DESIGN AND IMPLEMENTATION OF ANTENNA CONTROL SERVO SYSTEM FOR SATELLITE GROUND STATION

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ABSTRACT

This current article describes design, modeling and analysis in theoretical and experimental in implementing. The activities involves design and modeling concepts of drive control system for antenna reflector including implementing, optimizing, testing and commissioning of ground station antenna for remote sensing satellite tracking. The tracking mode is (OPT) Orbit Prediction Tracking for X-band ground station antenna. The work involves integration and establishment of drive chains for Elevation and AZ Axes of antenna, optimization/tuning of entire integrated system with use of approximations obtained from mathematical modeling and simulation studies. The simulation results are obtained in time domain as well as in frequency domain to analyze the system stability conditions in two different environments respectively. With the use of these results practical system has been optimized and experimental results obtained. Both the results are compared and show the results are very close to practical requirements and simulation results are validated with practical results. The Antenna Servo control System operationalised and tracked the real-time passes; the results confirm the goodness of operation, data reception, simple system engineering interface & efficiency of ground station antenna.

Keywords: AZ & EL Axes, Matlab+simulink, Optimization, Position control loop, Stability, X-band.

I. INTRODUCTION

Currently 7.5m size ground stations are used for data reception from remote sensing satellites. With these stations the cost impact on overall data reception systems is considerably increased [11]. Hence, the demand for Cost effective ground stations in the world is also considerably increased. It is possible to achieve desired link margin required to receive most of the
mission’s data from certain elevation angle. Further, it should be feasible to obtain some of the satellite data which is very useful for common public throughout the world that can be obtained easily and with less cost/ free cost. That is why the compact systems are required and the article aimed to deliver 4.5m antenna system as these size antenna systems are more flexible, less maintenance, less cost, simple system engineering interface and simple orbit prediction tracking system. Such system block diagram is as exhibited in figure-1.

**Figure-1.** Block diagram of X-band Ground Station Antenna Servo System

### II. DESIGN CONCEPT OF DRIVE CONTROL SYSTEM

Design of Antenna drive control systems involves the following steps [3, 7, 11]:

1. Estimation of total mechanical load acting on reflector
2. Deciding optimum gear ratio
3. Selection of Servo Motor
4. Selection of Servo Drive Amplifier
5. Selection of encoder with better resolution
6. Modeling of Drive control system

The mechanical loads can be estimated based on basic fundamental theories and Bernoulli’s principles. The wind loads and wind torque relations are expressed as indicated below:

\[
\text{Wind force (FW)} = \frac{1}{2} \rho v^2 A Cr N 
\]

\[
\text{Wind Torque (TW)} = \frac{1}{2} \rho v^2 A d Cm Nm 
\]

Wherein in the mathematical expression:
- \(\rho\) - Mass density of the air stream; \(A\) - Typical area of the body
- \(v\) - Wind velocity; \(d\) - Typical dimension of the body
- \(Cr\) and \(Cm\) - dimensionless force and moment coefficients, which are depends upon the properties of the body and Reynolds number.
The total mechanical load (torque) \( T = T_w + T_i + T_f \) Nm \( \text{... (3)} \)

\( T_w \) = Torque required to overcome wind loads

\( T_i \) = Torque required to overcome inertia of the body due to self weight.

\( T_f \) = Torque required to overcome friction in the body due to rotation.

The estimated load, design specifications & calculations are as exhibited in below TABLE.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reflector diameter</td>
<td>4.5M</td>
</tr>
<tr>
<td>Total torque</td>
<td>5760 N-m</td>
</tr>
<tr>
<td>Gear Ratio</td>
<td>960:1</td>
</tr>
<tr>
<td>Gearing system efficiency</td>
<td>90%</td>
</tr>
<tr>
<td>Motor torque</td>
<td>6 N-m</td>
</tr>
<tr>
<td>Drive switching</td>
<td>8 kHz</td>
</tr>
<tr>
<td>Motor Speed</td>
<td>3200 rpm</td>
</tr>
<tr>
<td>Required velocity</td>
<td>20 deg/Sec - AZ, 10 deg/ sec – EL</td>
</tr>
<tr>
<td>Encoder constant</td>
<td>0.055</td>
</tr>
<tr>
<td>Antenna Inertia</td>
<td>515.655 Kg/ m²</td>
</tr>
<tr>
<td>Co-efficient of friction</td>
<td>114.59</td>
</tr>
<tr>
<td>Basic operating wind velocity</td>
<td>16m/sec</td>
</tr>
</tbody>
</table>

### III. MODELING OF SYSTEM

Modeling of Antenna control servo system involves the following steps [3]:

1. Determine the physical system and its specifications.
2. Draw the functional block diagram of servo control system & represent it as schematic diagram.
3. Use schematic diagram to produce mathematical modeling & reduce the block diagrams of respective loops.
4. Analyze and design the system to meet the specified site requirements.

The technical block diagram comprising supply voltage, rectified input to Power Amplifier & then output driving voltage to permanent magnet synchronous motor, extending the electrical torque to mechanical load and logic circuit for drive amplifier is as shown in figure-2.

![Figure-2. Technical blocks single line diagram](image-url)
In the above figure load is Antenna, to control the Antenna, it is necessary to have the control on speed and currents of servo motor apart from controlling the position of load. Hence, these three controls viz. Speed, Current/ Torque & position of antenna forms essential three control loops as indicated in below figure-3.

**Figure-3** Antenna Control loops for satellite tracking

To obtain the mathematical modeling of the above three loops, the electrical representation/ equivalent circuit of servo motor, drive amplifier and antenna were carried and transformed the mathematical representations into S-domain. The design calculations/ specifications are used to represent and reduce each loop block diagrams which are shown in figure-4 & 5 respectively.

**Figure-4.** Rate loop control block reduction in mat lab simulink

The above block diagram will be further reduced to obtain the velocity loop gain/ transfer function and which is as expressed:

\[
G(V) = \frac{0.0125 s^2 + 99.33 s + 93.94}{s^2 + 59.22 s + 61.46} \quad \ldots (4)
\]

From the block diagrams, the inner most loop is current loop which is implemented in servo motor amplifier (figure-3). The motor torque is proportional to the current and hence the purpose of current loop is to provide a constant torque drive. The PWM inverter driving the 3 motor windings of the 3 phase AC servo motor generates winding voltages proportional to the command, in synchronization with rotor position. The output of current loop forms input to PWM inverter thus adjusting the motor voltages until measured current is equal to demand current. Each motor / amplifier has its own current controller – hence there are two current loops per axis. The sensed motor current is subtracted from the demand current and filtered through a PI controller and fed to the PWM amplifier. The current demand is fed from the outer speed loop. Hence a speed error
causes motors to accelerate or decelerate- the rate of acceleration is proportional to magnitude of speed error.

The velocity gain \( G(V) \) will be incorporated in position loop to obtain the final gain/ overall transfer function of the system to have better system stability. The position loop system incorporating rate loop system is as exhibited in figure-5.

![Figure-5. Position loop control block reduction in mat lab simulink](image)

The speed loop incorporated the current loops. The speed loop inside the position loop improves system damping. A high gain/ high bandwidth speed loop is desirable from the point of view of attenuating effect of torque disturbances, before these are sensed as significant position errors by the enclosing position loop. There is a single speed loop per axis. The ultimate performance of the servo is decided by the position loop controller [2, 6]. It encloses the speed loop with its output forming speed demand. The position error is computed as the difference between commanded position and measured position. The position feed-back is taken from the encoder by default. In case of fault in the encoder the position loop is closed by the position sensed through resolver.

The position error (demand position - actual position) is filtered through a position loop compensator (PI), which implements Type II servo. Type II ensures zero position offset for ramp inputs and a constant offset for acceleration (parabolic) inputs. Such system transfer function is as indicated below. The transfer function is obtained on further reduction of position loop block diagram is as expressed below:

\[
G(s) = \frac{2.0001x^2 + 7694.39x^2 + 8969376.05x^2 + 11699183.14x^2 + 4478176.812}{0.00007x^2 + 1.6229x^2 + 20956.714x^2 + 10035955.36x^2 + 40952144.93x^2 + 11710066.9x^2 + 4478176.812}
\]

\( \ldots \ldots \ (5) \)

From the transfer function and control loop block diagram, it is concluded that the above system is a sixth order, type-2 system, since it has two integrators one at input side another one at motor side. Hence, this servo system is capable to provide satisfactory steady-state and transient response to various types of commands such as step, ramp, and parabolic inputs [4, 10]. These responses are verified practically.

IV. COMPARATIVE ANALYSIS

In this section, the simulation results are validated with practical results, the comparative analysis between simulation and experimental results are exhibited.

4.1 Matlab simulation results of design & optimization:

The design and simulation results for rate loop and position loops are obtained and exhibited in figure-6 & 7 respectively. The results in time domain as well as frequency domains [8, 9] are analyzed. The transient behavior of system is studied, analysis carried out, stability conditions
fulfilled and the system is optimized to obtain the desired response. From the figure-7, the rise time of position loop is 0.33 sec, the bandwidth of position loop becomes 1.06Hz. It is very clear from the rate loop step response that the rate loop is having higher bandwidth than position loop, it is good to have higher bandwidth rate loop in point of view of attenuating effect of torque disturbances and less bandwidth of position loop as it encloses the rate loop.

![Figure-6. Rate loop Step response & bode plots of the system](image)

![Figure-7. Position loop step response & bode plots of the system](image)

![Figure-8. Nyquist response of the system for stability criteria](image)

The stability conditions are also verified from Nyquist criterion, the distance between the (-1, 0) point and polar plot of the loop transfer function is a measure of the relative stability of the system. The Cauchy’s theorem requires the system contour must not encircle -1+j0 point and all the roots must lie on left side of S-plane. The above plot satisfies the conditions of Cauchy’s principle and hence the system is stable.

4.2 Experimental/ Installation results and Operations

From the design, simulation & transient results, it was easy to predict and optimize the practical system in the point view of selecting PID variables of controller [1]. The actual system has been established with EL & AZ axes, initially tuned with proportional variable then integral variable and lastly with derivative variable as per the practical requirements and specifications [5]. Hence, the entire system is integrated, optimized, experimental results obtained, real-time passes tracked, data received as predicted and such system practical results are as exhibited in figure-9, 10 & 11 respectively.
From the above practical results, the bandwidth of position loop is about 1.0 Hz approximately in most of the cases either in Elevation or Azimuth axes respectively. It is clear that simulation results and practical results are almost same and behaves excellent in performance. The responses are even faster in the case of practical results. The rise time, overshoot and bandwidths are resulted as predicted and hence, the simulation results are validated with practical. Practically, in figure-11, AZ axis maximum velocity recorded to be 17deg/sec approximately; this velocity is at EL axis 87.5 deg for IRS Cartosat-2 mission. This can also to be verified from arithmetic relations as expressed:

\[
AZ \text{ Velocity} = \frac{V_{sat} \tan(EL) \text{ rad/sec}}{h \text{ (orbit height)}} \quad \text{.... (6)}
\]

Wherein, \( V_{sat} \) = Satellite velocity; \( EL = 87.5 \text{ deg/sec} \); \( h \) = height of orbit (639km);

Hence, it is summarized that the theoretical system results are validated with experimental system and results show the excellent performance of antenna servo control system.
V. CONCLUSION

Design, modeling and simulation results are excellent and very close to ideal performances. In this case, the rise time is about 0.3 sec; overshoot is 12.2% which is optimistic and settling time is less than 2.5 sec. Frequency domain specifications show adequate gain and phase margins for system to be stable. The rate loop is having high gain/ high bandwidth speed loop, which is desirable from the point of view of attenuating effect of torque disturbances, before these are, sensed as significant position errors by the enclosing position loop. It was easy to predict the approximations obtained from the simulation results to optimize the practical system. The experimental and simulation results are very close each other and almost same in response wise. In some cases, the experimental results are even better than the simulations that show the practical results are tunable, how best if you can tune the system that much performance can be obtained even further but provided that certain limitations like mechanical system performances has to be taken into considerations while operating and optimizing the system. Hence, the practical results are validated with simulation study and that show the way of approaching for designing and optimizing of any antenna servo control system.

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VII. REFERENCES

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