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**Addis Ababa University**  
**Addis Ababa Institute of Technology**  
**School of Electrical and Computer Engineering**

**Design and simulation of an elevator DC motor drive with cascaded position, speed and current control**

A thesis submitted to Addis Ababa Institute of Technology, School of Graduate Studies, Addis Ababa University

In partial fulfillment of the requirement for the **Degree of Master of Science in Electrical and Computer Engineering (Control Engineering)**

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**Addis Ababa, Ethiopia**  
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**Addis Ababa University**  
**Addis Ababa Institute of Technology**  
**School of Electrical and Computer Engineering**

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## Declaration

I hereby declare that this thesis entitled: **Design and simulation of an elevator DC motor drive with cascaded position, speed and current control** is my own work and that all source materials used for this thesis have been properly referenced. This thesis has been submitted in partial fulfillment of the requirements for M.Sc. degree in Electrical and computer engineering (Industrial control engineering) at Addis Ababa University. I would also like to declare that this thesis is not submitted to any other institution anywhere for the award of any academic degree, diploma, or certificate.

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## Abstract

An elevator drive control system design is very important in the elevator performance profiles for the safety and comfort of passengers. These profiles include the slowly accelerating to maximum recommended speed, smoothly running with specific constant speed, then safely decelerating and braking to stop when elevator reaches the desired elevator position. The safety and performance of elevator are highly related to the design and control of its drive system.

The aim of this thesis is to design a cascaded position, speed and current controlled electric elevator drive system to achieve smoothly operating elevator drive system which increases the accuracy and precision with which the elevator system responds to position commands.

Before going to the step by step design procedures for creating a cascaded control system the literature review of theories and backgrounds behind the elevator evolution and drive system, and also the mathematical modeling of the permanent magnet DC motor parameters and the regenerative elevator kinematics with load are discussed in detail. Then, design aspects such as modeling the convertor, tuning parameter of a control system to direct the motor as desired are carried out. Also analyzing the control performance of the system with and without cascaded control system through use of computer simulations has been investigated in this thesis work.

Finally, the cascaded position, speed and current controlled elevator DC motor drive has been modeled in MATLAB Simulink and simulation studies are carried out. The simulation results demonstrate that the proposed control results in 0% over-shoot for the desired positions of 4m and 40m with corresponding speeds of 0.8 m/s and 2m/s, respectively, during lifting and lowering full load tests. Zero %-overshoot results also achieved through smooth acceleration and deceleration with maximum starting and braking torques of 12NM and 17.5NM for the desired positions of 4m and 40m respectively. This illustrates that the designed cascaded controller can effectively and efficiently control the elevator drive operation with passenger comfort in respect of smooth driving system.

**Key words:** Permanent magnet DC motor, cascaded control system, Position, Speed and Current control

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## List of Symbols

$K_b$	electromotive force constant
$\theta_m$	Motor angular position
$\omega_m$	Angular speed of motor
$R_a$	Armature resistance
$L_a$	Armature inductance
$V_a$	Armature voltage of motor input
$V_R$	Armature resistor voltage
$V_L$	Armature inductor voltage
$I_a$	Armature current
$S$	Laplace operator
$J_m$	Motor's moment of inertia
$b_m$	Viscous friction coefficient of the motor
$K_t$	Torque constant
$\tau_l$	Load torque placed on the motor's shaft
$M_l$	Load mass
$V_c$	Linear car velocity
$J_p$	Moment of inertia of driving pulley
$g$	gravity acceleration
$M_c$	Car mass
$R_p$	Pulley radius
$M_{cw}$	Counter weight mass
$P$	Total power on motor shaft
$\eta$	Efficiency of the transmission system
$G_p$	Proportional controller transfer function
$K_p$	Proportional gain constant
$G_{Pi}$	Transfer function of PI controller
$T_c$	Time constant of the Proportional Integral controller
$Q$	Quadrant
$K_i$	Integral gain of Proportional Integral controller

$V_{ci}$	Control input
$\alpha$	Delay angle of convertor
$V_{rms}$	Line to line voltage
$K_r$	Converter gain
$V_m$	Peak supply voltage
$V_{cm}$	Maximum control input voltage
$f_s$	Supply frequency
$T_r$	Delay time of convertor
$B_l$	Load torque constant
$B_t$	Total friction coefficient
$\tau_{em}$	Electromagnetic torque of the motor
$J$	Total moment of inertia on the motor shaft
$T_m$	Mechanical time constant
$K_{ip}$	Gain of the current controller
$T_{ic}$	Time constant of the current controller
$T_m$	Mechanical time constant
$T_r$	Converter time delay
$T_1, T_2$	Electrical time constants of the motor
$G_{col}$	Open loop transfer function of the current control loop
$H_i$	Current control loop feedback gain
$\omega_n$	Natural frequency of the system in radians per second
$\zeta$	Damping ratio
$G_\omega$	Filter transfer function,
$K_\omega$	Gain of the filter
$T_\omega$	Time constant of the filter
$K_{ps}$	Proportional gain of the speed controller

$\omega_{cp}$	Crossover frequency of position control loop
$K_{pp}$	Proportional gain of the speed controller
$T_{sc}$	Time constant of the speed controller
$V_{dc}$	Direct current voltage
$V_{rms}$	Root mean square voltage
$T$	Transistor
$D$	Diode
$e_a(t)$	Electromotive force of motor

## List of Abbreviations

DC	Direct Current
PMDC	Permanent Magnet Direct Current
UK	United Kingdom
MRL	Machine Room-Less
VSC	Voltage Source Convertor
VSI	Voltage Source Invertor
AC	Alternate Current
EMF	Electromotive Force
RPM	Revolution per Minute
PID	Proportional Integral Derivative
RMS	Root Mean Square
<i>hp</i>	Horse power

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# Chapter 1

## 1. Introduction

### 1.1. Background of the study

Elevator drive system is one of important design aspects which need proper design considerations in modern buildings technology. The term elevator can be generally defined as a device consists of electromechanical system used for transporting passengers or goods from one level (floor) to another in vertical dynamics of the buildings by the mechanism of lifting and lowering in either of ascending or descending direction respectively in fixed guides [1]. Elevator drive system consist of different subsystems such as a car travelling in vertical guides suspended on pulley drive connected on motor shaft related to counterweight by hoisting and lowering mechanisms, the prime mover of elevator(electrical motor) subsystem, a source of power supply through power convertor subsystem and the drive control system as a general. The main design issue of any type of passenger elevators drive is to provide transportation in the different purpose buildings in a safe and better comfort manner. In the last two centuries, the development based on a design quality and construction of elevator drive systems increased gradually with the achievements of the technologies in electro-mechanics, power electronics and mechatronics [1].

There are two main types of elevators basically based on their prime mover and mechanism of their drive operations [2]. The first one is hydraulic elevator, which operates by hydraulic pressure tube principle as a prime mover of the system. In this type of elevator, the elevator car deriving is as a result of hydraulic pressure generated from pumped fluid into or out of the cylinder of the elevator. The second type of elevator is a traction elevator (electrical elevator), in which the overall system is driven by using an electric motor as a prime mover of the system. The drive system of the traction elevator is composed of the elevator car and a counterweight suspended on either side of steel ropes looped around the sheave, the driving pulley and also the electric motor which is prime mover of the drive. The electrical elevator is the type of elevator mostly used throughout the world, and it is the ideal choice especially for the range of medium to high-rise buildings because it is more energy efficient due to the regenerative energy usage approach of its drive system, and higher speed compared to hydraulic elevators [2].

The traction elevators can be further grouped in to two types based on whether the prime mover of the drive is connected through a reduction gear or directly to the driving sheave to transform rotational angular position to linear motion of elevator, named as geared and gear-less types. The geared type of elevator drive is the drive system generated by interconnection between the prime mover (motor) and the wheel of the driving pulley through the gear train. In gearless type elevators, the motor is connected to the driving sheave directly, which is more advantageous due to that about 25 percent more energy can be saved than using geared motor drives [3].

Control System that is monitoring the overall elevator system and its prime mover to be operated in good accuracy in general can be considered as brain of the elevator system so that the elevator drive control system design is very important issue in elevator drive construction. Generally an electrical (traction) elevator drive system is a complex system containing both mechanical and electrical components. The electrical part of the system involves an electric motor which is a prime mover of the system with its source voltage convertor and control system, while the mechanical part of elevator drive system is composed of suspended masses (the car and the counterweight) that moving vertically on guide rails, the suspension system (ropes or cables), and the driving pulleys system [4]. The elevator car is connected to the compensation rope, in order to reduce vibration during elevator's journey. The purpose of the counterweight in traction elevator system is to offset certain part of the weight of the elevator which results in reduction of the torque provided by the motor [4]. Additionally, in order to reduce the problems such as low efficiency, inaccuracy, deteriorations and audible noise in elevator drive operation, an elevator with linear motor propulsion and electromagnetic guiding system is the better selection in elevator drive system design to generate smoothly operating elevator drive system as much as possible [5] [6].

## **1.2. Statement of the Problem**

Elevator systems are one of the complex mechatronic systems in modern building design. Thus it is a very critical issue to design the elevator drive control system. Elevator drive system should be efficiently and accurately operated with the proper control system that will monitor its input signal and able to translate the signal into a control signal that will direct the actual elevator drive system operation.

The basic factors that govern the good performance of elevator drive system include its cost, speed of operation, safety, minimization of energy consumption, accuracy and reliability. A practical experiment for the functional validation and test of the designed and developed system is highly necessary in order to analyze the system performance and its stability. However, the opportunities to test the system experimentally and optimizing is often limited by the system size and complexity, which is very expensive because of safety requirements. Furthermore, investigating the relevant operating conditions of the system is too complicated, and attaining an efficient accuracy, faster control operation and stability for the system by using a single controller is too difficult especially in the presence of disturbance and load variation.

This difficult situations and conditions related to modeling, testing and performance analysis of elevator drive system can be solved by accompanying the design and simulations of electrical elevator drive control system with cascaded position, speed and current controlled drive system. In this thesis, design of a cascaded position, speed and current control using a gear-less PMDC motor drive as a prime mover is presented to develop a smoothly operating, stable and comfortable DC drive system for electrical elevator system.

## **1.3. Objectives of the research**

### **General Objective:**

The main objective of this thesis is to model, simulate and control an electric elevator drive system with cascaded position, speed and current control using a gear-less permanent-magnet DC motor.

### **Specific Objectives:**

The specific objectives of this thesis are:

- i. To model the core parts of the mechanical and electrical sub-systems within a DC elevator drive system that describes the motional performance of the system
- ii. To design controllers for position, speed and current control of gear-less PMDC motor for elevator drive system
- iii. To model elevator drive system using the proposed cascaded control system in MATLAB Simulink
- iv. To carry out simulation studies and analysis of results
- v. To draw conclusions and make recommendations for electric elevator drive control system based on the findings of this research

### **1.4. Methodology**

To meet the above objectives, the following methods will be employed. First of all the study of thesis started by deep literature review of elevator drive technology with their prime movers, and also the control systems with techniques corresponding to the elevator drive technology. Next the mathematical modeling of the electromechanical system of electrical elevator drive dynamics is developed and presented clearly with the dynamic equations by using Kirchhoff's law followed by Newton's law of motion.

Then by taking different assumptions related to elevator standard speeds, specifying load capacity of certain passenger elevator and other necessary assumptions of electrical elevator, the basic drive component selections and design are performed.

Secondly, the convertor modeling and controller design guidelines of cascaded position, speed and current controlled electric elevator drive system is developed as a main design part of this study. Then after the controller is designed with step by step approach in each individual control loop of the proposed electrical elevator drive system, tuning of the proposed controller parameters is continued by using certain important elevator drive system parameters from literatures reviewed.

Finally the Simulink model of the desired elevator drive system is developed in MATLAB software in order to test and investigate the performance of the drive system with the proposed controller. The reference input of the system is the position of elevator to be reached by assuming zero initial conditions.

The two different cases of elevator motion (ascending and descending), each of them with another two sub cases are considered to examine the system performance under the same controller action and the result is represented in graphical form.

### **1.5. Scope of the study**

The scope of this thesis study focuses on the modeling, design and simulation of cascaded position, speed and current controlled electric elevator drive part using gear-less PMDC motor as prime mover for the drive system, basically analyzing how to improve the performance, drive efficiency and stability of electric elevator driving system by designing and tuning of a proposed controller for each cascaded loops and proving its performance using MATLAB software. The study does not include the complete futures of the entire elevator system such as alarm system, door opening and closing operations and other similar sub systems rather than modeling and designing of the elevator drive system in order to develop elevator which performing with high travelling accuracy and stability. The methods and techniques contained within this paper are useful also to design and develop other application areas of digitally controlled electric drive systems such as compensators and control systems in manufacturing industries in addition to the electrical elevator drive control system.

## **1.5. The outlines of the thesis**

This paper presents the thesis work titled as design and simulation of an elevator drive with cascaded position, speed and current control prepared by dividing into five sections. Chapter one summarizes the background of electric elevator, statement of the problem, the objective, the methodology followed to do the thesis as well as the scope of the work. Chapter two presents the general elevator drive system evolutionary history by a detailed review of literature survey on the elevator drive technology, manufacturing companies and corresponding drive used as well as its operating and controlling principle. A developed mathematical modeling of PMDC motor and the entire elevator drive system, and also the concepts related to design of cascaded position, speed and current controllers for the electrical elevator drive system are also presented here. The design of elevator drive system components, convertor modeling and controller design for cascaded control system of the drive is presented in chapter three. In chapter four the parameter selection of the actuator for the modeled system to test performance of the drive and tuning of the controller parameters are discussed and presented. Also the simulation results and discussions based on the performance of the designed cascaded control system of elevator drive are presented here. Finally, chapter five summarizes the conclusions and recommendations for future work suggestions.

## Chapter 2

### 2. Electrical Elevator Drive System

#### 2.1. Introduction (The electric elevator drive system)

The overall structure of elevator system is shown below, which indicates how the major components are integrated as general overall of an elevator system. Basically the whole system is modeled by integrating the electrical system and the mechanical system. As shown in Figure 2-1 below, the electrical system mainly refers to the PMDC motor circuits as a prime mover of the elevator, a convertor to feeding the motor input voltage from the utility, a circuit controlling its voltage input, and also the sensors that provides input to the control system by monitoring the status of the mechanical system.

The mechanical system includes a car, a counter-weight, a rope connecting the two, a sheave that drive the rope to roll from the car side to counterweight or vice versa, and a brake system that helps to stop the car when reached the desired destination [14].

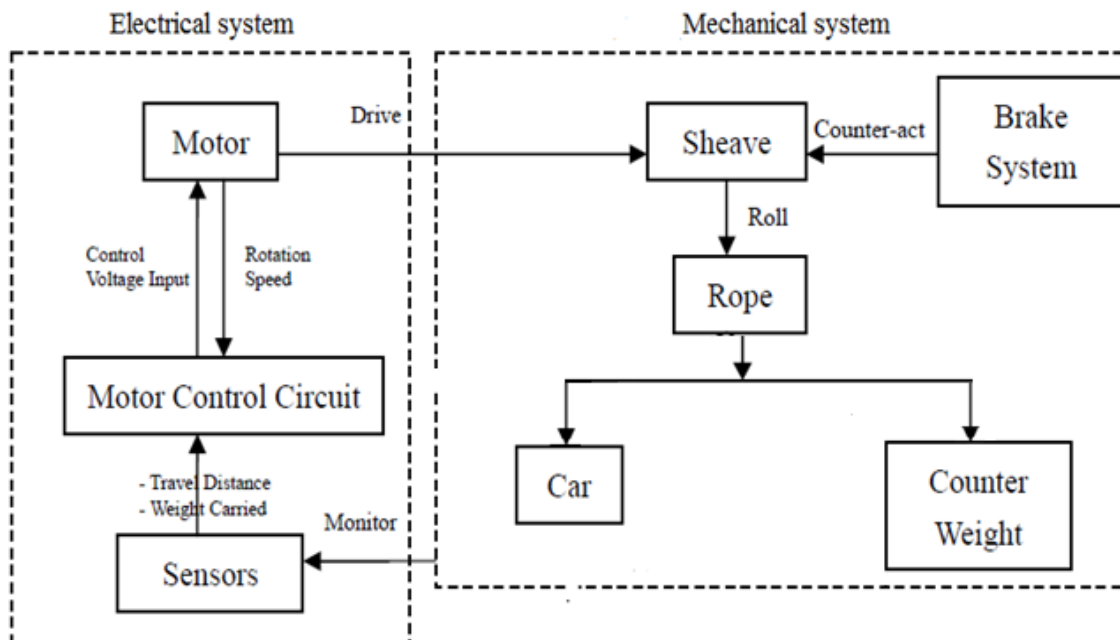


Figure 2-1: The general structure of electrical elevator system model [14]

A pair of guide rails is placed on two opposite sides of the car to guide the car during the elevator motion. The weight of the car and part of its load is balanced by the counterweight. The counterweight is basically constructed from steel frame and stacked fillers or weights secured by two or more tie-rods [15].

Both elevator car and counterweight are connected through traction ropes that pass through traction system surrounding the driving pulley at the top of the hoist way consisting of driving sheaves and electric motor. Similar to the passenger car, the counterweight is also guided by two guide rails along its sides during the vertical motion [15].

### **2.1.1. Regenerative electric drive systems**

Regenerative drives are another remarkable advancement in energy-efficient elevator technology, which operates by the principle of capability to recycle energy and providing reduction of energy wastage. More specifically, traction elevators use a counterweight to balance the weight of the elevator car and passengers. The counterweight is sized in an optimal way, approximately to a car loaded to 40%–50% of capacity [9]. There are different phases of operation of regenerative drives in which energy saving and harnessing occurs.

The first one is when the elevator system brake to allow the elevator speed slows down (decelerates) to stop safely the elevator system access energy is created. In a non-regenerative elevator drive systems, that energy is dissipated as heat through a heat resisters, the regenerative drives harnesses and save that energy [12]. Secondly, whenever an empty or lightly loaded elevator moves up, the elevator applies brakes to maintain the rated speed after reached the designed constant speed of the elevator. As in the case of slowing down, the energy generated here is usually lost again, but the regenerative drive harnesses and saves it.

Furthermore, when an empty or a lightly loaded elevator goes up, most of the work is done by the elevator's counterweight [12]. The regenerative drive harnesses that energy by transforming mechanical power into electrical power. The overall regenerative operation of electrical elevator drive system can be given as shown in Figure 2-2 below.

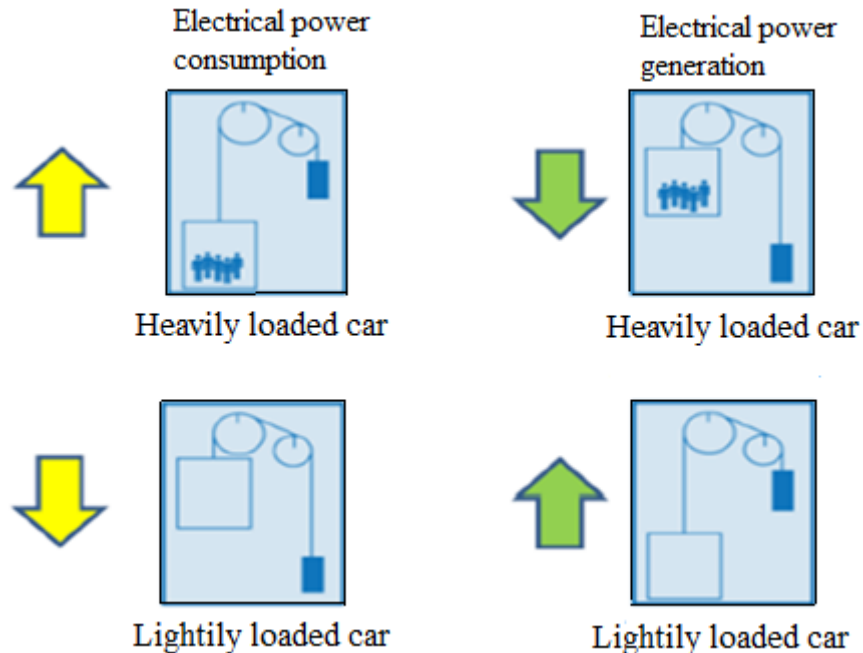


Figure 2-2: The regenerative elevator drive system [9]

Similarly, when a heavy elevator goes down, it applies brakes to maintain the desired speed. The regenerative drive harnesses that energy. Further, when a heavy elevator goes down, the motor partially rotates but gravity does most of the work. The regenerative drive again harnesses and save that spinning energy by transforming mechanical power into electrical power [12]. Generally, a regenerative drive can reduce energy consumption between 20% and 40% depend up on the designed system considerations, but the accumulate amount of energy savings depends on several factors including: length of traveling journey, design considerations, and type of equipment [9] .

### 2.1.2. Four Quadrant Operation of Electric Drive

DC motor's working principle is simpler than that of the AC motors, they are also easier to control and require simple electronics to operate. Torque in electric motors is produced due to the interaction among electromagnetic fields. Each part is permanently in contact with the brushes that drive the current to the rotor, and due to the change of position in the commutator, the current runs through the armature windings in different directions each time and produces a rotating magnetic field [16]. PMDC motor is the best selection of DC motors due to its robustness, high efficiency with minimum energy consumption, and reliability [18].

There are four possible modes or quadrants of operation of DC elevator drive, which is regenerative mode of operation as shown in Figure 2-3. In the plot of speed versus torque relation-ship, quadrant one is forward speed and forward torque. The torque is rotating the motor in the forward direction to attain a positive speed convention. Conversely, quadrant three is reverse speed and reverse torque which makes the motor to operate in motoring mode of operation in the reverse direction and spinning backwards with the reverse torque. Quadrant two is where the motor is spinning in the forward direction, but torque is being applied in reverse. Torque is being used to brake the motor and making the motor to be in generating mode of operation, and generating power as a result [17]. Finally, quadrant four is exactly the opposite to the operation of quadrant two. The motor is spinning in the reverse direction, but the torque is being applied in the forward direction. Again, torque is being applied to attempt to slow the motor and change its direction to forward again. Once again, power is being generated by the motor. When PMDC motor is operating in the first and third quadrant, the supplied voltage is greater than the back EMF which is forward motoring and reverse motoring modes respectively. When the motor operates in the second and fourth quadrant the value of the back EMF generated by the motor should be greater than the supplied voltage which are the forward braking and reverse braking modes of operation respectively [17].

Therefore, PMDC motors have the capability of regenerating energy when operating in the negative-load condition in traction elevator drive systems. Regenerative braking involves sending the regenerated energy from the elevator drive motor back to the electrical power source [18].

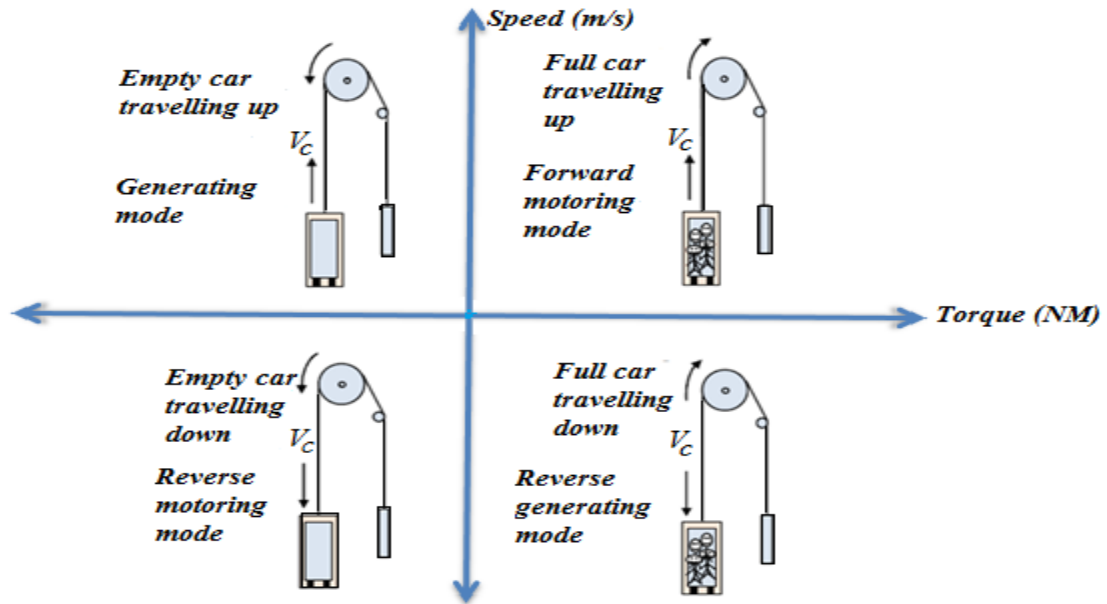


Figure 2-3: Four quadrant operation of elevator drive system [18]

### 2.1.3. Speed profile of Elevators working principle

Elevator speed is determined by the elevator service standard corresponds to the travelling distance. The speed should be selected such that it will provide short round time, almost 25 to 30 second interval for a medium height buildings to serve the passengers efficiently with a minimum weighting time as much as possible by handling the peak loads [19]. The principal requirements of an elevator system such as a shortest travel time and passenger comfort are directly related to the shape of the elevator speed versus time curve. Additionally, the elevator should increase speed slowly after it starts and reduce speed gradually before it stops in order to smooth the operation of the elevator and avoid vibration to provide a safe journey [20].

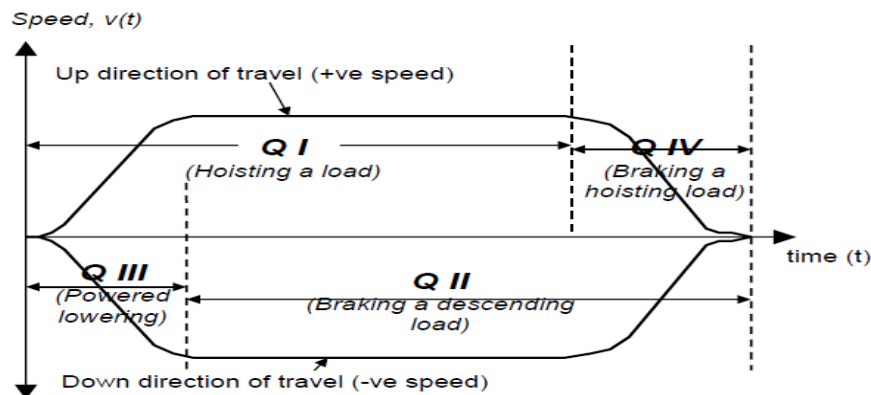


Figure 2-4: Four quadrant operation of elevator journey speed characteristic [20]

The speed-time curve as given in Figure 2-4 indicates the standard characteristics of elevator speed, which consists of three sections illustrating the three modes of operation in elevator drive system from starting to destination point of its journey.

First, the motor is rapidly accelerated or decelerates with high positive or negative torque respectively up to the recommended maximum constant speed, at which only small or no torque is required. After the constant speed phase, high braking torque is required to rapidly decelerate or accelerate the motor to stop at the desired position safely [21]. The general standard rules of recommended speed is given in Table 2.1 which is applied basically to commercial buildings, and may also use for similar height and purpose buildings with a wide range of speed [19].

Table 2-1: Recommended elevator speeds for different specified range of travelling distances [19]

Recommended standard of elevator speed ( $V_c$ ) range ( $m/s$ )	Travelling distance ( $h$ ) of elevator ( $m$ )
$V_c \leq 1.00$	$h \leq 20$
$1.00 < V_c < 1.50$	$20 < h < 30$
$1.50 \leq V_c < 2.50$	$30 \leq h < 45$
$2.50 \leq V_c < 3.50$	$45 \leq h < 60$
$3.50 \leq V_c < 5.00$	$60 \leq h < 120$
$V_c \geq 5.00$	$h \geq 120$

## 2.2. Voltage source conversion system

Voltage source converters (VSC) are an essential part of modern variable speed electric drives and other power electronics application systems to convert one form of power system to another form, either from AC to DC or vice versa [22]. The basic function of the VSC is to control the characteristics of electrical power such as voltage and frequency to obtain the desired form of power output.

Voltage source converters are used for different application purposes such as providing electrical power for DC loads and for adjustable speed drives such as hybrid vehicles, electric hybrid vehicles, elevators and renewable energy conversion systems.

Voltage source converters are classified based on the input and the desired output power as: DC/AC voltage source inverter, AC/DC voltage source converter and DC/DC voltage converter (choppers) [22]. In this thesis the two of them AC/DC converter and DC/DC converter will be modeled to fed elevator DC drive system.

### 2.2.1. AC/DC Voltage Source Converter

The power conversion system of AC/DC voltage source converter (VSC) is given below as shown in Figure 2-5 which consists of six electronic switches with full bridge diode rectifiers to allow bidirectional current flow capabilities and a filter capacitor at output DC side. Voltage source converters are an electronic circuit for which input power to the system is from the ac power source and generates the desired output dc voltage.

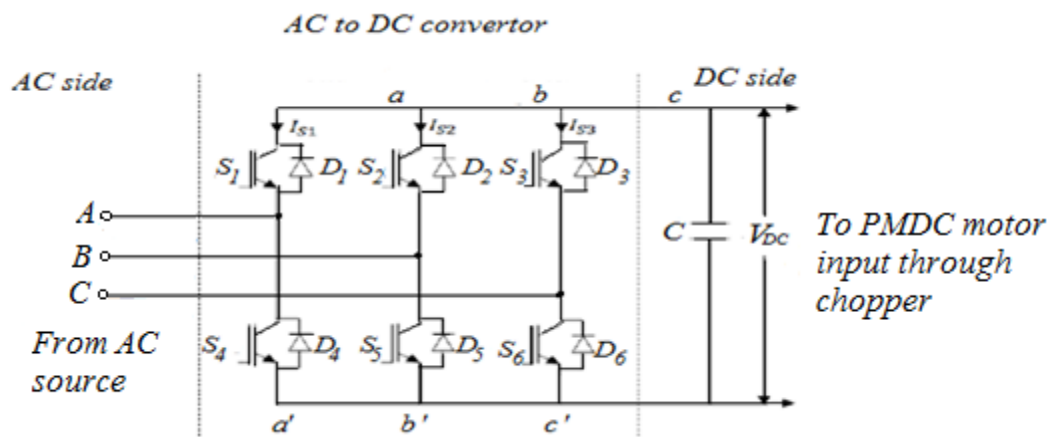


Figure 2-5: AC/DC voltage source converter [22]

Generally, there is a frequency difference between the power converters and the supply. The power converter switches are operating at a frequency usually higher than the supply frequency [22]. Such higher switching frequencies effectively reduce the harmonics content of the current waveform with smoother torque. In order to increase power quality by reduction of current ripple and total harmonic distortion in conversion system, either an inductive or inductive-capacitive filter can be added to the voltage source converter [22].

When the convertor input is directly from ac-grid line source, the DC-link voltage which produced from the ac-grid voltage, using a diode rectifier is given by [23]:

$$V_{DC-link} = 3 \frac{\sqrt{2}}{\pi} V_{rms-grid} = 3 \frac{\sqrt{2}}{\pi} * 380 = 513.17V$$

In this thesis, a transformer on the supply side is needed in order to step down the magnitude of the voltage that comes from grid to generate appropriate DC voltage needed to generate appropriate output voltage that matches with the desired motor input. So the thyristor bridge in a convertor model gets its ac supply through a step down three phase transformer and the dc output from the converter is fed to the armature of the dc motor through four quadrant chopper.

### **2.2.2. DC/DC four quadrant chopper**

A chopper is a static device that converts fixed DC input to a variable DC output voltage directly to supply DC electrical machines. It can be given another name as DC to DC converter. In choppers the transistors are commonly operates in the switching mode technique known as pulse width modulation (PWM), usually at frequencies between 1 kHz to 10 KHz [24]. In the PWM technique the average DC voltage is proportional to the pulse width. It is widely used in electric motor control system to operate in regenerative braking. Essentially, a chopper is an electronic switch that is used to interrupt one signal under the control of another by the actions of switches components (usually transistors) [24]. The switches in the four quadrant chopper can be switched in two different modes; the first mode is that output voltage swings in both directions from positive DC to negative DC voltage, and the second mode of operation is that a voltage swings from zero to positive DC voltage or from zero to negative dc voltage [24].

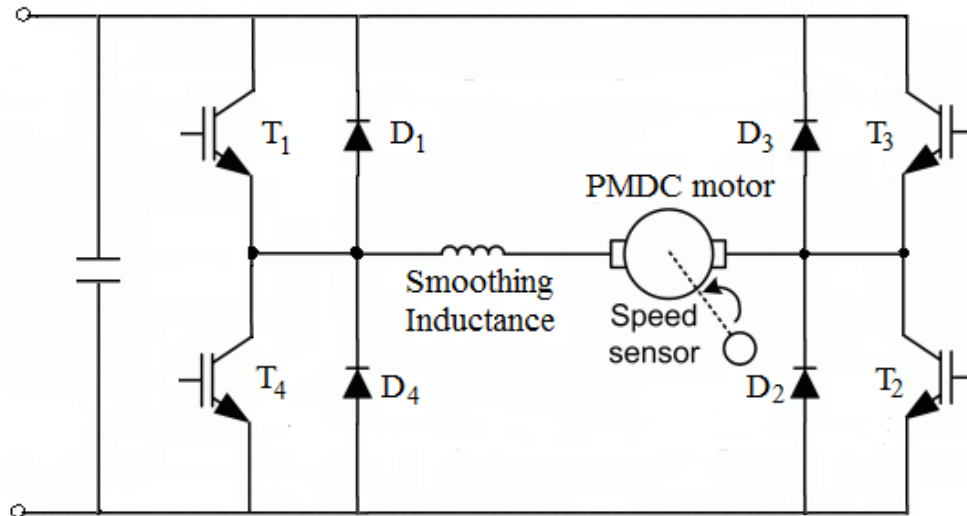


Figure 2-6: DC/DC four quadrant chopper [24]

The regenerative operation of the four quadrant chopper given by Figure 2-6 is directly related to the conducting behavior of corresponding switch components (transistors) in the circuit [24]. When transistors  $T_1$  and  $T_2$  are in conducting mode of operation, the chopper operates in quadrant one which is known as a forward motoring mode of operation. In this mode of operation both voltage and current are positive which results in the positive power flows from the source to the load. In the second quadrant the transistors  $T_4$  and  $T_2$  are switched on, in which the voltage is still positive but current is negative and results with a negative power, which means a power flows from a load back to the source if load is inductive type or back emf source such as motors [24]. In third quadrant is the operation of the chopper in which  $T_3$  and  $T_4$  are in conducting mode in pair. In this case both the voltage and current are negative which results in a positive power flow from a source to the load. Finally, in the fourth quadrant the voltage is negative but current is positive which is achieved through the reverse conduction of transistors  $T_2$  and  $T_4$ . Therefore the power is negative in this quadrant.

### 2.3. Literature review

The first traditional elevators technology was first developed during the 1800s which uses by the principle of steam or hydraulic pressure for a lifting mechanism which is hydraulic elevator type [7]. This mechanism uses a liquid most commonly water, which pumped into the cylinder to create pressure that capable of lifting the cab and reversely lowering it by force of gravity when the water removed back from the cylinder which was controlled by the passengers manually with valves.

Latter on with advancement of control technology, this mechanism is more enhanced to generate cab speed regulation by the principle of lever controls and pilot valves [7]. Recently, the general hydraulic elevator drive system operates by the working principle of pressurized fluid pumping force. When the valve is opened, the pressurized fluid will take the path of least resistance and return to the fluid reservoir, but when the valve is closed, it pushes the piston up and makes the elevator car to be lifted [8].

The other type of elevator system is the traction elevator, also known as electric elevator due to that it uses electrical drive system rather than hydraulic system. The first electrical elevator is developed during the mid-19th century in the U.K [8].

After certain advancement of elevator technology, the first passenger elevator which is traction type known as Otis passenger elevator was came to exist in 1857, in a New York City which is continued with development of different types of other elevator designs [8]. Later, with the advent of electricity, the electric motor was integrated into elevator technology by German inventor Werner von Siemens. With rapid evolution of motor technology and its control techniques multi-speed motors replaced the single speed model types of motor which helps to the development of a safely and smoothly operating electrical elevator drive system [8]. One of the most important elevator drive system design advancement is the machine room-less (MRL) technology since 1990s [9]. Earlier times, the elevator equipment was too massive so that the machine room was highly required and commonly placed on the top of the building above the hoist way and this machine room construction increases cost because it is needed to support a heavy machinery.

After motors are redesigned and the overall elevator structure becomes reduced by manufacturers, the need to build a machine room was eliminated. Recently, MRL traction (electrical) elevators are the most known elevator system throughout the world due to that they are more energy efficient especially when designed with regenerative drive systems where the MATLAB software is mainly used in the modeling and simulation of the elevator drive system [9].

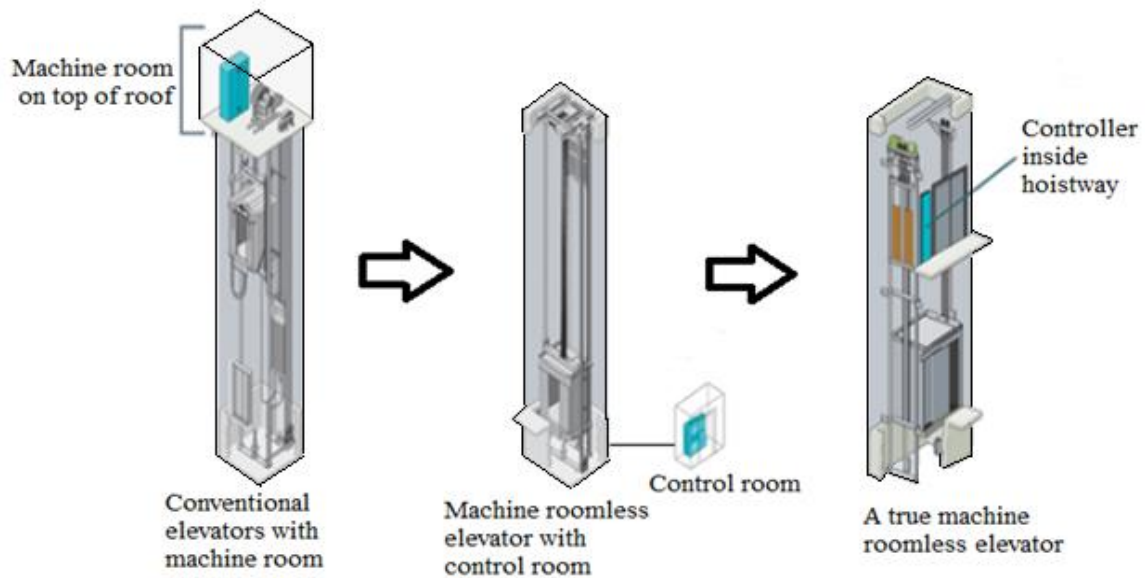


Figure 2-7: Machine-Room less revolution of elevators [9]

The two mostly known companies of elevators using machine-room less electric drives are the Kone and Otis companies. The working principle and driving approach as well as the prime mover of these two drive systems are discussed under the next sub topic of this literature review.

### 2.1.1. Kone and Otis Systems

The Kone Company developed a so called Eco-disc gearless permanent magnet synchronous machine in 1996, which is the first machine room-less (MRL) elevator drive designed by placing the motor inside the hub of driving pulley [10]. The car and counterweight suspended by strained steel cables are passing over this driving pulley; these cables are surrounded to the top of the elevator shaft and providing tension by the weight of the hanging car and counter-weight [11].

The Otis electric elevator drive system is the second type of machine-room-less elevator design which uses a flat steel belt in place of steel cables to support the elevator car and counter weight [12]. Similar to the Kone drive system, the prime mover of Otis elevator drive system is permanent magnet synchronous motor and operates by the principle of elevator car and counterweight suspension system to the drive pulley by attached to the ends of the belt anchored to the top of the elevator shaft so that the drive operation is basically related to applying the principle of newton's law to the tension provided by the suspended car and counter-weight provide on the belt [12].

The electric elevator drive system that is proposed in this thesis work is mostly related to the Otis working principle, in which the driving pulley is directly coupled with electric motor drive shaft without gear train and cascaded position, speed and current control system that governs the system performance. A gearless electric drive machines have more advantages than geared machines due to that they are more efficient and quieter in operation, reduces energy losses due to gear train and requires less maintenance.

### **2.1.2. Cascaded control system with P and PI controller**

A cascaded control system can provide better stability and faster control operation when compared to a system with single controller especially in the presence of disturbances and load variation. Control of both starting and braking torque is attained by controlling the motor current because of the relationship between the motor current and torque in both ascending and descending drive cases.

Finally, in order to overcome the parametric and modeling uncertainties of a system, control strategy based on P and PI controller is chosen for the desired system control in cascaded control technique. The proportional(P) and proportional-integral(PI) controller have been widely used in many different drive control applications because of their simplicity of operation, robust performance and also it is a linear control methodology with a very simple control structure.

One of the best features of P and PI controllers is the ability of applying cascade configuration by using more P and PI blocks together. The cascaded P and PI configuration in which input of one controller is controlled with another controller block achieves high flexibility and reliability, a better dynamic performance, gives best point tracking, disturbance regulation and reduced starting current that can be used for low and high capacity motors when compared with a single controller [13].

## **2.4. Mathematical Modeling of an Electric Elevator Drive system**

The dynamic equations of the overall elevator system is derived starting with the mathematical modeling of prime mover of the system which is PMDC motor drive, mainly based on the Newton's law combined with the Kirchhoff's laws.

### 2.4.1. Modeling Electrical component of the motor

The Permanent magnet direct current (PMDC) motor is a type of DC motors and its poles are constructed from permanent magnets. Its system is an example of electromechanical systems with electrical and mechanical components. In modeling PMDC motors and in order to obtain a linear model, the hysteresis and the voltage drop across the motor brushes is neglected. A simplified equivalent representation of the PMDC motor circuit is shown in Figure 2-8 below [25].

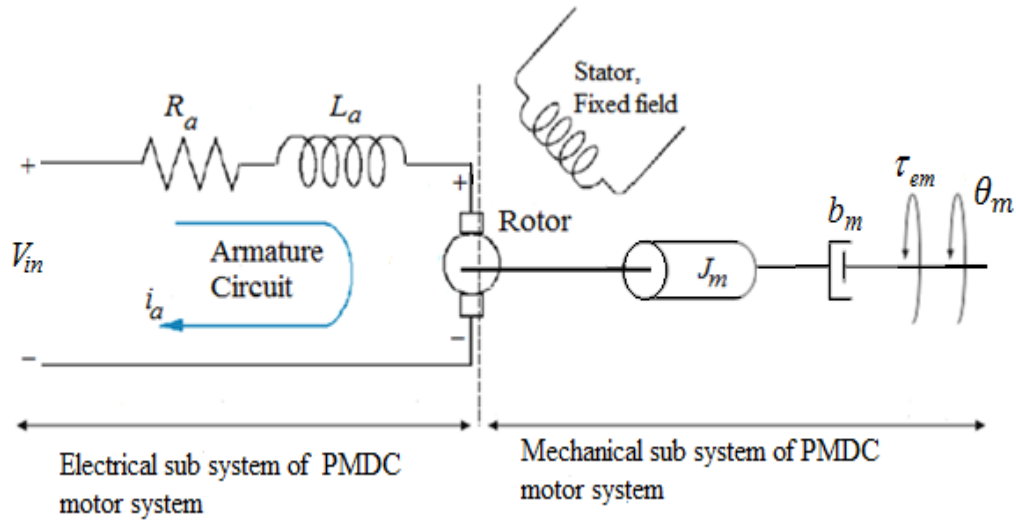


Figure 2-8: Equivalent circuit representation of the PMDC motor [25]

The torque developed by the motor,  $\tau_m$  is related to the armature current,  $i_a$  by a torque constant,  $K_t$

Which can be written as:

$$\tau_m = K_t i_a \quad (2.1)$$

Similarly, the induced electro motive force (EMF) is related to the motor shaft angular speed,  $\omega_m$  by a linear relation as:

$$e_a(t) = K_b \frac{d\theta_m(t)}{dt} = K_b \omega_m \quad (2.2)$$

Where,  $K_b$  = EMF constant

$\theta_m$  = motor angular position

Based on the Newton's law combined with the Kirchhoff's law, the mathematical model in the form of differential equations describing electric characteristics of the armature controlled PMDC motor can be derived; Applying Kirchhoff's law around the electrical loop of the motor:

$$\sum V = V_{in} - V_R - V_L - emf = 0 \quad (2.3)$$

Applying Ohm's law, substituting and rearranging, the differential equation that describes the electrical characteristics of PMDC motor can be obtained as follows.

$$V_{in} = R_a * i_a(t) + L_a \frac{di_a(t)}{dt} + K_b \frac{d\theta(t)}{dt} \quad (2.4)$$

Taking Laplace transform and rearranging, gives:

$$\begin{aligned} V_{in}(s) &= R_a I_a(s) + L_a s I_a(s) + K_b s \theta_m(s) \\ (L_a s + R_a) I_a(s) &= V_{in}(s) - K_b s \theta_m(s) \end{aligned} \quad (2.5)$$

Where,

$R_a$ = armature resistance	$L_a$ = armature inductance
$V_{in}$ = Input voltage of motor	$V_R$ = armature resistor voltage
$V_L$ = armature inductor voltage	$I_a$ = armature current
$K_b$ = EMF constant	$\theta_m$ = motor angular position

#### 2.4.2. Mechanical characteristics of the motor

Performing the energy balance on the PMDC motor system the mathematical model in the form of differential equations describing mechanical characteristics can be derived; the sum of the torques must equal zero, which is given by:

$$\begin{aligned} \sum \tau &= J * \alpha = \frac{J * d^2 \theta}{dt^2} \\ \tau_e - \tau_\alpha - \tau_\omega - \tau_{emf} &= 0 \\ K_t * i_a - \tau_{Load} - J_m \frac{d^2 \theta_m}{dt^2} - b_m \frac{d\theta_m}{dt} &= 0 \end{aligned} \quad (2.6)$$

Where,

$J_m$  = motor's moment of inertia       $b_m$  = the viscous friction coefficient of the motor

Taking Laplace transform of the equation above and rearranging, gives:

$$\begin{aligned} K_t * I(s) - \tau_{Load}(s) - J_m * s^2 \theta_m(s) - b_m s \theta_m(s) &= 0 \\ K_t I(s) - \tau_{Load}(s) &= (J_m s + b_m) s \theta_m(s) \end{aligned} \quad (2.7)$$

From the derived equations above and rearranging, the PMDC motor open loop system transfer functions can be derived. We can solve for the current from equation (2.5) which is given by:

$$I(s) = \left[ \frac{1}{(L_a s + R_a)} \right] [V_{in}(s) - K_b \omega_m(s)] \quad (2.8)$$

Then, the PMDC motor electrical component transfer function relating armature current and voltage is given by:

$$\left[ \frac{I(s)}{V_{in}(s) - K_b \omega_m(s)} \right] = \frac{1}{(L_a s + R_a)} \quad (2.9)$$

Similarly, the motor's mechanical component transfer function in terms of output torque and rotor speed is obtained from equation (2.7) as:

$$\left[ \frac{\omega_m(s)}{K_t I_a(s) - \tau_{Load}} \right] = \frac{1}{(J_m s + b_m)} \quad (2.10)$$

In case of no load attached,  $\tau_{Load}=0$ , then the equation becomes:

$$\left[ \frac{\omega_m(s)}{K_t I_a(s)} \right] = \frac{1}{(J_m s + b_m)} \quad (2.11)$$

Where,

$\omega_m(s)$  = motor angular speed       $K_t$  = torque constant

### 2.4.3. Block Diagram Representation of PMDC Motor Model

The PMDC motor electrical part transfer function relating input armature current,  $i_a$  and input voltage, and also the motor's mechanical component transfer function relating output torque and rotor speed is derived above. Also the electrical and mechanical components of the motor are coupled to each other through an algebraic torque equation by torque constant  $K_t$ . Using these relations we can build the block diagram model of the open loop PMDC motor system shown in figure below.

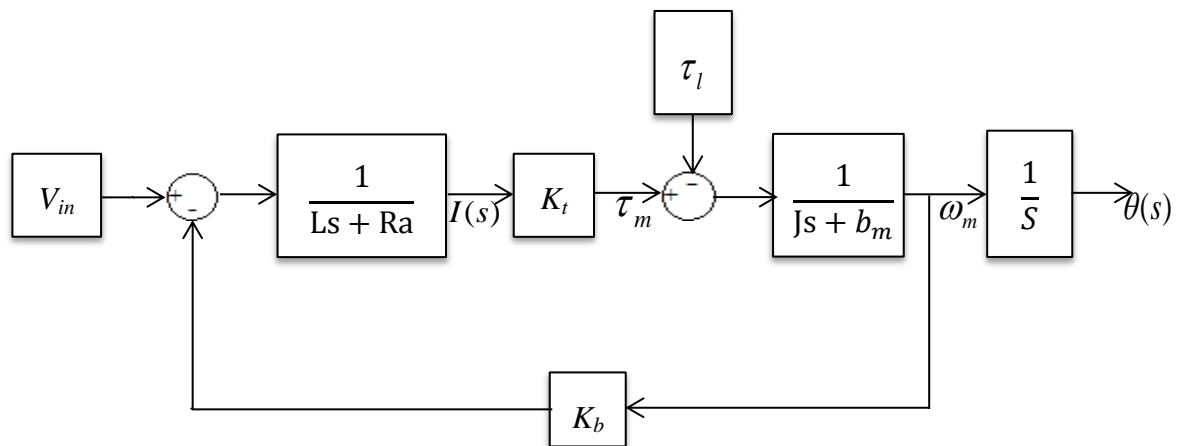


Figure 2-9: The block diagram representation of open loop PMDC motor system

### 2.4.4. Modeling a driving dynamics of the overall elevator drive system

Performing the energy balance analysis by applying the principle of Newton's law of motion on the overall elevator drive system, the mathematical model in the form of differential equations describing the characteristics of the elevator drive system can be generated. Several assumptions were made in developing mathematical model of the mechanical system of elevator drive.

The basic assumptions considered to develop mathematical model of elevator drive system in this thesis work are given as follows:

- The suspending ropes are considered as mass-less by the assumption of modeling a system with compensating ropes where the inertia of the ropes is integrated with the elevator car and counterweight inertias
- Additionally, the dynamics of the travelling rope, governor, the effect of air pressure and also other similar non basic friction effects were ignored

Using this assumptions and considering the elevator drive system given in Figure 2-10 below, the overall driving system characteristics in both ascending and descending cases of elevator drive system will be mathematically modelled and given below.

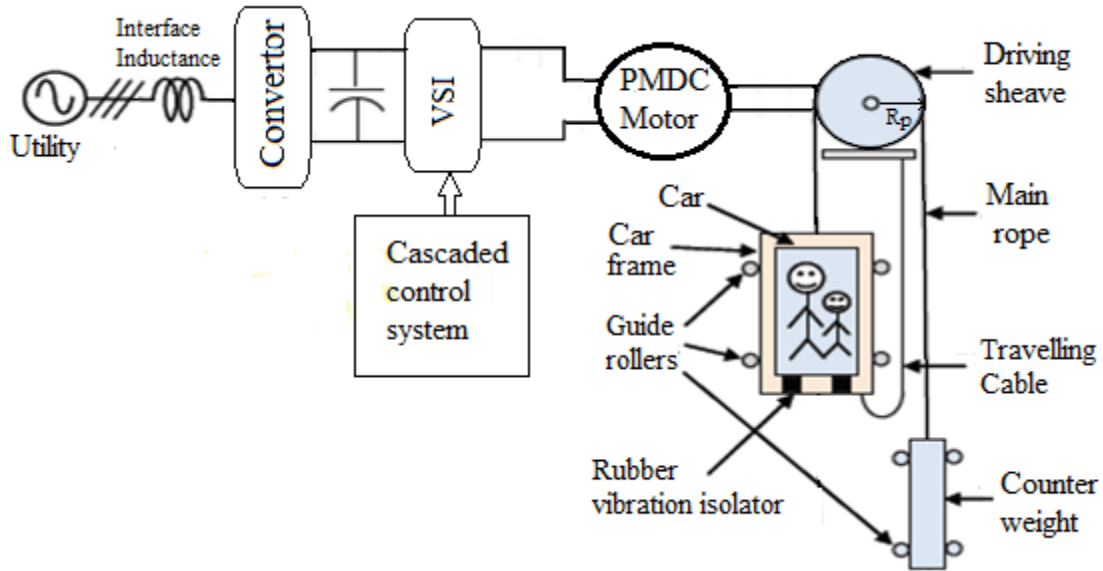


Figure 2-10: Physical model of traction elevator drive system [18]

The sum of the total driving torques of the overall drive system must equal to zero, so that:

$$\tau_{em} - J_m \frac{d\omega_m}{dt} - b_m \omega_m - \tau_l = 0$$

$$\tau_{em} = J_m \frac{d\omega_m}{dt} + b_m \omega_m + \tau_l \quad (2.12)$$

Where,

$J_m$  - is the motor's moment of inertia

$b_m$  - is the viscous friction coefficient of the motor

$\tau_l$  - is the load torque placed on the motor's shaft.

By applying the newton's law of motion to the overall elevator physical system in Figure 2-10, it is possible to calculate the resistive (load) torque, and then the motion equation of entire elevator drive system [26].

The load force for elevator car moving upward direction is given by:

$$F_l = (M_l + M_c - M_{cw})g + (M_c + M_l) \frac{dV_c}{dt} \quad (2.13)$$

The car linear speed  $V_c$  is in terms of the motor angular speed and radius of driving pulley attached to motor shaft given by:

$$V_c = R_p \omega_m \quad (2.14)$$

Then the load force equation can be rewritten as:

$$F_l = (M_l + M_c - M_{cw})g + (M_c + M_l)R_p \frac{d\omega_m}{dt} \quad (2.15)$$

The load torque is directly related to load force and inertia of the driving pulley with radius  $R_p$  as:

$$\tau_l = F_l R_p + J_p \frac{d\omega_m}{dt} \quad (2.16)$$

Substituting equation (2.15) in (2.16) for load force, the load torque equation when elevator car moving up is rewritten as:

$$\tau_l = (M_l + M_c - M_{cw})gR_p + (M_c + M_l)R_p^2 \frac{d\omega_m}{dt} + J_p \frac{d\omega_m}{dt} \quad (2.17)$$

Then by substituting equation (2.17) in (2.12) the overall equation of elevator drive system for ascending elevator car will be obtained as follows.

$$\tau_{em} = (J_m + (M_c + M_l)R_p^2 + J_p) \frac{d\omega_m}{dt} + b_m \omega_m + (M_l + M_c - M_{cw})gR_p \quad (2.18)$$

Similarly when elevator car accelerates moving down wards, the mass of counter weight ( $M_{cw}$ ) should be considered by ignoring a mass of elevator car ( $M_c$ ).

So the load force when elevator car moving downwards will be:

$$F_l = (M_{cw} - (M_l + M_c))g + M_{cw}R_p \frac{d\omega_m}{dt} \quad (2.19)$$

Then the load torque developed during elevator car is lowering is given by:

$$\tau_l = (M_{cw} - (M_l + M_c))gR_p + M_{cw}R_p^2 \frac{d\omega_m}{dt} + J_p \frac{d\omega_m}{dt} \quad (2.20)$$

Finally, the overall equation when elevator car is moving downwards (lowering) will be given by:

$$\tau_{em} = (J_m + M_{cw}R_p^2 + J_p) \frac{d\omega_m}{dt} + b_m\omega_m + (M_{cw} - (M_l + M_c))gR_p \quad (2.21)$$

Where:

$M_l$  = mass of the load

$V_c$  = linear car velocity

$\tau_{em}$  = electromechanical torque

$J_p$  = pulley moment of inertia

$g$  = gravity acceleration

$M_c$  = car mass

$R_p$  = pulley radius

$M_{cw}$  = counter weight mass

$b_m$  = the friction coefficient of the motor

Then based on the mathematical model of the elevator drive system developed in this chapter and using the concepts behind the elevator drive system, design and selection of the basic elevator drive components and the convertor modeling followed by step by step cascaded control system design with PMDC motor as a prime mover of the system will be developed in the next chapter.

## Chapter 3

### 3. Designing cascaded control system for elevator drive

#### 3.1. Introduction

There are different basic considerations in designing of passenger elevator system, specifically the elevator drive control system. The basic and important specifications needed to be considered in design aspect of elevator drive include: The number of floors in the building for which the elevator is going to serve, the distance between each floor, maximum load capacity of the elevator, the specific standard speed based on height of the building and the time in which the elevator operates with consideration of passengers comfort and safety to reach the desired destination. So in order to meet these requirements it is needed to design the basic parameters related to the above specifications as well as the control system which governs the drive system to operate smoothly and accurately. The design parameters to be considered before controller design consists of specifying and fixing elevator car dimension, rope strength, the selection of driving pulley radius on which car and counterweight are suspended, selection of the correct prime mover (efficient and cost effective motor rating) of elevator drive system. Then selecting a proper controller type and designing its parameters in order to develop proper control system to achieve a stable and efficient elevator drive system.

#### 3.2. Elevator drive components design and selection

Under this topic the drive components are designed by considering and specifying the maximum load capacity of the electric elevator which is to be operated under the control system of the elevator drive which is to be designed next in this chapter. The materials required and the maximum load capacity specifications for desired elevator drive which will be controlled with cascade control technique are discussed below.

##### 3.2.1. Designing elevator Car, Counterweight and Rope strength

The elevator car is designed by considering the number of passengers it is going to accommodate and serve at each a single way of its journey. Also it should have the capacity to handle the weight of the passengers travelling by the elevator [15]. In this thesis, by assuming that the proposed elevator is having the capacity to accommodate six passengers of approximately 65kg mass each at a time, the maximum load that the car can handle will be equal to  $65 \times 6 = 390\text{kg}$ .

The car with the dimensions of 1.5m\*1.5m\*2m is designed which efficiently can handle this load. Let the mass of empty car to be approximately 100kg, a mass of counterweight is usually designed as the sum of car mass and approximately 50% of maximum load as it is reviewed earlier in this paper.

All the mass of car with load and counter weight are suspended by the rope on the driving pulley. The total force exerted on the rope and its choice of selection can be determined by using Newton's formula. The force acting on the rope is the sum of counter weight, the weight of empty car, and weight of passengers [15].

Using Newton's law the force exerted on the rope can be given by:

$$F = mg \quad (3.1)$$

Where  $g$  is acceleration due to gravity and  $m$  is total mass suspended on the rope. Then substituting from the design values above, the force in the rope will be:

$$F = (100\text{kg}+390\text{kg}+300\text{kg}) * 9.81\text{m/s}^2 = 7749.9\text{N} = 7.7499\text{KN}$$

Therefore, a rope with the capacity to bear at least 8KN with specified thickness has to be chosen from the rope manufacturer's data sheet.

### 3.2.2 Selection of motor power rating and driving pulley radius

Motor sizing refers to the process of selecting the correct motor to run a given load. It is important to size a motor correctly due to the following basic reasons:

- If a motor is too small for an application it may not be sufficient to start the load and accelerate it up to the corresponding elevator speed or even if it can operate the load up to desired speed the motor will overheat and as the result it may burnout
- If a motor is much larger than the required load operation, then it needs too much money in purchasing such a large motor which in turn increases the cost
- Additionally, a motor typically operate inefficiently when running at very little power below the corresponding of its power rating

The motor used in this thesis work is a permanent magnet DC motor. Based on the design specification given above, the output power of the motor is calculated by using the general equation of force on the rope by assuming constant maximum linear car speed of 2m/s, which is taken from the desired standard speed given in Table 2-1 to design an elevator drive system for a building with ten floors above the ground (40m in height). Considering the elevator car moving upward (ascending) with the specified linear speed above, the total load lifting force ( $F_l$ ) developed during the journey can be given by the following equation as [26].

$$F_l = (M_l + M_c - M_{cw})g + (M_c + M_l) \frac{dV_c}{dt} \quad (3.2)$$

This equation is further simplified by assumption of constant car speed, and then its time derivative is zero, and equation 3.2 will be rewritten as:

$$F_l = (M_l + M_c - M_{cw})g \quad (3.3)$$

Then the energy required for upward moving elevator car is given by the energy equation based on load force and the linear distance traveled by elevator car as given by the following equation.

$$E = FS \quad (3.4)$$

So the power on motor shaft is given by a time rate of energy and given by the equation below.

$$P = \frac{E}{t} = \frac{FS}{t} = FV_c \quad (3.5)$$

From the elevator drive system, while ascending (upward moving) elevator car the counter weight moves downward (opposite direction to car movement) and doing certain work which reduce the required lifting force. This is the basic advantage of regenerative elevator drive system. Then equation of power is rewritten by substituting for lifting force as:

$$P = (M_l + M_c - M_{cw}) \cdot g \cdot V_c \quad (3.6)$$

Where,

$P$  = total power on motor shaft

$V_c$  = linear speed of elevator car

$g$  = gravitational force

$M_l$  = load mass

$M_c$  = car mass

$M_{cw}$  = counter weight mass

Substituting for designed parameters and evaluating for motor power gives:

$$P = (390 + 100 - 295) * 9.81 * 2 \frac{m}{s^2} = 3825.9 \text{ watt} = 3.8259 \text{ Kw} = 5.13 \text{ hp}$$

Additionally, the losses in transmission of power to the driving pulley must be considered and included due to that several assumption are considered when compared to the real physical elevator drive system. Therefore, the mechanical power output ( $P$ ) required for driving the load is given by another equation including the efficiency of the system as:

$$P_{\text{tractive}} = P/\eta \quad (3.7)$$

Where,

$\eta$  is efficiency of the transmission system

Let us consider the efficiency of the transmission system to be 0.85. Therefore the mechanical power output required is:

$$P_{\text{total}} = P / \eta = 3.8259 \text{ Kw} / 0.85 = 4.5011 \text{ Kw} = 6.034 \text{ hp}$$

Therefore, the motor with power rating of 7hp is selected to drive the specified elevator load safely.

Assuming the selected motor is kept at rated speed of 200RPM with drive pulley directly connected to motor shaft we can design for the radius of the pulley to much with the motor rating speed.

Then the radius of pulley ( $R_p$ ) using the angular speed of driving pulley ( $N_p$ ) = 200RPM can be determined by the relation of linear speed and angular speed of the pulley as follows.

$$\begin{aligned} V_c &= \omega_p R_p \\ R_p &= \frac{V_c}{\omega_p} \end{aligned} \quad (3.8)$$

Where,

$R_p$  = radius of pulley

$\omega_p$  = angular speed of driving pulley in *rad/sec*

$N_p$  = angular speed of driving pulley in *RPM*

Then, changing the angular speed into rad/s form, substituting the parameters and evaluating for the driving pulley gives:

$$R_p = \frac{2 \text{ m/s}}{20.944 \text{ rad/s}} = 9.55 \text{ cm} = 0.0955 \text{ m}$$

Therefore, a pulley with radius dimension of 0.0955m is selected in this design.

### **3.3. Convertor modeling and Structure of P and PI controller**

Under this topic, the structure of the PID controller as well as AC/DC convertor model which are to be used in designing cascaded control system for elevator drive are discussed and represented in form of transfer function.

#### **3.3.1. Structure of P and PI controller**

The structures of P and PI controller as their names indicate consist of parameters named as proportional and integral components. The derivative controller (D) can be used to reduce the rapid speed oscillation caused by high proportional gain of the controller, but it is not used in many controllers of different application areas because the derivative action causes the noise (random error) in the main signal to be amplified and reflected in the output [13]. Hence the most suitable controller for speed and current (torque) control is PI type controller.

In this chapter, P controller for position control loop and PI controllers for speed and current control loops are provided and designed in cascade integration technique for elevator drive with convertor fed PMDC motor as prime mover.

The general transfer function of the Proportional type (P) controller is given by:

$$G_p(s) = K_p \quad (3.9)$$

Where,

$$G_p(s) = \text{is P controller transfer function} \quad K_p = \text{Proportional gain constant}$$

Similarly, the Proportional Integral type (PI) controller transfer function is given by:

$$G_{PI}(s) = K_p + \frac{K_i}{s} = K_p \left( \frac{K_p s + K_i}{K_p s} \right) = K_p \left( \frac{\frac{K_p}{K_i} s + 1}{\frac{K_p}{K_i} s} \right) \quad (3.10)$$

By substituting  $T_c$  for  $K_p$  to  $K_i$  ratio in above equation, PI controller transfer function can be further simplified and represented by more general, equivalent transfer function as given by equation (3.11) below.

$$G_{PI}(s) = K_p \left( \frac{1 + T_c s}{T_c s} \right) \quad (3.11)$$

Where,

$$G_{PI}(s) = \text{Transfer function of PI controller,}$$

$$T_c = \text{Time constant of the PI controller,}$$

$$K_p = \text{proportional gain of PI controller and}$$

$$K_i = \text{Integral gain of PI controller}$$

### 3.3.2. Modeling convertor parameters

The converter can be considered as a black box with certain gain and phase delay to model it as a source conversion subsystem in dc drive control system applications [27]. The dc output voltage of the three phase controlled AC/DC converter is characterized mathematically as given by equation (3.12) below [28]:

$$V_{dc} = \frac{3}{\pi} \cos \alpha = \cos \left( \cos^{-1} \left( \frac{V}{V_{cm}} \right) \right) = \frac{3}{\pi} \frac{V}{V_{cm}} V_c \quad (3.12)$$

Similarly, the gain of the linearized controller based converter,  $K_r$  for a maximum control voltage  $V_{cm}$  is determined from the grid line to line root mean square voltage and the specified maximum control input voltage.

$$K_r = \frac{3V_m}{\pi V_{cm}} = \frac{3\sqrt{2}V}{\pi V_{cm}} = \frac{1.35V}{V_{cm}} \quad (3.13)$$

Where,

$V_c$  = control input

$\alpha$  = delay angle

$V$  = rms line to line voltage

$K_r$  = Converter gain

$V_m$  = Peak supply voltage

$V_{cm}$  = Maximum control input voltage

We can consider a converter as a sampled data system in which its sampling interval gives an indication of its time delay by using electronic switches, usually thyristors, in which the delay angle can be corrected in each cycle and will be ready for implementation within 60 degree which is the angle between two thyristors gating, so that the converter time delay can be considered as one half of this interval in time [28]. Therefore the delay time of convertor is given by:

$$T_r = \frac{60/2}{360} \times (\text{Time period of one cycle}) = \frac{1}{12} \times \frac{1}{f_s} \text{ sec} \quad (3.14)$$

Where,  $f_s$  = the supply frequency

$T_r$  = delay time of convertor

In this thesis a linear source convertor with maximum control voltage of  $\pm 10V$  is modeled to generate appropriate DC voltage needed to supply the PMDC motor used in elevator drive system from a 3-Phase AC source at 50Hz [27]. Substituting for the supply frequency in equation (3.14), the time delay of the convertor is equal to 1.667ms.

Then the converter with first order transfer function is modeled by using its gain and time delay which is given by [28]:

$$G_r(s) = K_r e^{-T_r s} \quad (3.15)$$

Then equation (3.15) can be re-represented as a first order time lag converter transfer function as:

$$G_r(s) = \frac{V_a(s)}{V_c(s)} = \frac{K_r}{1 + T_r s} \quad (3.16)$$

Where,

$$K_r = \frac{1.35V}{V_{cm}} = \frac{1.35 \times 230}{10} = 31.05V/V$$

Then the transfer function of the modeled converter with numerical values of its parameters is given by:

$$G_r(s) = \frac{31.05}{1 + 0.001667s} \quad (3.17)$$

### 3.3.3. Designing cascaded position, speed and current controller parameters

To design a particular control loop, the values of the parameters have to be adjusted so that the control input provides acceptable performance from the plant. In order to get an acceptable solution, there are several controller design methods that can be applied.

One of those methods is classical control design approach, which is a good PID controller design method due to simplicity of the methodology followed to design and tune the cascaded controller parameters which is going to be used in this thesis.

Although the method provides a first approximation in design, the response produced usually needs further manual retuning by the designer for robust performance. The general block diagram of cascaded control system of elevator drive with converter fed PMDC motor as prime mover of the system is shown below. In this paper the classical design approach followed by manual retuning is applied to achieve a stable system which is the system with no overshoot and the fastest settling time possible.

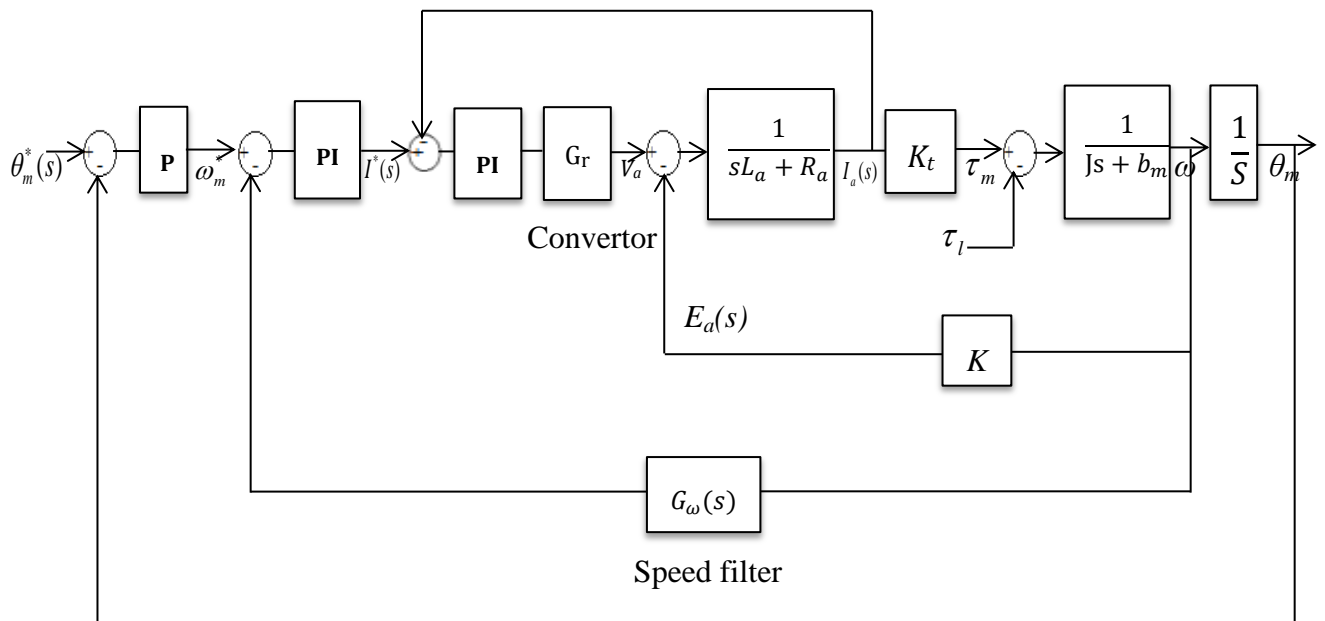


Figure 3-1: Block diagram representation of Cascaded control system with PMDC motor drive

First of all, the current control loop, which is the innermost loop, is designed due to that the performance of the outer loop is dependent on the inner loop. This innermost loop control is useful in preventing too much high current flow in both the converter and the motor. The control of the current is equivalent to the control of the torque, although there is not a direct measurement of torque.

Therefore the design and tuning of the inner loop has to precede the design and tuning of the outer loop. The current and torque are proportional in PMDC motor because of constant field flux so that the current can be considered as a control element [13]. The inner current loop will cross this back emf loop, creating a complexity in development of model as shown in Figure 3.1.

The interactions of these loops can be decoupled by the development of reduced block diagram using step by step block reduction as shown below. The load torque  $\tau_l$  is assumed to be proportional to angular speed and is given as [28]:

$$\tau_l(s) = B_l \omega_m(s) \quad (3.18)$$

Where,

$B_l =$  Load torque constant

Then, the inner most loop with load torque sub block diagram representation is as given below.

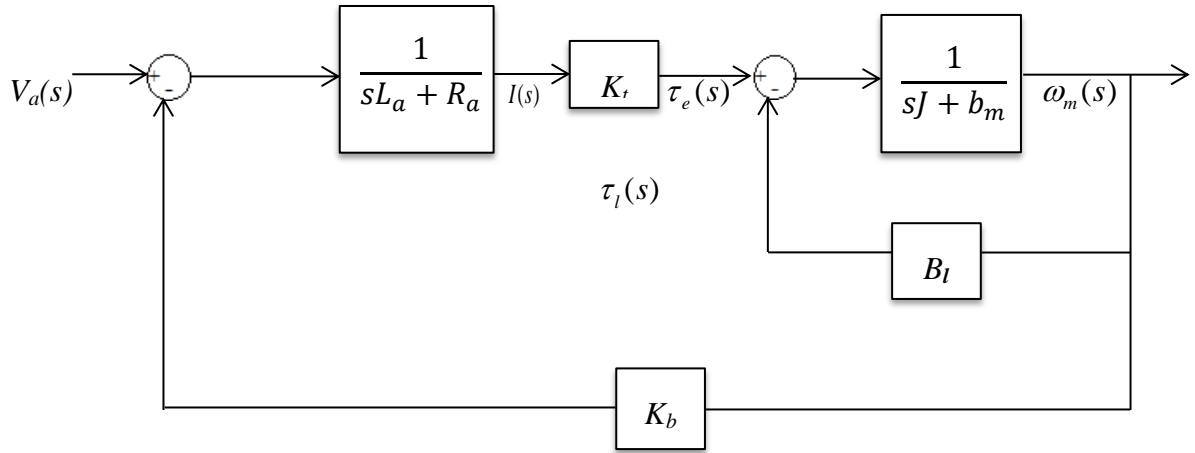


Figure 3-2: The inner loop of the motor [28]

Simplifying the inner load torque loop by using general block diagram reduction technique as:

$$\frac{\omega_m(s)}{\tau_e(s)} = \frac{1}{sJ + b_m} \cdot \frac{1}{1 + \frac{1}{sJ + b_m} B_l} = \frac{1}{b_m + B_l + sJ} = \frac{1}{B_t + sJ} \quad (3.19)$$

Where,

$b_m$  = Bearing friction coefficient of the motor

$B_l$  = load constant

$B_t = b_m + B_l$  is total friction coefficient

$\tau_{em}(s)$  = Electromagnetic torque of the motor

$\omega_m(s)$  = Rotor speed of the motor, rad/sec

$J$  = Total moment of inertia on the motor shaft

To decouple the inner current loop from the machine inherent induced emf loop, it is necessary to split the transfer function between speed and voltage into two cascaded transfer function, first between speed and armature current and then between armature current and reference input voltage [28] [29]. This will be achieved by moving feedback point before torque constant, assuming  $K_t$  is equal to  $K_b$  and rearranging the above block diagram and redrawn with corresponding transfer functions as follows.

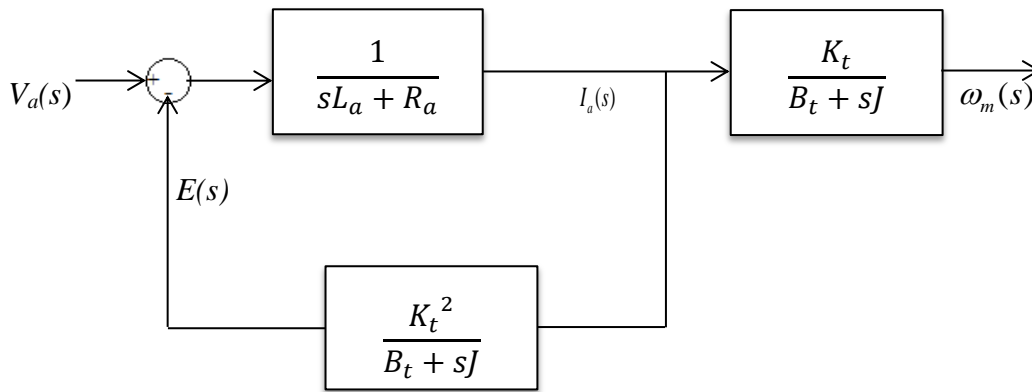


Figure 3-3: Block diagram of decoupled dc motor-load connected system transfer function

Then from above block diagram, transfer functions of motor-load inter connected system can be represented as two subsystems which can be represented as given in equation (3.20) below:

$$\frac{\omega_m(s)}{V_a(s)} = \frac{\omega_m(s)}{I_a(s)} \frac{I_m(s)}{V_a(s)} \quad (3.20)$$

So the motor and load subsystem transfer functions are given separately as follows; Motor subsystem transfer function is achieved by simplifying the feedback in above block diagram using block reduction technique, as given below.

$$\frac{I_a(s)}{V_a(s)} = \frac{\frac{1}{R_a + sL_a}}{1 + \frac{1}{(R_a + sL_a)} \frac{K_t^2}{(B_t + sJ)}} = \frac{B_t + sJ}{(R_a + sL_a)(B_t + sJ) + K_t^2} \quad (3.21)$$

The equation above can be further simplified and rewritten in general motor transfer function form as follows.

$$\frac{I_a(s)}{V_a(s)} = \frac{B_t + sJ}{(R_a + sL_a)(B_t + sJ) + K_t^2} = \frac{B_t(1 + sT_m)}{R_a(1 + sT_1)B_t(1 + sT_2) + K_t^2} \quad (3.22)$$

Then the transfer function of motor subsystem will be given by:

$$\frac{I_a(s)}{V_a(s)} = K_1 \frac{(1 + sT_m)}{(1 + sT_1)(1 + sT_2)} \quad (3.23)$$

Where,

$$K_1 = \frac{B_t}{R_a B_t + K_t^2} \quad (3.24)$$

Then substituting for system parameters from Table 3.1, the derived variable  $K_1$  is evaluated as:

$$K_1 = \frac{0.0869}{0.5 \times 0.0869 + 0.75^2} = 0.1434$$

$T_1$  and  $T_2$  are considered as electrical time constants of the motor and given by [27] [28]:

$$-\frac{1}{T_1}, -\frac{1}{T_2} = -\frac{1}{2} \left[ \frac{B_t}{J} + \frac{R_a}{L_a} \right] \pm \sqrt{\frac{1}{4} \left( \frac{B_t}{J} + \frac{R_a}{L_a} \right)^2 - \left( \frac{K_t^2 + B_t R_a}{J L_a} \right)} \quad (3.25)$$

$$-\frac{1}{T_1}, -\frac{1}{T_2} = -\frac{1}{2} \left[ \frac{0.0869}{4.8169} + \frac{0.5}{0.01} \right] \pm \sqrt{\left( \frac{0.0869}{4.8169} + \frac{0.5}{0.01} \right)^2 - \left( \frac{0.5 \times 0.0869 + 0.75^2}{4.8169 \times 0.01} \right)}$$

Which results in  $T_1 = 0.0201$  and  $T_2 = 3.7793$

Similarly, the load subsystem transfer function is given by:

$$\frac{\omega_m(s)}{I_a(s)} = \frac{K_t}{B_t + sJ} = \frac{K_t}{B_t(1 + sT_m)} = \frac{K_t/B_t}{(1 + sT_m)} \quad (3.26)$$

Where,

$T_m = J/B_t$  is mechanical time constant of the motor and evaluated from system parameter as:

$$T_m = \frac{4.8169}{0.0869} = 53.152$$

Based on the derived transfer function of the motor-load inter connected system above, the simplified current control loop of the converter fed motor drive with load can be generated as given in Figure3-4 assuming a feedback of current control loop is a unity gain in this design.

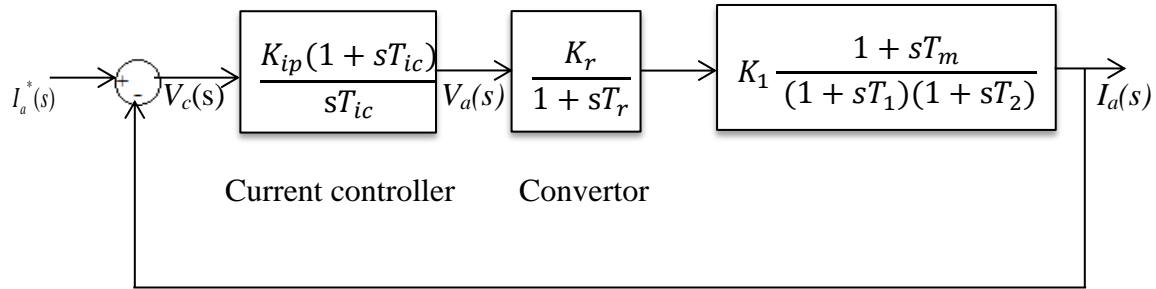


Figure 3-4: Current control loop

The open loop transfers function of the current control loop,  $G_{col}(s)$ , shown in Figure 3-4

**Figure 3-4** is given written as:

$$G_{col}(s) = \left( \frac{K_{ip} K_r K_1}{T_{ic}} \right) \frac{(1 + sT_{ic})(1 + sT_m)}{s(1 + sT_r)(1 + sT_1)(1 + sT_2)} \quad (3.27)$$

Since the current loop feedback is unity gain, the loop gain transfer function is given by the same transfer function as:

$$G_{col}H_i(s) = \left(\frac{K_{ip}K_rK_1}{T_{ic}}\right) \frac{(1+sT_{ic})(1+sT_m)}{s(1+sT_r)(1+sT_1)(1+sT_2)} \quad (3.28)$$

Where,

$K_{ip}$  = Gain of the current controller

$K_r$  = Converter gain V/V

$T_{ic}$  = Time constant of the current controller

$T_m$  = Mechanical time constant

$T_r$  = Converter time delay, sec

$T_1, T_2$  = Electrical time constants of the motor, sec

$G_{col}(s)$  = Open loop transfer function of the current control loop

$H_i(s)$  = Current control loop feedback gain (unity in this design)

The loop gain characteristic equation is a fourth order system as it is shown in above equation, and it is necessary to simplify in order to design a controller with the approximation of  $(1+sT_m) \cong sT_m$ , which results the loop gain transfer function reduced to:

$$G_{col}H_i(s) = \left(\frac{K_{ip}K_rK_1T_m}{T_{ic}}\right) \frac{(1+sT_{ic})}{(1+sT_r)(1+sT_1)(1+sT_2)} \quad (3.29)$$

By assuming that the time constants in the denominator have the relationship  $T_r < T_2 < T_1$ , and by selecting  $T_{ic} = T_2$ , equation (3.29) can be simplified and reduced to a general second order loop function as [27]:

$$G_{col}H_i(s) = \frac{K}{(1+sT_r)(1+sT_1)} \quad (3.30)$$

Where,

$$K = \frac{K_{ip}K_rK_1T_m}{T_{ic}} \quad (3.31)$$

Then the characteristic equation of the system relating  $i_a(s)$  and  $i_a^*(s)$  is given by:

$$1 + \frac{K}{(1 + sT_r)(1 + sT_1)} = 0$$

(or)

$$(1 + sT_r)(1 + sT_1) + K = 0 \tag{3.32}$$

Rewriting this characteristic equation in standard form gives:

$$T_r T_1 \left\{ s^2 + \left( \frac{T_r + T_1}{T_r T_1} \right) s + \frac{K + 1}{T_r T_1} \right\} = 0 \tag{3.33}$$

The general second order characteristic equation is given by:

$$s^2 + 2\zeta\omega_n s + \omega_n^2 = 0 \tag{3.34}$$

The relation between natural frequency ( $\omega_n$ ) and the drive parameters can be obtained by relating equation (3.33) and (3.34) and given as follows.

$$\omega_n = \sqrt{\frac{K + 1}{T_r T_1}} \tag{3.35}$$

Where,  $\omega_n$  is natural frequency of the system in radians per second

Similarly, the equation characterizing the damping ratio ( $\zeta$ ) is derived by substituting equation (3.35) into (3.34) for natural frequency ( $\omega_n$ ), and then interrelating with equation (3.33) which is given as follows.

$$\zeta = \frac{\left( \frac{T_r + T_1}{T_r T_1} \right)}{2 \left( \sqrt{\frac{K + 1}{T_r T_1}} \right)} \tag{3.36}$$

It is general truth for any system to be operated in a good dynamic performance (critically damped system), the system damping ratio is taken to be as 0.707. Hence equating equation (3.36) to 0.707 and rearranging, we get [29]:

$$K + 1 = \frac{(T_r + T_1)^2}{2T_r T_1} \quad (3.37)$$

By the assumption that  $K \gg 1$  and  $T_r \ll T_1$  equation (3.37) is further simplified and approximated as:

$$K \cong \frac{T_1^2}{2T_r} \cong \frac{T_1}{2T_r} = \frac{3.7793}{2 \times 0.001667} = 1133.56 \quad (3.38)$$

Then by equating the equation (3.31) to (3.38), the current controller proportional gain is designed to be:

$$K_{ip} = \frac{T_1 T_{ic}}{2T_r K_1 K_r T_m} \quad (3.39)$$

Then, substituting for system parameters given in the Table 3-1 and derived parameters above, the current controller parameters are evaluated as:

$$T_{ic} = 0.0201 \text{ and } K_{pc} = \frac{3.7793 \times 0.0201}{2 \times 0.001667 \times 0.1434 \times 31.05 \times 53.15} \cong 0.1$$

The second design step is the speed control loop which is the second innermost loop of the cascaded control system given in Figure 3-1. To design the speed control loop, the second order model of the current loop is replaced with an approximate first order model to minimize the design complexity in speed control loop, which helps to reduce the order of the overall speed loop gain function [27] [28]. The second order current loop is approximated by adding the time delay in the converter block to electrical time constant,  $T_l$  of the motor in equation (3.30) above.

Let  $T_3 = T_r + T_l$ , then the transfer function of the approximated system relating  $i_a(s)$  and  $i_a^*(s)$  is given by [28]:

$$\frac{I_a(s)}{I_a^*(s)} = \frac{\frac{K}{(1+sT_3)}}{1 + \frac{K}{(1+sT_3)}} \quad (3.40)$$

Then equation (3.40) can be re-arranged and simplified as:

$$\frac{I_a(s)}{I_a^*(s)} = \frac{K_i}{(1+sT_i)} \quad (3.41)$$

Where,

$$T_i = \frac{T_3}{(1+K_{fi})} = \frac{3.7793+0.001667}{1178.38} = 0.00321 \quad (3.42)$$

$$K_i = \frac{K_{fi}}{(1+K_{fi})} = \frac{1177.38}{1178.38} = 0.999 \quad (3.43)$$

$$K_{fi} = \frac{K_{pc}K_rK_1T_m}{T_{ic}} = \frac{0.1 \times 31.05 \times 0.1434 \times 53.15}{0.0201} = 1177.38 \quad (3.44)$$

Then the resulting simplified model of the current loop is a first order system, suitable for use in the design of a speed loop. The other speed control loop consideration is the filter in the loop feedback. Most of high performance systems use a dc tacho-generator and the filter required is low pass type with a time constant less than 10 ms [28].

The transfer function of the speed feedback filter is given by:

$$G_\omega(s) = \frac{K_\omega}{1+sT_\omega} \quad (3.45)$$

Where,

$G_\omega(s)$  = Filter transfer function,

$K_\omega$  = Gain of the filter

$T_\omega$  = Time constant of the filter

In this thesis, we select the tacho-generator transfer function assuming as low pass filter with its parameters to be  $K_\omega = 3$  and  $T_\omega = 0.01$  in order to design the speed controller. Then the resulting speed control loop with the first order approximation of the current control loop is shown in Figure 3-5 as given below.

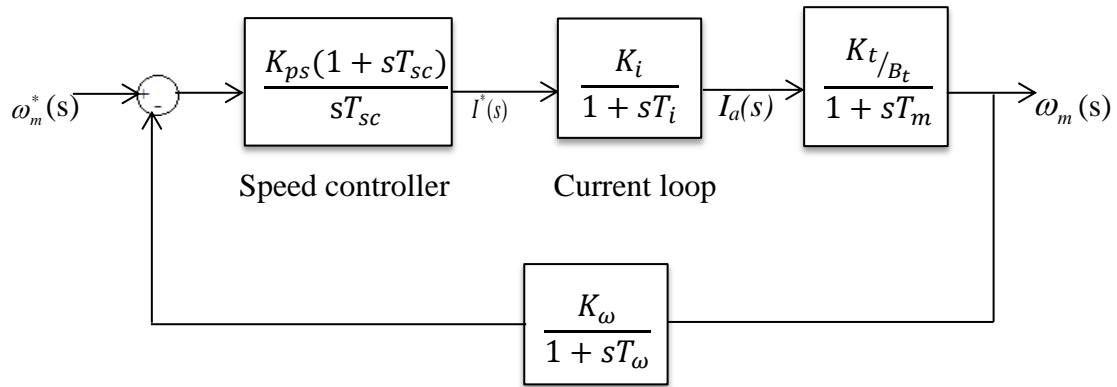


Figure 3-5: Speed control loop

The loop gain transfer function of this speed control loop is given by:

$$G_{sol}H_s(s) = \left( \frac{K_{ps}K_iK_tK_\omega}{B_tT_{sc}} \right) \frac{(1 + sT_{sc})}{s(1 + sT_i)(1 + sT_m)(1 + sT_\omega)} \quad (3.46)$$

Where,

$K_{ps}$  = proportional gain of the speed controller

$T_\omega$  = Time constant of the speed filter, sec

$B_t$  = Total friction coefficient Nm/rad/sec

$T_m$  = Mechanical time constant, sec

Similar to current control loop, by pole zero cancelation principle, the equation (4.46) which is a fourth order system should be reduced for analytical design of the speed controller, so that the following approximation is to be followed.

Approximating  $(1 + sT_m) \cong sT_m$  and substituting  $T_4 = T_i + T_\omega$ , then loop gain transfer function of the speed control loop is reduced to [28]:

$$G_{sol}H_s(s) = K_2 \frac{K_{ps}}{T_{sc}} \frac{(1 + sT_{sc})}{s^2(1 + sT_4)} \quad (3.47)$$

Where,

$$K_2 = \frac{K_i K_t K_\omega}{B_t T_m} = \frac{0.999 \times 0.75 \times 3}{0.0869 \times 53.15} = 0.487 \quad (3.48)$$

Then the general closed loop transfer function which relating the output speed to its input command with certain simplifications by merging its parameters to re-represent by simpler expression is as given below [28]:

$$\frac{\omega_m(s)}{\omega_m^*(s)} = \frac{1}{K_\omega} \left[ \frac{\frac{K_2 K_{ps}}{T_{sc}} (1 + sT_{sc})}{s^3 T_4 + s^2 + s K_2 K_s + \frac{K_2 K_{ps}}{T_{sc}}} \right] \quad (3.4)$$

$$\frac{\omega_m(s)}{\omega_m^*(s)} = \frac{1}{K_\omega} \frac{(a_0 + a_1 s)}{(a_0 + a_1 s + a_2 s^2 + a_3 s^3)}$$

Where,

$$\left. \begin{aligned} a_0 &= \frac{K_2 K_{ps}}{T_{sc}} \\ a_1 &= K_2 K_{ps} \\ a_2 &= 1 \\ a_3 &= T_4 \end{aligned} \right\} \quad (3.50)$$

It is important to optimize the speed loop transfer function to have a wider bandwidth and a magnitude of one over a wide frequency range to achieve a smooth speed tracking by considering its frequency response in which its magnitude is given by [28]:

$$\left| \frac{\omega_m(j\omega)}{\omega_m^*(j\omega)} \right| = \frac{1}{K_\omega} \sqrt{\frac{(a_0^2 + a_1^2 \omega^2)}{[a_0^2 + (a_1^2 - 2a_0 a_2) \omega^2 + (a_2^2 - 2a_1 a_3) \omega^4 + a_3^2 \omega^6]}} \quad (3.51)$$

This is optimization can be done by making coefficients of the two frequency terms  $\omega^2$  and  $\omega^4$  equal to zero, to yield the following conditions:

$$\left. \begin{aligned} a_1^2 &= 2a_0 a_2 \\ a_2^2 &= 2a_1 a_3 \end{aligned} \right\} \quad (3.52)$$

Then rewriting these conditions in terms of the motor and speed controller parameters by substituting equation (3.50) into equation (3.52) gives:

$$\left. \begin{aligned} T_{sc}^2 &= \frac{2T_{sc}}{K_2 K_{ps}} \\ K_{ps} T_{sc} &= \frac{2}{K_2} \end{aligned} \right\} \quad (3.53)$$

Similarly,

$$\left( \frac{T_{sc}}{K_2 K_{ps}} \right)^2 = \frac{2T_{sc}^2 T_2}{K_2 K_{ps}} \quad (3.54)$$

Then simplifying equation (3.54) gives design of speed controller proportional gain as:

$$K_{ps} = \frac{1}{2K_2 T_4} = \frac{1}{2 \times 0.487 \times 0.01321} = 77.72 \quad (3.55)$$

Then time constant of the speed controller is design by substituting equation (3.55) into equation (3.53) and evaluated as given below.

$$T_{sc} = 4T_4 = 0.0525 \quad (3.56)$$

Finally the position control loop, which is the outermost loop of the cascaded control system, is designed. Due to the presence of an integrator in the open loop transfer function,  $G_{pol}(s)$  of position loop, only a proportional controller is sufficient for position control to truck the desired position smoothly and properly [13].

Also similar to the approximation taken for current control loop in speed controller design, the speed control loop approximation is made and considered as a third order transfer function block in position control loop.

Then evaluating the speed control loop transfer function by substituting for system parameters, as well as speed controller parameters the simplified position control loop is given in Figure 3-6 below.

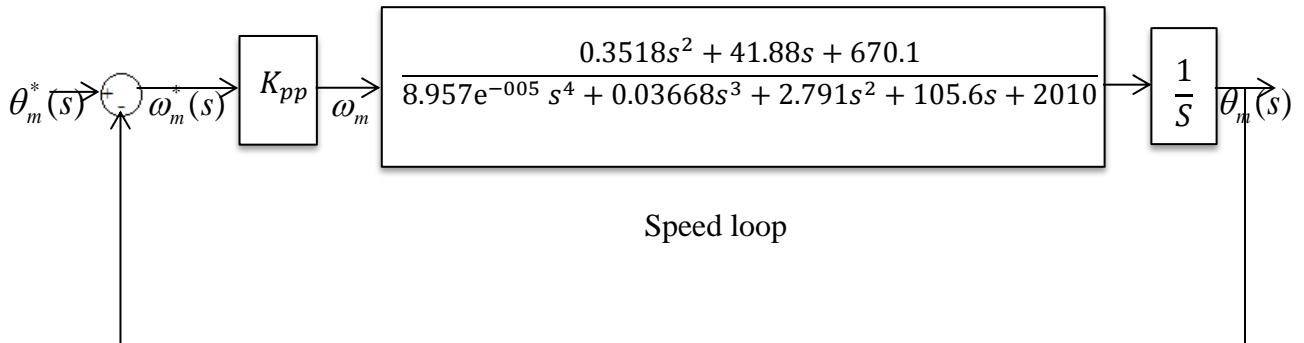


Figure 3-6: Position Control Loop

The open loop transfer function of position control loop is given by:

$$G_{pol}(s) = \frac{0.3518s^2 + 41.88s + 670.1}{8.957e^{-005} s^4 + 0.03668s^3 + 2.791s^2 + 105.6s + 2010s} \quad (3.57)$$

The proportional constant ( $K_{pp}$ ) is evaluated by the principle of stability of control system in frequency response by carrying out the stability analysis of position loop, by plotting the bode plot of the system [13].

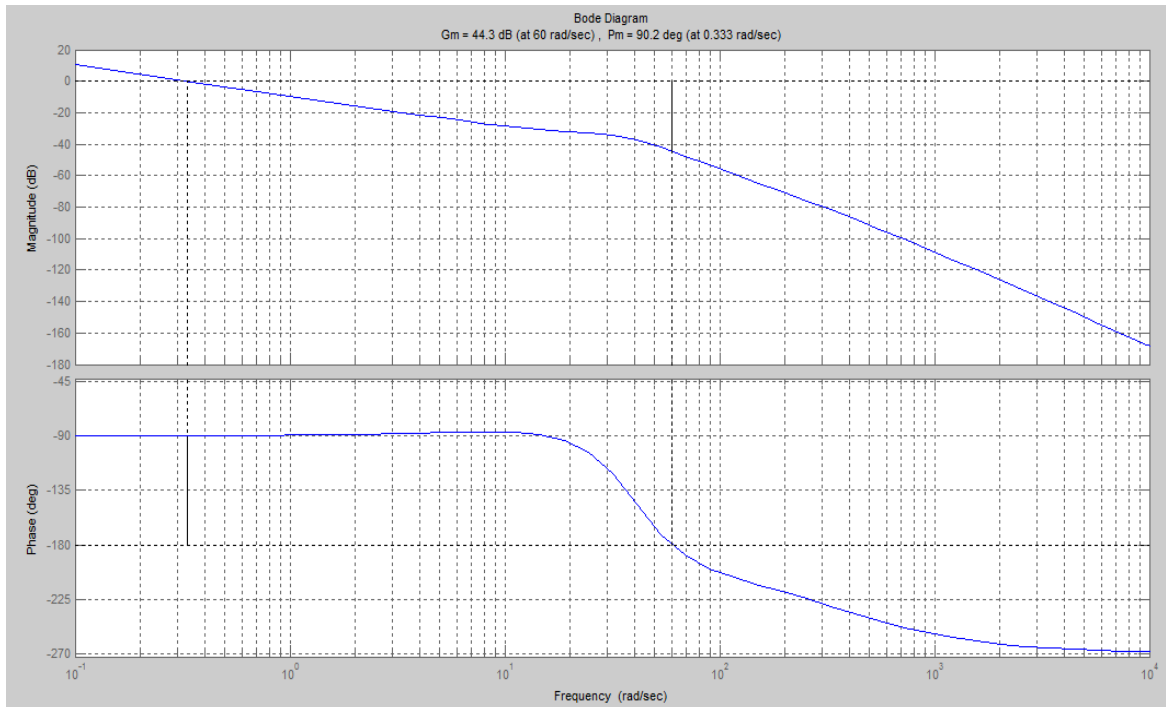


Figure 3-7: Bode plot of position open loop transfer function with  $K_{pp} = 1$

As we can observe from Figure 3-7 above, both the gain margin and phase margin of the system are indicated by bold vertical lines, which shows a wide range of stability. The phase margin measures how much phase variation is needed at the gain crossover frequency to lose stability. Similarly, the gain margin measures what relative gain variation is needed at the gain crossover frequency to lose stability. From these two concepts, we can estimate the safety margin for closed-loop stability of the desired system. Therefore we select a gain of proportional controller for position control loop within bandwidth of stability by manual tuning method, which is 10 in magnitude. The following figure shows bode plot of the system with the designed controller gain which is stable system, since both gain margin and phase margin are positive.

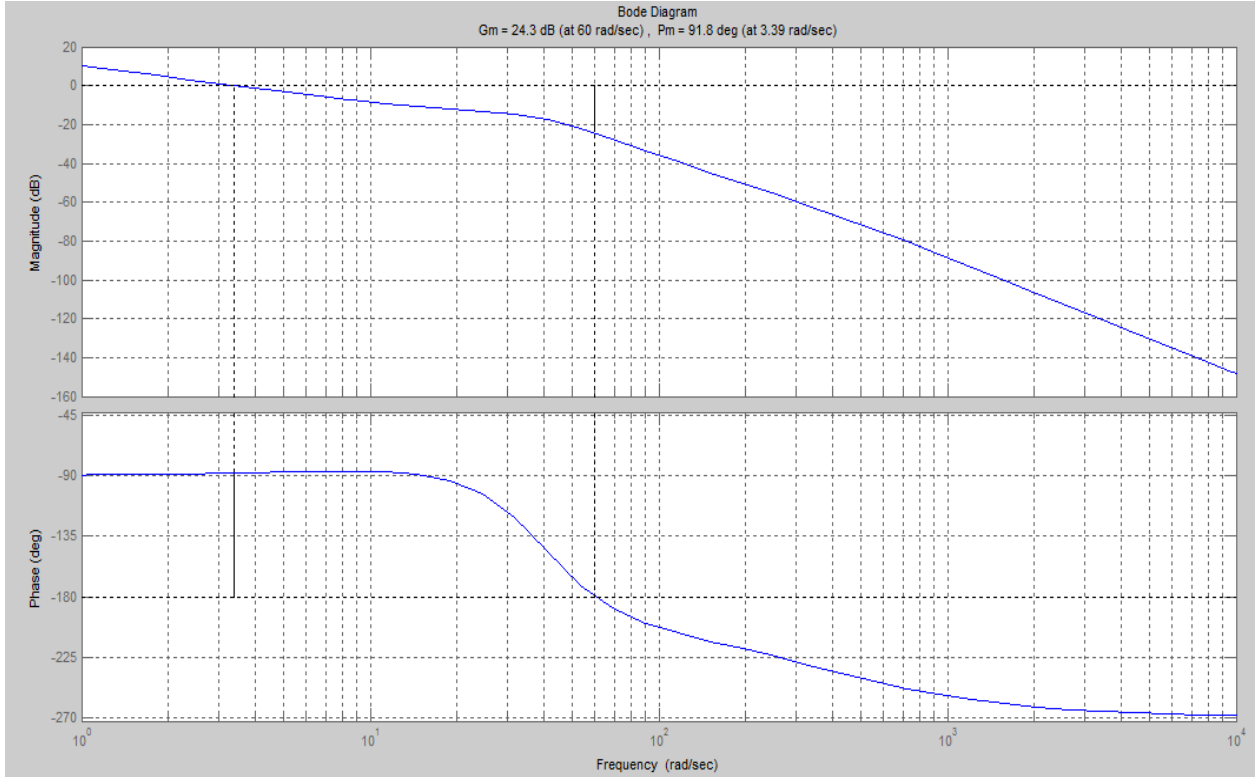


Figure 3-8: Bode plot of position open loop transfer function with  $K_{pp} = 10$

### 3.4. Parameters of the PMDC Motor and Elevator drive system

The value of the desired elevator car mass, counter weight mass and load of six passengers (65kg each) are considered and selected as 100kg, 300kg and 390kg respectively as indicated in this chapter above. Based on these load parameter values the drive prime mover components a rope with the capacity to bear at least 8KN, a motor with power rating of 7hp and rated angular speed of 200PM with driving pulley radius of 9.55cm are selected.

The computer simulations were done with typical standard values of the system parameters and the braking is occurred when passenger defined position is reached. Outputs of the system which have been used to evaluate the performance of the controller proposed are the actual stopping linear position of elevator, the motor current (torque), and the elevator linear speed profile which is initially accelerated, driving with the desired constant value and finally decelerated to zero at destination point in order to make the passenger journey safe and smooth. The system parameters used in the simulation was adapted from [18] and [28].

During the simulation of cascaded position speed and current controlled elevator drive, the basic input for controlling the controlled variables is the initial and destination position of elevator. The desired input position and the desired elevator linear speed to be achieved are 40m by 2m/s and 4m by 0.8m/s in both up and down direction respectively based on the standard speed profile of the elevator. As it is shown in Table 3-2, Parameters of the electrical elevator drive System with corresponding load specifications are generated to be used in simulation.

Table 3-2: Parameters of the PMDC Motor and Elevator drive system [18]

PMDC motor parameters		Elevator drive design parameters	
motor armature resistance, $R_a$	0.5 $\Omega$	Nominal motor speed, $\omega_m$	200rad/s
motor inductance, $L_a$	10 mH	Travel height	4m @0.8m/s and 40m (10 floors) @ 2m/s
motor rated DC voltage, $V_a$	220V	Pulley radius, $R_p$	0.0955 m
torque constant, $K_t$	0.75N.m/A	Pulley inertia, $J_p$	0.1 Kg.m <sup>2</sup>
Motor inertia, $J_m$	0.05Kg.m <sup>2</sup>	Car mass, $M_c$	100 Kg
Total viscous friction gain, $B_t$	0.0869N.m.s	Maximum load weight, $M_l$	390 Kg
Equivalent inertia of entire system, $J$	4.6189 Kg.m <sup>2</sup>	Counterweight Mass, $M_c$	300 Kg
		Gravitational acceleration, $g$	9.81 m/s <sup>2</sup>

As given in Table 3.3, the parameters which are to be controlled in the cascaded position, speed and current controlled elevator drive system are linear position and linear speed profiles of elevator and also current/torque of the motor.

### 3.5. P controller and PI controller parameters for cascaded control system

For the calculation with the classical approach, the parameters are chosen to achieve a critically damped system with 0% over-shoot [13]. The Proportional controller parameter for position control loop and proportional-integral controller parameters for speed and current control loop evaluated using the equations designed above, as well as elevator drive system and design parameters given in Table 3.2 above, are fine-tuned by manual approach and generated as given in Table 3.3 below.

Table 3-3: Tuned Controller parameters

Symbol	Parameter description	Designed value
$K_{pc}$	Proportional gain for current controller	0.1
$T_{ic}$	Time constant of the current controller	0.0201 sec
$K_{ps}$	Proportional gain for speed controller	77.72
$T_{sc}$	Time constant of the speed controller	0.0525 sec
$K_{pp}$	Proportional gain for position controller	10

## Chapter 4

### 4. Simulation Studies and Analysis of Results

#### 4.1. Introduction

This chapter presents Simulink model of the elevator drive system modeled mathematically in chapter two, with and without cascaded position, speed and current control. The numerical values are assigned for the designed controller parameters in chapter three. Then the model of elevator drive system is developed in computer Simulink model with and without cascaded position, speed and current control by considering both ascending and descending load. This model is used to simulate and observe the expected behavior of the system under the action of proposed control system, and simulation results are presented in the form of graphs. Finally, the results have been discussed in terms of the selected parameters to illustrate performance of the designed elevator drive.

#### 4.2. Simulink model and performance of the elevator drive system

##### 4.2.1. Simulink model of the elevator drive system

The Simulink model of overall elevator drive with cascaded control system and PMDC motor as its prime mover is developed in MATLAB software to investigate and analysis the performance of the desired elevator drive system under the designed controller action. As it is given with mathematical modeling of the drive system dynamics, there are two cases of system model that characterizing the ascending (lifting) and descending (lowering) dynamics of the elevator drive system. Then the Simulink model as well as simulation results of the overall drive system developed for the corresponding these two cases with and without cascaded control system are discussed below.

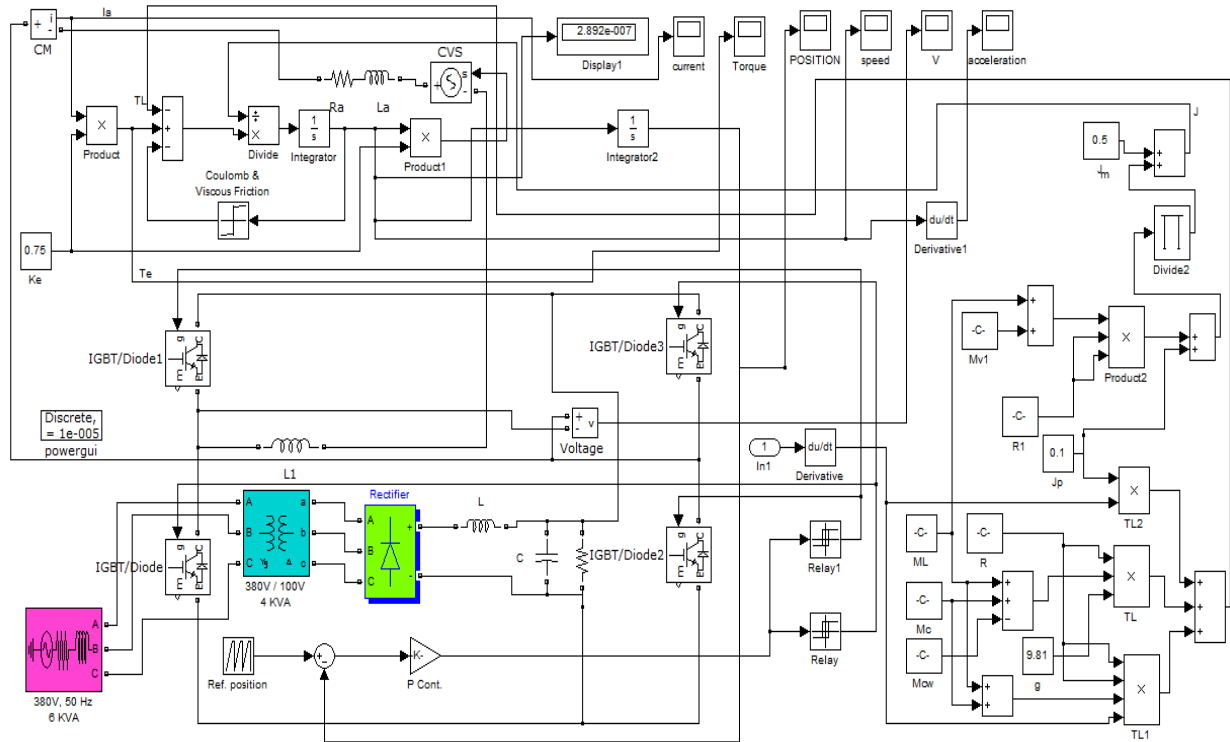


Figure 4-1: Simulink model of electrical Elevator drive system without cascade control

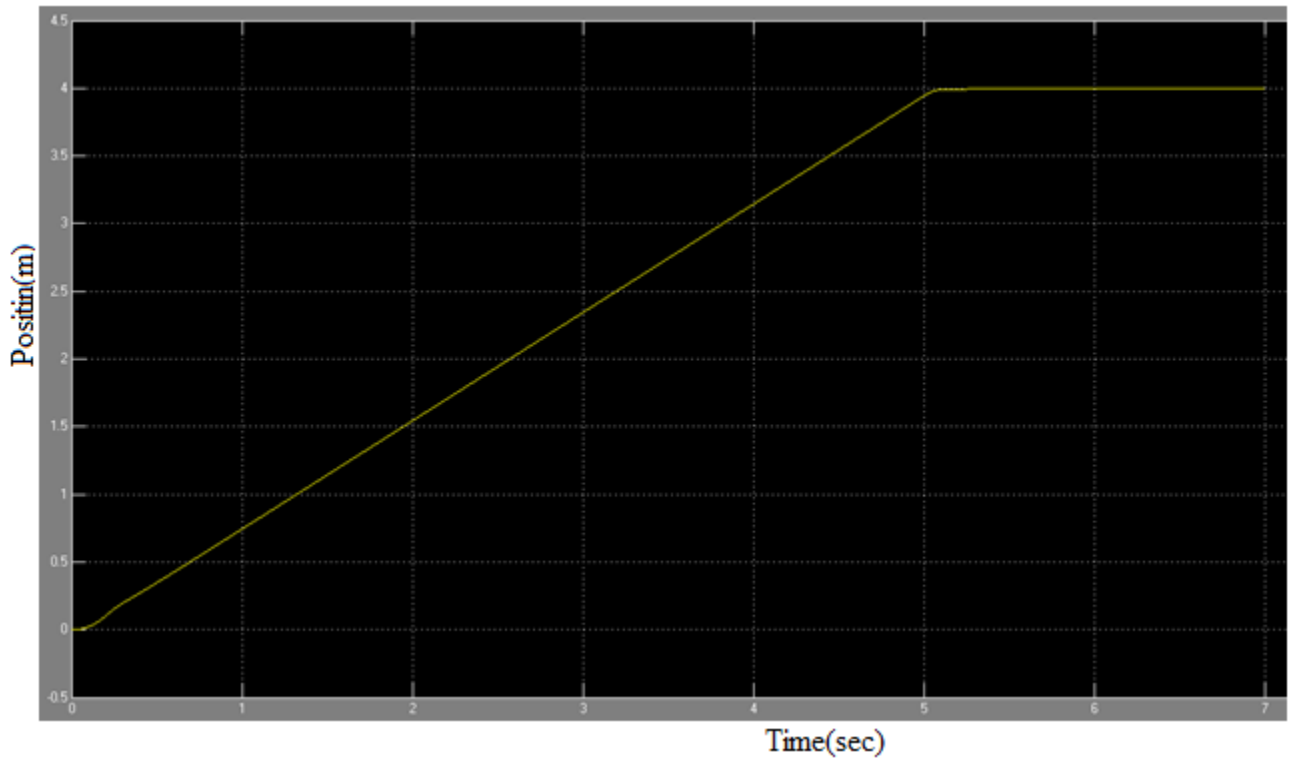


Figure 4-2 : Simulated position of 4m ascending elevator drive without cascade control

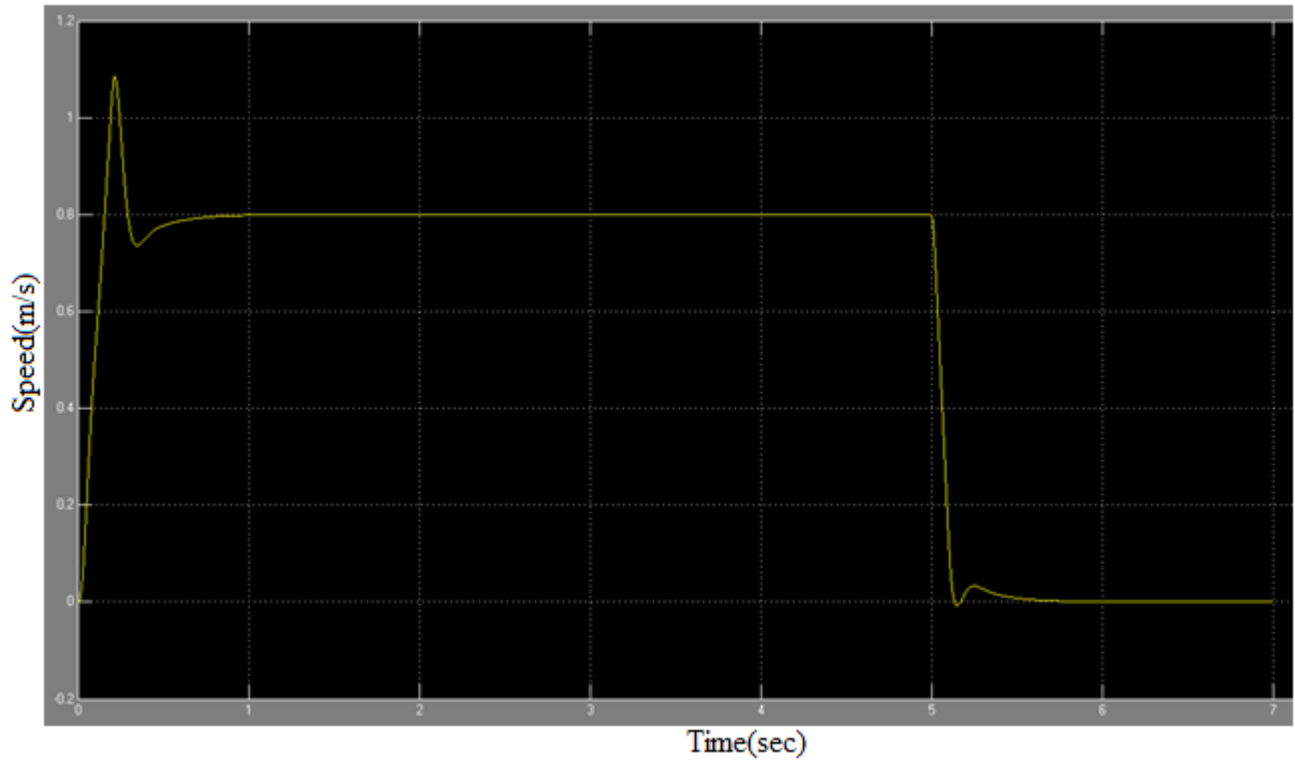


Figure 4-3 : Simulated speed of 4m ascending elevator drive without cascade control

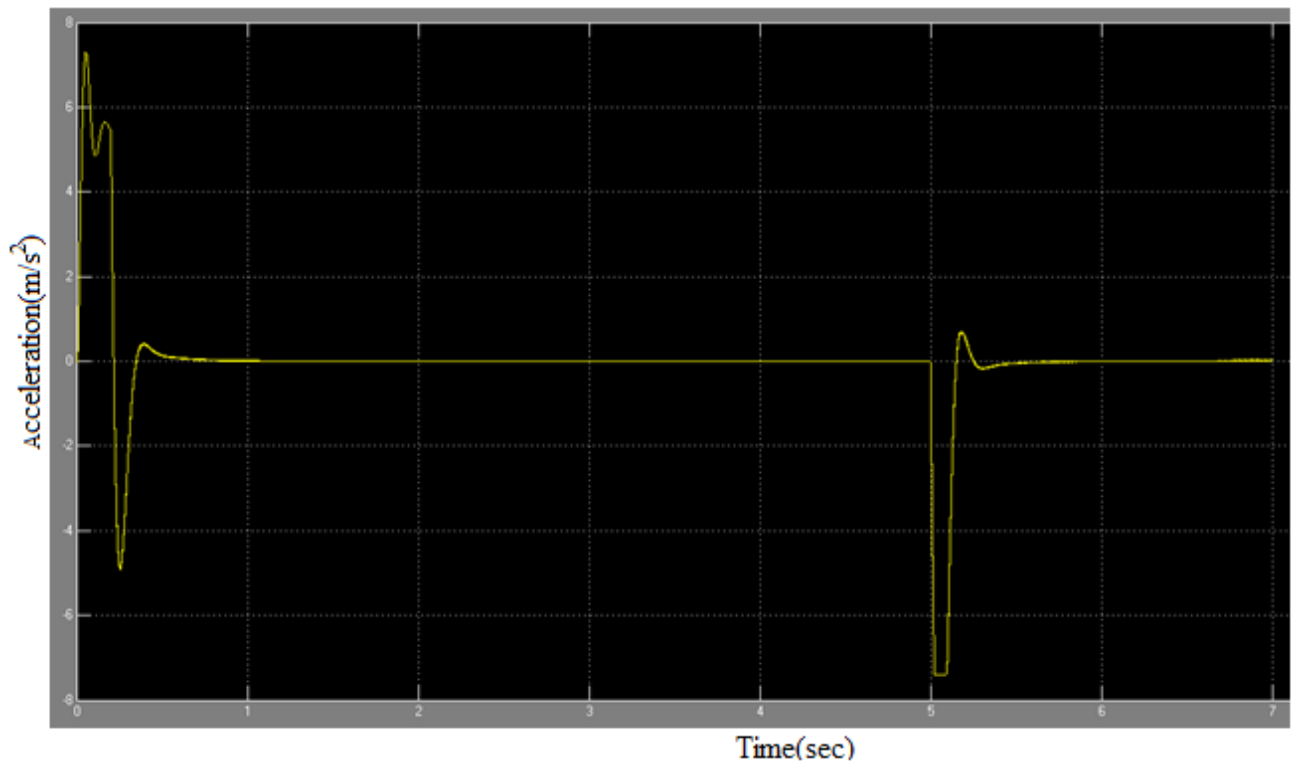


Figure 4-4: Simulated acceleration of 4m ascending elevator drive without cascade control

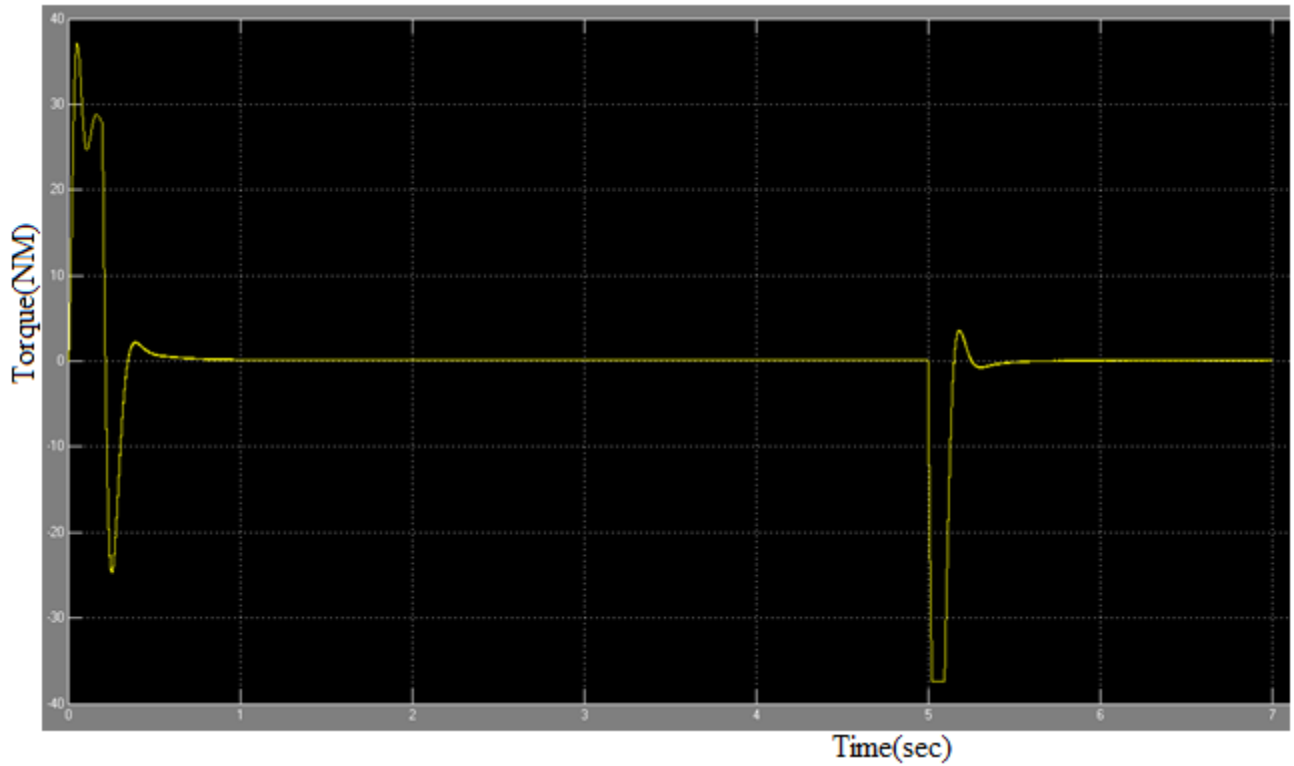


Figure 4-5: Simulated torque of 4m ascending elevator drive without cascade control

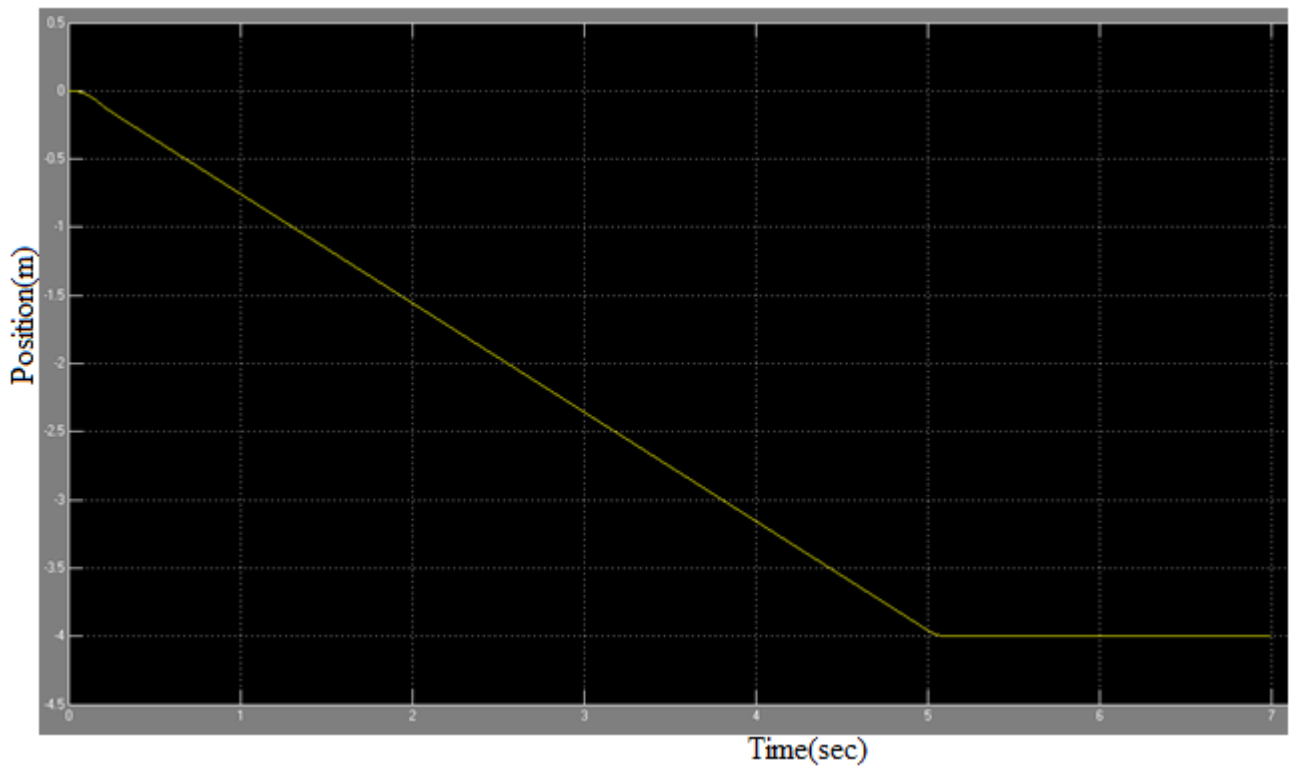


Figure 4-6: Simulated 4m descending position of elevator drive without cascade control

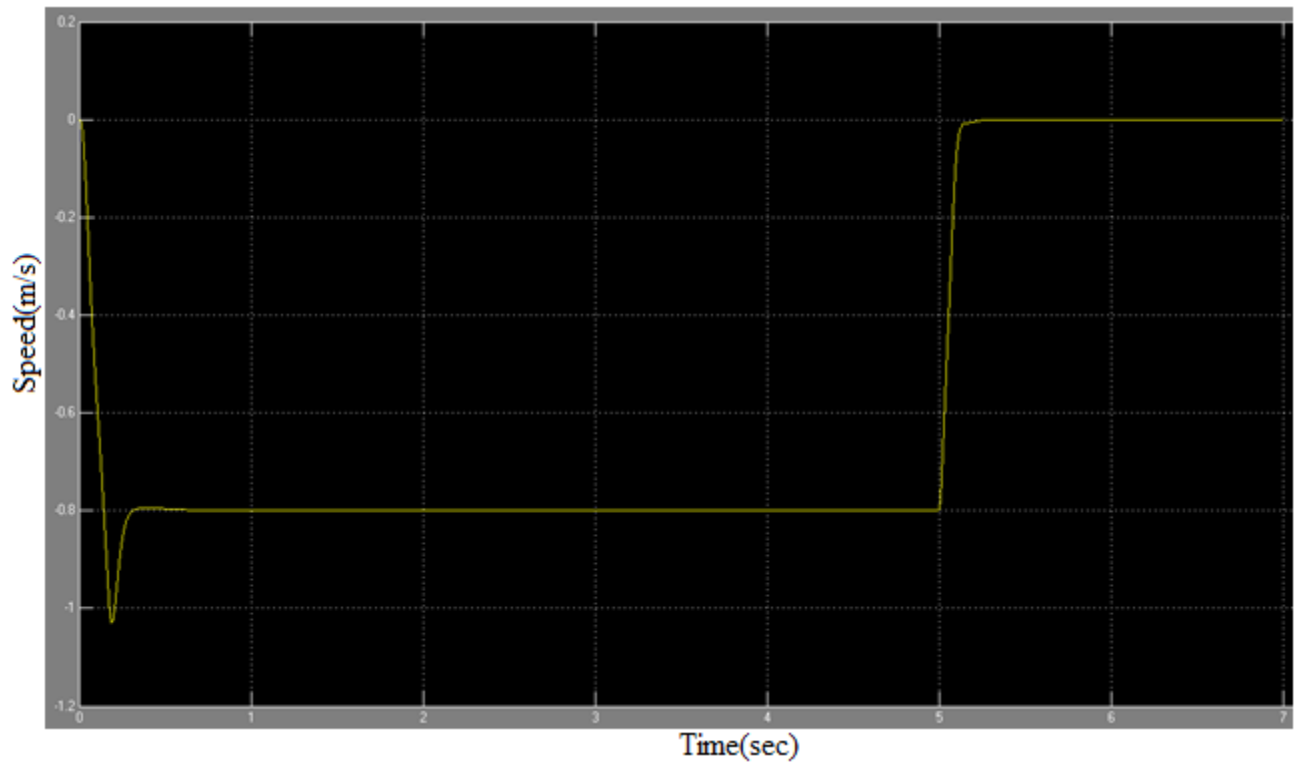


Figure 4-7: Simulated speed of 4m descending elevator drive without cascade control

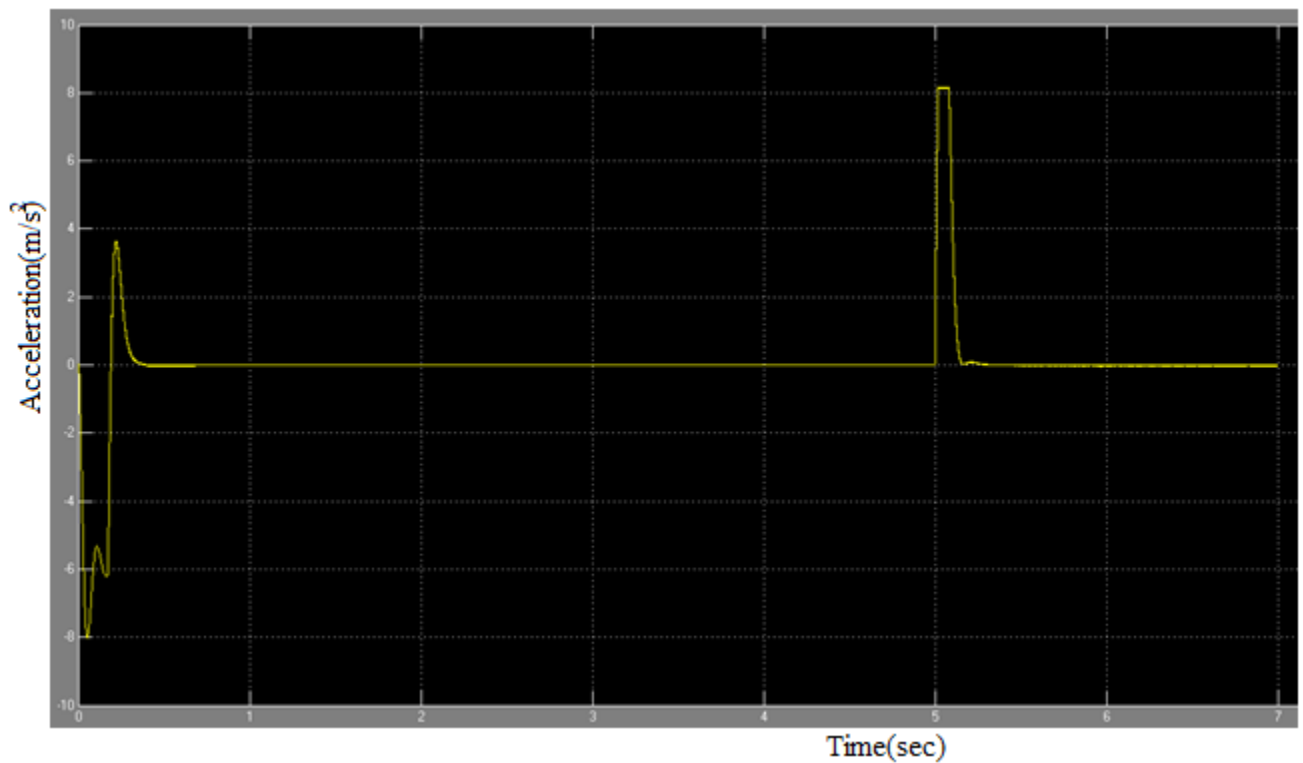


Figure 4-8: Simulated acceleration of 4m descending elevator drive without cascade control

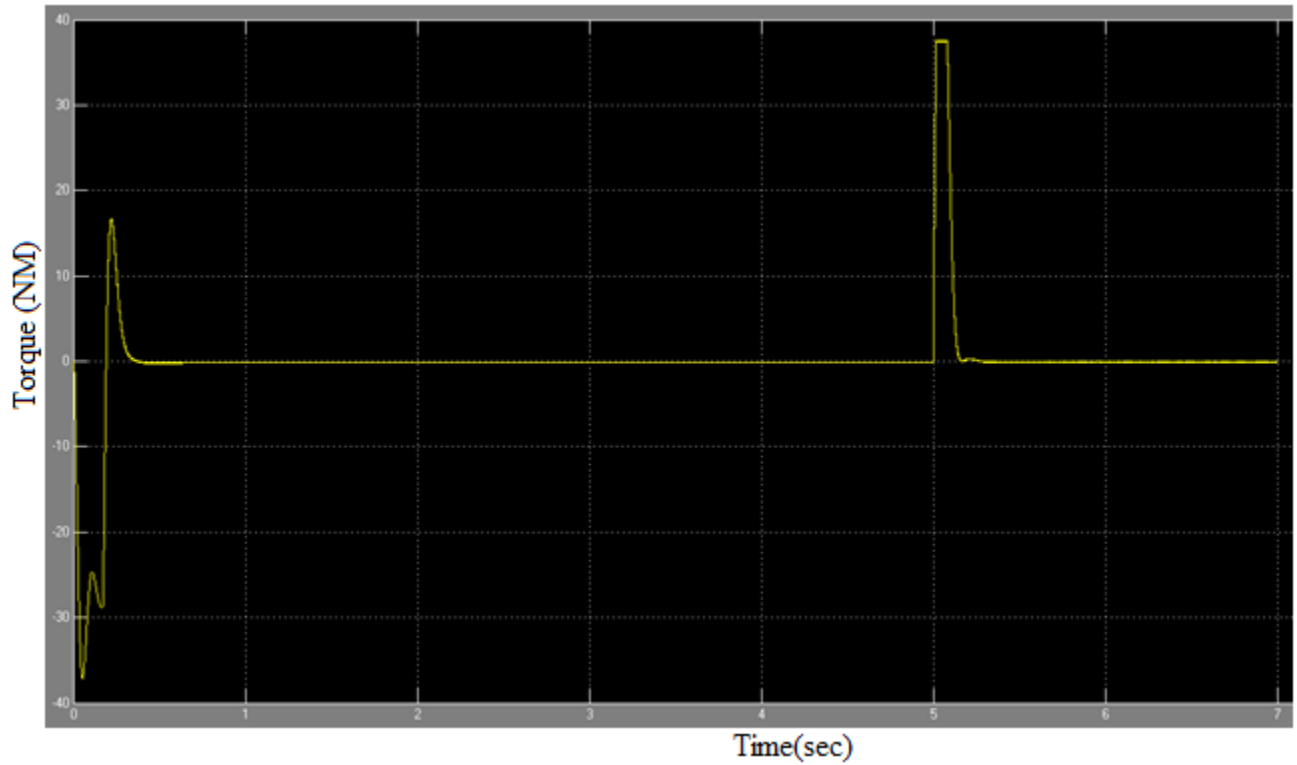


Figure 4-9: Simulated torque of 4m descending elevator drive without cascade control

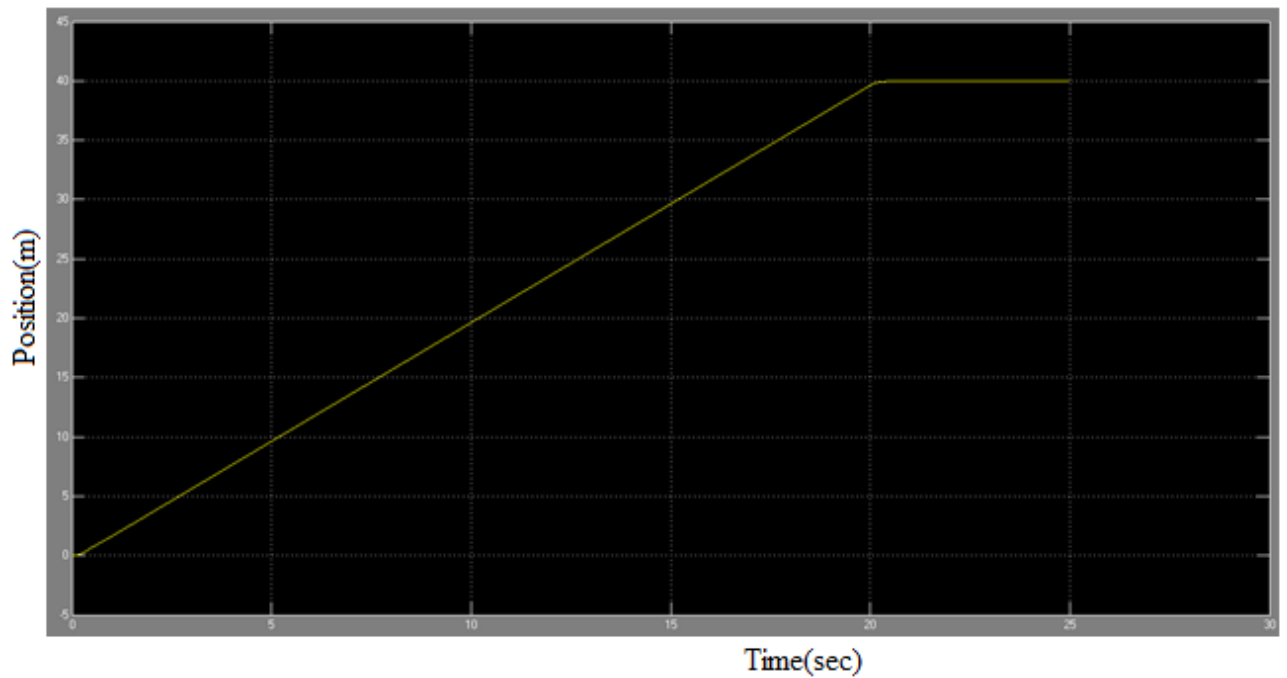


Figure 4-10: Simulated position of 40m ascending elevator drive without cascade control

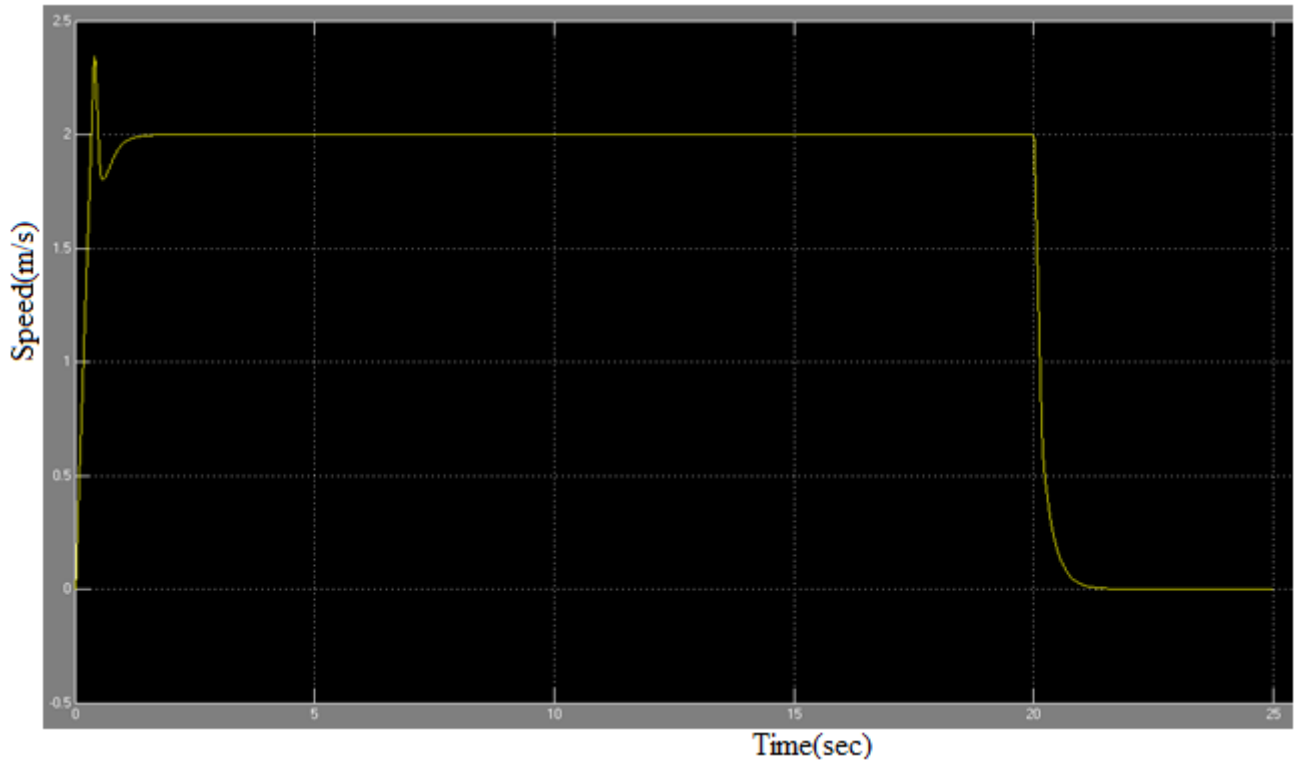


Figure 4-11: Simulated speed of 40m ascending elevator drive without cascade control

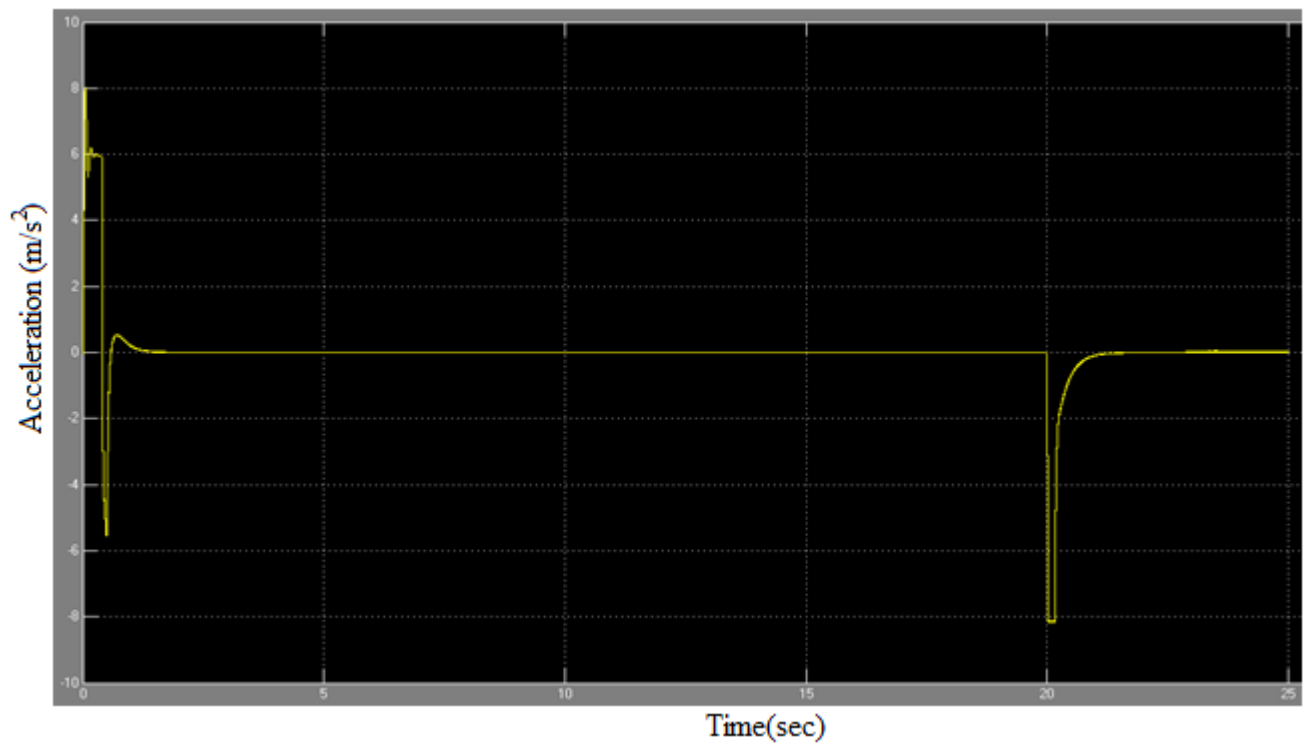


Figure 4-12: Simulated acceleration of 40m ascending elevator drive without cascade control

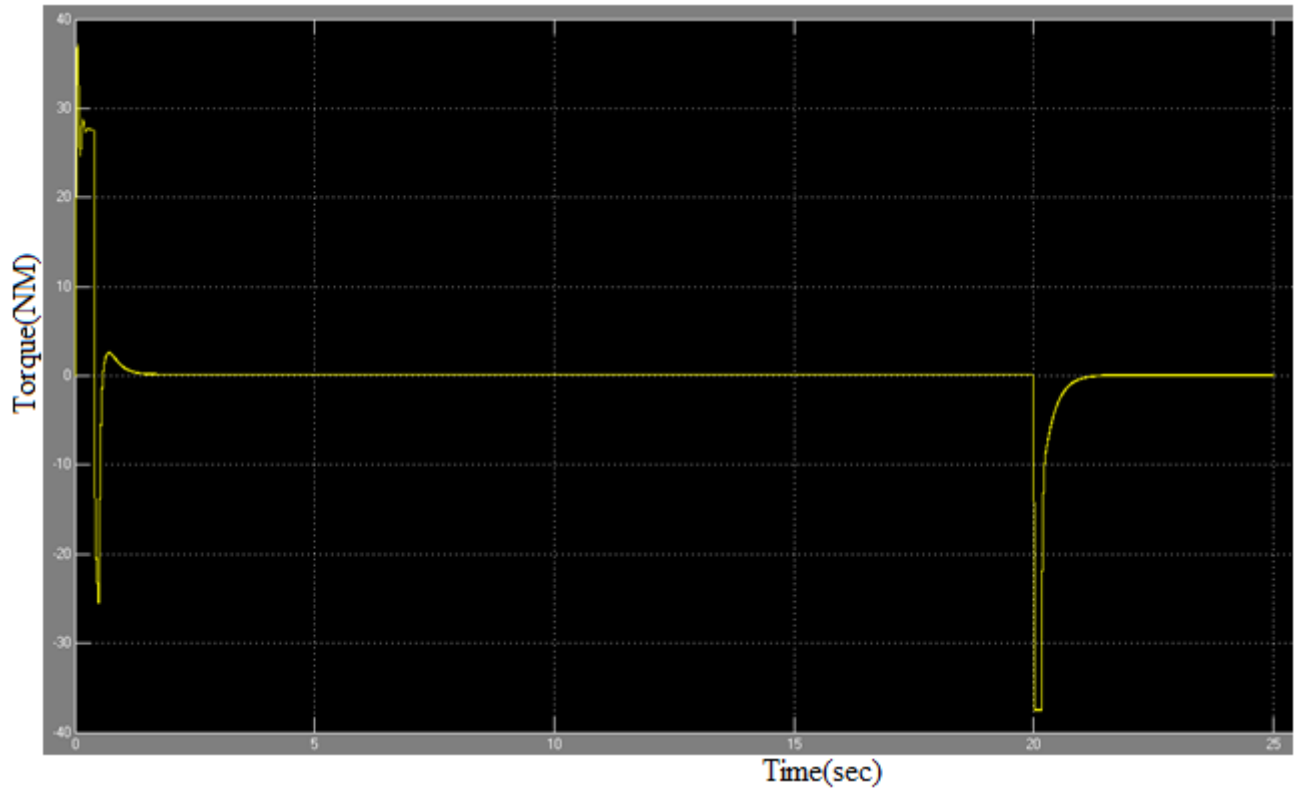


Figure 4-13: Simulated torque of 40m ascending elevator drive without cascade control

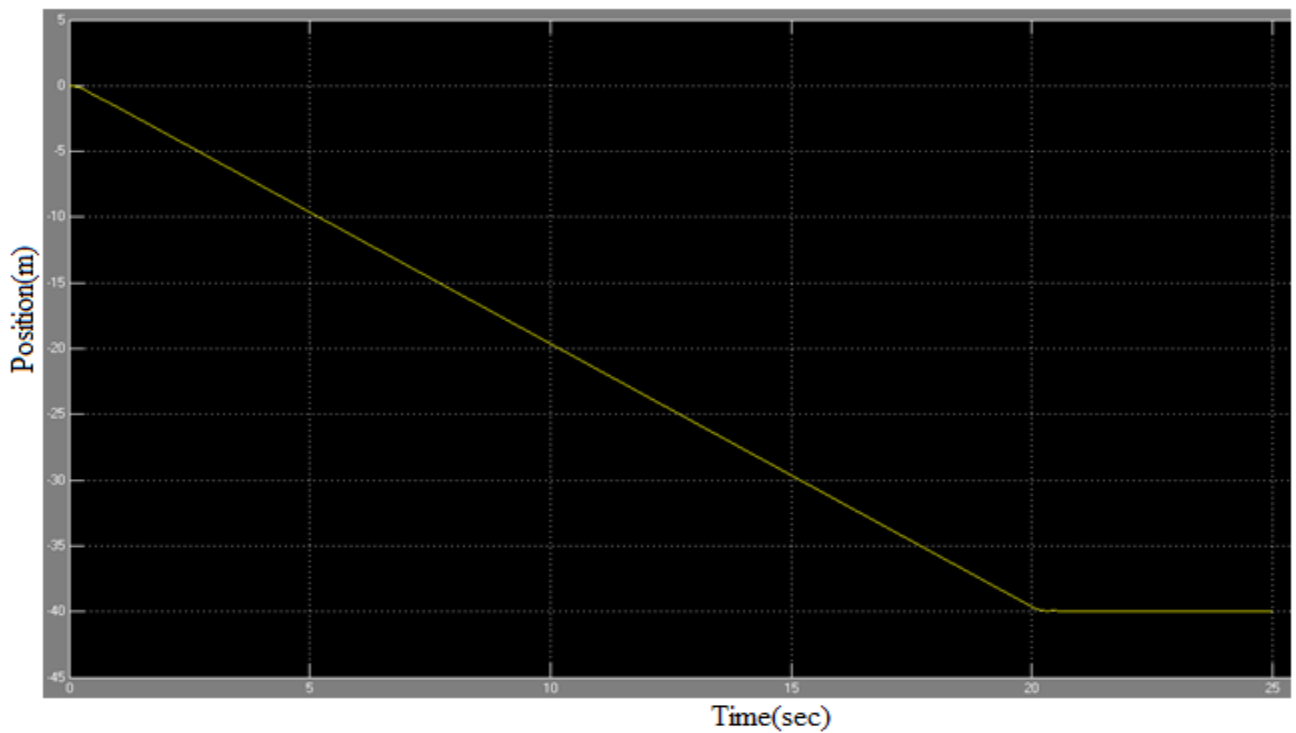


Figure 4-14: Simulated position of 40m descending elevator drive without cascade control

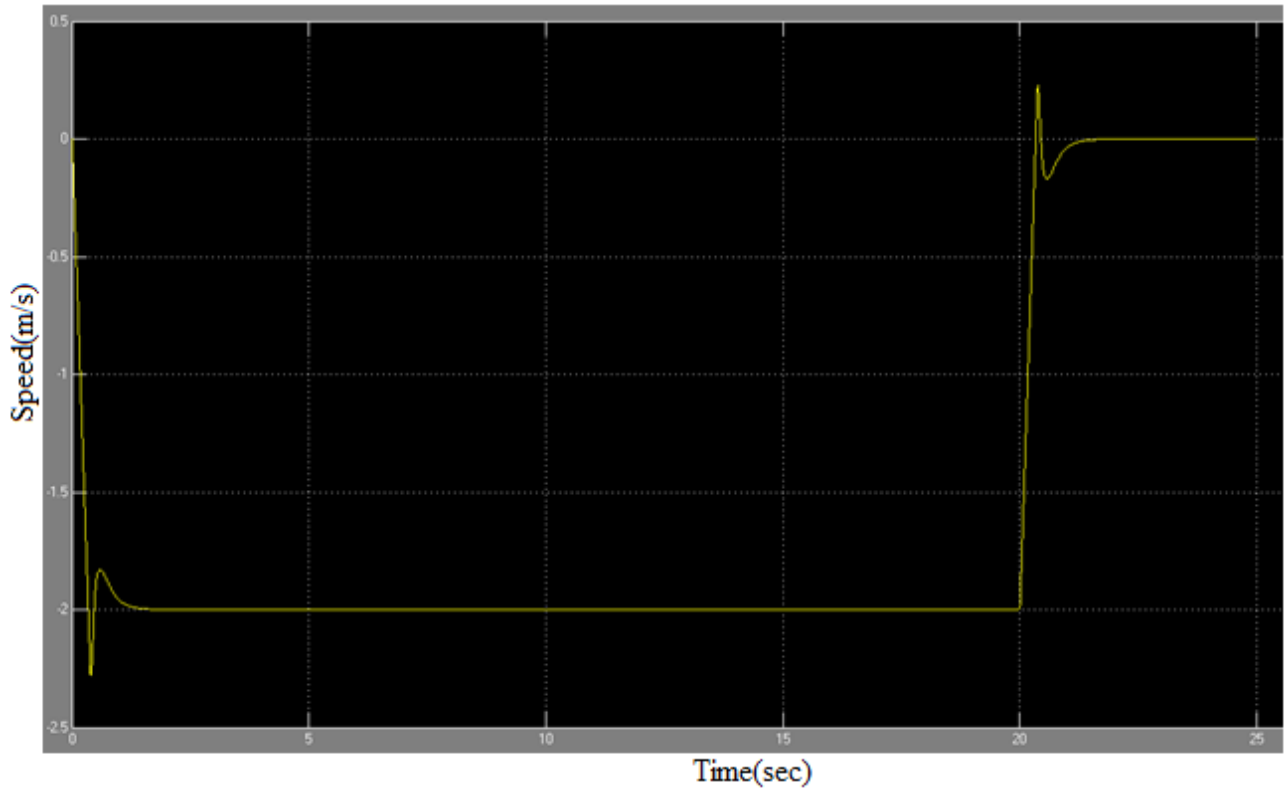


Figure 4-15: Simulated speed of 40m descending elevator drive without cascade control

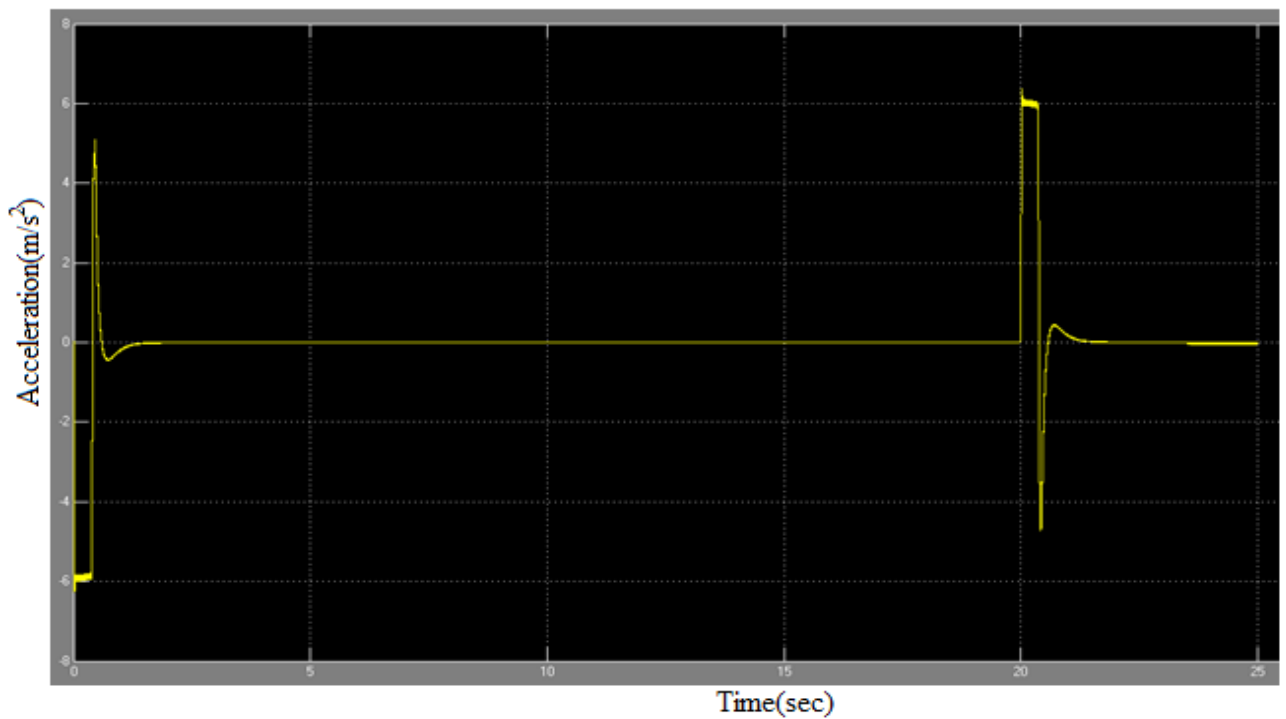


Figure 4-16: Simulated acceleration of 40m descending elevator drive without cascade control

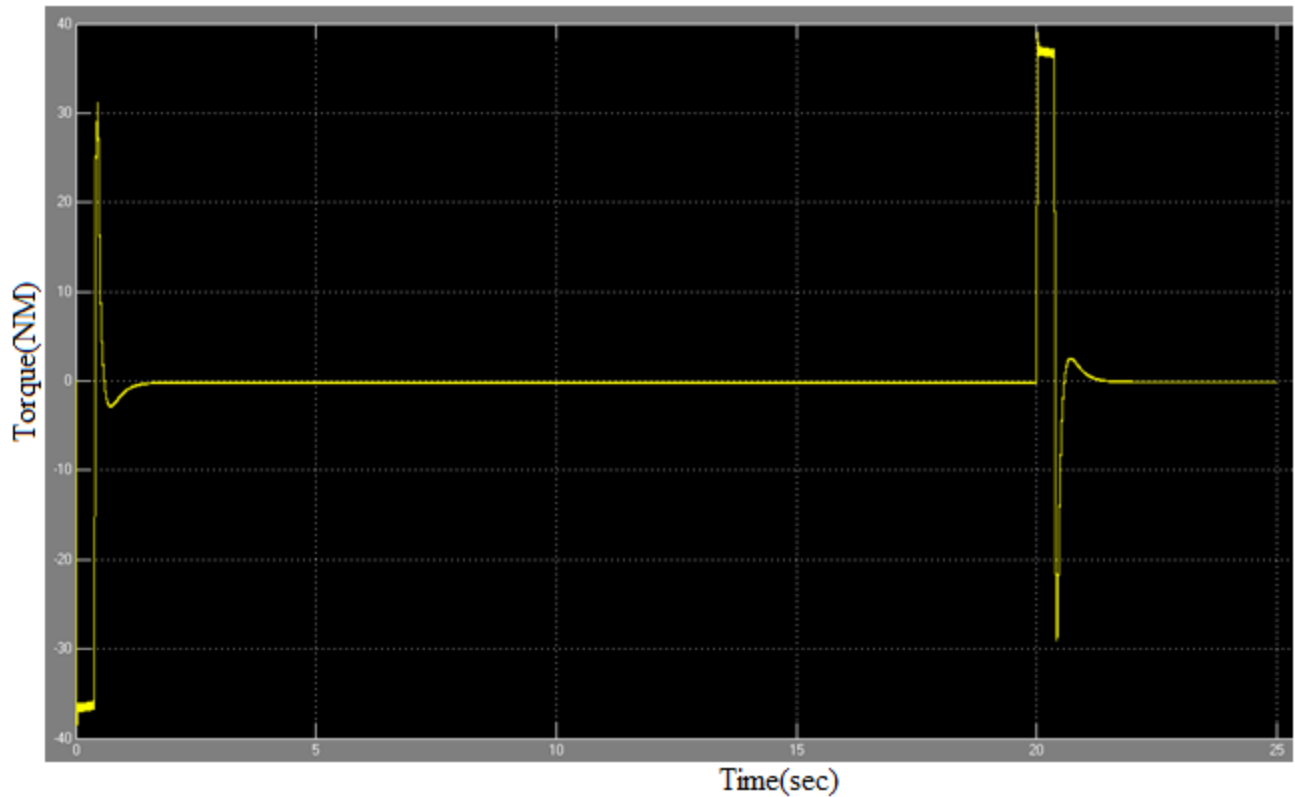


Figure 4-17: Simulated torque of 40m descending elevator drive without cascade control

As given in simulation results of elevator drive system without cascade control system above, in both ascending and descending cases we observe that that the distortion and non-comfort journey in all travelling distance have been resulted when cascaded controller is not applied. This is because of non-smoothly accelerating and decelerating profile of the drive with maximum overshoot results as we can indicate from speed results.

Next, the simulation result and discussions of elevator drive system under cascaded control system action is presented in order to compare the performance of the elevator drive with and without cascaded control system.



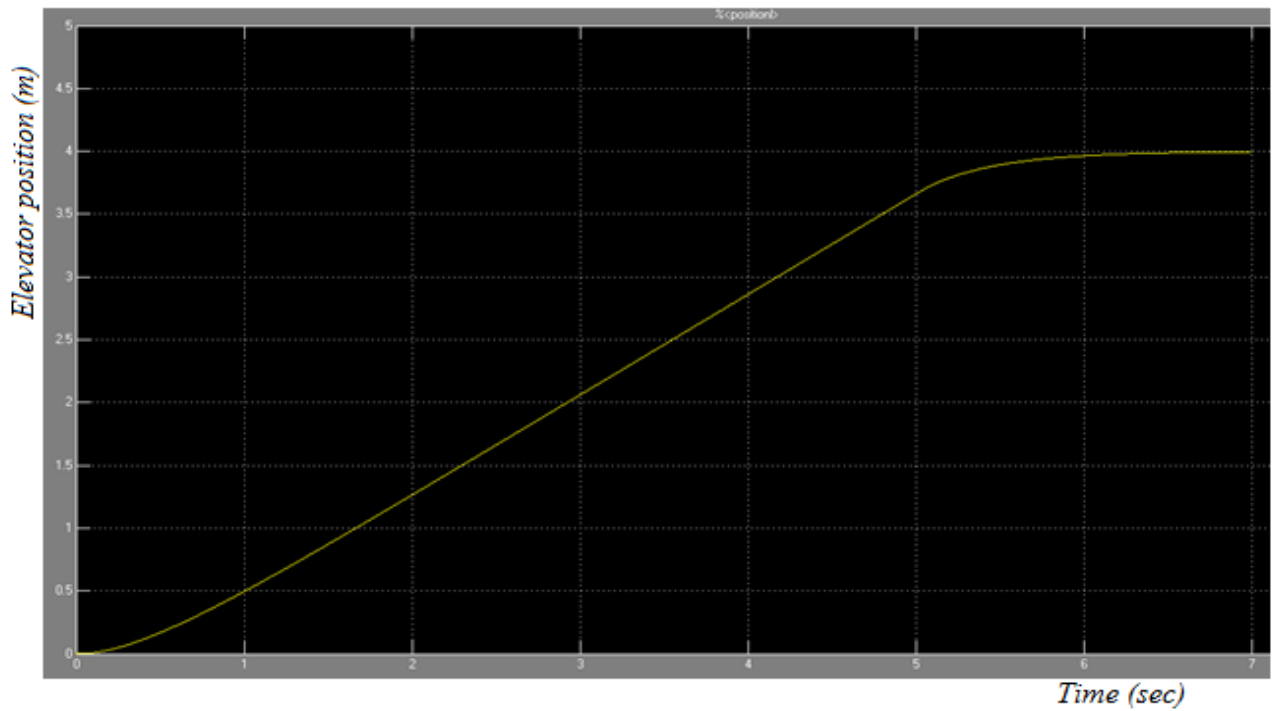


Figure 4-19: Simulated output position of electric elevator drive for elevator car moving to floor-1

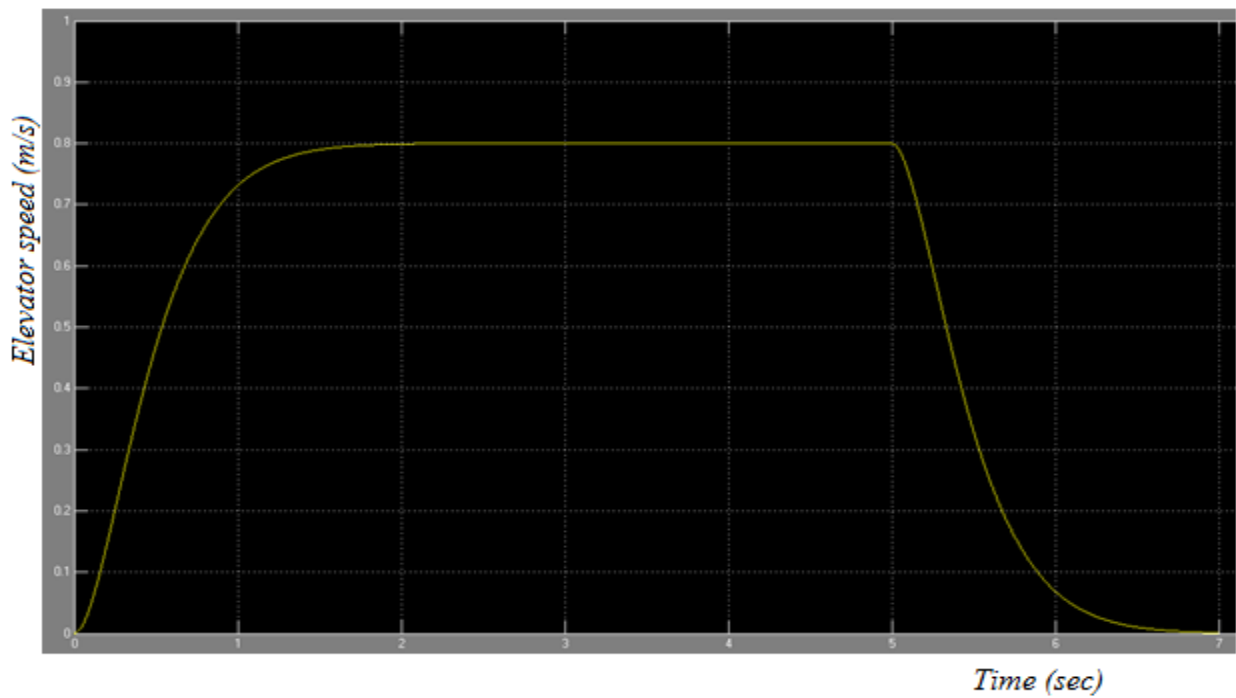


Figure 4-20: Simulated speed of elevator drives when elevator car moving to first floor

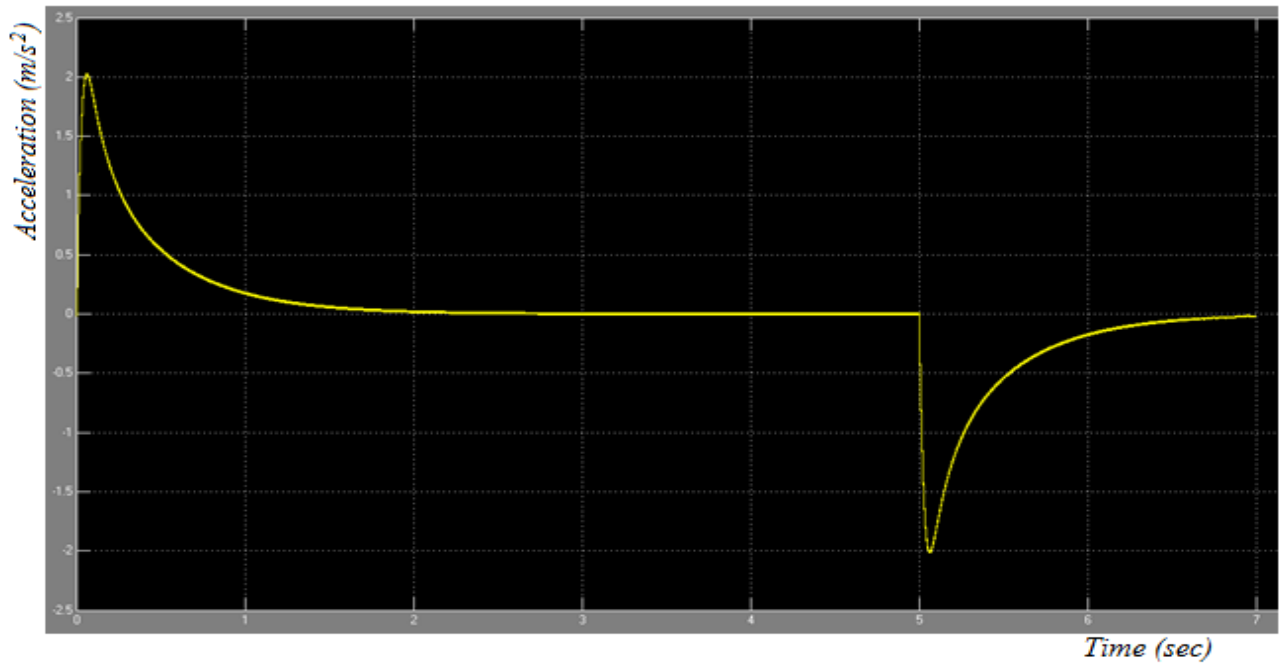


Figure 4-21: Acceleration of electric elevator drives when elevator car moving to first floor

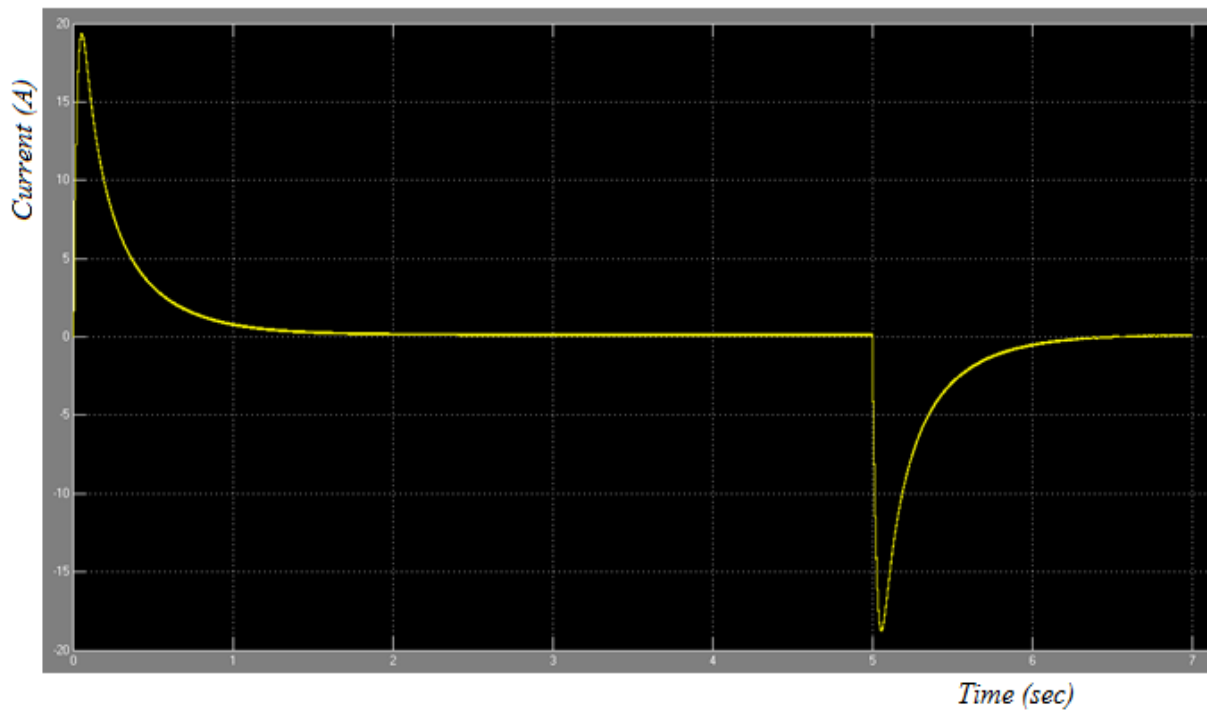


Figure 4-22: Simulated current of electric elevator drives when elevator moving to first floor

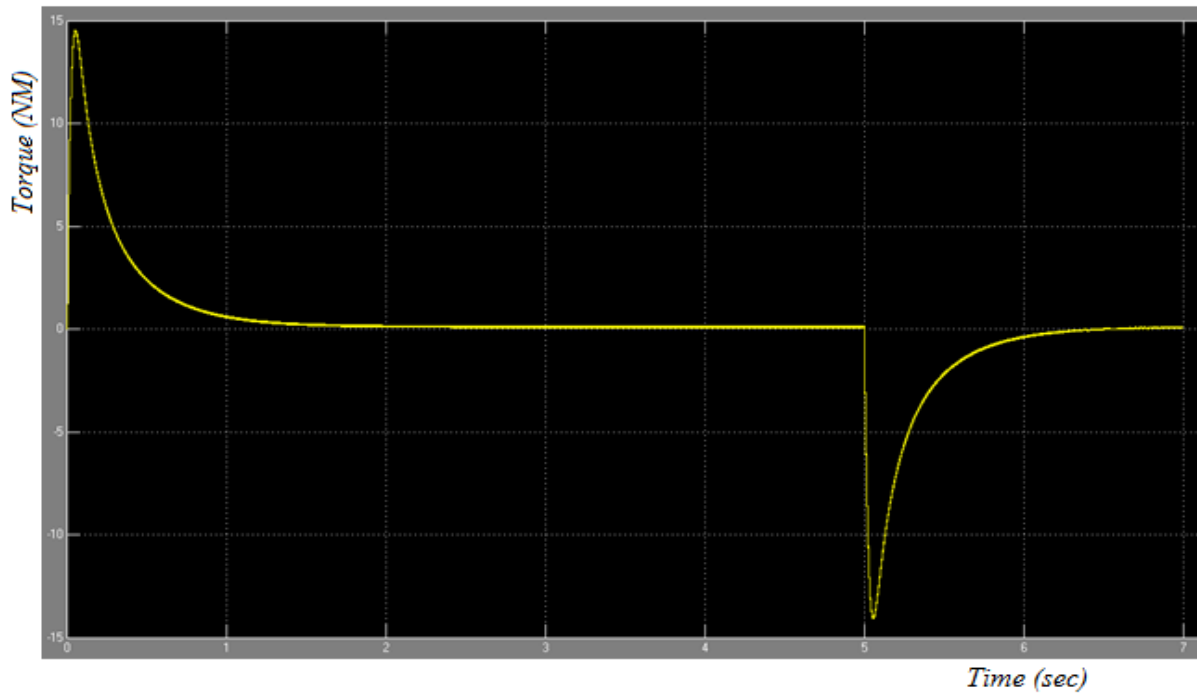


Figure 4-23: Simulated torque of elevator drive for elevator car moving to first floor

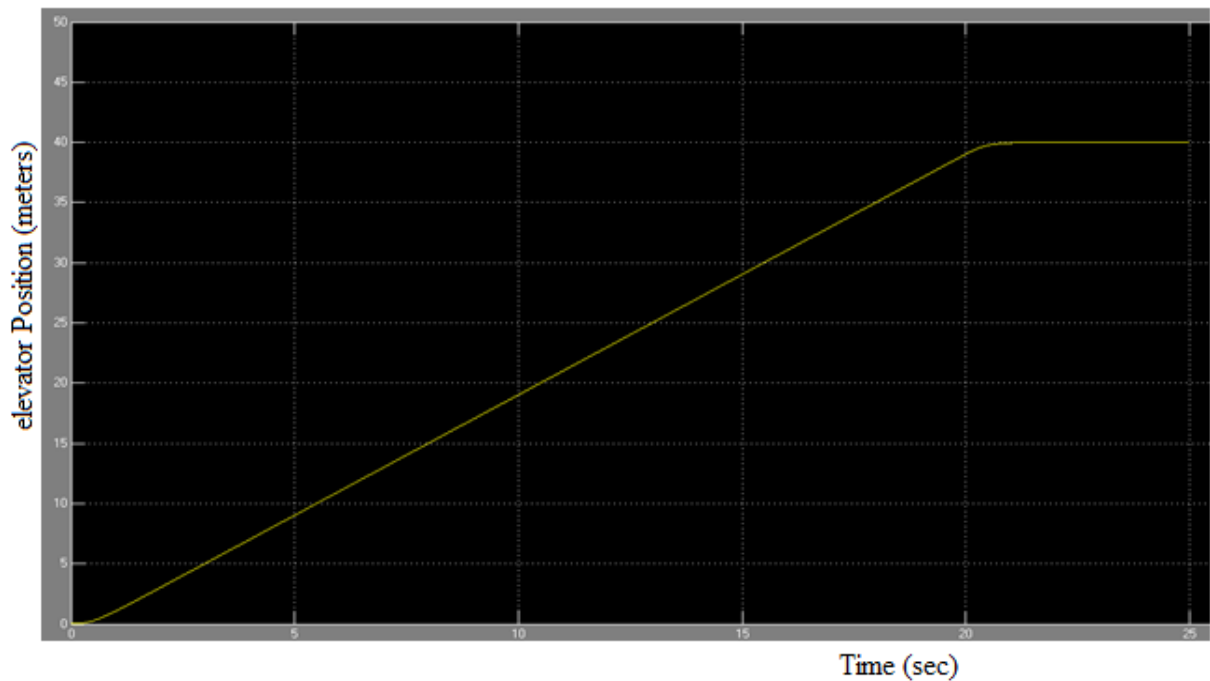


Figure 4-24: Simulated position of electric elevator drive when elevator moving to highest floor

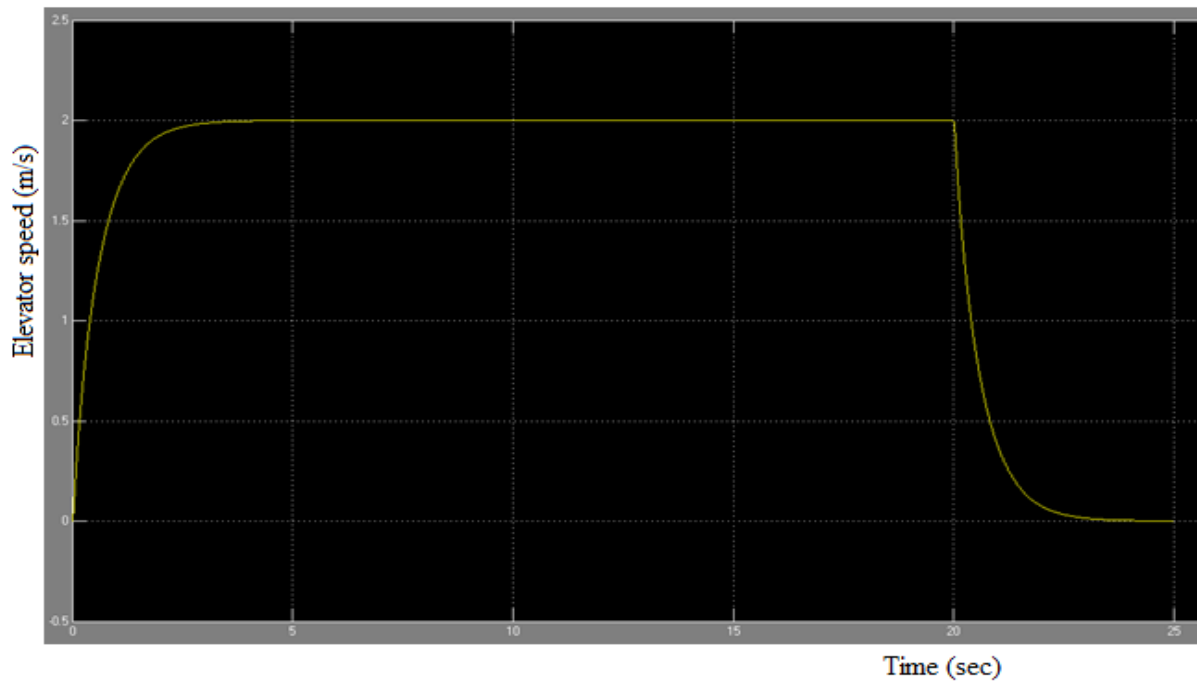


Figure 4-25: simulated speeds of 40m ascending elevator drive

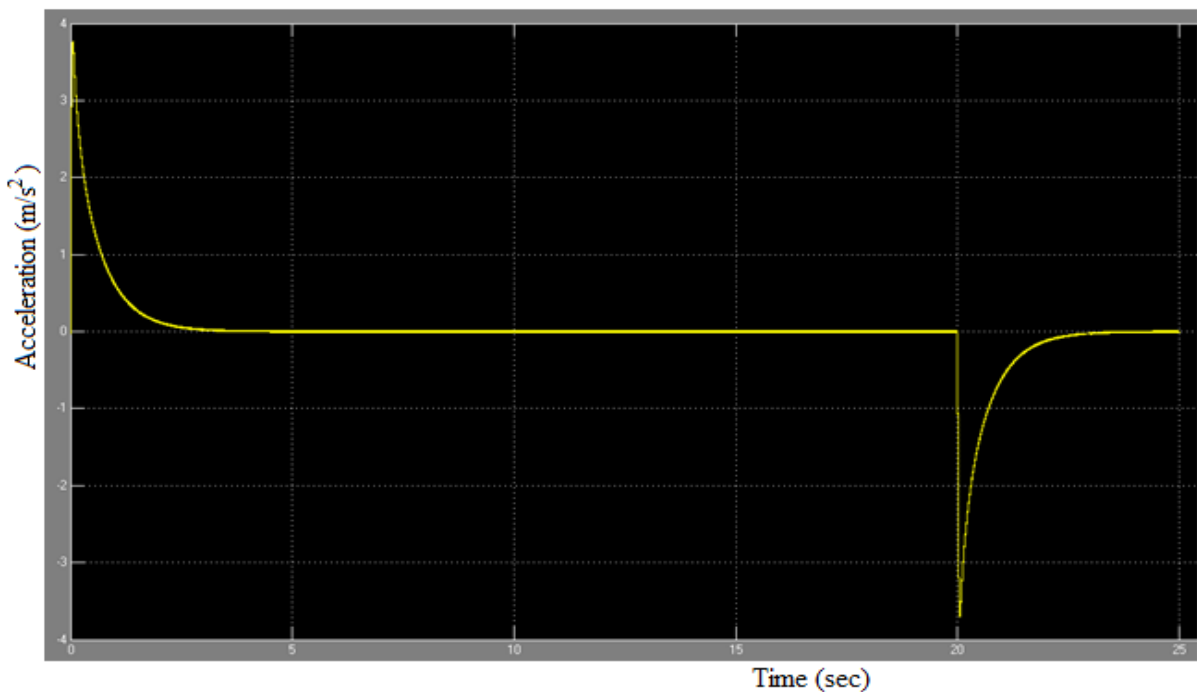


Figure 4-26: Acceleration profiles of elevator drive for 40m ascending elevator drive

As observed from Figure 4-26 above, the elevator drive with cascaded control system is smoothly accelerates and decelerates with maximum pick value of  $3.7\text{m/s}^2$  to operate with speed of  $2\text{m/s}$ .

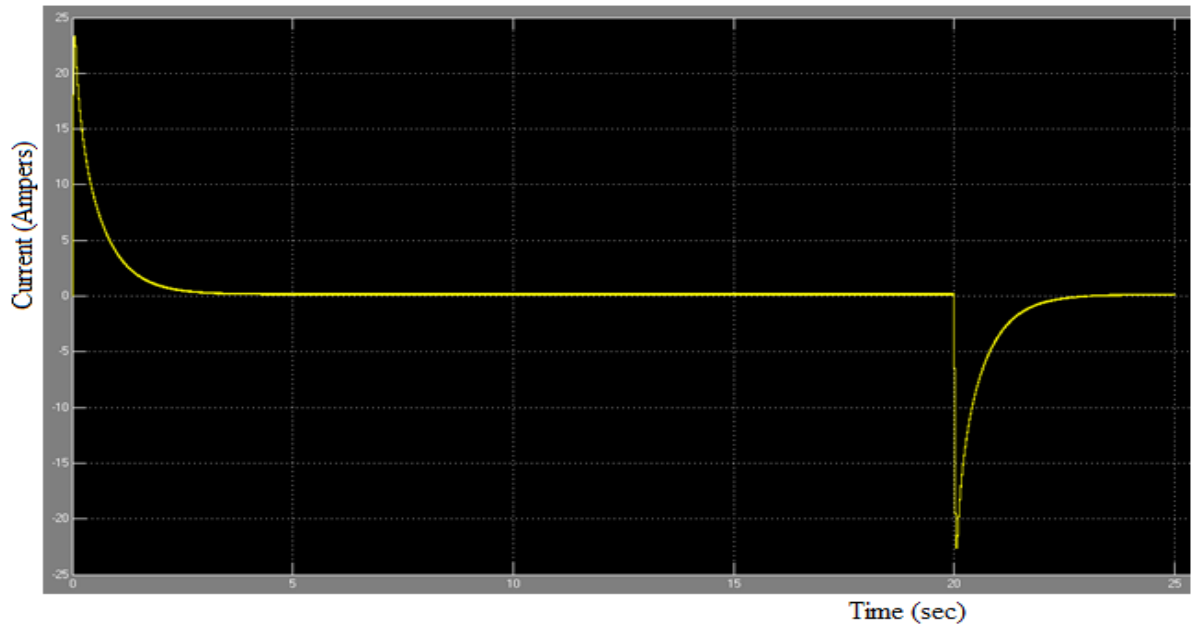


Figure 4-27: Simulated current of electric elevator drive when elevator car moving to highest floor

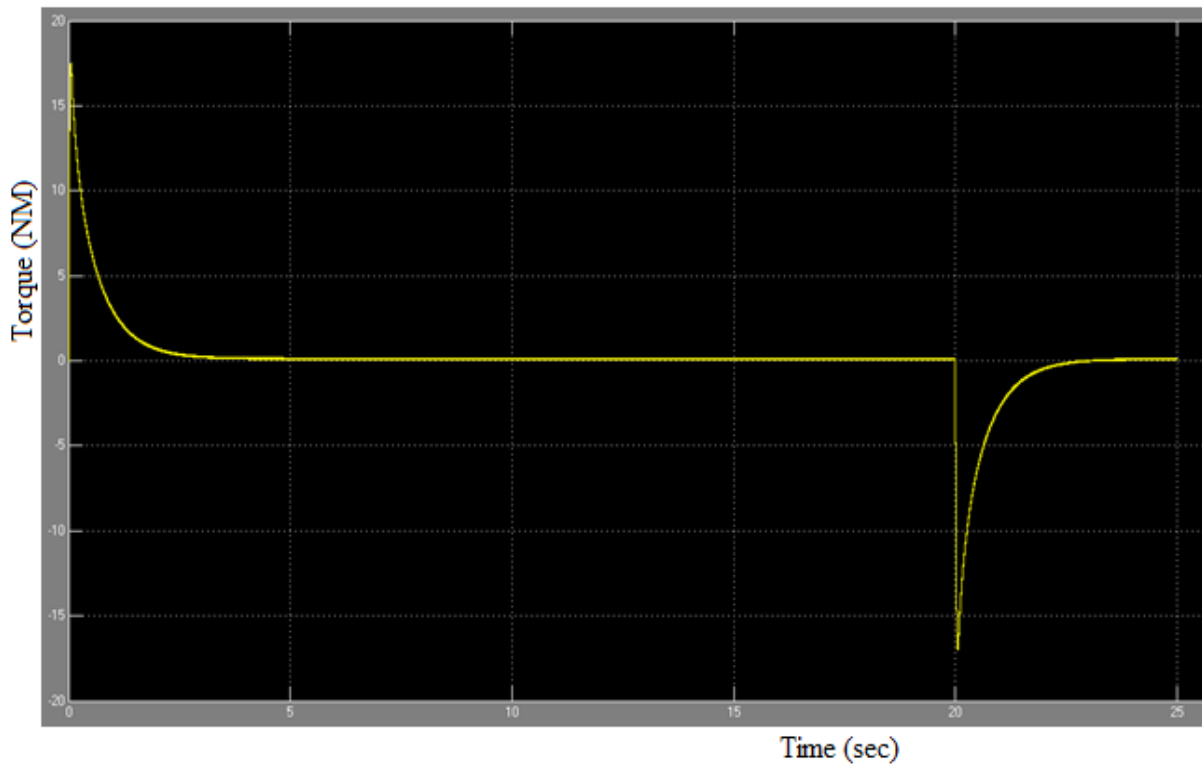


Figure 4-28: Simulated torque of electric elevator drive when elevator car moving to highest floor

As it is indicated from the above results, the designed cascaded control system effectively govern the elevator drive to be operated smoothly with recommended standard speed relative to the travelling distance. Also smooth acceleration and deceleration is achieved with minimized torque generated in order to protect the drive not to be damaged by high starting and breaking torque generation in the drive.

### Case ii. When the elevator is lowering from the top of the building

In this case, the elevator is initially placed at the highest position of the system which is taken to be the highest floor of the building. The elevator is then required to reposition itself by moving down to a reference position as preference of the passenger from the whole surface of the building. The profile of controlled parameters for moving to ninth floor which is four meter below the highest floor is presented here. Similarly profiles of the same parameters when elevator moving from highest floor to the ground floor which is 40m below the top floor of the building are simulated independently as a sample journey and given below.

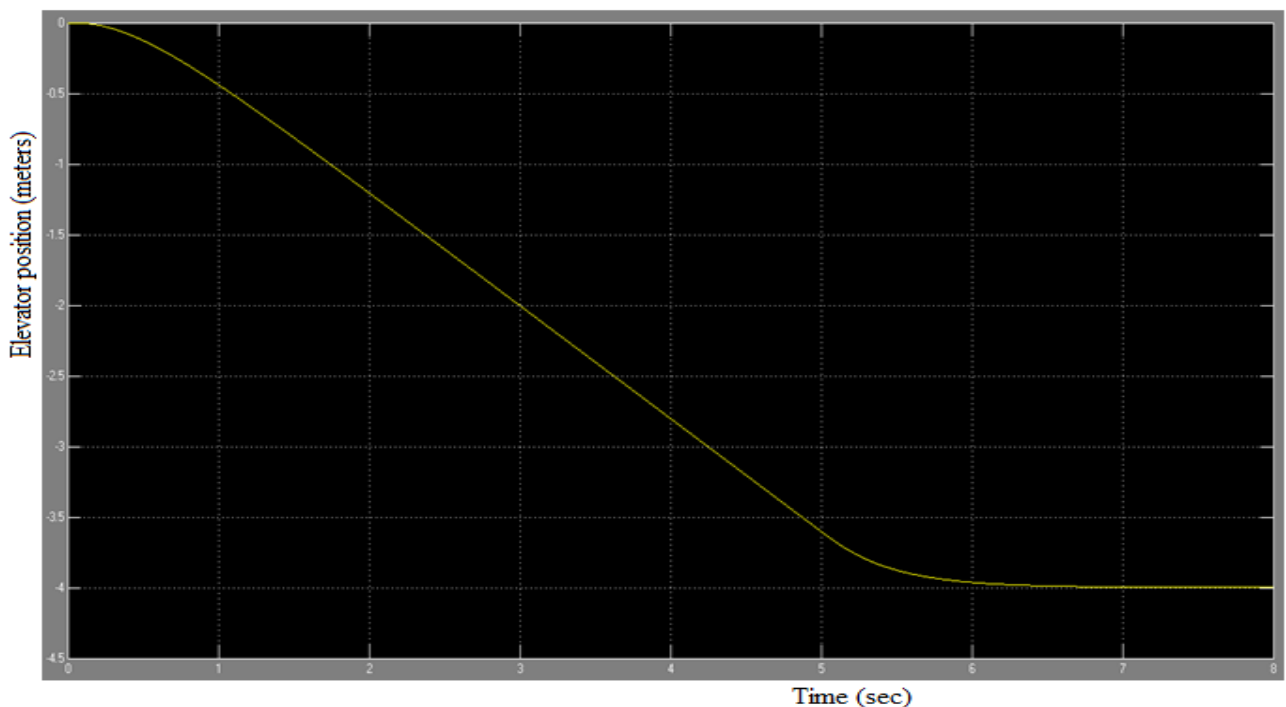


Figure 4-29: Simulated position of electric elevator drive for four meter descending elevator car from top floor to ground floor

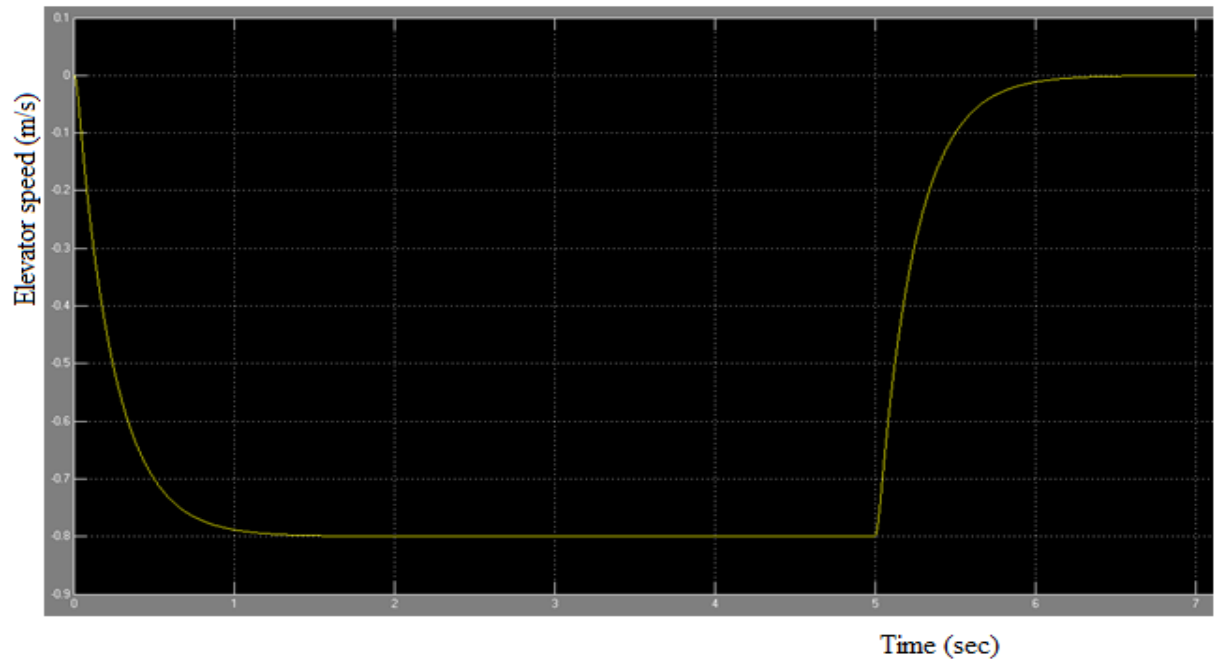


Figure 4-30: Simulated speed of electric elevator drive for four meter descending elevator car from First floor to ground floor

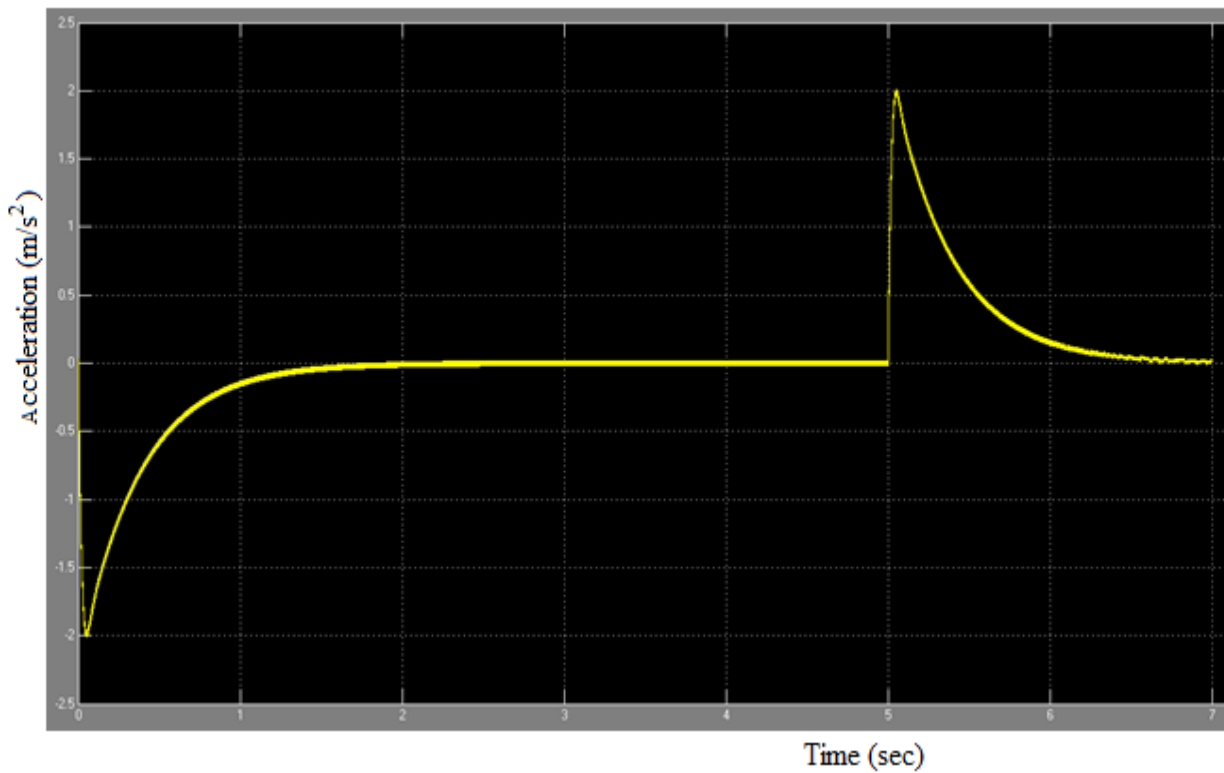


Figure 4-31: Simulated acceleration of descending 4m elevator drive

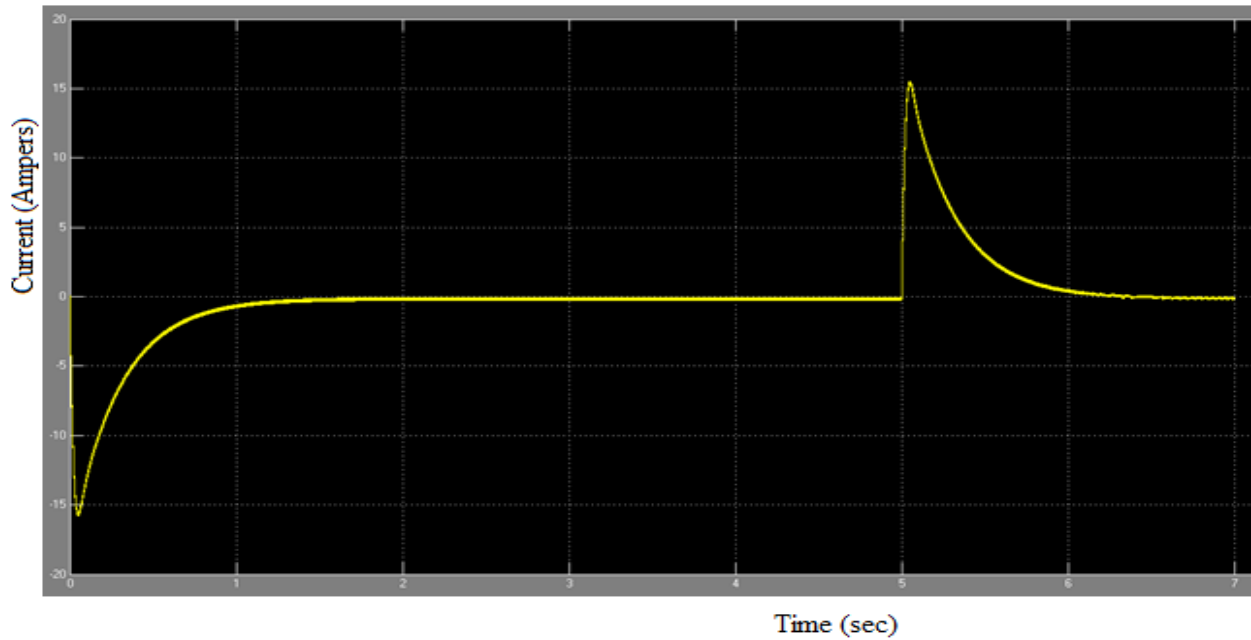


Figure 4-32: Simulated current profile of controlled electric elevator drive for 4m descending elevator

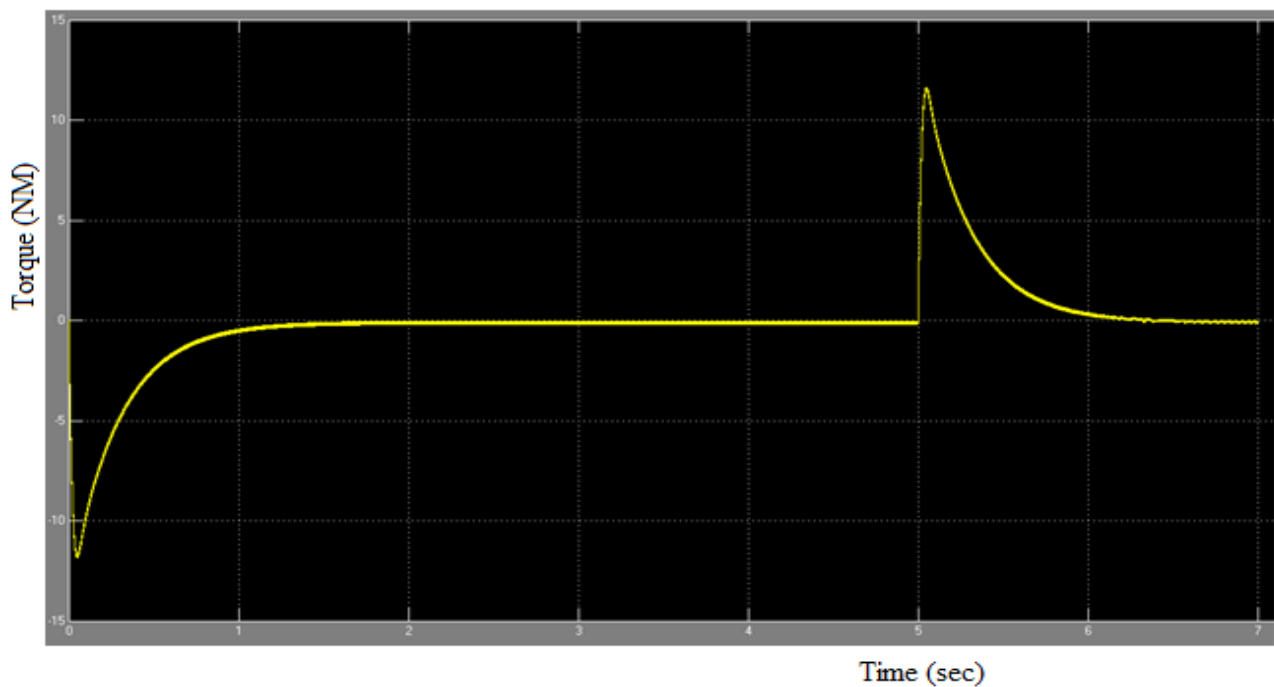


Figure 4-33: Simulated torque of controlled electric elevator drive for 4m descending elevator

As observed from Figure 4-33 above, the elevator drive with cascaded control system generates 12NM maximum pick values of starting and braking torque to descend position of 4m.

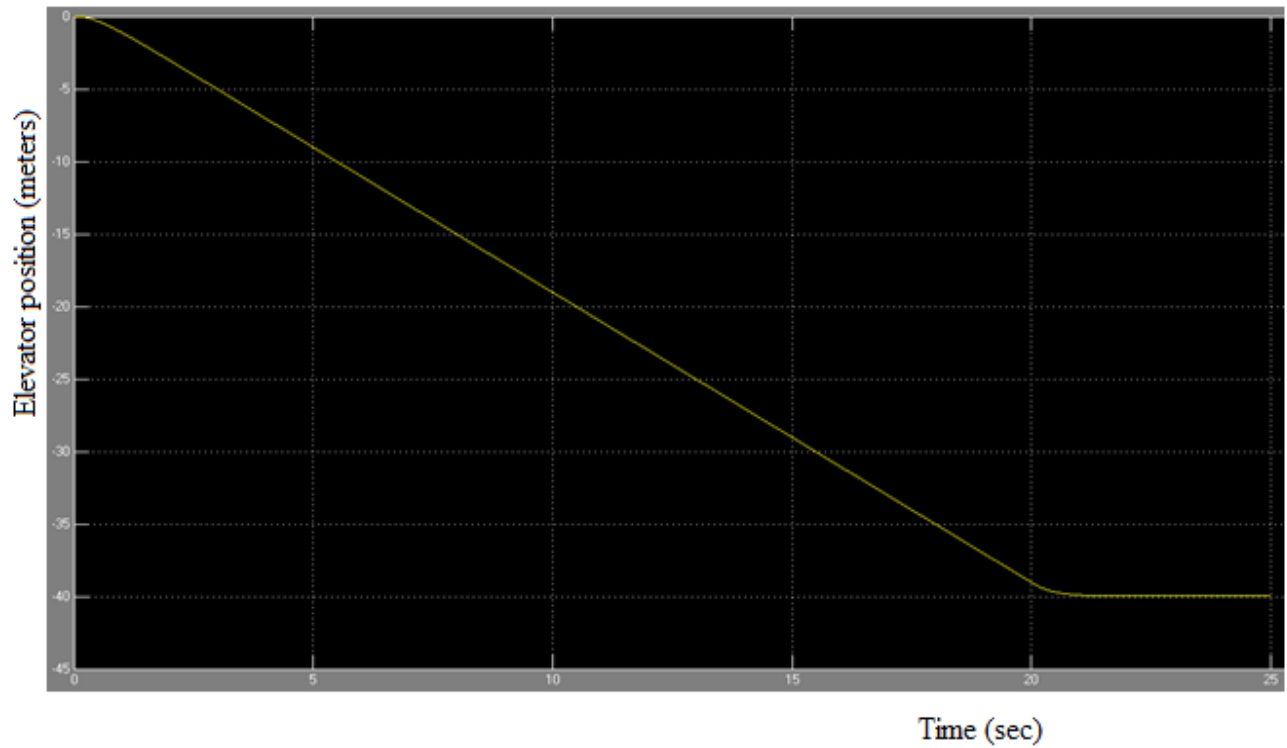


Figure 4-34: Simulated position of electric elevator drive for 40m descending elevator car

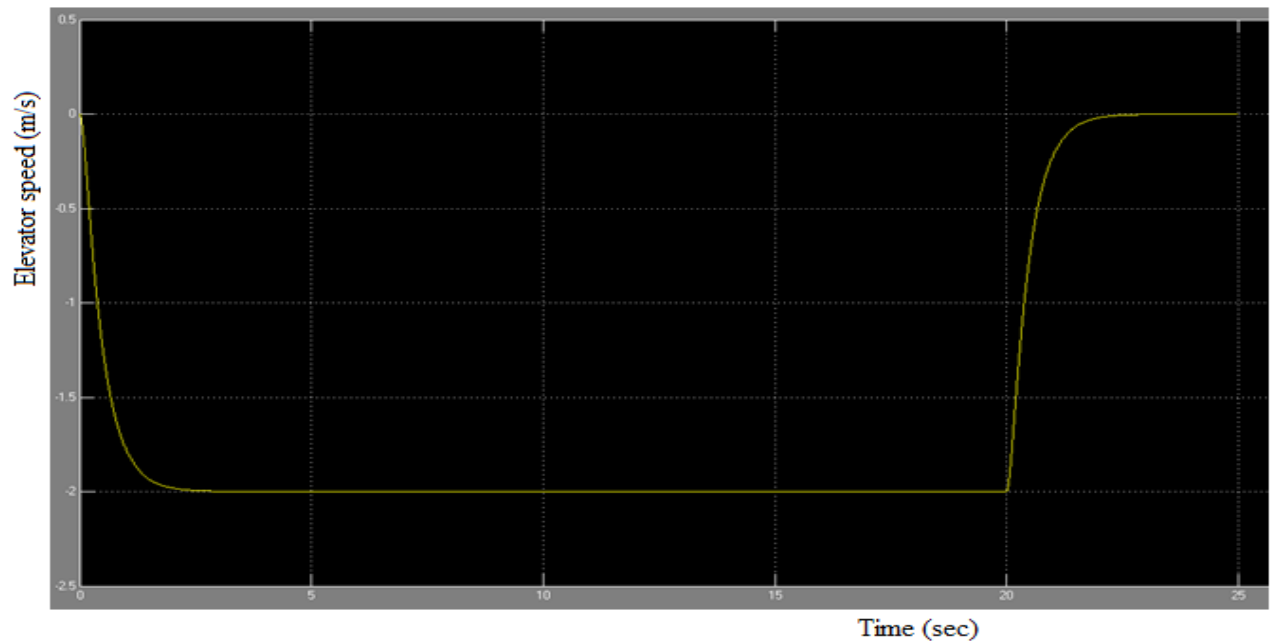


Figure 4-35: Simulated speed of electric elevator drive for descending elevator car to ground floor

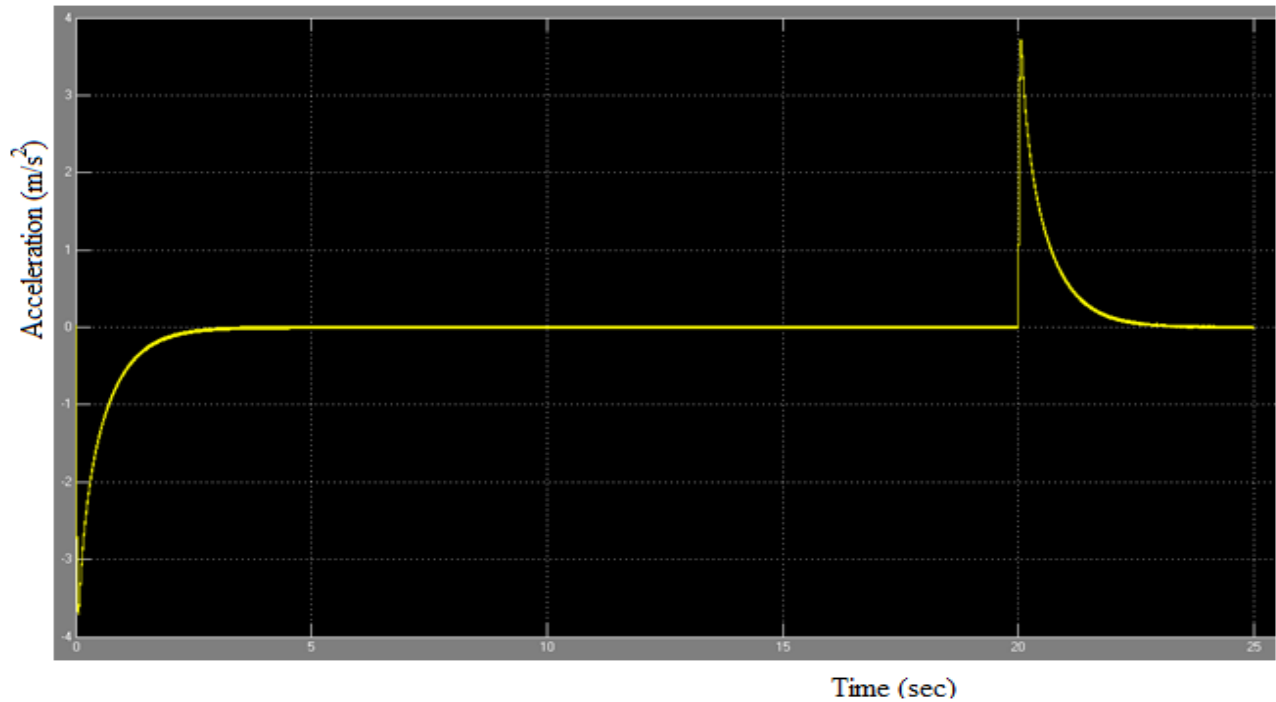


Figure 4-36: Simulated acceleration of elevator drive for 40m descending elevator car

As observed from Figure 4-35 and Figure 4-36 above, the elevator drive with cascaded control system is smoothly accelerates and decelerates with maximum pick value of  $3.7\text{m/s}^2$  to descend position of 40m with speed of 2m/s.

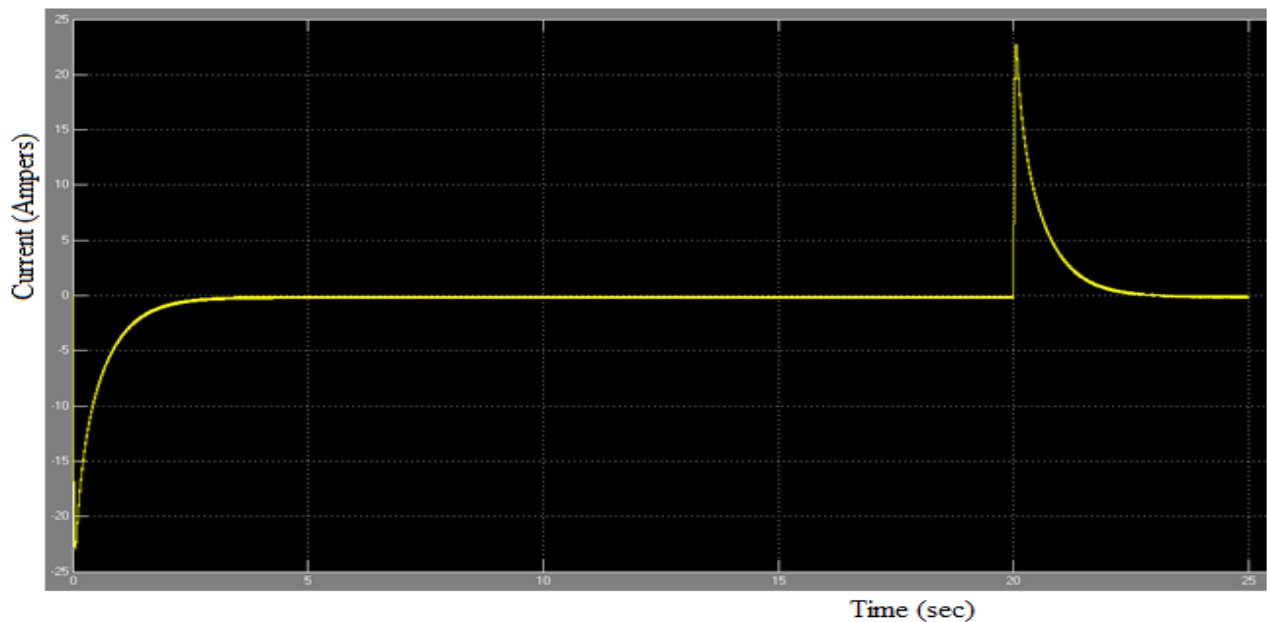


Figure 4-37: Simulated current of elevator drive for 40m descending elevator drive

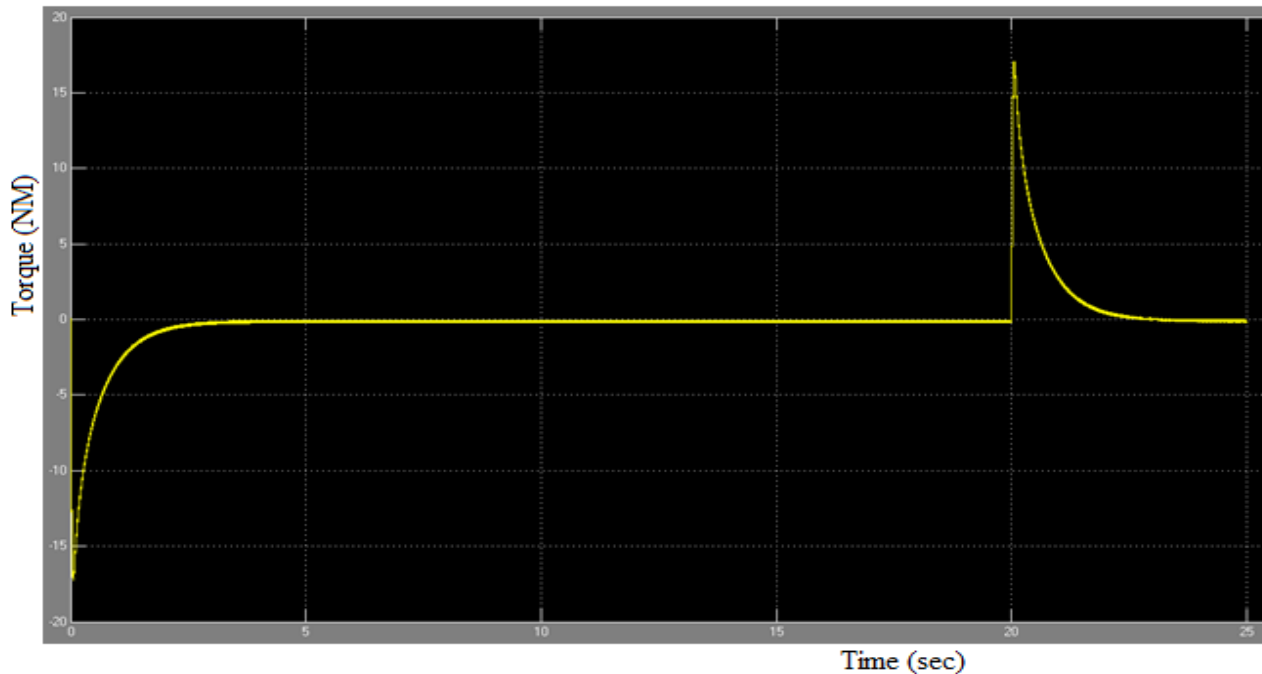


Figure 4-38: Simulated torque of electric elevator drive for descending elevator car to ground floor

As presented, the results by graphs above, the maximum amount of current and torque at start-up of the drive occurs in order to accelerate the elevator up to the rated speed. Then current through the motor is reversed to obtain braking torque in order to prevent the elevator car from accelerating beyond the desired maximum speed. During steady-state operation both current and torque remains approximately zero. As the elevator car approaches the desired set point, the motor must once again overcome inertia but in the opposite way as before. To start reducing the speed of the car, a braking torque is applied in opposite direction as before; this torque starts at its maximum value and diminishes exponentially to bring and stop the elevator drive system to destination position safely.

Generally, in both ascending and descending cases we observe that that the distortion reduction, safety and comfort journey in all travelling distance have been achieved under the designed cascaded controller action as desired because of smoothly accelerating and decelerating profile of the drive with 0% overshoot as we can indicate from speed and position results.

## Chapter 5

### 5. Conclusions, Recommendations and Suggestions for Future Works

#### 5.1. Conclusions

The aim of this thesis work is to design and simulating a controller for cascaded position, speed and current controlled elevator drive using PMDC motor as prime mover of the system. The mathematical model of the electrical elevator drive system with considerations of two cases, ascending and descending load movement has been discussed. Also the kinematics (motion) of electric elevator drive relative to the known standards has been studied. Then control strategies and design parameters of the system that allow us to plot travel profiles for any input of journey distance with maximum velocity as a basis for developing a regenerative elevator drive control strategies are also discussed.

P controller for position and PI controller for speed and current controllers with a suitable design method for implementing the elevator drive control system have been presented. The elevator drive system model is demonstrated in a MATLAB Simulink for testing and proving the controller performance of elevator specified controlled parameters for desired position and speed of elevator by using system and design parameters. As seen from the simulation results, the system can run smoothly, and has good control characteristics. Therefore the designed P controller for position control, as well as PI controller for speed and current/torque control successfully tracked a given speed profile with desired position.

The simulation that was carried out with the initial condition of the elevator position set to zero, and needed to ascend  $4m$  and  $40m$  above the ground generated the desired rated speed of  $0.8m/s$  and  $2m/s$  respectively with 0% overshoot, which are in the range of recommended standard profiles of elevator drive. Also the simulation that was carried out with the initial condition of elevator position set to zero, and lowering to  $-4m$  and  $-40m$  from the upper floor of the building to lower floor parts generated  $-0.8m/s$  and  $-2m/s$  respectively. Also the system accelerates and decelerates with maximum value not more than  $2m/s^2$  and  $3.75m/s^2$  respectively with these desired speeds in order to minimize the distortion for passenger comfort. These results illustrate that the performance of designed controller for elevator drive efficiently governing the performance of the drive to achieve passenger comfort.

## **5.2. Recommendations**

The design and simulation of cascaded position, speed and current controlled elevator drive demonstrates that the drive performance is satisfactory and yields the desired values of controlled parameters of elevator drive system. The proposed control for elevator system may be further applied to any other DC motor drive application areas such as escalators and in manufacturing companies for product motion control.

## **5.3. Suggestions for future work**

For anybody who wants to investigate further this study, the suggestions for future work are given as follows:

1. The performance of cascaded position, speed and current controlled elevator drive can be examined for larger number of passengers by maximizing the load capacity of the elevator drive in order to reduce waiting time of passengers on the same journey.
2. In this study, the dynamics of the system doesn't consider the governor and compensating rope dynamics and air pressure. So anyone can develop the system by including the indicated components dynamics in order to improve the efficiency of the system performance more.
3. Using the modified type of controllers by adding the concepts such as sliding mode control and linear quadratic controllers may also increase performance of the system more
4. Additionally, this thesis concerns only the drive subsystem of elevator system. The overall system of elevator can be further developed by adding the door opening and closing logic circuits, digital programming languages such as algorithms to call for the car directions, alarm system and adding safety components of the systems.

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## Appendices

### Appendix A: Parameters of the elevator drive and control system used in the simulation

$J = 4.6189 \text{ Kg.m}^2$	% Equivalent inertia of entire system
$R_a = 0.5 \text{ ohm}$	% armature resistance
$L_a = 0.01 \text{ H}$	% Total viscous friction coefficient
$V_a = 220 \text{ V}$	% armature input voltage
$K_b = 0.75$	% Back emf constant
$K_t = 0.75$	% Torque constant
$B_f = 0.0869 \text{ N.M.s}$	% Total viscous friction coefficient
$J_p = 0.1 \text{ Kg.m}^2$	% Inertia of drive pulley
$R_p = 0.0955 \text{ m}$	% Drive pulley radius in meters
$g = 9.8$	% gravitational constant
$M_c = 100 \text{ Kg}$	% mass of car
$M_{cw} = 300 \text{ Kg}$	% mass of counter-weight
$K_r = 31.05$	% convertor constant
$K_{pc} = 0.25$	% Proportional gain of current controller
$K_{ps} = 77.72$	% Proportional gain of speed controller
$T_{ic} = 0.0202 \text{ sec}$	% Time constant of current controller
$T_{sc} = 0.0529 \text{ sec}$	% Time constant of speed controller
$K_{pp} = 7$	% Proportional gain of position controller

## Appendix B: MATLAB codes to check stability of elevator drive system

```
%% simplification of speed control loop
```

```
sys1 = tf ([4.0803 77.72], [0.0525 0])
```

```
sys2 = tf ([0 0.999], [0.00321 1])
```

```
sys3 = tf ([0 8.631], [53.15 1])
```

```
sys4 = tf ([0 3], [0.01 1])
```

```
sys5 = series (sys1, sys2)
```

```
sys6 = series (sys5, sys3)
```

```
sys7 = feedback (sys6, sys4, -1)
```

```
%% generating open loop transfer function of position control loop
```

```
sys8 = tf ([0 1], [1 0])
```

```
sys9 = series (sys7, sys8)
```

```
pole (sys9) % generating poles of open loop transfer of position control loop
```

```
bode (sys9), grid % bode plot of open loop transfer of position control loop
```

```
margin (sys9), grid % checking margins of open loop transfer of position control loop
```

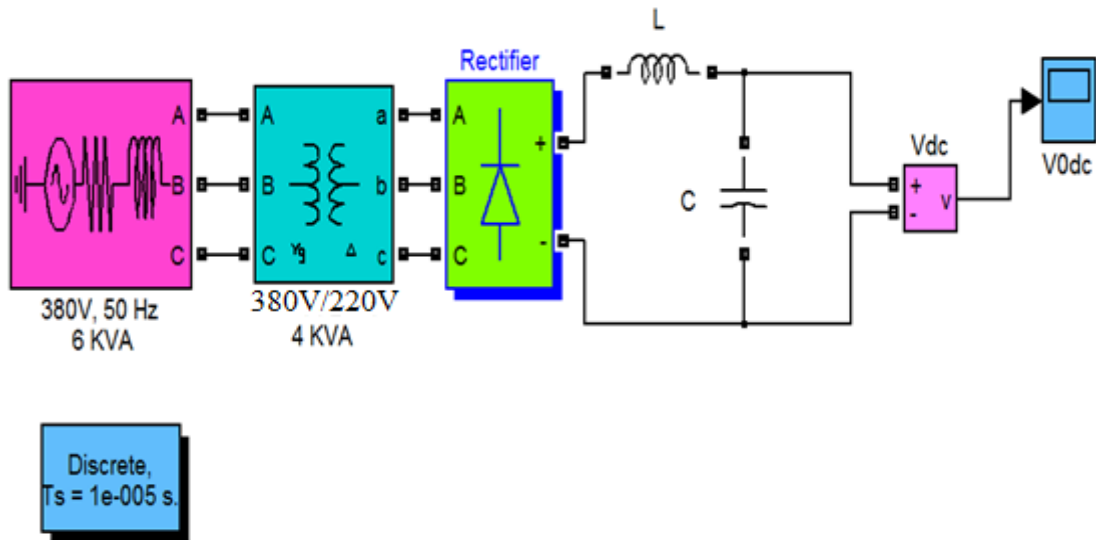
```
 $K_{pp} = 10$  % proportional gain of position control loop
```

```
sys10 =  $K_{pp}$  * sys9
```

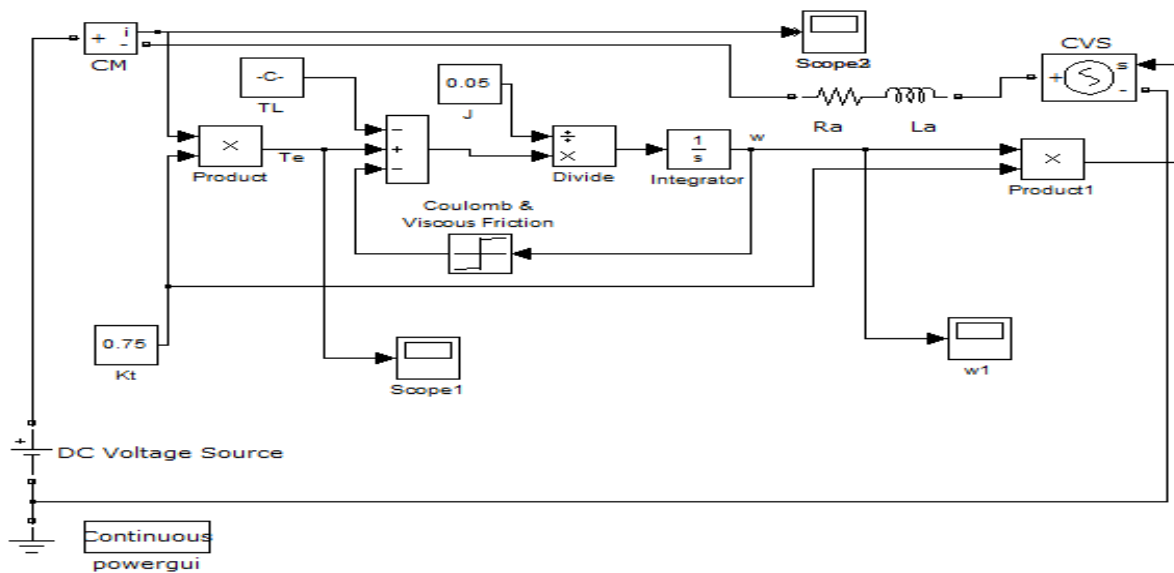
```
bode (sys10), grid % bode plot of position control loop with position controller
```

```
margin (sys10), grid % checking margins of stability for position control loop with gain
```

### Appendix C: Simulink models of elevator drive subsystems



AC/DC convertor sub-system Simulink model



PMDC Motor sub-system Simulink model