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RF cavity resonant control using minimal seeking Sliding mode controller

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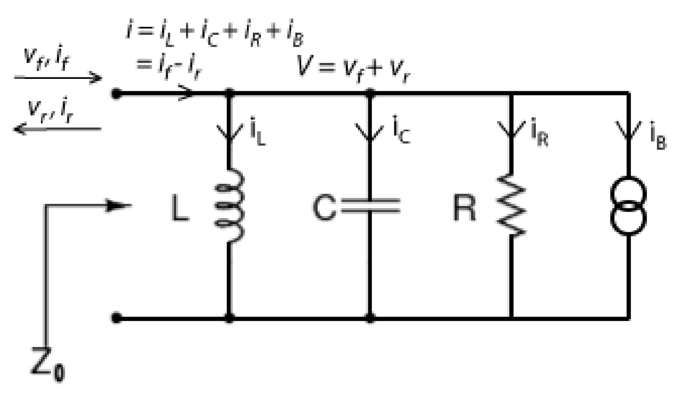
Abstract

Accelerating RF normal conducting cavities having Quality Factors of over 10^3. These cavities must be constantly tuned to maintain resonance for maximum power efficiency.Traditional tuning method uses 'phase comparison method' by monitoring the phase shift across the input and output of the cavity. This method suffers from phase drift due to diurnal temperature variations. Since 2017, TRIUMF ISAC-1 cavities are tuned using minimal seeking sliding mode controllers, which eliminate effects drift due to temperature changes. As with all extremum seeking algorithm, chattering[5,6] is present in the system, especially near the end-stage. This paper also includes a new chattering suppression method known as 'surface skipping', which is slated to be installed in ISAC-1 LLRF upgrade in 2023.

RF cavity equations



Cavity voltage V — Cavity phase

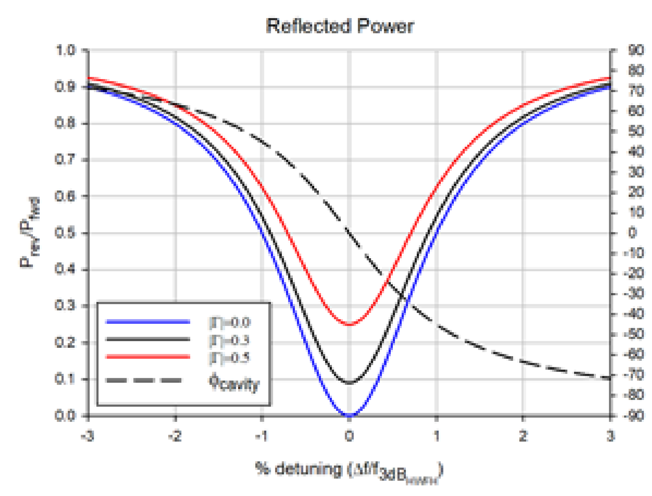
$$V \cong \frac{\Gamma+1}{1+(\Delta\omega\tau)^2}(1+j\Delta\omega\tau)v_F \qquad \phi = \tan^{-1}\Delta\omega\tau$$

Reflected voltage v_r $\quad v_r \cong v_f \frac{\Gamma + j\Delta\omega\tau}{1-j\Delta\omega\tau}$

Reflected power P_R $\quad P_R \cong P_F \frac{\Gamma^2+(\Delta\omega\tau)^2}{1+(\Delta\omega\tau)^2}$

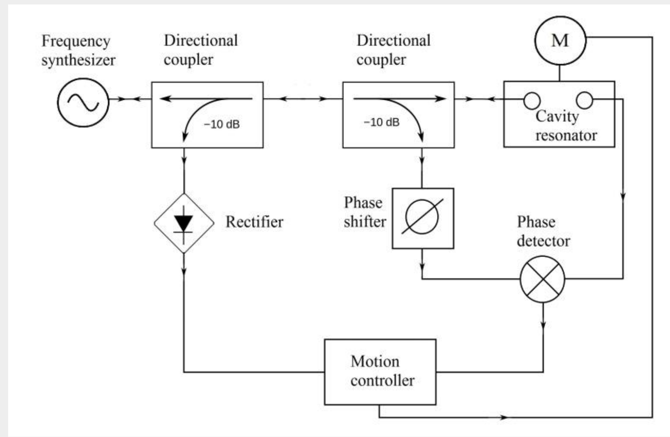
$$\frac{dP_R}{d(\Delta\omega)} = P_F\left(1-\Gamma^2\right)\tau^2\Delta\omega$$

when $\Delta\omega \to 0,\quad \frac{dP_R}{d(\Delta\omega)} \to 0,\quad \phi \to 0$



$$V \to V_{MAX} \text{ when } \Delta\omega \to 0$$

Phase alignment method



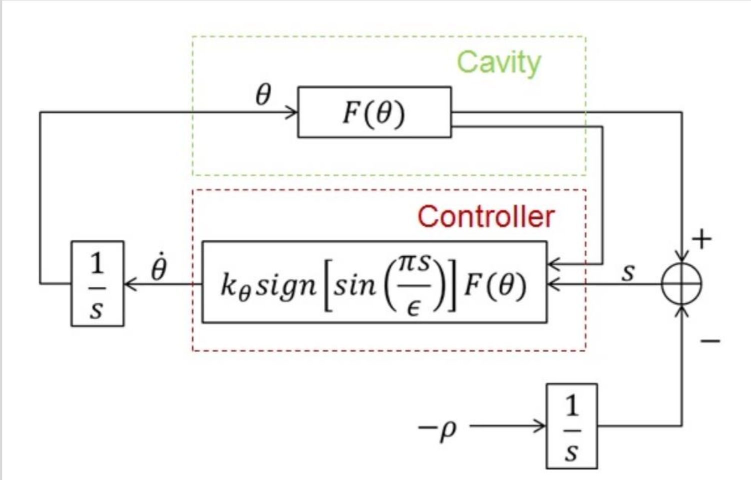
Disadvantage:

Sensitive to temperature and power dependent phase shift

Advantage:

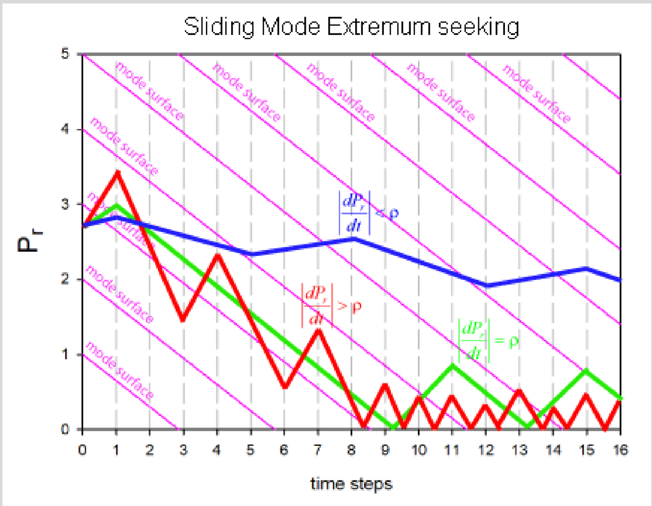
Monotonic response

Sliding Mode Extremum Seeking



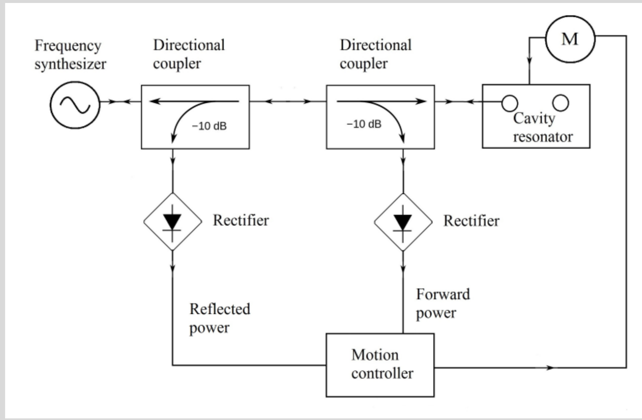
Functional diagram for sliding mode Extremum seeking

$$\dot{\theta} = k_0 \operatorname{sgn}\left[\sin\left(\frac{\pi s}{\varepsilon}\right)\right]F(\theta) \qquad s(t) = F(\theta) + \rho t$$

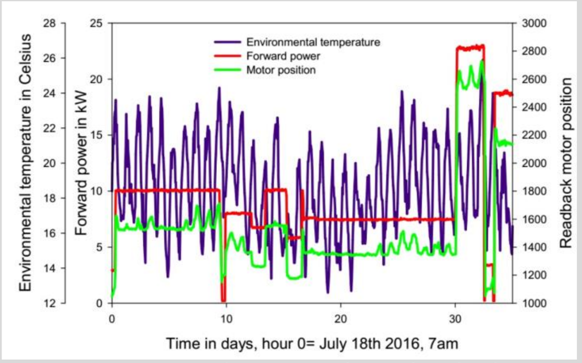


Sliding Mode Algorithm

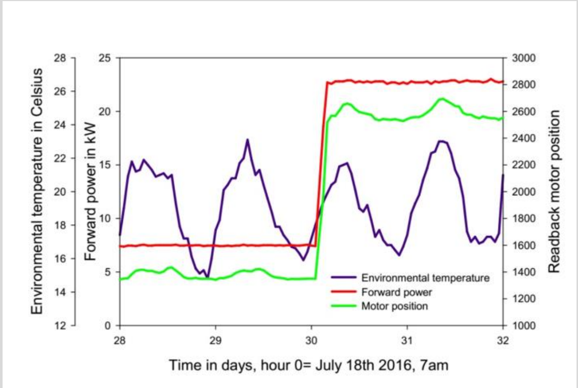
if ((s %2) >=0 && (s %2)<1) tuner in;
else tuner out;



Block diagram for sliding mode Extremum seeking



Long term performance (>35 days) of Sliding Mode in DTL5 showing diurnal temperature variation

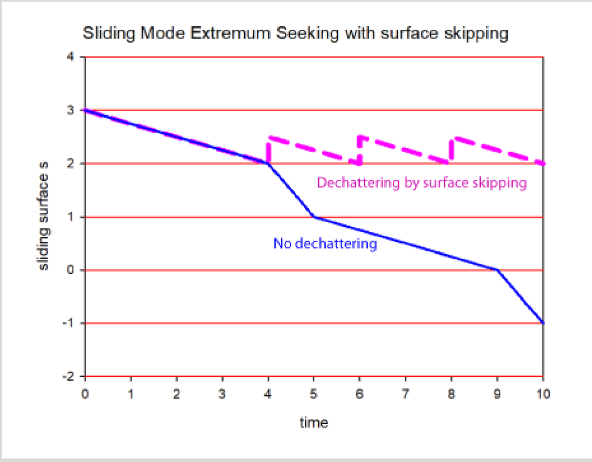


Expanded view of above showing 4 days

Sliding Mode surface skipping

Stone skimming
Image by Killy Ridols - Pstsgonia

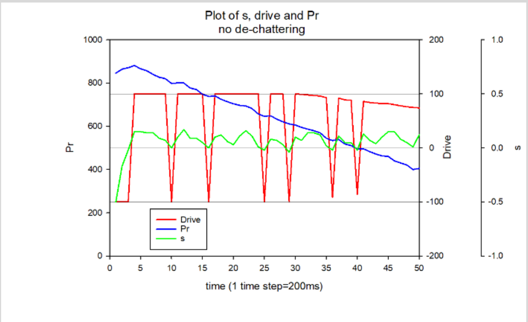
Depending on the rate of approach toward a sliding surface, the sliding function can be made to ‘skipping’ against the surface, resulting in no tuner directional change and dechattered.



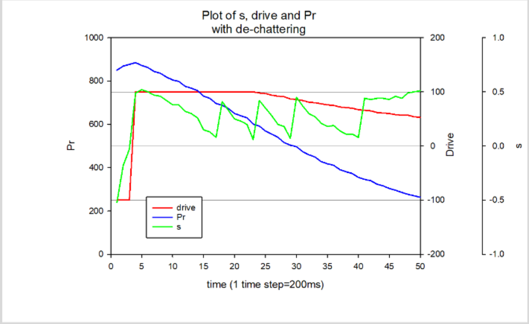
Sliding surface skipping
For dechattering

Algorithm for surface skipping dechattering

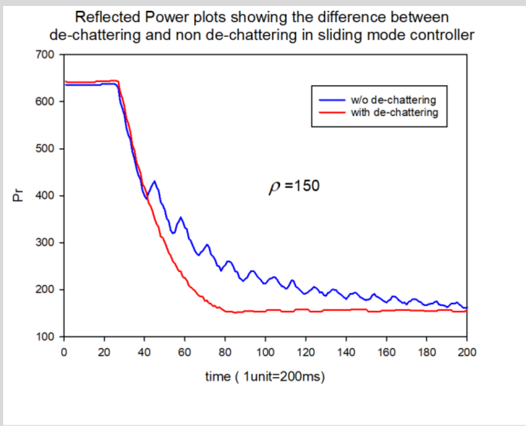
*if (reversePower < 1.25*slidingMode.deadband) dtx = 0.5*deltaTime;*
*if (reversePower < 1.00*slidingMode.deadband) dtx = 0.25*deltaTime;*
and to go into hibernation using the “end detection”:
*if (fabs(devAvg.val.avg) < 0.5 && reversePower < 1.5*slidingMode.deadband) {…}*
if (devAvg.val.avg < 1.0 && reversePower < slidingMode.deadband) {…}
if (SGAvgRev.val.der>0 && reversePower < slidingMode.deadband) {…}



Simulated result of cavity without Surface skipping dechattering.



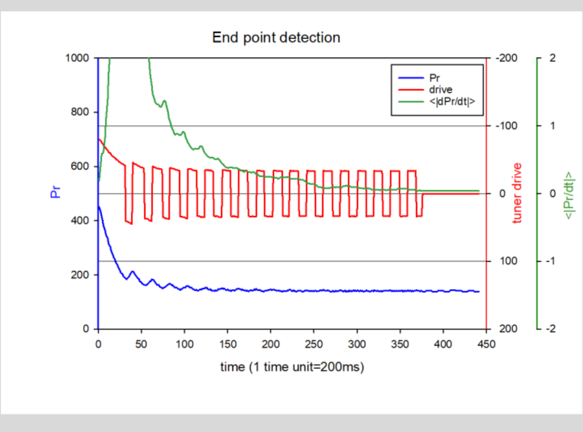
Simulated result of cavity with Surface skipping dechattering.



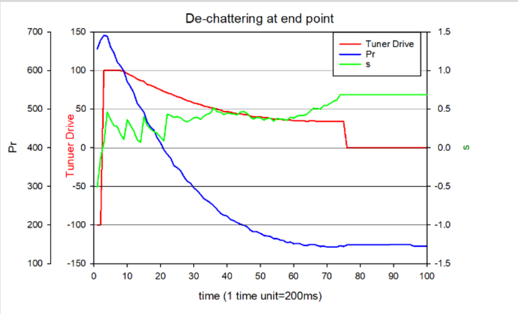
Comparison of Simulated result of cavity with and without Surface skipping dechattering.

End-point detection

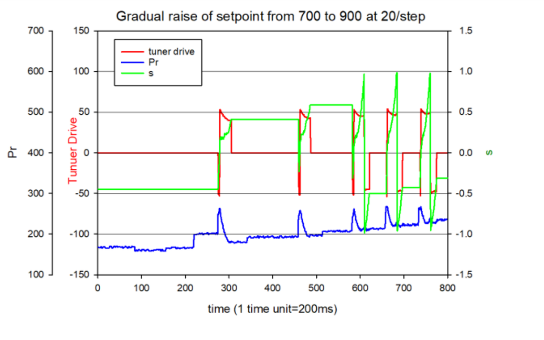
In any extremum seeking algorithm, the algorithm will continually hunting for the extremum, even when the extremum has been reached, Thereofor some end-point detection routine should be used to terminate the seeking movement.



Termination based on P_R only



Termination based on $\left\langle\left|\frac{dP_R}{dt}\right|\right\rangle <\approx \varepsilon$



Waking up from end-point suspension due to setpoint changes

Conclusion

The position preset, phase alignment and sliding mode controllers will be used in the new ISAC-1 resonance control. Based on each system’s strength and weakness, they will be used at different stages of powering up. The position preset mode is used during the initial stage of powering up, when the RF is not yet established and 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. Using a combination of these three modes, the system will benefit from fast ramp-up and resilient to diurnal temperature variations.

Reference

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[5] J. Gulder, V. I. Utkin, “The Chattering problem in sliding mode systems”, Proc. 14th Intl. Symp. Of Mathematical Theory of Networks and Systems” 2000.

[6] H. Lee, V. I. Utkin, “Chattering suppression methods in sliding mode systems”, Annual Reviews in Control, Vol. 32 Issue 2, 2007, p.179-183.