Extended Abstract for Model Based Fast Protection System for High Power RF Tube Amplifiers Used at European XFEL Accelerator

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***Abstract*—The driving engine of the superconducting accelerator of the European X-ray Free-Electron Laser (XFEL) are 27 Radio Frequency (RF) stations. Each of an underground RF station consists from multi-beam horizontal klystron which can provide up to 10MW of power at 1.3GHz. Klystrons are sensitive devices with limited lifetime and high mean time between failures. In the real operation the lifetime of the tube can be thoroughly reduced by failures. To minimize the influence of service conditions to the klystrons lifetime the special fast protection system named as Klystron Lifetime Management System (KLM) has been developed. The main task of this system is to detect all events which can destroy the tube as quickly as possible and switch off driving RF signal or HV. Detection of events is based on comparison of model of high power RF amplifier with real signals. Implementation is done in Field Programmable Gate Array (FPGA). For the XFEL implementation of KLM is based on the standard Low Level RF (LLRF) Micro Tele-communications Computing Architecture (MTCA.4 or xTCA).**

This article focuses on the klystron model estimation and implementation of KLM in FPGA. Results of the system implemented on MTCA.4 architecture will be presented in the end.

***Index Terms*—DESY, European XFEL, control systems, protection systems, model estimation, MTCA, FPGA, klystron**

I. Introduction

THE klystron is a high power RF amplifier. It is a specialized linear-beam vacuum tube. The RF system of European X-Ray Free Electron Laser (XFEL) [1] consists of 27 RF stations. The RF system provides RF power at 1.3GHz for the superconducting cavities. Each station consist of Multi Beam Klystron (MBK) that can produce 10 MW of power at 1.3GHz with repetition rate of 10Hz and 1.5ms RF pulse length. Those are very expensive devices. The XFEL should work continuously over 20 years with only 1 day per month for maintenance. In order to meet so demanding requirement lifetime of the tube should be in excess of 60,000 hours, or better. This is not always easy to achieve. Another problem with the klystrons is stability of work. At Free Electron Laser in Hamburg (FLASH) accelerator in DESY [2] 40% to 50% of accelerator downtime is caused by klystrons and modulators [3]. Detection of events in MBK and reaction to them is a key element in reducing failures time.

There are a few factors which can reduce lifetime and reduce stability of the tube. Some of the main are:

- RF breakdowns: may destructs cavity surface and can pollute RF window that increases reflected power;
- High RF reflections due to the breakdown somewhere in the waveguide system: may lead to beam loses;
- Work in deep saturation: may lead to beam losses and bad vacuum.
- Gun arc: destructs the cathode and anode surface and can pollute HV insulator and cathode;
- High vacuum level in the tube: can be a reason for the RF breakdown in the one of klystron cavities or HV breakdown in the gun area of the klystron.

To prevent occurrence of the destructive factors the fast interlock is required. The KLM which is fast interlock and measurement system was developed at DESY. Main idea of the system is to monitor available signal from klystron and react when klystron parameters are over normal values. Mainly it is done by comparing measured values with estimated model. When difference between measured values and estimated model reach threshold, error is reported. Reaction on event indicate interlock signal which switch off klystron drive signal. In order to prevent any damage that could be made to klystron, system should react as fast as possible.

The protection system was integrated with LLRF system for XFEL [4] and it was implemented on MTCA.4 architecture.

II. System overview

There are 6 RF and 4 analog signals available from klystron. Two of RF are the forward and reflected power signals from the directional coupler (DC) installed between the output of the preamplifier and klystron input cavity, the other four of RF signals are the forward and reflected power from high power DCs installed in each of the klystron's arms. The two of analog signals are the klystron cathode voltage and cathode current. RF signals are the main used for detection of events. All available signals are connected to KLM and KLM has one output signal that controls RF gate. Klystron with connected signals is presented in Figure 1.

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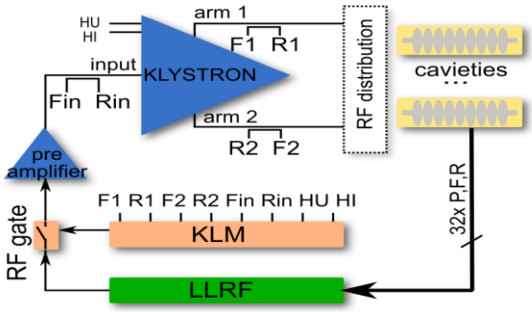

Fig. 1. Klystron with connected signals: F1- forward at arm 1; R1 – reflected at arm 1; F2- forward at arm 2; R2 – reflected at arm 2; Fin- forward at input; Rin – reflected at input; HU – high voltage; HI – high current;

Protection functions definitions are based on available signals from the klystron. One of the main is the correspondence of input and output forward power. Error condition:

$$A_{OEXP} - A_{OVS} \geq A_{FLIM} \quad (1)$$

where A_{FLIM} is maximum allowed difference between expected and measured amplitude, A_{OVS} is a vector sum of output amplitude at two arms and A_{OEXP} is expected output amplitude in function of input amplitude (A_{in}).

III. KLYSTRON MODEL

The MBK amplitude to amplitude (AM/AM) conversion can be characterized by modified Rapp's model, which models amplitude distortion but no phase distortion. Rapp's model can be used for systems that behave linear up to saturation point [5]. It uses three main parameters: saturation amplitude, signal gain of the amplifier, and parameter that controls the smoothness of the transition from linear to nonlinear region. The expression of the klystron AM/AM conversion with coefficients (p_i) and klystron voltage (U_H) is as follows [6]:

$$A_{OEXP}=f(A_{in},U_H)=\frac{p_1\cdot A_{in}\cdot U_H+p_2\cdot A_{in}+p_3\cdot U_H+p_4}{\left[1+\left(\frac{A_{in}}{p_0}\right)^{p_n}\right]^{1/p_n}}-p_3\cdot U_H-p_4 \quad (2)$$

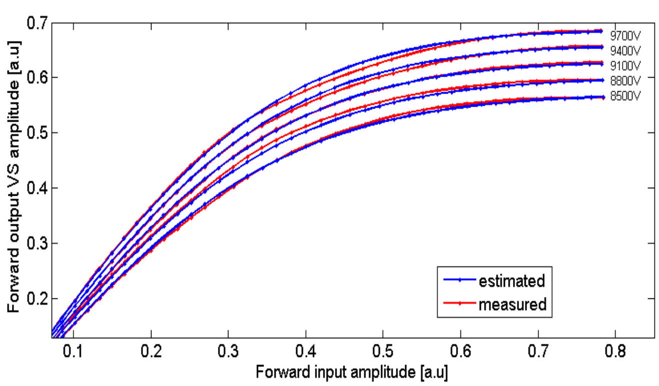

Fig. 2. Transfer curves of THALES TH1802 MBK for 5 different power supply voltages set, parameters estimated using 3 different voltages sets, R^2=0.995

Transfer curves of klystron for estimated model and measured values are presented in Figure 2.

IV. FPGA IMPLEMENTATION

Algorithms are implemented in FPGA and are optimized for low latency. Event detection is divided into a few main blocks, which are presented in Figure 3. Filed detection module uses non-IQ digital demodulation for amplitude computation [7]. Low pas filters are implemented as moving average. The model estimation module implements formula (2). Error detection implements (1).

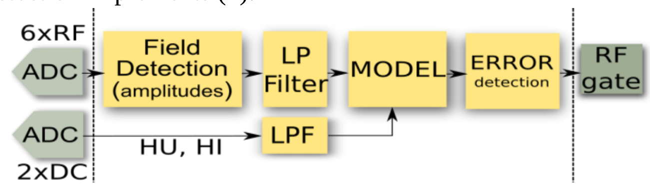

Fig. 3. Top block diagram of FPGA implementation of event detection, divided into blocks: filed detection, low pass filters (LPF), model estimation and error detection

V. RESULTS

Verification of implementation and measurements of the klystrons were performed at klystron test stand [8]. RF breakdown event is from klystron MBK TH1802 from Thales and is presented in Figure 4.

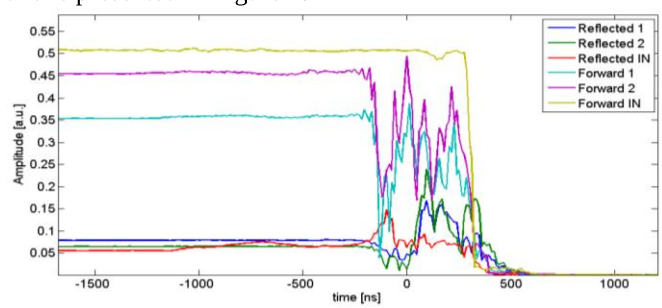

Fig. 4. Amplitude curves for all RF signals during RF breakdown event

VI. OUTLOOK

The system was successfully implemented and next integrated with LLRF system. Implementation was tested at klystron test stand. In the paper mathematical formulas for protection system and klystron model estimation were derived. KLM can properly detect different kind of error events. There is proper reaction on event. KLM switches off RF drive signal with around 500 ns of delay.

VII. REFERENCES

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