Performance of FPGA controller in ISAC-1 accelerator chain

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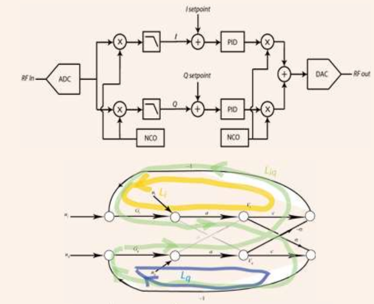
Abstract

The LLRF of five of TRIUMF's ISAC-1 accelerator cavities have been replaced by 3 similar FPGA based system. Excluding the 3 frequency prebuncher, these are the 2 Drift Tube Linacs and 2 bunchers, namely DTL4, DTL5, HEBT11 and HEBT35. The operating frequencies of these cavities are 11.76 MHz, 35.36 MHz for the bunchers and 106.08 MHz for both DTLS, with the RF power ranges from 1.5 kW and 13 kW for the 2 bunchers to more than 20 kW for the DTLs. These LLRF uses internal digital phase locked loops for frequency generation and synchronization, feedback control using Amplitude/Phase regulations. The FPGAs also have internal stepper motor controller for resonance control. Various modes of resonance control are possible, including phase comparison and minimum seeking slide-mode control. Operational performances including frequency generation and synchronization, amplitude and phase noises, tuning speeds, compatibility to original remote controls, are reported.

Comparison between I/Q control and Amplitude/Phase control

I/Q control



$$a=\frac{1}{s\tau+1},\quad b=\frac{\tau\Delta\omega}{(s\tau+1)^2},\quad c=\cos\psi \text{ and } \sigma=\sin\psi$$

Signal flowchart for I/Q control showing cross-talk due to loop length and detuning

$$\begin{pmatrix}V_i\\V_q\end{pmatrix}=\frac{1}{(s\tau+1)^2}\begin{pmatrix}s\tau+1 & -\tau\Delta\omega\\ \tau\Delta\omega & s\tau+1\end{pmatrix}\begin{pmatrix}u_i\\u_q\end{pmatrix} : \tau\Delta\omega$$

State equation for I/Q control

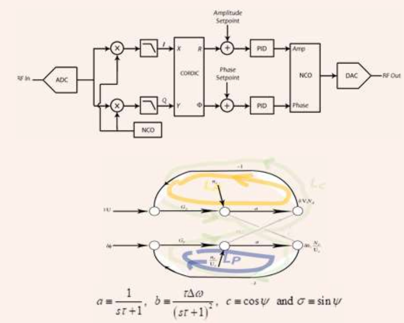
$$\frac{N_A}{n}=\frac{a}{1+Ga}\left[1+\sigma^2\frac{2Ga}{(1+Ga)^2}\right]$$

Amplitude noise for I/Q control

$$\frac{N_P}{n}=\frac{a}{1+Ga}\left[1+\sigma^2\frac{2Ga}{(1+Ga)^2}\right]$$

Phase noise for I/Q control

Digital Amplitude/Phase Control



$$a=\frac{1}{s\tau+1},\quad b=\frac{\tau\Delta\omega}{(s\tau+1)^2},\quad c=\cos\psi \text{ and } \sigma=\sin\psi$$

Signal flowchart for Amplitude/Phase control showing cross-talk due to detuning

$$\begin{pmatrix}\delta V\\ \delta\theta\end{pmatrix}=\frac{1}{(s\tau+1)^2}\begin{pmatrix}s\tau+1 & s\tau U_0\tau\Delta\omega\\ -\frac{\tau\Delta\omega}{U_0} & s\tau+1\end{pmatrix}\begin{pmatrix}\delta U\\ \delta\phi\end{pmatrix}$$

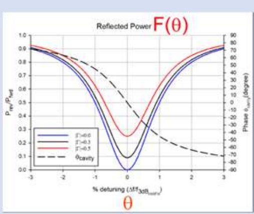
State equation for Amplitude/Phase control

$$\frac{N_A}{n_A}=\frac{a}{1+G_Aa}$$

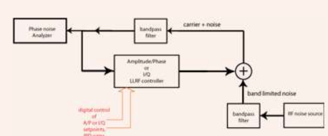
Amplitude noise for Amplitude/Phase Control

$$\frac{N_P}{n_P}=\frac{a}{1+G_Pa}$$

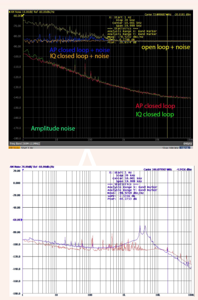
Phase noise for Amplitude/Phase control



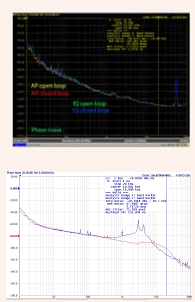
Reflected Power F(θ) vs Tuner Position θ



Experimental setup to measure noise
FPGA is programmed and reprogrammed to be either
I/Q feedback control or Amplitude/Phase control

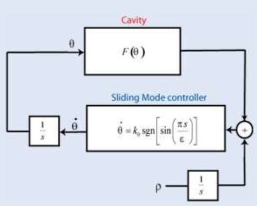


Cavity Amplitude noise



Cavity phase noise

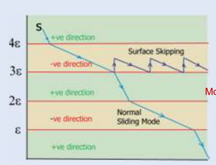
Sliding mode tuning control with surface skipping



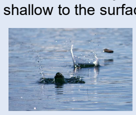
Sliding function $s(t)=P_r+\rho t$

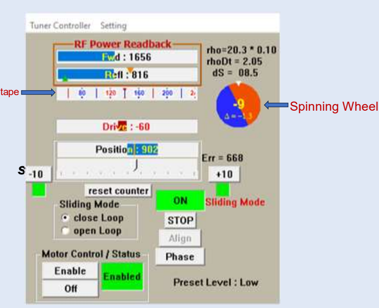
s is stationary when $\frac{dP_r}{dt}+\rho\approx<0$

Extremum (Minimum) Seeking Sliding mode controller block diagram

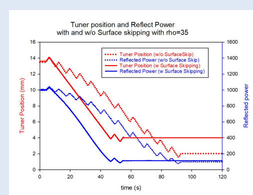


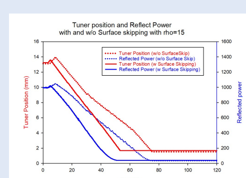
Surface skipping enables tuner/stone to stay in the region where the trajectory is shallow to the surface



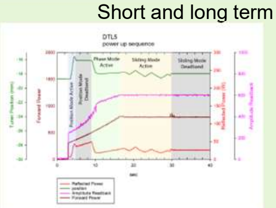


GUI tuning aid showing "Spinning Wheel" And "Moving Tape"

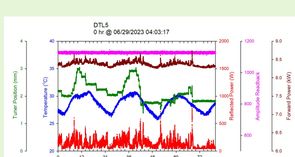




Short and long term performance of DTL5



Tuner response to automatic powering-up sequence showing tuner position responding to changes in reflected power



4-day plot showing tuner position tracking diurnal changes in temperature.

Conclusion

Calculations and measurements have shown that I/Q and Amplitude/Phase regulations provides comparable performances, but I/Q regulation requires control of loop phase to prevent cross-talks.

The position preset, phase alignment and sliding mode controllers are used in the new ISAC-1 resonance control. Based on each system's strength and weakness, they are being used at different stages of powering up. The position preset is used during the initial stage of powering up, when the RF is not yet established or is still in pulse mode. When the RF level reaches a preset value, and switching from pulse to CW is successful, the control enters into phase alignment mode. At this stage the RF will continue to be ramping up. When phase alignment is completed, the control will switch to sliding mode. When the reflected power is average below the prefixed value the sliding mode will enter in a sleep mode, only to be awoken when this value is exceeded the thresh-hold. When choosing for the sliding mode controller, it is advantageous to choose a larger rho, as the amount of chattering can be suppressed by the "switch surface skipping" method.