CLOSED LOOP RF TUNING FOR SUPERCONDUCITNG CYCLOTRON AT VECC

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Abstract

The RF system of Superconducting cyclotron has been operational within 9 - 27 MHz frequency. It has three tunable half-wave coaxial cavities as main resonators and three tunable RF amplifier cavities. A PC-based system takes care of stepper motor driven coarse tuning of cavities with positional accuracy ~20μm and hydraulically driven three couplers and three trimmers. The couplers, in open loop, match the cavity impedance to 50 Ohm in order to feed power from RF amplifier. Trimmers operate in closed loop for fine tuning the cavity, if detuned thermally at high RF power. The control logic has been simulated and finally implemented with Programmable Logic Controller (PLC). Precision control of trimmer (~20μm) is essential to achieve the accelerating (Dee) voltage stability better than 100 ppm. and also minimizing the RF power to maintain it. Phase difference between Dee-in and Dee-pick-off signals and the reflected power signals (from cavity) together act in closed loop for fine tuning of the cavity. The closed loop PID control determines the final positioning of the trimmer in each power level and achieved the required voltage stability.

INTRODUCTION

The RF cavities are consisting of three numbers of half-wave (λ/2) coaxial sections. Three numbers of RF power amplifiers (each 80 kW) are designed to drive power in each of these RF cavities [4]. These RF amplifiers are narrow band and have to be tuned for the user-required frequency. Output section of each RF amplifier has stepper-motor controlled tuneable sliding short plunger movement system. Similar sliding short movement systems are also developed for the tuning of main resonant RF cavities. There are three numbers of amplifier-cavity and six numbers of main resonator cavities, i.e., nine sliding-short movement system has been developed.

RF TUNING

Because of high-Q (quality factor), both RF amplifier-cavities and main resonator cavities are narrow band structure [2]. From cavity simulation results [1] it is found that in case of main resonator cavities, frequency shift produced at the highest frequency (27 MHz) is around 22 kHz/mm and at the lowest frequency (9 MHz) is around 0.4 kHz/mm. Fine frequency tuning requirement for RF amplifier-cavities is less than that of Main resonator cavities as the former has much less loaded Quality factor (Q). The RF power is capacitively coupled to the dee (accelerating electrode) of the main resonant cavity through Coupler (Coupling capacitor). The coupler is used to match the high shunt impedance of the main resonant cavity to the 50 Ohm output impedance of final RF power amplifier [2]. There is a vacuum variable capacitor formed between a insert and DEE (in each main cavity) called “trimmer capacitor”. Trimmer capacitor operates in closed loop for the adjustment of a small variation in tuned frequency due to thermal effect and beam loading of the cavity. Coupler can travel 100 mm. maximum and trimmer has a maximum of 20 mm. span of travel [5]. The Coupling capacitor and trimmer capacitor movement is based on hydraulic drive system. This system is responsible for the overall tuning of the system in closed loop [3]. Critical coupling between RF amplifier and RF cavity is achieved by analysing impedance matching and minimising VSWR. It also ensures minimal reflection at coupler port.

When RF power is fed to the cavity, it gets detuned because of thermal instability arising due to RF heating. The effect of the cavity tuning error results in decrease in dee voltages and change in phase. The precise movement of trimmer is necessary to compensate the change in volume of the cavity due to thermal expansion. The accurate position and stability depend on the lowest piston speed determined by minimum flow rate. The typical hydraulic valve has dead band and hysteresis error. The dead zone inevitably brings about steady-state position error, so the dead band is set according to position accuracy. The error due to this ultimately affects the stability of Dee voltage substantially. In addition to this variation in dynamic impedance of the RF cavity, increase the VSWR as well as reflected power which is harmful to the RF amplifier. The problem is further complicated as variation in vacuum level occurs due to variation of rf power inside the cavity.

PID CONTROL OF HYDRAULICALLY DIRVEN COUPLERS AND TRIMMERS

This system consists of a proportional-derivative-integral (PID) controller, hydraulic proportional control valve, position sensor and hydraulic drive system. A PID based feedback loop control system is implemented for the positioning of trimmer and coupler. The block

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diagrams of coupler control loop and trimmer control loop are shown in Fig.1 and Fig.2 respectively.

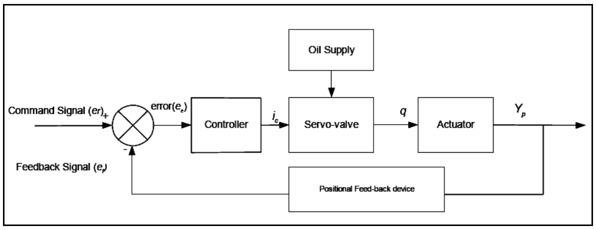

Figure 1: PID loop position control system for coupler

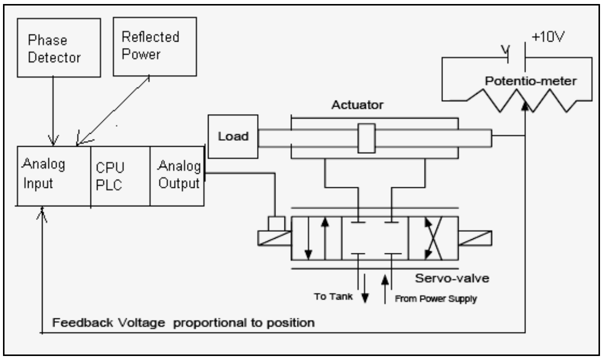

Figure 2: Control system for Trimmer

Under perfectly tuned condition, there will be a phase difference of 90 degree between dee-in pick-up and dee pick-up signal (as shown in Fig.3). A phase detector circuit detects this phase difference and phase error signal drive the trimmer to track the tuning condition of the cavity in closed loop operation. The error amplifier continuously monitors the input reference signal (U_r) and compares it against the actuator position (U_p) measured by a displacement transducer to yield an error signal (U_e).

$$U_e = U_r - U_p$$

The error is manipulated by the servo controller according to a pre-defined control law to generate a command signal (U_v) to drive the hydraulic flow control valve. The processing of the error signal in a controller is a function of the proportional, integral, and derivative gain compensation settings according to the control law.

$$U_o(t) = K_p \cdot U_e(t) + K_i \int U_e(t)dt + K_d \cdot \frac{dU_e(t)}{dt}$$

Where, K_p, K_i, K_d are the PID constants, U_e is the error signal and U_o is the controller output [6].

PHASE DETECTOR

The AD8302 based phase detector measures the relative phase between the Dee-in pick-off signal taken from the input of the coupling capacitor and the Dee pick-off signal from the cavity. The phase detector output signal acts on hydraulic valve which drives the movable plunger tuning into the cavity until there is resonance. Proper tuning is necessary in large dynamic range of the cavity voltages.

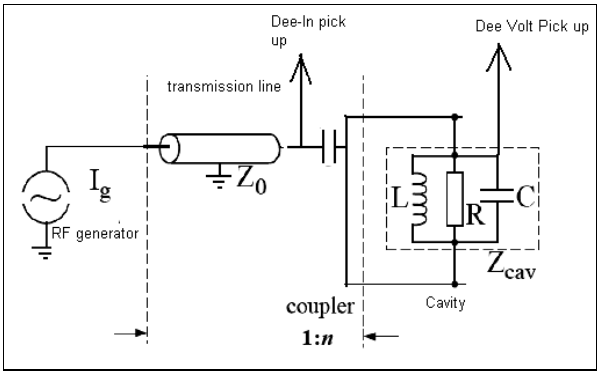

Figure 3: Block diagram of the trimmer control signal

THE EFFECT OF STATIC AND DYNAMIC FRICTION OF HYDRAULIC VALVE AND ACTUATOR

The tight sealing inside the valve and hydraulic cylinders enhances strong dry frictional effect. The static friction inside the valve and actuator possesses complex nonlinear behavior during the onset of the motion. It is modeled as a discontinuous nonlinear mapping between the velocity and static friction. The frictional force depends upon the velocity and direction of velocity. Coulomb and viscous frictional force restricts instantaneous movement of the spool of the valve. This stick-slip motion limits performance at movement accuracy of the valve. The high static friction and dynamic behavior of the frictional force impact significantly on the performance of the valve at low signals, results in chattering in the movement.

As a result of hysteresis, a large error signal is required to overcome the static friction of the valve and therefore the movement of the trimmer capacitor. Again, the large signal causes significant overshoot. Trimmer is unable to take correction at low error signal resulting in increase in reflected power. Detuning will result in the following undesirable effects (as shown in Fig.4).

- Reduce the cavity voltage and shift the cavity phase and so more input power will be needed to maintain the cavity voltage.
- Input phase should be changed to compensate the phase shift.
- High forward power is required to achieve the same dee voltages.
- The modified transmitter power (P) and resulting phase (ψ) are as follows.

$$P = P_0 \cdot \left(1 + \left(\frac{\Delta\omega}{\omega_{1/2}}\right)^2\right); \psi = \tan^{-1}\left(\frac{\Delta\omega}{\omega_{1/2}}\right)$$

Where, $P_0, \Delta\omega, \omega_{1/2}$ are power at tuned condition, change in frequency and half bandwidth of the cavity.

Both Dee voltage stability and relative phase stability between three dees are very important parameters for beam acceleration. The Dee voltage regulator will maintain the dee voltages and therefore a portion of additional power will reflect back to the generator and increase plate dissipation. This situation lasts until the error is significantly large and valves starts responding to the input.

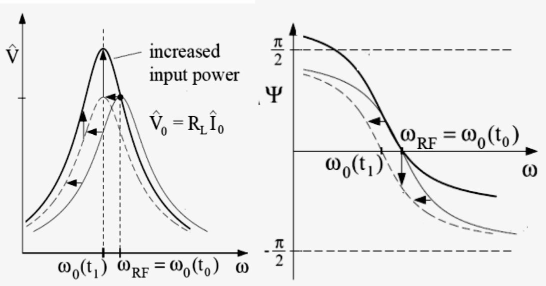

Figure 4: Effects of Detuning a) Increase in Power b) Change in Phase

CLOSED LOOP TRIMMER CONTROL

The closed loop control system is developed with the help of Siemens 315-2DP PLC to control trimmer. A 16 bit (15bit + 1 sign bit) analog input channel is used to sense the position of the trimmer. Linear potentiometer is used to measure the position of the trimmer. The PI controller works in a closed loop to minimise this error signal. The analog output channel is of 12 bit. This phase detector signal acts as an error signal for trimmer movement. It was observed that in case of small error signal, it takes longer time for the correction and some jittering effect in the movement of trimmer occurs due to the nonlinear behaviour of the valve and actuator at low flow condition. The dead-band of the valve causes the hysteresis resulting in variation in the reflected power.

To overcome the problem of jittering effect due to nonlinear behaviour of the valve and actuator at low error signal reflected power is also considered in the closed loop.

The square of the reflected power with suitable scaling factor is multiplied to the phase error. Now the sign of the product determines the direction of the movement and the error is magnified when there is substantial reflected power but the small phase error. Again total error reduced drastically when reflected power is small. It reduces the movement of trimmer when reflected power is small and provides large gain in case high reflected power. It mitigates the problem of nonlinear behaviour of friction and dead band of the valve. Substantial improvement is observed with introduction of this technique in the trimmer control loop and effect of jittering is completely eradicated [7].

INTEGRATED RF TUNING USER INTERFACE:

An integrated operational interface (as shown in Fig.5) is developed for the movement of nine stepper motors (for sliding shorts of three amplifier-cavities and six main resonator cavities), three couplers, three trimmer capacitors and frequency synthesizer. It has a feature to control each of the parameter independently and store in the database. An EPICS based data archiving system is also developed to monitor the effect of movement of trimmer on dee voltage, phase, forward power and reflected power.

Figure 5: User Interface of the RF Tune operation control.

CONCLUSION

The commercially available hydraulic drive based system has its limitation of precise movement at very low flow. Even response of the control system becomes critical for the high precision system. To overcome the effect jittering due to complex friction function inside the valve and actuator limits overall performance. The developed system has been operating satisfactorily round-the-clock with k500 superconducting cyclotron which has been commissioned with internal neon3+ beam in August, 2009.

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