COMMISSIONING OF THE LHC LOW LEVEL RF SYSTEM REMOTE CONFIGURATION TOOLS*

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Abstract

The LHC Low Level RF system (LLRF) is a complex multi-loop system used to regulate the superconductive cavity gap voltage as well as to reduce the impedance presented by RF stations to the beam. The RF system can have a profound impact on the stability of the beam; a mis-configured RF system has the potential of causing longitudinal instabilities, beam diffusion and beam loss.

To configure the RF station for operation, a set of parameters in the LLRF multi-loop system have to be defined. Initial system commissioning as well as ongoing operation requires a consistent method of computer based remote measurement and model-based design of each RF station feedback system.

This paper describes the suite of Matlab tools used for configuring the LHC RF system during the start up in Nov2009-Feb2010. We present a brief overview of the tool, examples of commissioning results, and basics of the model-based design algorithms. This work complements our previous presentation [1], where the algorithms and methodology followed in the tools were described.

INTRODUCTION

The LHC Low Level RF system (LLRF) is resident in multi-VMS crates near the RF power stage of the RF stations, 120m underground in a location relatively un-accessible without beam and completely un-accessible with beam in the machine and magnets energized.

The complexity of the feedback loops around the RF stations requires the setting of multiple parameters in the LLRF, to control the accelerating voltage in the cavities and minimize the impedance presented to the beam. An effective way to set those parameters is to calculate them based on a real mathematical model of the RF station. As such, the design of the feedback loop involves the identification of the RF station model and the calculation of the LLRF parameters based on the identified model. Criteria used to set the LLRF parameters include the stability of the system (beam dynamics, RF stations) and the overall performance of the RF station. Some of these criteria could include the minimization of the interaction between the beam dynamics and the cavity impedance, minimization of the impact of both perturbing signals and noise in the accelerating voltage on the beam dynamics. In order to set the LLRF parameters to fulfil these requirements, a suite of Matlab tools has been developed to interact with the resident hardware in the RF stations. In addition to the model-based design of the feedback systems, these tools operate remotely becoming critical due to the restricted access to the LHC cavern when the magnets are energized.

RF CONFIGURATION TOOLS: OVERVIEW

The architecture of the LHC RF station is depicted in Fig. 1. Details of its design and implementation are described in detail in [2]. The LHC LLRF is a Cartesian feedback system. The RF accelerating voltage is demodulated to base-band In-phase and Quadrature phase signals (IQ signals).
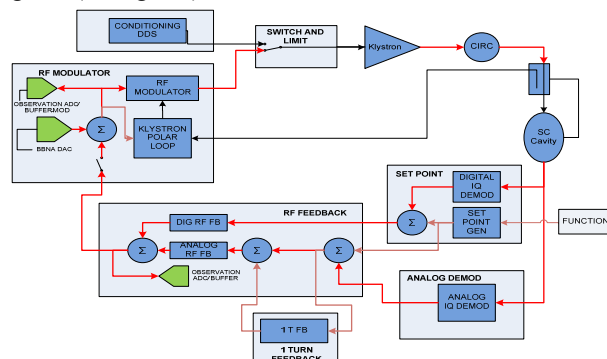

Figure 1: Simplified LHC RF station block diagram

These IQ signals are processed and then modulated back on to an RF carrier which is fed via a klystron back into the superconductive accelerating cavity. The LLRF is composed by several modules including a direct loop and the one-turn delay feedback that process the voltage cavity signals to minimize the interaction between the beam dynamics and the RF station impedance and set the voltage per RF station. The direct loop combines a digital path to set high gain in the low frequency base-band spectrum and an analog high frequency path to minimize the delay in the processing channel. The LLRF also includes a polar feedback loop around the power klystron to set its operation point and reject the klystron power supply ripple signals perturbing the RF cavity accelerating voltage.

To completely set the LLRF and the RF station, it is necessary to follow a procedure that is nearly automated by the remote configuration tools [1]. This procedure follows a sequence of steps as follows:

- Compensate off-sets in analogue path and modulator
- Compensate the phase difference between analogue and digital paths in the direct loop module.
- Identify notch filter in LLRF to compensate spurious klystron resonance.
- Measure klystron spurious resonance and set the notch filter in LLRF board.

- Identify open loop transfer function of the RF station and set the LLRF parameters for closed loop operation.
- Identify klystron polar loop dynamics and set polar loop parameters.
- Identify closed loop transfer function of the RF station and based on the open loop model extracted, set the LLRF parameters for closed loop operation.
- Identify the one-turn delay filter and set its parameters.

The three first steps involve the measurement of the LLRF modules and require manual changes of the RF station configuration. Those steps are not fully remote but are usually necessary only after a change of board in the LLRF system, requiring an access to the cavern area where the RF station in located. The rest of steps require minimum change in the RF station topology and are fully remote. The procedure described is generic and shows all the features included in the LLRF configuration tool. The final operation point of the RF station in closed loop can either be performed by measuring and identifying the RF station model with the station in either open loop or closed loop, depending upon the present operation of the RF station.

Network Analyzer: Identification of transfer functions.

Almost all the functions in the RF configuration tools are based on the identification of a transfer function between two different points in the system. This measurement technique is based on a base-band network analyzer (BBNA) built-in the LLRF hardware [1][3]. The technique consists in injecting a time domain random sequence through a particular defined DAC and measuring the time response of the circuit using a determined ADC (e.g., Fig. 1, BBNA DAC, observation ADC buffer). Based on those time domain signals, the transfer function of the system between the injection point and the measurement point is estimated calculating the quotient between Cross Power Spectral Density of the output and the input signals and the Power Spectral Density of the input signal. This estimator defines the transfer function $H_{meas}(\omega)$ for a given frequency span. In order to have a mathematical model of the measured system, a linear model $H_{model}(\omega)$ is fit to $H_{meas}(\omega)$ using a gradient descent optimization algorithm with a weighted least squared metric. The hardware contains several signal injection and measurement points in various locations of the RF station circuitry to estimate and model the particular transfer function necessary in the configuration process. More details about this implementation are described in [1].

RF CONFIGURATION TOOLS: RESULTS

In this section, the operation and results of different steps of the RF configuration tool will be presented. The

first two steps: Compensate off-sets in the analog path and modulator and Compensate phase difference between analogue and digital path in the direct loop module have been discussed in [1] with particular results. We will expand on those features of the RF configuration tool not presented in previous paper.

Measurement of the Klystron Spurious Resonance

The klystron spurious resonance is estimated by measuring the transfer function of the power klystron in a baseband span from -6MHz to 6MHz. For this remote measurement, the RF station is set in open loop (switch open in Fig. 1 and the klystron polar loop is in open loop) the BBNA input signal is injected in the modulator and the klystron output is measured via the ADC in RF Modulator. The klystron transfer function measured $H_{meas}(\omega)$ and the fitted model $H_{model}(\omega)$ are depicted in Fig. 2. The resonance frequency is estimated from the parameters of the mathematical model $H_{model}(\omega)$ and it is used to set the proper capacitance value in the LLRF notch filter such that its transfer function is the best cancelation of the klystron spurious resonance.
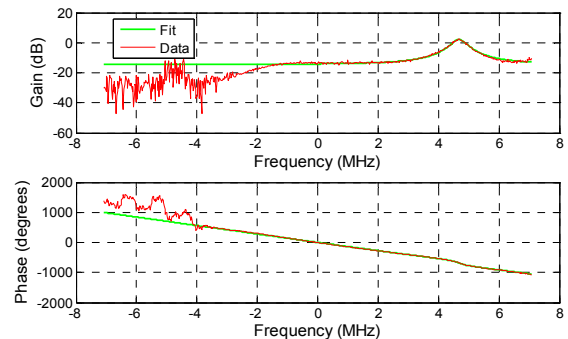

Figure 2: Klystron transfer function : Measured and fitted model

Identification of the Open Loop-Closed Loop Transfer Function of the RF Station.

The measurement of the open loop transfer function of the RF station is conducted by opening the switch in Fig. 1 and injecting the BBNA input signal trough the modulator. The open loop response is measured using the observation ADC in the RF Modules. The $H_{meas}(\omega)$ in baseband includes the contribution of both the LLRF and the high power RF components. Fig. 3 shows an example of the measured and the fitted mathematical model for the open loop transfer function of the LHC RF station 5, beam 1. In this case, the one-turn delay filter is not included in the system.

Similarly, the closed loop transfer function of the RF station is measured using the same configuration for the BBNA but the switch in Fig. 1 is closed. The measured and the fitted model for the closed loop transfer function of the LHC RF station 1, beam 1 is depicted in Fig. 4, for

the case where the one-turn delay filter is not included in the system.
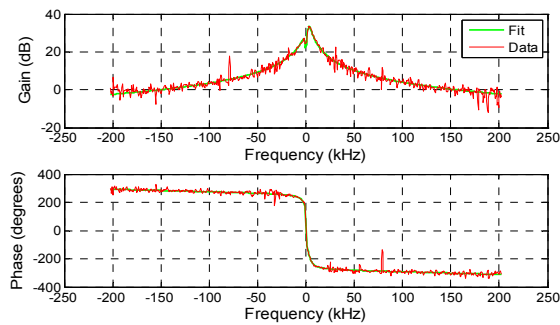

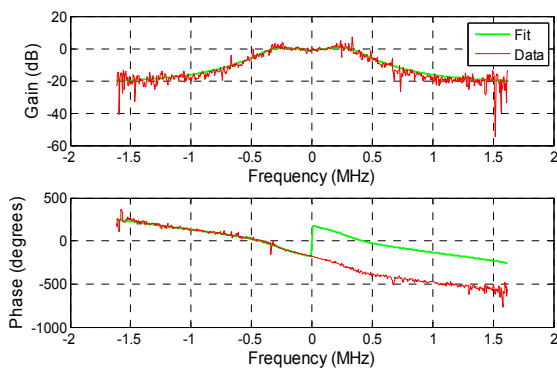Figure 3: RF station open loop transfer function : Measured and fitted model

Figure 4: RF station closed loop transfer function : Measured and fitted model

Identification of Klystron Polar Loop Dynamics and Setting the Polar Loops Parameters.

The klystron polar loop is an inner loop in the LLRF system to set the klystron operation point and reject signal perturbations from klystron power supply in the accelerating cavity voltage. Two parameters are adjusted in the polar loop to set the closed loop bandwidth at approximately 10KHz.
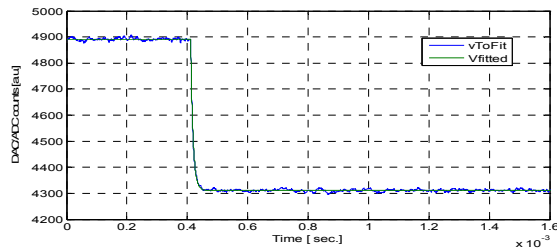

Figure 5: Klystron Polar Loop, step response in the gain channel : Measured and fitted model

The procedure starts with an identification of the klystron polar loop dynamics using a step function as stimulus signal. Based on a reduced linearized model of the polar loop, the dynamics is estimated and the loop parameters are adjusted to set the correct bandwidth. Fig.

5 shows the measured step response of the gain channel and the response predicted by the reduced model.

Setting the LLRF Parameters for Closed Loop Operation of the RF Station.

The LLRF system regulates the cavity accelerating voltages and reduces the cavity impedance presented by RF stations to the beam. The direct loop (analogue and digital paths) has different parameters to fulfil those requirements. The gain in the digital path is adjusted 20dB above the gain set in the analogue path to improve the RF station voltage regulation around the carrier frequency. The gain and phase of the direct loop is set based on the mathematical model of the open loop transfer function of the RF station so that the closed loop remains stable and fulfil the performance criteria. These criteria minimize the interaction between the RF station impedance with the beam dynamics for robust stability conditions defined by the gain and phase margin.

Identification of the one-turn delay filter and Setting its Parameters.

For stable operation at high currents, the LHC RF stations include a one-turn delay filter in the LLRF system to reduce further the interaction between the beam dynamics and the RF station impedance. The LLRF system regulates the cavity accelerating voltages and reduces the cavity impedance presented by RF stations to the beam in narrow bands around the revolution frequencies. This filter is characterized by three parameters, where two of them are adjusted by the RF configuration tool after identifying the mathematical model of the complete RF system.

CONCLUSIONS

We have presented an overview of the RF configuration toll and results from the commissioning of the RF station during Nov2009-Feb2010. These tools have been critical to configure remotely the LHC RF stations after the more strict CERN access rules to the LHC rings.

REFERENCES

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