High Power Amplifiers Chain Nonlinearity Influence on the Accelerating Beam Stability in Free Electron Laser (FLASH)

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Abstract—**The high power amplifiers transfer characteristics nonlinearities can have a negative influence on the overall system performance. This is also true for the TESLA superconducting cavities accelerating field parameters control systems. This Low Level Radio Frequency control systems uses microwave high power amplifiers (like 10 MW klystrons) as actuators in the mentioned feedback loops. The amplitude compression and phase deviations phenomena introduced to the control signals can reduce the feedback performance and cause electron beam energy instabilities. The transfer characteristics deviations in the Free Electron Laser in Hamburg experiment have been investigated. The outcome of this study together with the description of the developed linearization method based on the digital predistortion approach have been described in this paper. Additionally, the results from the linearization tool performance tests in the FLASH's RF systems have been placed.**

Index Terms—**High power amplifiers, klistron, AMAM, AMPM, linearization, digital predistortion, Free Electron Lasers .**

I. Introduction

Free electron lasers projects realized in Europe include linear accelerators built on the base of superconducting cavities technology. In the superconducting accelerator structures the electron beam is accelerated to relativistic velocities. The niobium resonators are fabricated according to the TESLA technology rules. In such facilities as FLASH, European X-FEL the single cryo-module comprises eight cavities. One to four cryomodule are powered by one RF station. The electromagnetic wave (generated from a microwave power amplifier – klystron) is sent to cavities through waveguides system. Due to particular accelerator sections power consumption requirements this 5 or 10 MW electron tubes are often working near to its limits. The nonlinearities that are present in this region of work are also decreasing the performance of LLRF control system feedback loop. Mentioned feedback loop is responsible for accelerating field parameters optimization in the cavities. The high power klystron together with two others microwave amplifiers act as actuators in this loop. The nonlinearities transfer characteristics have negative influence on the electron beam energy stability and though can cause degradation of the generated Free Electron Laser light parameters.

For that reason the high power amplifiers characterization, nonlinearities recognition and transfer characteristics linearization influence on the electron beam stability have been studied. Although the nonlinearities may not be critical issue in case of the FLASH accelerator RF stations control the influence on the LLRF loop performance and accelerating electron beam energy stability should be evaluated.

II. The nonlinearities measurement in FLASH

Nowadays the FLASH, Cryo-Module Test Stand (CMTS) and future European X-ray Free Electron Laser (X-FEL) are or will be equipped with the new complex diagnostic system. The system's main goal is High Power Amplifiers Chain (HPAC) components output monitoring (see Fig. 1).

As long as each of the HPAC device can introduce deviations to RF signal (such as signal compression or unwanted phase shift) – the access to each chain point should be provided. Currently installed systems consist of four channels: vector modulator output (forward signal), first preamplifier output (forward signal), second preamplifier output (forward signal), klystron output (forward and optionally reflected signal).

From each output, the RF signal is decoupled. The amplitude is adjusted to the working range of down-converters (in order to avoid its saturation). The 1.3 GHz signal is converted to lower frequency (for FLASH - 250 kHz). The signal representing envelope of RF signal carries important information about the amplitude and the phase of the control loop driving signal. Afterwards the analog to digital conversion takes place (depending on technical implementation for instance for FLASH - 1 MHz) in ADC's of the field controller and achieved result is converted to in In-phase (I) and Quadrature (Q) co-ordinates representation.

Described system together with the developed and implemented software tools create an environment which allows the system user to measure amplitude and phase transfer characteristics, on-line signal levels and shapes monitoring and others.

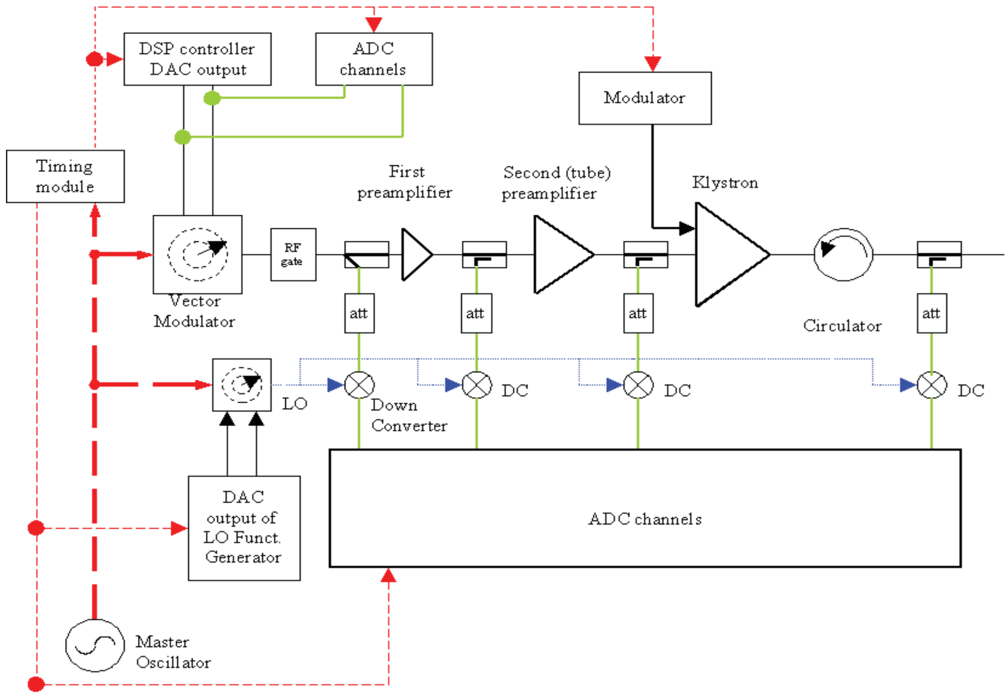

Figure 1. An overview of the setup of diagnostics system for HPC.

III. Transfer characteristics linearization

Various methods for the high power microwave amplifiers linearization are used in the different HPA applications areas (high power electronics, telecommunications etc.) [3],[4]. The most efficient and commonly used approaches are:

- feed forward – together with nonlinear HPA smaller error amplifier is used in order to reduce compression and phase distortion caused by the device nonlinearities,
- Linear amplification with Nonlinear Components LINC – in this solution two analogical devices with similar disturbances are used for the nonlinearities cancellation [cox]
- polar/Cartesian feedback – the control loop is established around the nonlinear device in order to reduce the nonlinearities phenomena,
- analog/digital predistorter – based on the measured system nonlinearities (or system model) corrected input signal is generated in order to counteract already recognized characteristics imperfections.

Presented solutions features has been collected and compared with each other (see Table I).

From the analysis of proposed comparison one can conclude that the digital predistorter is the most preferable linearization solution for the HPC in the RF systems of FLASH's accelerator. Moreover this solution can be easily integrated with the regular LLRF feedback loop controller.

Although successful analog solutions of predistorter have been realized in many systems [5] the digital based one offer improved performance required by modern linearity specifications and allows for linearizer adaptation to changing work parameters.

TABLE I. Different linearization methods comparison.

	Feed-forward	LINC	Feedback	Predistortion
Linearization accuracy	High	High	High (dependent on implementation)	High (dependent on implementation)
Implementation cost	High	High	Low	Low
Implementation complexity	High	High	Low	Low
Adaptation to different work conditions (HV level change)	Difficult	Difficult	Easy	Easy (transparent to the accelerator work)
Influence on the external feedback loop	Low	Low	Strong (limits LLRF feedback performance)	Low
Maintenance cost	High	High	Low	Low (only software maintenance)
Reconfiguration	Difficult	Difficult	Easy	Easy

The predistorter requires the definition of the amplitude and phase distortions in order to introduce the correction's to the amplifiers input signal. The data for the linearization tool can be achieved by means of the characterization or modeling of the device non-linearity. The data from the mentioned study may be used in different tool configurations. Basing on the well defined and precise models of the HPA nonlinearities the predistorter device that always precedes HPA provides amplifier's command signal correction in order to achieve linear behavior of the linearized amplifier. Generally when the magnitude of the amplifier gain decreases the predistorter gain increases and the phase of it is inverse of the HPA phase. Thus perfect tool solution performance is achieved for constant gain and phase characteristics. The predistorter can linearize amplifier's transfer functions up to the saturation level. Amplifiers installed in the FLASH accelerator though rarely achieve saturation level. The acceptable power levels for the superconducting cavities limit klystron outputs. That is why the predistorter developed for this implementation linearize the transfer characteristics up to the given limit.

A. Predistorter configuration

In the simplest configuration the digital predistorter consists of the mapping block. Device input signal coordinates (such as In-phase and Quadrature) are used to index look-up tables stored in the memory. This tables provide specific I' and Q' response of the predistorter. Output signal that contains information about the system distortions (in function of the input amplitude) is a signal that modulates carrier wave. The waveform prepared in such a way is the input signal to the nonlinear HPA. The capacity of the look-up tables required for storing mapping parameters may cause implementation challenges. For instance 18 bits resolution signals (as it is currently implemented in the LLRF Simcon DSP based field controller) would require tables of 247e10 size. For that reason an optional approach has been proposed. The solution using the complex multiplication and the interpolation of the intermediate values of the I and Q correction's (see fig. 2) has been developed. Proposed solution allows the significant table size reduction down to 32 words (18 bits) without significant increase of the correction signal quantization error.

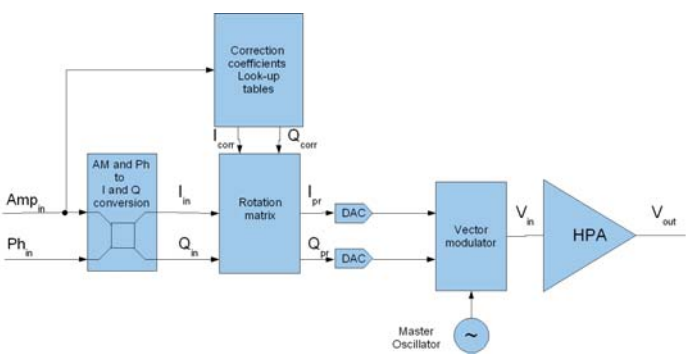

Figure 2. Overview of the predistorter configuration.

The amplitude of the system input signal has been taken as an address for the correction coefficient look-up table. The Icorr and Qcorr components of a result vector are the inputs to the rotation matrix. The complex multiplication of two vectors (Iin, Qin) and (Icorr, Qcorr) is executed there. Finally rotated and scaled input vector is achieved. This signal is modulated for the carrier signal in and applied to the input of HPAC.

B. The linearization in RF system of first accelerating module

The linearized high power chain consists of 5 MW klystron (produced by Thales) and 400W microwave tube preamplifier. It supplies 8-cavities cryo-module.

The study has been performed for following work conditions: cathode HV pulse level – 122 kV, RF pulse duration 750 us, output power limit about 1,44 MW, amplitude set point at the level of 10.68 MV/m (that corresponds gradient achieved in the cavity 5 at the level about 20 MV/m).

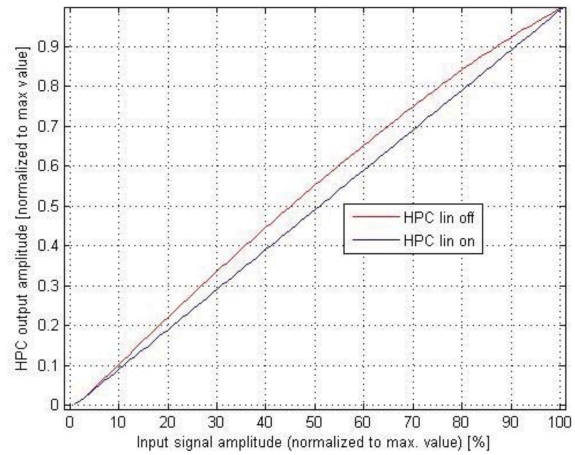

Figure 3. Amplitude transfer characteristic of HPC (ACC1) during test.

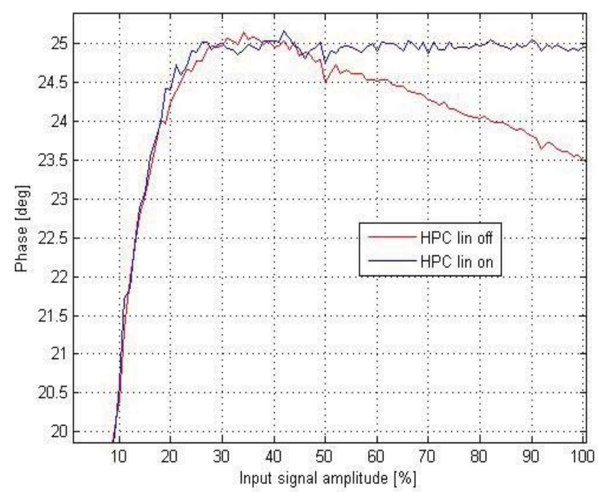

Figure 4. Phase transfer characteristic of HPC (ACC1) during test.

The nonlinearities measured for the given conditions have been shown in figures: amplitude transfer function – fig 3 and phase transfer function – fig 4.

It has been noticed that standard deviation from the linear characteristic has been 2 orders of magnitude smaller in case of LLRF loop working with predistorter. This study for the phase characteristics has shown error reduction by factor of 3. It has to be emphasized that work improvement has been demonstrated for the operating point located far from the saturation .

Additionally amplitude error during the RF pulse flat-top has been measured for the feedback loop gain in the range up to the 144 – in case where linearization was off and up to 136 – with linearization on (fig 5).

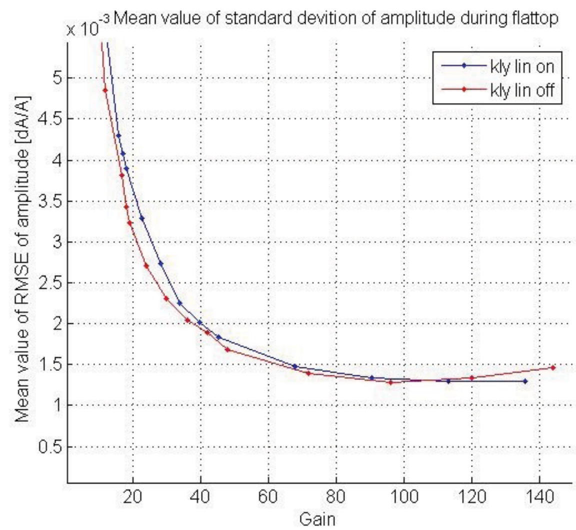

Figure 5. Mean value of the accelerating field amplitude error in function of the proportional feedback gain.

The set of 100 measurements of field amplitude stability has been done for each gain value. The standard deviation of the error has been calculated in each case. Afterwards the mean value of the RMSE was calculated from each set (for one feedback loop gain level). As far as RMS error has been calculated with linearization on and off the results comparison has been possible.

IV.Linearization vs. the beam energy stability in FLASH

The mean value of the field amplitude error standard deviation was achieved at the level of 1,3*10e-3 [dA/A] (fig 5). It can be concluded from the presented results that for higher gain achieved amplitude error can be reduced by linearization.

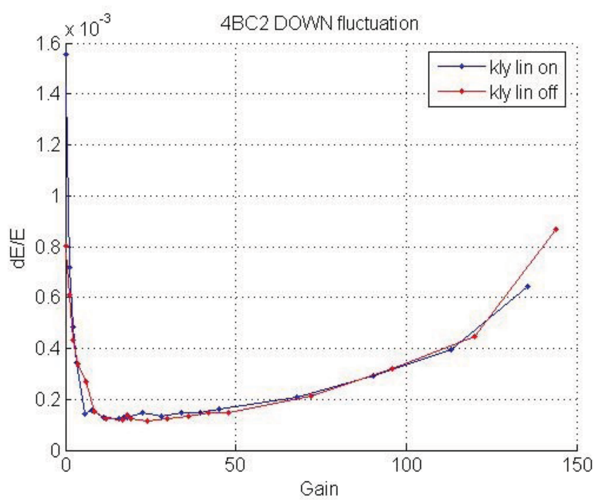

Figure 6. Beam stability measured after ACC1 section in FLASH. Measurement with and without linearization.

This effect is important from the RF station accelerating field stability point of view. Further more it has an influence on the accelerated beam energy dissipation. The electron beam stability has been measured after the first accelerating module in FLASH (see fig 6). From this analysis has been concluded that best pulse to pulse beam stability was achieved for low feedback gain (about 20-40). Nevertheless higher gain in case of linearized system has provided better stability in comparison original one. This phenomenon is especially important for the laser light production due to the SASE [5] effect in free electron lasers (FEL) experiments.

V.Conclusions

The digital predistortion method has been chosen as the most suitable and effective method for the HPC linearization for RF stations in FEL experiment based on TESLA technology. The improvement of the transfer characteristics due to the linearization implementation has been significant.

In order to evaluate the linearization tool to the LLRF feedback loop performance tests has been done in the accelerator environment – RF station for ACC1 in FLASH. Results that has been achieved during this study has proven the advantage of digital predistorter implementation. The amplitude stability improvement has been observed for higher gain values where the HPAC nonlinearities causes LLRF feedback loop performance degradation.

Additional study of the accelerated beam energy stability has been done. Electron bunch energy deviation has been reduced by virtue of HPC linearization and the field stability improvement.

Cavities amplitude signal stability has been calculated for the whole RF pulse flat-top phase duration. That is why is also recommended to perform the bunch-to-bunch analysis of the in-pulse beam energy spread for linearized HPC system. This study would also give an opportunity for RF station work performance improvement analysis thanks to the implemented linearization method.

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References

[1] T. Schilcher, "Vector Sum Control of Pulsed Accelerating Fields in Lorentz Force Detuned Superconducting Cavities", PhD Thesis, Hamburg, Germany 1998.

[2] R. Brinkmann et al. (eds.), "TESLA Technical Design Report – Part II: The Accelerator", DESY 2001-011, pp. II-19, March 2001; http://tesla.desy.de

[3] P. Garcia, A. Ortega, J. Mingo, A. Valdovinos, "Nonlinear Distortion Cancellation Using LINC Transmitters in OFDM Systems", IEEE Transactions On Broadcasting, Vol. 51, No.1, March 2005.

[4] R.I. Bogya, M.E. Magana, "Linear radio frequency power amplifier design using nonlinear feedback linearization techniques", Vehicular Technology Conference 2004, IEEE 60th Vol. 3, Issue, Sept. 2004, pp. 2259-2263, 2004

[5] Dong-Hee Jang at all. "Analog predistorter using a Cartesian vector modulator structure", Microwave and Optical Technology Letters, Volume 43, Issue 4 , pp 343 – 348, 2004 Wiley Periodicals, Inc