NUMERICAL SIMULATION OF THE INR DTL A/P CONTROL SYSTEM

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Abstract.
Stabilization of amplitude and phase in linear accelerator cavities can be realized by means of control systems, operating both in polar (A/P) and rectangular (I/Q) coordinate. In analyzing of linear control systems, as a rule, transfer functions are used, which, in turn, are the symbolic representation of the linear differential equation, connecting the input and output variables. It's well known that generally in A/P coordinate it is impossible to get two separate linear differential equations for amplitude and phase of RF voltage in a cavity except for estimating of the control system stability "in the small" near steady state values of variables [1]. Nevertheless, there is a possibility of numerical simulation of nonlinear A/P control system using up-to-date programs. Some results of the simulation are presented.

INTRODUCTION

In contrast to A/P, in I/Q coordinates it is succeeded in separating of both variables in two linear differential equations even for detuned cavity. That is why I/Q control systems became so popular last years, particularly, in connection with successful development of digital feedback systems. Despite obvious advantages of I/Q control system, its real application in pulse DTL RF system, operating at frequencies below 300 MHz, meets some difficulties. In this case RF amplifiers, as a rule, are based on application of vacuum tubes. The vacuum tube RF amplifiers construction inevitably contains bypass capacitors, which always are sources of RF parasitic radiation. Since I/Q control systems basically use standard integrated circuits: mixers, I/Q modulators and demodulators, working at low RF power level, its operation due to interferences from vacuum tube RF amplifiers, can be disturbed. That is why application of I/Q control systems is preferable for stabilization of accelerating field in cavities with klystron RF supply or with the low gain vacuum tube amplifiers in a case of CW accelerators.

Since at INR linear accelerator output RF power amplifier (PA) is connected with the DTL cavity (tank) by means of coaxial transmitting line (CTL) without circulator, the PA and the tank can be considered as a common high quality oscillating system [1]. At that, processes in the system are described by the first order linear differential equation with complex coefficients, which appear in result of two admissions:

- Transients in the high quality cavity are so slow that changing of amplitude and phase for the RF period can be not taken into account.
- Transients in the output RF power amplifier circuits and CTL are so fast in comparison with transients in the accelerator high quality cavity that steady-states are available in these circuits (including CTL) at every instant of amplitude and phase transients in the cavity.

These admissions allow simplifying not only the calculation of transients in the high quality tank, but also estimating parameters of control systems, stabilizing amplitude and phase of RF voltage in the DTL tank. As it was shown in [1] the first order - linear at complex variable plane, Differential Equation (DE) for a "complex envelope" of RF voltage in a high quality accelerator cavity can be presented in the following way:

$$T_n \frac{d\bar{U}_c(t)}{dt} + (1 - j\xi_c)\bar{U}_c(t) = \frac{T_n}{T_0} R_S(\bar{I}_g - \bar{I}_b)\,, \quad (1)$$

where $\bar{U}_C$ is a complex amplitude of accelerating voltage in the high-quality cavity; $\xi_c = (\Delta\omega_g + \Delta\omega_0)T_n$; $\Delta\omega_0, T_0, R_s$ are the own cavity detuning, cavity time constant and cavity shunt impedance; $\Delta\omega_g, T_n$ are the cavity "detuning" and "time constant" of the cavity, determined by the RF system parameters, such as internal resistance of the PA vacuum tube, coupling with CTL both from the side of the output RF power and from the cavity, length of the CTL [1,2]; $\bar{I}_g$ is a complicated function of RF supply parameters, listed above; $\bar{I}_b$ is a complex amplitude of the beam current resonance harmonic. So, one could say that Eq. (1) determines transient in common "PA-cavity" oscillating system. Moreover, as evident from Eq. (1), application of the complex envelope of RF in the cavity notably simplifies an analysis of control systems since both RF channel with the cavity and the feedback circuits are arranged in the same low-frequency domain. In polar A/P coordinates the complex amplitude $\bar{U}_c(t) = a_c(t)\exp(j\varphi_c(t))$. Substituting this expression in Eq. (1) and taking into account that $\bar{I}_g = I_g e^{j\varphi_g}$, $\bar{I}_b = I_b e^{j\varphi_b}$ it is easy to get from Eq. (1) the next system of the nonlinear differential equations for the real and imaginary parts of the Eq. (1):

$$\begin{aligned} T_n \frac{d\varphi_c}{dt} - \xi_c &= \frac{T_n R_s}{a_c T_0}(I_g \sin(\varphi_g - \varphi_c) - I_b \sin(\varphi_b - \varphi_c)) \\ T_n \frac{da_c}{dt} + a_c &= \frac{T_n}{T_0} R_s (I_g \cos(\varphi_g - \varphi_c) - I_b \cos(\varphi_b - \varphi_c)) \end{aligned} \quad (2)$$

In turn, in rectangular coordinate $\overline{U}_C = X_C + jY_C$ and Eq. (1) can be represented by the following system of two differential equations:

$$\begin{pmatrix} sT_n+1 & \xi_c \\ sT_n+1 & -\xi_c \end{pmatrix}\begin{pmatrix} X_c \\ Y_c \end{pmatrix} = \frac{T_n}{T_0} R_S \begin{pmatrix} \cos\varphi_g & -\cos\varphi_b \\ \sin\varphi_g & -\sin\varphi_b \end{pmatrix}\begin{pmatrix} I_g \\ I_b \end{pmatrix} \qquad (3)$$

Expressing X_C from the second DE and substituting it in the first one it is not difficult to get the linear DE of the second order for Y_C. Repeating the procedure for Y_C one can get the similar DE for X_C.

MODELLING OF A/P CONTROL SYSTEM

In the INR DTL cavity (tank) stabilization of the accelerating RF voltage is realized by means of the feedback RF signals from the tank pickup loops, controlling values of I_g and φ_g in Eq. (1), so that to support unchangeable values of amplitude and phase of the accelerating voltage. The feedback RF signals are transformed in the phase and amplitude error signals as result of comparison with phase (in phase detector) and amplitude (after amplitude detector) set points signals. The gained phase error signal controls phase shifter at RF pulse power level ~1Wt; the gained amplitude error signal controls the value of PA pulse plate voltage. For the A/P control system modelling was chosen the Matlab Simulink program. The main result of control system modelling by means of Matlab Simulink is a possibility of immediate observation of transients in any point of control system, following after changing of outside or inner parameter values. At that, for modelling of the A/P control system both systems of Eq. (2) and Eq. (3) are available, but the system Eq. (3) is simpler and more suitable, taking into account a possibility of conversion from polar system of coordinate to rectangular one and vice versa. The main blocks of the A/P control system Model are described below.

DE (differential equations) Block

First of all the system Eq. (3) has to be transformed to the form suitable for modelling in Matlab Simulink. The point is that because integration is a more numerically stable operation than differentiation, in Matlab ordinary differential equations are transformed into ones that use integration operators. It follows then that the number of Simulink *Integrator* block equals the order of the highest derivative. Hence, the system of Eq. (3) has to be transformed in the following way:

$$X_C = \frac{1}{sT_n}\left(R_S \frac{T_n}{T_0}(I_g\cos\varphi_g - I_b\cos\varphi_b) - X_C - \xi_C Y_C\right)$$

$$Y_C = \frac{1}{sT_n}\left(R_S \frac{T_n}{T_0}(I_g\cos\varphi_g - I_b\cos\varphi_b) - Y_C + \xi_C Y_C\right) \qquad (4)$$

In Fig.1 the model of the system Eq. (4) is presented. As the A/P control system is the subject of present investigation, the Simulink Extras Transformation blocks "Polar to Cartesian" and "Cartesian to Polar" are input. The blocks allow using the system of linear DE for analysis of the nonlinear A/P control system. It is obvious that without the Extras Transformation blocks the model in Fig. 1 can be used for I/Q control systems analysis too.

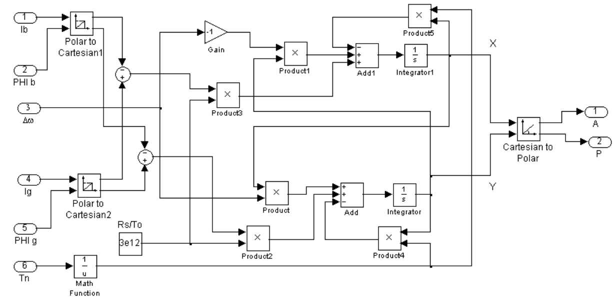

Figure 1: Model of nonlinear differential equations system.

Block "Feedback"

In Fig. 2 the block Feedback is presented. It consists of two separate networks. In amplitude control system feedback there are anode pulse modulator transfer function, time delay TD and limiter AD for positive signals, which ensures opening of the feedback only if pickup signal from the tank exceeds the amplitude set-point.

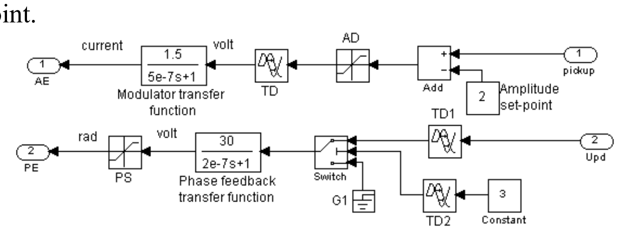

Figure 2: Model of the block "Feedback".

In phase control system except of the feedback transfer function, time delay TD1 and limiter PS, determining the phase shifter, the block "Switch" is input. It serves for creating of time delay (TD2) between the moments of the simulation beginning and the phase feedback closing.

Block "Timer"

The block transforms DC input signals I_g, φ_g, I_b, φ_b in pulse form and attaches the beam phase to the set-point phase φ_g and tank phase detuning *atan*ξ_c (see Fig. 3).

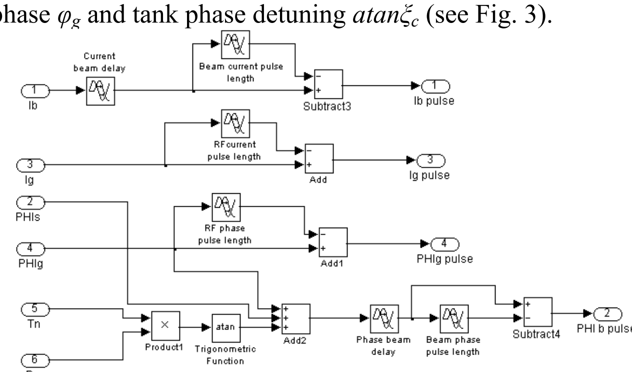

Figure 3: Block "Timer".

Block "RF Channel"

The block presents a transformer function of the series RF amplifiers, tuned at the master oscillator frequency.

The transformer function is input in Cartesian coordinates by means of two Simulink blocks "Polar to Cartesian" and "Cartesian to Polar" (see Fig. 4).

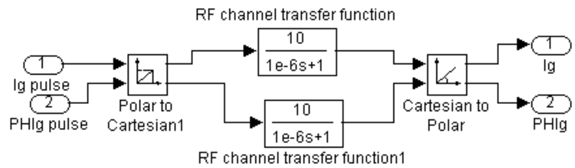

Figure 4: Block "RF channel"

Except of the subsystem blocks, listed above, there are a few additional math operation blocks: *block "PD"* (phase detector), which corresponds to well-known expression for the PD output signal:

$$U_{PD} \equiv \frac{U_C U_{SP}}{\sqrt{U_C^2 + U_{SP}^2}} \sin(\varphi_C - \varphi_g)\,, \qquad (5)$$

where Uc, φ_C – amplitude and phase of RF voltage in the tank; U_{SP}, φ_g – amplitude and phase of the set-point signal and block "PSS" (slow phase stabilization system), which compensates a constant phase shift due to tank detuning.

SOME RESULTS OF MODELLING

In Fig. 5 the common view of the Model is shown. All numerical data in the Model correspond to the third cavity of the INR DTL.

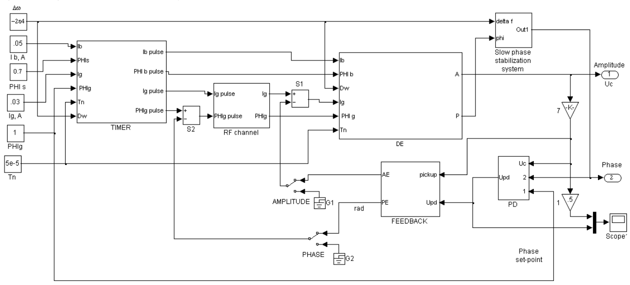

Figure 5: Common view of the control system Model

As can be seen from the blocks, presented above, numerical calculation of the control systems demands determination of the input values of cavity time constant T_n and detuning $\Delta\omega_g + \Delta\omega_0$, amplitude and phase of the beam current $\bar{I}_b$. As a rule, at INR DTL RF system a coupling of the CTL with the tank is chosen so that to minimize the VSWR value and, hence, value of the tank detuning $\Delta\omega_0 \sim 0$. Nevertheless, without a circulator between PA and tank, a value of $\Delta\omega_g$ is really always takes place, since its value, as and T_n value, depends on the CTL length, coupling PA anode-grid cavity with CTL and the PA supply. In turn, during RF channel operation all cited above parameters are optimized so that to achieve a maximum efficiency of the PA without a danger of overvoltage in the PA cavity [2], but not to minimize $\Delta\omega_g$ value. However, there is a possibility to estimate values of T_n and $\Delta\omega_g$, analyzing the amplitude and phase transients in the tank at the open fast amplitude and phase feedbacks. At that, sign and amplitude of the phase transients at the front edge of the phase pulse can be used for determination of the tank detuning value and a tangent to the RF envelope in the tank – for determination of the loaded tank quality.

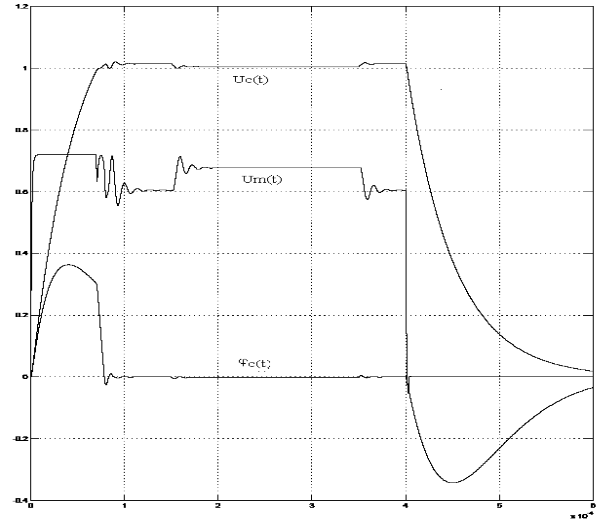

Figure 6: Envelope of RF voltage Uc(t), phase $\varphi_C(t)$ in the tank and anode modulator pulse Um(t)

As an example in Fig. 6 pictures of the signals in different points of the Model are shown. Parameters of the feedback transfer functions, tank (T_n and $\Delta\omega_g$), RF channel are pointed in Figs. 1-5. Beam loading is ~ 24%. Hidden parameters are following: transport delay in the amplitude feedback TD=2μs, in the phase feedback TD1=.5μs, time delay of the phase feedback closing is 70μs, T_n / T_0 =.5. The results of modelling are in good agreement with real measurement data, which have been done at the third DTL cavity. Certainly, results of modelling depend on specific parameters of RF channel and feedback networks, but some common peculiarities it is worthy to mention:

- Closing of the phase feedback near the flat top of RF pulse in the tank allows avoiding a danger of the amplitude degradation due to self exciting of the phase system at the leading edge of RF pulse.
- At $\Delta\omega_g \neq 0$ opening of the phase feedback as a rule makes poor quality of the amplitude stabilization system.
- At $\Delta\omega_g \neq 0$ the feedback gain in the amplitude or phase control systems, taken separately, is always higher than that of when both systems are closed.

REFERENCES

[1] V.V. Balandin et al. "Conceptual Design of a Positron pre-Accelerator for the TESLA Linear Collider", August 1999, TESLA 99-14.

[2] A.I.Kvasha "Investigation of overvoltages in the anode-grid cavity of the 200MHz pulse power amplifier of the MMF", Proceedings of the PAC2001, p. 1225.