode, corrector DC correction is required to circulate beam for the first turn. Beam was stored soon after tuning of RF parameters [4]. At Booster AC Mode, after booster power supply output waveform compensated closed to reference waveform, the beam could be ramped from 150 MeV to 210 MeV as Fig 8 shown. Beam loss at 210 MeV was due to vertical tune cross the resonance line 1/3 as Fig. 9 and it could also be observed that tune variation was as large as 0.25 for horizontal and 0.2 for vertical. It could be inferred that reference waveform generated from the measured I-B table provide by the magnet lab could be deviated from the actual machine. Therefore, the tune compensation had been done later so that beam had ramped to 3 GeV [4].

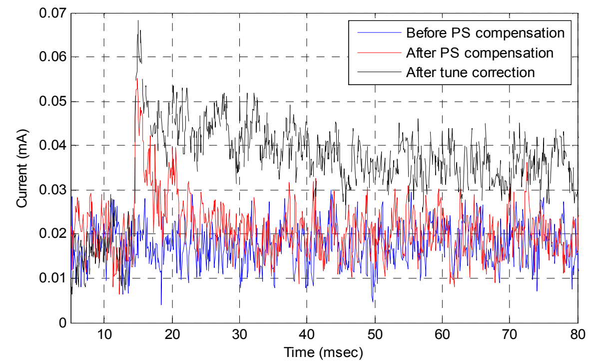

Figure 8: Booster beam current comparison before and after power supply waveform compensation and tune correction at single bunch mode.

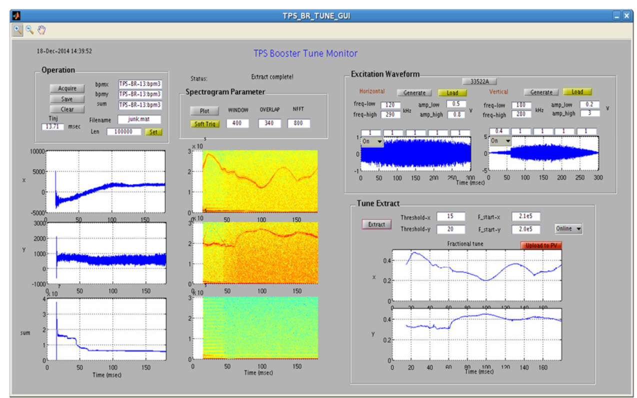

Figure 9: Tune monitor during Booster ramping before tune compensation. Vertical tune variation was as large as 0.25.

SUMMARY

Different response of booster power supply would result in unacceptable tracking error difference between dipole and quadrupole at injection during ramping. Several compensation schemes which modifying waveforms of booster power supply to fit the desired reference and reduced the NRE are presented in this report. Preliminary tests verify proportional and time - shift compensation scheme could effectively improve NRE to 0.2% for all dipole and quadrupoles power supply.

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