SIMULATION OF THE INR RAS DTL FREQUENCY STABILIZATION SYSTEM

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Abstract

Theoretical modeling by means of Matlab Simulink program and experimental investigation of heat processes in the INR Linac drift tube tanks allow studying influence of these processes at the tank resonance frequency and creating of the frequency control system model. At that, the main attention is paid to accordance of modeling results and processes in the real systems. In turn, creation of control frequency system model gives a possibility to optimize the structure and parameters of the control system, stabilizing tank resonance frequency, and increase the accelerator operation efficiency.

INTRODUCTION

The Matlab Simulink program was used before for analysis of the SNS Resonance Control Cooling System (RCCS) [1]. The model created in frames of Matlab Simulink has allowed taking into consideration the dependence of RF input power on cavity detuning values during transients, time delays that resulted from water flows through the heat exchanger, the dynamic process of water warm-up in the cooling system due to dissipated RF power on the cavity surface and a dynamic model of the heat exchanger with characteristics in close agreement to the real unit. Thanks to the Matlab Simulink model, investigation of a wide range of operating issues during both transient and steady state operation became possible. The main purpose of this work is creating of the similar model, correctly describing the work of the INR drift tube Linac frequency control system (FCS). The point is that during ordinary operation of the Linac with duty cycle value 0.02, RF power, dissipated in the DTL cavities, results in the considerable cavity detuning. It means that before inputting RF power in the cavity it has to be heated to the resonance temperature and after RF power inputting temperature of cooling water has to be decreased so that resonance temperature of the cavity metal was unchangeable. Just this function is fulfilled by the FCS by means of control both of the heater power and of the heat exchanger cold water flow rate.

To understand the model of the FCS it is important first of all to call the main blocks or subsections, which it consists of.

- *RF POWER;* it represents the dependence of dissipated RF power on the cavity detuning.
- *DRIFT TUBE;* it is used to determine the processes of cavity heating by RF loss in the drift tubes. At that, detuning of the cavity due to RF loss in the cavity walls didn't taken into account, as the wall specific loss are order lower than drift tube specific loss. Moreover frequency sensitivity to temperature of cavity wall is twice lower than that of drift tube.
- *COOLING*, which takes into account the process of water heating in the cooling system channels.
- *HEAT EXCHANGER*, which supplies the heat transfer values from the cooling system to the facility cold water with parameters very close to the actual unit.
- *Control Valve CV;* it determines a process of the cold water flow rate control through the heat exchanger
- *HEATER*,, by which is realized the control of water temperature, cooling the cavity drift tubes.

The system also contains time delays in the water pipes between cavity and the heat exchanger. A description of each block in details, the feedback circuits used, and modeling results will be presented.

BLOCK DESCRIPTIONS

RF POWER

This block presents the high quality cavity, where there is the well-known relation between the value of RF power $P_{RF}(t)$ dissipated on the cavity drift tubes surface and the cavity detuning:

$$P_{RF}(t) = \frac{Po}{1 + (2Q_n \dfrac{(df)_p(t) - (df)_0}{f_o})^2} \qquad (1)$$

Where Q_n is the loaded cavity quality factor, *Po* is the average RF power dissipated in drift tubes of the tuned cavity, $(df)_0 > 0$ is an initial deviation in tank frequency from the master oscillator (MO) frequency, and $(df)_p(t)$ is the tank frequency detuning due to tank heating by RF loss. In turn, it is supposed that $(df)_0 = (T_o - T_{in})S_o$, where T_0 is so-called resonance temperature, corresponding to the cavity resonance frequency 198.2 MHz (it used to be equal 25^0C); T_{in} is the initial drift tubes temperature; S_o is a sensitivity of the tank resonance frequency to the cavity drift tube metal temperature.

The RF power block presents the so-called self-regulating circuit, which is a consequence of the cavity with high quality factor. It can be said that this circuit creates additional negative feedback during overheating of the tank and positive feedback during underheating.

DRIFT TUBES

The block is described by means of the well-known [2] differential equation (DE):

$$C_m M_m \frac{dT_{md}}{dt} = P_{RF} + (hA)_m \left(\frac{T_{hi} + T_h}{2} - T_{md}\right), \quad (2)$$

where T_{md} - metal (copper) temperature, $(hA)_m$ - product of the copper heat transfer coefficient (h), and the heat exchange square in cooling channels (A). $C_m M_m$ – is the product of the copper specific heat and drift tube copper mass. As a rule value of $(hA)_m$ can't be calculated theoretically but is determined experimentally in a steady state [3]. DE (2) determines the process of tank metal heating by RF power P_{RF}, dissipated in the drift tubes, relatively to the average water temperature T_{ha}:

$$T_{ha} = \frac{T_{hi} + T_h}{2}. \quad (3)$$

Here T_{hi} and T_h are temperatures of water at the output and input of the cavity drift tubes cooling channels.

COOLING

The block presents the process of the heat transfer from the metal to the water in the closed cooling system. As follows from expression (2) value of the heat power, which is transmitted to the water during transient, is equal:

$$P_{wat} = (hA)_m (T_{md} - T_{ha}) \quad (4)$$

Taking into account expression (4) and the dependence water temperature on the water mass in the drift tubes cooling channels, one can get the next differential equation:

$$C_w M_w \frac{dT_{hi}}{dt} = (hA)_m (T_{md} - T_{ha}) + C_w F_0 (T_h - T_{hi}), \quad (5)$$

where C_w is the water specific heat, M_w – mass of water in the cavity drift tubes cooling channels, F_0 – water pump flow rate. Substituting in (5) expression (3) one can get final DE for temperature T_{hi}:

$$2C_w M_w \frac{dT_{hi}}{dt} = 2(hA)_m T_{md} - (2F_0 C_w + (hA)_m) T_{hi} + (2F_0 C_w - (hA)_m) T_h \quad (5')$$

HEAT EXCHANGER

For describing of processes in the heat exchanger (HE) it's used the next system of differential equations:

$$\begin{aligned} C_w M_h \frac{dT_{ho}}{dt} &= (UA)_{ov}(T2 - T1) + C_w F_h (T_{hi} - T_{ho}) \\ C_w M_c \frac{dT_{co}}{dt} &= (UA)_{ov}(T1 - T2) + C_w F_c (T_{ci} - T_{co}) \end{aligned} \quad (6)$$

In expression (6) $T1 = \frac{1}{2}(T_{hi} + T_{ho})$, $T2 = \frac{1}{2}(T_{ci} + T_{co})$, F_c and F_h are flow rates of cold and hot water. T_{ci} is a "cold" water temperature at the HE input, T_{co} is a cold water temperature at the HE output, T_{ho} is a "hot" water temperature at the HE output, and M_h and M_c are masses of water inside of the hot and cold water channels of the HE.

$$(AU)_{ov} = A \frac{U_1 U_2}{U_1 + U_2} \quad (7)$$

Here $U_1 = K_1 (F_h)^{0.8}$ is a heat transfer coefficient for the hot water into the thin metal wall between the hot and cold waters. $U_2 = K_2 (F_c)^{0.8}$ is a heat transfer coefficient for the metal wall into the cold water. A is the square of the heat exchange surface. Coefficients K_1 and K_2 in expression (7) are selected to provide the best coincidence of the dependence of $(AU)_{OV}$ on F_h and F_c with that of the real heat exchanger.

CONTROL VALVE CV

The control valve changes a value of cold-water flow F_c at the input of the heat exchanger, if the absolute value of temperature or frequency error signal exceeds permissible value (so called "gates"). If it is occurred the cold water flow rate F_c begins to change with constant speed so long as error signal returns in "gates". So in the CV block there is a possibility to change dimension of "gates" - by means of two Simulink blocks *Relay*, and a speed of the cold water changing-by means of the corresponding choice of a gain G1 (see Fig.1) and upper and lower limits of *Integrator*.

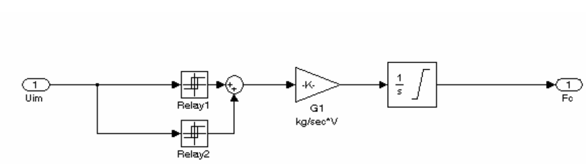

Figure 1: Model of the block CV.

HEATER

This block is the main device, which ensures the stabilization of the resonance temperature of the cavity by means of water temperature control in the drift tube cooling system. The block can be presented as:

$$C_w M_w \frac{dT_h}{dt} = P_h + C_w F_h (T_{ho} - T_h), \quad (8)$$

where P_h is controllable value of the heater power, T_h – temperature at the heater output, T_{ho} - temperature at the heater input.

FEEDBACK CIRCUITS

Modeling of the blocks cited above can be realized by means of the standard Simulink blocks using expressions (1), (2), (5'), (6) and (8). But till now some devices were disregarded, in particular - measuring elements, which created error signals for the FCS during both warming up the cavity before RF power inputting (temperature mode of operation TM) and after RF turning on (frequency mode FM); PID controller, which gains and transforms the temperature and frequency error signals for control of the heater and control valve with the optimal efficiency. Signal of the temperature error is produced as result of comparison of the resonance temperature T_o and temperature T_{hi} of water in the drift tube cooling system. Naturally, the last one coincides with temperature of the metal during cavity warming up when RF power is turned off. After RF power switching on the water and metal temperatures become different. At that, temperature water T_{sp} in a steady state and tuned cavity has to be decreased up to value: $T_{sp} = T_0 - \frac{P_0}{(hA)_m}$ In turn, the error signal has to be produced as result of comparison of MO frequency and the cavity resonance frequency. The comparison is realized by means of phase detector (PD), switched on between directed coupler (incident wave output) and cavity loop. Zero signal at the PD output corresponds to minimum of reflected wave at the second output of the directed coupler. So in the Model the error signal in FM operation was presented as $(df)_p = (T_{md} - T_0) S_0 K_{PD}$, where K_{PD} is a transfer constant of PD. Both TM and FM error signals (but each of them with separated gain) get into the same *PID controller*. Switching between modes of operation can be done in both manually and automatically.

Finally, two blocks *Time delays,* one between the main supply manifold of the cavity cooling system and block *CV* and another between the return manifold and the block *Heat exchanger,* are included in the cavity cooling system Model.

MODELING RESULTS

FCS modeling has been carried out for the third cavity of the DTL system. At that, during modeling it is necessary to keep in mind the values of the *Initial condition* temperature, T_{in}, in the Simulink block *Integrator* as well as the *Initial input* temperature, T_{ii}, in the *Transport Delay* blocks.

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. So in every above-mentioned block, described by a first order differential equation, there is one *Integrator* block with initial conditions that depend upon the starting temperature value, T_{in}, before simulation. As a rule, if the preliminary heating is realized by outside sources such as a *Heater* then $T_{in}= T_{ii}$.

As an example, in fig.2 the step responses of RF power P_{RF} (kW), common cavity detuning $df = (df)_o-(df)_p$ (kHz), cavity output water temperature T_{hi} (deg C), the cold water flow rate Fc (kg/sec) through the heat exchanger, the heater power P_h (kW) are shown. Here P_o=26kW (RF power pulse length - 400µs, repetition rate – 50 Hz), T_{ii}=T_{in}=20^{0}C and step input of RF power P_o took place at 1500-th sec after turning on of the system in TM operation; T_o=25^{0}C, F_o=10kg/sec; the chilled water temperature T_{ci}=10^{0}C. All other values, which are part of expressions (1) - (8), correspond to the third DTL cavity. In turn, PID controller parameters are chosen so that to minimize the transient without exciting of the closed system. As shown from the dependencies step input of RF power in the cavity results in noticeable changing in water cooling system operation and RF power level in the cavity. At that, duration of transient achieves 12-15 min and this value is close to the real one. The presented dependencies demonstrate the possibility of the Matlab Simulink Model to easily and quickly provide numerical estimations of transients in the FCS. It is important to

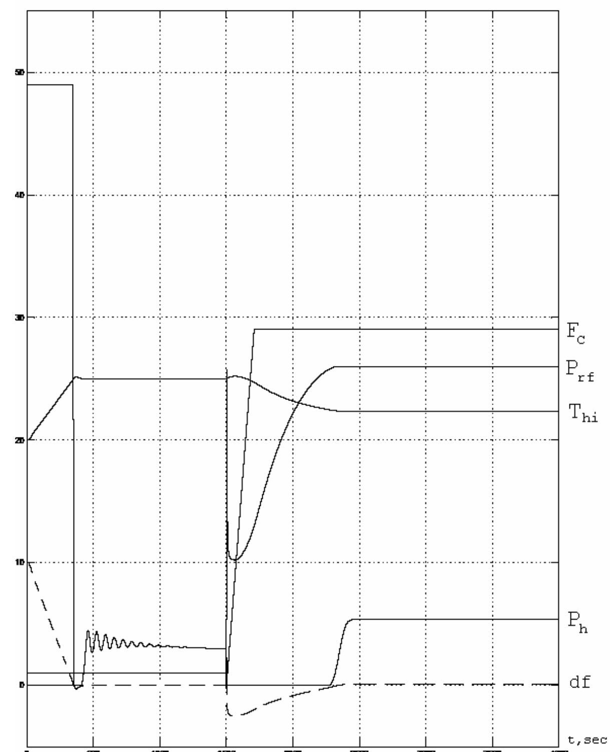

Figure 2: Example of transients in the DTL FCS Model.

use the Matlab possibilities in process of design and upgrade of the frequency control system. Just the such work was begun at DTL cavities of INR Linac this year. We expect, that broad abilities of Matlab will be able to check and optimize any operation condition of interest in the FCS environment.

REFERENCIES

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[3] F.G.Shinsky "Process Control Systems", McGraw-Hill, third edition, NY, 1982