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A controller for 97 MHz super-conducting QWR for NSC LINAC booster

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Abstract. A resonator controller has been implemented to stabilize the amplitude and phase of rf fields in the super-conducting resonators of NSC LINAC. Due to reduced losses these resonators have intrinsic band width of the order of 0.1 Hz at 97 MHz whereas the vibration-induced center frequency changes are of the order of a few tens of hertz. In the control strategy followed, the resonator is made the frequency selective part of an oscillator. The phase lock is achieved by dynamically adding a phase shift in the oscillator. A slow tuner minimizes the slow drifts in the resonator center frequency. In this paper we present the control strategy, implementation details and performance obtained with this controller.

Keywords. Resonator; variable reactance method; dynamic phase control; phase; amplitude stabilization.

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1. Introduction

The super-conducting bulk niobium resonators of NSC LINAC have Q-values in the range of 10^9. This implies that for a center frequency of 97 MHz the band width of the resonators is around 0.1 Hz. For an efficient acceleration of charged particles the amplitude and phase of rf fields in the resonators have to be stabilized with respect to the suitable references. The center frequency variation of the resonator is the main disturbance to the stabilization process. Vibration induced center-frequency changes are of the order of a few tens of hertz in these resonators. In addition, the helium pressure variation can shift the resonant frequency by hundreds of hertz. Since these two disturbances occur on two very different time scales, different strategies are adopted to counteract them. To counteract the fast frequency variations, the resonator is supplied with the additional reactive power [1]. For this scheme to work efficiently the resonator is suitably over-coupled with the power amplifier. Deforming the resonator using a slow tuning mechanism minimizes the slow variations of the resonator, center frequency reducing the load on the fast tuner. This results in more appropriate utilization of the dynamic range of the fast tuner and also the overall power requirement for the control comes down. In this paper we present the control strategy, implementation details and the performance obtained with this controller.

2. Control strategy

In order to decide upon the appropriate choice of the control strategy an experimental determination of the disturbance scenario, observed through the variations of center frequency changes of the resonator, revealed that most of the power of fast frequency variations lies between 65 Hz and 2 kHz. The majority of the peaks in the center frequency deviations are below 20 Hz but with occasional peaks going up to about 30 Hz. The slow component is due mainly to the helium pressure variations in the system. The total slow drift, over a period of several minutes, can be as high as a few hundred hertz, following any major disturbance in the plant. A cyclic variation, with a period of about 2.5 s, is also present due to helium plant. The amplitude of this variation is about 10 Hz. These measurements were taken in a test cryostat, where the resonator is supported only from the top. Also the helium plant was being run to cater to only the test cryostat. These observations indicate that the disturbances in the working LINAC would be much less with a better mounting of the resonators and optimal load conditions for the helium plant.

Two possible strategies were considered to counteract the fast changes in the resonator center frequency. The fast frequency variations can either be controlled by coupling a variable reactance to the resonator or by supplying the additional reactive power. In the following these are referred to as variable reactance (VCX) and dynamic phase control (DPC) methods respectively. In the practical implementation of the VCX method, a fixed reactance is coupled to the resonator via a switch that is operated periodically. The duty cycle of operation of this switch is changed dynamically to attain the phase lock. The advantage of this method is that large frequency excursions can be controlled. The rf amplifier is relieved of supplying the reactive power. But the tuning reactance and switches have to be inside the cryostat due to technical reasons. The incidental losses during switching and reactive power flow between the resonator and reactance act as a heat load on the cryogenic system. Also, being an ON/OFF type of control, some finite residual phase error is always present.

The DPC technique does not have any of the above-mentioned limitations. Practicability of the DPC technique can be ascertained by finding the total incident power requirement for phase locking. Under the optimal coupling between the power amplifier and the resonator, which occurs when the loaded bandwidth is equal to peak-to-peak frequency excursion, the total power requirement is given by the product of energy content of the resonator and the peak frequency excursion in rad/s [1]. For the resonators of the NSC LINAC with a stored energy of 0.116 J for 1 MV/m, we need about 200 W for a frequency deviation of 30 Hz at 3 MV/m. This power requirement is neither too large nor too small. Operating at, say, 4 MV/m will nearly double the power requirement. So, we can choose either of the control techniques for the NSC resonators.

Based on the DPC technique a controller has been successfully implemented for the BARC-TIFR resonators [2]. So, the other factors like the ease of implementation and available expertise have tilted our decision in favor of DPC technique. For the slow frequency variations a slow tuning mechanism is needed with either of the above-mentioned techniques.

3. The resonator controller based on DPC technique

The resonator can be accurately represented as a second-order band-pass filter around the resonant frequency. Also for the high quality factors involved, the ratio of output to input phasors (suitably scaled) is given by $1/(1+ix)$, where x is the frequency difference between the generator frequency and the resonator center frequency, expressed in terms of the number of half bandwidths. This expression suggests that if the resonator input is multiplied by $(1+ix)$, it is possible to maintain the resonator output constant both in phase and amplitude. This quantity ix is added by a feedback control mechanism in the controller as shown in figure 1. The phase difference between the master clock and the loop oscillations reduces the attenuation across the 90° branch. The addition of this 90° phase shifted signal to the originally present input would add both a phase shift and increase the input drive to the resonator. This increased drive ensures that the amplitude of the resonator does not change as the phase is corrected.

In this control strategy the resonator is run in a self-excited loop (SEL) [1] at the top of its resonance curve and loop oscillation frequency made equal to the reference frequency by tuning the resonator. This makes the reference frequency equal to the mean of the resonator center frequency. Under these conditions the SEL is phase locked to the reference clock. The parameter x arises due to vibration-induced center frequency variations and helium pressure variations in the system. The resulting phase error generates the required drive signal ix. The slow tuner control mechanism keeps the average of resonator center frequency equal to the reference frequency thus eliminating the need for extra power for the slow frequency shifts. An independent amplitude lock is required to take care of the demand of increased power due to, say, beam loading, gain changes of the rf amplifier, noise in the low-level electronics and residual coupling of the amplitude and phase feedback loops. Amplitude lock is also needed to ensure stability in the presence of electromechanical coupling.

4. Implementation

The controller implementation for the fast tuner section is similar to the one presented by Ben-Zvi *et al* [3]. Therefore, only additional remarks are brought out.

(a) It has been found that the rf hybrids are very sensitive to the power supply voltage variations. A highly regulated supply or an on-board regulator, especially for the input section of the rf strip is needed.
(b) The coupling from reference source to the main line needs to be minimized to avoid frequency pulling between the SEL and the reference source. RF amplifier–attenuator combinations have been used to achieve this.
(c) Gain shaping of the error amplifier chain helps to reduce the noise driving the control ports of the I-Q modulator. In the present case the gain in the feedback amplifier is brought down above 2 kHz.
(d) The residual drift of the amplitude detector may be unacceptably large. Two diodes have been used in the circuit implemented to reduce this temperature drift.

Slow tuning action is achieved by deforming a thin plate fixed at the open circuit end of the resonator. Slow tuner is based on the design developed at Argonne National Lab, USA. In the stand-alone mode it is a pressure control system, controlling the pressure in the niobium bellow mounted near the open circuit end of the resonator. Varying the pressure of helium gas inside a niobium bellow controls the plate movement. The bellow movement is coupled to the plate. The electronic control signals generated in the resonator controller

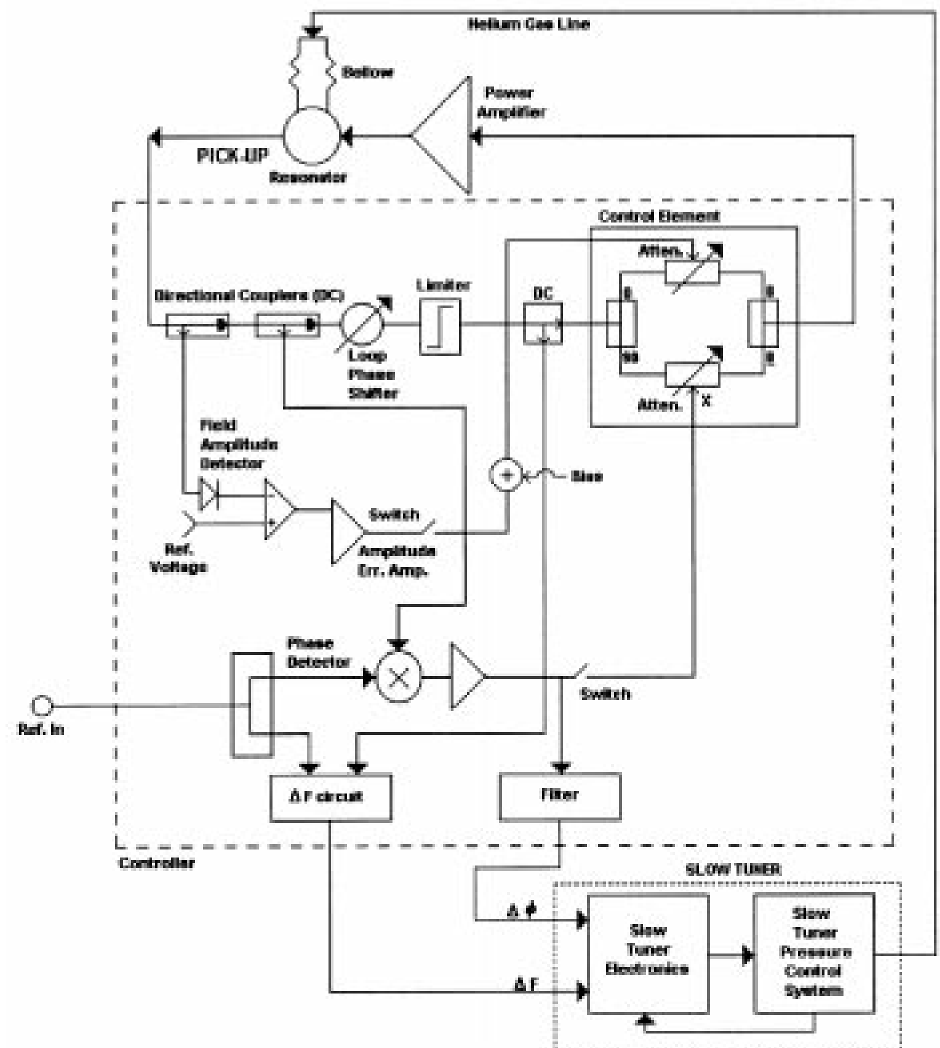

Figure 1. DPC controlled with slow tuner.

operate a proportional valve regulating the pressure inside the bellow. This in turn changes the centre frequency of the resonator. The resonator controller generates two main signals Δf and $\Delta\phi$ for the slow tuner action. Δf signal provides a voltage output proportional to the frequency difference between the master oscillator and the SEL. Δf is derived by implementing the relation $(xy' - x'y)$ where x and y are the quadrature components of input rf in the rotating frame of reference of the reference rf, indicates the derivative operation. This signal can be used to bring the resonator center frequency close to the reference frequency. $\Delta\phi$ is the control signal that is active during the phase lock and is obtained after filtering the vibration-induced components of the phase error signal. These signals after suitable buffering control the proportional valve.

The resonator controller has been designed to work under computer control. All the low frequency analog and digital input/output signals are brought together on a single connector on the controller module. The signals have been made compatible with those available from the corresponding CAMAC modules.

Provisions have been made on the card to make it suitable for controlling normal-conducting resonators as well. A normal-conducting resonator has very high gain in the phase feedback loop and a pole at very high frequency in the amplitude feedback loop (both due to increased bandwidth). This requires changing the gain and pole placement in the feedback amplifier chains. This feature is especially useful during the testing phase of the controller.

5. Stability considerations

When the resonator is driven at the top of its resonance curve the amplitude and phase feedback loops become decoupled. In the phase feedback loop SEL presents a pole at origin. The other poles come from the amplifiers in the feedback loop. These poles in the error amplifiers are placed beyond 100 kHz. This suggests that a large gain can be easily put in the feedback amplifiers. This ensures a large gain at the mechanical resonance frequencies extending from about 65 Hz to 2 kHz. Similarly, in the amplitude feedback loop the resonator places a pole at a frequency equal to half the loaded bandwidth of the resonator. So, here too, a large gain can be realized again in the loop. These large gains in the feedback loops help in minimizing the amplitude and phase errors. The incorporation of slow tuner in the feedback loop has not resulted in any instability at the low frequencies. This aspect will be further studied in detail once the dynamics of the slow tuner are fully understood. Electromechanical coupling is found to be weak and this has not caused any stability problem up to a field of 3 MV/m. This aspect will also be studied in detail in the near future.

6. Performance and discussion

The resonator controller has been tested with the super-conducting resonators of NSC LINAC on numerous occasions. The dynamic components of residual amplitude and phase errors have been measured to be below 0.1% and 0.3°. The drift in the amplitude is below 0.1% in amplitude and below 0.1° in phase, in the typical laboratory environment, after a warm up time of about half an hour. It has been possible to lock the resonators at 3 MV/m with a 200 W amplifier. The performance of the slow tuner control has been very satisfactory. It has been possible to run the resonator in phase-locked condition for days together. The results obtained indicate the suitability of this control scheme for the NSC resonators.

Reduction in the fast frequency deviations will go a long way in reducing the power requirement for control. A reduced rf power requirement implies a quieter and more reliable operation. This has necessitated a study of coupling of mechanical noise to the resonator and evolving an improved mounting of the resonator. If required additional damping mechanism will be incorporated.

In order to achieve the maximum contribution from the slow tuner as compared to the fast tuner to counteract the slow drifts, the slow tuner dynamics will be studied in greater detail. Electromechanical coupling will be studied in greater detail, since it may be possible to reduce the phase error at the expense of an increase in the amplitude error, especially at high field levels, by damping the vibrations through field variation.

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