LINEARIZATION OF DOWNCONVERSION FOR IQ DETECTION PURPOSES*

M. Grecki, W. Koprek, S. Simrock, DESY Hamburg

Abstract

The downconverter used in LLRF control system is a nonlinear device, thus not only the fundamental frequency but also its harmonics are present and sampled by ADC. The levels of higher order harmonics depend on the level of RF signal. For a downconverter used in FLASH LLRF system the harmonics are 30dB below the fundamental frequency component (in the worst case - at maximal RF signal level). These harmonics produce errors in IQ detector of up to a few percents in amplitude and one degree in phase. This paper contains the analysis of the error and propose the calibration method allowing to obtain the correction curve for detected amplitude and phase.

INTRODUCTION

Measurements of effective RF (Radio Frequency) field parameters (amplitude and phase) are of great importance in high-energy accelerators. For future XFEL linac the RF field must be regulated with precision of order of 0.01% and 0.01deg in amplitude and phase respectively [1]. In current FLASH [2] installation the RF signal is downconverted to Intermediate Frequency (IF) but keeping the information about amplitude and phase. The IF signal is then sampled in ADC (Analogue to Digital Converter) and processed in digital IQ detector computing the I (In phase) and Q (in Quadrature) components (the I and Q can be used further to obtain amplitude and phase [3]). The future LLRF system in FLASH will be using IF=9 MHz or even higher in order to move the signals away from electromagnetic noise present at surroundings. The process of downconversion is a nonlinear, not only the fundamental frequency but also its harmonics are sampled by ADC, causing errors in field detection. The errors caused by nonlinearity of the downconverter used in FLASH were investigated.

ANALYSIS OF DOWNCONVERTER NONLINEARITY

The downconverter used for field detection in FLASH LLRF system is an AD8343 chip based one. Each downconverter board consists of eight downconversion channels with common LO (Local Oscillator) input.

The dependency of downconverter output signal characteristics for variable RF signal level were measured using a programmable attenuator and a stable RF source. In order to obtain high stability of all required signals, the MO (Master Oscillator) with additional circuit for LO generation was used. The block diagram of measurement setup is presented in figure 1. The required measurement conditions were:

- stable and related phase RF and LO signals
- phase characteristic of attenuator measured before

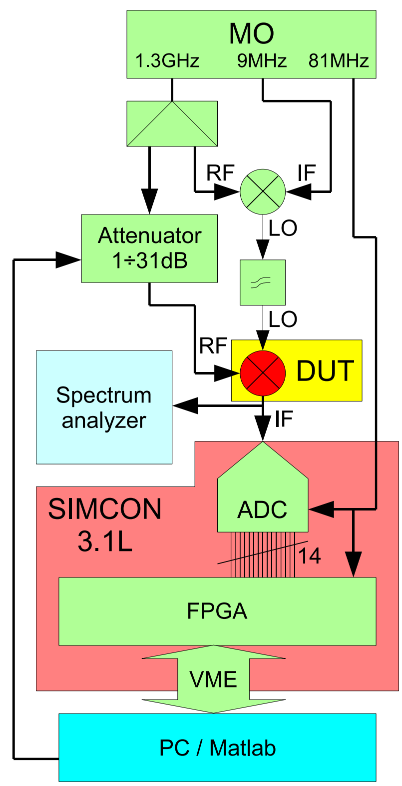

Figure 1: Block diagram of measurement setup.

For data acquisition the SIMCON3.1L board was used [4] and for spectral analyzis of IF signal a R&S FSP was used.

Measurements Results

The dependency of IF signal on RF level was identified using programmable attenuator and spectrum analyzer. Figure 2 presents the IF signal spectrum obtained for maximum input signal (0dBm).

Similar measurements were performed for different RF signal levels in the range 0 ÷ -31dBm. The measured harmonics for different input signal levels are presented in figure 3 (discrete points).

The downconverter output signal contains fundamental frequency and 4 significant harmonics (higher order har-

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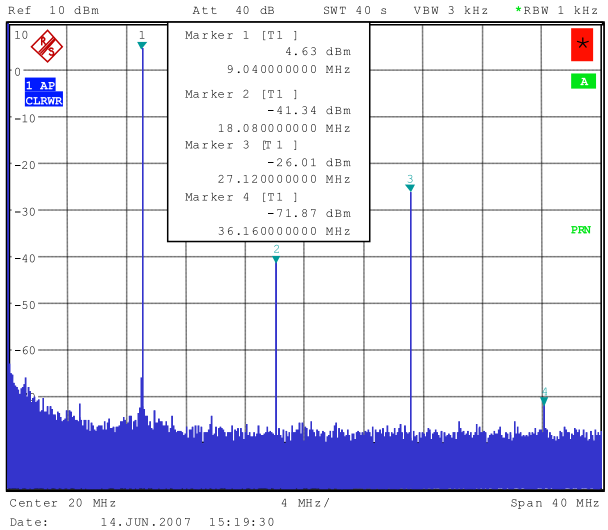

Figure 2: Spectrum of downconverter output signal (for RF level 0dBm).

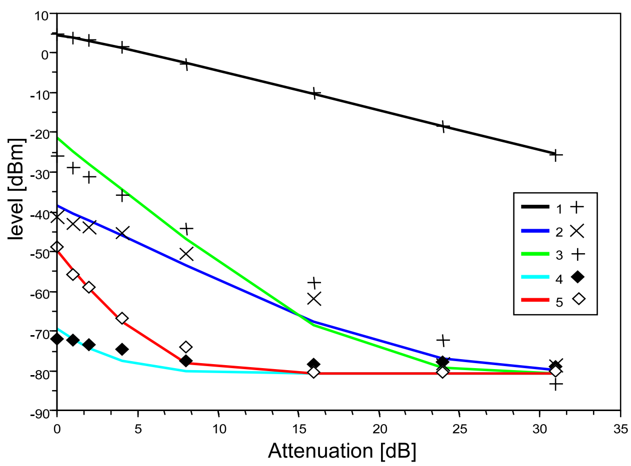

Figure 3: Results of downconverter nonlinearity measurements (solid points) and fitted of harmonic levels depending on signal level. The X-axis corresponds to attenuation of the input signal.

monics were covered by noise level). The harmonics levels depend strongly on input signal level. Unfortunately, the contradiction exists between the optimal operational conditions for low nonlinearity and noise level. The ADCs also should work utilizing majority of the input signal range. Therefore, downconverter operation with high signal levels resulting nonlinear behavior is unavoidable.

Downconverter Model

In order to analyze the downconverter behavior the simple model consisting of ideal mixer, nonlinear transfer block and noise source were proposed (figure 4).

The nonlinear transfer block was approximated by polynomial of the order 5.

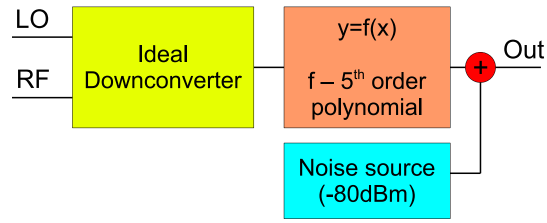

Figure 4: Model of downconverter.

$$y = a_1x + a_2x^2 + a_3x^3 + a_4x^4 + a_5x^5 \qquad (1)$$

The polynomial coefficients were identified by numerical algorithm fitting the measurement data to the nonlinear function. The comparison of the measurements data to the model is presented in Figure 3.

The polynomial is not perfect approximation of the downconverter nonlinearity. The model foreseen lower levels of 2nd and 3rd harmonics than it is measured for moderate attenuation (-15dB). However, as the model is a simple one it is well suited for further analysis.

IQ DETECTION OF DOWNCONVERTED SIGNAL

The final goal of the signal processing is to calculate the amplitude and phase (or I and Q components) of the RF field. Since, the IF signal consist of not only fundamental frequency but also higher order harmonics it is desirable to know how the harmonics, interfere with IQ detection. The IQ detection algorithm [5, 6] uses series of signal samples taken by ADCs synchronously with IF frequency (integer number of sampling frequency periods must fit in integer number of IF signal periods). One of the crucial point is to calculate I and Q with possibly low latency, thus, using as few samples as possible. The lowest number of samples for the IQ detection algorithm [5] is 3. However, using only 3 samples one makes the higher harmonics of the signal to overlap with fundamental frequency caused by aliasing phenomena. The aliasing makes that the fundamental frequency can not be distinguished from the overlapping harmonics and harmonic contribution gives an error that can be large with respect to the LLRF system requirements [1]. The harmonics aliased to the fundamental frequency creates superposition of rotating vectors (figure 5). Each vector rotates with frequency related to the harmonics number. The vector trajectory can be complicated in case when harmonics levels are high and several of them must be taken into account .

It can be easily shown that when the IF signal contains the harmonics up to the fifth one, the minimum number of samples must be 7 in order to avoid aliasing of harmonics with fundamental frequency. That means, the latency of the IQ detection algorithm expands significantly (over 2 times comparing to the minimum).

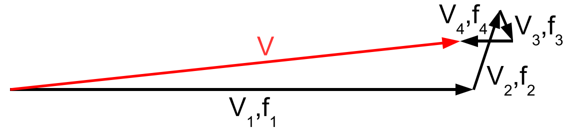

Figure 5: Superposition of field vectors comming from fundamental frequency and harmonics of IF signal. The measured vector V is a superposition of vectors V_i rotating with frequency f_i.

Knowing the relationship between parameters of downconverter (e.g. the phase of each harmonics when sample is taken) one can compensate the phase and amplitude error caused by harmonics and calculate the field vector corresponding to the fundamental frequency. If all V_2, V_3 and V_4 are known (figure 5) then the V_1 can be restored form the measured value V. Fortunately, using the IQ detection method [5, 6], the sampling process is perfectly synchronized with IF signal and the harmonics have constant phases in relationship to the fundamental frequency when the sample is taken. Therefore it is possible to develop correction tables that can be used for linearization of downconverter. The hardware implementation in FPGA will use the 2-dimensional lookup table with measured amplitude and phase as the indexes. The contents of this table is the phase and amplitude correction factors that modify the measured amplitude and phase. Both corrections can be made by addition of the correction value thus avoiding costly multiplication.

Since the relationships between harmonics depend on sampling time moment the downconverter must be calibrated together with ADC and clock distribution system.

LINEARIZER CALIBRATION

The idea of calibration of downconverter together with ADC and clock distribution system is based on sampling with high sampling rate and computation of amplitude and phase using variable number of samples. For example, if the IF=9MHz and sampling rate is 81MHz the amplitude and phase can be computed using 9 successive samples and also using only 3 samples taking every third sample (in this case the effective sampling rate is 27MHz). The difference between results is a correction value for sampling rate of 27MHz since 9 samples allows to compute the I and Q without errors generated due to aliasing the fundamental frequency with harmonics (for harmonics numbers from 2 up to 7). The figure 6 presents the phase calibration curve obtained for the real downconverter and ADC used in FLASH LLRF. It can be noticed that error caused by downconverter nonlinearity exceeds 0.1deg for RF signal level grater than -7dBm. Therefore in normal operating conditions of downconverter this level of error must be expected without linearization.

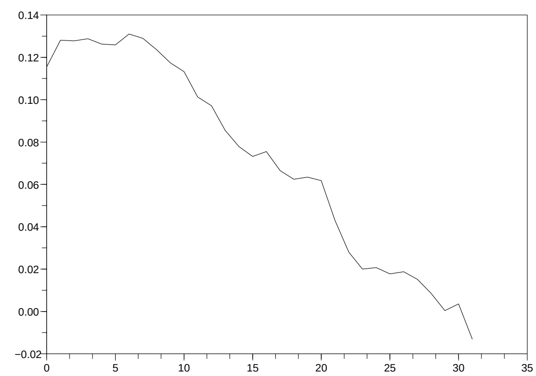

Figure 6: The phase correction dependency on RF signal level (measured in setup from figure 1). X-axis - RF attenuation [dB], Y-axis - phase [deg.]

CONCLUSION

In this paper the analysis of errors generated by nonlinear operation of downconverter was presented. The simple model for downconverter nonlinearity was proposed and fitted to the experimental data. The method of nonlinearity compensation was proposed basing on simulations made using this model. The simple method for downconverter calibration (estimation of correction tables) was suggested and implemented. In the future (after upgrade of downconversion scheme) this method will be implemented in the LLRF control system for FLASH.

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