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Design and Construction of a Magnetic Levitation System Using Programmable Logic Controller

Minhaj Ahmed[1,3,*], Md. Fahad Hossen[1,3], Md. Emdadul Hoque[1,3], Omar Farrok[2,4], Mohammed Mynuddin[2,5]

[1]Department of Mechanical Engineering
[2]Department of Electrical and Electronic Engineering
[3]Rajshahi University of Engineering & Technology, Rajshahi-6204, Bangladesh
[4]Ahsanullah University of Science and Technology, Dhaka-1208, Bangladesh
[5]Atish Dipankar University of Science and Technology, Dhaka-1230, Bangladesh
*Corresponding author: somo.ruet@gmail.com

Abstract The motivation of this paper is to design and fabrication a cost effective magnetic levitation (shortly called Maglev) system using PLC. For this purpose a stand, a 12 volt electromagnet, eddy current displacement sensor which input voltage is 24 volt and output voltage range is 0 to 10 volt for 0 to 10 mm displacement, Siemens Logo PLC setup board including CPU, cable, analog expansion module, an amplifier circuit & Logo soft software are used. Sensor senses the displacement of a target and gives corresponding signal in terms of voltage. This sensor output voltage is used as input in PLC input terminal. CPU works according to ladder diagram which is installed in program memory. The electromagnet is connected to the analog expansion output terminal. The current is controlled by PLC according to sensor signal which passes through the electromagnet. When distance between the sensor and target is increased the output sensor voltage is increased. PLC receives this voltage and decrease the current supply at output terminal. Thus the magnetic force is decreased and target is levitated at a desired position. When the distance between the sensor and the object is decreased, then current is increased in electromagnet which increases the magnetic force and the target returns to its levitate position. Finally the target is levitated. This paper will be helpful to simplify this control system and implement in different types of maglev study and industrial issues as well.

Keywords: *magnetic levitation, electromagnetic force, PLC, automatic control, mechatronics*

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1. Introduction

Maglev is the technique to suspend an object in the air by manipulating magnetic force. This magnetic force is used to counter the gravitational force of object. Maglev is one of the best recent technology. It has no physical contact between the motion object and stable part of the system. So there is no friction and wear in such type of technique. Its application is rapidly increasing in various industry. A maglev device uses magnetic fields to suspend an object in a desired position. It was experimented by many researcher with superconductors, permanent magnets, diamagnetic materials and they comprehend that maglev is quite complex technique. When the gap between the object and magnetic source is too long, then the strength of magnetic field will inadequate to sustain the weight of the object. By placing near to the magnetic source, the strength of magnetic field becomes very powerful and the magnetic field can easily attract the object till it makes direct contact with the magnet. From the above, it is clear that a maglev device is an intrinsically unbalanced system. An electromagnet will have to be constructed to solve this uncertainty. This electromagnet is a simple device which is made up of a magnetic material wound with a current conducting coil. This coil permits to pass a varying current through it and hence generate a varying magnetic field or force. The generated magnetic force can attract any object in its domain. By controlling the amount of force exerted on the object and developing a stabilizing controller that can use measurements of position and velocity as feedback parameters in favor of balance the position of the object [1].

The objectives of this project are to design and fabricate the maglev system as well as to develop a ladder diagram and controlling system using LOGO PLC, to stabilize an object at a desired vertical position.

Figure 1. Magnetic Levitation [2]

2. Ease of Use

1) Maglev Train [3]. 2) Maglev Car [4,5]. 3) Maglev Stirrers [6]. 4) Bearing Less Centrifugal Pump [7].5) Magnetic Bearings [8]. 6) Maglev Wind Turbine[9].

3. Programmable Logic Controller (PLC)

3.1. Definition of PLC

PLC is a digital computer consists of integrated used for automation of electromechanical devices to execute control functions. According to NEMA PLC is a "Digital electronic devices that uses a programmable memory to store instructions and to implement specific functions such as logic, sequencing, timing, counting, and arithmetic to control machines and processes". It was created in favor of replace the sequential circuits which were commonly used for machine control. It is widely used for automation of electromechanical processes in many industries [10].

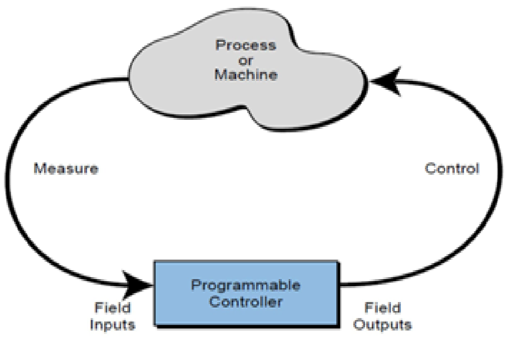

Figure 2. PLC conceptual application diagram

3.2. Basic Component

All programmable controllers contain a CPU, memory, power supply, I/O modules, and programmable devices. Basic parts of the PLC are as follows:

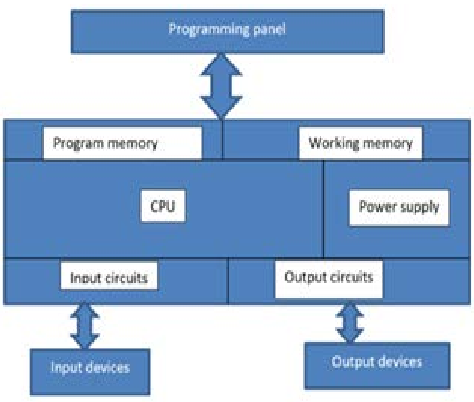

Figure 3. Basic components of PLC

4. Magnetic Levitation Techniques

History says that in the last few decades, maglev was experimented by many people using permanent magnets. Experiments were made to pursue the proper setting of permanent magnets to suspend another magnet (which size is must smaller than permanent magnet) or any ferrous material object. Earnshaw's theorem [11] however, manifests that maglev using permanent magnet is not mathematically possible. There are many alternative method to generate magnetic fields other than permanent magnet those can be used for levitation. Electro-dynamic system is one of them. The operating principle of electro-dynamic system can explain from Lenz's law. Electro-dynamic levitation also results from an effect discovered in superconductors. This effect is known as Meissner effect [12].

Magnetic suspension is one of the simplest method which is used to levitate any object (ferrous material) electromechanically. An electromagnet is positioned just above the object which is to be levitated. The gravitational force of the object is opposed by the magnetic force of electromagnet. A position sensor which works as a feedback is placed just below the object at a certain distance. The senor senses the position of the object and delivers this information to the control. According to the information provided by the sensor, the control unit supplies current to the electromagnet.

There are many techniques for levitation. These techniques are as follows: (1) Levitation using permanent magnets [13,14]. (2) Levitation using diamagnetic materials [15]. (3) Levitation using superconductors [16]. (4) Levitation using induces eddy currents in a conducting body [17]. (5) Levitation using current passing conductor in a magnetic field. (6) Levitation using inductance, capacitance, resistance circuit and the electrostatic force of attraction [18]. (7) Levitation using inductance, capacitance, resistance circuit and electromagnetic force of attraction [19]. (8) Levitation using controlled DC electromagnet [20]. (9) Levitation using mixed μ (permeability of material) system [21].

5. Methodology

5.1. Basic Concept of Levitation

In this project current is controlled by PLC. This current passes through the electromagnet which creates magnetic force on the desired object (such as cylindrical ball, bar, ferrous materials, door hinge etc). If load is increased the sensor senses the displacement and delivers signal to the control unit (PLC). PLC receives the signal and increased current supplied to the electromagnet. Thus magnetic force is increased and object is levitated a stable position. If load is decreased vice-versa activity is occurred. The block diagram is given bellow:

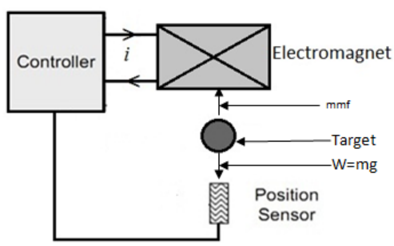

Figure 4. Block diagram of levitation concept with feedback system

5.2. Control and Regulate Basics [22]

In engineering field, quantities can be both controlled and regulated. At the time of controlling, a quantity is manipulated in such a way without being able to compensate for outside influences. Similarly to compensate for outside influences a quantity is maintained at a specific value at the time of regulating.

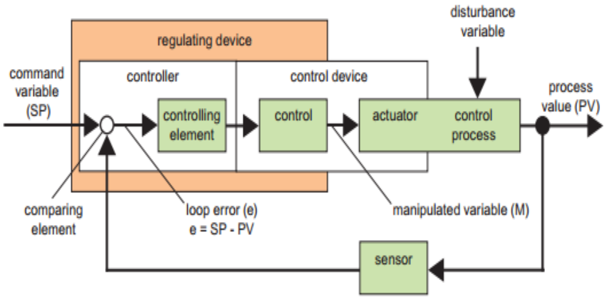

Figure 5. Basic concept of regulating with feedback control system [23]

In order to compare the command variable with the process value, the comparing element uses the sensor. If the command variables and process value differ from one another, this consequences a positive or negative loop error that in turn changes the process value.

5.3. Control Loop

By means of the regulating device, the process value x influences the manipulated variable M. Thus a close circuit is created which is also known as a control loop.

5.4. Loop Error

The difference between the command variable and the process value is the loop error. Again, loop error is the deviation of a process value (PV) from a set value (SP).

The loop error e brings about a change to the manipulated variable M. If with a desired temperature of 21 °C (= command value SP), the room temperature is 24 °C (= process value PV), then the loop error is:

$$e = SP - PV = 21°C - 24°C = -3\ °C$$

In this case, the negative sign indicates a reversing action, the heat output is reduced.

There are mainly three kinds of controller: 1. P controller 2. I controller 3. D controller

5.5. P Controller

P controller stands for proportional-action controller. It alters the manipulated variable M proportional to the loop error. The P controller works instantly. P controller cannot minimize the loop error to zero.

5.6. I Controller

I controller stands for integral-action controller. It changes the manipulated variable M proportional to the loop error and to the time. I controller does not work instantly. It can completely minimize a loop error.

5.7. PI Controller

A PI controller minimizes the loop error instantly and will finally minimize the loop error to zero.

$$M_n = M_{Pn} + M_{In} = k_P \times e_n + k_I \times \left(T_S / T_I\right) \times e_n + M_{In-1}$$

M_n: Manipulated variable at the time n, M_{Pn}: Proportional part of the manipulated variable, M_{In}: Integral part of the manipulated variable, M_{In-1}: Manipulated variable of the I controller at the time n-1(also called integral sum), k_P: Gain of the P controller, k_I: Gain of the I controller, T_S: Sampling time, T_I: Integral time, e_n: Loop error at the time n.

The following picture shows a jump in process value and step response of the controller:

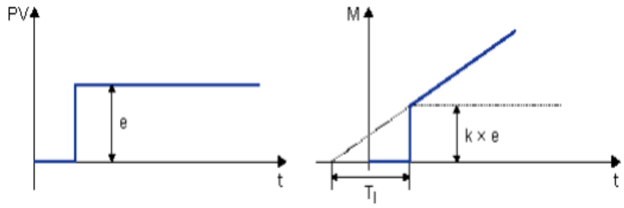

Figure 6. Response of PI- Controller Summary [23]

The features of PI controller is given below: 1.The P controller components instantly intercept an occurring loop error.2.The I controller components can minimize the rest loop error. 3. The controller components supplement each other so that the PI controller works instantly and accurately. For this reason this controller is used in this job.

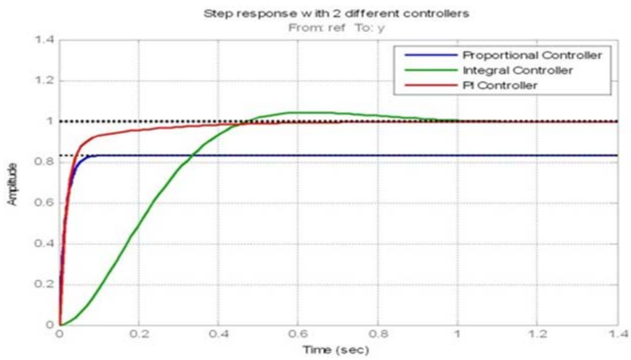

Figure 7. PI controller response

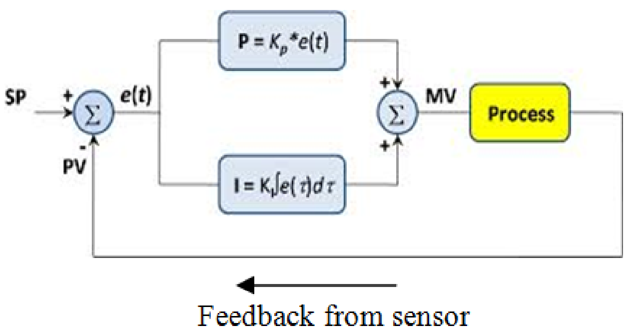

Figure 8. Block diagram of maglev system with feedback control

6. Physical View of Maglev System

The physical structure as shown in Figure 9 consists of an electromagnet, a displacement sensor, a control unit (PLC), a limiter and an object or target. The target that is to be levitated between electromagnet and sensor without any physical contact. In general, when the current passes through the electromagnet, a magnetic force is produced which will withstand the weight of the levitated object. Since the electromagnetic force is very quick response, so any low amount of current that will tend the levitated object in unstable region. A controller is used for that case. The purpose of the controller is to control the amount of current to keep the levitated object in stable position.

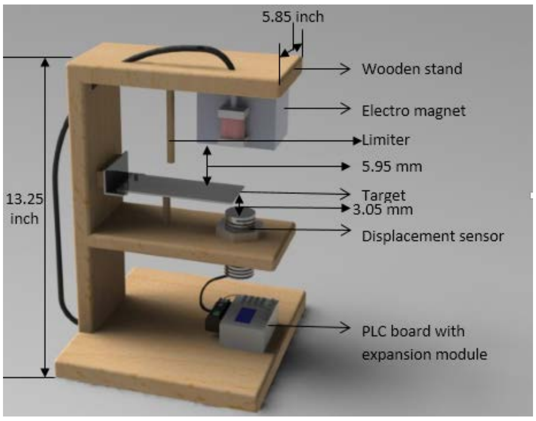

Figure 9. Structural drawing of the magnetic levitation

7. System Components

7.1. Actuator

A type of magnet in which the magnetic field is produced by the flow of electric current is shown in Figure 10. The magnetic field vanishes after the current is break off.

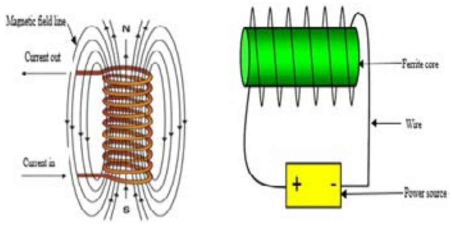

Figure 10. Basic construction of electromagnet [2]

The motivation of the magnetic actuator is to deliver a force. That magnetic force which will carry the load which is being supported. The suspended object must be capable to interact with magnetic forces because the bearing force is turning to be magnetic. This signifies the suspended load must be made of ferromagnetic material. The general block diagram of an electromagnet is shown in Figure 11.

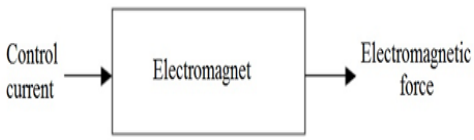

Figure 11. Block diagram of actuator

7.2. The Sensor

The electromagnet helps to regulate the strength of the magnetic field by controlling the current flow through it, but it is important to know when and by how much to regulate the strength in a real application. The sensor gives this information. There are many different types of sensors [24] that detect the distance between objects.

1. Proximity Sensor 2.Hall Effect Sensor 3. Ultrasonic Sensor 4. Capacitive Displacement Sensor

7.3. Eddy Current Displacement Sensor

Eddy current displacement sensors are non-contact devices used for the measurement of noncontact position, displacement and proximity. It is capable to measure the position or change of position of any conductive target without any kind of physical contact with high accuracy. The other name of eddy-Current sensors are inductive sensors.

The basic operating principle of inductive proximity sensors is electrical inductance. A fluctuating current induces an electromotive force (emf) in a target object which is the basic phenomenon of inductance. Eddy circuits developed in the metallic object when a metal object moves into the inductive proximity sensor's detection field, by magnetically push back eventually minimize the inductive sensor's oscillation field. When the oscillator becomes decreased to an adequate level, the sensor's detection circuit monitors the oscillator's strength and activates an output from the output circuitry.

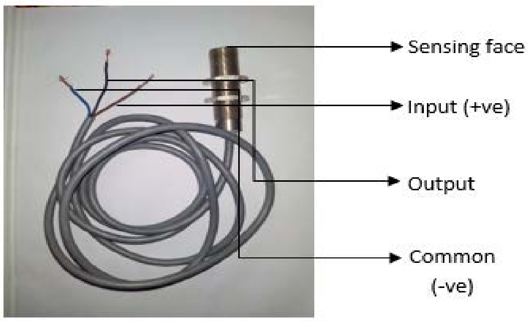

Figure 12. Physical view of a eddy current displacement sensor sensor

7.4. Control System

Analog Control, Digital Signal Processing (DSP), Microcontroller, PLC are some control system. Among those PLC is used. The sensor delivers a signal (voltage) that is proportional to the position of the target. When the object has displaced from its levitated position, the sensor provides a signal to the control unit (PLC). Then the PLC regulates the supply of current to electromagnet according to the information provide by sensor to bring back the disturbed object to its stable position.

8. Experimental Setup

8.1. Power Source

In this project 12 Volt & 24 Volt DC power supply are used which is obtained by 12V, 2A AC to DC Adapter & 24V, 6A AC to DC power supply. 12V Adapter & 24V power supply are needed to operate power amplifier with Electromagnet and Logo PLC with external module. The solar energy can also be used as power source of Electromagnet and Logo PLC. These systems are mounted together on a base plate to form the test bed. This configuration allows for portability of the system and rigid but adjustable positioning of the components. In order to design a user friendly controller for the maglev system, the system element must be modeled or characterized correctly.

8.2. Structural Elements

The elements whose are used to construct this system are given below: 1.Wooden frame2.Aluminums sheet 3.Iron bar 4.Plastic 5.Super enamel wire.

Figure 13. Experimental setup

8.3. Logo PLC CPU and Expansion Module Connection

In this project main controlling device is PLC. The analog output of Displacement sensor is the analog input of PLC I7 terminal act as analog input AI1 which range is 0-10V, 0-20 mA or 4-20 mA. Analog expansion card is attached with CPU and the analog output of AQ1 (current or voltage) is send to the power amplifier input. In online test mode the process is observed by the Computer monitor i.e the input and output analog voltage.

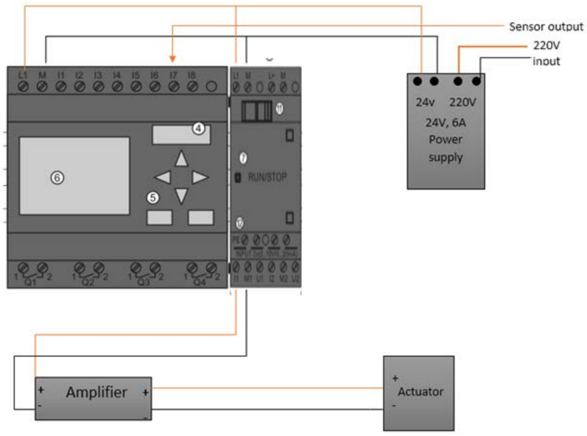

Figure 14. Wiring diagram of Logo to the system

Power amplifier Circuit consists of MJ11032 Darlington power transistor [25], potentiometer [26], resistor [27].

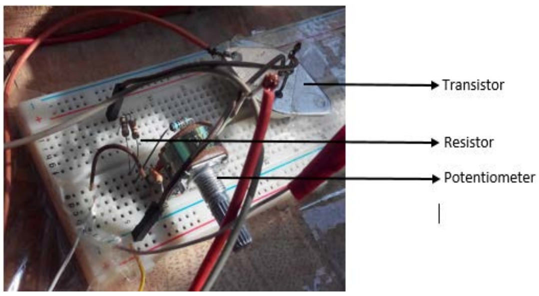

Figure 15. Power amplifier circuit

8.4. Actuator (Electromagnet) Design

An electromagnet is a type of magnet where a magnetic field is produced by electric current.The prime design criteria of an electromagnet is the lifting power. The lifting power of an electromagnet is depend on type of material and number of winding. E core shape is selected for design of electromagnet. Laminated iron core was selected to make the electromagnet because it has good permeability and hysteresis properties and the range of operating temperature is high. The core have the following dimension:

Length of the core, L_c : 39mm
Width of the core, D_c : 26mm
Height of the core, H_c : 33mm
Wire specification,18 AWG ; 1050 winding
Super enamel.
Air gap : 5.94mm
Weight of the object,
$W = mg = 24\times10^{-3}\times9.8 = 0.235N$
Voltage rating, 12V(±20%)
Current rating, 0.35 A
Power,P=VI=12×0.35=4to4.5watt

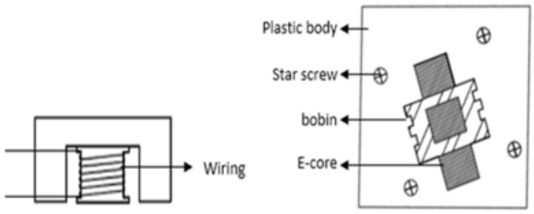

Figure 16. 2D top R.S view of actuator

8.5. Force Calculation

The strength of electromagnetic force depends on electromagnetic field. Again the strength of electromagnetic field depends on how much current will pass through the electromagnet. Electromagnetic field increases with increasing current. The basic characteristic of ferromagnetic material is that the saturated value of magnetic field is nearly 1.6 teslas that is for good permeability core steels. But when the magnetic field reaches at saturated value, then the magnetic field will not increase though the current still pass through the clectromagnet.

The equation of maximum electromagnetic force for I shape core electromagnet is:

$$F = \frac{B^2 A_p}{2\mu_0 \times 3}$$

where, F is the force (Newtons), B is the electromagnetic field (Teslas), A_p is the pole faces area = (57 × 17)= 0.969×10^{-3} m^2, μ_0 is the permeability of free space (air) = $4\pi \times 10^{-7}$ HM^{-1}

Since the E shape core has 3 poles, so for E-shape the force will be one-third of I shape core electromagnet.

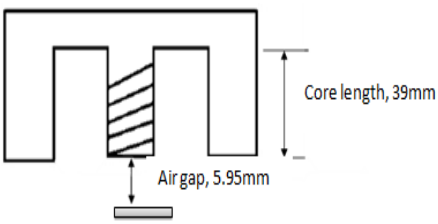

Figure 17. Dimensions of E-shaped electromagnet

Figure 17 depicts the dimensions of the E-shaped electromagnet.

The number of turns (N) for the electromagnet was chosen 1050 (18 AWG) and estimating the maximumu current (I) that could pass through the electromagnet is about 0.35 Amp. Again the magneto-motive force is the product of the current which will pass through the electromagnet and the number of turns of the wire across the electromagnet. Then, the magneto-motive force (mmf):

$$mmf = I \times N \text{ AT}\left(\text{Ampere} - \text{Turns}\right) = 367.5 \text{ AT}$$

Also, for the air-gap of 5.95mm mmf is:

$$AT = H \times L$$

$$H = \frac{AT}{L} = 61764.70 \text{ T/m}$$

L is the air-gap length = 5.95mm.

In the air-gap the magnetizing force (H) is:

$$H = \frac{B}{\mu_0}$$

Therefore, $B = H \times \mu_0 = 0.0775$ wb/m^2.

As the ferromagnetic material is saturated at about 1.6t eslas, the flux in the air-gap and the total flux in the core will be same..

The total flux is obtained to be, $\Phi_c = B \times A_c$

Where, A_c is the core area =0.02972 m^2

Hence,

$$\Phi_c = 2.303310^{-3} \text{ wb}$$

Hence the electromagnetic force for the air-gap 5.95 mm is computed as

$$F = \frac{B^2 A_p}{2\mu_0 \times 3} = 0.772 \text{ N}$$

But due to eddy current loss, poor insulation of the wire and lamination of the core this calculated lifting force must be multiplied by a factor (C) to obtain the actual lifting force.

The factor C is given by, C= 0.1

Then, the actual lifting force exerted by the electro-magnet is

$$F = 0.772\text{N}.$$

9. Experimental Results

9.1. Sensitivity of the System

The sensitiveness of the system is how the system interacts at the time of functioning under harsh condition. The system depicts a high notch of sensitiveness with the variation of the distances of the hanging object. The output voltages remain in a consistent trend over the various set of data collected while operation is enduring.

Figure 18 represent that the curve shows almost linear behavior from 2.5 mm to 5 mm. So the minimum gap between the sensor and the target should be maintained within the above value. Therefore the reaction of the system when some ferromagnetic material is brought closer to the sensing element is clearly evident by the curve.

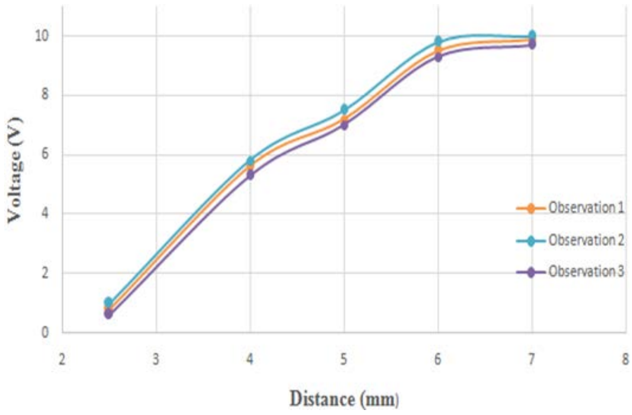

Figure 18. Sensitivity of the position sensor

9.2. Characteristics Curves of Maglev System

Identical trial works are performed to observe the attributes of the developed system. The below figures represent the different characteristics of the developed maglev system with varying different parameters (current, air gap, load). The motion of the existing setup can control only in the vertical direction. Therefore by aligning the object perfectly between the sensor and the electromagnet, the vibration of the object can be minimized. Figure 19 shows the current increases with increasing load because more current have to pass through the electromagnet coil to keep the object in stable position. Figure 20 illustrates the dynamic response of the developed maglev system. It is observed that with the increase in the air gap the control current also needs to increase to produce more magnetic force.

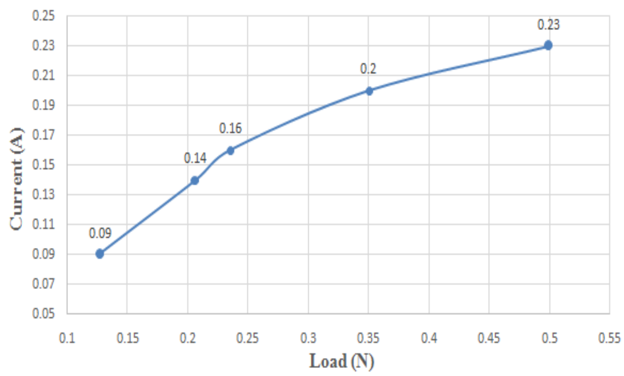

Figure 19. Variation of control current at different loads

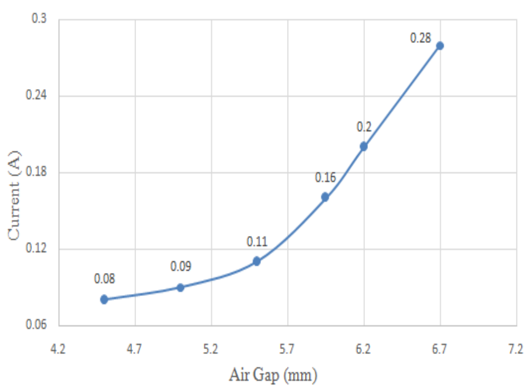

Figure 20. Variation of current at different air gap

9.3. System Realization

A stable maglev system is developed by logo PLC using a PI controller. At the same time, the system is suitably controlled by the controller. From the experiment, it is observed that the power consumption of the system is approximately 2 to 4 watt. It is considerably low regarding the stability of the system. It is seen from the figure that the system is stable using PLC. The levitation is shown in Figure 21 where the object is levitated at a stable position. The target is levitated at 6.56 V & 0.168 A.

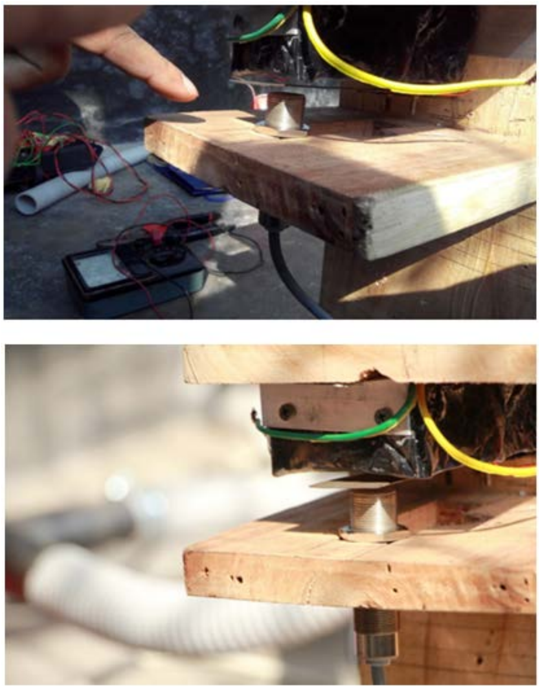

Figure 21. Realization of maglev system

9.4. Ladder Diagram

Ladder diagram of this project is quite simple and small. One digital make contact I2 and one brake contact I1, PI controller SF001, one analog input & one analog output A1 & A2 blocks are used to design the program. The parameter of PI controller is adjusted such as Controller amplification gain KC = 0.01, Integration Time (TI) = 1 second, Set value (SP) = 500 (5 volt), Manual output (Mq) = 0, Direction = Upwards (+), Sensor = 0-10 V, Sensor gain = 1.00 & offset = 0.

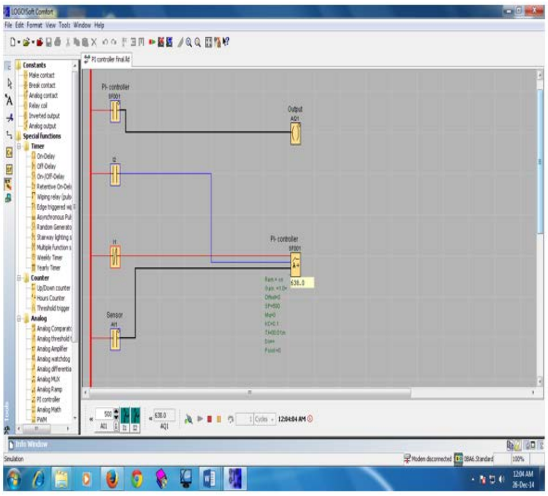

Figure 22. Ladder diagram online test simulation view

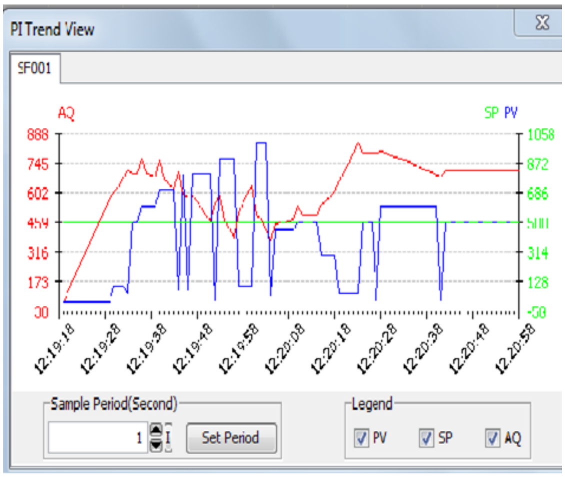

Figure 23. PI controller response and fluctuation diagram

In Figure 23 shows the PI response in online test mode. At starting time i.e 12h: 19min: 18s Process value (PV) was 100 (1V). After 1min 40s the process value is same as set point (SP) or reference value 500. During this time there are randomly changes the process value and output (AQ). When the process value is same as set value, the output is fixed at 637 (6.37 Volt) and the levitation is done by actuator.

10. Conclusions

This paper focuses on the arrangement of maglev system as well as design of a controller to keep the object in levitated position without any disturbances by controlling the amount of current through electromagnet.

Magnetic levitation system has been designed and fabricated. A ladder diagram has been developed for controlling system. Since the displacement sensor can detect the object to the amount of distance is limited to 1 to 10 mm, so when the distance range will increase then the sensor cannot deliver any signal (voltage) to the control unit (PLC). As the sensor response is not linear function, so the maglev system is intrinsically unbalanced system. However, this paper displays the control of single actuated, single axis maglev system. The single degree-of-freedom motion of the levitated object is controlled manually by tuning the controller gains. PI controller is used for its low cost, simplicity and stability. Furthermore, the energy consumption of the system is quite satisfactory. Finally, the object is levitated at a desired levitated position without friction and any kind of physical contact.

N.B: If anyone wants to see our project Video, Please check this link:-

https://www.youtube.com/watch?v=fjeD5chMfX4(low resolution)

https://www.youtube.com/watch?v=u_i9ByQ_LRM(high resolution)

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Biography of Authors

Minhaj Ahmed[1,*] has received his B.SC degree with Mechanical Engineering from Rajshahi University of Engineering & Technology (RUET), Rajshahi-6204, Bangladesh, in December 2014. Currently he is an Assistant Engineer of Refrigerator R&D at Walton Hi-Tech Industries Ltd, Gazipur, Bangladesh. His current research interest is in area of refrigeration & air conditioning system, Energy, Automation.

Md. Fahad Hossen[1] has received his B.Sc. degree in Mechanical Engineering from Rajshahi University of Engineering & Technology (RUET), Rajshahi-6204, Bangladesh, in December 2014. Currently he is an Assistant Engineer of Abul Khair Steel Melting Ltd, Sitalpur, Chittagong, Bangladesh. His current research interests are in area of energy, automation, fluid machinery, manufacturing process.

Md. Emdadul Hoque[2] is a Professor & Head of Mechanical Engineering Department at Rajshahi University of Engineering & Technology, Rajshahi, Bangladesh.

Education profile:
PhD: Saitama University, Japan
M. Eng. : Nanyang Technological University, Singapore
B.Sc. Engg.: Rajshahi University of Engineering & Technology, Bangladesh.
Research Interest:
Mechatronics
Vibration Isolation and Control
Maglev System
Active Zero-Power Control
Renewable Energy
Energy Harvesting

Omar Farrok[3] is the Faculty in the department of Electrical and Electronic Engineering (EEE), Ahsanullah University of Science & Technology (AUST), Dhaka-1208, Bangladesh. He has received his B.Sc. and M.Sc. Engg. degree in the department of Electrical and Electronic Engineering (EEE) from Rajshahi University of Engineering & Technology (RUET), Rajshahi-6204, Bangladesh, in 2006 and 2009, respectively. His current research interests are in area of machine, mechatronics, control and automation.

Mohammed Mynuddin[4] has received his B.Sc. degree with Engineering in Electrical and Electronic Engineering (EEE) from Chittagong University of Engineering &Technology (CUET), Chittagong-4349, and Bangladesh, in 2011**.** Currently he is a Lecturer dept. of EEE at Atish Dipankar University of Science and Technology, Dhaka, Bangladesh .He is a member of the Institution of Engineers, Bangladesh (IEB) His membership ID is M-32776. His current research interest is in the area of OFDM, Cognitive Radio, Wireless Communication, Digital Signal Processing, Industrial Automation, Power System Analysis and Electrical Machine, Renewable Energy.