Chapter 20

The GMRT Servo System

V. Hotkar

20.1 Introduction

The GMRT servo system is a dual drive position feed-back control system. It can track a source in the sky with an rms accuracy of $\sim 0.5'$. To realise such a system practically, the expertise from various engineering disciplines are put to work. In order to understand such a system, one has to become familiar with the theory of feedback control systems as well as its application for position control. This chapter discusses these issues. The material is presented in an simplified form and an effort has been made to use, wherever possible, graphical explanations instead of a mathematical treatment.

20.2 Objectives of the GMRT Servo System

The servo systems used for position control of the radio telescopes must meet following objectives.

1. Ability to point anywhere in the sky.
2. High pointing & tracking accuracy.
3. Able to accelerate rapidly in the direction of source.
4. Able to manoeuver remotely

The first requirement is met by making a two axes mount for the antenna. For large antennas like those used in the GMRT (i.e. with weight in excess of 80 tones) an alt-azimuth mount is preferred. In such a mount the antenna can be moved in two axes viz. azimuth and elevation. The azimuth axis movement is parallel to the horizon, while elevation axis movement is normal to the horizon. Alt-az mounts are mechanically simple, yet very stable.

Radio telescope antennas are required to point within +/- 10HPBW at any given wavelength of operation of the antenna. This means that the pointing accuracy of the antenna should be fairly good. The following issues are of concern when trying to achieve high accuracy pointing or tracking:

1. Structural deformation due to gravity.
2. Structural vibrations/deformations due to wind forces.
3. Servo positioning error.

Note that not only can the reflecting surface of the antenna be affected by gravity, the feed support legs too could deform, leading to a displacement of the feed from the focus of the antenna. The GMRT antennas are built using a novel technique (nicknamed "SMART") involving a stainless steel mesh which is attached to rope trusses by wires which are are tensed appropriately in order to achieve the desired parabolic reflecting surface. This results in a dramatic reduction in the gravitational and wind loading on the structure, as well as in the total weight of the dish.

20.3 The GMRT Servo System Specifications

A summary of the GMRT Servo Specifications is given in Table 20.1.

Table 20.1: GMRT Servo system summary

Dish mount	Altitude-Azimuth mount.
Drive	Dual drive in counter torquing mode.
Dish movement	Azimuth +270 to −270 deg.
	Elevation 15 deg to 110 deg.
Dish slewing speed	Azimuth 30 deg/min.
	Elevation 20 deg/min.
Minimum Tracking speed	Azimuth 5 arcmin/min.
	Elevation 5 arcmin/min.
Maximum Tracking speed	Azimuth 150 arcmin/min.
	Elevation 15 arcmin/min.
Tracking & pointing accuracy	1 arcmin for wind speed $<$20 kmph.
Gear reduction ratio	Azimuth 18963.
	Elevation 25162.
Antenna acceleration	Full speed in $\geq$ 3 sec for both axes.
Design Wind speed	40 kmph Operational.
	80 kmph Parking.
	133 kmph survival.
System operating voltage	415 VAC, 3 Phase, 50 Hz.
Antenna parking	Antenna parking using 96 V DC battery.

20.4 Control System Description

The GMRT servo system is a closed loop position feed-back control system, designed for tracking & positioning of the GMRT radio telescopes. The use of dual drive and counter-torque, eliminates non-linearity due to back-lash associated with the gearbox.

20.4.1 Closed Loop Control Systems

All automatic control systems use −ve feedback for controlling a physical parameter like position, velocity, torque etc. The parameter which has to be controlled is sensed by a suitable transducers and fed back to the input, for comparison with the reference value (see Figure 20.1. This subtraction of the sampled output signal with that of reference input is called as −ve feedback. The difference signal, called the “error” is then amplified to drive the system (referred to as actuation) in such a manner that the output approaches the set reference value. In other words the system is designed to minimize the error signal.

All practical loads have inertia and spring constants due to which there is a delay in actuation. Hence, even though a system may be designed for −ve feedback, due to inherent time lags, the feedback may turn into +ve feedback at certain frequencies. If the loop gain is more than unity at some frequency at which the feedback is +ve, the system will oscillate. Hence, in designing control systems great care has to be taken to avoid such situations.

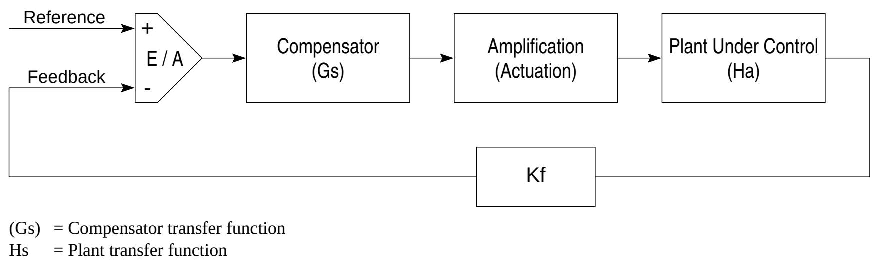

Figure 20.1: Closed loop control system.

20.4.2 Principles of Position Control

For controlling a heavy load, one could, (as illustrated in Figure 20.2) use three nested feedback loops viz. a position loop, a velocity loop and a current loop. This configuration allows independent tunning of the loop parameters without affecting the adjacent loop. A current amplifier is used to amplify the current for driving the motor. The position is sensed by a suitable transducer. The velocity of the antenna is generally sensed by the tachometers mounted on the motor shaft.

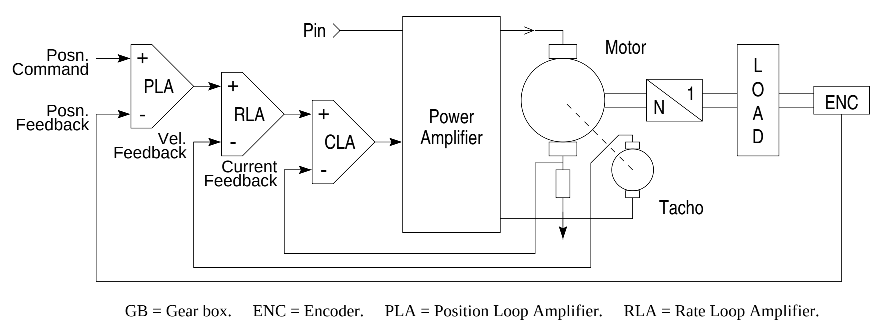

Figure 20.2: Three nested feed back loop.

The block diagram shown above can not be directly used in all position control applications. The back-lash which is inherent in any gear box, introduces a non-linearity in the position loop. Such a system exhibits a phenomena called as “limit cycle hunting”. This affects the positioning accuracy of the antenna.

20.4.3 Position Loop Amplifier

The position loop amplifier (PLA) has two inputs viz. command input and feedback input. In an automatic position control system, the output of the position sensor is filtered, scaled and then applied to the PLA. The command signal is applied to the other input of the PLA. The PLA (which can be either analog or digital) subtracts its two inputs to generate an error signal. This error signal is then applied to the compensator.

A compensator is designed depending on the application. For example the GMRT antennas are used for tracking of stellar radio sources which are moving at constant speed in the sky (15^o/hr, the speed of the earth's rotation). For such an application, a position system having type II response is required. With a type I position compensator and with the use of rate loop in the position control, the overall system response is of type II .

Type of position system	Pointing Error	Tracking Error
Type O	Finite	Finite
Type I	Zero	Finite
Type II	Zero	Zero

Parameters like the structural natural resonant frequency (Wc) and the frictional (Bc) constants of the structure are required for the design of the position loop compensator . The main objective while designing the position compensator is that it should offer enough attenuation at the natural resonant frequency of the structure.

The output of the PLA acts as velocity command. If the target's angular position is far removed from the current position, then the error is very large and could saturate the PLA . The saturation of the PLA is considered as a fixed velocity command to the rate loop. The rate loop moves the antenna with a constant velocity towards the target position. As the antenna approaches the target position, the error at the output of the PLA goes on reducing, which commands the rate loop to reduce the speed of the antenna. When the antenna is at the target position the error at the output of the PLA goes to zero, which translates to a zero speed command to the rate loop. The sign of the error signal at the output of the PLA decides whether the antenna is to be moved forward or reverse .

20.4.4 Rate Loop Amplifier

The function of the Rate Loop Amplifier (RLA) is to control the velocity of the antenna. In position control applications, the rate loop improves the transient response of the position loop by adding a pole in the position loop.

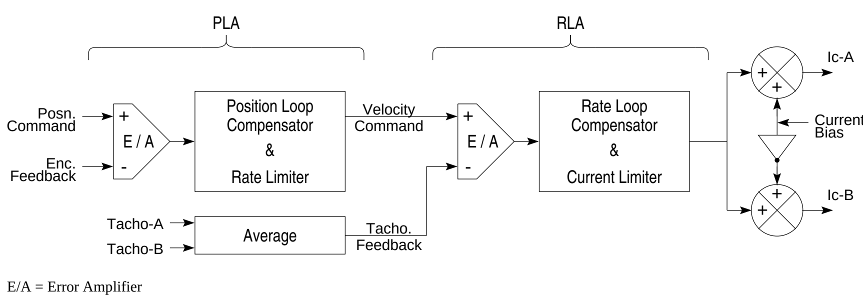

Figure 20.3: Rate loop amplifier.

The output of the PLA which acts as a velocity command, is applied to the one input while tachometer signal is applied to the other input. The RLA subtracts both the input signals and generates an error signal which is then applied to the compensator. For position control applications like the GMRT the rate loop compensator can be of phase flag type (Type O) which avoids limit cycle hunting. The electro-mechanical time constant of the combined motor and load determines the bandwidth of the compensator. The output of the RLA acts as a command to the current loop. If the command speed is more than the actual speed, then the error at the output of the RLA becomes large, which commands the current loop to pass more current through the motor.

For GMRT antennas, where a dual drive system is used, the rate loop controls the antenna velocity by sensing the tacho signal from both the motors. Both these tacho signals are averaged and then applied to RLA as feedback. A voltage corresponding to torque bias is added/subtracted at the output of the rate loop, to generate two current commands. These two current commands are applied to the two current loop amplifiers, for controlling currents in accordance with the rate loop.

20.4.5 Current Loop Amplifier

The function of the Current Loop Amplifier (CLA) is to control/regulate the current of the motor which results in the control of the motor torque. The current of the motor is sensed either by a resistive shunt or with a Hall effect sensor. The control of over current should be fast in order to protect the power semiconductors during starting/stopping of the motor or in the event of fault. Also the steady state error of the current should be zero (as any error in torque affects the speed). These requirements can be met by using a "PI" (Proportional Integral) compensator.

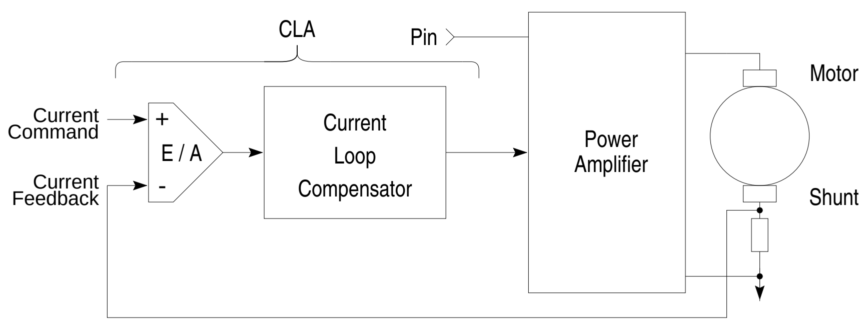

Figure 20.4: Current loop amplifier.

The current signal is filtered, scaled and then applied to the CLA. The output of the RLA which acts as a current command, is applied to the other input. The CLA subtracts both the input signals and generates the error signal. The error signal is applied to the proportional-integral (PI) compensator. In a 3-phase SCR amplifier like one used at the GMRT, the motor current has a 150 Hz component along with the DC component. As the current is sampled and fed back to the loop amplifier, the 150 Hz component of the current gets injected into the loop. This is like injecting a noise into a system. In order to avoid oscillations in the loop, the current loop compensator is designed to heavily attenuate the 150 Hz signal component. The filtered output of the error amplifier is applied to the 4-quadrant power amplifier.

20.5 Servo Amplifiers

Servo amplifiers are 4-quadrant, regenerative power amplifiers, supplying appropriate power to the motor as commanded by a control voltage. These amplifiers are capable of

Table 20.2: Servo amplifier specifications

Type	3-Phase, SCR based, 4-quadrant fully regenerative.
Control Type	Phase angle control with current loop.
Input Volts	275VAC L-L, 50 Hz, 3-Phase, 4-wire.
Command Volts	+/- 10 Volt.
Maximum Current	+/- 80 Amp.
Protection	Over current & over speed.

suppling energy to the load, as well as absorbing energy from the load. They are designed to convert the kinetic energy of the combined motor load, into electrical energy while the load is decelerating.

The GMRT servo amplifier is a three phase, half wave, four-quadrant, fully regenerative, SCR CLA for the control of permanent magnet DC brush type motors. A CLA is a device, which keeps the current through the motor proportional to a commanded input signal.

20.6 Servo Motors

Servo motors are special category of motors, designed for applications involving position control, velocity control and torque control. These motors are special in the following ways:

1. Lower mechanical time constant.
2. Lower electrical time constant.
3. Permanent magnet of high flux density to generate the field.
4. Fail-safe electro-mechanical brakes.

For applications where the load is to be rapidly accelerated or decelerated frequently, the electrical and mechanical time constants of the motor plays an important role. The mechanical time constants in these motors are reduced by reducing the rotor inertia. Hence the rotor of these motors have an elongated structure. For DC brush type motors, the permanent magnets are mounted on the stator, while the armature conductors are on the rotor. The rotating conductors make contact with the stationary electrical source via a brush-commutator assembly. A DC tacho is mounted on the motor shaft, for indicating the shaft speed in-terms of a voltage. These motors also come with fail-safe electro-mechanical brakes. In the event of failure of the utility mains, the antennas are stopped by these brakes.

20.7 Gear Reducers

Generally the motors which are commercially available deliver low torque at high speed and can not be used for driving the load directly. Gear reducers are used to increase the torque so as to meet the torque demand of the load . For servo application i.e. for positioning the load, the gear reducers should possess following characteristics.

1. Bi-directional energy flow

Table 20.3: Servo motor specifications

Type	DC brush type, permanent magnet field.
Horse Power rating	6 HP.
Rated motor voltage	150 V (DC).
Rated motor current	80 Amp (Continuous).
Rated motor speed	2250 rpm.
Continuous stall torque	47 N-m.
Peak Torque	111 N-m.
Torque Sensitivity	0.56 N-m / Amp.
Back E.M.F. Constant	59 V / krpm.
Armature resistance	0.045 Ohm.
Armature inductance	0.33 mH.
Tacho sensitivity	17 V / krpm.

2. Low back-lash
3. Low moment of inertia
4. High efficiency

The bi-directional reducers means that, the energy can be transferred from input to output as well as from output to input. During deceleration, the motor is forced to act like a generator, converting the kinetic energy of the load into electrical energy. The deceleration of the load is decided by the rate of consumption of the electrical energy produced. Planetary gear boxes meets this requirement and are hence used at the GMRT.

20.8 Position Sensors

Optical position sensors are the sensors of choice for highly accurate positioning of antennas. There are two broad styles of the encoders viz. incremental and absolute. An incremental encoder is made of a glass disc and a light interrupter. Transparent and opaque markings are put on the outer periphery of the glass disc. Light emitted from a lamp or LED is interrupted by the glass disc and received by a photo diode. As the disk rotates, the light falling on the photo detector is interrupted by the opaque markings, leading to pulses in the photdetector. These pulses are counted to determine the change in position. The disk has an index marker, is used to provide a reference. Though incremental encoders are simple in construction and provide a cheap solution for position sensing, they suffer from one drawback. On the failure of the power to the encoder or the electronic circuit, the electronic counter looses its count value, and hence all information as to the current position. Hence, upon the resumption of the power to the antenna, one would need to move the antenna until the index marker pulse is received, a procedure called “homing”. For large antennas like those at the GMRT, this is unacceptable and hence absolute encoders have to be used.

In an absolute encoder, a pattern corresponding to a gray code is printed on the glass disc. The glass disc moves through a light emitter and a set of light detectors. The number of light detectors are in proportion with the number of bits of the encoders. This enables the encoder to generate a binary word corresponding to the angular position of its shaft. The electronics housed inside the encoder converts the gray code to the natural

Table 20.4: Encoder specifications.

Type	Optical, absolute shaft encoder.
Resolution	17 bit (10 arcsec).
Max . Shaft speed	600 rpm.
Max. Data rate update	100 kHz.
Illumination	light emitting diode.
Input Power	+ 5V DC at 300 mA.
Output Code	Natural binary.
Output data format	Serial.
Data transmission	RS −422 differential line driver.
Serial output	MSB first, LSB last & then parity bit.
Count Direction	CW increasing.
Operating temp.	0° C to $+70^\circ$ C.

binary . Also the parallel code gets converted into serial format for transmitting over long distance cable. The encoder is directly mounted on each axis of an antenna.

20.9 Dual Drive

For a large antenna, the torque required to move the antenna is high, hence the large ratio gear reducers are used to meet the required torque demand. It is almost impossible in practice to manufacture a gear box which can deliver a large power with no back-lash. Any effort to reduce back-lash by tight coupling of pinions increases the friction of the gear box which reduces its efficiency. With the use of large gear ratios the backlash, hysteresis, and between the motor shaft and the load shaft increases. With the increase in these parameters the nonlinearity in the position loop increases, which leads to position loop instability. There are various ways to reduce the back-lash mechanically but they are inefficient and are unsuitable for a giant antennas like those at the GMRT. Instead one uses a dual drive. Here a pair of motors, gearbox and pinion are used to drive the common load.

Two amplifiers individually drive the motors. When the load is to be held at some position, the torque produced by two motors are equal and opposite, thereby eliminating the backlash. The net torque on the load is zero hence it does not move. For a slight movement of the load in a given direction, one motor increases its torque in that direction while the other reduces its torque. The load will be subjected to a net torque which causes small movement of the load.

20.10 Digital Controller

The digital controller for GMRT antennas, is built around Intel's 8086 processor running at 8 MHz and is called as the "Station Servo Computer" The 8086 is a bus master, controlling two slave processors 8031, for analog and encoder interface. The position loop of both the axes of the GMRT servo system is implemented digitally in this servo computer. The elevation and azimuth axes angles along with time, are fed to the servo computer by the antenna base computer (ABC, see Section 24.2.4). The servo computer computes the error of both the axes and performs necessary filtering (compensation). The compensator output is converted into analog signal by using 16 bit DAC and then applied to the rate loop.

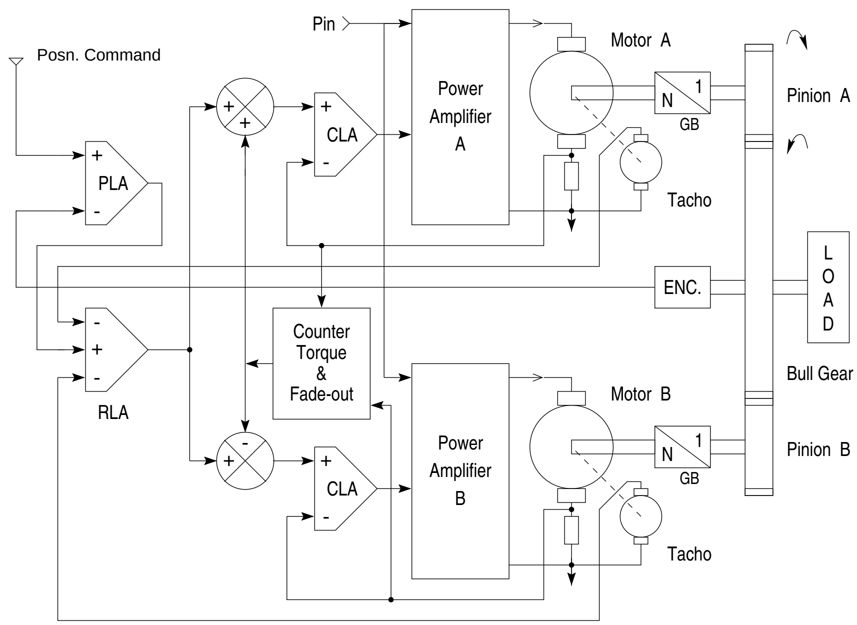

Figure 20.5: Dual drive position control system.

For the digital implementation of a position loop, the sampling rate must be large enough. The "S" domain transfer function of the compensator is converted into a "Z" domain transfer function, by using the "Tustins approximations". The Z-domain transfer function is further converted into a difference equation, to be solve recursively at a regular interval. Tustin proposes that the sampling frequency must be greater than 10 times the compensator bandwidth. With 1.5 Hz as a structural resonant frequency of the GMRT antennas, the position loop bandwidth can be around 0.4 Hz to 0.5 Hz . For a 0.5 Hz loop bandwidth the sampling rate should be more than 5 Hz. This sets the lower limit of the sampling rate. The upper limit of the sampling rate is determined by the processor speed, other tasks of the processor, the transport lag etc. We have chosen 10 Hz as a sampling rate. The processor is interrupted at regular interval of 100 ms to run the real time programme.

20.11 Servo Operational Commands

The central control station sends commands to a group of antennas via an optical fiber link (see Chapter 24). Some of the operational commands, related to the servo is described next.

1. COLDSTART: On receiving this command, the servo system removes the stow-lock pins, releases the motor brakes, enables the servo amplifiers, holds both the axes at the current angle and waits for next command.

2. MV arg1,arg2: Move along the azimuth and elevation axes to the angles arg1 and arg2 respectively. The servo system releases the motor and moves the antenna.

3. TRACK arg1,arg2,arg3: Track in azimuth and elevation axes with the destination angle as arg1 and arg2 and the time parameter as arg3.
4. HOLD: Holds both the axes. On receiving this command, servo system releases brakes of both axes motors and holds the antenna in position.
5. STOP: Stops both the axes. On receiving this command, servo system disables amplifiers & applies brakes to both axes motors.
6. CLOSE: Close the observations. On receiving this command, servo system positions the elevation axis to 90:00:00 deg., disables all amplifiers, applies brakes to all motors & inserts the stow-lock pin.
7. STOW: Inserts the stow-in pin in the elevation axis and locks the axis.
8. SWRELE: Releases stow-in pin from the elevation axis and frees the axis.
9. RSTSERVO: Resets the station servo computer.