UNIVERSAL CONTROLLER FOR DIGITAL RF CONTROL

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Abstract

Digital RF control systems allow to change the type of controller by programming of the algorithms executed in FPGAs and/or DSPs. It is even possible to design a universal controller where the controller mode is selected by change of parameters. The concept of a universal controller includes the self-excited-loop (SEL) and generator driven resonator (GDR) concept, the choice of I/Q and amplitude or phase control, and allows for different filters (including Kalman filter and method of optimal controller synthesis) to be applied. Even time-varying mixtures of these modes are possible. The implementation of such a controller is presented.. The controller is optimized for pulsed operation with ms pulses which allow use of finite length tables for measurement and control.

INTRODUCTION

The universal controller should support the some or all of the following features which are controlled by parameters setting:

- SEL/VCO and GDR driven operation
- Amplitude, phase, I and Q control
- Combinations of control
- Frequency sweep mode
- Feedback/Feedforward
  - Beam loading compensation
  - Adaptive Feedforward
- Controller Filter
- Klystron Linearization
- Cavity Frequency Resonance Control
  - Motor Tuner
  - Piezotuner

Therefore one controller should be able to cover a variety of applications without the need for recompilation and synthesis of a new FPGA configuration. However some features may increase the latencies significantly while others may need a vast amount of available resources. Another possibility is the change of configuration if total latency exceeds A block diagram with most of the desired features is shown in figure 1.

SEL AND GDR CONTROLLER

Self-excited loops have been traditionally employed [1] in accelerators where the cavity resonance frequency is susceptible to large fluctuations with respect to the cavity bandwidth prohibiting turn-on with a fixed frequency source. However most accelerators such as SNS, FLASH, European XFEL, CEBAF etc. will be able to operate with generator driven systems (GDR) but may benefit from being able to switch to SEL operation [2].

Self-excited Loop Operation

The SEL requires no rf reference signal for driving the cavity at its resonance frequency. In its basic configuration the loop consists of the klystron with power transmission system, the cavity with input and probe coupler, a coaxial cable connecting the probe to the klystron (additional amplifiers are needed), a loop phase shifter and a limiter in the probe signal path. If the phase shift in the loop is multiple of 360 degrees and the gain > 1 than system will form an oscillator starting from noise and finally driving the cavity at its resonance frequency. The limiter prevents excessive power to be incident to the cavity. An additional amplitude controller can be used to stabilize the field. Phase lock to an external reference can be achieved by measurement of the phase error with respect to the external reference and an electrical loop phase shifter as actuator which is driven by the amplified error signal.

Self-excited loops can be realized in digital control system with vector-demodulators for field detection and vector-modulators for control acting as down- and up-converters for the cavity field. The loop phase shifter, limiter, and amplitude controller are realized by the digital controller in the baseband.

GDR Driven Resonator Operation

In the generator driven system, a rf reference frequency from the Master Oscillator serves as a drive signal for the cavity (amplified by the klystron). The cavity probe signal is fed to a field detector which measures amplitude and phase or I and Q of the field vector. In the case of amplitude and phase control the measured amplitude and phase are compared to the setpoint values and the resulting error signals are amplified and filtered to drive the actuators for amplitude and phase. The loop is realized as negative feedback loop. The GDR is usually employed if the resonance frequency remains close to the operating frequency (< bandwidth). In this case the accelerating fields can be established after a shutdown without initial cavity frequency tuning.

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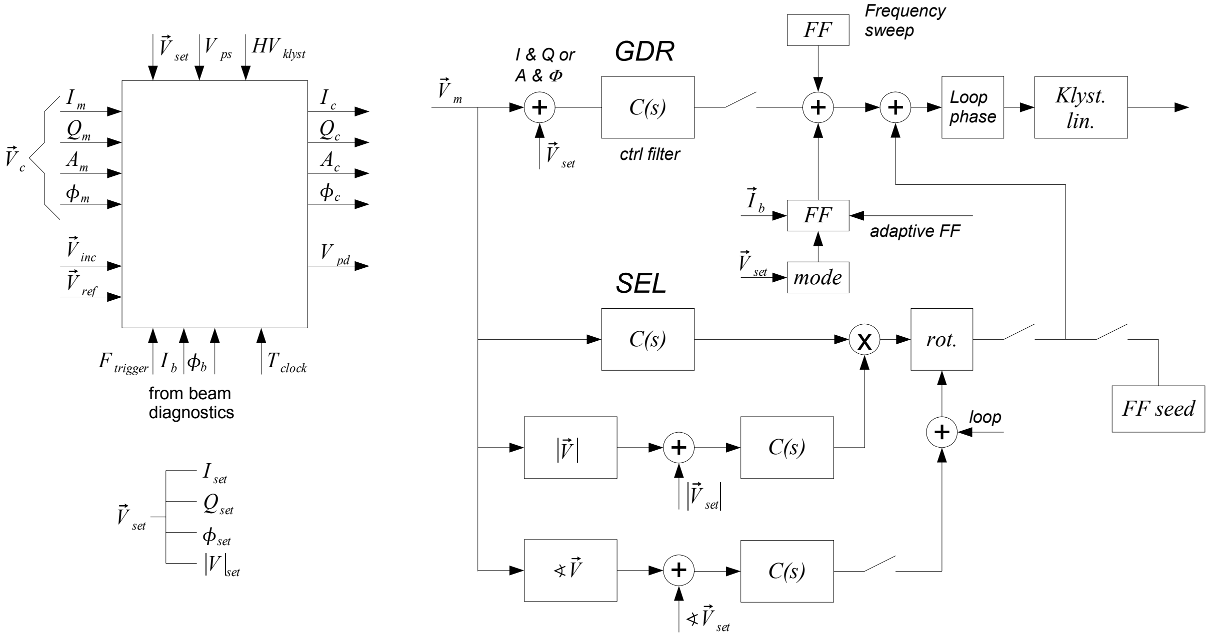

Fig. 1. Block diagram and signal flow in Universal Controller

IQ or Amplitude/Phase Control

The designer of the rf control system has the choice between amplitude and phase controller, I and Q controller or a mixture of amplitude and Q control if phase errors are dominated by cavity resonance perturbation. For the self-excited loop amplitude control is required during start-up to limit the cavity field. Whether using amplitude and phase or IQ control, in both cases detectors for the vector components, comparators with setpoints, filters for the resulting error signals, and actuators for control are required. Conversions from amplitude and phase to IQ and vice versa can be employed for control and monitoring purposes.

A digital controller can provide any mixture of amplitude, phase and IQ control by selecting the gain for each quantity.

CONTROLLER FILTERS

The controller filter amplifies the errors signal with the desired filter characteristics. For low latency they are implemented as fixed point algorithms using state space representation. The filter order is optimized for the required response (i.e. 4-th order for PID–controller followed by notch-filter). Higher order filters will add latency in the *computation and by the filter characteristics* and should be avoided if possible.

FEEDFORWARD MODES

The feedforward tables are used for

- Open loop operation
  - Start-up
  - Coupler/cavity conditioning
- Cancellation of repetitive errors
- Seeding of the self-excited loop
- Frequency sweep

The trigger starts the table while the clock provides synchronisation with beam and rf frequencies.

Open Loop Operation

Open loop operation is usually required during start-up of the rf system to verify the calibration parameters, the cavity tuning, the loop phase and the loop gain. Once gradient is established all parameters can be verified. Initial start-up requires moderate power levels to prevent interlock trips such as coupler sparcs and cavity quench.

For coupler and cavity conditioning the open loop operations allow loading of feedforward tables with appropriate shape (i.e. with power spikes) to reduce the conditioning time.

Beam Loading Compensation

The feedforward is composed of several tables such that *beam loading compensation can be added*. If toroids and/or beam phase monitors are available the information can be used to scale the beam loading compensation tables according to measured beam current and beam phase.

Adaptive Feedforward

Slow changes of perturbations or system parameters such as klystron gain can be corrected by periodic updates of the feedforward table. Based on the residual amplitude and phase errors the algorithms corrects the feedforward tables according to system model. The goal is to have fast adapting algorithms which are robust against changes in operating parameters.

Seeding of SEL

For faster start-up of the self-excited loop an initial seed signal consisting of a short feedforward pulse may be used. This allows start-up with a pre-determined phase. In cases of low noise levels in the SEL, the start-up time can be reduced by several orders of magnitude.

IMPLEMENTATION IN FPGA AND DSP

I&Q to A&P Conversion

The conversion from the Cartesian to polar coordinates is the most time-consuming operation in the controller. The simplest solution involves application of the CORDIC algorithm, as it is provided by Xilinx as a parameterized core. Unfortunately, the latency time of the core is quite large, 37 clock cycles with 18-bit accuracy of inputs and outputs for a single conversion, giving 74 clock cycles of conversion in both ways (740 ns at 100 MHz clock). The alternative approach involves using division/square root core and polynomial approximation of sine, cosine and arcus tangent functions. 18-bit division at radix 4 consumes 9 cycles per division. The arcus tangent function can be approximated with the accuracy 0.01 degree by the fourth-order polynomial. To approximate a sine with the accuracy of 0.01% the fifth order polynomial is required. Using this approach the conversion in two directions can take below 20 clock cycles.

Trigger, Clock and Other Timing

For digital field detection and up-conversion, the clocks of the ADC and DACs must be synchronized with the master oscillator. The machine trigger guarantees synchronization with the pulsed structure of the accelerator. Timings internal to the digital controller may be synthesized in the PLLs of the FPGA.

Latency and Resource Limitation

Experience at FLASH at DESY have shown that the typical resource requirements and latencies of the digital rf controller implemented in a Virtex II are as follows:

- 20% for digital IQ detection and vector-sum of 8 cavities. Latency of the order of 100 ns.
- 20% for digital controller with PI control and feedforward and set point tables. Latency of the order of 100 ns.

It is expected that the implementation of all possible features in the universal controller will exceed the available resource and latency requirements.

OTHER OPTIONS OF OPERATION

Frequency Sweep Mode

The frequency sweep mode is used to vary the rf frequency driving the klystron. The variation can be programmed to be linear with time, at a constant frequency offset or to follow a pre-programmed pattern. It is used to search the cavity resonance frequency including other passband modes, condition couplers without exciting the cavity, and follow the resonance frequency of a cavity during tuning.

In the frequency sweep mode, the control vector of the vector-modulator or digital up-converter is rotated with a variable angular frequency. This can be accomplished with phase varying feedforward tables or a time varying loop phase. The rate of phase change determines the offset frequency, the direction of rotation the sign of the frequency change.

VCO Mode

In the VCO mode the controller can be used to phase lock the cavity frequency drive to the cavity resonance frequency as in a conventional PLL. The VCO is simulated by implementing a time variable loop phase where the rate of loop phase change can be controlled. This rate determines the frequency offset to the rf reference frequency. The range of the VCO can be limited by limiting range of the offset frequency. Offset frequencies of several MHz can be achieved.

Klystron Linearization

There are different approaches well known for high power amplifier amplitude and phase nonlinearities compensation as for instance fast feedbacks around amplifier or feedforward configuration with two nonlinear device usage. The most reliable, flexible and cost effective solution can be adaptive pre-distorter [3]. This method would use AM to AM and PM to AM characteristics achieved from off-line and on-line tests for klystron driving signal correction.

Generation of Bode Plots

The possibility of amplitude, phase, and IQ modulation as well as frequency sweeps support the measurement of transfer functions (bode plots). In this case the quantity under investigation is modulated with a frequency varying sinusoid while the detector signal is measured as a time varying vector. From the measured amplitude and phase response the transfer function can be calculated and displayed.

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