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PERFORMANCE TESTS OF A DIGITAL LOW-LEVEL RF-SYSTEM AT THE TPS*

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Abstract

A digital low-level RF (DLLRF) control system for the cavity gap voltage is now common throughout the world. At the Taiwan Photon Source (TPS) we installed and operated a DLLRF in the booster ring in 2018 successfully and plan to install it also in the storage ring in 2019. Operational and beam loading tests of the DLLRF at the storage ring are ongoing. The performance of the DLLRF in the presence of a large number of 60 Hz harmonics and its stability for gap voltage and phase will be discussed.

INTRODUCTION

The TPS was designed to operate at 3 GeV, a frequency of 500 MHz, a gap voltage of 2.8~3.5 MV and a beam current of 500 mA. The normal operating beam current of the TPS is currently 400 mA with plans to test 500 mA in the second half of 2019. As the beam loading increases, the power loading of the RF system becomes severe and noise effects are expected to get worse. The LLRF of the TPS is now an analogue system and does not provide enough noise rejection to handle the heavy beam loading situation in the future.

After overcoming several difficulties, including non-synchronization phenomena due to jitters, cavity station phase shifts while the front end is turned on/off and the noise effect on the reference signal, we began to run beam loading tests with the DLLRF from the end of 2018 during machine study times of the TPS. First, the gap voltage stability for the digital and analogue systems are recorded through the same monitor device. Second, the frequency spectrum analyses and BPM results are compared between the digital and analog systems with 0 mA and 30 mA beam loading. Finally, high beam loading at 400 mA was tested and related phenomena monitored.

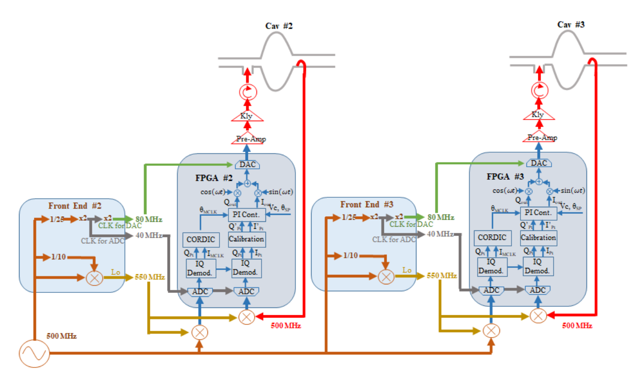

Figure 1: DLLRF architecture of the TPS storage ring.

DLLRF ARCHITECTURE

The TPS storage ring has two KEKB type super conducting cavities placed at two different straight sections. Each of them has an individual low-level system based on the DLLRF architecture of the TPS storage ring as shown in Fig. 1. The reference signal, MCLK from IC, goes into each front end to create various synchronized CLKs and Lo signals. It also is passed into the FPGA to participate in the IQ demodulating function and phase synchronization. The detailed work principle could be seen in our previous study [1]. The cavity gap voltage is controlled by setting the amplitude (V_c) and station phase (θ_{sp}). The station phase means the phase leads the MCLK by θ_{sp} degrees. Thus, the actual phase of the DAC output is regulated by the PI controller in order to lock the cavity phase to be equal the phase of the MCLK plus the station phase. By regulating the individual station phase of Cavity #2 and #3, the phase difference between both cavities is created by adjusting the injection efficiency and power balance.

STABILITY

The stability improvements of the DLLRF system will be discussed by comparing the variation and standard deviations of the RF amplitude and phase for the analog and the digital systems. The TPS storage ring operates at a total gap voltage of 2.8~3.5 MV or about 1535 kV for each cavity. The cavity electric field stability is monitored by a circular buffer function implemented in the FPGA of the DLLRF system. The monitor sampling rate is 6.14 kHz, the length of data is 2^{14} and the total time is 2.66 sec. The monitoring results of the analogue and digital system are shown in Fig. 2. The black and red lines are from the analogue and digital systems, respectively. For easy discussions, the results of the digital system are shifted with an offset of about 64 kV and 96° in amplitude and phase, respectively. In Fig. 2(a), the maximum amplitude variations of the analogue and digital systems are ±24 kV and ±4 kV. The maximum phase variations are ±1.07° and ±0.29° for the analogue and digital systems in Fig. 2(b). The standard deviations of the amplitude and phase were 0.48% and 0.313° for the analog and were 0.06% and 0.070° for the digital system.

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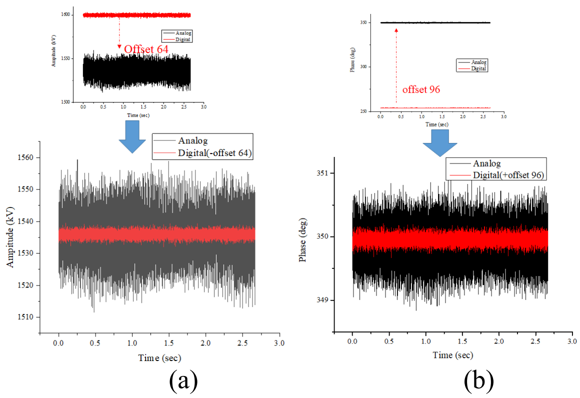

Figure 2: (a) Amplitude and (b) phase comparisons between analogue and digital system.

FREQUENCY SPECTRUM

Harmonics of 60 Hz and other noise sources are observed in the frequency spectra as shown in Fig. 3. From Fig. 3(a), we conclude that the strongest 60 Hz harmonic in the analog system was -50 dBc at 120 Hz with many more harmonics stronger than -65 dBc even at higher harmonics. Besides the 60 Hz harmonics, special signals at 3.12 kHz and 6.06 kHz could be found with intensities of -64.45 dBc and -59.11 dBc as shown in Fig. 3(b). The frequency of 3.12 kHz originates from some other storage ring subsystems. The frequency of 6.06 kHz comes from the rotation frequency of the pulse step modulator (PSM) in the transmitter. In the digital system, the strongest intensity of all 60 Hz harmonics was -78.57 dBc occurring at 60 Hz and there were only two other harmonics larger than -80 dBc as shown in Fig. 3(c). The signal of 3.12 kHz was reduced down to -85.37 dBc under digital controls as shown in Fig. 3(d). However, the digital system couldn't suppress the intensity of the PSM rotation frequency. Fortunately, the 6.06 kHz noise did not appear in the beam so far.

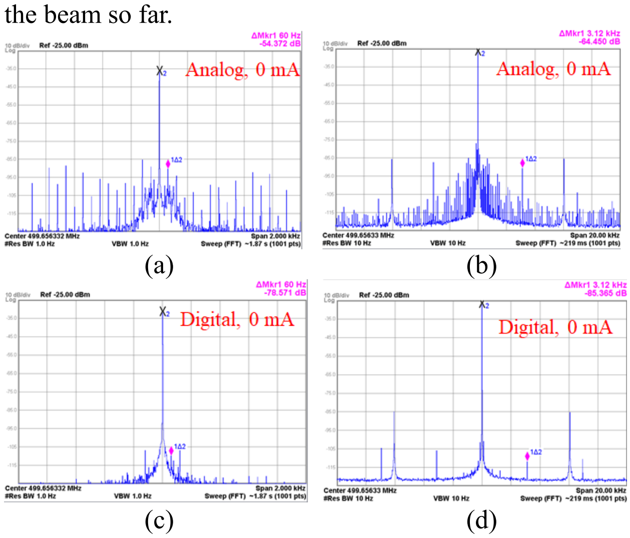

Figure 3: Frequency spectra of the cavity gap voltage for (a) the analog system with a 2 kHz span, (b) the analog system with a 20 kHz span, (c) the digital system with a 2 kHz span, and (d) the digital system with a 20 kHz span.

BEAM LOADING TEST

Since the DLLRF showed an outstanding suppression of 60 Hz harmonics for no beam loading, the test performance with beam loading was eagerly expected. A low beam loading test at 30 mA was done to compare the analogue and digital systems. The current of 30 mA is a specific beam loading used for orbit corrections at the TPS. Figure 4 shows the test results at 30 mA. The distribution of the noise from 60 Hz harmonics is similar to the no beam loading test results. However, the intensity at 3.12 kHz increased from -64.45 dBc to -53.00 dBc in the analog system but was still suppressed to -82.73 dBc in the digital system. The rotation frequency showed a little frequency offset when the DLLRF is adjusted by the PI controller.

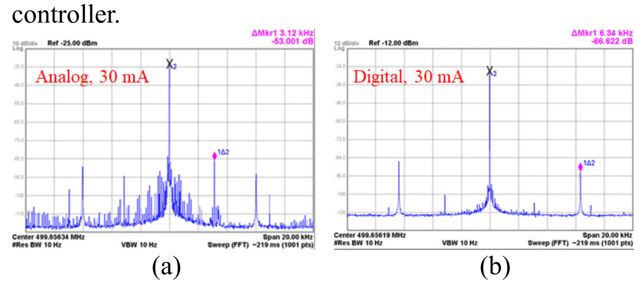

Figure 4: The frequency spectrums of (a) the analogue and (b) digital systems at 30 mA beam loading.

A variation of the cavity gap voltage affects the beam position via the dispersion effect as represented by BPM results. Figure 5 shows the results of BPM014 data analyzed by a Fourier transform in the range from 1 Hz to 4 kHz based on the analysis principle referred to by the study of Huang et al. [2]. In Fig. 5(a), much noise existed at frequencies over 500 Hz in the horizontal plane for the analog LLRF but did not appear in the digital LLRF. The suppression of 3.12 kHz equaled the phenomena shown in the frequency spectrum. The digital LLRF had a good suppression at 3.12 kHz. The cavity gap voltage did not directly induce a disturbance of the beam in the vertical direction. Thus, the beam position showed only a small improvement at 60 Hz and 120 Hz with the digital LLRF as shown in Fig. 5(b). The phenomena at low frequencies might have come from devices located near the SRF cavity or transmitter through interference. The little improvement at low frequencies also indicates that the main disturbance did not come from the SRF system.

High beam loading tests were done and the injection efficiency reached 85% after fine tuning of the station phases for both SRF systems. For more details of the parameter tuning please refer to the article of Liu et al. [3]. The frequency spectra of the cavity gap voltage with 200 mA and 400 mA beam current are shown in Fig. 6, where in 6(a) and 6(b), it can be noted that the signal at 6.34 kHz is larger than that for 8.3 kHz for a beam current of 200 mA, but is just the opposite for 400 mA. While increasing the beam current, the intensity of 8.3 kHz increases. This could lead to an oscillation of the gap voltage, cause a beam trip and could be an obstacle to achieve a beam

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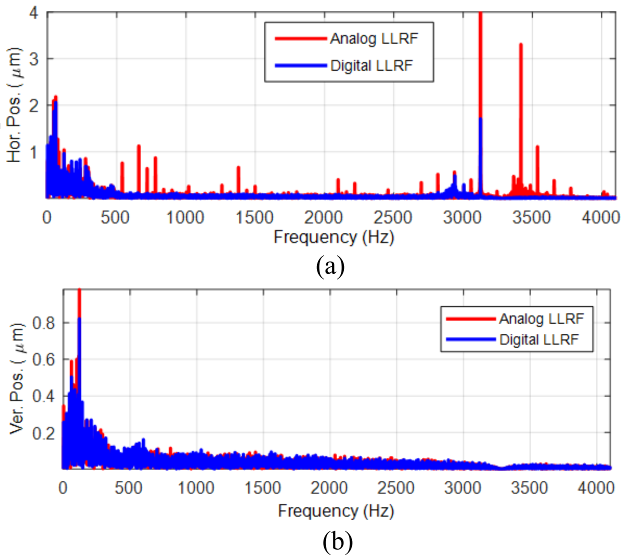

Figure 5: BPM results in the range of 1 Hz to 4 kHz in (a) the horizontal and (b) vertical plane.

current of 500 mA. Turning off the trace average of the spectrum analyzer, the 8.3 kHz signal was up to -64.5 dBc as shown in Fig. 6(c). This phenomenon didn't appear in the analog system thus it might be characteristic for the PI controller in the digital system. Fortunately, it could be fixed by fine tuning the k_I of the PI controller. In Figs. 6(c) and 6(d), the intensity at 8.3 kHz decreased from -64.50 dBc to -71.80 dBc when k_I was changed from 0.0151 to 0.0128.

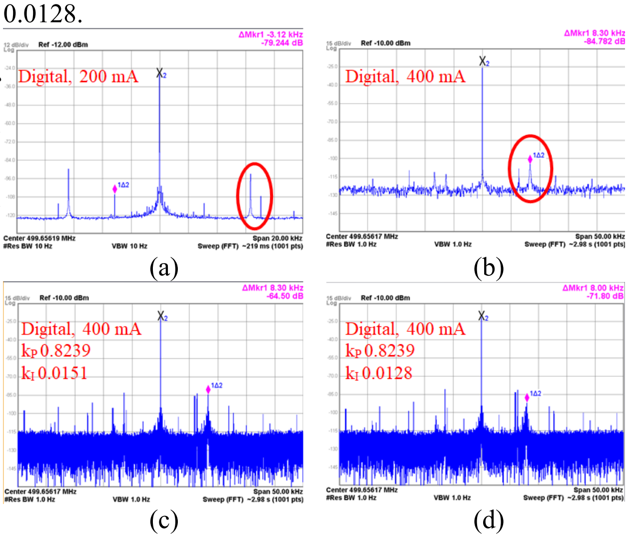

Figure 6: Frequency spectra of the digital system with trace average at (a) 200 mA and (b) 400 mA and without trace average at 400 mA while (c) k_I 0.0151 and (e) k_I 0.0128.

CONCLUSION

Based on results of spectrum analyzes, the DLLRF system shows an outstanding suppression capability for 60 Hz harmonics. The maximum variation of the gap voltage and phase are ±4 kV and ±0.29° and their standard deviations are 0.06% and 0.070°, respectively. From Fourier transform results of BPM data, we found that the DLLRF also improved the beam position perturbance at 60 Hz harmonics. The test to store a beam current of 400 mA with the DLLRF at the TPS was successful. For beam currents of over 450 mA, however, we had some unstable situations with the new DLLRF system. Solving these problems should allow us to reach the desired maximum beam current of 500 mA.

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