MODELING AND PERFORMANCE EVALUATION OF DCCTS IN SSRF*

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Abstract

Direct Current Current Transformer (DCCT) is the most commonly used high precision current monitor in modern particle accelerators including Shanghai Synchrotron Radiation Facility (SSRF). Three types of noise have been observed in the output signal of the DCCT in the storage ring of SSRF: power line noise, beam current related narrow band noise and random square wave noise from nowhere. This article will discuss the noise removal algorithms in SSRF and the performance of the DCCTs afterwards.

INTRODUCTION

As the biggest science research facility in China, SSRF has started user run with 7 beam lines since March, 2009. The whole facility contains a 150 MeV LINAC, a full energy booster and a 3.5 GeV storage ring and has offered 77200 hours' user time. Since the demand for the beam quality is being increasing with the growth of the user group, the accuracy of the measurement of the direct current (DC) component of the beam current has become particularly important.

According to the design requirements of the SSRF as a third generation light source, a high precision DC beam current monitor with the ranger greater than 400 mA and the resolution requirements for booster and storage ring are 50 μA@10 Hz and 10 μA@1 Hz respectively. The refresh rate of the DC beam current and the corresponding lifetime should not be lower than 1 Hz in order to keep the machine to operate normally.

The New Parameter Current Transformer (NPCT) sensor from the Bergoz Instrumentation has been evaluated at the SPEAR3.[1] NPCT175 with a resolution of 1 μA/$\sqrt{\text{Hz}}$ was chosen to meet the design requirements. Two DCCTs were positioned at section 15 and 17 and were named DCCT15 and DCCT17 respectively. The sensor is designed to be sensitive to the electromagnetic fields so that a shielding system is needed to isolate the sensor from the outside fields. The design of the shielding system was borrowed from SPEAR3 (see the exploded view in Fig. 1) since it seems rational enough and it is proved to perform competently on that machine.

The PXI bus industrial computer was selected as the input-output (IO) controller platform for its compatibility, stability, availability for various of IO boards and the CPU computing capability. In order to choose a proper digital voltmeter (DVM) module from the 4070 series of National Instrumentation (NI), a noise test was made between NI4070 (6.5 bit) and NI4071 (7.5 bit). Another test using the NPCT175 and NI4070 as a whole system was also processed. The result is shown in Fig. 2 and we can see that:

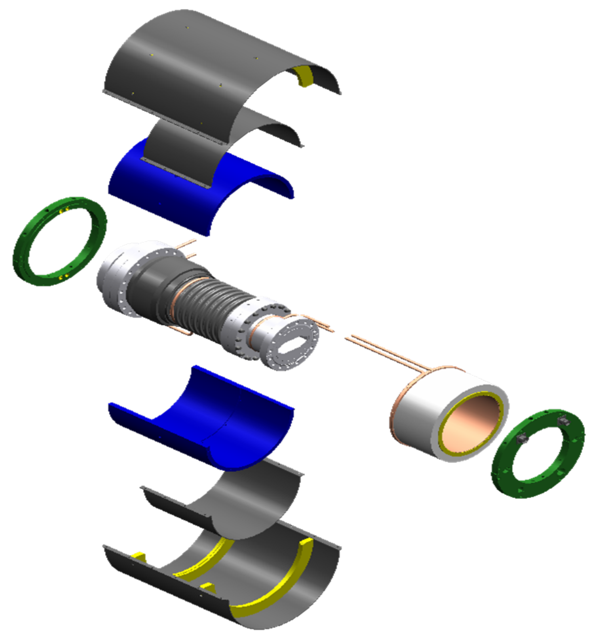

Figure 1: Exploded view of the shielding system designed by SPEAR3.

- The performances of NI4070 and NI4071 are quite close when the sampling rate is higher than 200 Hz;
- The noise of the DVMs—both NI4070 and NI4071—is much less than the NPCT-DVM system when the sampling rate is lower than 40 Hz which means the noise of the sensor has a great contribution to it;
- The performance of the NPCT-DVM system is close to that of the DVMs when the sampling rate is higher than 40 Hz.

The sampling rate was chosen to be a relatively high value of 10 kHz because showing more details of the beam current waveform was preferred, especially during the commisioning. NI4070 DVM was selected as the data acquisition module of the DC beam current monitor system since the performance of NI4071 wouldn't be significantly

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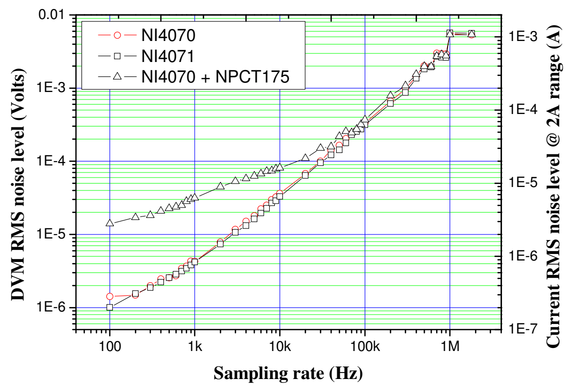

Figure 2: Noise test result of DVM and NPCT.

better. The PXI input-output controller (IOC) then fetches the signals from the DVM with the 10 kHz sampling rate. The 2 Hz data are also provided by averaging the raw signal waveform.

NOISE IN DCCT

Despite the elegant shielding design from SPEAR3, the DCCTs still suffers from various kinds of noise including narrowband noise, square wave noise and zero drift, etc.

Narrowband Noise

A waterfall plot (see Fig. 3) is a good tool to show narrowband signals with highlighted lines. At least 3 types of narrowband noise can be seen appearing in the DCCT system:

- power line noise (50 Hz) and its harmonics, which are stable all the time;
- other frequency specific noise, e.g., the one whose frequency is 1.147 kHz, but the amplitude varies through time;
- frequency drifting noise, e.g., the one whose frequency drifted from 4.4 kHz to 2.2 kHz.

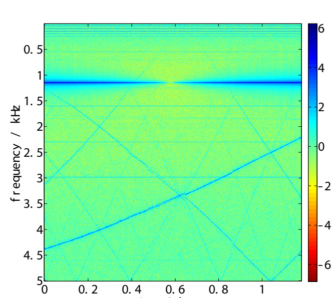

Figure 3: Waterfall plot of the spectrum of the DCCT.

A further study on the narrowband noise, as shown in Fig. 4, gives the fact that the amplitude of narrowband noise are approximately proportional to the beam current. Both DCCTs behave alike but DCCT17 seems more sensitive to the noise. This may due to the slight differences during the installation.

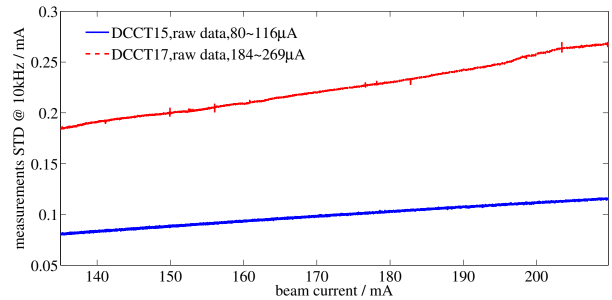

Figure 4: Amplitudes of the narrowband noise are approximately proportional to the beam current in both DCCTs.

Square Wave Noise

The square wave noise appears randomly without any warnings. This noise can be seen at every cycle for days and disappear for the next few weeks. We can see this noise approximately once a week, on the average. The noise always presents the shape of square waves with indefinite periods and fixed amplitudes ($-60\,\mu$A for DCCT17 and $-600\,\mu$A for DCCT15). The square wave noise has a great contribution to the measurement error. It affects the resolution of the system considerably, especially for lifetime measurements.

Performance Before Optimization

A comprehensive evaluation was made before any workarounds were applied as shown in Fig. 5. The DCCT15 has a better performance than DCCT17 does, due to the installation process. There's a great potential to enhance the system, although both DCCTs have already met the primary requirements.

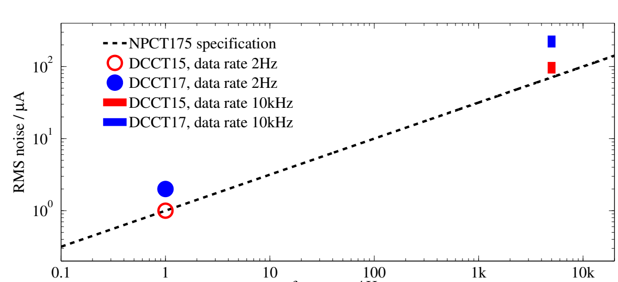

Figure 5: Amplitudes of the narrowband noise are approximately proportional to the beam current in both DCCTs.

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DCCT MODELING

After the analysis of the beam current monitor system in SSRF, the DCCT output is considered to contain:

- DC component of beam current (main signal),
- NPCT175 sensor noise,
- AC component of beam current and its harmonics,
- square wave noise,
- power line noise,
- other frequency specific noise,
- zero drift,
- DVM electrnoic noise.

Another experiment was made to try to determine where the narrowband noise came from. A reasonable guess would be that this noise should be invoked by the beam current for the linear relation between its amplitude and the beam current. A reverse 179 mA current was then provided to DCCT17 when the beam current is about 180 mA to cancel out the DC component. The spectra of the output waveform with or without the reverse current are shown in Fig. 6 to see whether the average current of the beam takes part in the noise. There're no significantly different results between those situations. This implies that the noise may be related to the alternative current (AC) component of the beam current or some kind of wake field.

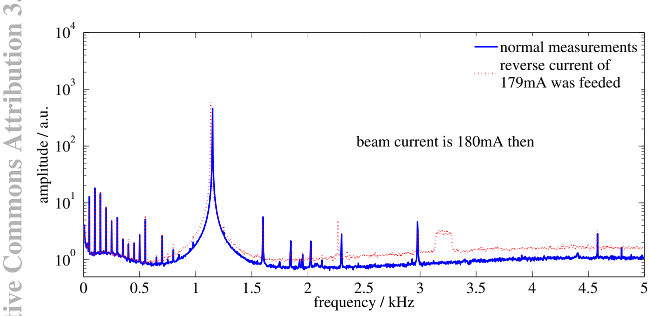

Figure 6: Comparion of the spectra.

The probability of appearance of the square wave noise seems current related to us. The DCCT data were archived for two weeks since June 11, 2012 in order to obtain a rough and qualitative conclusion. The absolute values of the difference data of the 2 Hz DCCT readings show that the square wave does not occur at the current lower than 197 mA (see Fig. 7). The distribution is quite interesting and it seems that the square wave "tends" to appear at some beam currents than others.

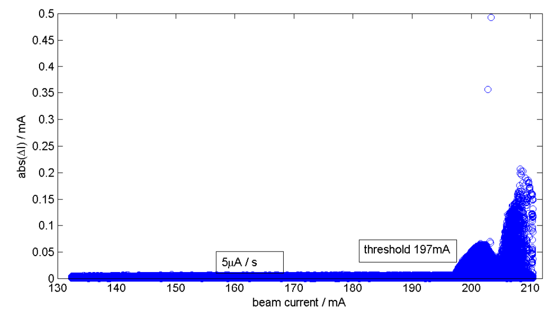

Figure 7: The square wave noise has a threshold and an interesting distribution.

WORKAROUND AND ACHIEVEMENTS

Since the frequency and the amplitude of the frequency drifting noise are both changing during the machine operating, an adaptive notch filter has been developed to trace the frequency and suppress the noise. The other narrowband noise can benefit from this filter as well. Another evaluation has been made after the notch filter was applied, the resolutions of DCCT15 and DCCT17 have been improved from about 100 μA and 200 μA to 12.4 μA and 30 μA, respectively, for the 5 kHz data as shown in Fig. 8.

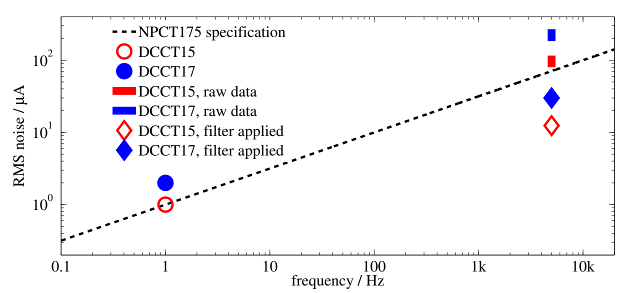

Figure 8: The resolution has a great improvement after using the adaptive notch filter.

The square wave noise does not seem easy to be removed with traditional time-domain or frequency-domain filtering means, so a discrete Kalman filter[2, 3] has been used to suppress this noise with its efficient computationial (recursive) means to estimate the state of a process by minimizing the mean of the squared error. This filter is very powerful for it can do estimations of states at anytime even the precise nature of the modeled system is unknown like our situation.

The resulting waveform is more satisfactory than had been anticipated. The standard deviation of the beam current measurement has been reduced from 53 μA to 6 μA for the 2 Hz data. The corresponding standard deviation of lifetime measurement has also been decreased from 1.052 hours to 0.168 hours.

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CONCLUSIONS

The combination of NPCT175 from Bergoz Instrumentation and PXI4070 DVM from National Instrumentation was chosen to meet the design requirements in SSRF. In order to screen the sensor from electromagnetic fields outside, the shielding system designed by SPEAR3 was applied. Various kinds of noise, including narrowband noise, random square wave noise and zero drift, still exist despite the elegant shielding design. An adaptive notch filter and a Kalman filter have been developed to minimize the system measurement error and the results are exciting. The narrowband noise has almost be suppressed to the electronics limit and the square wave noise has been filtered with little remaining.

Some other appreaches have also been tried, e.g., optimize the installation process to reduce the zero drift or use BPM sum signal as the replacement for the DCCT[4]. Anyway, those methods are merely stopgaps. We'll keep looking for the source of the noise and try to remove it from the roots.

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