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DEVELOPMENT OF A TUNER CONTROL SYSTEM FOR LOW-ENERGY SUPERCONDUCTING LINAC AT RAON*

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Abstract

We propose a tuner control system for low-energy superconducting linac at RAON. The frequency error of the superconducting cavities must be smaller than a few of Hz to operate in beam acceleration mode. To minimize the freuqency error as much as possible, the error is calculated in the low-level RF(LLRF), and the proposed tuner control system changes the superconducting cavity frequency by using a mechanical tuner and a motor attached to the cavity directly. This control system deals with not only the initial frequency error of the cavity but also the frequency drift of the cavity induced by external disturbance such as the slow fluctuation helium pressure automatically. In addition, an automatic proportional gain calibration technique is also proposed. In this paper, the detailed operation and techniques will be described.

INTRODUCTION

The low-energy superconducting linac at RAON has been tested and installed in the SCL3 tunnel by the end of December 2021. In this low-energy section, there are two types of the superconducting RF cavities, a quarter-wave resonator (QWR) and a half-wave resonator (HWR) which target resonance frequencies are 81.25MHz and 162.5MHz respectively. The total number of QWR cavities and QWR cryomodules are 22(1 QWR caivity per a cryomodule). Also, there are two types of cryomodules for HWR cavities, HWRA type(2 HWR cavities per a cryomodule) and HWRB type(4 HWR cavities per a cryomodule), and the number of HWRA and HWRB cryomodules are 13 and 19 respectivevly.

Every cavity has a frequency tuning system, which consists of a mechanical tuner and a cryogenic stepping motor inside of the cryomodule. The stepping motor is driven by a power stage directly which exists in the SCL3 gallery.

The RF control bandwidths of QWR and HWR cavities are from 100Hz to 200Hz, therefore, the frequency error needs to be minimized as much as possible to excite cavities at target frequency during beam acceleration mode. Therefore, an automatic tuner control system to compensate the frequency error caused by external disturbances is required.

In this paper, a tuner control system for QWR and HWR cavities is proposed to compensate the frequency error of cavities by using this frequency tuning system automactically.

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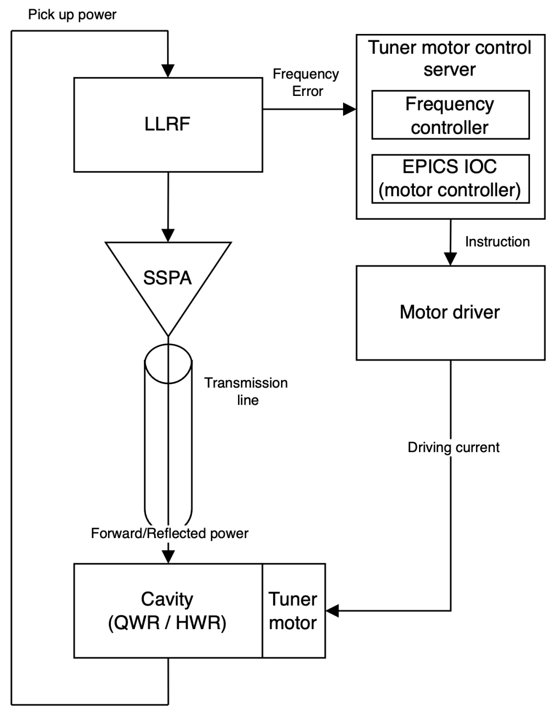

Figure 1: Tuner control system for SRF cavities.

CONTROL SYSTEM OVERVIEW

The tuner control system and RF system for one superconducting RF cavity are shown in the Fig. 1. There are a tuner motor control server, a motor driver, a cryogenic stepper motor, and a mechanical tuner for a cavity. The cryogenic stepper motor is attached to the mechanical tuner directly in the cryomodule. The motor driver generates driving current which makes the stepper motor rotated.

In the tuner motor control server, there are two programs running on it. The EPICS IOC [1] is for giving instruction to the motor driver via EPICS network. The frequency controller is a c++ program that controls tuner motor automatically when the feedback switch is on. The frequency controller acquires the frequency error of the cavity from LLRF via EPICS network.

In LLRF, the frequency error is calculated in two ways [2]. In self-excited loop(SEL) mode, the frequency error is obtain by differentiating measured phase. In generator-driven resonator(GDR) mode, the phase difference between the forward power and the pick-up power is used for the frequency error.

Eight tuner motors for cavities are controlled by one tuner motor control server. Therefore, there are a total of 16 tuner control servers for the low-energy section.

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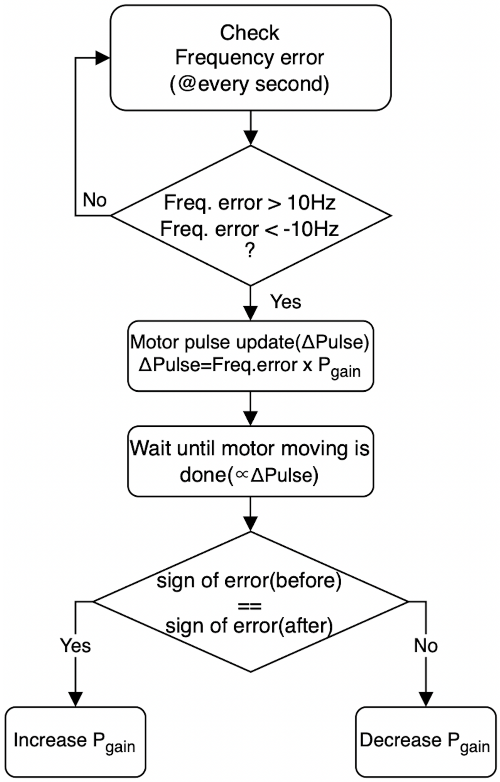

Figure 2: Frequency control logic when the LLRF operates in SEL mode.

EPICS IOC and Frequency Controller

The main process variables (PV) of the EPICS IOC [1] for tuner motor are the current pulse and the target pulse. The current motor pulse is the read-back value from the motor driver that counts the pulse of the output driving current. This current pulse shows the position of the stepping motor. The target pulse is the target position of the stepping motor. The EPICS IOC automatically gives the motor driver moving instructions until the current pulse reaches the target pulse.

The frequency controller controls the EPICS IOC for the motor driver directly to remove frequency or phase error of cavities. The error used by the frequency controller for frequency tuning changes depending on the operation mode of the LLRF. When the LLRF operates in SEL mode, the frequency error is used. On the other hand, when the LLRF operates in GDR mode, the measured phase difference between the forward and pick-up power is used for frequency tuning [2] as mentioned above. The detailed control logic for the frequency controller is described in the next section.

FREQUENCY CONTROL LOGIC

The flow-chart of frequency control logic is shown in the Fig. 2. In case of when the LLRF operates in SEL mode, the frequency controller fetches frequency error at every second. If the frequency error is higher than the pre-determined threshold(in this case +/-10Hz), then the controller calculates Δpulse(=frequency error × P_{gain}). The controller added the calculated Δpulse to the target pulse of the EPICS IOC, so that the current pulse of EPICS IOC and the motor position varies as much as the Δpulse.

The P_{gain} is very important parameter to minimize the motor movement. If the Δpulse to make the frequency error of cavity zero can be accurately calculated, the movement of the tuner can be done at once. However, each cavity and tuner has different frequency tuning gain, and therefore, P_{gain} should be characterized and optimized individually for all cavities and tuner. In this sense, a automatic gain calibration for the frequency controller has been proposed.

As shown in Fig. 2, after waiting frequency settling time for the motor and the tuner, the frequency controller compares between the sign of the error before tuner movement and the sign of the error after the tuner movement. If these signs are the same which means that the P_{gain} is lower than the optimum value, then the controller increases the P_{gain}. On the other hand, if these signs are not the same which means that the P_{gain} is higher than the optimum value, then the controller decreases the P_{gain}. The increment and decrement of the P_{gain} can be set small enough to find the optimum value of P_{gain}.

In case of when the LLRF operates in GDR mode, the error used for this control logic is the phase difference between forward and pick-up power measured in the LLRF as mentioned in the above and the other things to control the frequency of cavities are the same as when the LLRF operates in SEL mode.

With this control logic, the proposed frequency controller can remove the frequency error of the cavity and find the optimum value for proportional gain in background.

VERIFICATION OF THE CONTROL LOGIC

To verify the proposed frequency controller without cavities and tuners, the motor driver with EPICS IOC and a tuner emulator are used. The motor driver operates without a real tuner motor attached to the cavity and just generates output driving current. The tuner emulator is based on the self-feedback mode and direct digital synthesizer(DDS) mode of the LLRF. The self-feedback mode of the LLRF is that the output of the LLRF is fed back to the pick-up power monitoring port by itself. The DDS mode is that the LLRF generates RF signal with the user-controlled frequency. With these configuration, if the tuner emulator controls the DDS frequency of the LLRF according to the current pulse of the EPICS IOC, the frequency error monitored in the LLRF is the difference between the DDS frequency and the target frequency. In this way, the tuner emulator can be modeled successfully.

The test result of the frequency controller using the tuner emulator is shown in the Fig. 3. In this test, two of the frequency controllers and tuner emulators are verified at the same time because one motor driver could hold two of tuner motors. 'SCL32-RF:LLRFT03:' and 'SCL32-RF:LLRFT04:' are the prefix of LLRF PV

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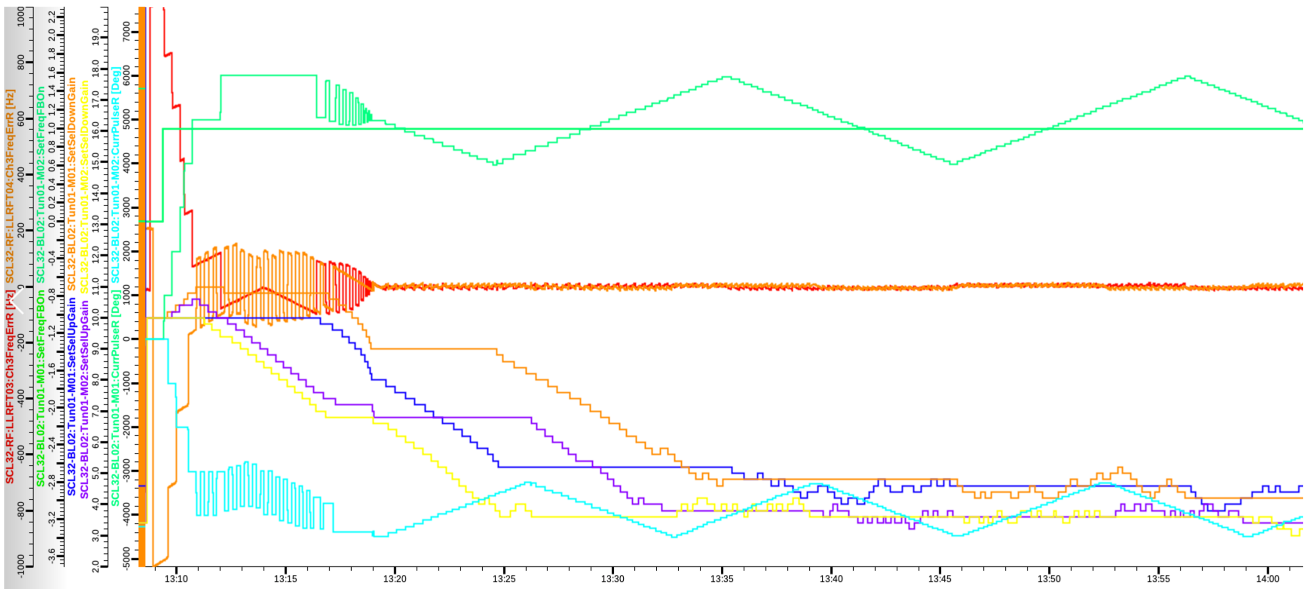

Figure 3: Verification result of the frequency controller using the tuner emulator.

names. ‘Ch3FreqErrR’ is the frequency error monitored in the LLRF. ‘SCL32-BL02:Tun01-M01:’ and ‘SCL32-BL02:Tun01-M02’ are the prefix of the motor driver PV names. ‘CurrPulseR’ is the current pulse of the motor driver. ‘SetSelUpGain’ and ‘SetSelDownGain’ are the proportional gain for the frequency controller mentioned in the above, and ‘SetFreqFBOn’ is the feedback switch whether the frequency controller operates or not. With these PVs, the verification for the frequency controller is conducted.

Initial frequency errors for ‘SCL32-RF:LLRFT03’ and ‘SCL32-RF:LLRFT04’ were set to 1kHz and -1kHz respectively. Also, a sawtooth-like frequency error were modeled in the tuner emulator too. After ‘SetFreqFBOn’ was turned on, the frequency controller started to operate, and the frequency error was also eliminated as time went on. The frequency controller also found the optimum values for the proportional gains as the feedback cycles repeated. The saw-tooth like movements of the current pulse showed that the frequency controller changed the current pulse to compensate the saw-tooth patterned frequency error modeled in the tuner emulator successfully.

CONCLUSION

In this paper, the tuner control system for low-energy superconducting linac is proposed. Based on the frequency and phase error measured in the LLRF, the tuner control system gives instructions and drives the stepping motor attached to the tuner directly inside of cryomodule. The test result shows that the proposed tuner control system can remove the initial frequency error and compensate the frequency drift of the cavity. In addition, the proposed gain calibration technique finds the optimum value for proportional gain for each cavity and operates in background.

REFERENCES

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[2] H. Jang et al., "Upgrade and Performance Test of the FPGA-Based Digital LLRF for RAON Accelerator”, *J. Korea Phys. Soc.*, vol. 77, no. 5, pp. 418-424, 2020. `doi:10.3938/jkps.77.418`