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Abstract

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Abstract

The LCLC RF gun requires a water based thermal system to tune the resonance frequency of the cavity to $2856.03MHz$. The RF system operates in pulsed mode with bursts of $2-3\mu sec.$ duration at a repetition rate of $30-120Hz$. The thermal system operates in combination with the low-level RF system (LLRF) to set the operation point of the cavity. The LLRF system controls the amplitude and phase of the cavity voltage and defines the necessary slow signals to the thermal system. The thermal system operates by pre-heating / pre-cooling the water and mixing both channels to achieve the temperature to control the cavity resonant frequency. The tune control of the RF gun includes two systems with different dynamics. The dynamics of the thermal system is slow while the RF system is fast. Additionally, different actuators in the system present limits that introduce non-linearities to be taking into account during the start up process. Combining these characteristics, a controller is designed for the resulting hybrid system that allows convergence in large for all the operation conditions and achieve the performance in the magnitude and phase of the cavity voltage required around the operation point.

INTRODUCTION

The operation conditions and the performance of the RF gun for the Linac Coherent Light Source (LCLS) are controlled with a combination of both the thermal and the RF systems. The first one controls the tuning of the RF cavity regulating its internal temperature and the second system adjusts the phase and amplitude of the EM field inside the cavity. Both systems are linked through a slow channel that defines the set-points for the thermal system variables based on the estimation of the cavity resonance frequency performed by the LLRF system.

The thermal system is dedicated only for the RF gun and controls the temperature of the cavity by mixing two pre-regulated water flows, one hotter and the other cooler than the regulated water temperature. The RF system operates at $2856.03MHz$ in pulsed mode with bursts of $2-3\mu sec.$ duration at a repetition rate of $30-120Hz$. The amplitude and phase of the cavity voltage is controlled by the LLRF system, at a rate of $30-120Hz$, by adjusting the power delivered to the RF cavity by the klystron station 20-6.

A computer simulation model of both systems was created to study the transient behavior and the performance in steady state of the RF gun and mainly to assist in the design and to define the location of the major elements of the thermal system. Based on that model, the control loops for both the RF and the thermal system were designed and commissioned.

This paper describes the overall system, focusing in the modeling and simulation of the thermal system. Design criteria for the components and control algorithms are discussed and simulation and experimental results are presented.

SYSTEM DESCRIPTION

The RF system operates in pulse mode, generating RF pulses at a repetition rate of $30Hz$ in the first operation stage of the system, to finally operate at $120Hz$. The average RF power heating the cavity is about $1KW$ for the $30Hz$ repetition rate, increasing to $4KW$ at $120Hz$. The amplitude and phase of the cavity voltage is controlled adjusting the power delivered by the klystron to the RF cavity. This power is controlled by operating a feedback loop that updates those variables at the station operation rate. More details of the LCLS LLRF system are described in [1].

Fig. 1 depicts a general block diagram of the RF gun system, including the thermal and RF systems. Both systems are linked by the water control algorithm, which is based on the cavity temperature and the cavity resonance measured by the RF system. The inlet water temperature to the RF cavity is controlled by mixing pre-regulated cold and hot water. In order to allow different operation conditions of the RF gun, the inlet water temperature required by the RF cavity changes in wide range to compensate dissipated powers between 0 to $4KW$. To keep the resolution in the control of the final temperature, the hot water and cold water pre-regulated supplies track the required inlet water temperature. The range of variation of the inlet water temperature for normal operation is between $64.4^oF(18^oC)$ and $100.2^oF(38^oC)$, while the hot water can be regulated between $67.4^oF(19.66^oC)$ and $103.2^oF(39.55^oC)$ and the cold water controlled between $61.4^oF(16.33^oC)$ and $97.2^oF(36.22^oC)$.

Calibrated Resistor Temperature Detectors (RTD) included inside the RF cavity and the measure of the load angle ϕ_L of the cavity are used to estimate the resonance of the cavity. Based on these signals, a control algorithm is implemented in EPICS to define the set-points of the thermal control loops.

THERMAL SYSTEM AND MODELING

A scheme of the thermal system is depicted in Fig. 2. The thermal system uses as primary water source the SLAC

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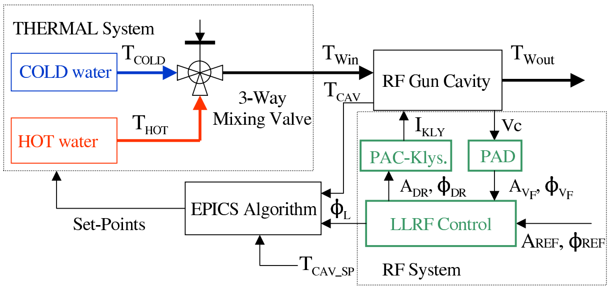

Figure 1: RF Gun System Block Diagram.

water distribution and preheats this water with a heat-exchanger (HTX-2). This preheated water flows through the heater (HTR) where it is regulated to the temperature defined by the set-point T_{HOT}. The heat recover HTX-2 allows using the heat excess of the water leaving the RF cavity, thus reducing the necessary power rating of the heater. The hot water leaving the heater is diverted in two flows, one of them is mixed with the cold water in the final mixing valve. The other flows through the second heat-exchanger (HTX-1) used to generate the cold water source. The cold water temperature is regulated to the temperature set by the set-point T_{COLD} by adjusting the flow of chilled water at $56 - 60^oF$ $(13.3 - 15.55^oC)$. Both the hot and cold water sources are mixed to regulate the inlet water temperature to the RF cavity. The set point T_{Win} of the inlet water is defined by measuring the tune of the RF cavity using the RF LLRF system capabilities. Based on this recirculating design to achieve the specifications, the size of the thermal devices can be reduced. Therefore, the complete system can be placed near to the RF gun limiting to a minimum the transport delay in the system. This condition improves enormously the time response of the system during transients (start-up).

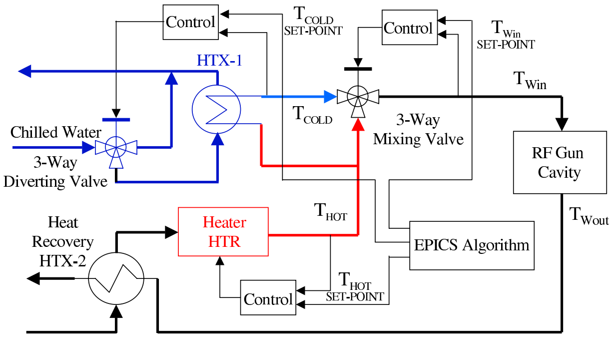

Figure 2: Thermal System Block Diagram.

For thermal devices, the relationship among their state variables is described by partial differential equations (PDE). The model created in the simulation is a reduced one that approximates the PDE by a set of ordinary differential equations (ODE). As such, the 3-dimension devices are simplified assuming equal behavior for all the points in the 2-dimensions perpendicular to the flow and sectioning the system in the flow direction in elemental pieces. A trade-off between complexity in the simulation and precision of the model exist to define the number of sections representing the device. The model defined by the ODE set is non linear.

RF SYSTEM AND MODELING

The pulsed power is delivered from the klystron station 20-6 to the RF gun through a long wave guide, dissipating almost all the reflected power from the cavity during the front/trailing edge of the RF pulse. The amplitude and the phase of the cavity voltage are detected by the Phase and Amplitude Detector (PAD), a LLRF sub-circuit that measures the signal taking 128 samples at $102MHz$ on the flat area of the pulse and averages those samples to give an estimation of the IN-PHASE/QUADRATURE magnitude per pulse. The high power RF pulse is generated by shaping in the LLRF modulator a pulse such that the reflected power is minimized. The amplitude of the pulse and the relative phase of the $2856.03MHz$ RF signal is adjusted every time the pulse is generated by the Phase and Amplitude Controller (PAC). (Figure 1).

The control of both the amplitude and phase of the cavity voltage is performed by an algorithm that calculates the amplitude/phase reference for the PAC modulator based on the amplitude/phase measured by the PAD demodulator. This algorithm operates at a rate of $30Hz - 120Hz$.

Since the closed loop control is performed at a repetition rate equal to the pulse rate and input/output cavity samples are calculated per pulse after measuring the variables in steady state, the relation between input and output cavity variables is defined by a static map parametrized by the cavity de-tune. Defining $V_{C_{IN}}(t)$, $V_{C_Q}(t)$ the output variable of the cavity and $I_{G_{IN}}(t)$, $I_{G_Q}(t)$ the forward input current to the wave guide, the n^{th} samples of the cavity variables at $t = n\ T_s$ are related by

$$\begin{bmatrix} V_{C_{IN}}(n) \\ V_{C_Q}(n) \end{bmatrix} = \begin{bmatrix} \frac{\sigma^2 R_C}{\sigma^2+\Delta\omega^2} & -\frac{\sigma R_C\ \Delta\omega}{\sigma^2+\Delta\omega^2} \\ \frac{\sigma R_C\ \Delta\omega}{\sigma^2+\Delta\omega^2} & \frac{\sigma^2 R_C}{\sigma^2+\Delta\omega^2} \end{bmatrix} \begin{bmatrix} I_{G_{IN}}(n) \\ I_{G_Q}(n) \end{bmatrix}, \quad (1)$$

where R_c cavity shunt resistance including the wave guide loading, $\sigma = 1/2R_cC$, and $\Delta\omega = \omega_{RF} - \omega_o$, the cavity de-tune. The control algorithm operates in AMPLITUDE/PHASE formalism and it is an integral control for the PHASE and an integral control with gain adaptation for the AMPLITUDE. The klystron driving signal components are calculated as

$$\phi_{DR}(n+1) = \phi_{DR}(n) + G_\phi(\phi_{REF} - \phi_{V_F}(n)), \quad (2)$$

$$\text{for} \quad |(\phi_{REF} - \phi_{V_F}(n))| \leq \phi_{ERROR}max$$

$$A_{DR}(n+1) = A_{DR}(n) + G_A \frac{A_{DR}(n)}{A_{V_F}(n)}(A_{REF} - A_{V_F}(n)),$$

$$\text{for} \quad A_{corr}min \leq \frac{A_{REF}}{A_{V_F}(n)} \leq A_{corr}max.$$

SYSTEM DESIGN

The RF gun is specified for operation in pulsed mode at a repetition rate of $30 - 120$ Hz with an electric field between 100MV/m - 140 MV/m. The voltage phase stability is 0.1 deg RMS and the voltage amplitude error less than 1/1000 RMS measured during a period of 2 sec. These specifications set the operation conditions for the thermal system as described above (T_{Win} $=64.4^oF - 100.2^oF$) and the regulation of the inlet water temperature better than 0.05^oC (0.1^oF).

The overall system is perturbed by intrinsic variations in the output klystron power (e.g. power supply variation / ripple), noise and errors associated with RF measurements, SLAC water distribution temperature variations, etc.. The complete system combines SLOW and FAST dynamics. The thermal system is intrinsically slow, defined by the transport delays, the 4-8 sec full stroke mixing and diverting valves and the thermal time constant of the devices and the RF cavity. The RF system fast dynamics are characterized by a static map between input/output variables at sampling rates of $30 - 120Hz$.

The separation between slow-fast dynamics allows designing the feedback loops independently, considering the coupling variables as either parameters or fast perturbations. The RF feedback can be designed considering that the cavity temperature or the cavity resonance frequency is a parameter that change in a defined range. Assuming the perturbations in the RF system are additive noise and errors in the cavity voltage detection and forward power perturbation in the klystron, then $V_F(t) = \beta V_C(t) + n_I(t)$ and $I_G(t) = I_K(t) + \Delta_K(t)$. Combining these equations with (1) and (2), the cavity voltage $V_C = [A_C\ \phi_C]^T$ in frequency domain ($z = e^{i\ \omega\ T_s}$) is

$$\begin{aligned} V_C(z) &= T(z,\Delta\omega)\, n_I(z) + S(z,\Delta\omega)\, \Delta_K(z) \\ &+ T(z,\Delta\omega)\, V_{REF}(z). \end{aligned}$$

where $T(\omega, \Delta\omega)$ is a matrix defining the transfer function between output and reference signals and $S(\omega, \Delta\omega)$ is the sensitivity matrix and $V_{REF} = [A_{REF}\ \phi_{REF}]^T$.

The thermal system is non-linear, where the RF power applied to the cavity appears as a fast external perturbation. To simplify the overall controller, individual proportional-integral units (PI) where used to control the principal variables. The criteria used to define the controller parameters was based on the assumption that each feedback loop operates independently, modeling the coupling with the other loops as a perturbation. Based on these assumptions and a linearized model of the thermal devices, the PI parameters were estimated using the Internal Model Control (IMC) strategy [2].

During the commissioning of the system the RF gun operates at a repetition rate equal to $30Hz$. Under this condition, the T_{HOT} and T_{COLD} set-points are keep constant at 90^oF (32.22^oC) and 100^oF (37.77^oC), while T_{Win} is controlled by the EPICS algorithm. Steady state and transient results measured during commissioning and operation are depicted in Figs. 3 and 4. The first plot shows the RF cavity temperature T_{cav} and the inlet water temperature T_{Win} measured during 24 hrs with the RF cavity operating at $V_c = 5.8MV$. The second plot depicts the the transient response of T_{cav} and T_{Win} after the RF power is turned OFF and re-applied 6 minutes later. The resonance frequency of the cavity change at $\tilde{6}5KHz/^oC$.

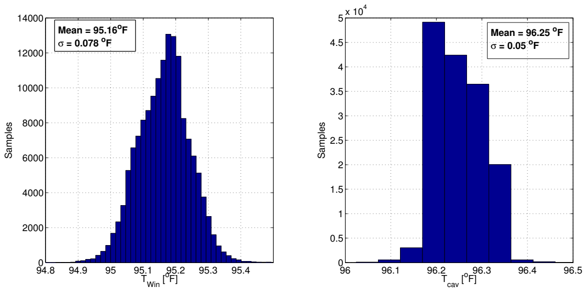

Figure 3: Histogram of the inlet water temperature T_{Win} and RF cavity temperature T_{cav}. (Sampling. rate = 1 Hz).

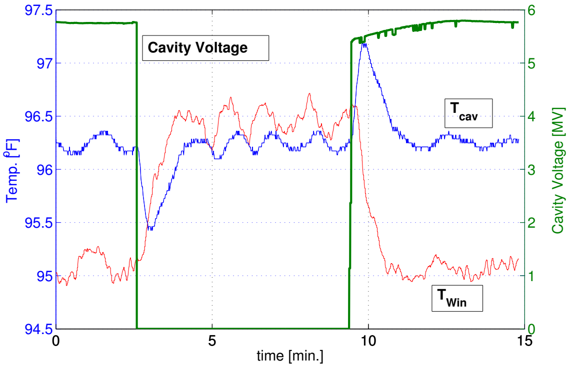

Figure 4: Time response of inlet water temperature T_{Win} and RF cavity temperature T_{cav} to a sudden change in RF power.

CONCLUSION

The analysis and design of LCLS RF gun control system have been presented. Simulations of both the thermal and RF system were conducted to define the large signal behavior of the system and define the rating of the thermal devices. The RF gun has been commissioned and operated at $30Hz$. Future improvements are necessary in the slow control algorithm to define variable set-points for all the thermal variables. This feature is required when the RF gun operates at $120Hz$.

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