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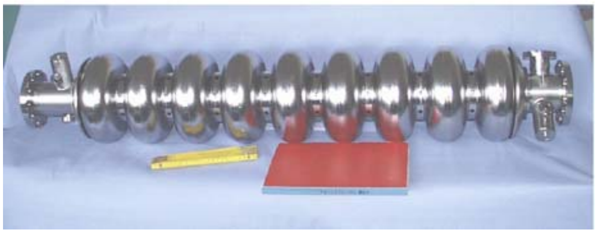

ADAPTIVE CONTROL OF A SC CAVITY BASED ON THE PHYSICAL PARAMETERS IDENTIFICATION

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Abstract

A digital control of superconducting cavities for a linear accelerator is presented. FPGA based controller supported by MATLAB system was developed to investigate the novel firmware implementation. Algebraic model in complex domain is proposed for the system analyzing. Identification of the system parameters is carried out by the *least squares* method application. Control tables: Feed-Forward and Set-Point are determined for the required cavity performance, according to the recognized process. Feedback loop is tuned by fitting a complex gain of a corrector unit. Adaptive control algorithm is applied for feed-forward and feedback modes.

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A digital control of superconducting cavities for a linear accelerator is presented. FPGA based controller supported by MATLAB system was developed to investigate the novel firmware implementation. Algebraic model in complex domain is proposed for the system analyzing. Identification of the system parameters is carried out by the *least squares* method application. Control tables: Feed-Forward and Set-Point are determined for the required cavity performance, according to the recognized process. Feedback loop is tuned by fitting a complex gain of a corrector unit. Adaptive control algorithm is applied for feed-forward and feedback modes.

INTRODUCTION

LLRF - Low Level Radio Frequency control system is under development in order to improve regulation of accelerating fields in the resonators (Fig. 1) [1] . Control section, powered by one klystron, may consist of many cavities. Fast amplitude and phase control of the cavity field is accomplished by modulation of a signal driving the klystron through a *vector modulator*. Cavities are driven with 1.3 ms pulses to an average accelerating gradient of 25 MV/m. The cavity RF signal is *down-converted* to an intermediate frequency of 250 KHz, while preserving the amplitude and phase information. ADC and DAC converters link the analog and digital parts of the system with a sampling interval of 1 µs. Digital signal processing is executed in the FPGA system to obtain field vector detection, calibration and filtering. Control feedback system regulates the vector sum of the pulsed accelerating fields in multiple cavities. The FPGA based controller stabilizes the detected real (in-phase) and imaginary (quadrature) components of the incident wave according to a given set point. Adaptive feed-forward is applied to improve the compensation of repetitive perturbations induced by the beam loading and by dynamic Lorentz force detuning. Control block applies the value of the cavity parameters, estimated in the identification system, and generates the required data for the controller. A system model was developed for investigating the optimal control method of the cavity. The control system was experimentally introduced in the first cryo-module with 8 cavities - ACC1 of the VU-FEL TTF (FLASH) in DESY.

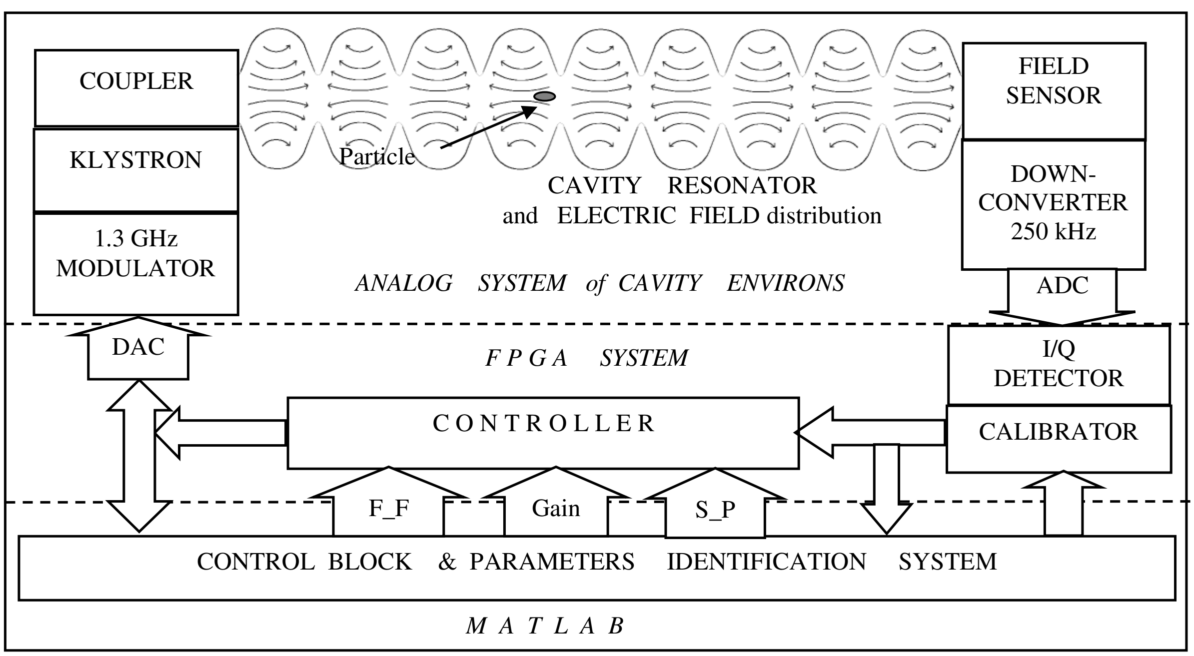

Fig 1. Functional block diagram of Low Level Radio Frequency Cavity Control System

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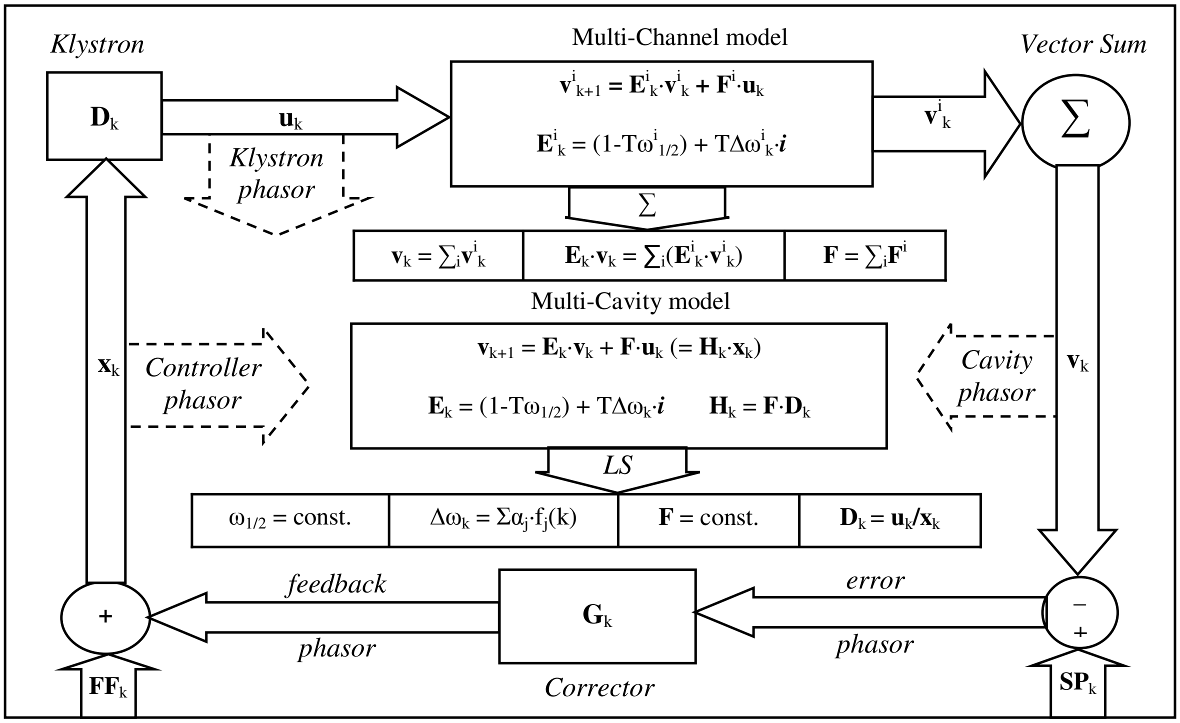

Fig 2. Algebraic model of LLRF control system

CONTROL SYSTEM MODELING

A discrete-time model in complex domain is introduced to analyze the LLRF digital control system (Fig. 2) [2]. A signal is modeled by a complex envelope called "phasor". It is represented by real (in-phase) and imaginary (quadrature) components or alternatively by amplitude and phase, related to the reference frequency of 1.3 GHz of the carrier signal. Modules of the system form a phasor according to their characteristics described by complex factors. Electrical model of the cavity is assumed as the only dynamic part characterized by non linear factor $\mathbf{E}_k = (1\text{- } T\omega_{1/2}) + T\Delta\omega_k \cdot \mathbf{i}$, with constant half-bandwidth $\omega_{1/2}$ and time varying detuning $\Delta\omega_k$, for step k with sampling interval T. Cavity environment is divided for two static parts represented by the linear factor $\mathbf{F}$ and the non linear klystron unit with time varying factor $\mathbf{D}_k$. In a practical application of a linear accelerator one klystron drives many cavities. Therefore, parallel multi-channel system, driven with a common klystron phasor $\mathbf{u}_k$, for vector sum control is considered. Each single cavity i-th channel with a cavity phasor $\mathbf{v}^i_k$, is modeled by difference equation, for step k:

$$\mathbf{v}^i_{k+1} = \mathbf{E}^i_k \cdot \mathbf{v}^i_k + \mathbf{F}^i \cdot \mathbf{u}_k. \tag{1}$$

Summarizing equation (1) for all channels and introducing new resultant variables: $\mathbf{v}_k$, $\mathbf{E}_k$ and $\mathbf{F}$, yields the multi-cavity model of the same structure like single channel model, but with new parameters in the case of diverse operational condition for cavities. Including the klystron unit to the cavity system the ultimate model, driven with the controller phasor $\mathbf{x}_k$, is given by

$$\mathbf{v}_{k+1} = \mathbf{E}_k \cdot \mathbf{v}_k + \mathbf{H}_k \cdot \mathbf{x}_k, \tag{2}$$

where total factor $\mathbf{H}_k = \mathbf{F} \cdot \mathbf{D}_k$.

FPGA based controller executes procedure of feed-forward driving supported by feedback according to prearranged control tables: $\mathbf{FF}_k$, $\mathbf{SP}_k$, $\mathbf{G}_k$ (Fig. 2). A cavity phasor $\mathbf{v}_k$ is compared to the reference phasor $\mathbf{SP}_k$ (set point) creating an error phasor. An error phasor is multiplied by a complex gain $\mathbf{G}_k$ of the corrector unit, producing a feedback phasor. A superposition of a feedback phasor and a compensating phasor $\mathbf{FF}_k$ (feed-forward) results in a controller phasor $\mathbf{x}_k$. Consequently, the controller model is expressed for step k:

$$\mathbf{x}_{k+1} = \mathbf{FF}_k + \mathbf{G}_k \cdot (\mathbf{SP}_k - \mathbf{v}_k). \tag{3}$$

Control tables are determined for required cavity performance, according to the control algorithm based on estimated parameters of the cavity system.

PARAMETERS IDENTIFICATION OF CAVITY SYSTEM

Control algorithm based on the cavity system model (2), requires identification of the process parameters [3]. Therefore, two complex, time varying factors $\mathbf{E}_k$ and $\mathbf{H}_k$, should be recognized in the equation (2). The LS - *least square* method is proposed for parameters estimation in a noisy and non stationary condition. Firstly, linear decomposition is carried out for the multi-cavity model. Time varying detuning $\Delta\omega_k$ can be approximated for each k-th step by series of base functions f_j with unknown, but constant coefficients α_j. Consequently, the multi-cavity model is expressed by matrix equation for step k: $\mathbf{v}_{k+1} = \mathbf{w}_k \cdot \mathbf{z}$, where $\mathbf{z}$ is resultant column vector of unknown values, $\mathbf{w}_k$ is matrix of model structure. In a practical application of LS method, N steps of a measurement range is considered creating 2N over-determined scalar equations, expressed by the matrix form, as follows: $\mathbf{V} = \mathbf{W}\cdot\mathbf{z}$, where, $\mathbf{V}$ – total output vector, $\mathbf{W}$ – total matrix of model structure. The unique and optimal solution for the vector $\mathbf{z}$ according to the LS method is given by $\mathbf{z} = (\mathbf{W}^T*\mathbf{W})^{-1}*\mathbf{W}^T*\mathbf{V}$. Algorithm for the identification of cavity parameters was implemented in Matlab system applying *cubic B-spline* set of functions for linear decomposition of step-varying detuning [3].

Second stage of the estimation procedure engages non linear part of the model described by the complex equation $\mathbf{u}_k = \mathbf{D}_k\cdot\mathbf{x}_k$ for the klystron unit (Fig 2). Finally the factor $\mathbf{H}_k$ from equation (2) is estimated, as follows: $\mathbf{H}_k = \mathbf{F}\cdot\mathbf{u}_k/\mathbf{x}_k$.

The prior estimation (filtering) for measured data: cavity, controller and klystron phasor, was performed for *off-line* identification of the parameters.

CONTROL OF CAVITY SYSTEM

The required cavity performance is: driving in resonance during *filling* and field stabilization for *flattop* range. A cavity is driven in feed-forward and feedback mode to fulfill desired operation condition. Combining equation (2) and (3) yields resulting equation for the cavity control system, as follows:

$$\mathbf{v}_{k+1} = \mathbf{E}_k\cdot\mathbf{v}_k + \mathbf{H}_k\cdot[\mathbf{FF}_{k-1} + \mathbf{G}_{k-1}\cdot(\mathbf{SP}_{k-1} - \mathbf{v}_{k-1})]. \quad (4)$$

Recognition of the cavity system factors: $\mathbf{E}_k$ and $\mathbf{H}_k$, allows determining the control tables: feed-forward - $\mathbf{FF}_k$, set point - $\mathbf{SP}_k$ and complex gain - $\mathbf{G}_k$. Solution of equation (4) gives estimated formulas presented in tab. 1, for two modes of operation within two ranges. Complex gain $\mathbf{G}_k$ is determined for the loop gain L assumed as constant scalar parameter for the steady state cavity *phasor* $\underline{\mathbf{v}}_k = L\cdot(\mathbf{SP}_k - \underline{\mathbf{v}}_k)$. The loop gain L value is limited due to the stability condition. Estimated cavity parameters are considered as actual values for the required cavity performance and are applied to create the control tables for a next pulse. But new control tables modify the trajectory of the nonlinear process and again new parameters are estimated. This iterative processing quickly converges to the desired state of the cavity, assuming repeatable conditions for successive pulses. Stochastic fluctuations of the required trajectory are reduced by averaging processing (filtering) for successive pulses.

CONCLUSIONS

The cavity control system for superconducting linear accelerator project is preliminary introduced in this paper. Digital control of the superconductive cavity has been performed by applying FPGA technology system in DESY. Identification of the resonator parameters has been proven to be a successful approach in achieving required performance, i.e. driving on resonance during *filling* and field stabilization during *flattop* time while requiring reasonable levels of power consumption. Feed-forward and feedback modes were successfully applied in operating the cavity. Preliminary application tests of FPGA controller have been carried out using the superconducting cavities in ACC1 module of the VUV-FEL (FLASH) setup.

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Table 1. Control tables formulas

Table / *Range*	FEEED-FORWARD	SET-POINT	GAIN
Filling	$\mathbf{FF}_k = T\omega_{1/2}\cdot v\cdot\exp(\boldsymbol{i}\varphi_{k+1})/\mathbf{H}_{k+1}$ $\varphi_{k+1} = \varphi_k + T\Delta\omega_k$	$\mathbf{SP}_k = v\cdot[1-\exp(-k\cdot T\omega_{1/2})]\cdot\exp(\boldsymbol{i}\varphi_k)$	$\mathbf{G}_k = L\cdot T\omega_{1/2}/\mathbf{H}_{k+1}$ L = const.
Flattop	$\mathbf{FF}_k = \mathbf{V}\cdot T(\omega_{1/2} - \Delta\omega_{k+1}\cdot\boldsymbol{i})/\mathbf{H}_{k+1}$	$\mathbf{SP}_k = \mathbf{V} = V\cdot\exp(\boldsymbol{i}\Phi)$	$\mathbf{G}_k = L\cdot T(\omega_{1/2} - \Delta\omega_{k+1}\cdot\boldsymbol{i})/\mathbf{H}_{k+1}$