Nuclear Instruments and Methods in Physics Research A 795 (2015) 399–408

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

An offset tone based gain stabilization technique for mixed-signal RF measurement systems

Gopal Joshi [a,*], Paresh D. Motiwala [a], G.D. Randale [a], Pitamber Singh [a], Vivek Agarwal [b], Girish Kumar [b]

[a] BARC, Mumbai 400085, India
[b] IIT Bombay, Powai, Mumbai 400076, India

ARTICLE INFO

Article history:
Received 8 November 2014
Received in revised form
11 May 2015
Accepted 8 June 2015
Available online 19 June 2015

Keywords:
Offset tone
RF gain stabilization
RF instrumentation and control of accelerators

ABSTRACT

This paper describes a gain stabilization technique for a RF signal measurement system. A sinusoidal signal of known amplitude, phase and close enough in frequency is added to the main, to be measured RF signal at the input of the analog section. The system stabilizes this offset tone in the digital domain, as it is sampled at the output of the analog section. This process generates a correction factor needed to stabilize the magnitude of the gain of the analog section for the main RF signal. With the help of a simple calibration procedure, the absolute amplitude of the main RF signal can be measured. The technique is especially suited for a system that processes signals around a single frequency, employs direct signal conversion into the digital domain, and processes subsequent steps in an FPGA. The inherent parallel signal processing in an FPGA-based implementation allows a real time stabilization of the gain. The effectiveness of the technique is derived from the fact, that the gain stabilization stamped to the main RF signal measurement branch requires only a few components in the system to be inherently stable. A test setup, along with experimental results is presented from the field of RF instrumentation for particle accelerators. Due to the availability of a phase synchronized RF reference signal in these systems, the measured phase difference between the main RF and the RF reference is also stabilized using this technique. A scheme of the signal processing is presented, where a moving average filter has been used to filter out not only the unwanted frequencies, but also to separate the main RF signal from the offset tone signal. This is achieved by a suitable choice of sampling and offset tone frequencies. The presented signal processing scheme is suitable to a variety of RF measurement applications.

1. Introduction

Even in a primarily digital implementation of an RF signal measurement system, a small yet critical analog front-end is required. Any drift effects, e.g. due to temperature, humidity, aging effects, etc. of the components in this analog section will cause a change in gain and/or phase, thus degrade the measurement quality. To counter these drift effects, a compensation technique utilizing a calibration tone based gain equalization has been employed for particle accelerator instrumentation and control systems, especially, for precise beam position monitors, where the gain of two or four analog channels has to be free of drift effects to ensure an accurate measurement of the beam position. In these systems, the calibration tone signal is divided in equal parts and added, i.e. superimposed to the input of the RF processing channels. Relative drifts in the measurement channels result in a difference of magnitude and/or phase of the demodulated calibration tone. A correction factor is deduced to compensate the measured error. In pulsed systems, the calibration tone can be of same frequency as that of the measured RF signal [1]. In continuous wave systems, the frequency has to be close to but different from the RF signal at the main input [2,3]. However, these systems do not intend to measure a well calibrated absolute value of the RF signal magnitude, still they perform a very stable, reliable measurement over long periods of time, thanks to the gain equalization. A double side band suppressed carrier (DSBSC) signal method has also been established to cancel out the phase difference between two signal processing channels [4]. The DSBSC signal is split and added to the two RF paths at suitable points. The phase of both offset tones contained in the DSBSC signal is measured at the end of these two paths. In this technique, the frequencies of both calibration tone signals are symmetric, below and above the frequency of the RF signal to be measured. Under the assumption that the average value of the phase of the two tones gives the phase of the RF paths at the frequency of the RF reference signal, one can compute and correct for phase differences between the two paths. Phase drift between the two

* Corresponding author.
E-mail addresses: gjos@barc.gov.in, gopaljos@gmail.com (G. Joshi).

http://dx.doi.org/10.1016/j.nima.2015.06.015
0168-9002/

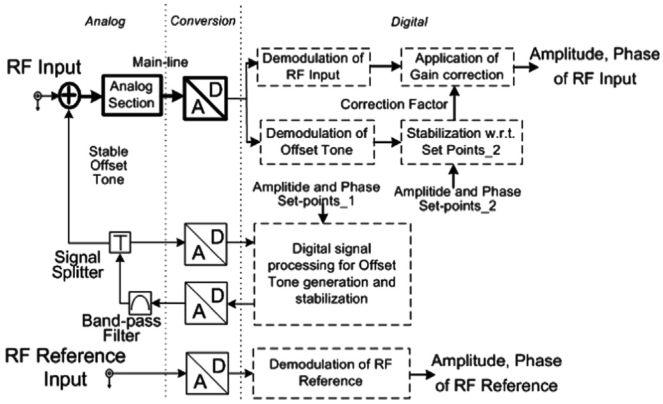

Fig. 1. Block diagram of offset tone based gain stabilization of main-line.

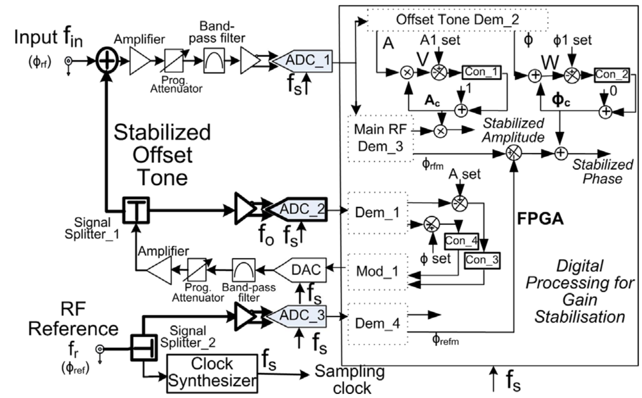

Fig. 2. System Architecture – Offset tone based Gain Stabilization. A stable offset tone is added with the main RF signal at the input of the analog section. The stabilization of the injected offset tone in the main-line is carried out in the digital domain.

channels of 15 mdeg has been measured at 2856 MHz using this technique, which is being used in the low level RF system of SPX [5].

Fig. 1 shows a simplified block diagram explaining the technique proposed in this paper. The objective is to stabilize the measured values of amplitude and phase of input RF signal in digital domain against drift in the analog section and the digitizer, shown in block in the figure. In order to achieve this, an offset tone is generated and stabilized in amplitude and phase with respect to 'set-points_1' using a feedback loop, which spans both analog and digital domains. This stable offset tone is added to the main RF signal at the input of the analog section of the main-line. In the digital domain the offset tone is separated out from the main RF input and demodulated. The amplitude and the phase of the demodulated offset tone signal are stabilized with respect to set-points_2, to counteract the drift of the analog section and the digitizer in the path of the main-line. The correction factor required during this stage of stabilization of the offset tone, is also applied to the demodulated main RF signal, which passes through the same analog section and the digitizer. This stabilizes the measurement of the magnitude of the main RF signal. If an RF reference, synchronized to the input RF signal, is available, then the measured phase difference between the RF signal and the RF reference can also be stabilized. This point is explained in detail in Section 2.

The signal processing described above achieves a stable gain for the RF signal measurement system. This feature gives the opportunity to perform an absolute measurement of magnitude and phase of the RF input signal with the help of a simple calibration procedure. The technique is especially suited for direct-conversion systems, as the overall stability of the system requires just a few simple broad-band RF components of high inherent quality, i.e. long term gain and phase stability over a wide temperature range. This point is also explained in detail in Section 2.

2. Principle of operation

Fig. 2 shows a detailed block diagram of a RF measurement system using an offset tone based gain stabilization. The RF input section is optimized for a frequency f_{in} of the RF input signal to be analyzed. The RF input signal passes through this analog section before digitization by ADC_1. Essential features of this section are – programmable gain and filtering. An offset tone at frequency f_o is generated by updating the DAC with a periodic sequence, such that the output of the DAC contains a component at frequency f_o. This component is separated out by filtering the output of the DAC using a band-pass filter. A signal splitter is used to feed both, ADC_2 for stabilization, and the main RF input with this stabilized offset tone. For the later, a coupler is used to superimpose the offset tone to the RF-signal, indicated in Fig. 2 by a '+' sign. The offset tone is stabilized at two stages. At the first stage the objective is to generate a stable offset tone at the input of the signal splitter_1 against the variations in the offset tone generation circuit. To achieve this, amplitude and phase of the offset tone at the input of ADC_2 are demodulated in Dem_1. These are stabilized with respect to the settable references 'A set' and 'ϕ set', respectively. This is achieved with the help of feedback loops, which span both analog and digital domains. In modulator Mod_1, the outputs of the controllers Con_3 and Con_4, modulate the amplitude and the phase of the otherwise periodic sequence, which is used to generate the offset tone. At the second stage the objective is to stabilize the offset tone as received at the output of the main-line. To achieve this, amplitude and phase of the offset tone demodulated in Dem_2, at 'V' and 'W' in Fig. 2, are made equal to settable references 'A1 set' and 'ϕ1 set', respectively. This is achieved by multiplying the demodulated offset tone by a complex correction factor, ($\boldsymbol{A_c}$, $\angle\boldsymbol{\phi_c}$), in the digital domain. As shown in Fig. 2, this complex correction factor is generated with the help of feedback loops, which are entirely in the digital domain.

The stability of the gain (magnitude) of the two branches emanating from the signal splitter, which are shown in block in Fig. 2, is ensured by careful design. Under this condition, the processing described above achieves a settable and stable gain (magnitude) in the main-line, based on mag(G_o) of the offset tone, which is proportional to the ratio of set points 'A1 set' and 'A set' and is given by

$$\text{mag}(G_o) = \Delta_A \frac{\text{A1set}}{\text{Aset}}. \tag{1}$$

where Δ_A is the ratio of the magnitudes of offset tone at the output of ADC_2 to that injected into the main-line of ADC_1.

The stabilization of the phase of the main-line signal processing imposes additional requirements in the system implementation and signal processing. For the phase stabilization of the main-line with respect to the offset tone, the phase difference of the offset tone measured after digitization by ADC_1 and ADC_2, should be free from uncertainty introduced due to the sampling process and in the phase difference measurement. If the same clock source is used for sampling of ADC_1 and ADC_2, and the phase of the offset tone in the demodulators Dem_1 and Dem_2 is measured with respect to a common reference signal, this uncertainty basically vanishes. Under these conditions the phase of the main-line signal processing is stabilized based on the phase of the offset tone, pha(G_o), which is given by

$$\text{pha}(G_o) = \phi\text{1set} - \phi\text{set} + \Delta_\phi. \tag{2}$$

where Δ_ϕ is the difference in the phase of the offset tone at the input of ADC_2 and the injected offset tone in the main-line.

In order to stabilize the gain of the main-line for the main RF input signal, the correction factor, ($\boldsymbol{A_c}$, $\angle\boldsymbol{\phi_c}$), is also applied to the