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TESLA cavity modeling and digital implementation in FPGA technology for control system development

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Abstract

The electromechanical model of the TESLA cavity has been implemented in FPGA technology for real-time testing of the control system. The model includes Lorentz force detuning and beam loading effects. Step operation and vector stimulus operation modes are applied for the evaluation of a FPGA cavity simulator operated by a digital controller. The performance of the cavity hardware model is verified by comparing with a software model of the cavity implemented in the MATLAB system. The numerical aspects are considered for an optimal DSP calculation. Some experimental results are presented for different cavity operational conditions.

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1. Introduction

The majority of existing accelerators are controlled by analog control systems. A fully digital solution of such systems has recently become possible with the advent of FPGA chips equipped with DSP capabilities. A new generation of digital controllers may integrate new tasks like: system identification and simulation, continuous and multichannel measurements, massive data acquisition, continuous diagnostics and exception handling, introduction of real-time feed-back between the beam quality (electrical and optical) and system parameters, building a rich database of the system behavior in changing working conditions, etc. The above tasks rest on the assumption that the idle time, of the accelerator working in pulsed mode, may be efficiently used for the intensive DSP calculations. The introduction of new features is expected to result in: increased system safety, shorter design time, less human resource requirements, less consumed material and occupied space by the control-diagnostic system, less power consumption, increased reliability in adverse environments and lower cost.

The TESLA accelerator uses nine-cell superconducting niobium resonators to accelerate electrons and positrons. The acceleration structure is operated in a standing π-mode wave at the frequency of 1.3 GHz. The RF oscillating field is synchronized with the motion of a particle moving at the velocity of light across the cavity (see Fig. 1). The LLRF (low level radio frequency) cavity control system for the TESLA project has been developed in order to stabilize the accelerating fields of the resonators. The control section, powered by one klystron, may consist of many cavities. One klystron supplies the RF power of 10 MW to the cavities through the coupled waveguide with a circulator. The cavities are driven with pulses of 1.3 ms in duration and the average accelerating gradients of 25 MV/m. The control feed-back system regulates the vector sum of the pulsed accelerating fields in multiple cavities. The fast amplitude and phase control of the cavity field is accomplished by modulation of the signal driving the klystron. The cavity RF signal is down-converted to an

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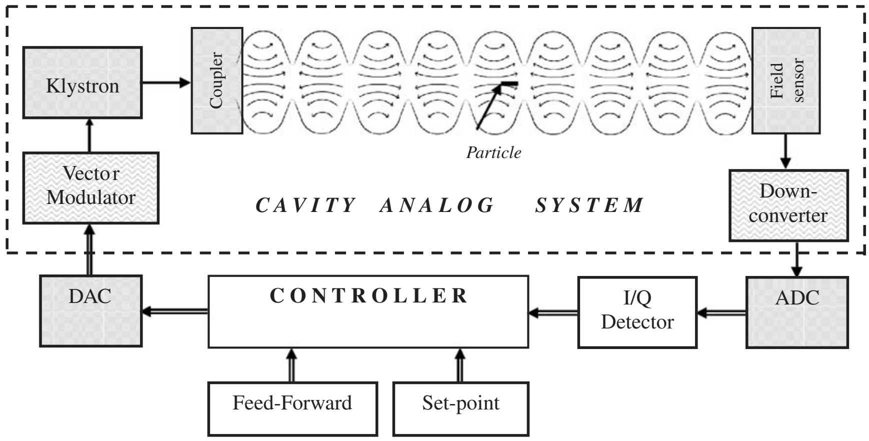

Fig. 1. Cavity environment and simplified block diagram of the cavity control system.

intermediate frequency of 250 kHz preserving the amplitude and phase information. The ADC and DAC converters link the analog and digital parts of the system. The digital signal processing is applied for the detection of the field vector as the complex envelope represented by real—I (in-phase) and imaginary—Q (quadrature) components (I/Q detector). The digital controller stabilizes the complex envelope of the cavity wave, according to the desired set point. Additionally, the adaptive feed-forward is applied to improve the compensation of repetitive perturbations induced by the beam loading and by the dynamic Lorentz force detuning.

The theoretical verification of the existing superconducting cavity model [1–3] lead to the synthesis of a digital algorithm efficiently implemented in the FPGA structure. This cavity simulator was used for evaluation of the control algorithms and for investigation of the optimal control method. The FPGA hardware implementation of the cavity model is intended for real-time operation.

2. The cavity model

2.1. Electrical circuit model

The following considerations are limited to a single cavity represented as LCR circuit coupled to a waveguide driven by a klystron. This approach is sufficient for the purpose of cavity control modeling [1–3]. The circuit model of the cavity environment is presented in Fig. 2. The currents (J) and voltages (U) are represented in *Laplace space*. The klystron as a power amplifier is modeled by the RF current generator J_k driving the waveguide via a circulator. The waveguide, as a transmission line, is parameterized by characteristic impedance Z_0 and time delay T_w. The cavity is represented as resonant LCR circuit with impedance $Z_c(\mathbf{s}) = (1/R + \mathbf{s}C + 1/\mathbf{s}L)^{-1}$ coupled to the waveguide. Beam loading is modeled as a current source $-J_b$ supplied by the electromagnetic field of the cavity. The bunched beam current has $\sim$2 ps pulse duration, 1 MHz rate and an average value of 8 mA.

The *forward wave* is represented by current J_f and voltage $U_f = J_f Z_0$. The *reflected wave*, represented by current J_r and voltage $U_r = J_r Z_0$ is terminated by the circulator load, matched to the waveguide ($J_f = J_k$). Superposition of the forward and reflected wave, represented by current $J_1 = J_f - J_r$ and voltage $U_1 = U_f + U_r = (2J_k - J_1)Z_0$ drives the coupler, which converts the signals according to transformation ratio 1:N. The output signals of the coupler are represented by current $J_2 = J_1/N$ and voltage $U_2 = NU_1 = U_c = (2J_k/N - J_1/N)N^2 Z_0$. Superposition of the output current of the coupler and beam loading results in the cavity current J_c and cavity voltage U_c, related by impedance Z_c.

Introducing the cavity loaded impedance $Z_L = N^2 Z_0 \| Z_c$ (parallel connection) and defining the transformed generator current $J_g \equiv J_k/N$, results in the cavity voltage $U_c = (2J_g - J_b)Z_L = JZ_L$. Therefore, the cavity loaded impedance $Z_L(\mathbf{s})$ can be represented by the transfer function in the corresponding forms:

$$
\begin{aligned}
Z_L(\mathbf{s}) &= (1/R_L + \mathbf{s}C + 1/\mathbf{s}L)^{-1} \\
&= \omega_0 \cdot \rho\mathbf{s}/(\mathbf{s}\omega_0/Q_L + \mathbf{s}^2 + \omega_0^2) \\
&= \omega_{1/2} \cdot R_L/(\omega_{1/2} + (\mathbf{s}^2 + \omega_0^2)/2\mathbf{s}),
\end{aligned}
\quad (1)
$$

where the following *secondary* parameters (derived from the *primary* LRC parameters) are applied: resonance frequency $\omega_0 = 2\pi f_0 = (LC)^{-1/2}$, characteristic resistance $\rho = (L/C)^{1/2}$, shunt resistance $R_L \equiv R \| N^2 Z_0$, loaded quality factor $Q_L = R_L/\rho$, half-bandwidth (HWHM)

$$\omega_{1/2} = 2\pi f_{1/2} = 1/2CR_L = \omega_0/2Q_L.$$

Due to the stability of the RF generator frequency ω_g, and narrow resonator bandwidth, the cavity voltage can be modeled in the *time domain* as *analytical signal* represented as a vector or phasor in the complex domain:

$$
\begin{aligned}
\mathbf{u}(t) &\equiv [u_r, u_i] \equiv u_r + \boldsymbol{i}u_i = a(t)(\cos(\omega_g t + \varphi(t)) \\
&\quad + \boldsymbol{i} \cdot \sin(\omega_g t + \varphi(t))) = a(t)\exp(\boldsymbol{i}(\omega_g t + \varphi(t))),
\end{aligned}
\quad (2)
$$