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A NEW BEAM LOADING COMPENSATION AND BLOWUP CONTROL SYSTEM USING MULTI-HARMONIC DIGITAL FEEDBACK LOOPS IN THE CERN PROTON SYNCHROTRON BOOSTER

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Abstract

As part of the LHC Injectors Upgrade, the CERN Proton Synchrotron Booster (PSB) has been upgraded with new wide-band Finemet cavities and a renovated Low-Level Radio Frequency system with digital cavity controllers implemented in FPGAs. Each controller synchronously receives the computed revolution frequency, used to generate 16 harmonic references. These are then used to IQ demodulate the voltage gap and modulate the 16 RF drive signals each controlled through a Cartesian feedback loop (with individual voltage and phase control). The sum of these digital drive signals is then sent to the cavities. In addition, a configurable blow-up system providing a sinusoidal or custom noise pattern can be used to excite the beam. An embedded network analyzer allows studying the stability of the feedback loops of the individual harmonics. The 16 harmonic feedback loops have been successfully operated during 2021, allowing to reduce the beam induced voltage and control the longitudinal emittance of the beam. In this paper we present the system architecture as well as the performance of the complete cavity controller during operation in the PSB.

INTRODUCTION

The Low Level Radio Frequency (LLRF) system of the CERN Proton Synchrotron Booster (PSB) has been significantly upgraded during the Long Shutdown 2 (LS2) as part of the LHC Injectors Upgrade project [1]. In order to cope with the new wide-band Finemet™ cavities [2], the new LLRF system is capable of controlling the phase and amplitude of 16 harmonics of the revolution frequency, and includes extra functionalities not present in the previous system.

The LLRF system of the PSB has been conceived to be fully modular, meeting the accelerator architecture. This system belongs to a family of LLRF systems used to operate several machines at CERN [3]. An overview of the system architecture can also be found here [4].

The PSB consists of 4 superposed rings with 3 straight sections used for Radio Frequency (RF) cavities. The High Level Radio Frequency (HLRF) system provides a single RF drive and voltage gap monitor signal for each ring and straight section. The cavity controller feedback loops in the LLRF system have been designed to cope with these 12 systems individually.

As already shown in simulations [5] and during the previous beam tests [4], the induced voltage in the cavities would compromise the longitudinal stability of the beam. Thus, a precise system including individual phase and magnitude control of the voltage in the cavity is required.

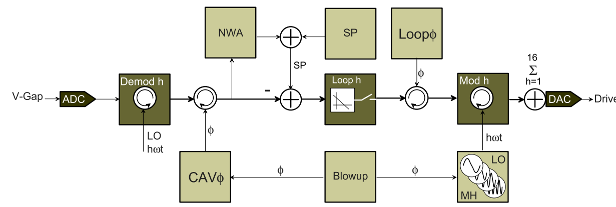

Figure 1: Building blocks of the multi-harmonic digital feedback system implemented in FPGA. Demodulator, feedback loop and modulator blocks are replicated 16 times.

SYSTEM ARCHITECTURE

Figure 1 shows an overview of the multi-harmonic digital feedback loops implemented in Field-Programmable Gate Arrays (FPGA). The voltage gap is digitized with a fixed frequency clock at about 122.7 MHz. This signal is digitally demodulated into 16 IQ pairs using a multi-harmonic source. For each harmonic, there is a cavity rotator allowing to individually control the cavity phasing. These are used to compensate different delays of the gap return cables of the different cavities. Moreover, it is used to set the phase of the RF signal in the cavities to be same in the 3 straight sections as perceived by the beam.

The setpoint (SP) of the feedback loop is set using a voltage function for each individual harmonic. The loop rotator allows using a phase function for each individual harmonic to insure loop stability. This rotator subtracts the cavity rotator phase in order to make both controls independent. The setpoint generation includes a limiter to avoid driving the cavities beyond their operating frequency range or setting a setpoint beyond the voltage acceptance limits. It also provides a mechanism to ramp the voltage up or down when an overflow condition is detected.

IQ values produced after the loop rotator arrive at the modulator, which applies a feed-forward compensation in gain and phase before up-modulating them using the corresponding harmonic local oscillator signal. All harmonics are then summed digitally and converted to the analog RF drive signal sent to the HLRF system.

Multi-harmonic Source

In order to increase the regulation bandwidth (decrease electronics delay), reduce cabling and optimize the resources usage, all harmonic feedback loops for the same cavity

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are implemented in the same device, by means of a multi-harmonic local oscillator (MHLO) source [6].

This MHLO source relies on the synchronous distribution of the revolution frequency over the 3 boards controlling the voltage in one ring. The implementation has been carefully chosen to minimize the FPGA resources and to ease the timing closure.

Fixed Frequency Clock Operation

Another fundamental change in the implementation paradigm of the new digital LLRF system for the PSB is the introduction of fixed frequency clock operation scheme [7], being already used in other machines of the same LLRF family [3].

While traditionally, LLRF systems have been using a sweeping frequency clock following the revolution frequency changes, the new LLRF system in the PSB uses a fixed frequency clock scheme having, among others, the following advantages:

- No need to use a complex Digital Direct-Synthesizer (DDS) scheme.
- Digital converters operated at their optimal frequency.
- Harmonic distortion out of band. Maximum oversampling ENOB gain.

However, a reliable Frequency Tuning Word (FTW) distribution and absolute synchronism between system-wide Numerically Controlled Oscillators (NCO) are required. Special care has been taken to filter aliasing bands while keeping a constant gain over the whole frequency range.

Feed-forward Compensation

For a good feedback loop stability, the RF drive is changed in a feed-forward manner compensating gain and phase. This system allows to cope with gain and phase non-linearities across the complete chain: from RF drive to voltage gap monitor. Through this, the closed-loop gain and phase margins can be optimized.

The feed-forward compensation tables are computed by measuring the gain and phase response of the system in the whole frequency range. This measurement is only performed during commissioning as the response is expected to remain the same. At system initialization, the values of these tables are populated in the hardware.

The frequency step size is selected in order to cover the whole operating frequency range, as the number of rows in the tables is constant. Four values are stored for each row in the table: gain, gain slope, phase and phase slope. During operation, for each frequency value of each harmonic, a set of gain and phase compensation values are computed by interpolation.

An example of feed-forward compensation values is presented in Fig. 2. In this example, measurement values have been taken between approximately 975 kHz up to about

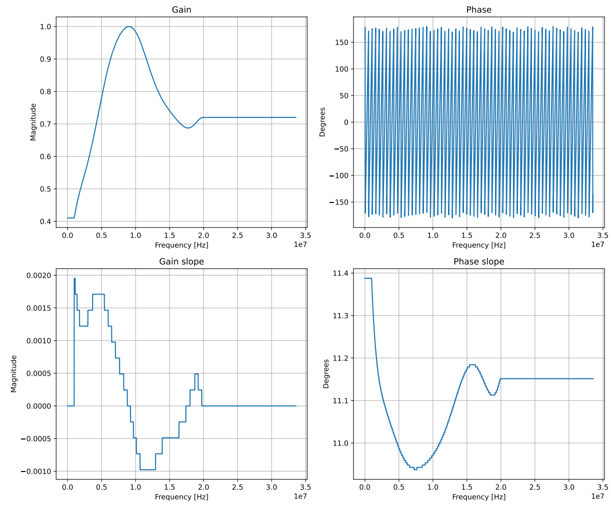

Figure 2: Example of the values of an operational feed-forward compensation table. The gain and phase compensation values are computed for different frequency values. The slope values are used for interpolating the actual gain and phase corrections.

20 MHz. Outside of the measurement range, the phase values are extrapolated. Other values are kept constant to the last measured value. Gain values are normalized at the maximum gain, having other frequencies attenuated to obtain a constant system gain. Phase values continuously wrap around the minimum and maximum phases (180 degrees) as expected.

Embedded Network Analyzer

A new feature of the PSB LLRF system is the embedded network-analyzer. This mechanism allows measuring the closed loop response by injecting a controlled modulation around the main carrier frequency in addition to the setpoint (see Fig. 1). The acquired response can be then used to evaluate the loop stability. The embedded network analyzer can be used on any harmonic.

An example of network analyzer acquisition is shown in Fig. 3. From the acquired data (in closed-loop), the open-loop response and the gain and phase margins can be computed. The feedback loops for all the harmonics have been scanned over different frequencies in the range of operation in order to optimize all loop parameters.

Longitudinal Blow-up

The new longitudinal blow-up mechanism allows introducing a phase modulation with a sinusoidal or noise pattern excitation imposed on the RF drive signal being sent to the cavities. The blow-up system acts at the MHLO source by modifying the phase of all the reference signals for the different harmonics. The configuration includes the frequency and amplitude of the modulation as well as the moment in the accelerator cycle to be applied. It can also be configured to be applied to a specific harmonic, via the cavity rotator previously presented.

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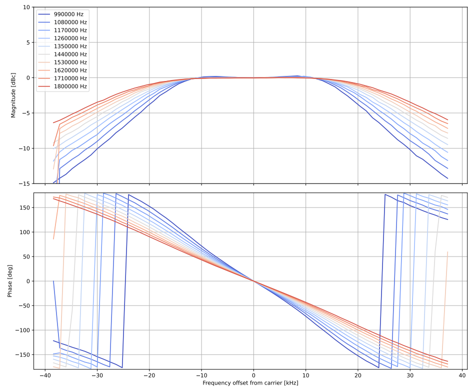
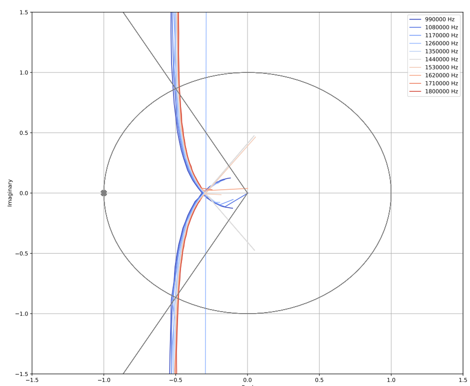


(a) Closed-loop response



(b) Computed open-loop response

Figure 3: Embedded network analyzer acquisition and computation of open-loop response. The average gain margin is 10.24 dB whereas the average phase margin is 60.10 degrees.

When exciting the MHLO source, the resulting RF waveform will preserve its shape. In contrast, when using an individual harmonic, the blow-up system will change the RF bucket shape. Currently, the PSB is being operated with sinusoidal modulation on harmonic 10 whereas other blow-up mechanisms are being investigated [8].

COMMISSIONING AND OPERATION RESULTS

During the commissioning of the new LLRF system in the PSB [8], new feedback loops were put into operation. For the first time, 16-harmonic feedback loops were capable of controlling the electric field in the Finemet™ cavities and successfully reduce the induced voltage in the cavities. As an example, Fig. 4 shows the difference on the detected voltage on harmonics 3 to 16 when operating without and with the 16-harmonic feedback loops. This figure shows the successful removal of the induced voltage in the cavities, and therefore a better control of the beam. This scheme has allowed producing all operational beams with the required beam characteristics within the LHC Injectors Upgrade project.

While measuring the response of the system and optimizing the feedback loops configuration, improvements on the HLRF system were identified [9]. These modifications have been shown to have a more stable system response, which would allow for optimizing the loops responses and their stability.

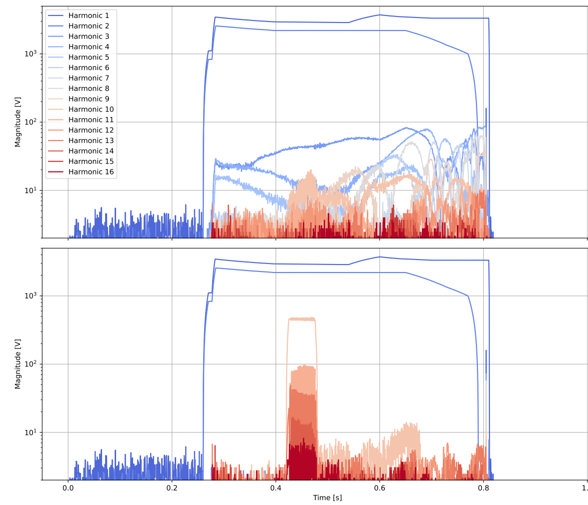


Figure 4: Detected voltage of one cavity when enabling only harmonic 1 and 2 feedback loops (upper figure) or 16 loops (lower figure). When all loops are enabled the blow-up phase noise contribution can be observed in harmonic 10. The beam intensity during this measurement was about 95 10^{10} protons per bunch.

CONCLUSION

A new system for precisely controlling the RF voltage in the PSB cavities has been put in operation during LS2. This system includes 16-harmonic feedback loops for a better suppression of the induced voltage in the new wide-band Finemet™ cavities, which have also been put in operation during this period. New features have been added in order to provide a better control of the longitudinal emittance of the beam and an easier system configuration and diagnostics.

In the future, an optimization of the loop configurations is foreseen with the modified HLRF system. New features will also be available as required.

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