

# **CELSM MAGNETIC LEVITATION SYSTEM CONTROL USING FSMC-PID**

A PROJECT REPORT

submitted by

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to

the APJ Abdul Kalam Technological University  
in partial fulfillment of the requirements for the award of the Degree

of

Master of Technology

in

Electrical and Electronics Engineering

with specialisation in

*Industrial Instrumentation and Control*



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## DECLARATION

I undersigned hereby declare that the project report entitled "**CELSM Magnetic Levitation System control using FSMC-PID**", submitted for partial fulfillment of the requirements for the award of degree of Master of Technology in Electrical and Electronics Engineering with specialisation in Industrial Instrumentation and Control , of the APJ Abdul Kalam Technological University, Kerala is a bonafide work done by me under supervision of *Prof. Sumayya Jaleel*, Assistant Professor, Department of Electrical and Electronics Engineering. This submission represents my ideas in my own words and where ideas or words of others have been included. I have adequately and accurately cited and referenced the original sources. I also declare that I have adhered to ethics of academic honesty and integrity and have not misrepresented or fabricated any data or idea or fact or source in my submission. I understand that any violation of the above will be a cause for disciplinary action by the institute and/or the University and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permission has not been obtained. This report has not been previously formed the basis for the award of any degree, diploma or similar title of any other University.

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**CERTIFICATE**

This is to certify that the report entitled " **CELSM Magnetic Levitation System Control Using FSMC-PID** " submitted by **SNEHA SAJAN** , (Reg. No. **TKM20EEII18**) of fourth semester to the APJ Abdul Kalam Technological University in partial fulfillment of the requirements for the award of the Degree of Master of Technology in Electrical and Electronics Engineering with specialisation in Industrial Instrumentation and Control, is a bonafide record of the project work done by her under our guidance and supervision. This report in any form has not been submitted to any other University or Institute for any purpose.

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# Abstract

In a magnetic levitated system, the object is suspended without any kind of contact other than magnetic fields. Main application of this magnetic levitation is seen in maglev trains. Nowadays, all focus in this field is for creating a high speed, smoother and quieter vehicle system. Maglev trains benefits more to industry than conventional trains such as low maintenance cost, high speed, less affected by weather, increased power efficiency, less noise and many more. The significant area to be checked is the control part of a maglev system so that it can provide more efficient results. The fuzzy based SMC control of the MAGLEV system of the controlled excitation linear synchronous motor (CELSM) with PID as current controller is presented in this work. The simulation model is created and compared to other control methods. The results show that better maintenance of the magnetic levitation air gap is obtained under FSMC-PID control strategy, as well as the ability to deal with changes in the magnetic levitation system. The feasibility and superiority of the modified control method have also been demonstrated.

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# Abbreviations

<b>CELSM</b>	Controllable Excitation Linear Synchronous Motor
<b>EDS</b>	Electrodynamic suspension
<b>EMS</b>	Electromagnetic suspension
<b>FSMC</b>	Fuzzy Sliding Mode Control
<b>FBG</b>	Fibre Bragg Grating
<b>GWO</b>	Grey Wolf Optimizer
<b>LQR</b>	Linear–Quadratic Regulator
<b>MAGLEV</b>	Magnetic Levitation
<b>PMLSM</b>	Permanent Magnet Linear Synchronous Motor
<b>SMC</b>	Sliding Mode Control

# Notations

$R_f$	Resistance, $\Omega$
$I$	Excitation Current, $A$
$m$	Mass of Mover and Platform, $Kg$
$\mu$	Permeability
$g$	Acceleration due to Gravity, $m/s^2$
$K$	Magnetic Levitation Coefficient
$N$	Number of Turns
$z$	Levitation Height, $m$
$F$	Total Disturbance, $N$
$\omega$	Switching gain
$\theta$	boundary thickness
$\dot{s}$	Reaching Law
$z^*$	Reference Levitation Height, $m$

# Chapter 1

## Introduction

### 1.1 General Background

Magnetic levitation (Maglev) systems have become a major topic of concern nowadays which will carve a revolution in transportation engineering. Jonathan Swift identified the magnetically elevated island of Laputa in Gulliver's Travels (1726), which could exceed an altitude of many kilometres. The magnetic levitation has even achieved a tremendous height in the comics Dick Tracy and Spiderman. British cleric and physicist Samuel Earnshaw showed yet another major weakness in magnetic levitation in 1842 [1]. Display that a secure suspension cannot be accomplished, since only interaction with static magnets is required. The segment which is suspended becomes unstable in at least one direction. In March 1912, it was only discovered by engineer and inventor Emile Bachelet that a US patent was given for his "broken transmission." At a major exhibition in New York, he exhibited a study of a magnetic levitation train aiming to attract buyers. A guarantee of high intensity land delivery. One of the main magnetic lift uses is to provide wind tunnel assistance for aircraft models. Researchers also found that often mechanical support systems interact with airflow, causing greater resistance than the standard. The method developed at MIT in the 1950s by Jane Cover and colleagues was magnetic levitation (although it was named the "magnetic levitation and stabilization system"). Another approach to prevent Enshaw's rule when utilizing displacement magnets and having optimum amplification is to displace the magnets in a conductor's presence, triggering eddy currents in the conductors and, as a consequence, repulsion throughout the magnets. It's to go. It is the foundation of an electronic magnetic levitation train device developed by the

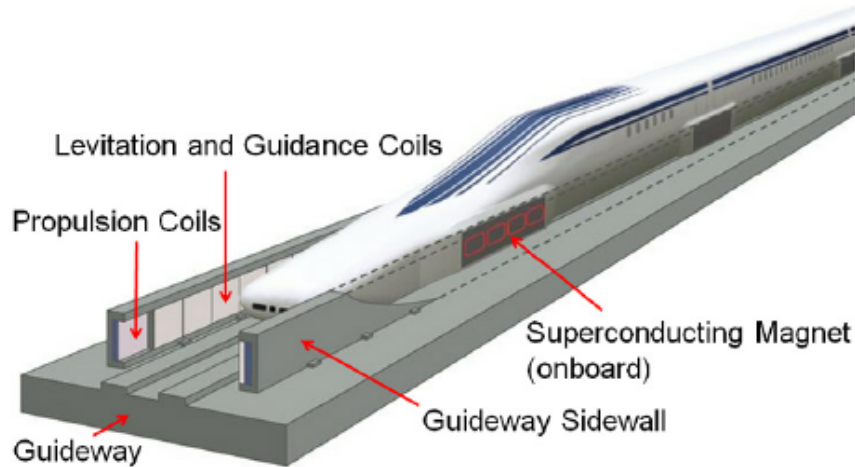


Figure 1.1: Magnetic Levitated Train

National Railways and implemented by James Powell and Gordon Dumby in the 1960's. The strong superconducting electromagnet within the car will cause eddy currents in the conductive route and the eddy currents will float until the car exceeds an appropriate distance [2]. Suspension by alternating current field may also be accomplished by repulsion and inductance from eddy current. This is the reason for the 1912 Bachelet sponsored Maglev train. Induction AC and upstream manufacturing, lift melting is an important industrial application that can melt and mix extremely high energy metals without the need for crucibles.

A new type of linear motor is that the controlled excitation linear synchronous motor (CELSM)[3]. The electromagnetic attraction within the vertical direction is controlled by the excitation current, and also the platform is suspended thereon. The controllable excitation maglev system employed in this paper differs from traditional permanent rail technology systems in this it's directly suspended by the traditional force of the linear motor itself, and therefore the variation of the levitation height causes the air gap field to alter, causing the electromagnetic force in both the horizontal and vertical directions to vary, making the system's stable operation more sensitive to the electromagnetic force. MAGLEV system may be a typical scheme, which possesses the features of parameter perturbation, multivariable and powerful coupling. Therefore, it's required to develop an appropriate controller to alter the levitation height of the maglev system so the suspended object can maintain a stable levitation under varied disturbances

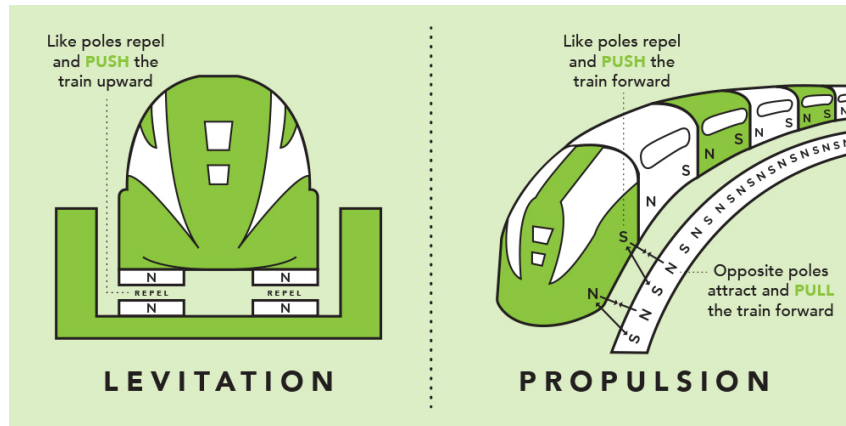


Figure 1.2: Levitation and Propulsion in MAGLEV Train

## 1.2 Objectives

The objective is to develop a Fuzzy Sliding Mode Control with a PID as current controller, in order to resist the external disturbances of Controllable Excitation Linear Synchronous Motor (CELSM). For this, initially mathematical modelling of Magnetic Levitation System is done and then it is incorporated with FSMC-PID Controller. This FSMC-PID controller is then compared with FSMC-PI Controller

## 1.3 Scheme of project work

The project work is organized in 6 chapters. Chapter 1 titled by Introduction includes general background, objective and scheme of project work. Chapter 2 deals with the literature review done for this work. In Chapter 3, the Magnetic Levitation System, its theory of operation and Mathematical modelling of Controllable Excitation Linear Synchronous Motor (CELSM) is discussed. In Chapter 4, Methodology of this proposed control system is introduced. Chapter 5 sums up the simulation results and analysis. Chapter 6 deals with the conclusion of the work.

# Chapter 2

## Literature Review

### 2.1 Literature Survey

Many control approaches have been adopted to maintain the air gap between base and the platform or to maintain the position of object in desired position in a maglev system. Optimized PID Controller is introduced in [4]. In this, object is suspended uniformly in the air gap by adjusting the electromagnetic force of the ML system with the help of PID controller since over 90 % of the commercial controllers are being implemented based on the PID algorithms, thanks to its simplicity, ease of implementation and robustness. The grey wolf optimizer (GWO) is used here to optimise the parameters of the PID controller. This algorithm adjust the controller parameter while minimising system performance metrics. The proposed controller's efficacy is demonstrated by comparing it to the traditional tuning criteria.

A maglev system based on a LQR controller was compared to a standard PID and fuzzy logic controller [5]. The results demonstrate that the PID controller, with a rise time of 0.042 s, has a shorter rise time than the LQR, which has a rise time of 0.16 s. The LQR controller, on the other hand, has a faster settling time of 0.166 seconds compared to PID's 5.2 seconds. Maji et al. [6] suggested and compared a LQR-based maglev controller to a conventional PID controller in real-time simulation. The LQR controller was shown to deliver better outcomes in terms of stability performance. The LQR controller produced a response with a 7-second settling time and no overshoot. Many non-linear controls are used to control the maglev system[7]. Backstepping is one such control which shows better settling time than a conventional PI controller. Back-step is a technique which has a control mechanism to maintain a reference signal[8]. Because of durability and reliability in severely nonlinear situations, the sliding

mode technique allows the magnetic levitation mechanism to be regulated and stabilised [9]. When system characteristics, nonlinear models, external disturbances, and uncertainty change, the sliding mode control (SMC) approach is intrinsically robust. An SMC for a maglev system was developed in [10], and the findings showed that the control methods are robust to parameter fluctuations. To solve the chattering problem, the proposed technique uses an adjustable neural terminal SMC.

Fuzzy logic control is the most commonly used technique to incorporate artificial intelligence in control systems. FLC is used to adjust the PID controller parameters for better results[11]. Two most commonly used fuzzy models are Mamdani or Sugeno model. The most challenging part in this method is setting of fuzzy rules. Many FLC based maglev system is proposed with different algorithms and the performance was outstanding when comparing with normal PID controllers[12]. FLC based PID and PSO were also proposed with better results than conventional PID[13].

Genetic Algorithm (GA) based PID optimization is also proposed and is compared with Z-N tuning method[14]. It was found that faster response when compared with Z-N is obtained in GA and is observed that GA has better flexibility and stability when compared with conventional methods[15].

The Fuzzy- SM Control algorithm, which is based on fuzzy adjusted reaching law by adjusting the switching gain, is proposed in [16]. Here the sliding mode controller is designed by considering the sliding surface with an extra term of integral and the reaching law with saturation function instead of sign function. The fuzzy logic controller is set up to approximate the switching gain by using the fuzzy rules designed, and the approximated value is given back to the controller, after which the fuzzy incorporated sliding mode controller is created [17]. The benefits of the SMC toleration to parameter disturbance and external agitation are combined with the fuzzy system's approximation characteristics to effectively lessen chattering and improve anti-interference capacity [18].

This paper introduces FSMC-PID control of maglev system of linear motor with Fuzzy incorporated SM control as the position controller and a PID controller used as the current controller for controlling the excitation current for maintaining the levitation air gap between the platform and the mover. This ensures the stability of the levitation system, and verify the effectiveness of the method through simulation by reducing the response time.

# Chapter 3

## Design Concept

### 3.1 Magnetic Levitation system

Magnetic levitation is defined as equilibrium of a body without any contact in the solid surface by the result of magnetic field. Fig 3.1 shows is a typical magnetic levitation system where a spherical body is levitated using Electromagnetic suspension technique.



Figure 3.1: Typical MAGLEV System.

## MAGLEV Train

Trains working based on this technology is called as maglev trains. Recently, our focuses are to making accurate and high speed travelling system so all attentions comes to magnetic levitation systems[19]. In last decade Japan and china developed maglev train system for public transport. Its main advantage is its frictionless path. The basic open loop maglev system is nonlinear so they developed an excellent control platform for controlling and evaluating.

A maglev train system is actually like a flying train system. Its main parts are:

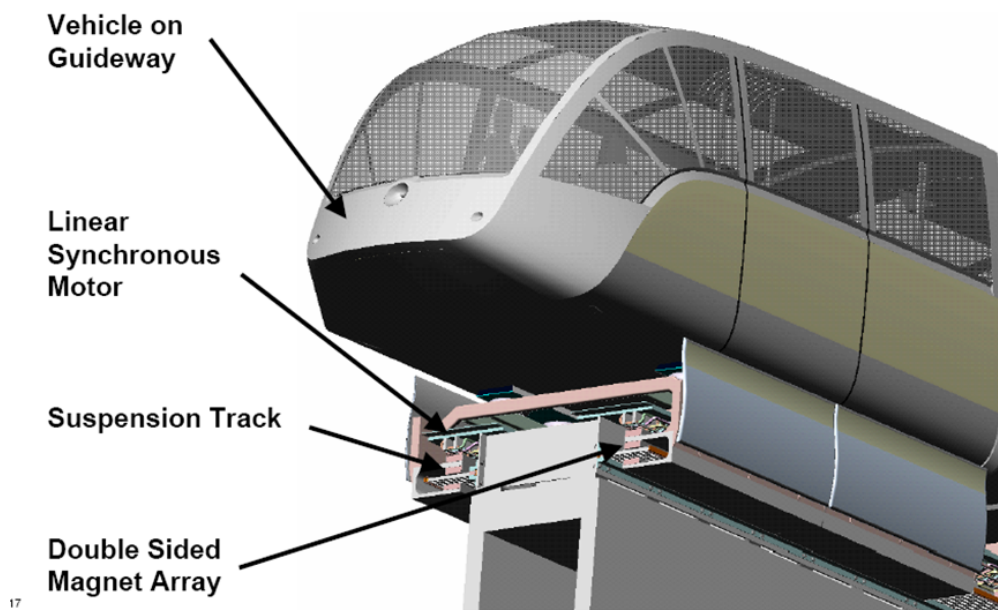


Figure 3.2: Main Parts of MAGLEV Train.

### A. Suspension System

Mainly three types of technologies used for levitating bogies from the track. Those are :

#### i. Electromagnetic suspension (EMS):

In this technology train levitates above a steel track because of the attraction force from an electromagnet fitted in the lower parts of the locomotive. It keeps always a distance from track approximately 15 millimetres. The main disadvantage of this technology is it required other system for motion. Fig 3.3 shows the structural diagram of Electromagnetic suspension system.

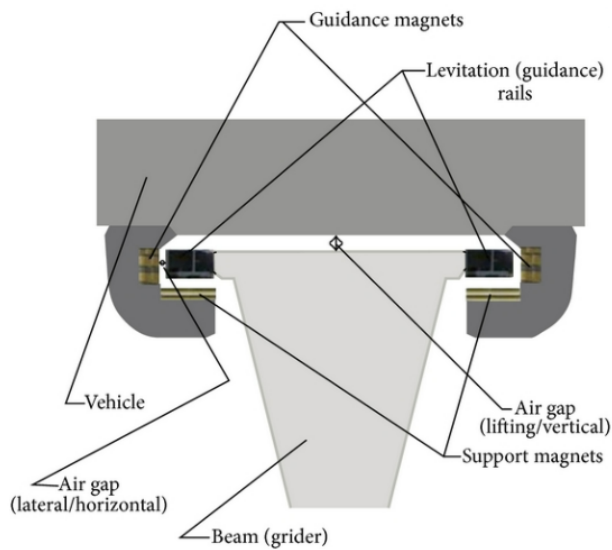


Figure 3.3: Structural diagram of EMS maglev system.

**ii. Electrodynamic suspension (EDS):**

This technology is based on induction machines principle. That is electromagnetic coils are attached in to the locomotive and track. Then an alternating current passes through this coil. The train will move according to the frequency of supply current. In this technology levitation is happening because of the repulsion between tracks. But at rest flux linkage is low so current induced in the coil below the train is not large enough to levitate the weight of the bogie. Due to this reason train need some extra wheels or systems for slow speeds. Fig 3.4 shows the structural diagram of Electrodynamic suspension system

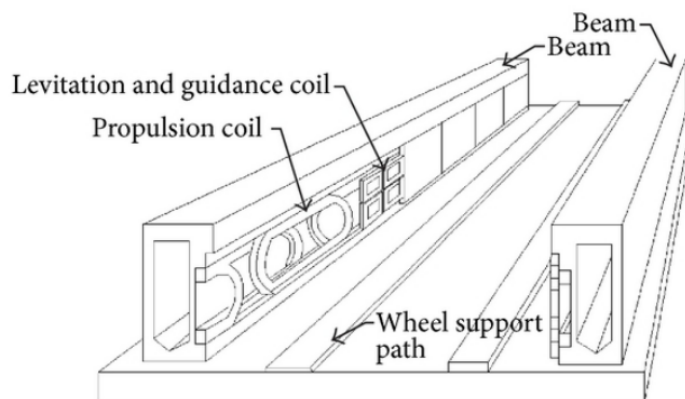


Figure 3.4: Structural diagram of EDS maglev system.

### **iii. Stabilised permanent magnet suspension:**

In this suspension system opposing sets of rare earth magnets repelling each other and set the system in floating conditions.

### **B. Control system**

In any technology it needs to keep an air gap between track and train. Any electromagnetic system cannot provide a stable magnetic field. It need stabilisation system. Such systems continuously sensing the air gap and if any deviation happens it will stabilise by altering the current through the coils.

### **C. Feedback (sensor) system**

Displacement transducers are used for measuring air gap. Two transducers are located for detecting longitudinal and transverse deflections. Nowadays (FBG) Fibre Bragg grating sensors are used Because of the Electromagnetic induction problem . with respect to the sensor output voltage(Vs) feedback system will control the coil magnetising current.

### **D. Propulsion system**

In EMS system another set of electromagnets are used for propulsion. In the case of EDS trains there is no need of another system for propulsion.

### **E. Guidance system**

Null Flux systems are used for guidance it is a coil which is wound in two sides of the track. When the vehicle is in the straight ahead position, no current flows through the coil. But if it moves any curvature the flux in one part of the coil is more than the other side. It will create a changing flux that generates a field that slow down one side switching speed of the driving system.

### **Principle of Maglev**

In Magnetic Levitation system , the levitation height is acheived by using Electromagnetic force between the maganets on the Base and platform [20]. Basic explanation of the Principle of Magnetic Levitation is following;

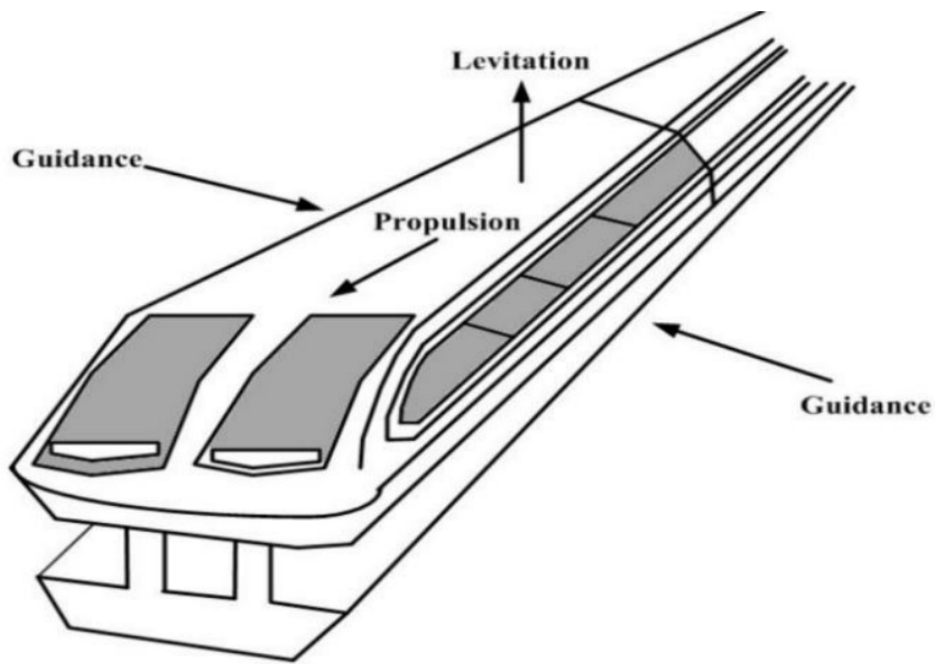


Figure 3.5: Primary Motions in a MAGLEV System.

### I. Principle of Magnetic Levitation

Levitation coils are being installed on the guideway side. When the magnet on the mover passes an electric current will get induced within the guideway coils which will in turn act as temporary electromagnet. Thus will create some repulsive force which pushes the vehicle upwards and will levitate the Maglev Vehicle

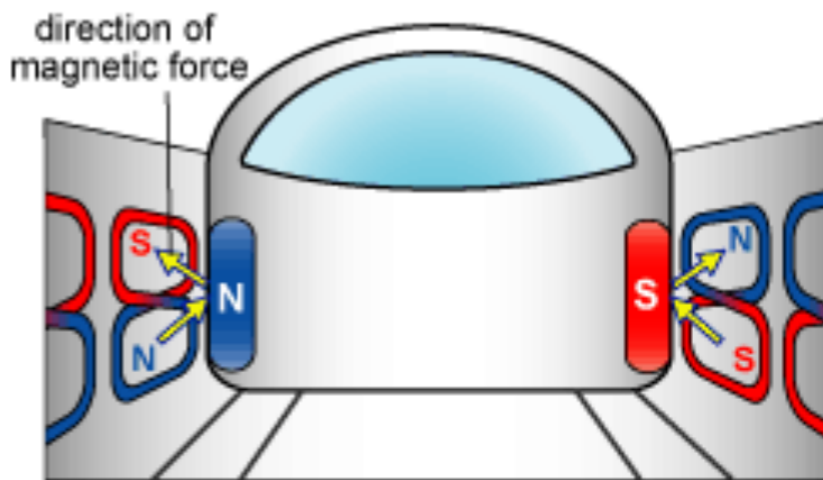


Figure 3.6: Principle of magnetic levitation.

## II. Principle of Propulsion

The attractive and repulsive force between the superconducting magnets are used to achieve propulsive motion or linear motion. A 3 phase sinusoidal current is used to energize the guideway coils which will create a magnetic field on it. The vehicle is attracted and pushed by this magnetic field and thus linear motion of vehicle is achieved

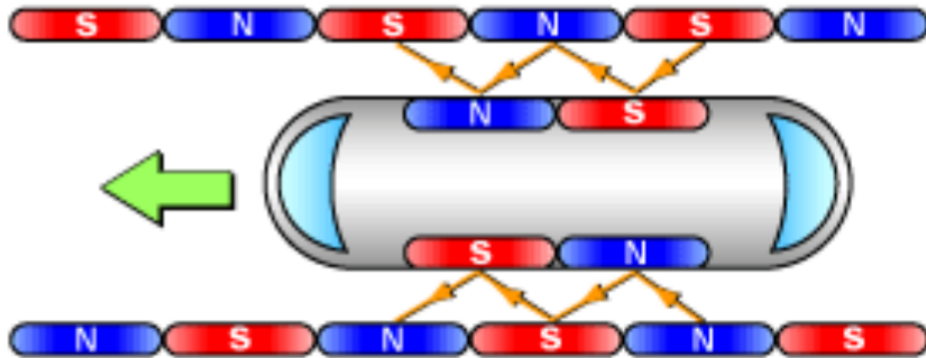


Figure 3.7: Principle of Propulsion.

## III. Principle of Lateral Guidance

A loop will create when the levitation coil is facing each other. When the levitating vehicle is not in the line, there will not be any flow of current in the loop. It will create a change in flux when the vehicle is moved out off the line which in turn generate a magnetic field that brings back it to the line.

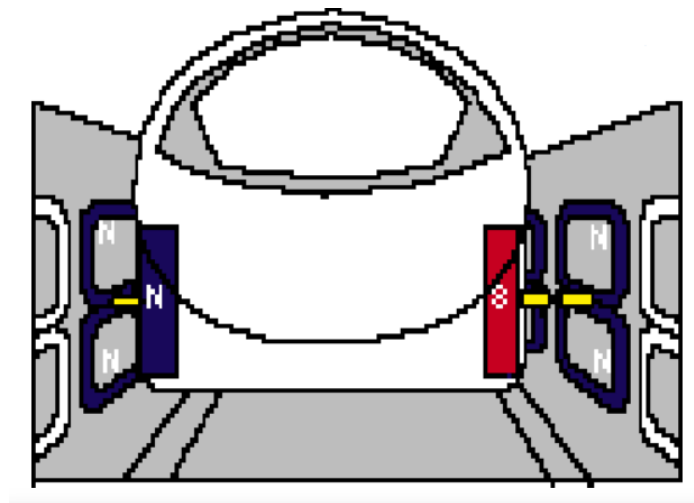


Figure 3.8: Principle of Lateral Guidance.

## Magnetic levitated train control system

Before going to complex system we can analyse a simple magnetic levitated train model. it is a simple form of a magnetic train system without considering its friction and complex attributes. This includes a train boggy, electromagnet, permanent magnet, controlling circuit, driving circuit and displacement sensors. Related to the eddy current sensors output controller try to improve the magnetic force against to gravitational problem. That means when the current through the electromagnet decreases the bogie will be going down due to gravitational force the sensor will sense that distance and output of the controller start to increase, in this manner the bogie keep in a permanent distance.

Levitation and linear Motion is achieved by electrically powered linear induction motor or linear synchronous motor. In induction motor power is supplied to the mover by means of electromagnetic induction

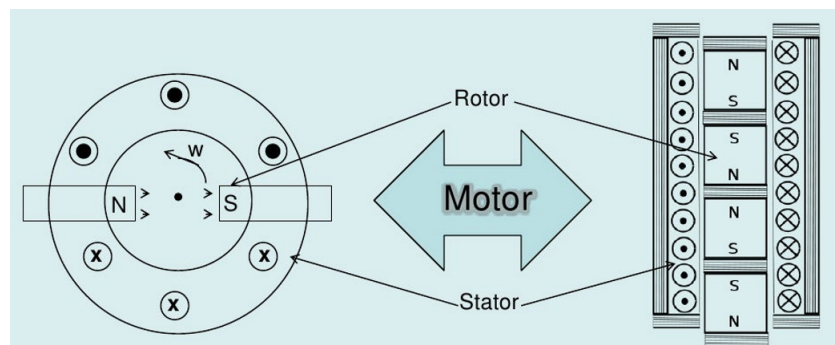


Figure 3.9: Induction Motor and Linear Induction Motor.

## 3.2 Application Of Magnetic Levitation

### 3.2.1 Magnetic Levitation Trains

Most important use of magnetic levitation is Maglev trains. In this the train moves along the guideway with the help of magnetic fields and thus levitation and propulsion motion occurs. Shanghai's Transrapid system, which employs a German model, was the first MagLev commercially implemented in March 2004.

### 3.2.2 Magnetic Bearing

In a magnetic bearing, an electromagnet positioned on the stator causes the rotor to levitate and rotate. Since there is no touch, there is no friction, drag, or component wear. Flywheels are employed as energy storage devices, blood pumps, micro positioning systems, and semiconductor industries all require magnetic bearings.

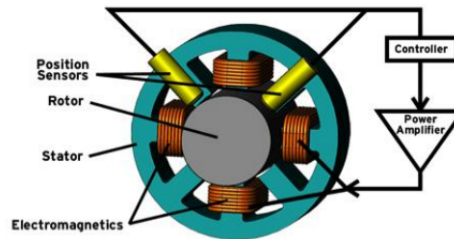


Figure 3.10: Magnetic bearings with sensors.

### 3.2.3 Launching Rockets

A track has been constructed by NASA's Marshall Space Flight Center in Huntsville, Alabama, to magnetically levitate a spacecraft and provide launching velocity to attain earth escape velocity. The goal of the project is to create space travel at a lower cost. It can travel at a speed of 964 km/hr without using any fuel.

### 3.2.4 Magnetic levitation wind turbine

Researchers from the Guangzhou Energy Research Institute claim that magnetic levitated wind turbines can be up to 20% more efficient than conventional wind turbines. A massive wind turbine having vertical blades and neodymium magnet support is suggested. Since the performance is higher, less space is needed than with a typical wind turbine to produce the same amount of power.

There are numerous additional application areas that are constantly being researched. The new technology known as MagLev has been the subject of intense investigation.

### 3.3 Controllable Excitation Linear Synchronous Motor (CELSM)

The key components of the magnetic levitation feed platform are levitation platform, linear synchronous motor, long grating sensing element, a displacement sensor, and a platform base. The magnetic levitation feed platform's three-dimensional structure is depicted in Fig.3.11

In comparison to permanent magnet linear synchronous motors (PMLSM), controlled excitation linear synchronous motors can alter its flux linkage. The horizontal feed subsystem and the vertical suspension system are two aspects of the CELSM mathematical model. The CELSM system is a nonlinear, time variant, strongly coupled system that is susceptible to interference. The horizontal system and the suspension system are strongly coupled because they share the same air gap magnetic field. The CELSM is strongly influenced by parameter changes, external disturbances, and the drive system's end impact.

As a result, for CELSM's high-speed and high-precision positional observation needs, an effective technique for avoiding disruptions must be implemented.

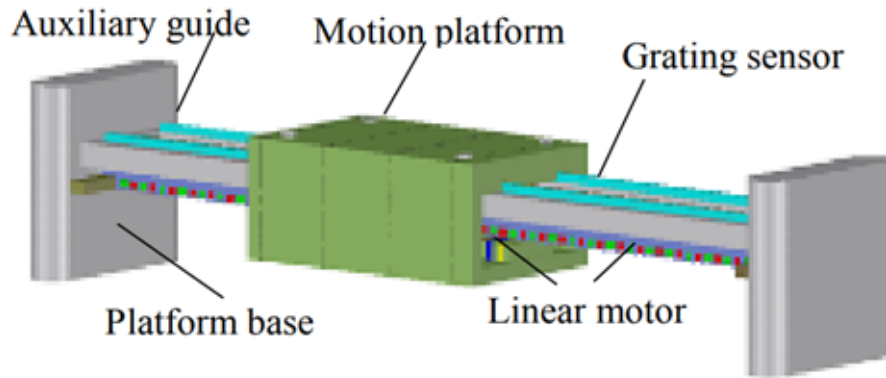


Figure 3.11: Structural diagram of CELSM Maglev system.

### 3.4 Mathematical Modelling of CELSM

The current travelling through the magnets determines the magnetic force, which may be computed using the following equation

Voltage equation for the CELSM;

$$u = R_f I_f + N \frac{d\phi}{dt} \quad (3.1)$$

Flux Equation;

$$\phi = \frac{NI\mu A}{2z} \quad (3.2)$$

Equating eqn(3.2) in eqn(3.1), we get

$$u = R_f I + \frac{\mu_0 N^2 A}{2} \cdot \frac{\dot{I}}{z} - \frac{\mu_0 N^2 A I}{2} \frac{\dot{z}}{[z]^2} \quad (3.3)$$

$$F = \frac{\mu_0 N^2 A}{4} \left[ \frac{I}{z} \right]^2 \quad (3.4)$$

Total Force equation;

$$m\ddot{z} = mg - F \quad (3.5)$$

Let  $x_1 = z, x_2 = \dot{z}, u = I^2$ , thus the state equation of the magnetic levitation system is

$$\mathbf{x} = (x_1 x_2 x_3)^T = \begin{pmatrix} z & \dot{z} & I \end{pmatrix}^T \begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = \frac{K}{m} \frac{x_3^2}{x_1^2} - \frac{F}{m} - g \\ \dot{x}_3 = \frac{x_2 x_3}{x_1} - \frac{R x_1 x_3}{2K} + \frac{x_1}{2K} u \end{cases} \quad (3.6)$$

$$K = \frac{\mu_0 N^2 A}{4} \quad (3.7)$$

where,

$R_f = Resistance$

$u = Excitation Voltage$

$g = Gravity$

$f = Disturbance$

$I = Excitation Current$

$A = Area$

$m = Mass$

$K = Magnetic Levitation Coefficient$

$\delta = Air Gap Height$

$\mu = Permeability$

$N = Number of turns$

## **3.5 Summary**

The Magnetic Levitated System and its mathematical modelling is studied in this chapter. The working principle of Magnetic Levitation System is explained here. The chapter also discusses the theory of operation of CELSM. The next chapter deals with the methodology used to control and maintain the stability of MAGLEV system.

# Chapter 4

## Methodology

### 4.1 Magnetic Levitation Control System

According to Eq. 3.3 and Eq. 3.6, the model of MAGLEV control system is established in Simulink environment. Fig. 4.1 depicts the control system structure of the CELSM maglev

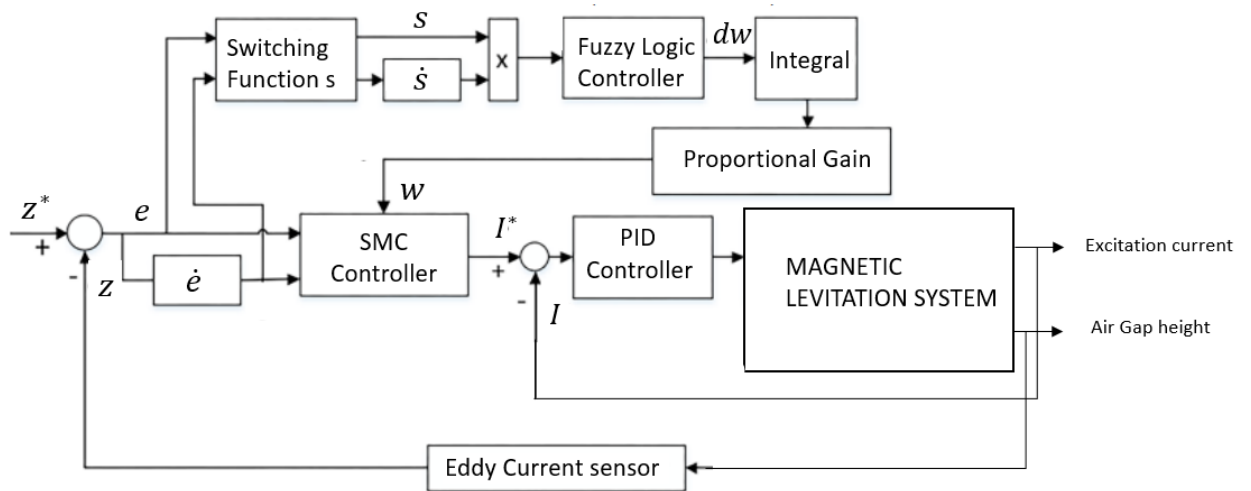


Figure 4.1: Block Diagram of MAGLEV Control System.

control system. A position controller, a current controller, and a maglev system make up the control system. A PID controller is used in the current loop, whereas an Fuzzy based Sliding Mode Controller (FSMC) is used in the position loop.

Here is considering a linear motor having a stator and mover, where stator is excited using 3 phase sinusoidal supply and mover is excited using DC supply which will create a magnetic effect. Thus magnetic levitation and linear motion occurs, which in turn create a gap between

the platform and base. Here this gap is controlled by adjusting the DC supply used for exciting the mover. A reference airgap height is compared with the actual airgap and the error between this is minimised using the sliding mode controller. The input to the sliding mode controller is error, its derivative and the reaching law  $w$ . Here the reaching law is obtained using fuzzy logic rules by adjusting the switching function  $s$ . The switching function and its derivative is used as the input for the fuzzy logic controller and will get  $dw$  as output. An integral term is used to get  $w$  and steady state error can also be minimized due to the integral action. Since reaching law is obtained using fuzzy logic, chattering can also be reduced. The reference excitation current from the sliding mode controller is compared with the actual current and this error is controlled by using a PID controller. Thus the current get adjusted and level between the platform and base is maintained.

## 4.2 Controller Design

### 4.2.1 Sliding Mode Controller

SMC controller is a commonly used robust control technique. It can precisely control external disturbance in a non-linear system. It ensures stability and consistency in the non-linear systems

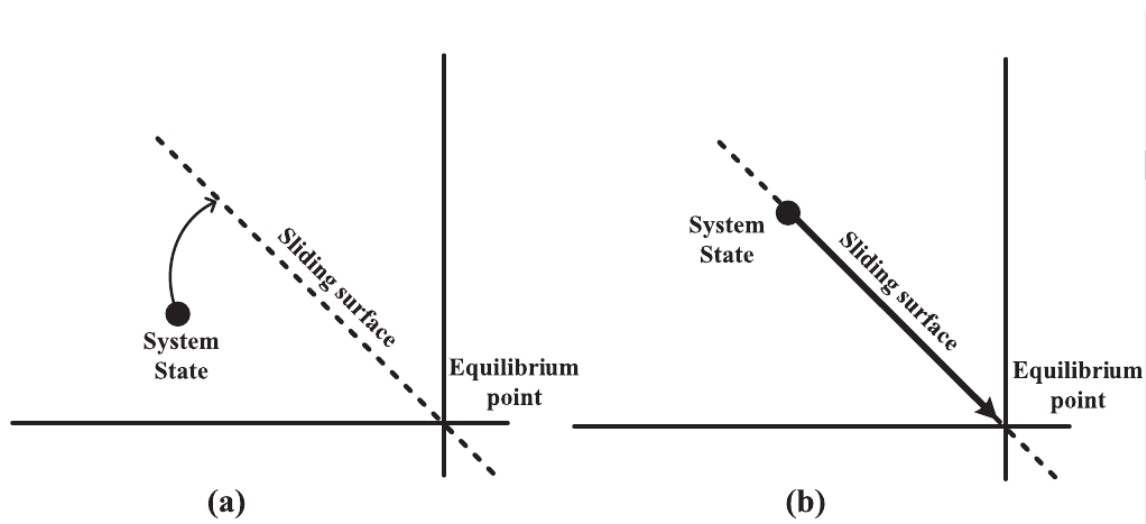


Figure 4.2: Two phases in Sliding Mode.

Fig. 4.2 shows the two phases of sliding mode controller one is reaching phase and other is sliding phase. Reaching phase is attained using reaching law and sliding phase is reached

using control law. The input to the sliding mode controller is error, its derivative and switching gain and output it provide will be the reference excitation current.

## 4.2.2 Design of SMC

Designing a sliding surface and its control is the challenging step. The magnetic levitation air gap height error is defined as

$$\ddot{e} = \ddot{Z}^* - \ddot{Z} \quad (4.1)$$

where the reference magnetic levitation air gap height  $z^*$  is 0.0025m, and the actual measured magnetic levitation air gap height is  $z$ .

The switching function is designed as

$$s = ce + \dot{e} + b \int_0^t e dt \quad (4.2)$$

Integral terms are used in the switching function to reduce the steady-state error and guarantee its accuracy. The attenuation effect is intensified as the system state approaches the equilibrium point, and the system state converges to zero in a finite time.

$$\begin{aligned} f_0 &= ce(0) + \dot{e}(0) \\ &= -0.0005c \end{aligned} \quad (4.3)$$

$$\dot{s} = -w \text{sat} \left( \frac{s}{\theta} \right) \quad (4.4)$$

where,

$\omega$  = *Switching gain*

$\theta$  = *Boundary thickness*

$f_0$  = *Initial value*

$s$  = *Reaching Law*

Here saturation function is selected for the reaching law instead of sign function to minimize chattering issue. Take the derivative of switching function which is given by

$$\dot{s} = c\dot{e} + \ddot{e} + b\dot{e} \quad (4.5)$$

The 2nd derivative of levitation gap height is

$$\ddot{Z} = \frac{Ku}{mx_1^2} - g \quad (4.6)$$

The 2nd derivative of the levitation height error is

$$\ddot{e} = \ddot{Z}^* - \ddot{Z} = g - \frac{Ku}{mx_1^2} \quad (4.7)$$

Substituting eq.(4.7) into eq.(4.5), we get

$$\dot{s} = c\dot{e} + g - \frac{Ku}{mx_1^2} + be \quad (4.8)$$

According to eq.(4.4) and eq.(4.8), eq.(4.9) can be obtained.

$$c\dot{e} + g - \frac{Ku}{mx_1^2} + be = -w(t) \text{sat} \left( \frac{s}{\theta} \right) \quad (4.9)$$

The final control law of the system is

$$u = \frac{mx_1^2}{K} \left( c\dot{e} + g + be + w(t) \text{sat} \left( \frac{s}{\theta} \right) \right) \quad (4.10)$$

### 4.2.3 Fuzzy Logic Controller

Fuzzy logic controller is a controller which is based on human reasoning by setting rules based on different conditions that we need to make the system more efficient. The advantage of this system is that it doesn't require any mathematical model to solve the issue but skill is required to create rules for a particular Fuzzy logic controller. Compared to other traditional methods FLC has proven that it is more effective in solving poorly defined issues. Fig 4.3 shows the block diagram of Basic Fuzzy Logic Controller. Its includes Fuzzifier, Intelligence and Defuzzifier. Fuzzifier converts crisp set into fuzzy input sets. Intelligence uses rules to provide fuzzy outputs and Defuzzifier converts those fuzzy output sets to crisp outputs.

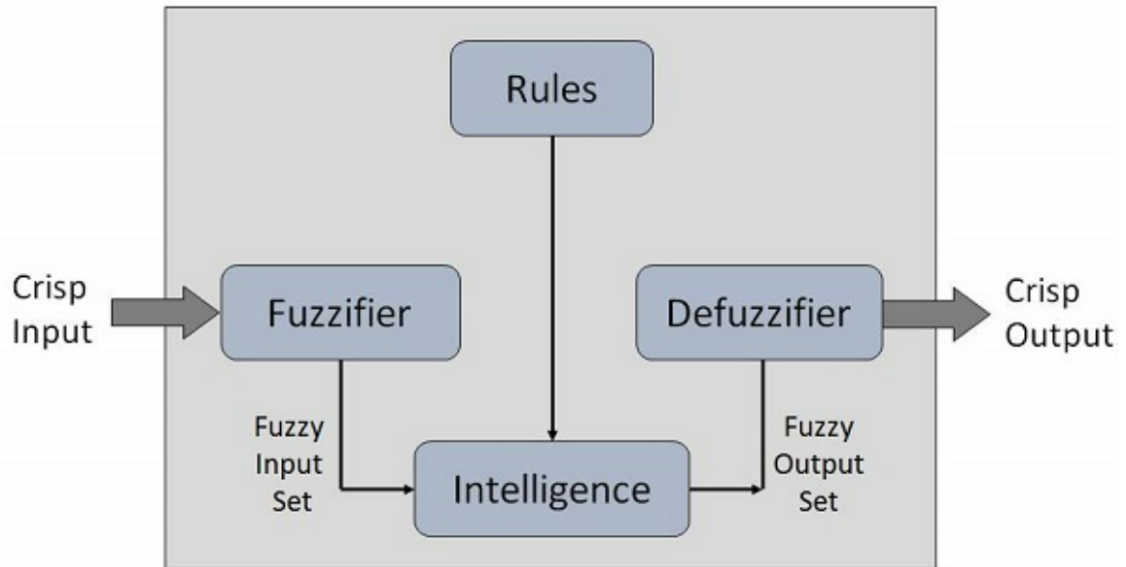


Figure 4.3: Fuzzy Logic Controller

#### 4.2.4 Fuzzy Logic Controller Design

A fuzzy logic controller with switching function adjustment mechanism is used to resolve the issue of variation in the parameter and lack of anti-interference ability of the controller. In this, Switching gain, input of Sliding mode controller is obtained from the Fuzzy Logic Controller thus chattering can be reduced further. The input to fuzzy logic controller is  $s\dot{s}$  and output taken is  $d\omega$ . The relationship between these input and output is designed as

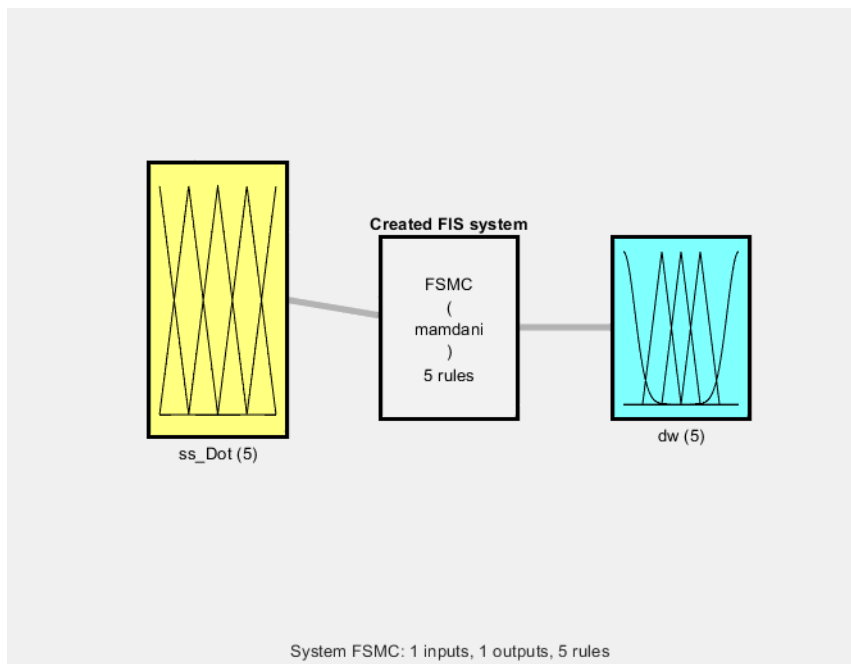


Figure 4.4: FIS System

$$s\dot{s} = \{NB \quad NM \quad ZO \quad PM \quad PB\}$$

$$d\dot{w} = \{NB \quad NM \quad ZO \quad PM \quad PB\}$$

The fuzzy rules are :

R1: IF  $s\dot{s}$  is NB then  $d\dot{w}$  is NB;

R2: IF  $s\dot{s}$  is NM then  $d\dot{w}$  is NM;

R3: IF  $s\dot{s}$  is ZO then  $d\dot{w}$  is ZO;

R4: IF  $s\dot{s}$  is PM then  $d\dot{w}$  is PM;

R5: IF  $s\dot{s}$  is PB then  $d\dot{w}$  is PB;

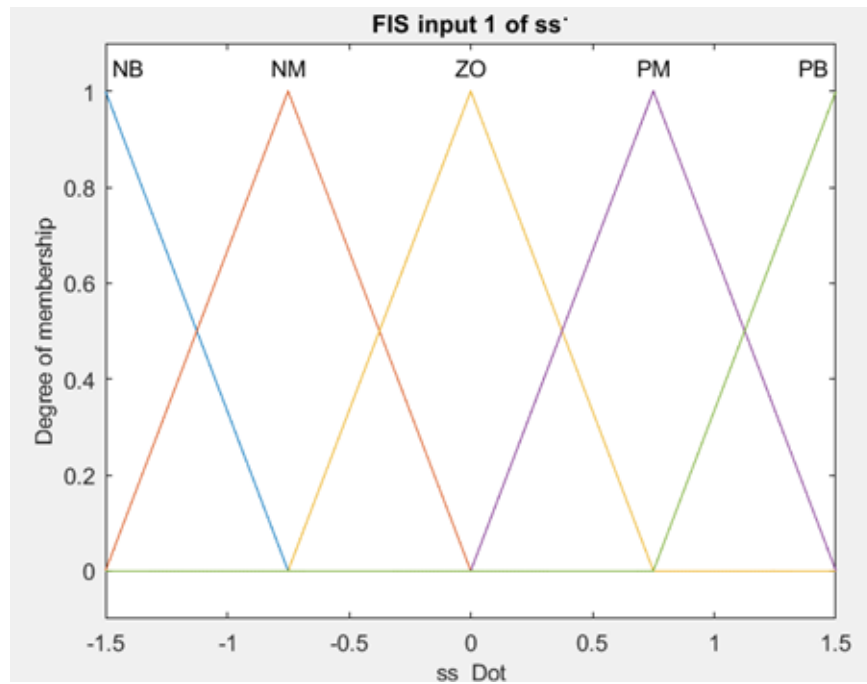


Figure 4.5: Membership function of  $s\dot{s}$

Fig 4.5 and Fig 4.6 shows the membership function of input  $s\dot{s}$  and output  $d\dot{w}$  respectively

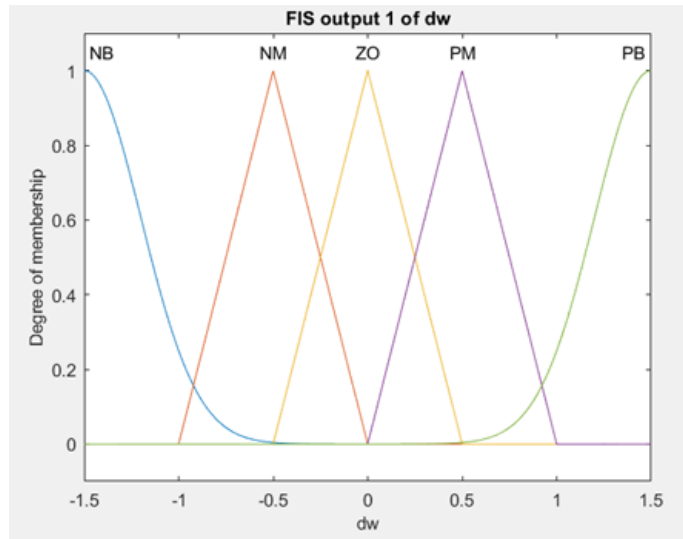


Figure 4.6: Membership function of  $dw$

where,

NB = Negative Big

NM = Negative Medium

ZO = Zero

PB = Positive Big

PM = Positive Medium

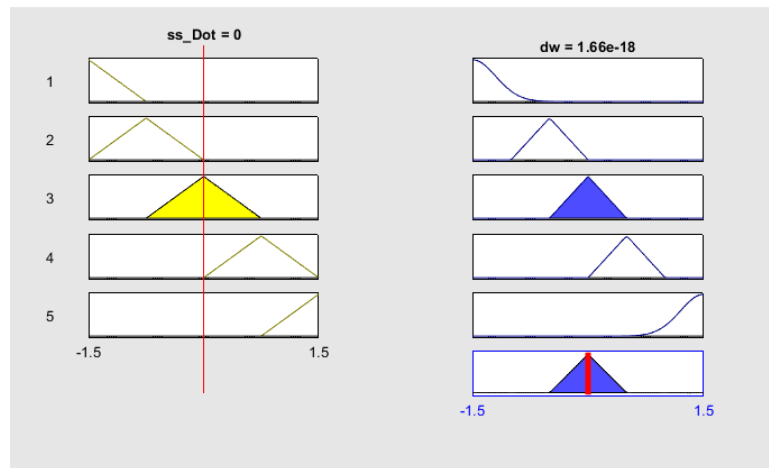


Figure 4.7: Fuzzy logic inference rule viewer

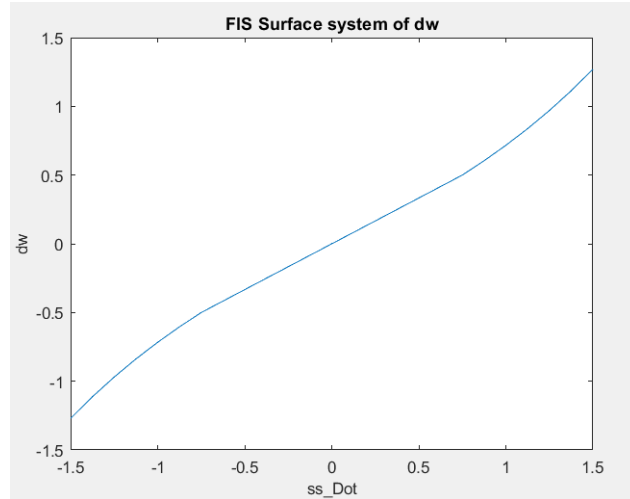


Figure 4.8: Fuzzy inference system input-output graph

Fuzzy logic controller is incorporated with the Sliding Mode Controller for maintaining the stability of the maglev system by controlling the levitation height. Eqn.(4.10) is the final control law for the Fuzzy sliding mode controller which is used as the position controller. A PID controller is used here as the current controller. The output we get from the Fuzzy Sliding Mode Controller is the reference excitation current. This reference current is compared with the actual current by using a PID controller Control Equation of PID Controller for Current Loop

$$u = k_p (I - I^*) + k_i \int_0^t (I - I^*) dt + k_d \dot{I} \quad (4.11)$$

### 4.3 Summary

This chapter addressed the methodology and controllers involved in the system. The next chapter deals with the simulation results analysis of proposed Magnetic Levitated Control System based on FSMC-PID Control.

# Chapter 5

## Simulation Results and Discussion

### 5.1 Model Validation

Simulink was used to simulate the proposed control system of the CELSM maglev system. The effect of the controller on control system is simulated and confirmed. The Magnetic Levitation system parameters are set as in Table 5.1.[3]

Table 5.1: System Parameters

Symbol	Meaning	Quantity
m	Total Mass	200 Kg
$R_f$	Resistance	0.92 ohm
$\mu$	Permeability	$4\pi * 10^{-7}$
g	Gravity	9.81 m/s <sup>2</sup>
K	Maglev Coefficient	0.0015
f	Disturbance	30N

The controller's parameters are set as follows. The value of c is low, indicating that the system's response time is quick and its anti-disturbance ability is robust. The chattering issue of the proposed system will be more if the value of c is too tiny. The simulation analysis yielded a value of  $c = 900$ . The system has a fast response, strong tolerance capabilities, and minimum chattering if d is significant. According to the simulation results,  $d = 35$ . If b is big, the system has a quick response time and a high resistance to disturbances. The system will become unstable if the value is too high. Therefore,  $b = 3.5 \times 10^4$  is obtained from the

simulation analysis. If the value of  $\alpha$  is small, the response of the system will be fast but chattering will be more. Here a 30 N load is given as disturbance. The simulation analysis shows that  $\phi = 0.05$ ,  $\alpha = 1/3$ ,  $\eta = 1$ ,  $k_p = 23$ ,  $k_i = 700k_d = 342$ , are obtained.

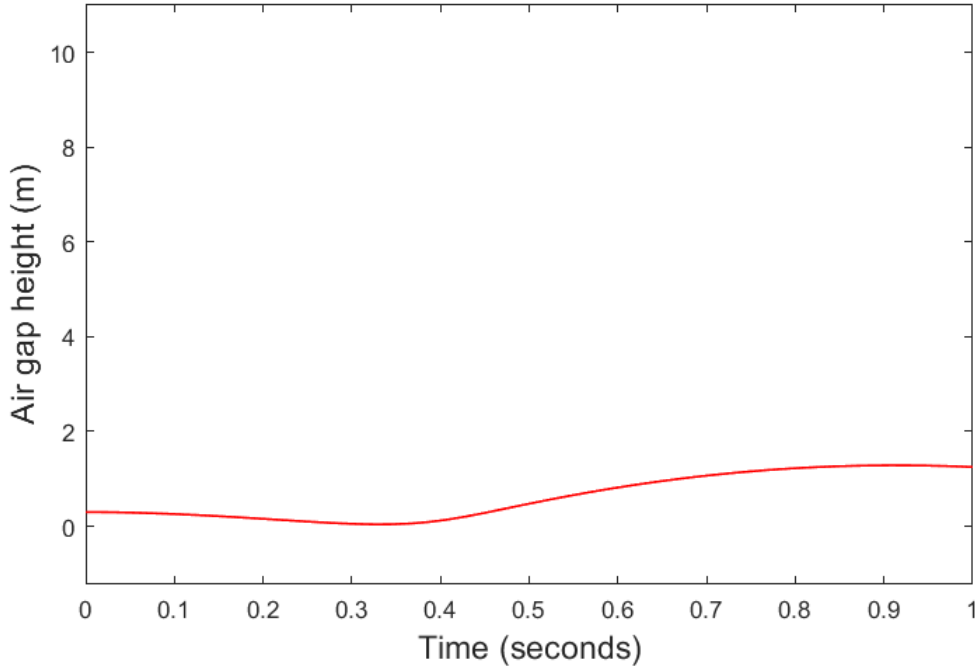


Figure 5.1: Open Loop response of Airgap Height

Fig. 5.1 and Fig. 5.2 shows the levitation height and current open loop response of magnetic levitation system with a 30 N load disturbance which clearly depicts that without a robust control, system cannot withstand the external disturbance.

The motor begins with a 3 mm air gap to analyse the motor's starting performance. The air gap height no longer exceeds the permissible error band which evaluate the dynamic performance index of the system.

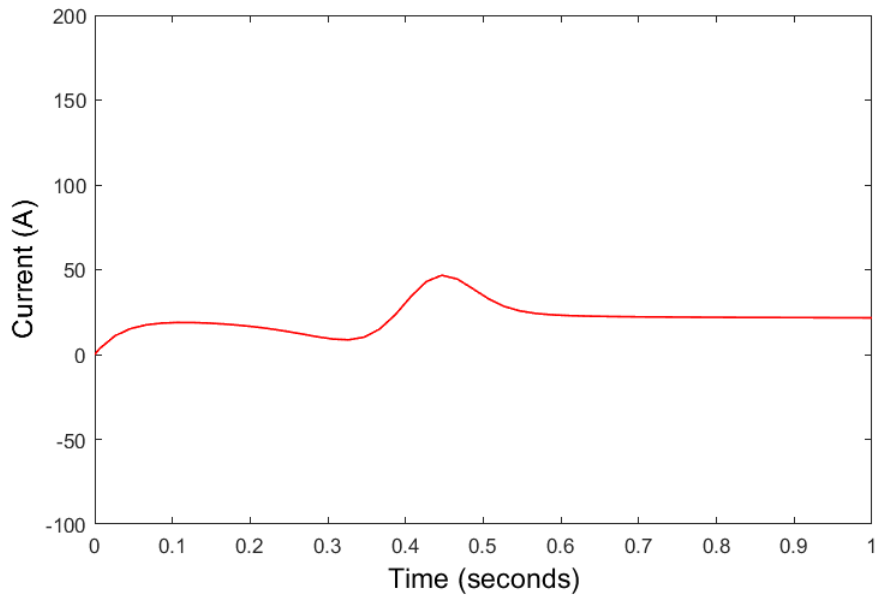


Figure 5.2: Open Loop response of Excitation current

## 5.2 FSMC-PID Control

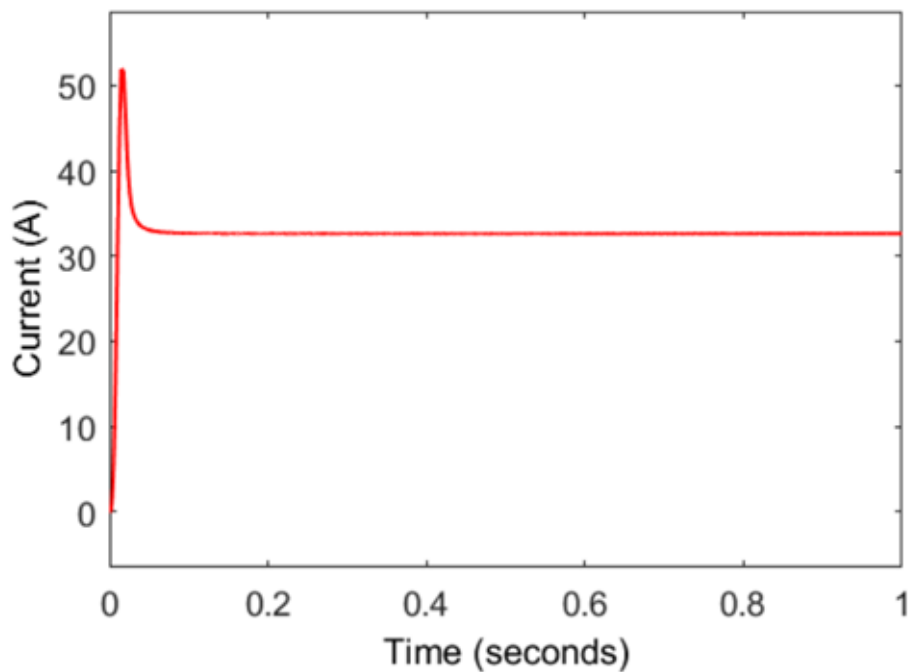


Figure 5.3: Response of excitation current for FSMC-PID Controller

Response of Excitation Current for FSMC-PID controller is shown in the fig. 5.3 where the current got stabilised at 33 A

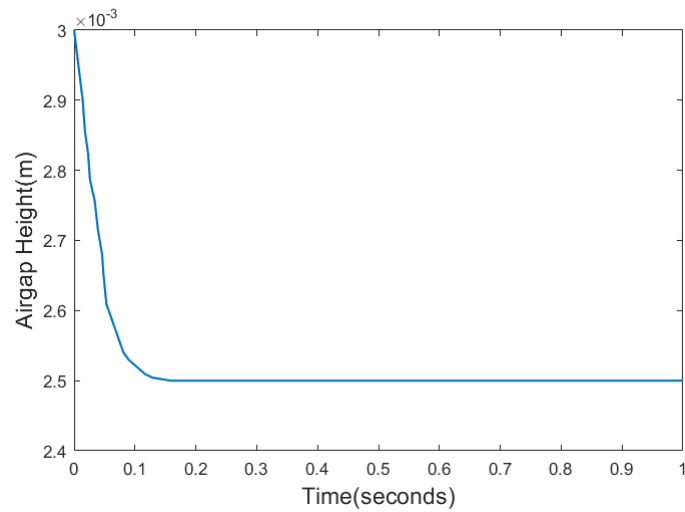


Figure 5.4: Response of levitation height using FSMC-PID controller with a 30N load disturbance

FSMC-PID control of magnetic levitation system is shown in the Fig. 5.4 which settles at 0.15s.

### 5.3 FSMC-PI Control

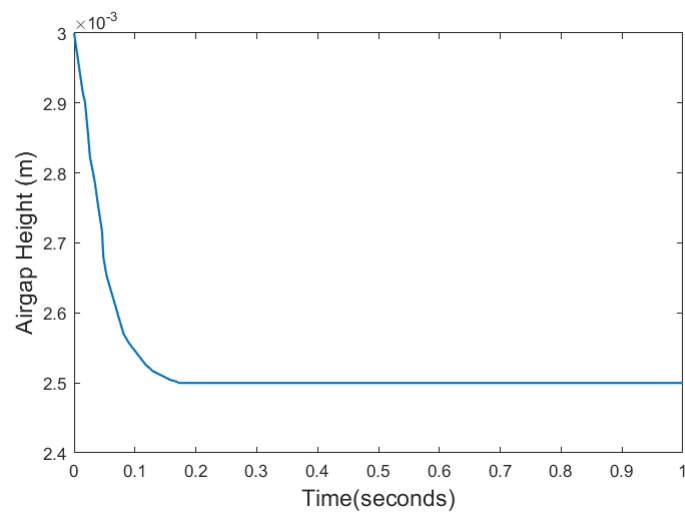


Figure 5.5: Response curve of levitation height using FSMC-PI controller with a 30N load disturbance

FSMC-PI control of magnetic levitation system is shown in the Fig. 5.4 which settles at 0.175s.

## 5.4 Comparison of FSMC-PID & FSMC-PI

Fig. 5.4 depicts the air gap height curve of system with FSMC-PID control and Fig.5.3 is its corresponding excitation current. Fig. 5.5 depicts the levitation height response of system with FSMC-PI control. From that it can be concluded that fast settling or fast response is achieved when using FSMC-PID controller.

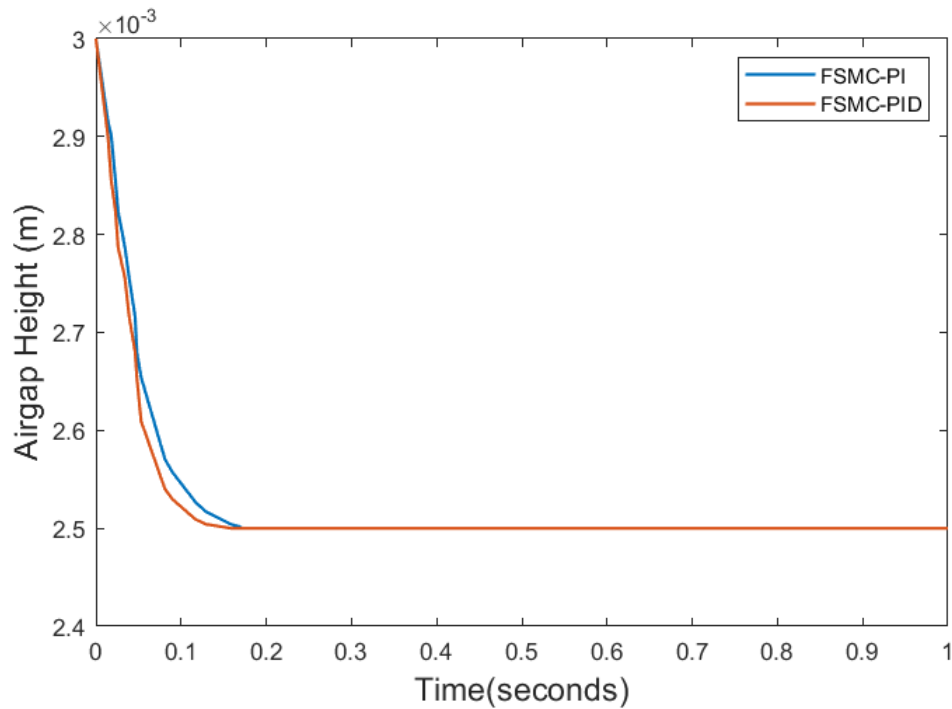


Figure 5.6: Comparison curve of levitation height

## 5.5 Summary

This chapter discusses the various simulation results obtained from the MAGLEV control system using FSMC-PI and FSMC-PID controllers. From this, it can be concluded that FSMC-PID shows better response.

# Chapter 6

## Conclusion and Future Scope

A Fuzzy based sliding mode position controller with PID as a current controller is suggested for the CELSM maglev platform. In this work, conclusion obtained through the research is that the control accuracy of the system is improved with better settling time in the proposed FSMC-PID control of controllable excitation linear synchronous motor of magnetic levitation system. Finally, the Simulink software simulation results of the magnetic levitation control system demonstrate that the proposed controller solves the difficulties of slow response time and also control system features good control performance, a minimal overshoot, a quick response time, robust resistance, and precise tracking.

The future scope of the project includes the Levitation height control scheme with more complex control methods which consider the constraints and optimal parameters.

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# List of Publications

- [1] Sneha Sajan, Sumayya Jaleel, "CELSM Magnetic Levitation System control using FSMC-PID", *International Congress on Control Systems* , 2022. (Accepted)