UNIVERSITY OF TURKISH AERONAUTICAL ASSOCIATION
INSTITUE OF SCIENCE AND TECHNOLOGY

SPEED CONTROL FOR A DC MOTOR BASED ON DOUBLE FEEDBACK CONTROL CIRCUIT BY USING PID CONTROLLER AND PWM

MASTER THESIS

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The Department of Electrical and Electronic Engineer

The Program of Electrical and Electronic Engineering

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Osamah Abdulsalam Suhry, having the student number 1406030003 and enrolled in the Master program at the Institute of Science and Technology at the University of Turkish Aeronautical Association, after meeting all of the required conditions contained in the related regulations, has successfully accomplished, in front of the jury, the presentation of the thesis prepared with the title of Speed Control for a DC Motor Based on Double Feedback Control Circuit by Using PID Controller and PWM.

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Thesis Defense Date: 13.12.2017

UNIVERSITY OF TURKISH AERONAUTICAL ASSOCIATION
INSTITUTE OF SCIENCE AND TECHNOLOGY

I hereby declare that all information in this study I presented as my Master's Thesis called: "Speed Control For a DC Motor Based on Double Feedback Control Circuit by Using PID Controller and PWM" has been presented in accordance with the academic rules and ethical conduct. I also declare and certify with my honor that I have fully cited and referenced all the sources I made use of in this present study.

05.12.2017

Osamah SUHRY

To My Parents

ACKNOWLEDGMENTS

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December 2017 Osamah SUHRY

TABLE OF CONTENTS

LIST OF TABLE

LIST OF FIGURES

ABBREVIATIONS AND NOMENCLATURE

PC	**:**	Personal Computer
DC	**:**	Direct current
PID	**:**	Proportional integral derivative
PWM	**:**	Pulse width modulation
GPI	**:**	Generalized proportion integral
LQR	**:**	Linear – quadratic regulator
IDE	**:**	Integrated development environment
CCM	**:**	Continuous current mode
P.S.B	**:**	Power system block set
ADC	**:**	Analog to digital converter
FPGA	**:**	Field programmable gate array
DSP	**:**	Digital signal processor
BLDC	**:**	Brushless DC motor
DSC	**:**	Digital signal controller

LIST OF SYMBOLS

B	:	Viscous friction coefficient
C	:	Capacitor of Buck converter
ΔV_c	:	Peak – to – peak ripple voltage of the capacitor
ΔI	:	Peak -to- peak ripple current of inductor L
e_b	:	The back emf
e_L	:	Inductor voltage of Buck converter
e_{ss}	:	Steady state error
i_a	:	The armature current
i_c	:	Capacitor current
i_L	:	Inductor current
i_f	:	Field current
J	:	Moment of inertia
K	:	*Duty ratio*
K_{cr}	:	Critical controller gain
K_D	:	Derivative constant
K_E	:	Voltage constant
K_I	:	Integral constant
K_P	:	Proportional constant
L	:	Inductor of Buck converter
L_a	:	The armature inductance
L_{af}	:	Field-armature mutual inductance
L_f	:	Field inductance
Ө	:	Phase angle
P.O	:	Percentage overshoot
P_{acu}	:	Armature circuit copper losses
P_c	:	Constant losses
P_{cr}	:	Critical period
P_{fcu}	:	Field circuit copper losses
P_{in}	:	Input power
R_a	:	The armature resistance
R_{ex}	:	External resistance
R_f	:	Field resistance
T_2	:	Torque due to friction and iron losses
T_e	:	Torque produced by motor
T_L	:	Load torque
t_p	:	Peak time
t_r	:	Rise time
t_s	:	Settling time
v_c	:	Capacitor voltage
V_a	:	Armature terminal voltage
V_d	:	Diode voltage

$\mathbf{V_f}$	:	Field voltage
$\mathbf{V_o}$	:	Output voltage of Buck converter
$\mathbf{V_s}$	:	Source voltage of Buck converter
W	:	Power
$\boldsymbol{\omega_n}$	:	Natural frequency
$\boldsymbol{\omega_r}$	:	Speed of motor
$\mathbf{X_{La}}$	:	Armature reactance
$\mathbf{X_{Lf}}$	:	Field reactance
$\mathbf{Z_a}$	:	Armature impedance
$\mathbf{Z_f}$	:	Field impedance
Z	:	Damping ratio

ABSTRACT

SPEED CONTROL FOR A DC MOTOR BASED ON DOUBLE FEEDBACK CONTROL CIRCUIT BY USING PID CONTROLLER AND PWM

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A separately excited DC motors are widely used in many variable speed drives. Open-loop operation of the motor is unsatisfactory in the industrial and automation applications. Therefore, if the drive requires constant-speed operation under any changing in system parameters, the closed-loop control is necessary. The speed control of the DC Motor was usually implemented using analog methods, which have some disadvantage such as complex circuits and low reliability. The digital control of the adjustable speed DC drive systems that employ the double feedback control circuit using PID controller and pulse width modulation (PWM) by means of Arduino UNO with DC motor is studied in this thesis. This type of Arduino Kit has many advantages such as high-speed operation capacity, low cost and high flexibility that makes it possible to work with real time. The closed-loop control of the motor has also been designed using MATLAB, Simulink which basically consists of two feedback loops. In this thesis, we have implemented PID controller by considering the disturbance in external torque, DC supply, inductance and capacitor of buck converter which were not considered in literature until this work. Moreover, the hardware design and software programming of the proposed adjustable speed systems are also discussed. The practical results show that the proposed digital speed control system has fast response less than (0.04 Sec) and small overshoot less than (0.05%) of the desired speed.

Keywords: DC motor, double feedback close loop control, pulse width modulation (PWM), DC-DC buck power converter, PID controller.

ÖZET

PID KONTROLÖR VE PWM KULLANILARAK ÇİFT GERİ BESLEME KONTROL DEVRESİNE DAYALI BİR DC MOTOR İÇİN HIZ KONTROLÜ

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Bağımsız olarak uyarılmış DC motorlar birçok değişken hızlı tahrikte yaygın olarak kullanılmaktadır. Motorun açık devrede çalıştırılması endüstriyel ve otomasyon uygulamalarında yetersiz kalmaktadır. Bu nedenle, sürücünün herhangi bir değişen sistem parametresi altında sabit hızla çalıştırılması gerektiği durumlarda, kapalı devre kontrolü gereklidir. DC Motorun hız kontrolü genellikle karmaşık devreler ve düşük güvenilirlik gibi bazı dezavantaja sahip olan analog yöntemler kullanılarak gerçekleştirilmektedir. Bu tez çalışmasında, DC motor ile Arduino UNO vasıtasıyla darbe genişlik modülasyonu (PWM) ve PID kontrolörü kullanan çift geri besleme kontrol devresine sahip uyarlanabilir hızlı DC tahrik sistemlerinin dijital kontrolü araştırılmaktadır. Bu tip Arduino Kiti, yüksek hızda çalıştırma kapasitesi, düşük maliyet ve gerçek zamanlı çalışmayı mümkün kılan yüksek esneklik gibi pek çok avantaja sahiptir. Motorun kapalı devre kontrolü, temel olarak iki geri besleme döngüsünden oluşan MATLAB, Simulink kullanılarak tasarlanmıştır. Bu tezde, dış tork, DC besleme, endüktans, düzenleyici dönüştürücü kondansatöründeki bozunum göz önünde bulundurularak PID kontrolör uygulanmıştır, bu faktörler literatürde bu tezden önce değerlendirilmemiştir. Bunun yanında, önerilen ayarlanabilir hız sistemlerinin donanım tasarımı ve yazılım programlaması da tez içerisinde ele alınmıştır. Elde edilen pratik sonuçlar, önerilen dijital hız kontrol sisteminin (0.04

saniye) den daha az olmak üzere hızlı cevap verdiğini ve istendik hızdan (%0.05) daha az küçük bir oranda sapma gösterdiğini ortaya koymuştur.

Anahtar Kelimeler: DC motor, çift geri beslemeli kapalı devre kontrolü, darbe genişlik modülasyonu (PWM), DC-DC düzenleyici güç dönüştürücüsü, PID kontrolör.

CHAPTER ONE

INTRODUCTION AND PERTINENT LITERATURE

1.1 Background

The Direct Current (D.C), which is shown in figure (1.1), have been widely used in industry applications such as hybrid vehicles, double-hulled tankers, robotics, paper and textile mills and many other high-precision digital tools. This large usage of D.C motor can be attributed to their several inherent advantages such as their simple construction, reliability, robustness, low maintenance needs, low cost and continuous control characteristics [1]. Without the existence of convenient controlling system, it is practically impossible to achieve the desired task for any industrial application.

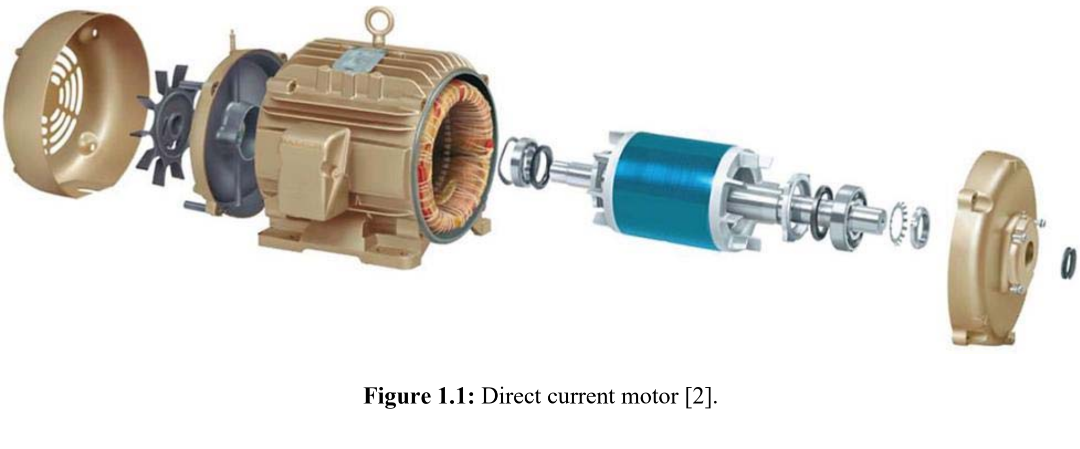

Figure 1.1: Direct current motor [2].

Speed control of DC Motor was usually implemented using analog methods, which have some disadvantages such as complex circuits and low reliability. To achieve optimal efficiency of the D.C motor, several modern control techniques have been developed to control the speed of D.C motor. One of these methods is proportional the plus integral plus derivative (PID) controllers. However, there are many other control methods that are used to control the speed of the D.C motor, the

(PID) controllers is preferred as it is more easily to implement and it can be used for high performance applications. As we know, the speed of the D.C motor depends on the input value of the power supply across the terminals of the D.C motor. The pulse width modulation (PWM) is a commonly used method to provide variable output voltage for controlling the speed of the D.C motors by varying the duty cycle. Moreover, high development of various solid state switching devices have been made in the form of diodes, transistors and thyristors along with various analog/digital chips used in firing/controlling circuits. DC drives are more accessible for control in innumerable areas of applications. Finally, for obtaining a smooth motion of D.C motor, a DC chopper represents a better solution for the D.C motor speed control. Driving the D.C motor with a PWM signal increases the current ripple and the harmonics, which gives better performance. The DC chopper control method has been used for the lower acoustic noise, the less current and for the fewer current harmonics [3].

1.2 Literature Survey

As mentioned the previous section, D.C motors have been widely used in industry applications. Therefore, more attention is given to their control requirement. In the recent period, intelligent methods of control have been proposed to enhance the performance of the D.C motors such as neural network, fuzzy control, hybrid control, flatness control, sliding mode control and many other control methods have been used as numerical methods to construct the control system. However, PID controller is still the most popular and common among them.

The following survey covers different control methods and some of the available related works that give a versatile knowledge about available speed control of DC motors.

Mattavelli et al, 1998 [4] proposed a general-purpose sliding-mode controller, which can be used in most dc/dc converter topologies. The circuit complexity is same to the current mode controller and it provides extreme robustness and speed of response against line, load and parameter variations. The same group derived small signal models for dc/dc converters with sliding mode control, which allow the estimation of the control coefficients, the analysis of parameters of the variation effects, the evaluation of the closed loop performance like audio susceptibility, input and output impedances and the reference to the output transfer function [5].

Daniel Logue and Philip. T. JSrein, 2000 [6] proposed a power electronic and electric machines toolboxes based on the MATLAB/SIMULINK simulation package. Switching and averaged power electronic models, as well as dynamic and steady-state machine models were included. The toolboxes not only provided many components for simulation, but also it introduced a systematic method for the construction of additional block components. The SIMULINK environment provided a direct access to the computational ability of MATLAB through a convenient, block diagram oriented programming environment.

Lyshevski, 1999 [7] showed some combinations of the power electronic converters connected to the DC motors.

Linares-Flores and Sira-Ramírez, 2004 [8]–[10] presented a design for smooth angular velocity tracking controllers for a DC/DC Buck converter–DC motor system. In [8], they implemented a smooth starter for a DC/DC Buck power converter–DC motor system, applying a differential flatness control. In addition, in [9], they carried out the average generalized proportional integral (GPI) control law, with the intention of solving the angular velocity trajectory tracking task. Likewise, they presented the dynamic output feedback control [10], using the energy shaping and damping injection method have been presented in [11], for the same task.

El Fadil and Giri, 2006 [12] designed a regulator using the back stepping technique for control the angular velocity of a DC motor through a DC/DC Buck power electronic converter. Also, they showed the adaptive's and non-adaptive controllers design, where they presented through numerical simulations which approved that the adaptive controller is better than the non-adaptive controller.

Ahmad, 2010 [13] compared the performance between the proportional–integral (PI), the PI + fuzzy controllers and the linear–quadratic regulator (LQR), in order to solve the angular velocity tracking task for the DC/DC Buck power electronic converter–DC motor system. This is similar to the aforementioned work and task.

Sureshkumar and Ganeshkumar, 2011 [14] presented the comparative performance between the PI and the back stepping controllers via numerical simulations.

Mohd Tumari *et al*. 2012 [15] the H–infinite control has been performed, using linear matrix inequality techniques for controlling the angular velocity tracking of a DC motor, driven by the DC/DC Buck power electronic converter.

Sira-Ramírez and Oliver-Salazar, 2013 [16] developed a robust control law using flatness–based controllers and active disturbance rejection, with the purpose of the combination of two DC/DC Buck power electronic converters to control a DC motor. The designed controller is used to drive the angular velocity tracking in the DC motor.

Silva-Ortigoza et al, 2013 [17] introduced a two stage control based on the differential flatness for the angular velocity control without taking into account the velocity measurement of a dc/dc buck converter- dc motor system. They showed that the proposed control scheme effectively provided robustness to the tracking performance when parametric uncertainties related to the system appear through numerical simulation that included a Σ-Δ modulator.

Finally, Mayra Antonio and Daniel Munoz, 2015 [18] designed a smooth starter, based on dc/dc buck powers converter, for the angular velocity trajectory tracking task of the D.C permanent magnet motors. It is integrated by a control linked to D.C motors based on the differential flatness at the high level, and the control related with the dc/dc buck converter based on a cascade control scheme at the low level. The control at the high level allows the D.C motor angular velocity to track a desired trajectory and also provide the desired voltages profile that must be obtained by the output of the dc/dc buck power converter. At the low level, cascade control have been designed, considering a sliding mode control for the inner current loop and the PI controller for the outer voltage loop. This hierarchical controller has been tested using MATLAB-Simulink and DS1104 board from the dSPACE.

1.3 Problem statement

D.C motors are widely used in all industry applications. The speed of the D.C motors has to be varied according to the application. Some application required constant speed, while other applications require a variation in the speed with time against the internal and the external change of the parameter of D.C motor circuit (external torque, terminal power supply, inductor and capacitor value of power converter). Therefore, there is a need for more efficient and reliable D.C motor control system for now and future applications. The use of (PID) controller with (PWM) techniques for speed control of D.C motors with the above mentioned challenges gives good performance in steady state operation, small overshoot, fast transient response and low steady state errors.

1.4 Aim of the work

The aim of the present work is based on simulation, construction, and validation of a topology of a DC/DC Buck power converter–DC motor system to control the speed of DC motors by designing and building a closed loop control system which gives theoretically small overshoot, small steady state error and good dynamic response under any disturbance in the system parameters.

To achieve the above goals, the following steps have been considered:

1. Finding the mathematical equations that our control circuit based on.
2. Finding the parameters of the DC motor in order to be used in MATLAB/ Simulink-model.
3. Designing and building BUCK converter circuit to feed the DC motor.
4. Constructing a PWM design to fire the electronic switch circuit and give the appropriate duty cycle for buck converter circuit.
5. Designing a multiple feedback loop control scheme with proportional integral derivative (PID) controller for the DC motor control by using Ziegler-Nichol method and then simulating it by using MATLAB Program.
6. Programming a complete software program using integrated development environment (IDE) Code of Arduino Uno Kit to generate PWM and to change the duty cycle of the triggering voltage according to the data that are received from the set points and actual speeds.

1.5 Thesis Outline

In this thesis, an introduction to the speed control of the DC motors and a historical reviewing on related subjects are presented in Chapter One. In Chapter Two, the theoretical analysis and equations of the DC motors and Buck converter have been explained. Chapter three gives some theoretical concepts on tuning PID controllers and pulse width modulation generation. In Chapter Four, computer simulation of open and closed loop control systems and discussion of the results have been presented. Chapter Five explains, in detail, the experimental work that has been done in this thesis and its results. Finally, the conclusions and some suggestions for future work have been given in Chapter Six.

CHAPTER TWO

THEORETICAL CONCEPTS OF DC MOTOR AND BUCK CONVERTER

This chapter is dedicated for the theory of the DC motors in detail, its transfer function and equivalent circuit equations. Definition of the DC-DC Buck converter, the design and the application in the speed control of the DC motor are also given.

2.1 Direct Current (DC) Motors

The direct current motor or DC motor converts DC electrical energy into mechanical energy. The DC motor produces a mechanical rotary action at the motor shaft, where the shaft is physically coupled to a machine or other mechanical device to perform many types of works [19]. DC motor is very suitable for many industrial applications. For example, DC motor is used to provide a high starting torque and also is used where accurate control over the speed or the position of the load is required, and it can be decelerated or accelerated quickly and smoothly. In addition, the direction easily can be reversed. Because of its multiple characteristics and wide range of applications, different functional types of DC motors can be listed as shown in figure (2.1).

Recently, brush less DC motors, induction motors and synchronous motors have gained wide spread use in Electrical Traction. However, there is a persistent effort towards making them behave like DC motors through innovative designs and control strategies [25]. Hence, DC motors are always good proving ground for the advanced control algorithms because the theory is extendable to other types of motors. DC motors have long been the primary means of Electrical Traction and they have torque/speed characteristics that are compatible with most mechanical loads [20].

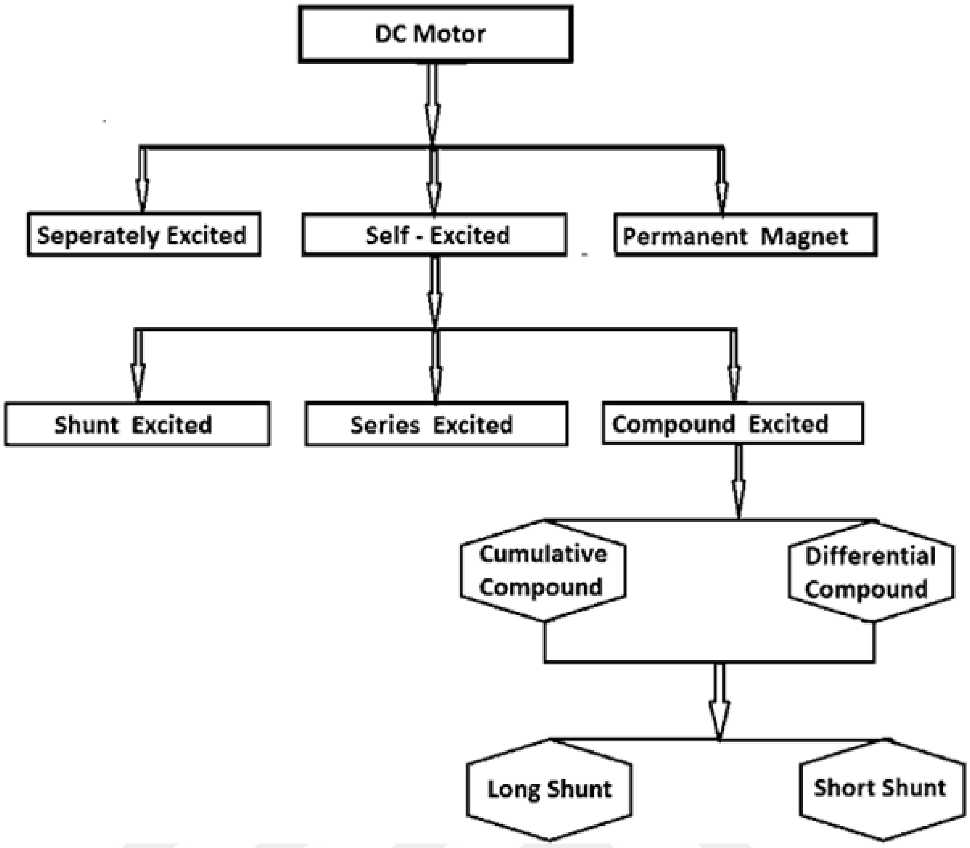

Figure 2.1: Different types of DC motor [21]

The various types of DC motors give us a variety of control methods which allows performing a variety of applications. Table 2.1 illustrates the types of DC motors with their advantage and disadvantage. Theoretically, when the voltage increases, the speed of the DC motor also increases. Thus, the speed control of DC motor can be controlled by varying the average voltage supply [25].

Table 2.1: Type of DC motor with advantages and disadvantage [25]

Types	**Advantages**	**Disadvantages**
Series Coils	High starting torque	Varies speed
Permanent Magnets	Variable speed Compact and small Cheap	Heavy magnets Constant magnetic field strength
Shunt Coils	Constant speed	Low starting torque
Stepper motor	Very precise control for position and speed	Expensive Require a switching control circuit

2.1.1 Separately Excited DC Motors

The DC motor, which is used in this work, is separately excited DC motor manufactured by TERCO Company. From the name, we can suggest that in case of a separately excited DC motor, the supply is given separately to the armature winding and the field windings. The main special fact in these types of DC motor is that, the armature current is not the current which flows through the field windings, as the field winding is energized by a separate external source of DC current as shown in figure (2.2). In order to find the parameters of the DC motor, many tests are made as it is explained in Appendix A1.

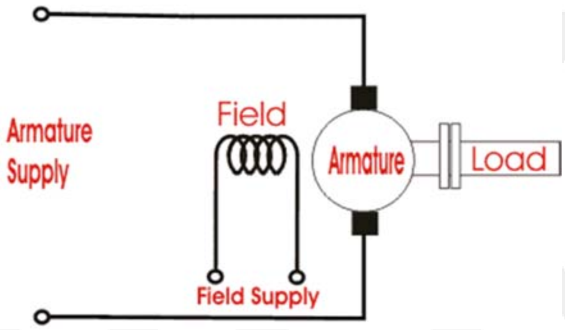

Figure 2.2: Separately excited of DC motor [21]

2.1.2 The Components of the DC Motor

In general, the simple two poles of the Dc motor has six basic parts which are rotor or armature, stator, axle, brushes and field magnets. Table (2.2) shows the parts of the Dc motor with its explanation, and the figure (2.3) is illustrates the parts of the DC motor.

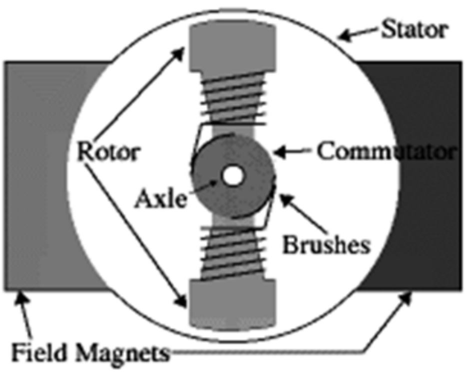

Figure 2.3: The parts of the DC motor [26]

Table 2.2: Description of DC motor [25]

Parts	Descriptions
Rotor	Consists of the windings that are electrically connected to the commutator. It is rotating together with the axle and attached commutator with respect to the stator.
Axle	Attached with rotor and commutator.
Commutator	Consists of conductive segments which represent the termination of the individual coils of wire distributed around the armature.
Stator	Represents the stationary part of the DC motor which includes the motor casing.
Brushes	Remain stationary with the motor's housing but mount (or brush) on the rotating commutator.
Fields Magnet	Winding that represents the north and south polarization.

2.1.3 Speed Control of DC Motors

The speed control of the DC motors could be achieved by using mechanical or electrical techniques. In the past, the speed control of the DC drives was mostly mechanical, and therefore requiring large size hardware to implement. Advances in the area of power electronics have brought the total revolution in speed control of the DC drives [22].

Among the three kinds of the DC motors, series, shunt and separately excited DC motors, the separately excited DC motors are mostly used. Different speeds can be obtained by changing the armature voltage and the field voltage. The significant feature of separately excited DC motor configuration is its ability to produce high starting torque at both high and low operation speeds [23]. Adjustable speed drives may be operated over a wide range by controlling the armature or the field excitation. Speeds below rated are achieved by armature voltage control and above rated speeds are achieved by using field excitation variation [22] [24].

The armature control is more preferred than the field control because the requirement of constant armature current is a serious disadvantage (Providing a constant current source is more difficult than providing a constant voltage source). The time constants of the field-controlled DC motor are generally large compared with the time constants of a comparable armature-controlled DC motor. This is why the separately excited DC motor, controlled by armature control, was selected in this study [27]. Figure (2.4) shows the equivalent circuit of the separately excited DC motor which has the field winding connected to a separate source of DC power.

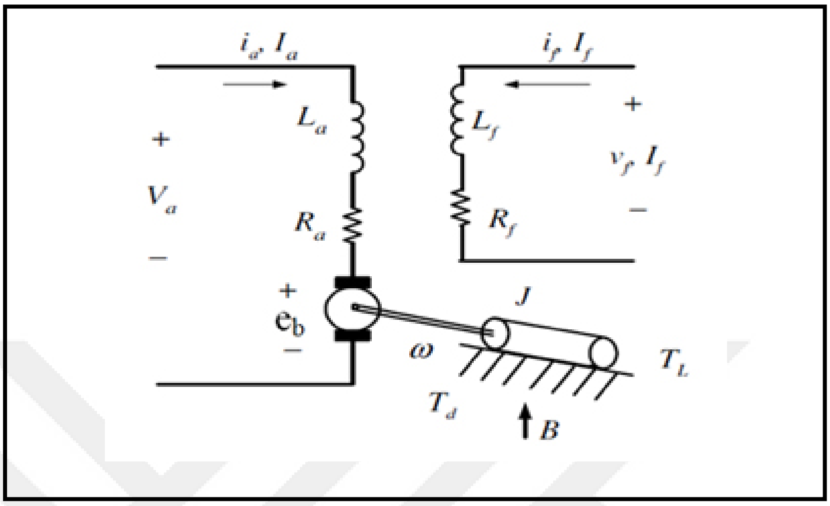

Figure 2.4: Equivalent circuit of the separately excited DC motor [1].

The equations describing the characteristics of the separately excited motor can be determined from Figure (2.4) as shown [2-1]:

$$V_f(t) = R_f\, i_f(t) + L_f \frac{di_f(t)}{dt} \qquad (2-1)$$

$$V_a(t) = R_a\, i_a(t) + L_a \frac{di_a(t)}{dt} + e_b \qquad (2-2)$$

$$e_b = K_e \omega_r \qquad (2-3)$$

$$K_E = L_{af} i_f(t) \qquad (2-4)$$

The DC motor equation which illustrates the relationship between the speed and the applied voltage on the armature can be written as follows:

$$V_a(t) = R_a i_a + L_a \frac{di_a}{dt} + K_E \omega_r \qquad (2-5)$$

The electromechanical torque equation can be expressed as follow:

$$T_e(t) = K_E i_a(t) \qquad (2-6)$$

While the dynamic equation is:

$$T_e(t) = J\frac{d\omega_r}{dt} + B\omega_r + T_L \qquad (2-7)$$

Where:

V_a: The input terminal voltage (source), (V);

e_b : The back emf, (V);

R_a : The armature resistance, (ohm);

i_a : The armature current, (Amp);

L_a : The armature inductance, (H);

L_{af}: The field- armature mutual inductance, (H);

J : Moment of inertia of motor shaft, (Kg-m^2);

T_e : Torque that produced by motor, (N-m);

ω_r : Rotor speed, (rad/s);

B : Viscous friction coefficient, (N-m/rad/sec);

T_L: The load torque, (N.m);

K_E: The motor constant, (V/A- rad/s).

2.1.4 Motor Transfer Function

Due to the use of Laplace Transforms, the modeling equations (2-5 to 2-7) can be expressed in terms of (*S*) as follows (T_L=0):

$$(Js + B)\omega_r(s) = K_E I_a(s) \qquad (2-8)$$

$$(L_a s + R_a)I_a(s) = V_a(s) - K_E\omega_r(s) \qquad (2-9)$$

By eliminating, I_a(s), it is possible to get the following open-loop transfer function, where the rotational speed is the output and the armature voltage is the input.

$$\frac{\omega_r(s)}{V_a(s)} = \frac{K_E}{(Js + B)(sL_a + R_a) + {K_E}^2} \qquad (2-10)$$

There is another method to represent the system response of the DC motor by using the state-space equation. The governing equations above can be expressed by choosing the rotational speed and the electric current as state variables. Again the armature voltage is treated as the input and the rotational speed is chosen as the output.

From (2-5) & (2-7) we have.

$$\frac{di_a}{dt} = \frac{1}{L_a}\vartheta - \frac{R_a}{L_a}i_a - \frac{k_e}{L_a}w \qquad (2-11)$$

$$\frac{dw}{dt} = -\frac{b}{J}w + \frac{k_m}{J}i_a \qquad (2-12)$$

By comparing these two equations to:

$\dot{x} = Ax + B\vartheta$ & $y = Cx$

$$\frac{d}{dt} = \begin{bmatrix} i_a \\ w \end{bmatrix} = \overset{A}{\begin{bmatrix} -\frac{R_a}{L_a} & -\frac{K_e}{L_a} \\ \frac{K_m}{j} & -\frac{b}{j} \end{bmatrix}} \begin{bmatrix} i_a \\ w \end{bmatrix} + \overset{B}{\begin{bmatrix} \frac{1}{L_a} \\ 0 \end{bmatrix}} \vartheta \qquad (2-13)$$

$$y = \overset{c}{\begin{bmatrix} 0 & 1 \end{bmatrix}} \begin{bmatrix} i_a \\ w \end{bmatrix} \; c = (B\;AB) = \begin{pmatrix} \frac{1}{L_a} & -\frac{R_a}{L_a^2} \\ 0 & \frac{K_m}{jL_a} \end{pmatrix} \qquad (2-14)$$

$\det C = \frac{K_m}{JL_a^2} \neq 0$, so we can know from this equation that the system is controllable.

To write the system response by this method, we have to put A, B and C matrix in this form:

$$H(s) = C(SI - A)^{-1}B \qquad (2-15)$$

$$\begin{bmatrix} 0 & 1 \end{bmatrix} \left\{ \begin{bmatrix} s & 0 \\ 0 & s \end{bmatrix} - \begin{bmatrix} -\frac{R_a}{L_a} & -\frac{k_e}{L_a} \\ \frac{k_m}{J} & -\frac{b}{J} \end{bmatrix} \right\}^{-1} \begin{bmatrix} \frac{1}{L_a} \\ 0 \end{bmatrix} \qquad (2-16)$$

$$H(s) = \frac{w}{\vartheta} = \frac{K}{(JS+b)(LS+R)+K^2} \qquad (2-17)$$

2.2 DC-DC Converters (Choppers)

The switching converters convert the electrical voltage from one level to another level by switching action. They are commonly used because of their efficiency and their smaller size compared to the linear regulators. DC/DC power converters have a very large application area. These DC/DC power converter are extensively used in regular switching power supplies, personal computers and Dc motor drive application. The large variety in circuits topology ranges started from single transistor buck, boost and buck boost power converters to the complex configurations included two or four devices. Moreover, employing resonant or soft-switching techniques to control the losses caused by switching.

There are some different methods to classify the DC/DC power converters. The isolation facility of the primary and the secondary portion is one of them. This isolation is usually made by using a transformer, which has the primary portion at the input side and the secondary at the output side. The control loop depends on another smaller transformer or theoretically by optocoupler as feedback circuit. Therefore, the output side is electrically isolated from the input side. This type consists of PC power supply and Fly-back DC/DC converter with an addition to the AC/DC bridge rectifier in the front. Because of the area to implement this large transformers and other off-chip components are very massive and costly. However, in portable devices like laptops, it is difficult to prefer the isolated DC/DC converter.

The non-isolated DC-DC converters are found in many forms, while the main forms are:

1. Step down DC/DC (Buck) converter.
2. Step up DC/DC (Boost) converter.
3. Step up-down DC/DC (Buck Boost) converter (opposite polarity).
4. Step up-down DC/DC (Cuk) converter.

The similar methods for controlling and analyzing have been applied for many of these converters. The simplest power converter circuit is the DC/DC buck converter. This type of circuits is used for many voltage regulator and power management applications. Hence, the design and the analysis of the control structure has been done by using the buck converter circuit to control the motor speed. All the equations, designs, figures and discussions in this thesis are attentive with DC/DC buck converter.

2.2.1 Step-Down (Buck) Converter

The name "Buck Converter" presumably is evolved from the fact that the input voltage is bucked/chopped or attenuated in amplitude and a lower amplitude voltage appears at the output. The basic topology of the DC/DC buck converter consists of a controlled switch S_w, an uncontrolled switch D (diode), a capacitor C, an inductor L and a load resistance R. Figure (2.5) shows the equivalent circuit for the DC/DC buck converter.

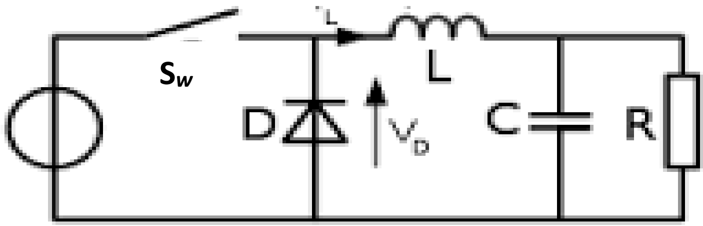

Figure 2.5: The equivalent circuit of the buck converter [29]

2.2.1.1 Advantages and Disadvantages of Step-Down (Buck) Converter

A buck converter or step-down voltage regulator provides non-isolated, switch-mode dc-dc conversion with the advantages of simplicity and low cost.

DC chopper has many advantages over the other means of speed control applications, these advantages are [24][29]:

a) Fast dynamic response;
b) High energy efficiency;
c) Flexibility in control;
d) Fewer ripples in the armature current;
e) Ability to control at low speeds;
f) Reduction in overall size and cost of the system;
g) Light weight and compact control.

2.2.1.2 The Control of Step-Down (Buck) Converter

One method of controlling the output voltage is employing switching at constant frequency, i.e., constant switching time period ($T = t_{on} + t_{off}$), and adjusting the on-duration of the switch to control the average output voltage. In this method, which is called duty cycle control or pulse-width modulation (PWM), DC motors are most commonly driven by PWM signals with respect to the motor input voltage [28].

For the circuit in Figure (2.6), the output voltage (V_o) equals the input voltage V_s when the switch is ON, and it is zero when the switch is OFF. By varying the duration for which the switch is ON and OFF, it can be seen that the average output voltage can be varied. In continuous-conduction mode of operation, assuming an ideal switch, the circuit operation can be divided into two modes. Mode one begins when the switch is ON for the time duration t_{on}, the diode D_m is off, and the diode-voltage V_d equals the source voltage Vs, the inductor current passes through the switch. This results in a positive voltage (V_s - V_o) across the inductor, which, in turn, causes a linear increase in the inductor current i_L. Mode two begins when the switch is turned off, the diode D_m is on, and the diode-voltage V_d is zero (assuming the diode is ideal), because of the inductive energy storage, the current i_L continues to flow. This inductor current continues to flow through the L, C load and diode D_m and it falls until the switch is switched ON again in the next cycle. The equivalent circuit for the operation mode is shown in Figure (2.7). The waveforms for the voltages and the currents of the main element are shown in Figure (2.8) [30,31].

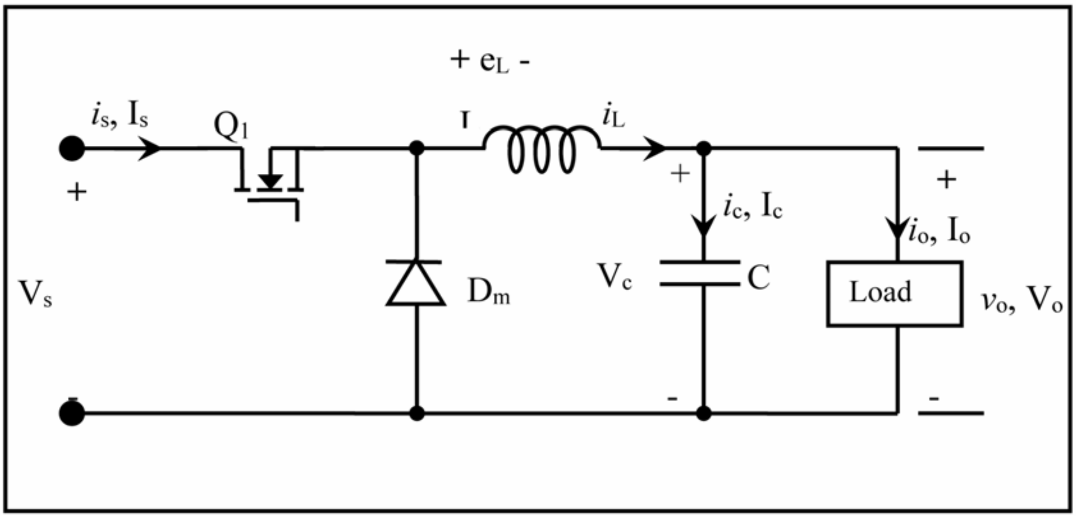

Figure 2.6: Circuit diagram for the buck converter [29]

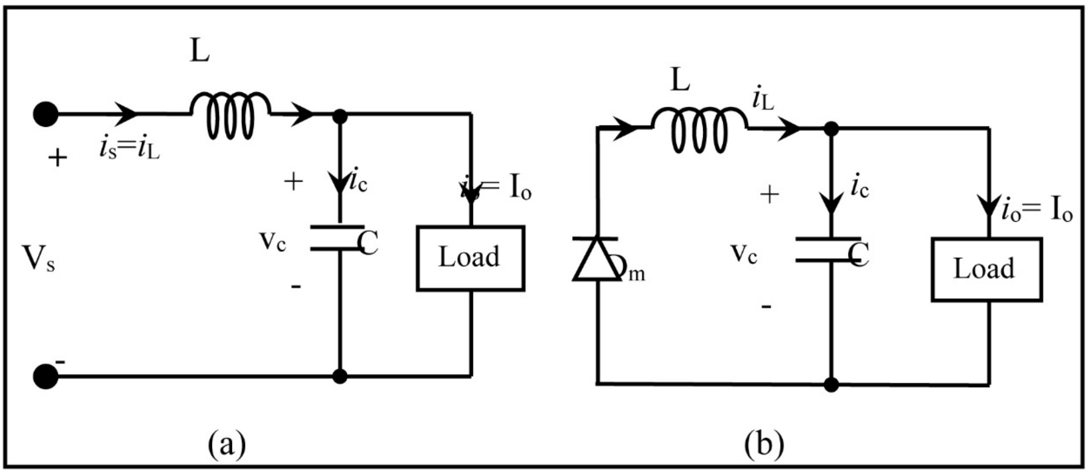

Figure 2.7: Equivalent circuits for the modes of the operation (a) Mode 1 switch is ON (b) Mode 2 switch is OFF [29]

By assuming that the power devices are ideal and neglecting the resistance of the inductor, the voltage across the inductor L, in general, is

$$e_L = L\frac{di}{dt} \qquad (2-18)$$

Assuming that the inductor current rises linearly from I_1 to I_2 in time t_1, refer to Figure (2.8).

$$V_s - V_o = L\frac{I_2 - I_1}{t_1} = L\,\frac{\Delta I}{t_1} \qquad (2-19)$$

or

$$t_1 = \frac{L\Delta I}{V_s - V_o} \qquad (2-20)$$

The inductor current falls linearly from I_2 to I_1 in time t_2, hence

$$-V_o = -L\,\frac{\Delta I}{t_2} \qquad (2-21)$$

or

$$t_2 = \frac{L\Delta I}{V_o} \qquad (2-22)$$

Where $\Delta I = I_2 - I_1$ is the peak- to- peak ripple current of the inductor L. From equating the value of ΔI in equations (2-19) and (2-21), we can obtain:

$$\Delta I = \frac{(V_s - V_o)t_1}{L} = \frac{V_o t_2}{L} \qquad (2-23)$$

Substituting $t_1 = KT$ and $t_2 = (1 - K)T$ yields of the average output voltage:

Where K is the duty ratio $0 \leq K \leq 1$

$$V_o = V_s\frac{t_1}{T} = KV_s \qquad (2-24)$$

Assuming a lossless circuit, $V_s I_s = V_o I_o$ and the average input current is:

$$I_s = KI_o \qquad (2-25)$$

The switching period T can be also expressed as:

$$T = \frac{1}{f} = t_1 + t_2 = \frac{L\Delta I}{V_s - V_o} + \frac{L\Delta I}{V_o} = \frac{LV_s\Delta I}{V_o(V_s - V_o)} \qquad (2-26)$$

This gives peak – to – peak ripple current as:

$$\Delta I = \frac{V_o(V_s - V_o)}{fLV_s} \qquad (2-27)$$

or

$$\Delta I = \frac{V_s K(1-K)}{fL} \qquad (2-28)$$

Using Kirchhoff's current law, the inductor current i_L can be written as

$$i_L = i_c + i_o \qquad (2-29)$$

If it is assumed that the load ripple current Δi_o is very small and negligible, then $\Delta i_L = \Delta i_c$. The average change of the capacitor current, which flows for $t_1/2 + t_2/2 = T/2$, is

$$I_c = \frac{\Delta I}{4} \qquad (2-30)$$

The capacitor voltage is expressed as:

$$v_c = \frac{1}{C}\int i_c \, dt + v_c(t=0) \qquad (2-31)$$

Also, the peak – to – peak ripple voltage of the capacitor is

$$\Delta V_c = v_c - v_c(t=0) = \frac{1}{C}\int_0^{T/2} \frac{\Delta I}{4} dt = \frac{T\Delta I}{8C} = \frac{\Delta I}{8fC} \qquad (2-32)$$

Substituting the value of ΔI from equation (2-27) or (2-28) in equation (2-32):

$$\Delta V_c = \frac{V_o(V_s - V_o)}{8LCf^2 V_s} \qquad (2-33)$$

or

$$\Delta V_c = \frac{V_s K(1-K)}{8LCf^2} \qquad (2-34)$$

In DC-DC converter applications, the aim is obtaining a constant output voltage in spite of the disturbances in the input voltage and the load current. Therefore, the idea behind using the negative feedback for control is to build a circuit that automatically adjusts the duty cycle as needed to obtain the desired output voltage with high accuracy, regardless of the disturbances in input and load [1,32, 33].

Finally, we concluded them from the previous equations the most important two equations that help us to design our converter:

1- The inductor current must work as CCM (continuous current mode)

So L must be > $\frac{(1-K)R}{2f}$,

We see if R is constant, the value of L will depend on K

2- The ripple value of output voltage;

$$\frac{\Delta v_O}{v_O} = \frac{1-K}{8LCf^2} \text{ so}$$

$$C_{min} \text{ for less ripple} = \frac{v_O}{\Delta v_O}\frac{1-K}{8Lf^2}$$

And we know $v_o = v_s * K$

From these equations for this thesis, the suitable value for this design is:

$$L = 5.5mH, C = 47\mu F, E(v_s) = 220V$$

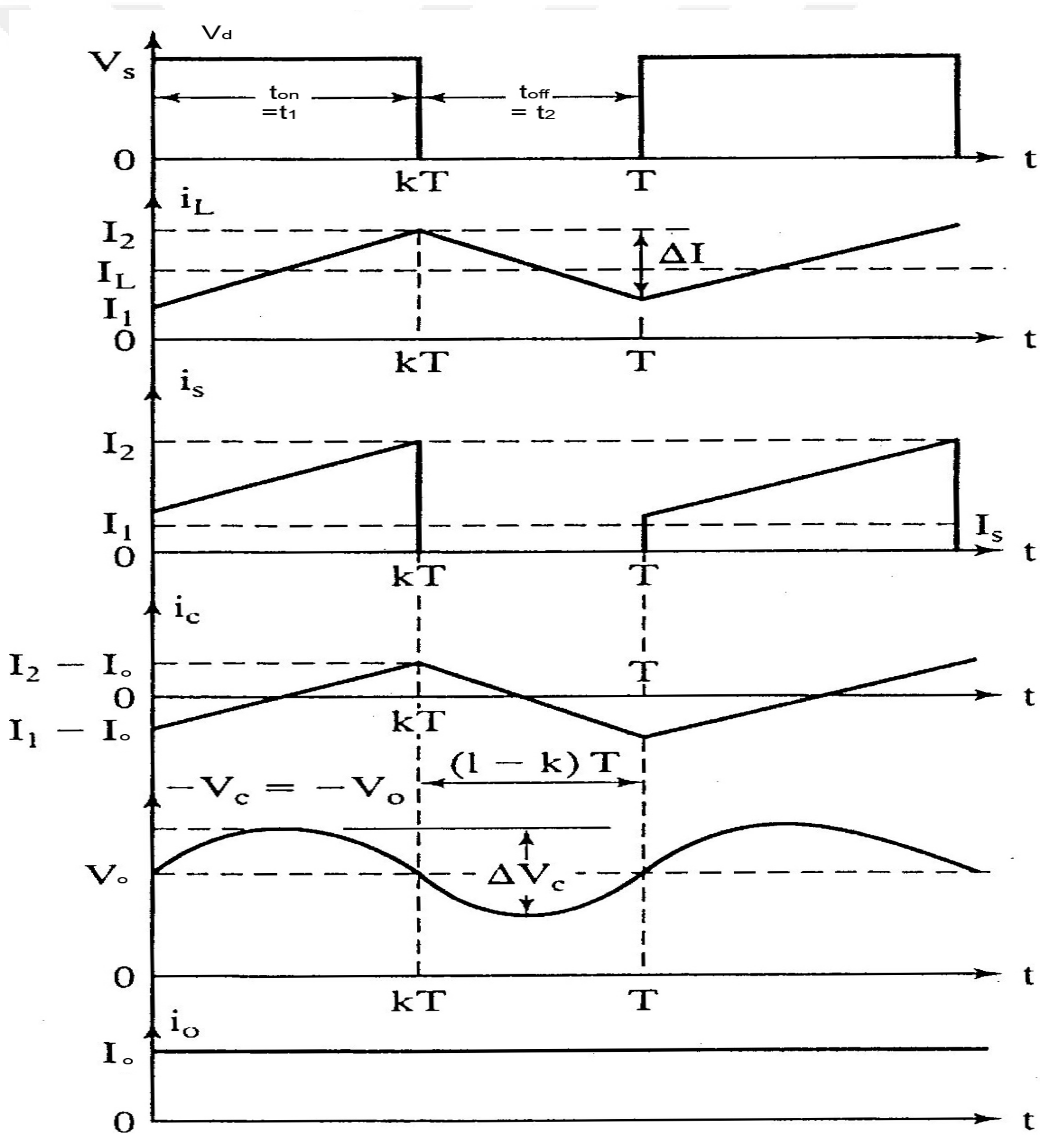

Figure 2.8: Waveforms for the voltages and currents for buck converter element [1]

CHAPTER THREE

THEORETICAL CONCEPTS OF TUNING PID CONTROLLER AND PWM GENERATION

This chapter is dedicated for explaining the theory of control system in detail, its types and the basic components of the control system. The principles of continuous controllers and the definition of Transient Response Specifications are also mentioned in detail. The Ziegler-Nichols Rules for Tuning PID Controllers are detailed within this chapter. Finally, it explains the pulse width modulation principles and how it feeds the electronic switch to control the speed of DC motor.

3.1 Control System

The Control system represents a very popular class of embedded systems. The control system seeks to make the output of the physical systems track the desired reference input which sets at the physical system inputs. The control systems content of the subsystem and the process assembled for controlling the process's output. In other words, control system is an interconnection of components forming a system configuration which will provide a desired system response [34].

Control system is an integral part of today's life. Many applications around us such as the self-guided vehicles which deliver materials to workstations in the aerospace, the fire rockets, the shuttles lift off to earth orbit, and control of the angular velocity of the DC motor is involved in many devices applications [24].

3.1.1 Types of Control Systems

There are basically two types of control systems:

1) Open loop control system– Open loop control system is the first type of control systems that uses only the current state to figure the output results. The

output results depend only on the present input values so the output values are controlled directly and only by the input signal without any feedback signal. The basic representation of this system is an amplifier and a transducer. The construction of this control type starts with a subsystem called the input transducer. This transducer converts the input signal to the form that can be easily used by the controller. The next stage is that the amplifier receives a low – level input signal from the input transducer and amplifies it to the value which is enough to drive the plant to perform the desired job. The block diagram of the open loop system is shown in figure (3.1). Open loop control system is not as commonly used as close loop control system because of the low accuracy of the former one.

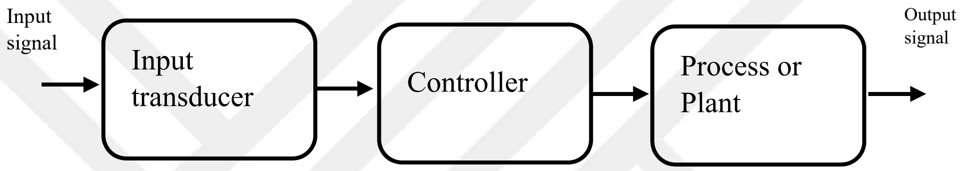

Figure 3.1: Block diagram of open loop control system

2) Close loop control system– The close loop control system is a second type of control system and it is sometimes called the feedback control. In this type of control, the output signal depends on the present value of the input signal and the previous value of the output signal. The term close loop control implies the use of a feedback control action in order to reduce the error within the system. The accuracy of the output in close loop control depends on the feedback path which can be made very accurate in electronic control systems and circuits. Actions are initiated by the difference between the two responses to make the actual response of the system approaches the desired response. Hence, the difference between them drives toward zero. Basically the close loop system uses two transducer. The first transducer converts the input signal to a form that can be used by the controller. The second one measures the output response of the plant and converts it into a form that can be used by the controller and provides the measurement results through a feedback path to the input where the output is compared with respect to the desired response, then this error signal is used to drive the plant via an actuating signal provided by the controller. The close loop system has the ability to regulate itself when variations or disturbance in its own characteristics are present. Close loop systems are commonly

more used than the open loop systems because of the previous reason [27]. The block diagram of the close loop system is shown in figure (3.2).

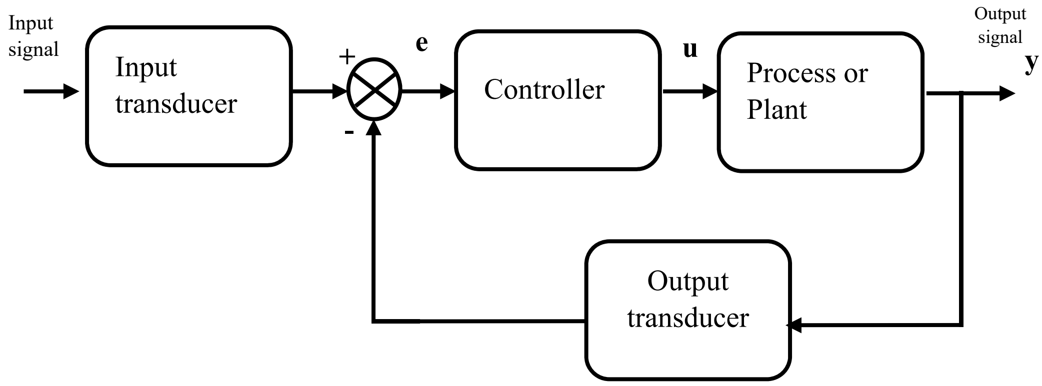

Figure 3.2: The block diagram of close loop system [27]

3.1.2 The Objectives of the Control System

1) Transient response – The transient response is important for any control system. For example in an elevator, a slow transient response makes the passengers impatient whereas an excessively rapid response makes them uncomfortable. The transient response of the plant must be appropriate. The control systems are designed to achieve the desired transient response by adjusting various design components or parameters.

2) Steady state response – The steady state response resembles the input signal and it usually represents what remains when the transients decay to zero. For example this response represents an elevator stopped near the fourth floor. We can concern the accuracy of the steady state response like the level (floor) that the elevator must be on it so the passengers can exit. The control system designer must take into account the steady state errors and the corrective action must be taken to reduce the steady state error.

3) Stability- The total response of the system represents the sum of the natural response and the force response. The natural response depends only on the system and not on the input, and it describes the way in which the system dissipates or acquires energy. On the other hand the force response depends on the input. For the best control system, the natural response must approach zero leaving only the force response. On some systems, the natural response grows much greater than the force response or oscillates out of the bonds. This situation is called instability. Instability

in control system may lead to physical device destruction if there is no stop limit in the design.

4) Finance- As the control systems are designed to meet the desired needs in prepare budge, the control system designer must take the economic impact of the design in his consideration.

5) Robustness- The design should be robust and the system must be insensitive to parameter changes [34].

3.1.3 Control Strategies

Feedback and feed forward are two types of control schemes that react automatically against the change in the dynamics environment.

1) Feedback control: This technique compensates for all disturbance of the system. If any disturbance affects the controlled variables and in the moment that variable corrupt from its set point, the controller will take the action which changes the output in such a way to bring the variable back to its desired value. The system does not know which disturbance enters the system but it just tries to return the variable to its set point. The major disadvantage of this type of control can compensate the noise in the system only after the controlled variable has deviated from its set point.

2) Feed-Forward Control: This controller works by first measuring of the disturbance and then compensating it before the controlled variable is corrupted from the set point. In this type of control, the corrupt of controlled variable is minimized as compeer to that in feedback control.

The disadvantage of this type of control represents unmeasured variable when making its decisions and corrupting from the set point. Theses blind spots can cause the break down for the control system. Feedback and feed forward controls may coexist in the same system to give the best control system [27].

3.1.4 The Basic Components of the Control System

1) Sensor-Transmitter: This sensor senses or measures the output of the process. Generally, the sensor is physically connected to the transmitter which takes

the sensors output as an input and converts the signal to a form that can be transmitted to the controller.

2) Controller: It is like the brain for the control system. The controller receives the signal from the transmitter and compares it with the desired value. Depending on the results of the comparison, the controller takes the decision to maintain the output at the desired value.

3) Final Control Element: It receives the signals from the controller. It is also called the actuator. It translates the control signal into an action on the control element. Thus, the actuator is a device that converts the control signal into a physical action.

All these components together perform three basic operations in the control system:

1) Measurement: the measurements are basically done by sensor-transmitter combinations.

2) Decision: the controller is responsible for taking the decision, and it depends on the basic measurements to maintain the variable to be controlled at the desired value.

3) Action: The system takes an action on the basis of decision taken by the controller and this is done by the final controlling element [39].

3.1.5 Parts of The Control System

The control system consists of many parts such as:

1. Plant: It is also known as the process and the physical system to be controlled. In this thesis, the DC motor is the plant.

2. The controlled variables or the outputs: They are the output signals of the plant that we need to control. In our thesis, the speed and the armature current of the Dc motor represent the controlled variables which are to be control

3. Manipulated variable: The manipulated variables are used to maintain the controlled variables at the desired set point. In our thesis, the output of the controllers (speed control and armature current control) are the manipulated variables.

4. Reference: It is the desired value which we want to see at the output. In this thesis, the reference or the set point is the desired speed of the DC motor.

5. Actuator: It is the device that we use to control the input of the plant. In this thesis, the PWM generator is the actuator.

6. Controller: It is the system that we use to control the plant's outputs for the desired operation. In this thesis, two PID controllers are used for controlling the speed and the armature current of the DC motor by providing the signal to the PWM generator which changes the pulse width of the PWM output. This operation makes the actual speed overlapping with the desired speed all the time.

7. Lag time: It is the required time for returning to the set point after the change in plant variables is measured by the control system.

8. Dead time: It is the elapsed time between the errors and the corrected action.

9. Transient: It is the temporary variation in the load parameters after which this parameters returns to its desired value.

10. Offset: It is the difference between the set point (desired value) and the measured variable after a new controlled variable level is reached.

11. Disturbance: It is the undesirable additional input to the plant which tries to corrupt the controlled variables from its set point. This signal will be compensated by the controller [27].

3.1.6 Continuous Controllers

1) Proportional Controller: or P controller is the most common controller among the continuous controllers. In proportional controller, the outputs amplitude of the process is measured by a suitable sensor, and it converts it to an electrical signal by a transducer. This signal is compared with the set point, and the difference between these two signals is the error. This error value is amplified by multiplying it with the constant gain, which is called the proportional gain. This final signal will be fed to the plant or to another controlling element. In the proportional controller, the manipulated variable value is proportional to the error signal [34].

$$Y = Kp * e$$

Where Y = controller output

Kp = proportional gain

e = error

2) PI controller: As most processes cannot work with offset, they should be controlled at their set points and to achieve this extra intelligence, a proportional control is added by providing an integral action to the original proportional controller. Now, the controller becomes proportional-integral controller.

$$Y = Kp.e + Ki \int e.dt$$

Ki= Integral gain of the PI controller

3) PD controller: the aim of using the PD controller is to increase the stability of our system since it has the ability to predict the future error of the system response which can help in avoiding the effects of the sudden change in the error signal value.

$$Y = Kp.e + K_D \frac{d_e}{d_t}$$

K_D= Derivative gain of the PI controller

4) PID: The aim of using PID controller is to achieve zero steady state error, no oscillation, higher stability and fast response (short rise time). The main reason for using derivative gain in addition to PI controller is to eliminate the oscillation and the overshoot occurring in the output response of the system [37].

$$Y = Kp.e + Ki \int e.dt + K_D \frac{d_e}{d_t}$$

3.1.7 Determining the Transient Response Specifications

In many practical cases, the desired performance that is characteristic of the control systems is specified in terms of time-domain quantities. System with energy storage cannot respond instantaneously and it will exhibit transient responses whenever they are subjected to inputs or disturbances. The transient response of the practical control system often exhibits damped oscillation before reaching to the steady state. Figure (3.3) shows the transient and the steady state response analysis.

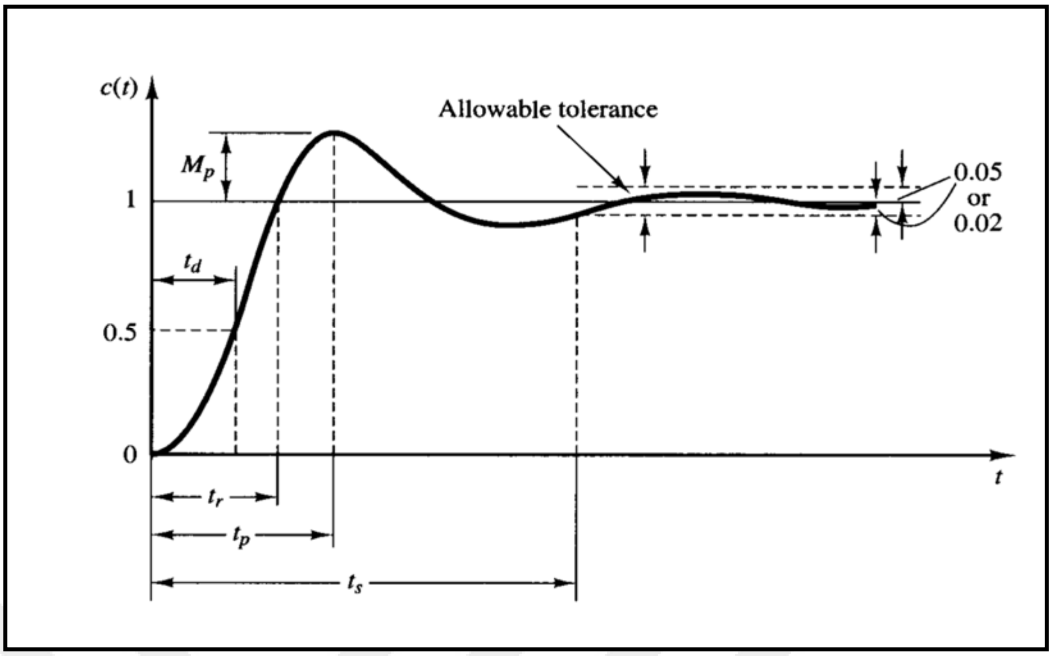

Figure 3.3: Unit step response of a control system [17]

Some parameters, which describe the performance of this circuit, must be calculated from the step response of a control system, these parameters are [34]:

1. Damping ratio (ζ)(zeta): It is the ratio of the damping coefficient in the system's differential equation to the critical damping coefficient.

$$\zeta = \frac{actual\ damping}{critical\ damping}$$

2. Natural frequency (ω_n) in radian/second: It is defined as the frequency at which a system tends to oscillate in the absence of any driving or damping forces.
3. Percent overshoot (P.O): It is the percentage by which the peak of the response exceeds the final value.
4. Time to peak overshoot (t_p): It is the required time by the response to reach its first peak.
5. Settling time (t_s): It is the required time by the system to settle down within (usually 5% 0r 2%) range of the final value.
6. Steady state error (e_{ss}) is the difference between the input and the output of the system in the limit as time goes to infinity.

Where the percentage overshoot (P.O) and time to peak (t_p) overshoot are calculated according to the following equations:

$$\text{P.O.} = 100e^{-\zeta\pi/\sqrt{1-\zeta^2}} \qquad (3-1)$$

$$(t_P) = \frac{\pi}{\omega_n * \sqrt{1-\zeta^2}} \qquad (3-2)$$

The settling time (t_s) can be calculated from equation (2-3) and (2-4) for 2% and 5% criteria, respectively as shown below:

$$t_s = \frac{3.9}{\zeta * \omega_n} \qquad (3-3)$$

$$t_s = \frac{3}{\xi * \omega_n} \qquad (3-4)$$

3.1.8 Tuning Rules for the PID Controllers

As mentioned earlier, industrial controllers may be classified according to their control action as [34,35]:

1. Proportional controllers (P).
2. Proportional-plus-integral controllers (PI).
3. Proportional-plus-derivative controllers (PD).
4. Proportional-plus-integral-plus-derivative controllers (PID).

The proportional term (P) corresponds to the proportional control. The integral term (I) gives a control action that is proportional to the time integral of the error. This ensures that the steady state error becomes zero. The derivative term (D) is proportional to the time derivative of the control error. There are many variations of the basic PID algorithm that will substantially improve its performance and operability [36].

If a mathematical model of the plant can be derived, then it is possible to apply various design techniques for determining parameters of the controller that will meet the transient and the steady-state specifications of the closed-loop system. However, if the plant is so complicated that its mathematical model cannot be easily obtained, then analytical approach to the design of a PID controller is not possible. Then, it must resort to the experimental approaches for the tuning of PID controllers.

The process of selecting the controller parameters to meet a given performance specifications are known as controller tuning. Ziegler and Nichols suggested rules for tuning PID controllers (meaning to set values for K_P, K_I and K_D) based on the experimental step responses or based on the value of the K_P, that results in marginal stability when only the proportional control action is used [36]. Ziegler-Nichols rules, which are presented later, are very convenient when mathematical models of the plants are not known. These rules can, of course, be applied to the design of systems with known mathematical models.

3.1.9 Ziegler-Nichols Rules for Tuning PID Controllers

Ziegler and Nichols proposed rules for determining values of the K_p, K_I and K_D based on the transient response characteristics of a given plant. The determination of the PID controllers' parameters or tuning of the PID controllers can be made by engineers on site through experiments on the plant. Numerous tuning rules for PID controllers have been proposed since the Ziegler-Nichols proposal was introduced.

There are two methods called Ziegler-Nichols tuning rules:

1. The Method of the step response.
2. The Method of Frequency Response.

The second method is used in this work because the S shape that must be obtained cannot be obtained by the first method because the proposed control system is involving an integrator in the transfer function. The following steps have been done in the PID design procedure:

1. The controller is switched to the pure proportional (P) action.
2. The gain of the P controller is continuously increased until the closed loop shows permanent oscillations. The value of the gain at this state is denoted as the critical controller gain Kcr.
3. The length of the period Pcr (critical period) of the oscillations is measured as shown in Figure (3.4).

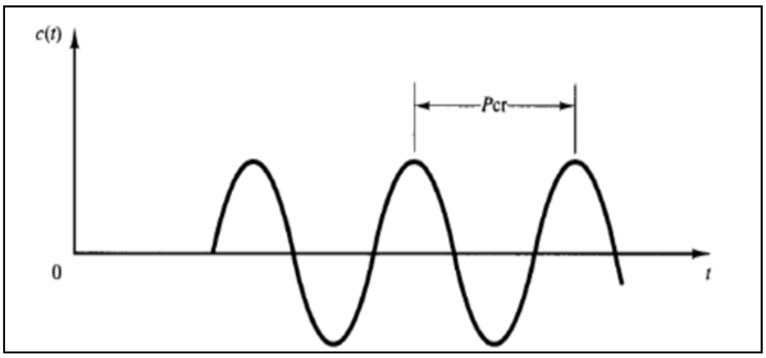

Figure 3.4: Sustained oscillation with period P_{cr} [17].

From K_{cr} and P_{cr}, one determines the controller tuning values K_p, K_I and K_D using the formulas given in Table (3.1) according to the type of the conventional control. Notice that the PID controller is tuned by Ziegler-Nichols rules and can be given by the following equation [28].

$$G_C(S) = K_P\left\{1 + \frac{1}{T_I s} + T_D\, s\right\} \qquad (3-5)$$

Table 3.1: Ziegler-Nichols tuning rules (second method)

The type of controller	K_p	T_I	T_D
P	$0.5K_{cr}$	0	0
PI	$0.45\ K_{cr}$	$P_{cr}/1.2$	0
PID	$0.6\ K_{cr}$	$0.5P_{cr}$	$0.125P_{cr}$

Where $T_I = K_P/K_I$ and $T_D = K_D/K_P$

3.2 Pulse Width Modulation (PWM) Principles

Pulse Width Modulation is the standard established method for driving the DC motors and the principle involves powering the motor with a series of pulses. In the PWM switching occurs at constant switching frequency. The switching control signal, which controls the state (on or off) of the switch, is generated by comparing a signal-level control voltage $v_{control}$ with a repetitive waveform as shown in Figure (3.5). The control voltage signal is obtained from the difference between the actual output voltage and the desired value. The frequency of the repetitive waveform with a constant peak, which is shown to be triangle, establishes the switching frequency. The frequency is kept constant in a PWM control. When the control signal is greater than the triangle waveform, the switch control signal becomes high, causing the switching to turn on. Otherwise the switch is off. In terms of $v_{control}$ under the peak of the triangle waveform $v_{triangle}$, the switch duty ratio can be expressed as:

$$K = \frac{t_{on}}{T_s} = \frac{v_{control}}{\hat{v}_{triangle}} \qquad (3-6)$$

The result is an electrical signal that is either ON (+V) or OFF (0V). With the amount of time, the signal remains varied in order to control the speed of the motor.

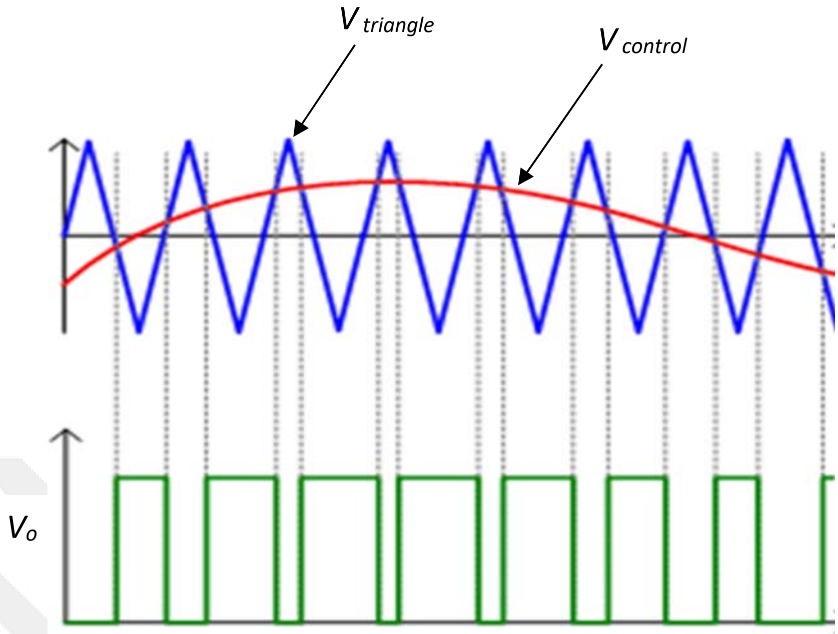

Figure 3.5: Pulse width modulation waveform [40]

The technique of varying the period of a PWM signal has the effect of generating an effective voltage across the motor coils anywhere between zero and the supply voltage. This technique is useful for a number of reasons, primarily because of the way the power components respond to the different signals. In a typical modern motor drive, the PWM signal will be generated by a control device. This PWM signal is fed to the switch. The generated PWM signal passes through amplification and isolation stages, and then it is fed to the Buck converter switch in order to deliver the desired power to the motor [38].

In a modern buck converter, power transistors are used to switch the signals for the motor. Typically the power transistors are MOSFET transistors because they are capable of switching large currents without dissipating too much of energy and as such can be made.

CHAPTER FOUR

COMPUTER SIMULATION AND EVALUATION OF DC MOTOR CONTROL

This chapter presents three major parts: first is the design of the Buck converter circuit and how to be implemented on the computer using MATLAB programme. The second part is the design of the open loop simulation model of the DC motor control system, while the third part describes the design of multiple feedback loop control system and simulating it using Simulink library and P.S.B library in MATLAB.

After that the design has been tested with four disturbances situations (external torque, input voltage, the capacitor and the inductor), it is applied to open loop control system and close loop control system with constant desired speed. Also, these disturbances have been applied to close loop control system with varying the desired speed. Each of the above situations have been studied separately to approve that the control system used in this thesis could achieve the wanted goal which is keeping the actual speed tracks the desired speed although applying the internal or external disturbance on the DC motor control circuit.

4.1 Buck Converter Circuit Design

The design of the Buck converter circuit requires knowing the optimum values of the inductor (L) and the capacitor (C) that represent the fundamental components of the circuit.

The inductor and the capacitor values used for designing the Buck converter circuit depend on some defined values such as: the value of the required output power, the switching frequency, the percentage of duty cycle, input and output currents, and the magnitude of each capacitor voltage and the inductor current.

Where the values of the input voltage, percentage of duty cycle and switching frequency are fixed as shown below:

a) Direct power supply Input voltage V_{in} equals to 220 V.

b) Percentage of duty cycle (K) equals to 50%.

c) Switching frequency (f_s) equals to 5 KHz.

d) Load current (armature current of motor) (I_a) equals to 12A.

Then, the peak to peak ripples of the capacitor voltage (ΔV_c) and the inductor currents (ΔI_L) are chosen to be:

(ΔV_c) = 0.9 % of V_C

(ΔI_L) = 33 % of i_L

The following assumptions are made while designing the circuit parameters:

a) Neglecting the state of saturation in the heart of inductance.

b) Neglecting the internal resistance for the capacitor.

c) Assuming that the transistor and diode are ideal.

d) All the values of circuit elements are fixed and not changed by any temperature change or any other factor.

4.1.1 Buck Converter Inductor and Capacitor Calculations

For a duty cycle (K) equals to 50% and input voltage equals to (220V), the average output voltage and input current can be calculated according to equations (2-7) and (2-18) as follows:

V_{out} = 220*0.5 =110V

I_s= 0.5*12 = 6A

The time for one cycle is,

$$T_s = \frac{1}{f_s} = 200\mu s$$

According to the equations (2-34), $t_{on} = 0.5 * 200 = 100\mu s$ then:

(ΔV_c) = 0.9 % of V_c ⟶ $\Delta V_C = 0.99V$

(ΔI_L) = 33 % of i_L ⟶ $\Delta I_L = 1.98A \cong 2A$

The values of the inductor (L) and the capacitor (C) can be calculated according to the equations (2-20) and (2-26) as follows:

$$L = \frac{110(220 - 110)}{5000 * 2 * 220} = 5.5mH$$

$$C = \frac{110(220 - 110)}{8 * 5.5 * 10^{-3} * 0.99 * 5000^2 * 220} = 50\mu F$$

Due to limitation in practical components, the value of the capacitor is approximated to $47\mu F$; this value is used in simulation and experimental work.

4.2 Simulation Using MATLAB Programme

The basic purpose of the representation on the computer is to build a computer model that simulates the practical system as much as possible, and in this way, the study and the analysis for each element of the department separately can be done. Besides, the possibility of designing the system and learning the values of the necessary elements before the construction of the practice on the ground to give the best response are required, in addition to the study of severe cases of fault that are difficult to be studied in practice. Therefore, the best representation on the computer depends primarily on the correct parameters of some circuit elements that are taken by measuring the practical elements of the circuit. The second depends on the range of the assumptions which were the basis for building the representation programme.

4.2.1 Simulation of Open Loop Control System

In this section, MATLAB simulation software is presented for the open loop speed control system of the DC motor with uniform PWM technique based on the selected switching frequency value.

The MATLAB simulation model of the open loop speed control system for the DC motor is given in Figure (4.1). The model consists of four major parts: DC input voltage, Buck converter circuit, DC motor and PWM logic generator. All the parameters of the DC motor are included, armature resistance and inductance (R_a and L_a), Field resistance and inductance (R_f and L_f), Field – armature mutual inductance (L_{af}), moment of inertia (J), and viscous friction coefficient (B). These parameters are found by made several tests on the DC motor which is explained in details in Appendix (A1). Figure (4.2) shows the simulation subsystem for uniform PWM logic generator.

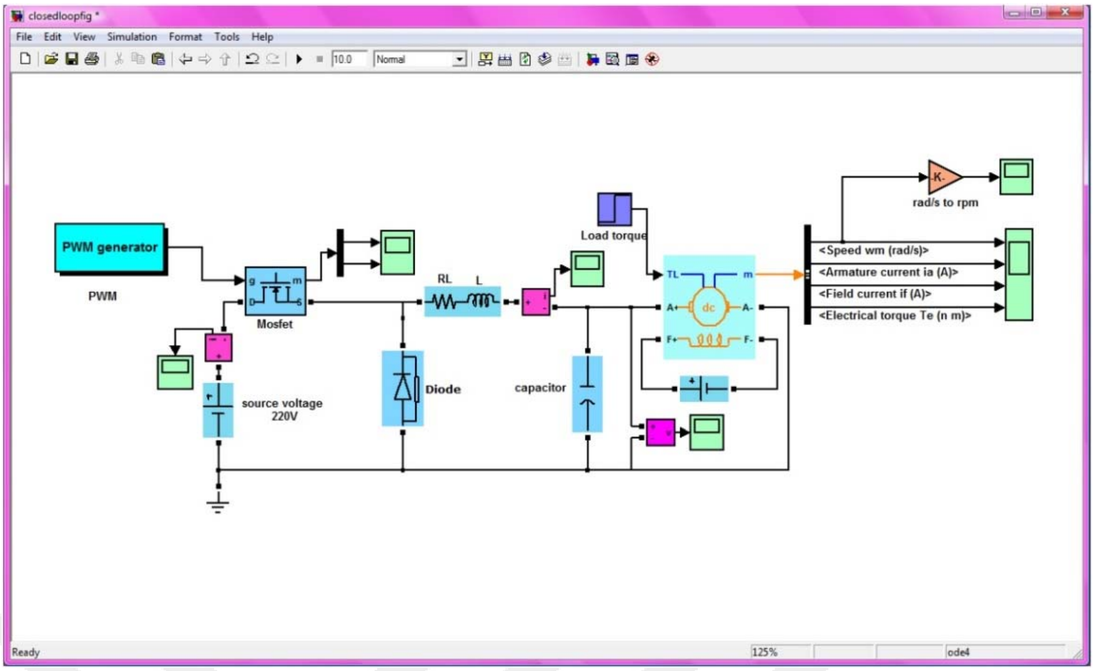

Figure 4.1: Simulation model of the open loop speed control system

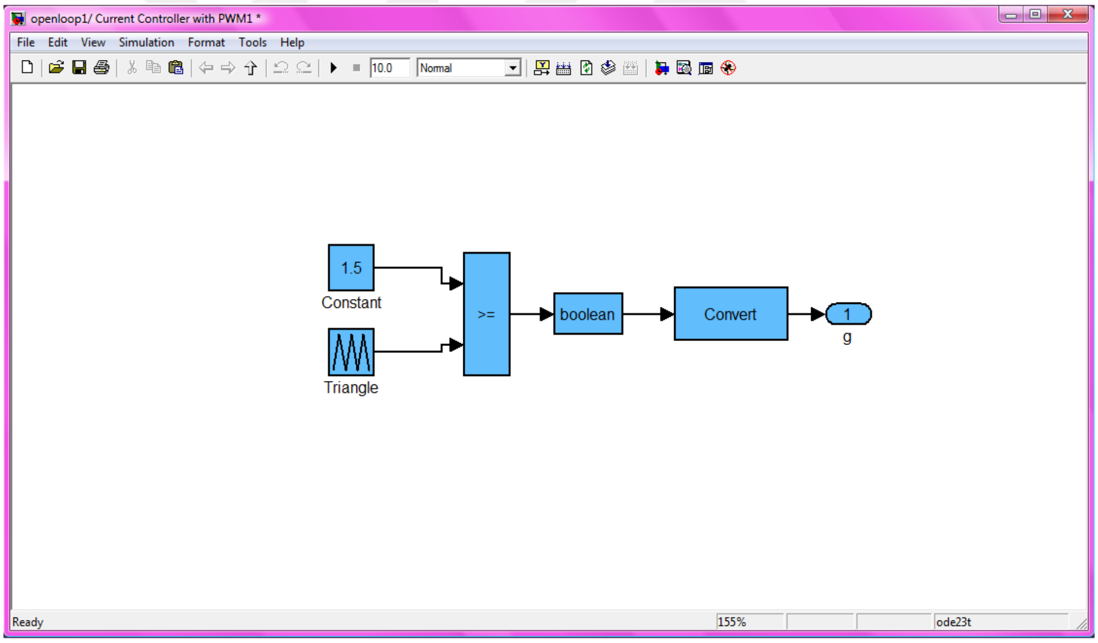

Figure 4.2: Simulation subsystem model for the uniform PWM logic generator

4.2.2 Simulation Results of the Open Loop Speed Control System

Figure (4.3a) shows the control signal compared with triangular wave, and the resulting PWM logic control signals at duty ratio K = 0.5, and frequency =5 KHz. The control and the gating signals are zoomed as shown in Figure (4.3b) in order to show the waveform in detail. Figure (4.3c) shows the output of PWM pulses signal.

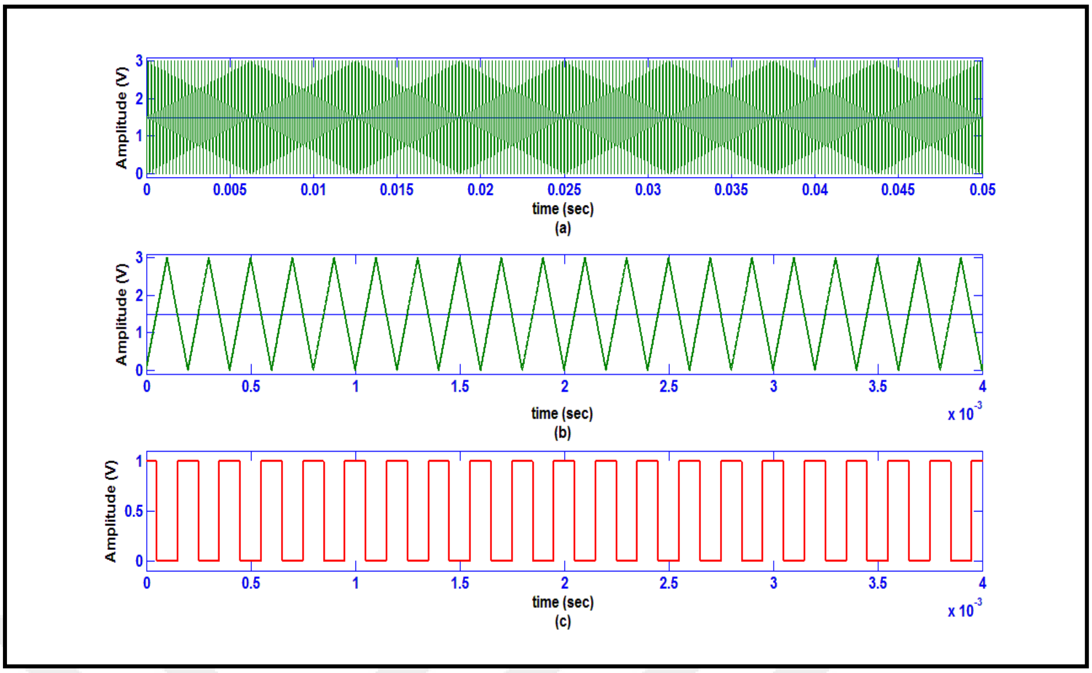

Figure 4.3: PWM waveform **(a)** carrier and control signals **(b)** zooming carrier and control signals **(c)** triggering signal

A unit step speed response of the DC motor is taken with the DC input voltage of 220V and duty ratio 0.9 as shown in Figure (4.4).

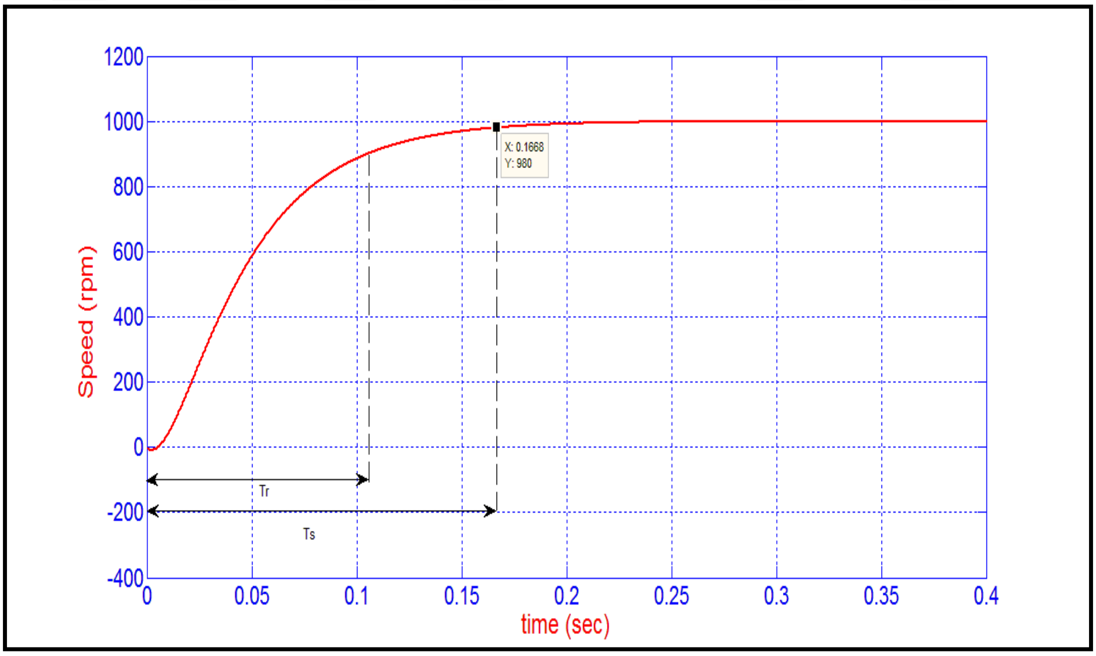

Figure 4.4: Step speed response for open loop speed control system

Four tests are performed on the open loop control strategy to examine the system. These tests show the effect of changing the external torque, DC power supply, the capacitor and the inductor of the buck converter on the speed of the DC motor. The above variable parameters represent the most disturbance that has an effect on the DC motor work. This thesis studied the effect of changing each of these parameters on the speed of the DC motor separately.

4.2.2.1 Simulation results of the open loop speed control system with disturbance in external torque

Two tests are performed on the open loop control strategy to examine the system. Figure (4.5) shows the speed response when a sudden load torque is applied to the motor at duty ratio K =0.5, at time (t= 0.4 sec), and a step load torque is changed from 2 N.m to 8 N.m. At the instant of the change, it is noted that the speed is reduced gradually from 590 rpm to 305 rpm and remains on this new value.

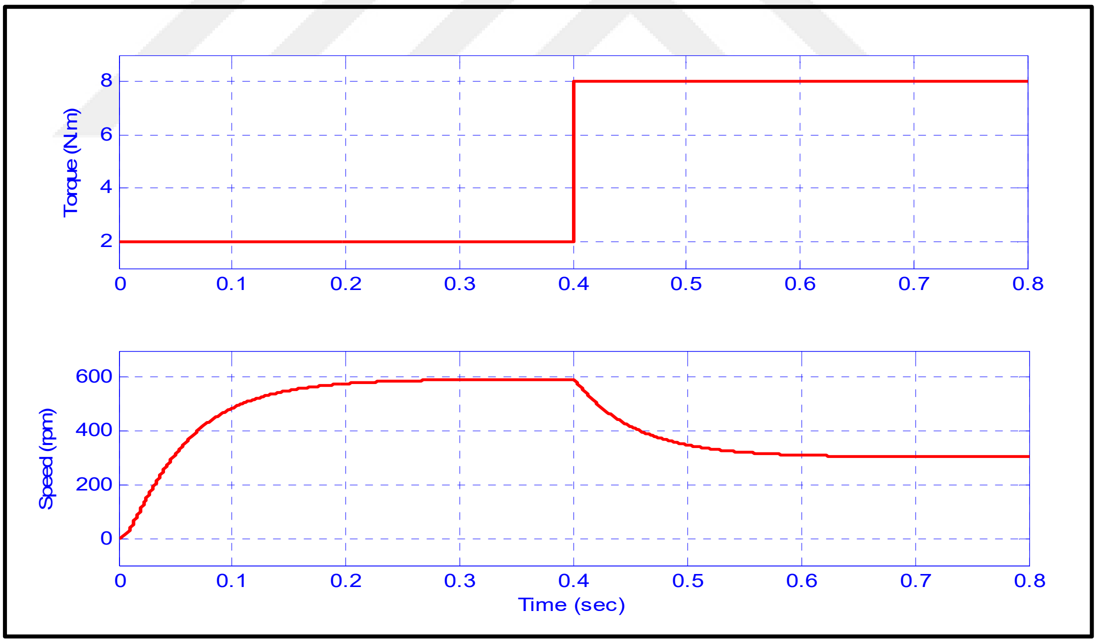

Figure 4.5: MATLAB simulation result of the speed with the sudden increase of load

The second test is reducing the load torque from 10 N.m to 3 N.m. It is noted that the motor speed is increased at the same time from 327 rpm to 600 rpm as shown in figure (4.6).

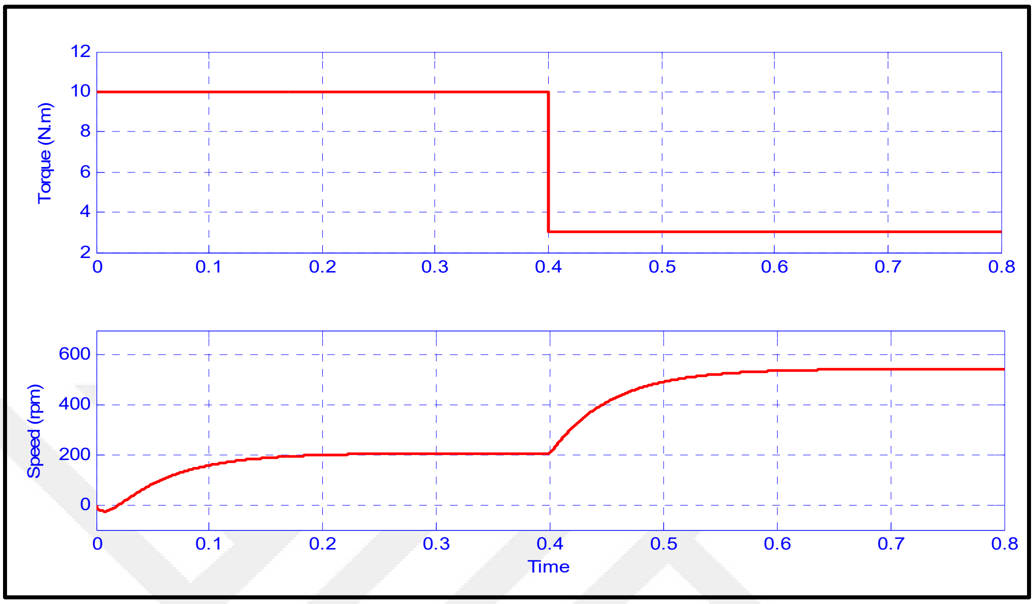

Figure 4.6: MATLAB simulation results of the speed with the sudden decrease of load

Figure (4.7) shows the simulation results of armature current (I_a), field current (I_f) and the electrical torque (T_e). From the simulation results of Figure (4.7), it is noticed that the armature current has an overshoot more its rated value, 12 Ampere. Note that, the field current stays constant since the motor is separately excited.

Figure (4.8) shows the switching voltage (V_s), the diode voltage (V_d) and the armature voltage (V_a) of the DC motor which also represents the capacitor voltage of the buck converter. From Figure (4.8), it is noticed that the peak to peak ripple capacitor voltage ΔV_c is less than 1% of the capacitor voltage value as designed in section 4.1.

The inductor current (i_L), switching current (i_s) and capacitor current (i_c) are shown in Figure (4.9), and the peak to peak ripple inductor current (ΔI_L) is the same as design in section 4.1.

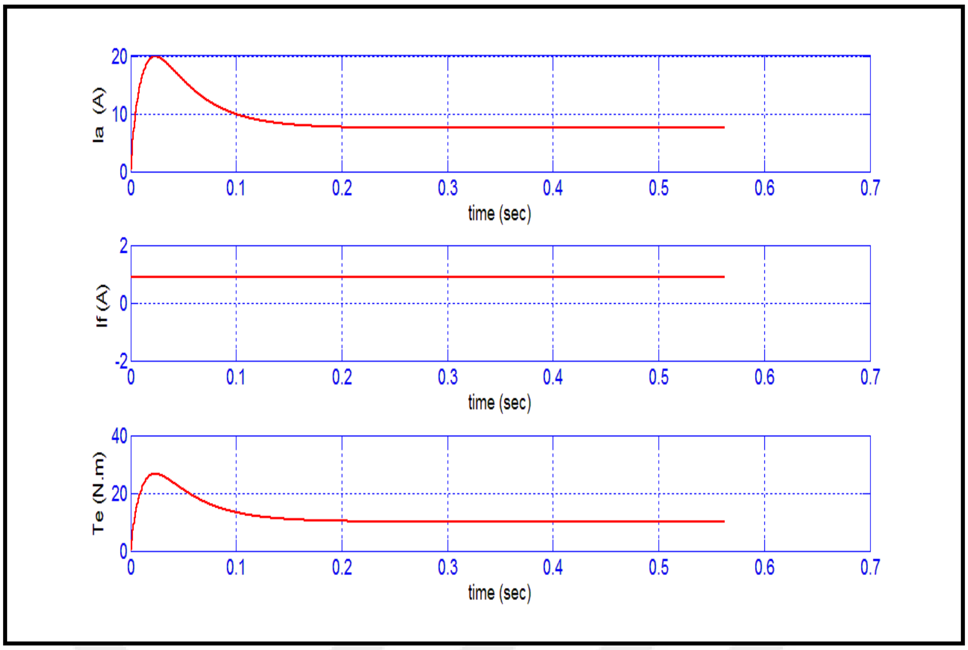

Figure 4.7: Simulated armature current (I_a), field current (I_f) and electrical torque (T_e) for open loop control system

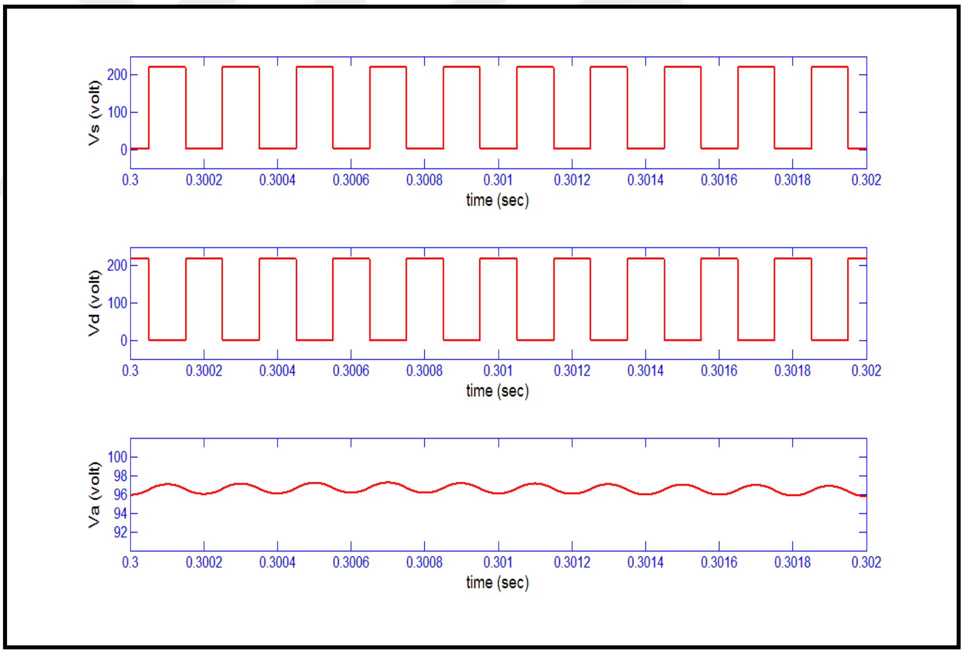

Figure 4.8: Simulated switching voltage (Vs), diode voltage (Vd) and armature voltage

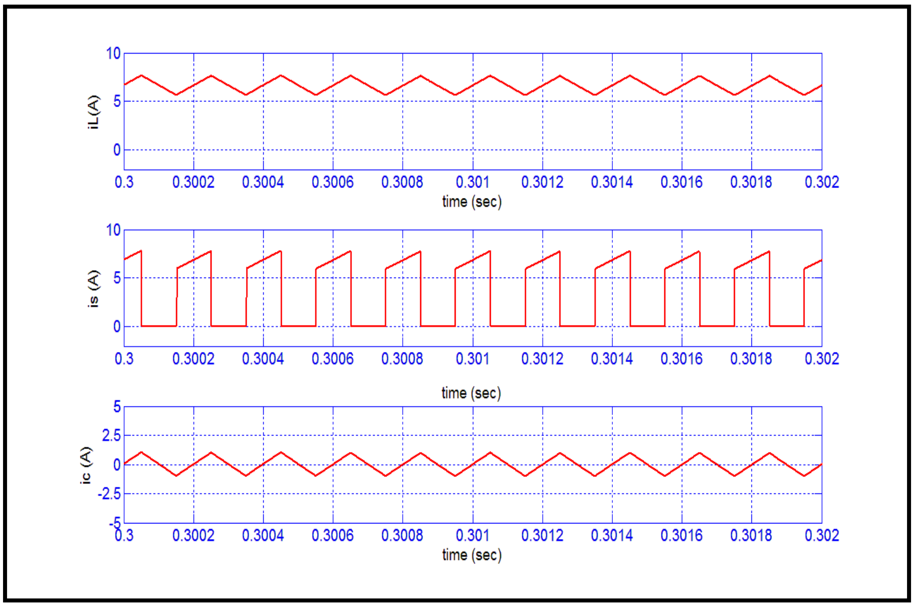

Figure 4.9: Simulated inductor current (i_L), switching current (i_s) and capacitor current (i_c)

4.2.2.2 Simulation of the Results of the Open Loop Speed Control System with disturbance in DC power supply

Two tests are performed on the open loop control strategy to examine the system speed response when a sudden changing happens in the applied DC power supply. Figure (4.10) shows the speed response against the change in the power supply that feeds the DC motor at duty ratio K =0.5, time (t= 0.4 sec) the dc power supply was changed from 220 v to 190 v. At the instant of change, it is noted that the speed is reduced gradually from 500 rpm to 400 rpm and remains on this new value.

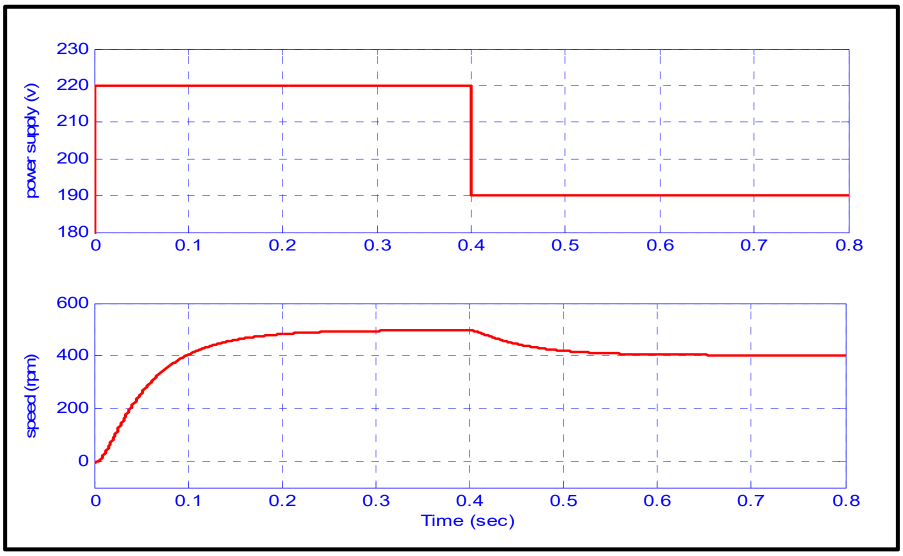

Figure 4.10: MATLAB simulation results of the speed with the sudden decrease of the DC power supply

The second test is increasing the input DC power supply from 220 V to 250 V. It is noted that the motor speed is increased at the same time from 500 rpm to 592 rpm and remains on this new value as shown in Figure (4.11).

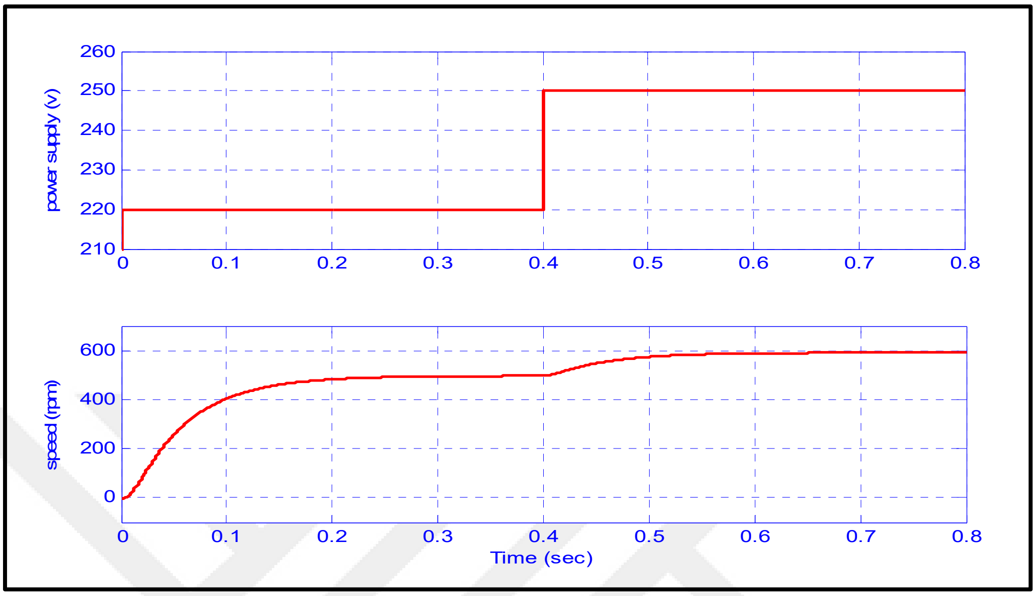

Figure 4.11: MATLAB simulation results of the speed with the sudden decrease of the DC power supply

4.2.2.3 Simulation results of the open loop speed control system with the disturbance in buck converter's capacitor

The test is performed on the open loop control strategy to examine the system speed response when a sudden rise happens in the value of the buck converter's capacitor. Figure (4.12) shows the speed response against the change in the value of buck converter's capacitor at duty ratio K =0.5, time (t= 1 sec), the value of buck converter's capacitor is changed from 47µF to 147µF. At the instant of change, it is noted that the speed is reduced suddenly from 597 rpm to 594 rpm and return to its normal value gradually after 0.2 sec.

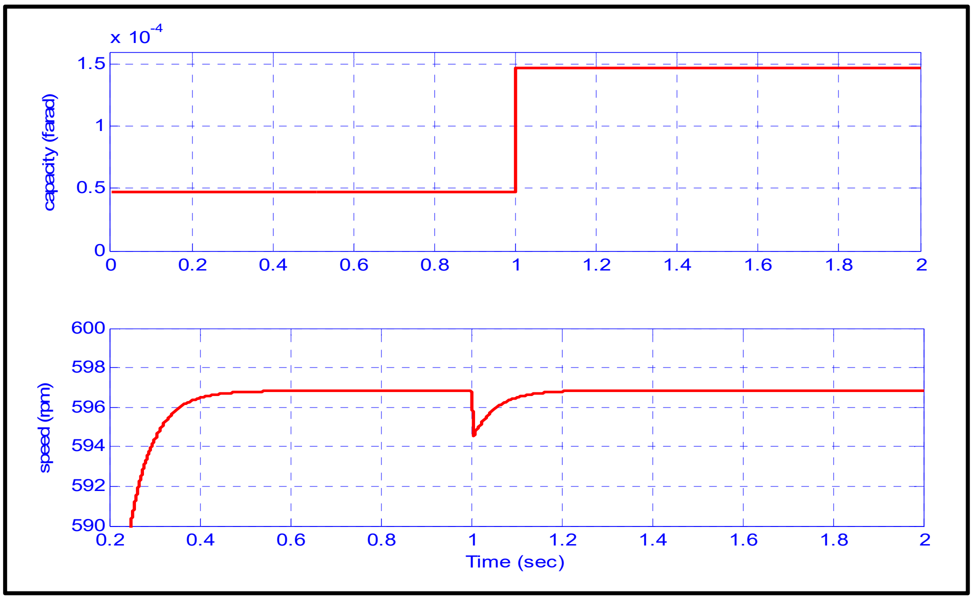

Figure 4.12: MATLAB simulation speed result with the sudden increase in the capacitor

1.2.2.4 Simulation results of the open loop speed control system with the disturbance in buck the converter's inductor

Figure (4.13) shows the speed response against the change in the value of buck converter's capacitor at duty ratio K = 0.5, time (t= 1 sec), the value of buck converter's inductors is changed from 5.5mH to 15.5mH. At the instant of change, it is noted that the speed is increasing suddenly from 593 rpm to 602 rpm and remains on new value.

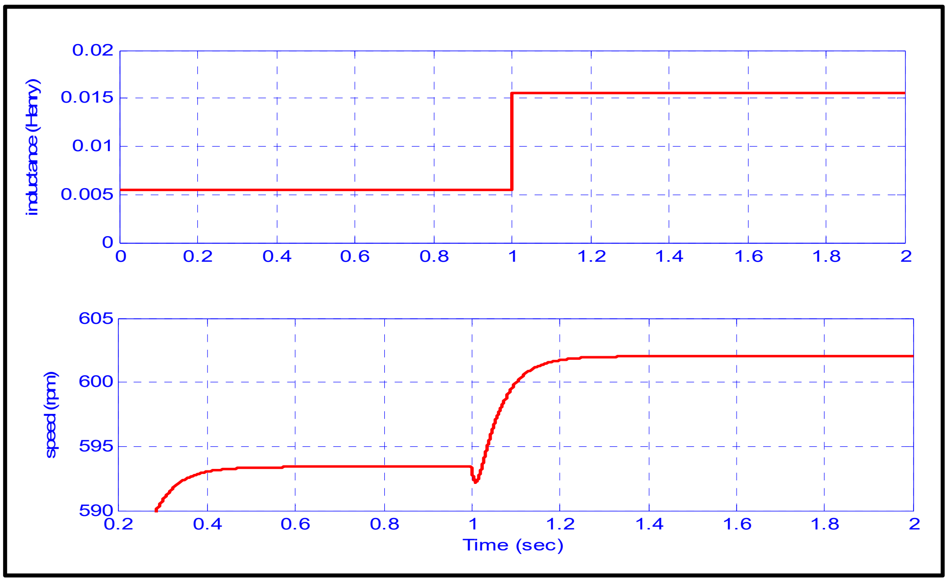

Figure 4.13: MATLAB simulation results of the speed with the increase in the inductor

From the open loop step response shown in Figure (4.4), it is noted that the system transient period is somewhat large, as well as the desired speed is obtained by changing the duty ratio, and this needs to make a look up table to know the value of the speed at each duty ratio. From Figures (4.5) and (4.6), it is observed that the speed is decreased from its desired value when the sudden load torque is applied and increased when the load torque is decreased and remains at this new value. Also, if we look to the results of the change in the DC power supply, buck converter's capacitor and inductor in figures (4.10), (4.11), (4.12) and (4.13), we see the desired speed deviates from its set value for short or long time. In fact, this is a big problem in any control system when it is not giving the desired values if any disturbance happens.

Moreover, It can be noted from Figures (4.7) that the armature current exceeded the rated value of the armature current of the DC motor and this may cause damage to the coils of the motor. Due to all these problems, Open-loop operation of the motor can be unsatisfactory in many industrial applications, therefore closed loop control system is designed to solve these problems.

4.3 Closed Loop Control System for the DC Motor

The closed-loop speed control system in this thesis is composed of a separately excited DC motor, pulse width modulation (PWM) generator, Buck converter, Proportional Integral Derivative type (PID) speed and current controllers. The block diagram representation of the system is shown in Figure (4.14); the closed-loop control of the motor has basically two feedback loops. The outer loop is a speed feedback loop and the inner loop is the current feedback loop. The controllers used in these loops are both of PID type.

Whenever a reference speed is given, the control system automatically compares the reference speed to the motor's actual speed, which is directly measured from the speed sensor. Based on the equation for the motor's mechanical motion, the speed error is the torque profile. Therefore, the output of the speed controller can be considered as the torque or the current reference value. An adjustment is made to the reference speed so that the motor speed follows the given reference value, and the motor achieves the steady state quickly. The current controller regulates the motor's actual current and the reference current, and tracks the reference current and load in time. The output of the current controller is the PWM duty ratio, which directly controls the MOSFET to ON or OFF states.

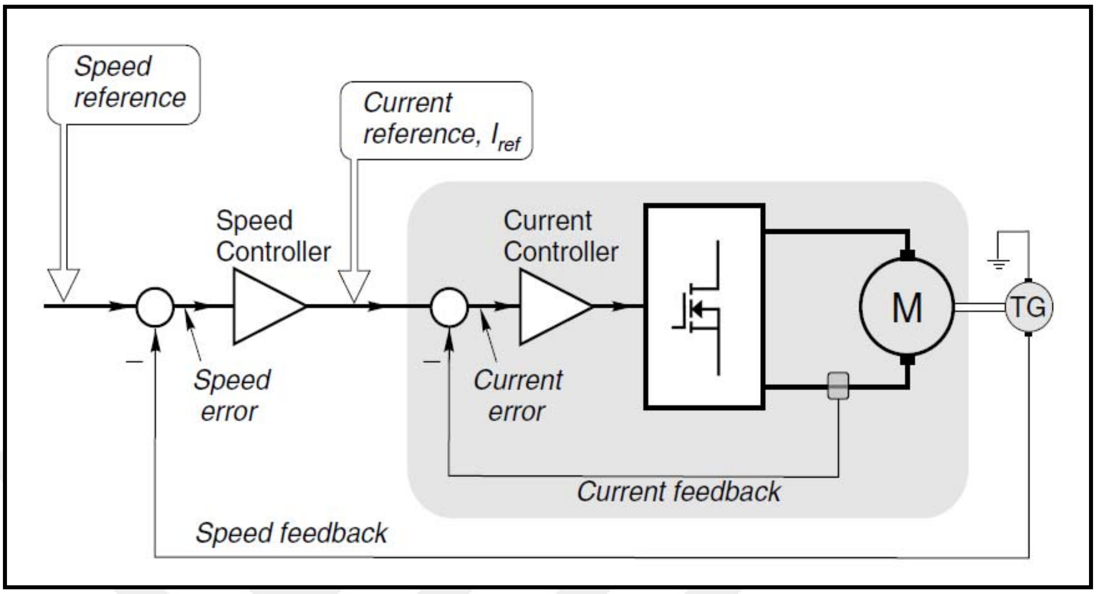

Figure 4.14: Schematic diagram of the controlled-speed drive with current and speed feedback control loops [25]

It is important to prevent excessive converter currents from flowing, so that the current control loop provides the means to end this problem. As long as the current control loop functions properly, the motor current can never exceed the reference value. Hence, by limiting the magnitude of the current reference signal as shown in Figure (4.15), the motor current can never exceed the specified value. The characteristics of the speed controller are shown in the shaded panel of the Figure (4.15), from which it can be seen that for small errors in speed, the current reference increases in proportion to the speed error, thereby ensuring 'linear system' behavior with a smooth approach to the target speed. However, once the speed error exceeds a limit, the output of the speed-error amplifier saturates and therefore no further increases in the current reference. By arranging for the maximum current reference to correspond to the full (rated) current of the system, there is no possibility of the current in the motor and converter to exceed their rated values, no matter how large the speed error becomes [37,38].

The current control loop is designed to be much faster than the speed control, so that the proposed DC chopper control system has a fast dynamic response to any parameter changes where control is crucial to the given application [3].

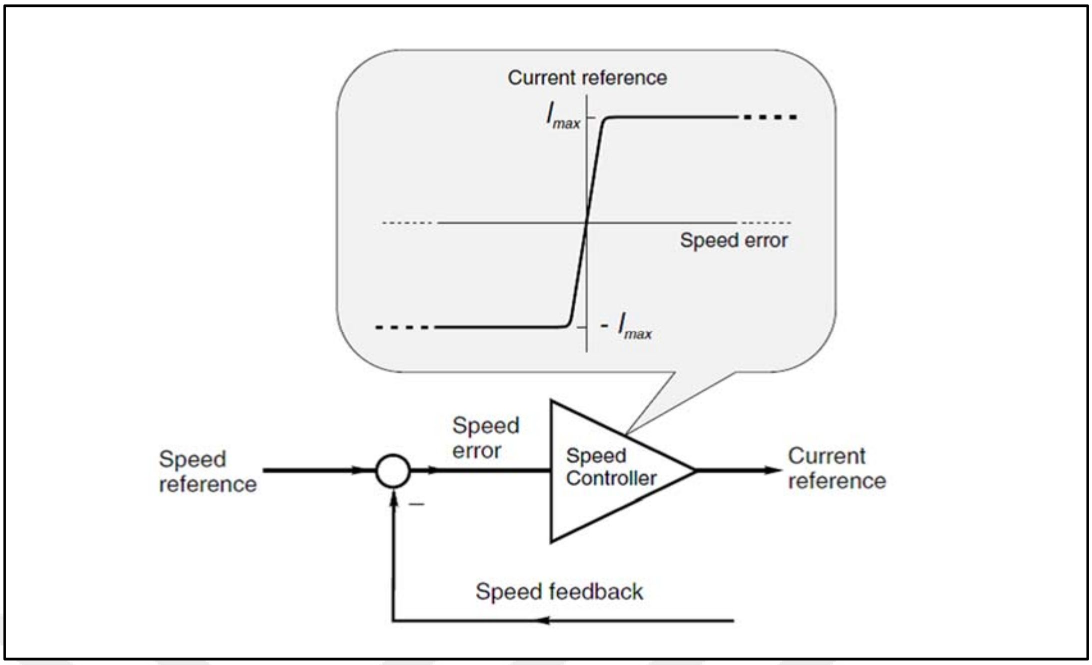

Figure 4.15: Detail showing the characteristics of the speed error amplifier [25]

4.4 Simulation of the Closed Loop Control System

Two Closed loop control systems have been built. The first is by using MATLAB Power System Block Set (P.S.B) library and the second is by using MATLAB Simulink library.

4.4.1 MATLAB P.S.B Library Closed Loop Control System

The MATLAB simulation using (P.S.B) library for the DC motor control system with the multiple feedback loop PID control is shown in Figure (4.16). Figure (4.17) shows the simulation subsystem for the PID speed controller. The values of the K_P, K_I, and K_D for the two loops are computed in the next section.

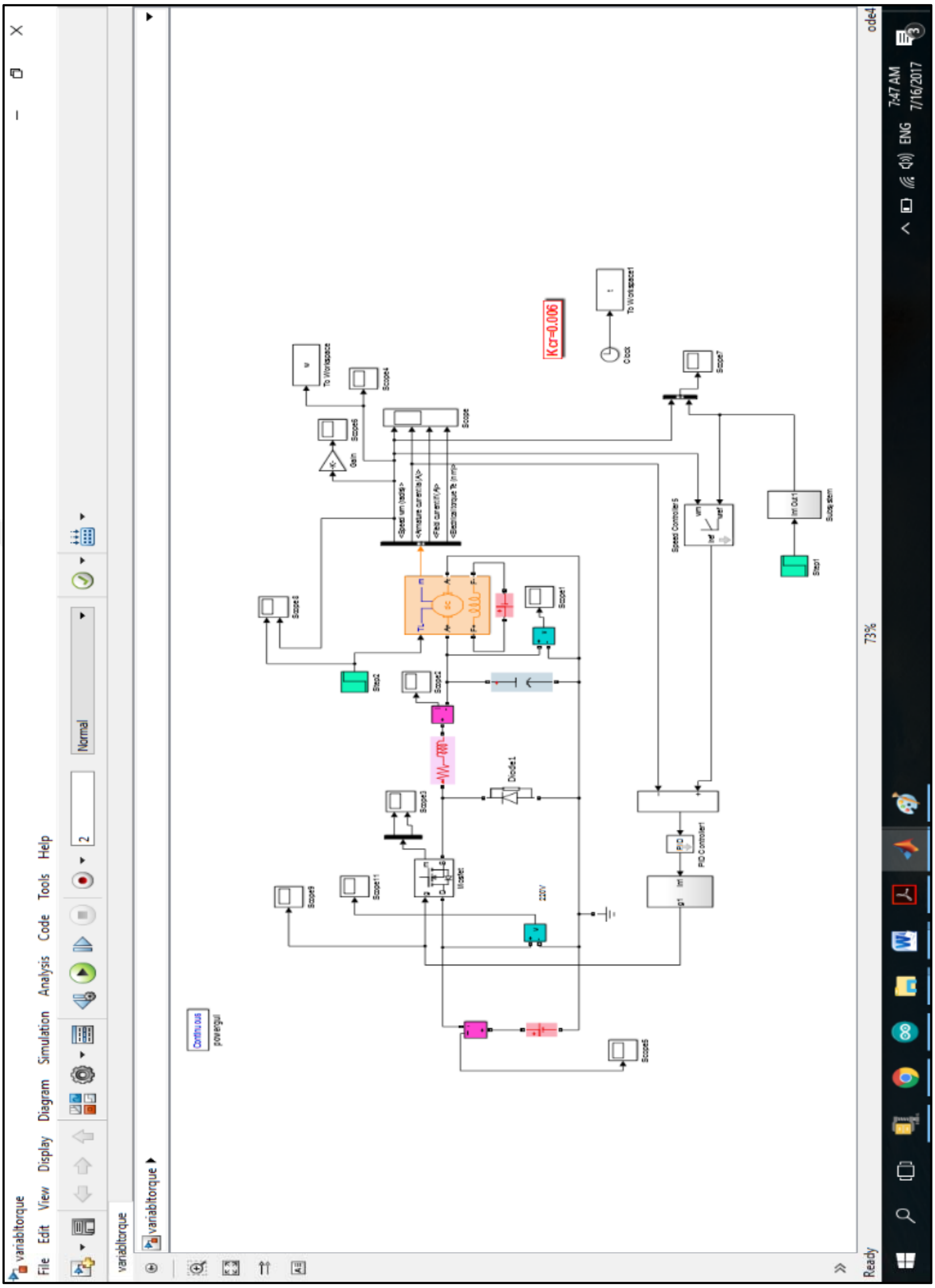

Figure 4.16: Simulation model of the DC motor control system with the multiple feedback loops using P.S.B library

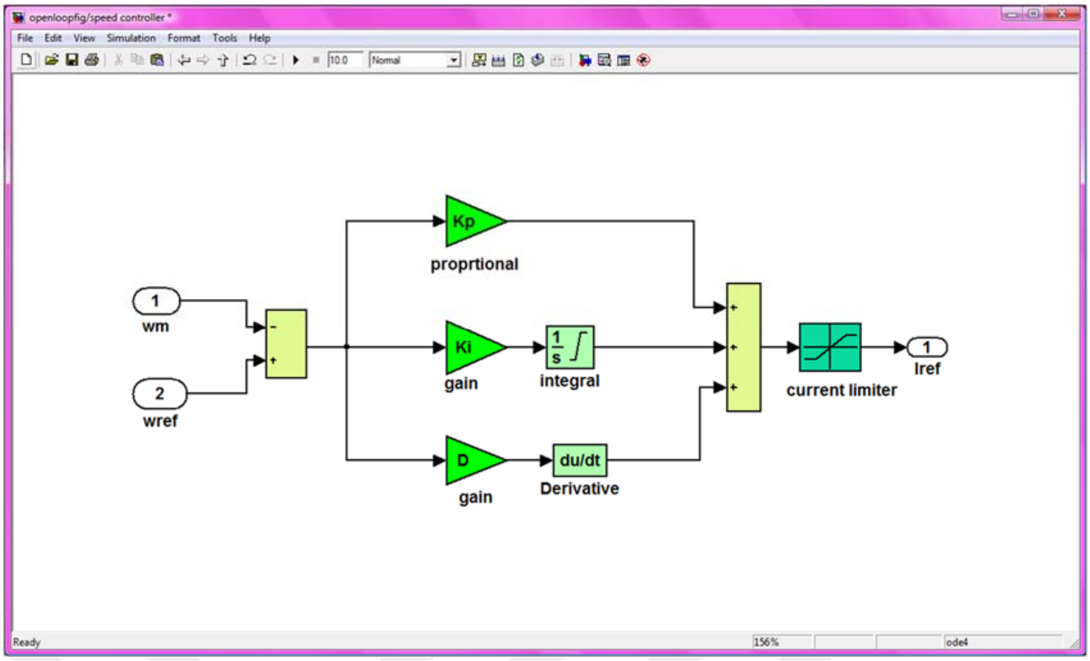

Figure 4.17: Subsystem simulation speed controller

4.4.2 MATLAB Simulink Library Closed Loop Control System

To verify the model obtained earlier by using P.S.B library and to prove the equations in Chapter Two, Simulink library is used. It gave the same results for the speed variation. The block diagram for the separately excited dc machine was developed according to the motor and the Buck converter equations shown in Figure (4.18). The inputs include the armature, the field voltages, and the load torque. Where the outputs are the windings currents, the developed torque, and the shaft speed.

The buck converter with ideal switching devices will be considered here to convey the way in which these types of systems are modeled [6]. The equations corresponding to the converter in continuous conduction mode described in section 2.2 of the Chapter Two are implemented in Simulink as shown in Figure (4.19).

By combining Figures (4.18) and (4.19) with the designed two feedback controllers, the Simulink model of the system is obtained as shown in Figure (4.20).

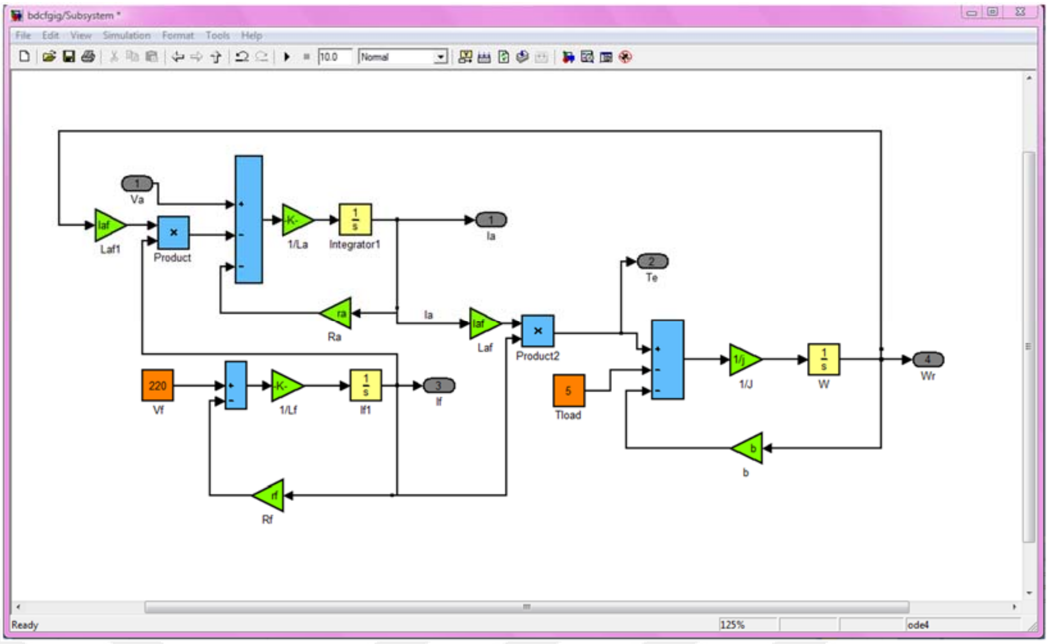

Figure 4.18: Separately excited DC machine Simulink block diagram

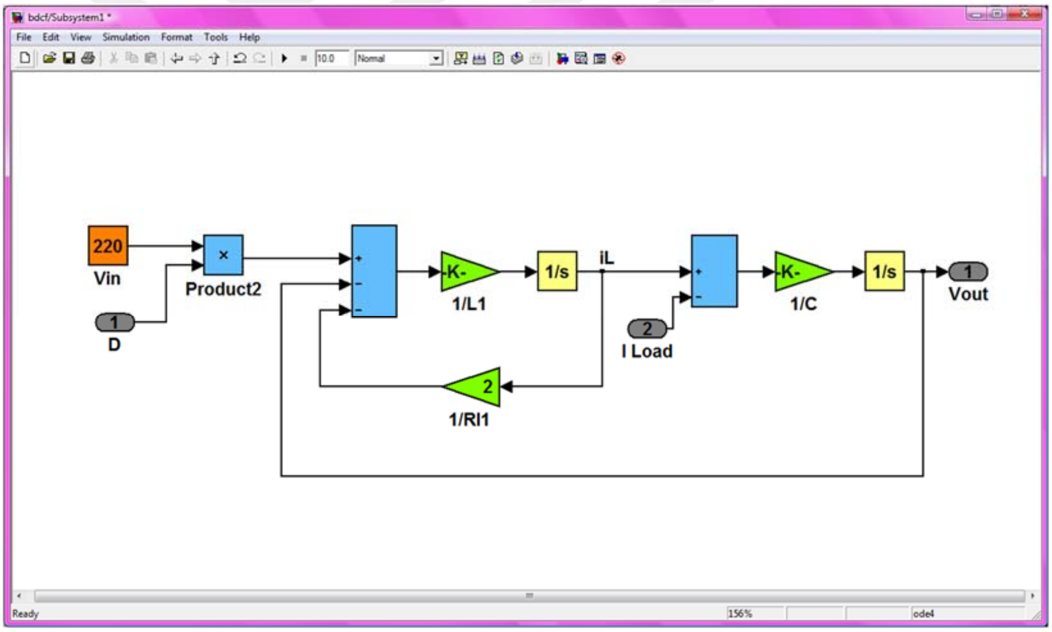

Figure 4.19: Simulink model of buck converter

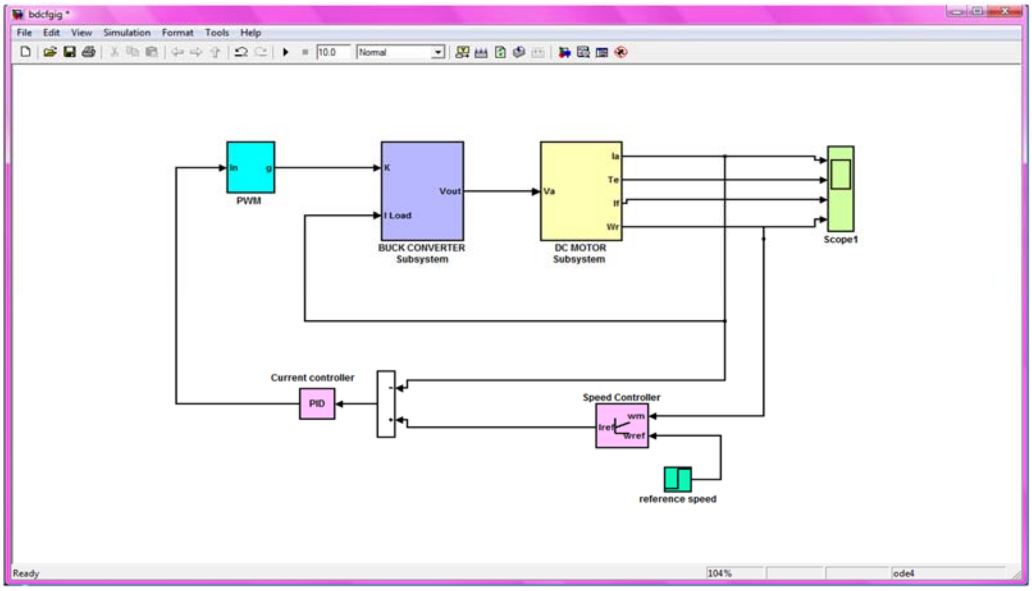

Figure 4.20: The Simulink of the DC motor control system with the multiple feedback loops

4.4.3 PID Controller Design

For calculating the gain factors of the PID controller (K_P, K_I and K_D), Ziegler-Nichols methods have been used. The first step is to find the critical gain by using the P-control and increasing the gain factor from (0) to the critical value K_{cr} where the output exhibits sustained oscillations. The second step is to determine the value of P_{cr} from the generated pulses in the first step by measuring the time between peak to peak. Then the values of **(**K_{cr}) and the period of the sustained oscillation P_{cr} are recorded. For the inner loop (current feedback loop), K_{cr} and P_{cr} are recorded as follows:

P_{cr} =0.006, K_{cr} = 0.35

From the obtained values of K_{cr} and P_{cr}, and using table (2-1) as initial estimation with some tuning to give the best performance for the system, the PID parameters are:

K_P = 0.21 K_I = 70 K_D = 0.002

To design PID controller for the outer loop (speed feedback loop), the above steps must be repeated as they were used for the inner current loop. The values of K_P, K_I and K_D for the outer loop are obtained, and these values are:

K_P = 9 K_I = 3000 K_D = 0.008

4.4.4 Simulation Results for the Closed Loop Control System

The swiftness of the response is measured by the rise time T_r and the peak time T_p. The similarity with which the actual response matches the step input is measured by the percent overshoot and the settling time T_s. The swiftness of a response to a step input depends on ζ and ω_n, the response is faster for larger ω_n and lower ζ. The swiftness of the response, however, will be limited by the overshoot that can be accepted [21]. The speed response obtained by Simulink library as shown in Figure (4.21) is approximately the same as the speed response that is obtained by the P.S.B library, which is shown in Figure (4.22). From the step speed response of the DC motor shown in Figure (4.22), it is observed that the rising time (T_r) is equal to (0.105 sec), small settling time (T_s) equals (0.115 sec), and the peak time (T_p) equals (0.1207 sec). As these values are evaluated, the damping ratio (ζ) and the natural frequency (ω_n) values may be calculated from equations (2-30) and (2-31) in Chapter Two as:

(ζ) = 0.8 ω_n = 43.47 rad/sec

The value of the Percentage Overshoot (P.O) is evaluated from equation (2-29) as follows:

$$100 * e^{-\pi * 0.8/\sqrt{1-0.8^2}} = 1.5\ \%$$

From above results, it is noted that the response has a small settling time and percentage overshoot, and the steady state error of the output speed equals to zero.

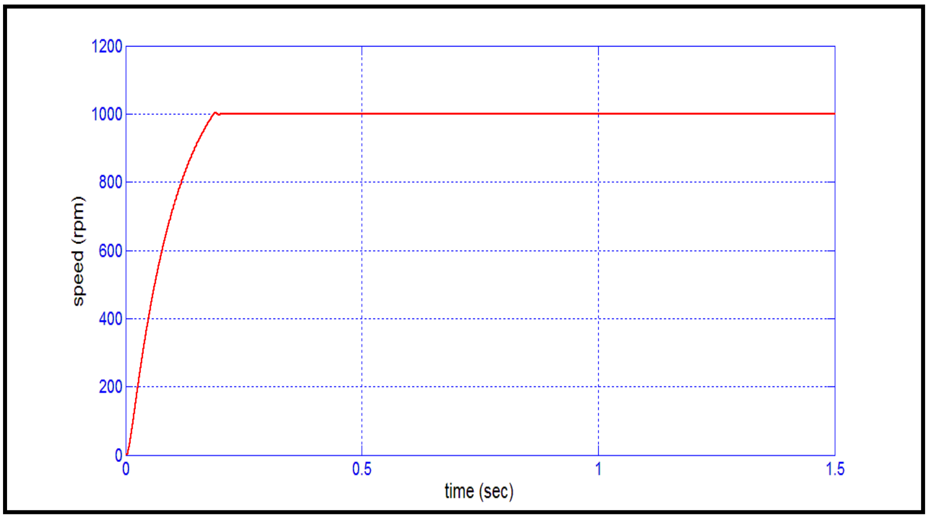

Figure 4.21: Step speed response of the DC motor using Simulink library

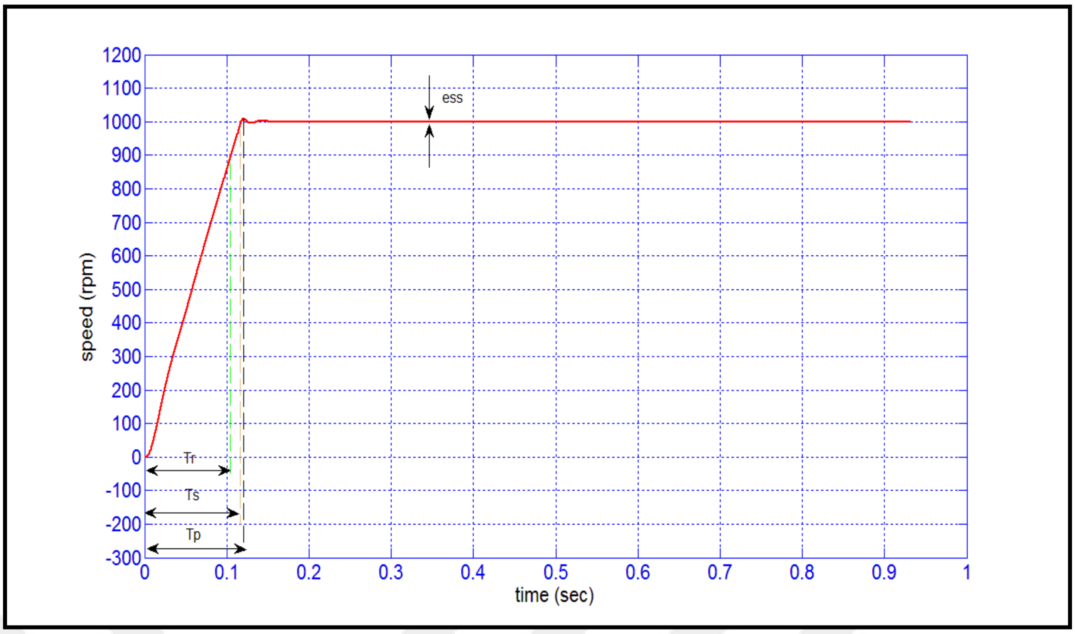

Figure 4.22: Step speed response of the DC motor using the P.S.B library

4.4.4.1 Simulation the results of the close loop speed control system with the disturbance in external torque

Figures (4.23) and (4.24) show the speed response of the motor when a sudden load torque is applied at (0.25 sec). It can be seen that the speed descends appreciable and resumes the setting value quickly; it does not exceed 0.05 sec and the overshot value does not pass 0.5% of the setting speed value.

Figure (4.25) shows the speed response when the load torque is decreased from 6 N.m to 2 N.m. It is noted that the speed is increased suddenly and then it resumes to the setting value. Figure (4.26) shows the armature current, field current and the electrical torque, respectively, of the simulation of the DC motor with closed loop control system. From this Figure, it is noted that the armature current does not exceed the rated current of the DC motor. By comparing the step response of the open loop system shown in Figures (4.4), (4.5) and (4.6) with the step response of the close loop system shown in Figures (4.18),(4.19) and (4.20), it is observed that the closed loop control improves the transient response. The settling time decreases from 166.7ms in the open loop to 115ms in the closed loop, and the final value remains constant under any disturbance change with zero steady state error.

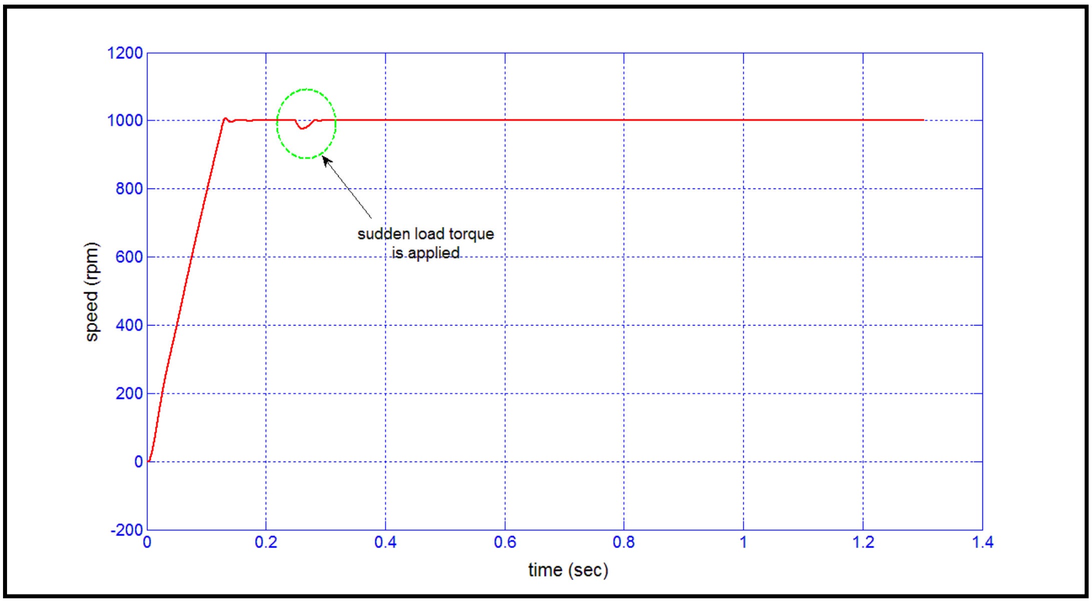

Figure 4.23: MATLAB Speed Simulation for a given sudden load

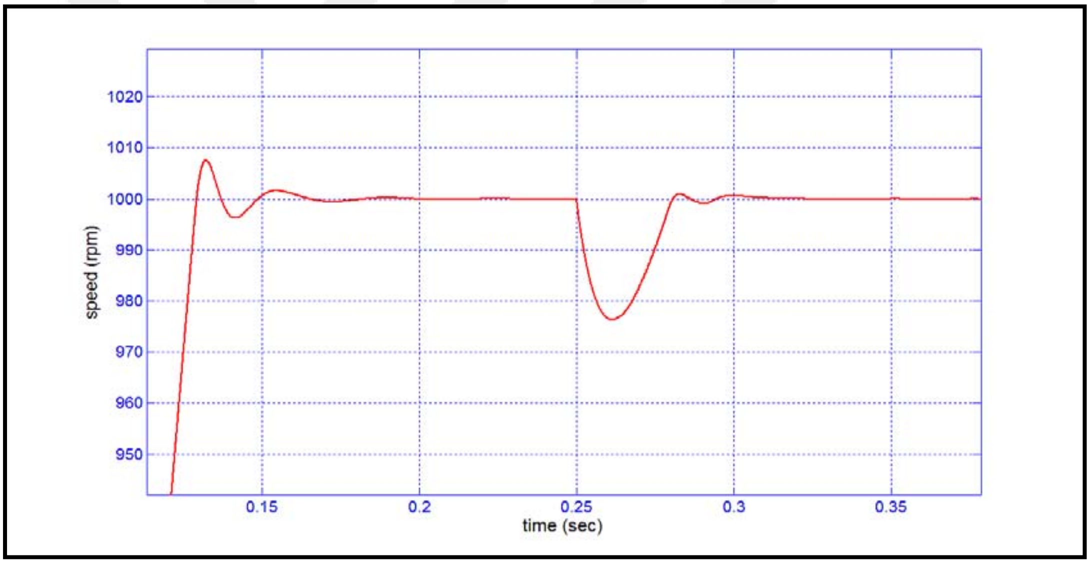

Figure 4.24: Zooming on the diagram of figure (4.23)

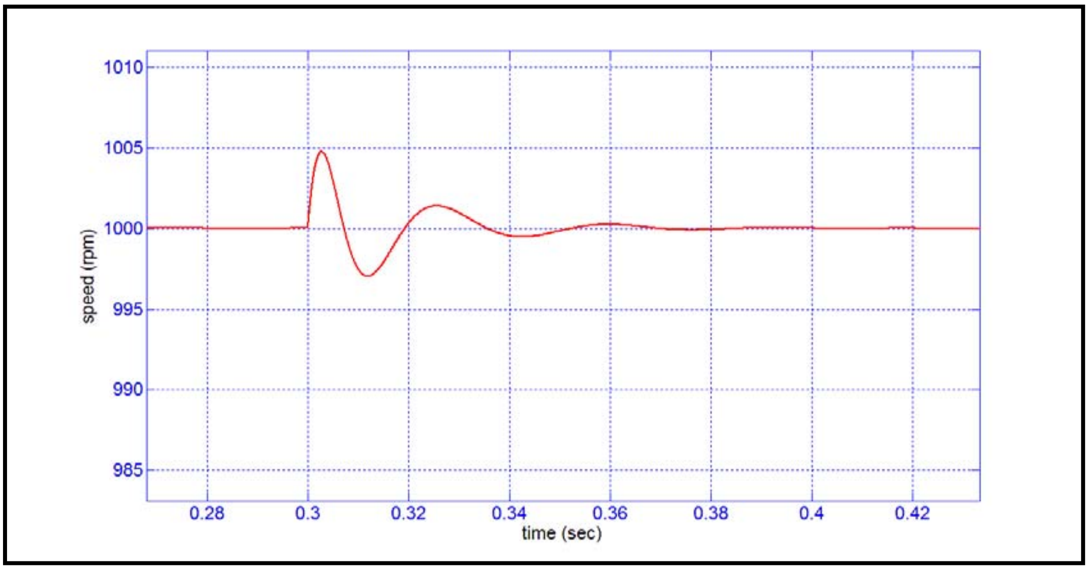

Figure 4.25: Speed response when the load torque decreases suddenly

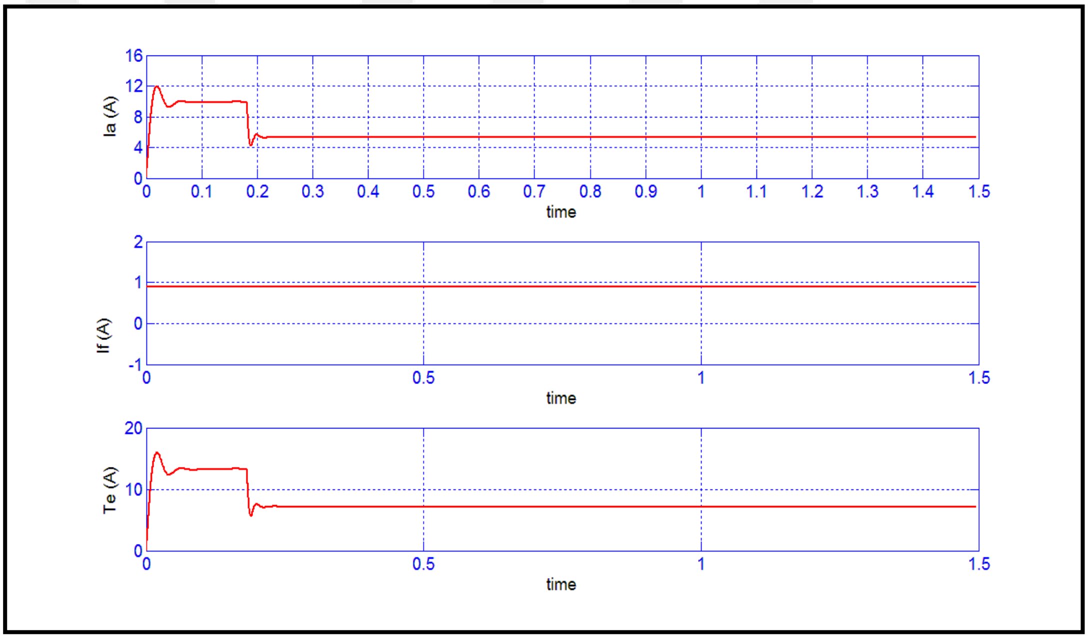

Figure 4.26: Simulation results of the armature current (I_a), field current (I_f) and electrical torque (T_e) for closed loop control system

4.4.4.2 Simulation results of the close loop speed control system with the disturbance in the DC power supply

Figure (4.27) shows the speed response of the motor when a sudden dropping in the DC power supply happens at (1 sec). The DC power supply decreased from 220V to 190V. It can be seen that the speed descends considerably and reaches the setting value quickly; it does not exceed 0.05 sec, and the overshot value does not exceed 0.03% of the setting speed value.

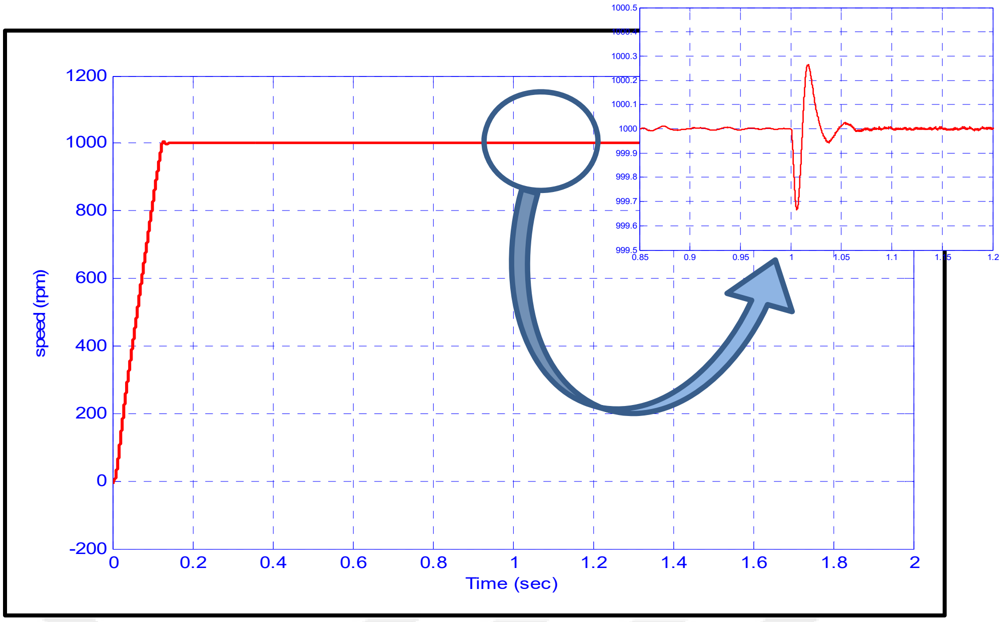

Figure 4.27: Speed response when the DC power supply decreases suddenly

Figure (4.28) shows the speed response when a sudden rising in the DC power supply happens at (1 sec). The DC power supply increased from 220V to 250V. It can be seen that the speed ascends considerably and reaches the setting value quickly; it does not exceed 0.05 sec. and the overshot value does not exceed 0.03% of the setting speed value.

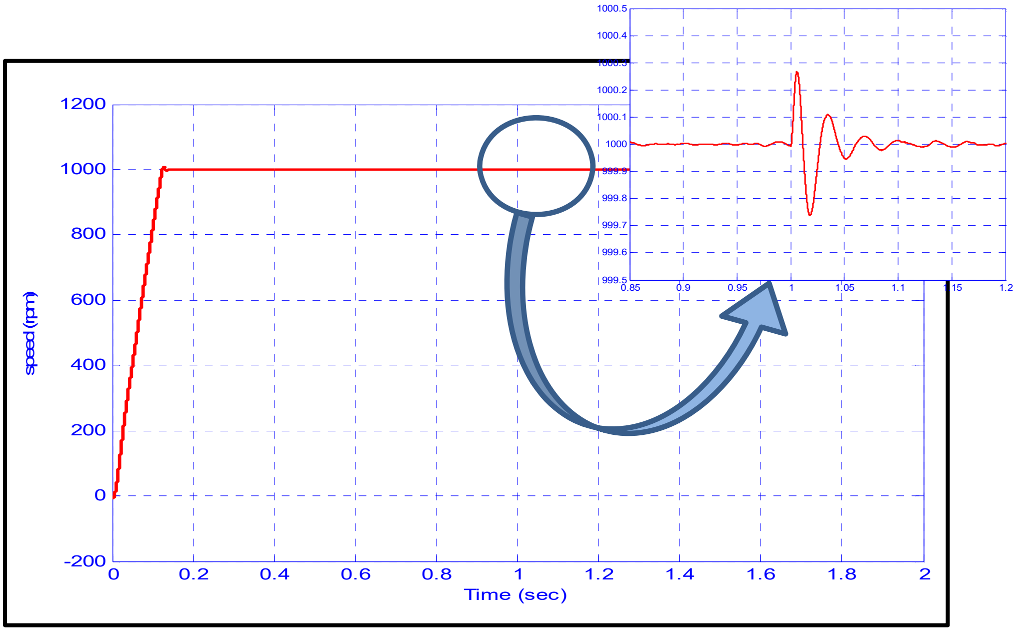

Figure 4.28: Speed response when the DC power supply increases suddenly

4.4.4.3 Simulation results of the close loop speed control system with the disturbance in the buck converter's capacitor

Figures (4.29) shows the speed response of the motor when a sudden rising in the buck converter's capacitor happens at (1 sec). The buck converter's capacitor increased from 47μF to 147 μF. It can be seen that the speed descends considerably and reaches the setting value quickly; it does not exceed 0.05 sec and the overshot value does not exceed 0.2% of the setting speed value.

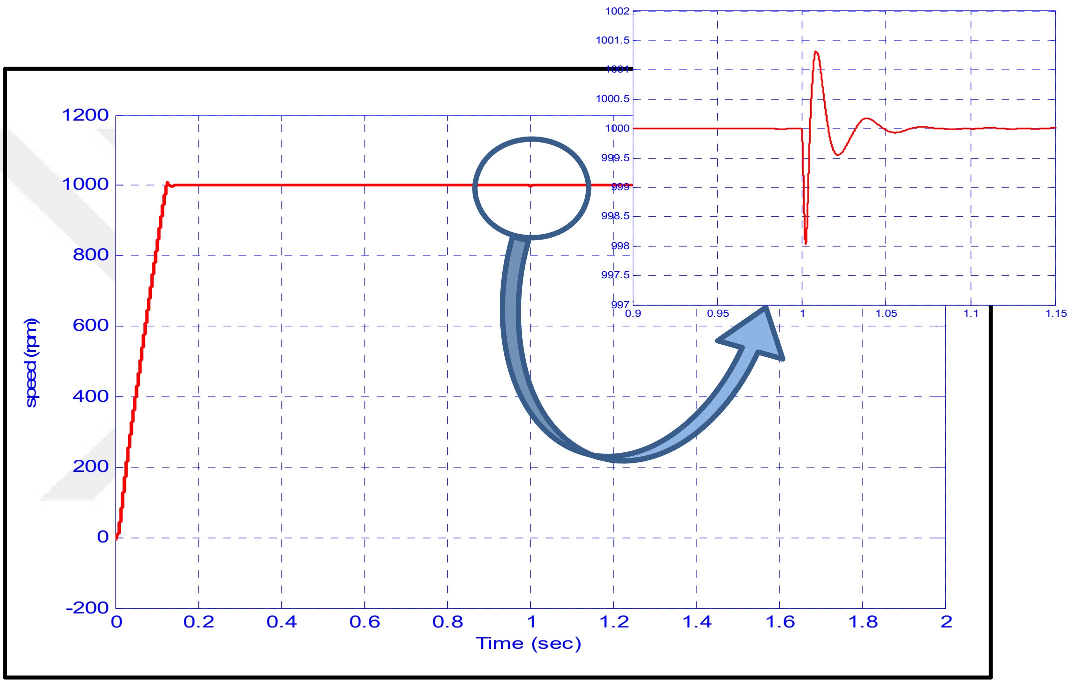

Figure 4.29: Speed response when the buck converter's capacitor increases suddenly

4.4.4.4 Simulation results of the close loop speed control system with the disturbance in the buck converter's inductor

Figures (4.30) shows the speed response of the motor when a sudden rising in buck converter's inductor happens at (1 sec). The buck converter's inductor increased from 5.5mH to 7.5mH. It can be seen that the speed descends considerably and reaches the setting value quickly; it does not exceed 0.01 sec and the overshot value does not exceed 0.01% of setting speed value.

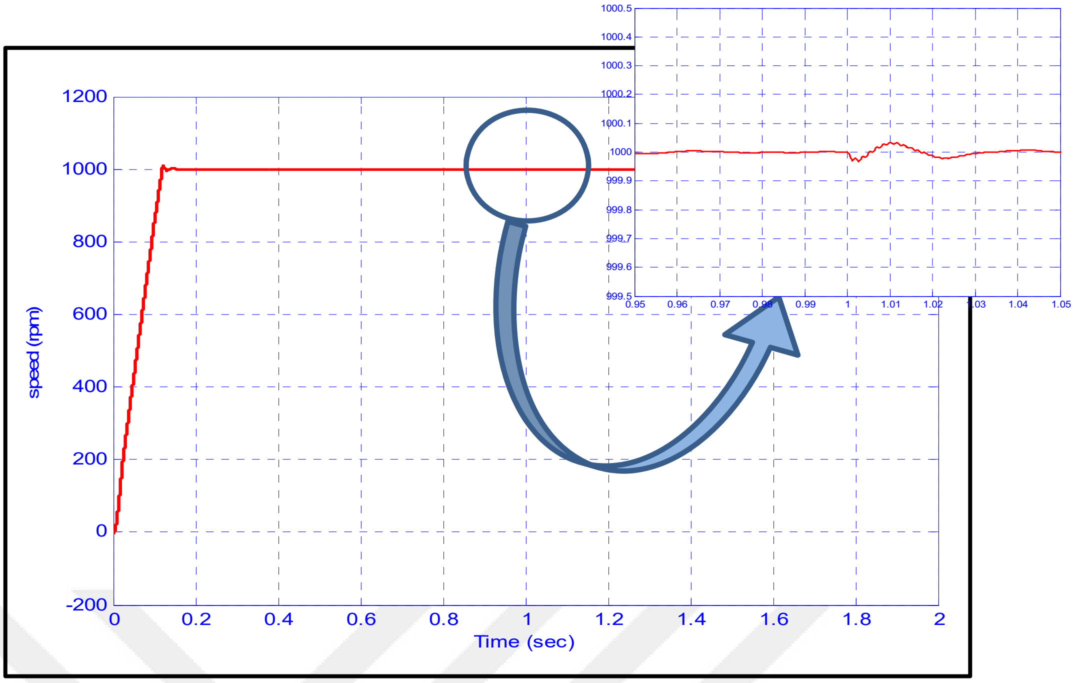

Figure 4.30: Speed response when the buck converter's inductor increases suddenly

4.4.5 Simulation Results for the Closed Loop Control System With the Variable Desired Speed

In some DC motor applications, the variable speed tracking is wanted. For approving this goal, the system has been tested when the desired speed was a variable. Figure (4.31) shows the effect of the change in the external torque, DC power supply, the buck converter's capacitor and the inductor value at the same time when the wanted speed is changing with the time. At the time (1 sec), the external torque changes from 2N.m to 5N.m, the DC power supply which feeds the DC motor drops from 220 V to 200 V. The capacity value of capacitor is increased from 47µF to 147µF and the inductance of inductor increased from 5.5mH to 7.5mH. Although, all these changes happens at the same time, the actual speed deviates not more than 1% of desired speed value for a period of time less than 0.02 sec.

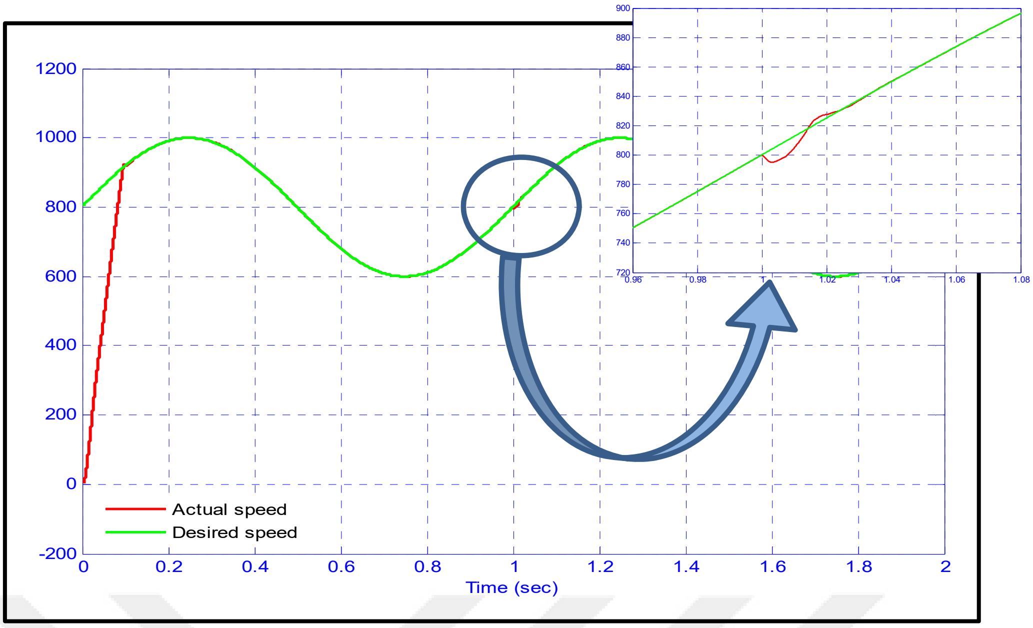

Figure 4.31: Simulation results for the closed loop control system with the variable desired speed

According to the experimental results obtained by Matlab simulation, the main purpose of this thesis has been successfully achieved, since the actual speed of the DC motor tracks the desired speed. The obtained results have shown the robustness of the control system when uncertainties occur in the external torque, system's power supply, the inductance of the buck converter and the capacitance of the buck converter. This control achieved the wanted goals either when the desired speed is constant or variable with time. It is important to underline that these type of disturbance variations don't happen in practice at the same time. However, the experiments were undertaken to demonstrate that the proposed controller presenting a good performance under any disturbance in the system parameters, which would make it possible for the introduction of this controller in practical applications.

Table (4.1) shows the comparison between this thesis results and others work results. This table illustrates that using the double PID controller with PWM as a control system for a DC motor. It gives a high response tracking for the actual speed to desired speed under the disturbances in external torque, power supply, capacitor and inductance of the system and this design available to implement in a practical model. The results show that the control system can be implemented with constant and variable desired speed.

Table 4.1: The comparison between control systems

	Control type	disturbance	Practical implementation	Speed type
Ref [4]	Switch mode	Torque power supply	Not	Constant
Ref [7]	Flatness control	Torque	Not	Constant
Ref [9]	PI controller	Power supply	Not	Constant
Ref [12]	Adaptive control	Torque	Not	Variable constant
Ref [18]	Hierarchical control	Torque Power supply Capacitor inductor	Not	Variable Constant
This thesis	Double PID and PWM	Torque Power supply Capacitor inductor	Exist	Variable Constant

CHAPTER FIVE

HARDWARE IMPLEMENTATION OF THE CLOSED LOOP SPEED CONTROL SYSTEM

In this chapter, the hardware implementation of the closed loop speed control system has been presented. The hardware implementation is based on ATmega328 Arduino UNO Kit. It is used as a controller on the system. To prove the validity of the computer simulation results, an experimental system has been setup and practical results for the system condition are obtained and discussed.

5.1 Hardware Configuration

The block diagram for practical closed loop control system configuration is shown in Figure (5.1). From the Figure, it can be noted that the practical circuit consists of five major parts, ATmega328 Arduino UNO Kit, drive circuit, sensors circuits, buck converter circuit, and the last is the DC motor. All these parts will be discussed in detail in this chapter. The DC motor which is used in this work is fan manufactured by Marxlow Company with 2.4W, 24V. We use different types of the DC motors which were used in the Matlab simulation to prove the validity of the implementation of this control circuit on any type of the DC motors. The fan has been put on the wide side of a pipe, the narrow side of this pipe was used to shed the torque on the DC motor by closing and opening this orifice. The feedback speed is taken from speed sensor applied to one of the Arduino UNO Kit digital pins that is compared with a reference speed. The speed Error signal is obtained from this comparison which is represent the desired armature current, after that ACS712 current sensor have been used to read the armature current. the value that obtained from the current control it used to generate PWM. The PWM generator is applied to the driver circuit of the DC chopper. The pulse width of the chopper switching variation depends on the error signal and thus the motor runs at the constant speed.

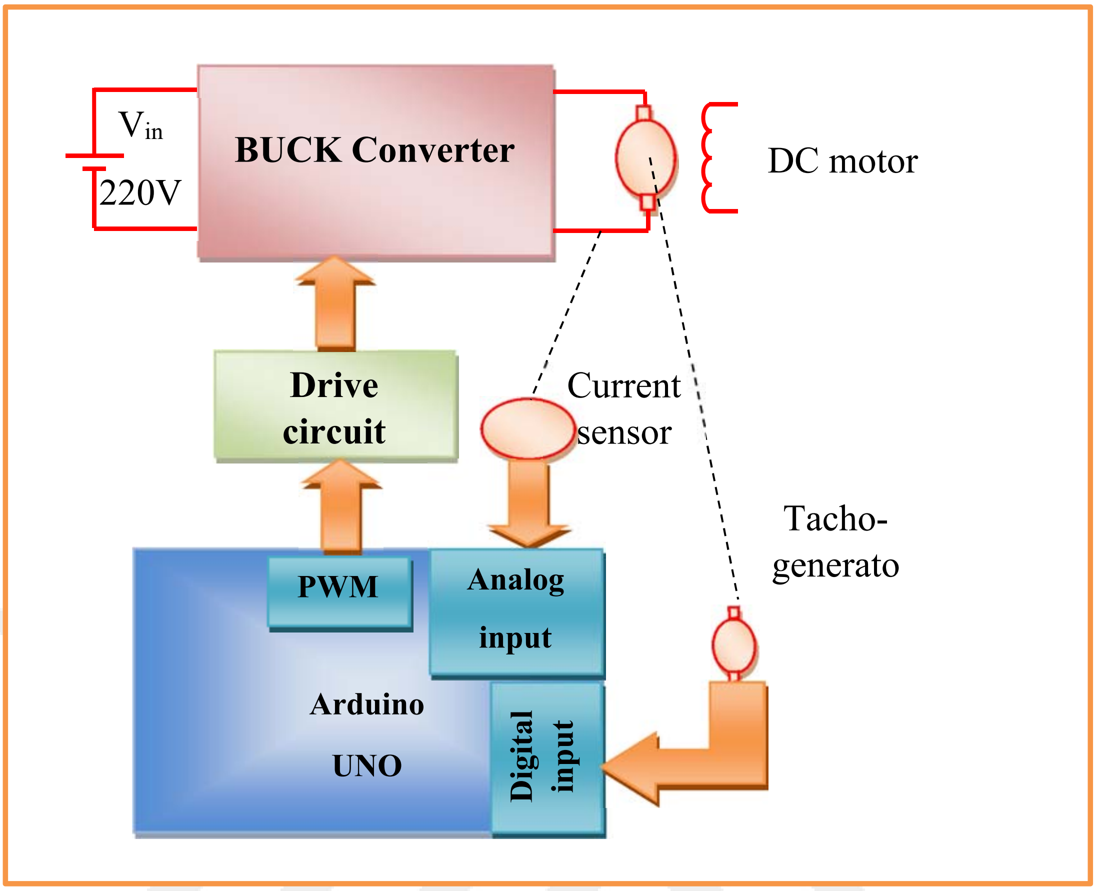

Figure 5.1: Block diagram for practical closed loop speed control system

5.2 ATmega328 Arduino UNO Kit

The ATmega328 Arduino UNO Kit is used to receive and compare the reference signal, the actual speed and current signal, then generate the PWM data according to the error signal that is obtained from the comparison operation. Figure (5.2) shows the schematic diagram of ATmega328 Arduino UNO Kit, all pins functions that are used in this Kit in practice are shadowed. These functions are I/O Interface, analog interface, and expansion functions, where I/O Interface function (pin number 3,5,6,9,10 and 11) is used to generate PWM signal from Arduino UNO, another Digital I/O pins (pin number 2,4,7,8,12 and 13) is used to read the actual speed of the DC motor obtained from Lm393light sensor. Lm393light sensor is used to measure the fan's speed, while (pin number from A0 to A5) is used to receive data from current meter then convert these data from analog to digital values to enable Arduino UNO to process it. There are other pins used to provide the DC voltage (VCC, GND) for current and speed sensor instead of any external power supply.

Figures (5.3) and (5.4) show the PWM signal output from Arduino Kit with two different values of the duty cycle.

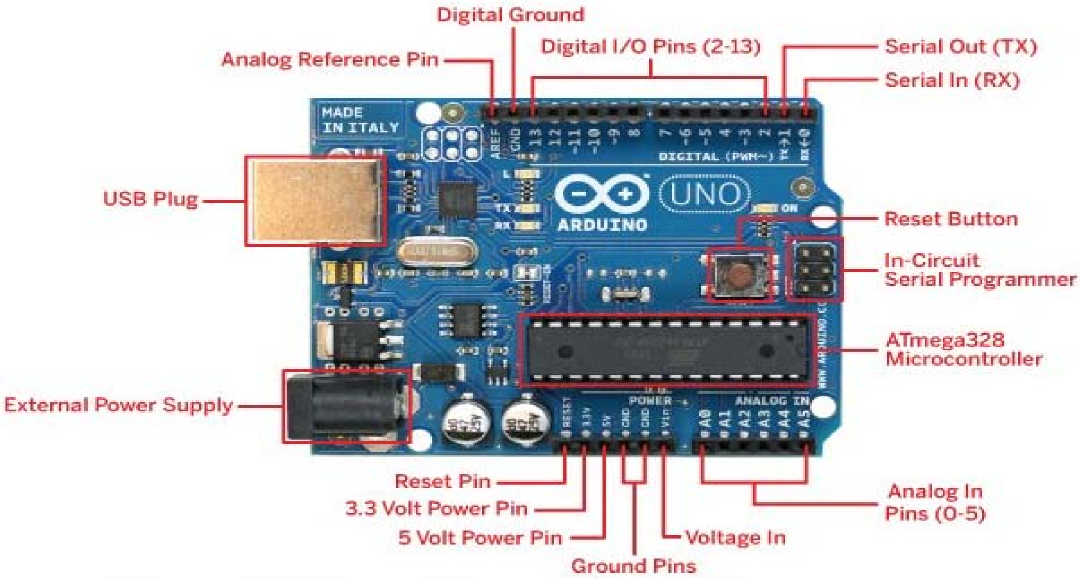

Figure 5.2: Schematic diagram of the ATmega328 Arduino UNO Kit [41]

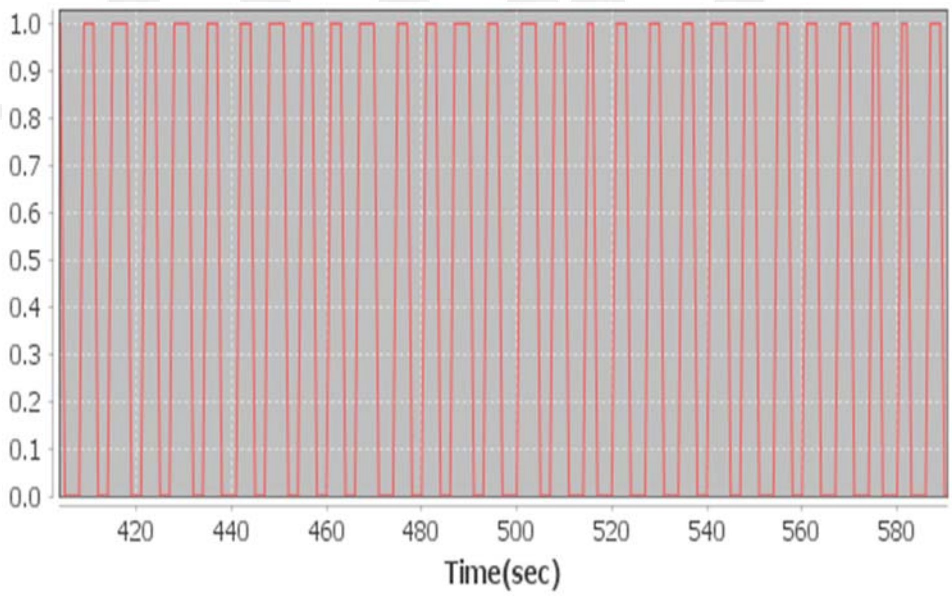

Figure 5.3: The output PWM signal from the Arduino Kit with 50% duty cycle

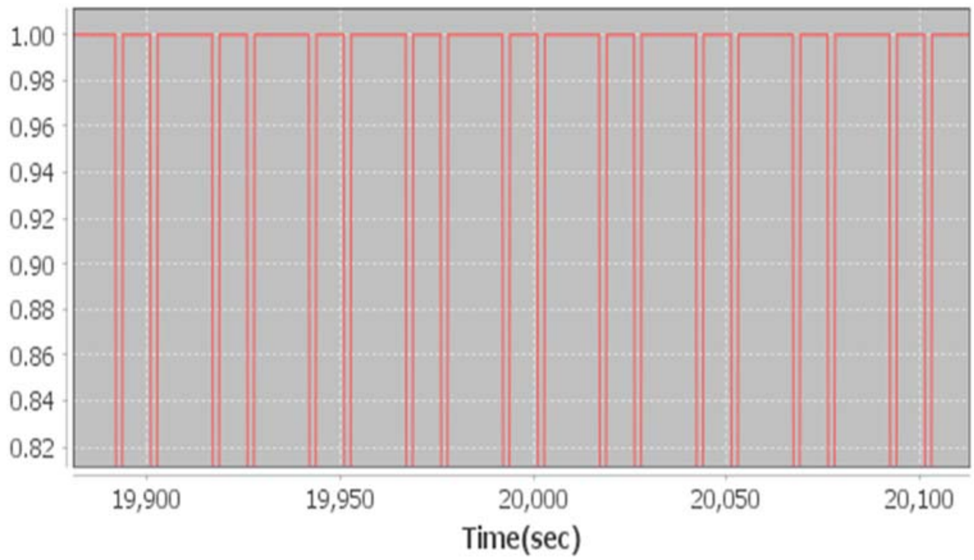

Figure 5.4: The output PWM signal from the Arduino Kit with 90% duty cycle

5.3 Programing of Arduino UNO Kit

Arduino kits are programed by many versions of an integrated development environment (IDE). This program has a text editor for writing codes and it provides a platform that allows for Arduino to communicate with other device. The used programing language in Arduino (IDE) is C language. In this thesis, we work on the latest version of (IDE) which is Arduino 1.8.3.

The code that was written inside the (IDE) is called sketch. To test our control system, three sketches have been built, the first sketch is for open loop control system, the second sketch is for the close loop control system with constant speed and the last sketch is for the close loop control system with variable desired speed. These sketches are illustrated in appendix A2.

For displaying the results of our circuit, we need to build a java code on eclipse program. By using jSerialComm, we can make a connection between the Arduino kit and our PC throw the eclipse program. The java code that was used in eclipse is illustrated in appendix A3. The main programme goes into a forever loop as shown in the developed software flowchart in Figure (5.5).

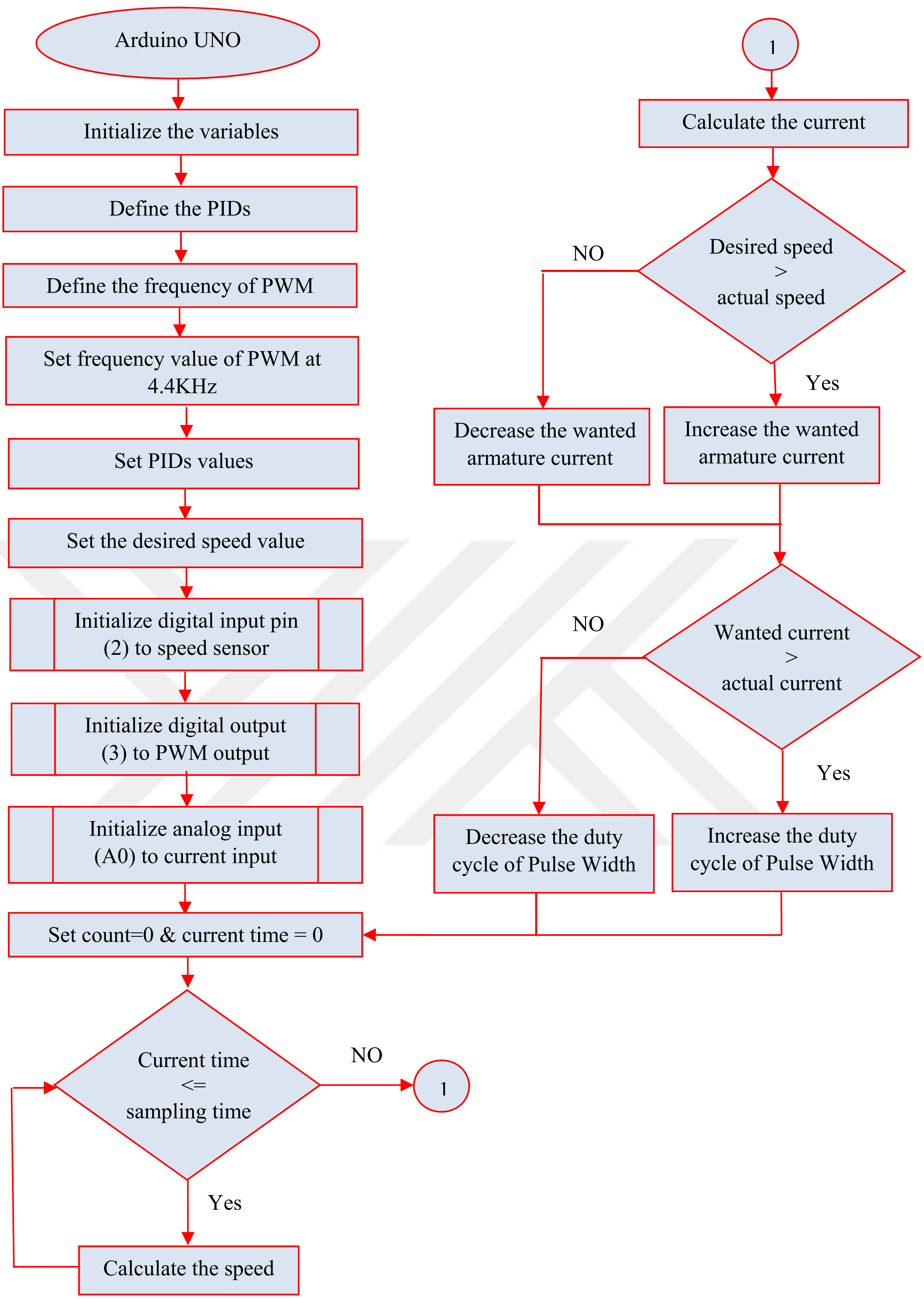

Figure 5.5: Developed software flowchart

5.4 The Design of Practical Control Circuit

The practical control circuit has been designed to achieve the best results for reboots control system by low implementation cost. The control system is designed to keep the actual speed tracks the desired speed over the time even if any disturbance happens in the external or the internal parameters of the system.

To know the value of the inductor and the capacitor of the buck power converter, we need to know the Dc motor and the circuit parameters which are shown below:

a) Direct power supply Input voltage V_{in} equals to 22 V.
b) Percentage of the duty cycle (K) equals to 50%.
c) Switching frequency (f_s) equals to 4.4 KHz.
d) Load current (armature current of motor) (I_a) equals to 0.1A. according to equations (2-17) and (2-18):

V_{out} = 22*0.5 =11V

I_s= 0.5*0.1 = 0.05A

The time for one cycle is,

$$T_s = \frac{1}{f_s} = 227\mu s$$

(ΔV_c) = 0.9 % of V_c ⟶ $\Delta V_C = 0.1V$

(ΔI_L) = 33 % of i_L ⟶ $\Delta I_L = 16.5mA$

The values of the inductor (L) and the capacitor (C) can be calculated according to the equations (2-20) and (2-26) as follows:

$$L = \frac{11(22-11)}{4400 * 0.016 * 22} = 75mH$$

$$C = \frac{11(22-11)}{8 * 75 * 10^{-3} * 0.1 * 4400^2 * 22} = 4.7\mu F$$

Also, we need to calculate the PID values, by the estimation with some tuning to give the best performance for the system, the PID parameters for the inner current loop are:

$K_P = 0.04$ $K_I = 1.6$ $K_D = 0.001$

To design the PID controller for the outer loop (speed feedback loop), the above steps must be repeated as they were used for the inner current loop. The values of K_P, K_I and K_D for the outer loop are obtained, and these values are:

$$K_P = 0.11 \; K_I = 3 \; K_D = 0.008$$

Figure (5.6) shows the fan which represents the Dc motor in the designed circuit, the Arduino Uno which carries the microcontroller that manage the control circuit according to the program that has been built inside it, the Mosfet (IRL Z44N) as the electronic switch which works on the DC voltage less than 5v, the buck power converter, the power supply which is AC/DC a transformer (220v – 22v) and the laptop to inject the program to Arduino and read the results on its screen.

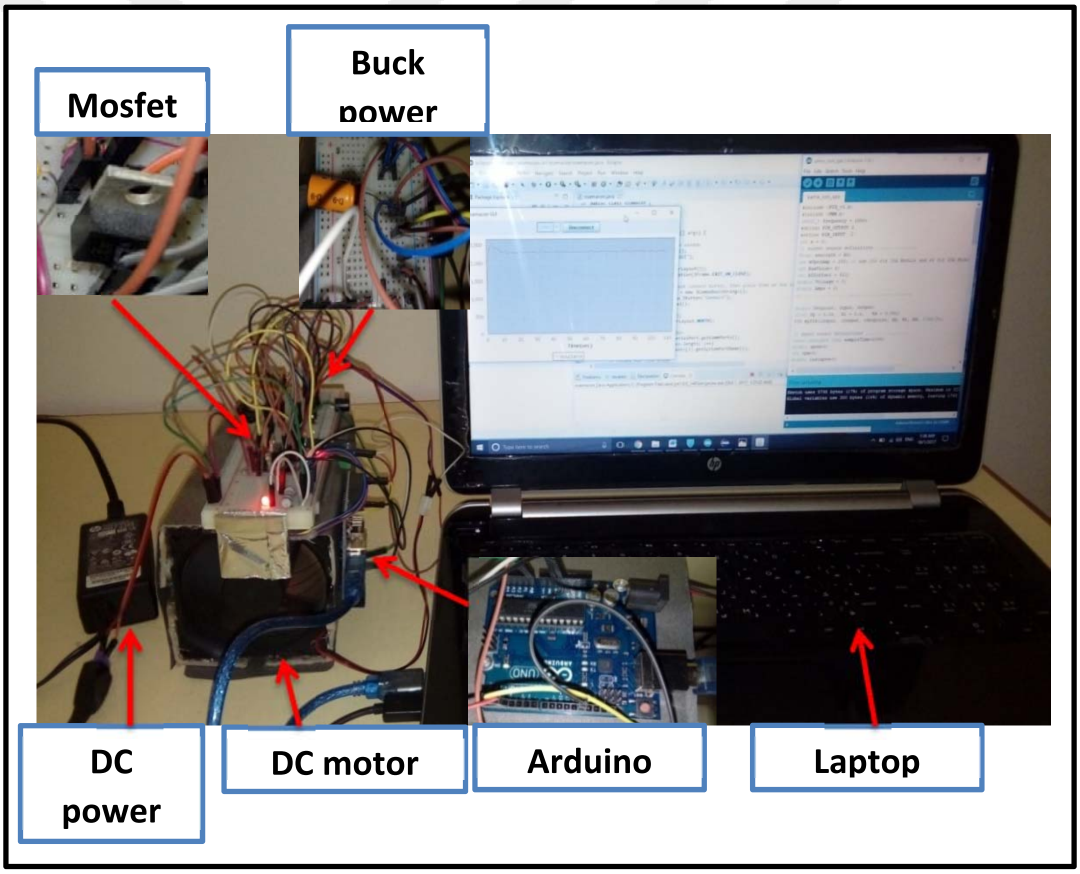

Figure 5.6: A photograph of all power and electronic circuits

5.5 The Results of the Practical Control Circuit

The practical test have been done on the Dc motor (fan) to prove that the double feedback control built on the PID control with pulse width modulation. Using the DC motor with another parameter values is to prove that the control circuit which designed is available to be implemented in wide practical applications. So, all the experimental tests which have been done by Matlab simulation will be implemented in practice.

5.5.1 The Effect of the Disturbance in External Torque on the Dc Motor (Fan)

As shown in figure (5.7), the speed of DC motor (fan) decreased when the external torque has been applied on the fan and by applying the external torque on the fan by closing the back terminal of the tube that the fan fixed on front terminal of it. Figure (5.7) shows the effect of the external torque on the open loop control. We can see that the speed of the fan decreased from 2220rpm to 1950rpm and still on this value.

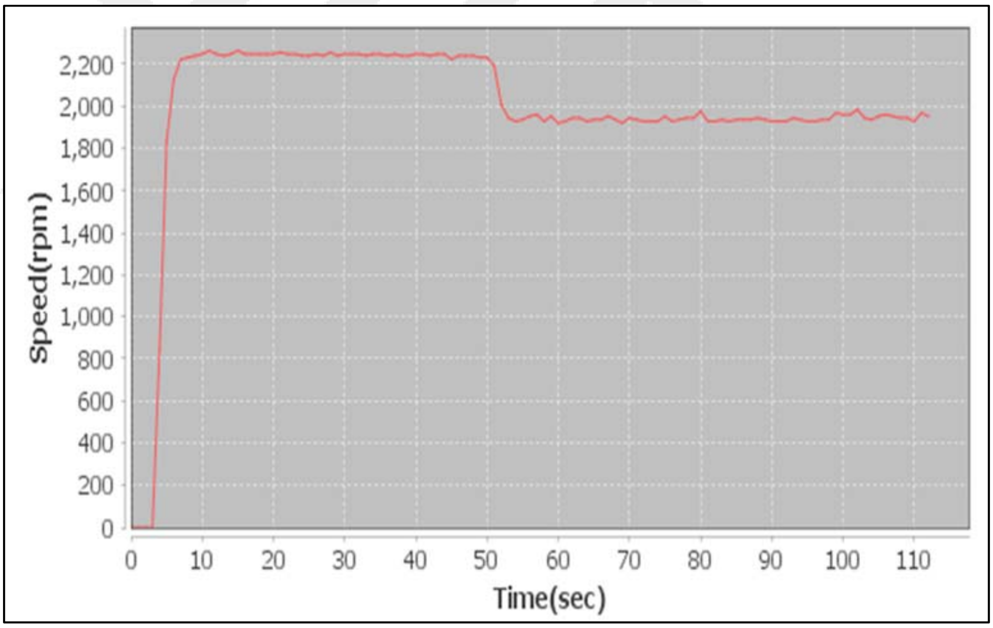

Figure 5.7: Applying external torque to the fan with open loop control

Figure (5.8) shows the effect of external torque on the close loop control system. We can see the speed of the fan decreased for less than 1% of the sitting time for a period of time less than 2 sec then returns to the setting value quickly.

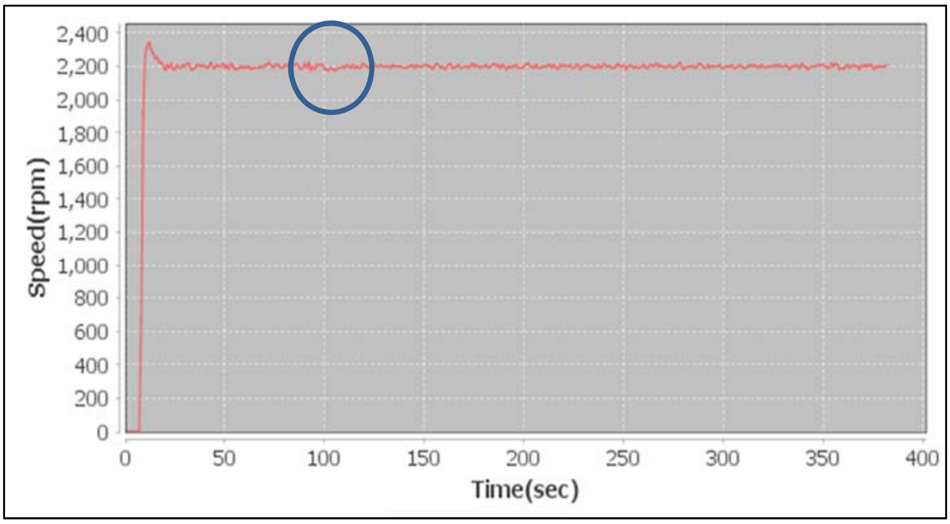

Figure 5.8: Applying external torque to the fan with close loop control

5.5.2 The effect of Disturbance in External Power Supply on the Dc Motor (fan)

As shown in figure (5.9), the speed of the Dc motor (fan) decreased when the external power supply decreased from 22v to 18v. Figure (5.9) shows the effect of the decrease in the power supply on the open loop control. We can see that the speed of the fan decreased from 2220rpm to 1750rpm and still on this value.

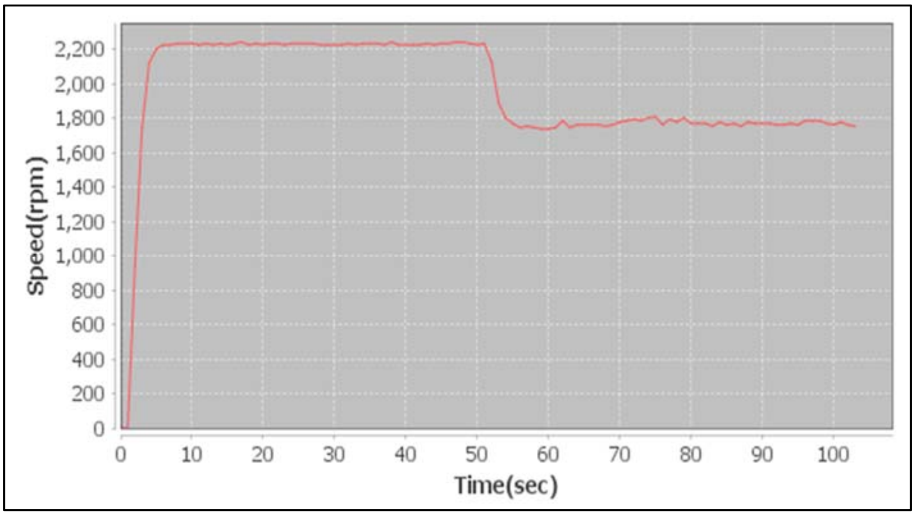

Figure 5.9: The decrease of the external power supply of the fan with the open loop control

Figure (5.10) shows that the speed of the fan decreased for less than 10% of the sitting time for a period of time less than 2 sec then returns to the setting value quickly.

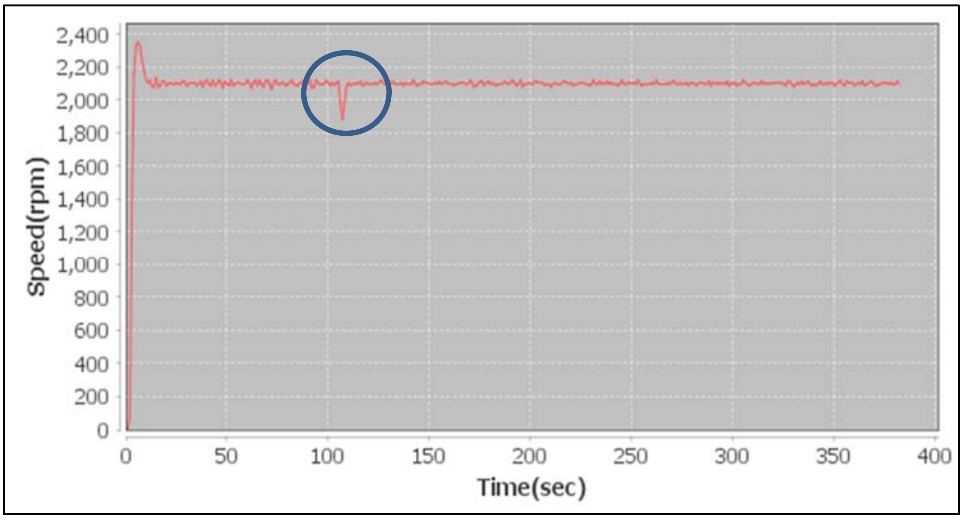

Figure 5.10: The decrease of the power supply of the fan with close loop control

5.5.3 The Effect of Disturbance in the Internal Inductance on the Dc Motor (Fan)

Figure (5.11) shows the effect of the decrease in the buck converter's inductance from 75mH to zero on the open loop control. We can see that the speed of the fan increased from 2220rpm to 2350rpm and still on this value.

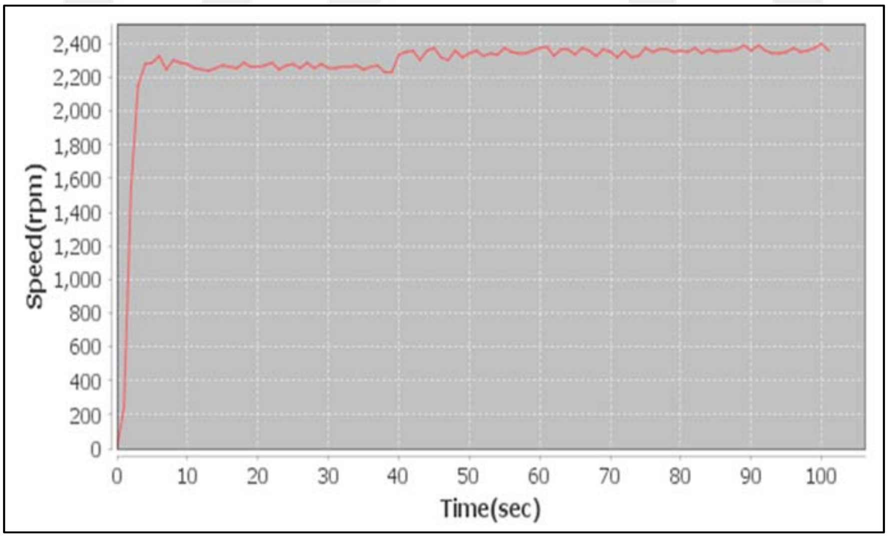

Figure 5.11: The decrease of buck converter's inductance in open loop control

Figure (5.12) shows the effect of the decrease in the buck converter's inductance in the close loop control system by making a short circuit on the terminals of the inductor (inductance value = 0). We can see that the speed of the fan increased for less than 5% of the sitting time for a period of time less than 2 sec then returns to the setting value quickly.

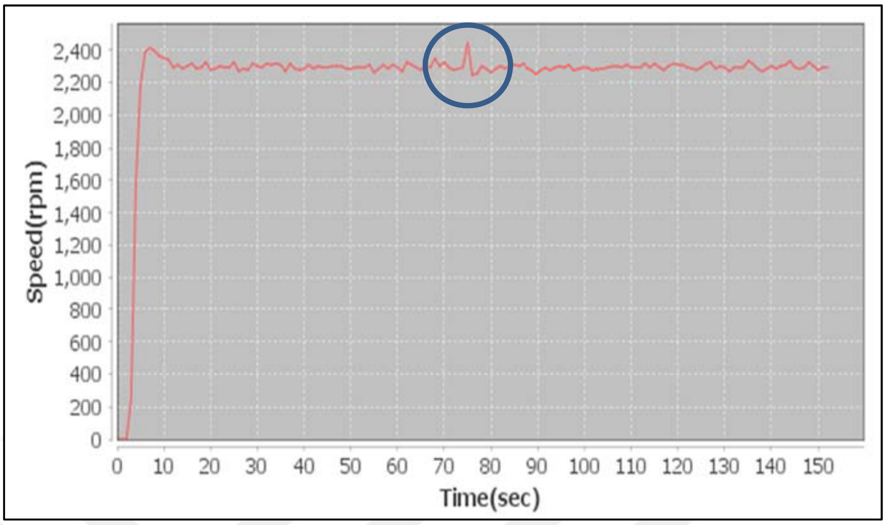

Figure 5.12: The decrease of the buck converter's inductance in the close loop control

5.5.4 The Effect of the Disturbance in the Internal Capacitance on the Dc Motor (Fan)

As shown in figure (5.13), the speed of the Dc motor (fan) increased when the value of the capacitor increased from 4.7µf to 24.7 µf in the open loop control. Figure (5.13) shows that the speed of the fan increased from 1900 rpm to 2100 rpm and continuous rising until the saturation of the new value of the capacitor happens.

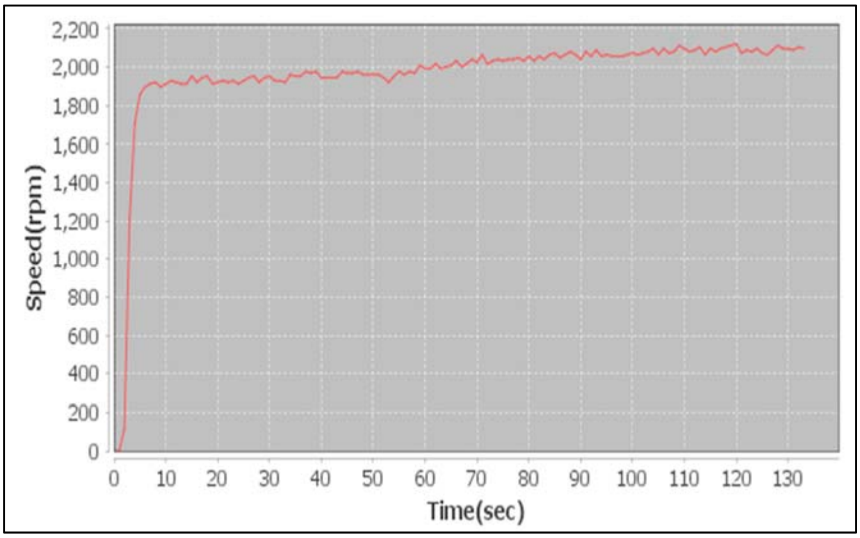

Figure 5.13: The increase of the buck converter's capacitance in the open loop control

Figure (5.14) shows the effect of increasing the buck converter's capacitance in the close loop control system by changing the capacitor value. By changing the capacitor value from 4.7µf to 24.7µf, we can see that the speed of the fan increased for less than 5% of the sitting time for a period of time less than 2 sec then returns to the setting value quickly.

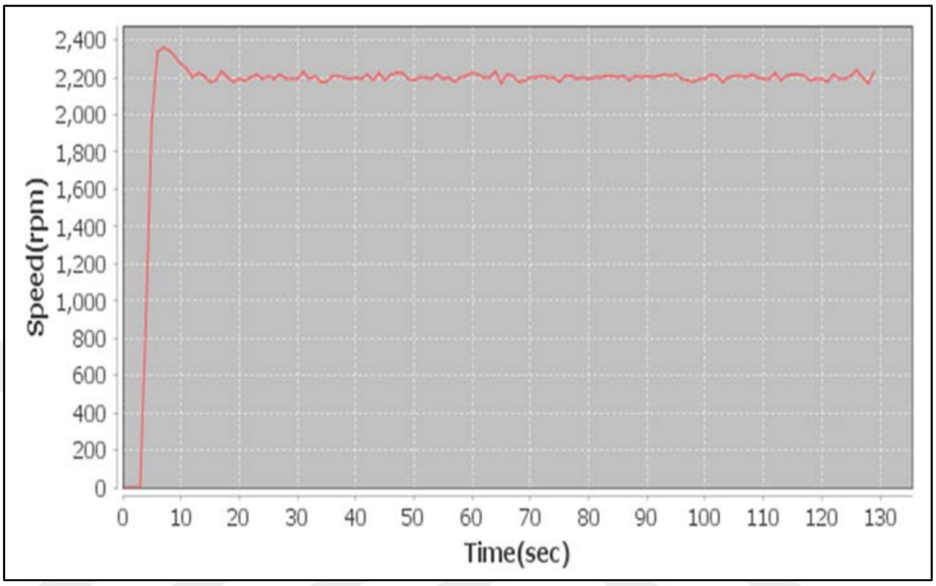

Figure 5.14: The increase of the buck converter's capacitance in the close loop control

5.5.5 The Effect of the All Internal and External Disturbance (Together) on the Closed Loop Control System With the Variable Desired Speed

Figure (5.15) shows the test result of our close loop control system when the desired speed is variable with time. To show the robustness of the control system, we applied all disturbance that we have applied before at the same time in this test. Although, all these disturbances have been applied at the same time, the actual speed deviates not more than 4% of the desired speed value for a period of time less than 3 sec.

Figure (5.16) shows the implementation of the same system with the same parameters in Matlab simulation to prove that the validity of implementing the control system in this thesis for any DC motor with different parameters in Matlab simulation or in practice model.

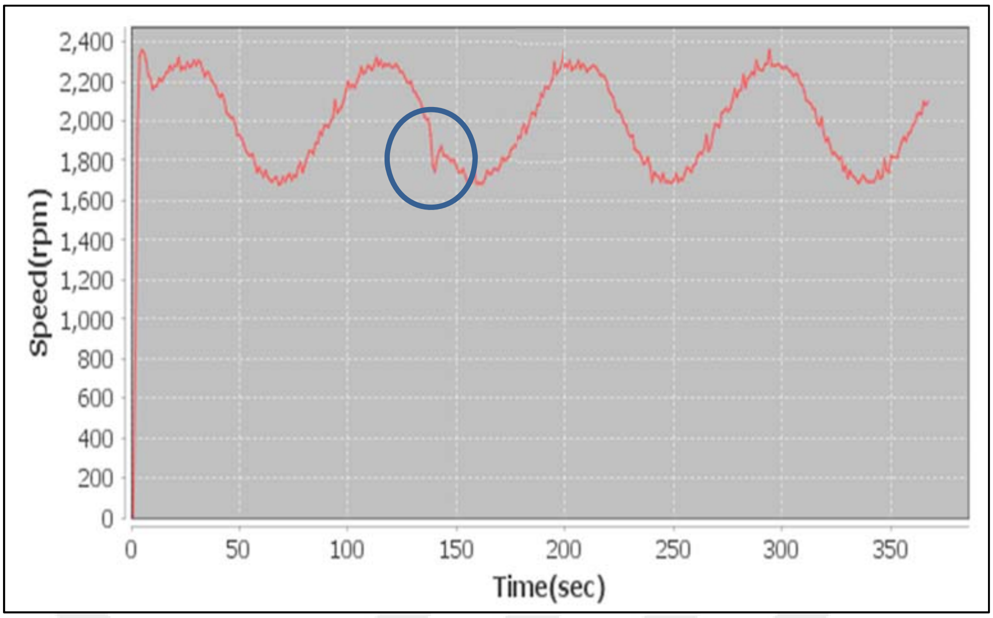

Figure 5.15: The disturbances effect on the DC motor when the desired speed is variable with time

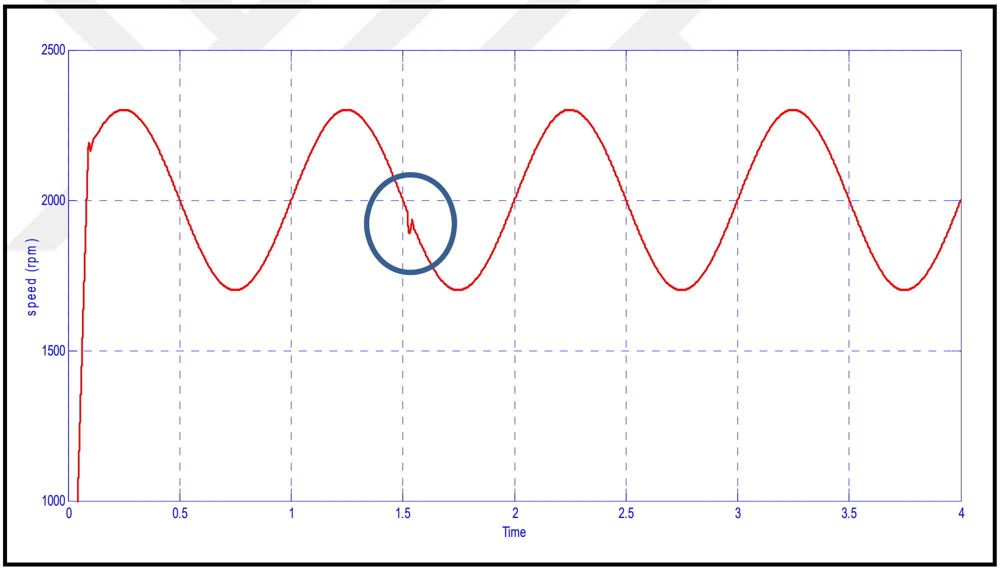

Figure 5.16: The disturbances effect on the DC motor when the desired speed is variable with time implemented in Matlab simulation

The previous results show the ability of the control system that has been designed to response to any external or internal change of the circuit parameters. The parameters that we have studied are examples for that and these tests can be implemented on any circuit parameter, in which the changing in its value causes a change in the DC motor speed. We can see a bit of variation between the simulation results and the practical results. This variation in results is related to the efficiency of the pieces that are used in our practical tests.

CHAPTER SIX

CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

The work presented in this thesis shows that the digital control of the Double Feedback Control Circuit By Using PID Controller and Pulse width modulation (PWM) is used to control the DC motor speed. The variation in the motor speed is obtained by varying the pulse width applied to the switch that was generated by using the Arduino UNO Kit. The speed of the DC motor is taken as a feedback and according to the difference between the set point speed and the present speed, the desired current value is set. By comparing the desired current value with the actual current value, in the inner control loop, the duty cycle of the PWM is specified, which is given as switching pulses to the buck converter. The DC motor finally reaches the desired speed and the closed loop speed control is achieved. This technique is also applied when the desired speed is variable with the time. To prove that the system is robust and the actual speed good tracks the desired speed, internal and external disturbance are applied to the control system.

In order to verify the effectiveness of the practical circuitry, the system model has been built using MATLAB program. The DC motor and the buck converter have been modeled with a closed loop control system of multiple loops, inner current control loop and outer speed control loop. This two loops including the PID controller. The validity of the system has been examined with different disturbance types.

The following conclusions are obtained from the thesis work:

1. The simulation of the closed loop DC motor control with multiple loop PID control optimize the tracking performance with fast dynamic response and robustness in the presence of the input speed variation or the transient loading condition.

2. Based on the controller requirements for the high performance motor drive, an Arduino UNO based system was designed, tested, and experimentally verified.
3. The system provides enough processing power and memory space for the execution of the modern control algorithms and gives the ability to control motor drives at high rotational velocities.
4. The system provides flexibility and easy interface to any of the major sizes of the motor drive.
5. The designed system provides easy method to change the speed without any change in the software.
6. The designed Buck converter circuit provides a pure DC source to the DC motor that gives a stable desired speed.
7. The experimental result of the motor response with the closed loop speed control system is less than 0.5% for a period of time not more than 0.04 Sec comparing with open loop speed control system it was more than 80 % and remains at this value.
8. DC motor speed control, based on the Double Feedback Control Circuit By Using PID Controller and Pulse width modulation (PWM) using Arduino UNO, has the following advantages: good control ability, fast dynamic response, and small overshoot.

There are some ideas for future work and recommendations to improve this research. The following points display these ideas:

1. Implementation of adaptive and intelligent controller such as neural network algorithm controller or fuzzy logic controller to the same system.
2. Implementing the multiple closed loop PID control practically.
3. Using FPGA chip (Soft Core Processor or Hard Core Processor) or DSP instead of Arduino UNO kit to control the speed of DC motor.
4. Applying the Double Feedback Control system on the other motors types.
5. Implementation of the Digital Signal Controller (DSC) for speed control of the DC motor.

REFERENCES

[1] Mohamed H. Rashid, "*Power Electronics Circuits, Devices and Applications*", Third Edition, Person Prentice Hall, ISBN 0-13-122815-3, 2004.

[2] http://www.inverter-plc.net/motor/bir_fazl%C4%B1_motorlar

[3] H. Xu, K. King, and Y. Jani, "*High Performance DC Chopper Speed and Current Control of Universal Motors Using a Microcontroller*", IEEE Industry Applications Conference, PP.701 -705, 2007.

[4] P. Mattavelli, L. Rossetto, G. Spiazzi, and P. Tenti, " General-purpose sliding-mode controller for DC/DC converter applications, " in *Proc. IEEE PESC Rec.,*pp. 609-615, Jun. 1993.

[5] P. Mattavelli, L. Rossetto, G. Spiazzi, and P. Tenti, " Small-signal analysis of DC/DC converters with sliding mode control, " *IEEE Trans. Power Electron*., vol. 12, no. 1, pp. 96-102, Jun. 1997.

[6] D. Logue and Philip. T. JSrein, "*Simulation of Electric Machinery and Power Electronics Interfacing Using MATLAB/ SIMULINK*", IEEE, PP. 34 – 39, 2000.

[7] S.E Lyshevski, *Electromechanical Systems, Electric Machines,and applied mechatronics. Boca Raton FL, USA: CRC press 1999.*

[8] J. Linares-Flores and H. Sira-Ramı́rez, "A smooth starter for a DC machine: A flatness based approach," in *Proccedings of the 1st Interna-* Mexico, Sep. 8–10, 2004, pp. 589–594.

[9] J. Linares-Flores and H. Sira-Ramı́rez, "Sliding mode-delta modulation *of the 2nd IFAC Symposium on System Structure and Control*, Oaxaca, Mexico, Dec. 8-10-2004,PP.405-409.

[10] J. Linares-Flores and H. Sira-Ramı́rez, "DC motor velocity control through a DC-to-DC power converter, " in proccedings of the IEEE 43rd 9*Conference on Decision and Control*, Atlantis, The Bahamas, Dec. 14–17,2004. vol. 5, PP. 5297-5302.

[11] R. Ortega, A. Loria, P. J. Nicklasson, and H. Sira-Ramı́rez, *Passivity- Based Control of Euler-Lagrange Systems* London, U.K.: Springer- Verlag, 1998.

[12] H. El Fadil and F. Giri, “Accounting of DC-DC power converter dynamics in DC motor velocity adaptive control,” in *Proccedings of the IEEE International Conference on Control Applications*, Munich, Germany, Oct. 4–6, 2006, pp. 3157–3162.

[13] M. A. Ahmad, R. M. T. Raja Ismail, and M. S. Ramli, “Control strategy of buck converter driven DC motor: A comparative assessment,” *Australian Journal of Basic and Applied Sciences*,, vol. 4, no. 10, pp.4893–4903, 2010.

[14] R. Sureshkumar and S. Ganeshkumar, “Comparative study of pro- portional integral and backstepping controller for buck converter,” in *Proccedings of the International Conference on Emerging Trends in Electrical and Computer Technology,* Tamil Nadu, India, Mar. 23–24,2011, pp. 375–379.

[15] *M.* Z. M. Tumari, M. S. Saealal, M. R. Ghazali, and Y. A. Wahab, “H-infinity with pole placement constraint in LMI region for a buck- converter driven DC motor,” in *Proccedings of the IEEE International Conference on Power and Energy*, Kota Kinabalu Sabah, Malaysia, Dec 2-5,2012,PP. 530-535.

[16] H. Sira-Ramı́rez and M. A. Oliver-Salazar, “On the robust control of Buck-converter DC–motor combinations,” *IEEE Transactions on Power Electronics*, vol. 28, no. 8, pp. 3912–3922, 2013.

[17] R.Silva-Ortigoza, J. R. García-Sánchez, J. M. Alba-Martínez, V. M. Hernández-Guzmán, M. Marcelion-Aranda, H. Taud, and R. Buatista-Quintero," Tow-stage control design of a buck converter/ DC Motor system with velocity measurements via a *Σ-Δ* modulator " *Math. Prob. Eng.,* vol. 2013, pp. 1-11, 2013. [Online]. Available: http:/dx.doi.org/10.1155/2013/929316.

[18] Ramón Silva-Ortigoza, Victor Manuel Hernández-Guzmán, Mayra Antonio-Cruz, and Daniel Muñoz-Carrillo, " DC/DC Buck Power Converter as a Smooth Starter for a DC Motor Based on a Hierarchical Control " *IEEE Transactions on Power Electronics*, vol. 30, no. 2, FEBRUARY 2015. [Online]. Available: http://www.ieee.org/publications_standards/publications/rights/index.html

[19] Theraja, B. L., and R. S. Sedha. *A textbook of electrical technology*. 2006.

[20] K. Sundareswaran and M. Vasu, “*Genetic Tuning of PI controller for Speed Control of DC Motor Drive*”, IEEE,PP. 521-525 vol.2, 2000

[21] https://www.electrical4u.com/types-of-dc-motor-separately-excited-shunt-series-compound-dc-motor/

[22] V.K. Chinnaiyan, J. Jerome, J.Karpagam and S. S. Mohammed, “*Design and Implementation of High Power DC-DC Converter and Speed Control of DC Motor Using TMS320F240 DSPS*”, IEEE Proceedings of India International Conference on Power Electronics, PP. 388-392, 2006.

[23] J. Zhou, Y. Wang and R. Zhou, “*Global Speed Control of Separately Excited DC Motor*”, IEEE, PP. 1425-1430, 2001.

[24] Y. S. Ettomi, S. B. M. Noor, S. M.Bashi and M. K. Hassan, “*Micro Controller Based Adjustable Closed-Loop DC Motor Speed Controller*”,IEEE- SCOReD, PP.59-63, 2003.

[25] Hughes, Austin, and Bill Drury. *Electric motors and drives: fundamentals, types and applications*. Newnes, 2013.

[26] https://www.scribd.com/document/195893391/DC-MOTOR-2

[27] Katsuhiko Ogata “*Modern Control Engineering*”, Fourth Edition, Prentice-Hall, Inc 2002.

[28] B. J. Patella, A. Prodic, A. Zirger and D. Maksimovic, “*High-Frequency Digital PWM Controller IC for DC–DC Converters*”, IEEE Transactions on Power Electronics, VOL. 18, NO. 1, JANUARY 2003.

[29] F. Antritter, P. Maurer and J. Reger, “*Flatness Based Control Of A Buck-Converter Driven Dc Motor*”

http://www.rt.e-technik.uni-erlangen.de/PUBLIKATIONEN/PDF/Antritter2006_154.pdf.

[30] Timothy L.Skvarenina., "*The Power Electronics Handbook*”, Industrial Electronics Series, CRC Press LLC. ISBN 0-8493-7336-0, 2002.

[31] K. M. Smedley, and S. Cuk, “*One-Cycle Control of Switching Converters*”, IEEE Transactions on Power Electronics, PP.625-633, VOL. 10, NO. 6,1995.

[32] Yangyang Wen, “*Design And Implementation Of A Digital Controller With DSP For Half-Bridge DC-DC Converters*”, M.Sc thesis, University of Central Florida, 2004.

[33] F. Hsieh, N. Yen and Y. Juang, "*Optimal Controller of a Buck DC–DC Converter Using the Uncertain Load as Stochastic Noise*", IEEE Transactions on Circuits and Systems: Express Briefs, VOL. 52, NO. 2, FEBRUARY 2005.

[34] Richard C. Dorf, Robert H. Bishop,," *Modern Control Systems*", Eleventh edition, Pearson Education, Inc., ISBN 0-13-20L710-2, 2008.

[35] Texas Instruments Inc., "*TMS320x281x DSP Event Manager (EV) Reference Guide*", Literature Number SPRU065E, June 2007.

[36] IEEE Power Engineering Society, "*IEEE Guide: Test Procedures for Direct-Current Machines*", IEEE Std ll3-1985.

[37] GOPAL, Madan. *Control systems: principles and design*. Tata McGraw-Hill Education, 2002.

[38] Czarkowski, Dariusz; Kazimierczuk, Marian K. Energy-conservation approach to modeling PWM DC-DC converters. *IEEE Transactions on Aerospace and Electronic systems*, 1993, 29.3: 1059-1063.

[39] Nagrath, I. J. *Control systems engineering*. New Age International, 2006.

[40] https://www.multisim.com/help/components/pulse-width-modulation-pwm-components.

[41] P. D. Minns, C Programming For the PC the MAC and the Arduino Microcontroller System. Author House, 2013.

APPENDIX

Appendix-A: DC Motor Parameters

A 1. DC Motor Parameters

To find the parameters of the separately excited DC motor, a laboratory DC motor producers by TERCO Company have been chosen, as a sample to applying our control circuit on it. The model of the DC motor that have been chosen is shown in the figure (A1.1):

MV1028 DC Machine

Complete with interpoles. This machine is used in test machine sets such as motors or generators, mounted on a 10 mm thick anodized aluminium plate to be placed on the machine bed MV 1004.

General Data	MV1028-225	MV1028-226
Generator	2.2 kW 1500 rpm	2.2 kW 1800 rpm
Motor	2.0 kW 1400 rpm	2.0 kW 1700 rpm
Excitation	220 V 0.8 A	220 V 0.8 A
Armature	220 V 12 A	220 V 12 A
Moment of inertia	J = 0.012 kgm²	
Dimensions	465 x 310 x 310 mm Shaft height 162 mm	
Weight	50 kg	

MV1028-225 is designed for tests on AC motors with 50 Hz ratings.
MV1028-226 is designed for tests on AC motors with 60 Hz ratings.

MV1034-225 and MV1034-226 DC-Machine

Same as MV 1028 but with through shaft with two couplings.
For central mounting on the machine bed.
See also text under MV1026-225 resp. MV1026-226 (Page 7)

Figure A1.1: Data sheet of MV1028-255 model of DC motor from TERCO company

A 1.1 The parameter value from the data sheet

The power of DC motor (P) and the speed of DC motor (ω) and the armature current (I_a) and the armature voltage (V_a) and the field winding (Excitation) current (I_f) and the field winding (Excitation) voltage (V_f) and the moment of inertia are existed in the data sheet of produced company as shown below.

The power of DC motor (P) = 2 KW

The speed of DC motor (ω) = 1500 rpm

The armature current (I_a) = 12A

The armature voltage (V_a) = 220V

The field winding (Excitation) current (I_f) = 0.8A

The field winding (Excitation) voltage (V_f) = 220V

The moment of inertia (J) = 0.012kgm^2

A 1.2 DC Motor Tests:

To find the parameters of the DC motor, several tests have been done, as shown in the following subsections:

A 1.2.1 AC Test on the Armature Winding

The armature windings resistance (R_a) and inductance (L_a) are obtained by applying single phase 50 Hz alternating voltage to the armature circuit terminals of the machine as shown in Figure (A1.2).

The values R_a and L_a are calculated where R_a is equals (5.97 Ω) and the value of L_a is equals (60.57mH). The following equations were used to find these values [28].

$$\theta = \cos^{-1}\frac{P}{VI} \qquad (A1-1)$$

$$\theta = \cos^{-1}\frac{723.9}{220*11}$$

$$\theta = 1.26$$

$$Z = \frac{V}{I} \qquad (A1-2)$$

$$Z = \frac{220}{11} = 19.95$$

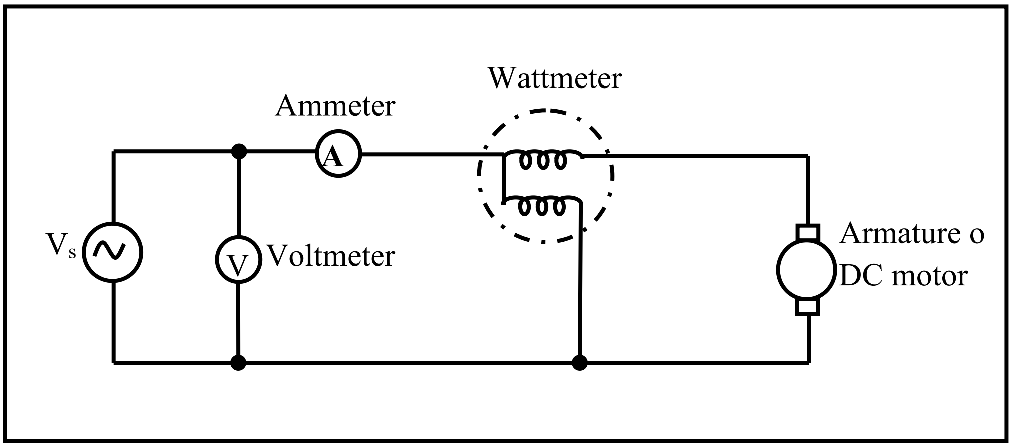

Figure A1.2: Circuit diagram of AC test to find R_a and (L_a)

$$R_a = z\cos\theta = 5.97\Omega \qquad (A1-3)$$

$$X = z\sin\theta = 19 \qquad (A1-4)$$

$$L = \frac{X}{2\pi f} = 60{,}57\ mH \qquad (A1-5)$$

A 1.2.2 Direct Current (DC) Test on the Field Winding

The field winding resistance (R_f) of the DC motor is obtained by applying DC voltage on the field and according to equation (A1-6) the value of R_f is found, and its equals 246.7Ω. The circuit diagram is shown in Figure (A1.3).

$$R_f = \frac{V}{I} = \frac{220}{0.89} = 246.7 \qquad (A1-6)$$

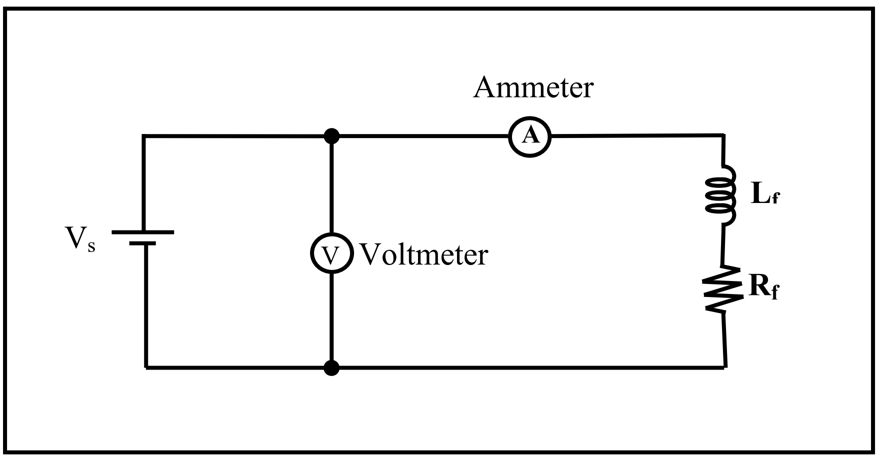

Figure A1.3 Circuit diagram of (DC) test on the field winding.

A 1.2.3 AC Test on the Field Winding

AC test is used to calculate the field inductance L_f, by connecting the circuit as shown in Figure (A1.4). And according to the following formula, the value of L_f will be calculated and its equals 52H.

$$Z = \frac{V_s}{I} = \frac{220}{0.0094} = 23255 \qquad (A1-7)$$

$$X_L = \sqrt{Z^2 - (R_{ex} + R_f)^2} \qquad (A1-8)$$

$$X_L = \sqrt{(23255)^2 - (16300 + 246.7)^2} = 16340$$

$$L_f = \frac{X_L}{2\pi f} = \frac{16340}{2*\pi*50} = 52H \qquad (A1-9)$$

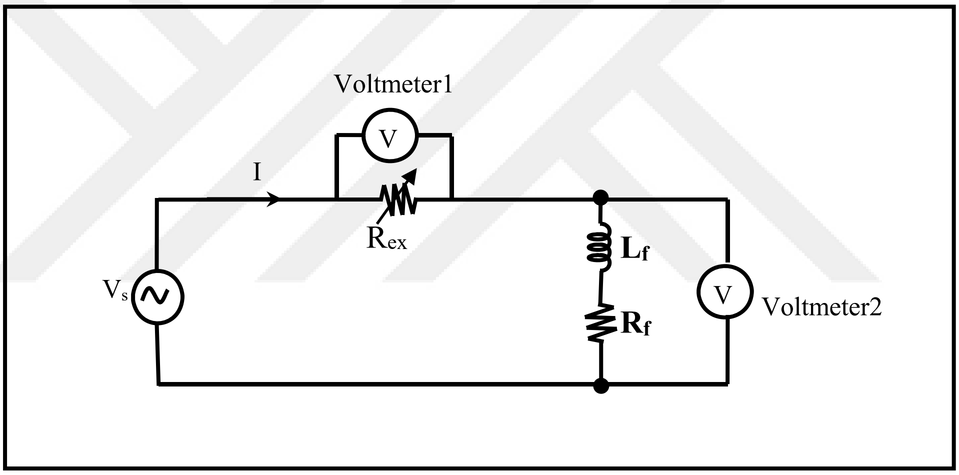

Figure A1.4 Circuit diagram of (AC) test on the field winding.

Next, the DC motor was connected as a generator (with no load) to make $E_a = V_a$. Different readings of the rotor speed (N) is used to obtain different values of the armature inductance voltage E_a. Then the average value of E_a is used to calculate K_E according to the following equation and it is equals 1.3(V/A- rad/s).

$$K_E = \frac{E_a}{\omega} \qquad (A1-10)$$

Where E_a is equable to V_a at no load which is the voltmeter reading across the armature winding.

Now To calculate the mutual inductance L_{af}, the following name plate values are used:

First we need to convert the speed of DC motor from rpm (revolutions per minute) to rad.s^{-1}, if N turns are performed in one minute, (N/60) turns are performed in one second. So one turn is equal to 2π radians.

$$\omega[rad.s^{-1}] = \frac{2\pi}{60} * N[rpm] \quad (A1-11)$$

$$\omega[rad.s^{-1}] = \frac{2\pi}{60} * 1500 = 157 \quad (A1-12)$$

and

Power of DC motor is 2 KW

Speed is 1413 rpm

Armature current I_a = 12 Ampere

Then, the rated load torque is:

$$T_L = \frac{P}{\omega} = \frac{2000}{148} = 13.5N.m \quad (A1-13)$$

In the steady state condition

$$J\frac{d_\omega}{d_t} = 0 \quad (A1-14)$$

By using equation (2-6) and (2-7), viscous friction coefficient (B) is calculated, and it is equal to 0.014 N.m.s.

By using equation (2-4), the mutual inductance (L_{af}) is calculated, and it is equal to 1.6H.

A 1.2.4 Constant Losses Test

To find the moment of inertia, the constant losses must be found firstly. Constant losses consist of rotational and magnetic losses. The value of the armature voltage (which is the same as the field voltage since the connection of the motor is shunt connected) as shown in Figure (A1.5). The DC motor constant losses can be calculated according to the following equations [28].

$$P_{acu} = I_a^2 * R_a \quad (A1-15)$$

$$P_{acu} = 2^2 * 5.97 = 24.84w$$

$$P_{fcu} = I_f^2 * (R_f + R_{ex}) \quad (A1-16)$$

$$P_{fcu} = 0.75^2 * (246.7 + 46) = 164.6w$$

$$P_{in} = I_{in} * V_{in} \qquad (A1-17)$$

$$P_{in} = 2.78 * 220 = 613.36$$

$$P_c = P_{in} - (P_{acu} + P_{fcu}) \qquad (A1-18)$$

$$P_c = 613.36 - (24.84 + 164.6) = 423$$

Where

P_{acu} Armature circuit copper losses.

P_{fcu} Field circuit copper losses.

P_c Constant losses.

R_{ex} = external resistance connected in series with the field circuit of the DC motor

And according to the following formula, the torque (T_2) due to friction and iron losses will be calculated.

$$T_2 = \frac{P_c}{\omega} \qquad (A1-19)$$

$$T_2 = \frac{423}{172.7} = 2.45$$

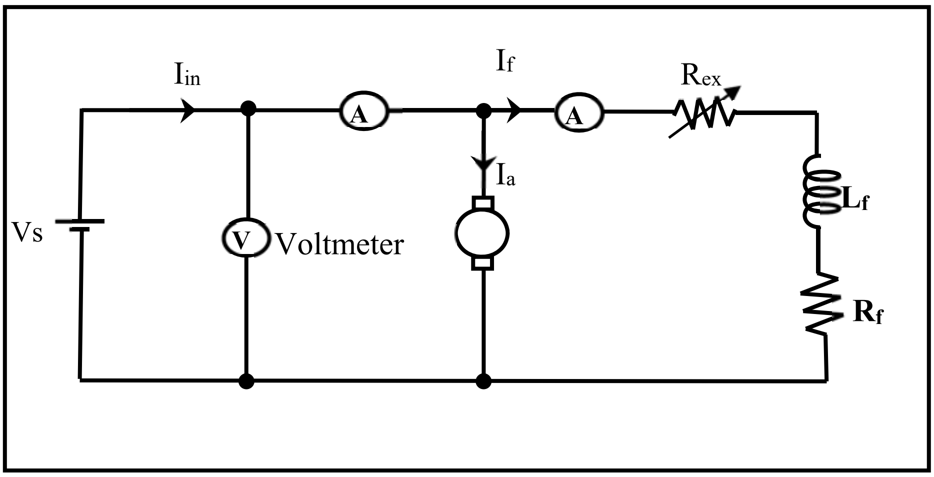

Figure A1.5: Circuit diagram for constant losses test

A 1.2.5 Retardation Test to Calculate Moment of Inertia (J) of the motor

The circuit was connected as shown in Figure (A1.6) then running the motor at speed (n_1) 10% above the rated speed after that open the switch (S) and record the time (t) taken by the machine to slow down to speed (n_2) 10% below the rated speed. From equation (A3-20) the moment of inertia can be calculated, and it is equal to 0.012 Kg.m^2.

$$J = \frac{T_2 * t}{2\pi(n_1 - n_2)} \qquad (A1 - 20)$$

$$J = \frac{2.45 * 0.96}{2 * \pi * (172.7 - 141.3)} = 0.012$$

Where n_1 and n_2 are motor speed in rad/s and T_2 can be found from the previous test.

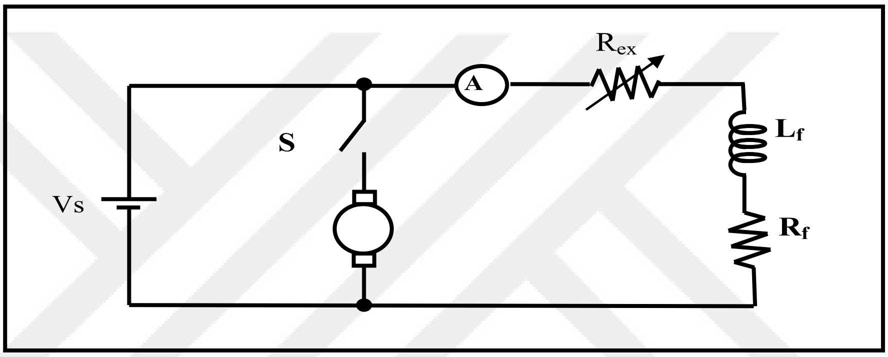

Figure A1.6: Circuit diagram of retardation test.

Appendix B: IDE Sketch

(Arduino code for close loop control system)

```
#include <PID_v1.h>

#include <PWM.h>

#define PIN_OUTPUT 3

#define PIN_INPUT 2

int32_t frequency = 1000;

//int j =0; variable used when variable speed wanted

// current sensor definitions................

float analogIn = A0;

int mVperAmp = 100; // use 100 for 20A Module

int RawValue= 0;

int ACSoffset = 512;

double Voltage = 0;

double Amps = 0;

// PIDs definitions............................

double Setpoint, Input, Output;

double Setpoint01, Input01, Output01;

float Kp = 0.04, Ki = 1.6, Kd = 0.001;
```

```
float Kp01 = 0.11, Ki01 = 3, Kd01 = 0.008;
PID myPID(&Input, &Output, &Setpoint, Kp, Ki, Kd, DIRECT);
PID myPID01(&Input01, &Output01, &Setpoint01, Kp01, Ki01, Kd01, DIRECT);
// speed sensor definitions.................
int sampleTime = 1000, double sped = 0, int rpm = 0;
 double lastsped = 0, int sampleRate = 100;
void setup() {
pinMode(PIN_INPUT,INPUT);
pinMode(PIN_OUTPUT,OUTPUT);
Setpoint = 2100;
myPID.SetMode(AUTOMATIC);
myPID01.SetMode(AUTOMATIC);
myPID.SetSampleTime(sampleRate);
myPID01.SetSampleTime(sampleRate);
Serial.begin(9600);}
void loop() {
// calculate the speed……………
int rpm=getRPM(); }
int getRPM() {
//{ for (int j=0;j<360;j++);
//{ Setpoint = 2000+300*sin(6*j*DEG_TO_RAD); when variable speed wanted.
 { int kount=0;
 boolean kflag=LOW;
 unsigned long currentTime = 0;
```

```
unsigned long startTime = millis();
while (currentTime<=sampleTime) {
if (digitalRead(PIN_INPUT)==HIGH) {
kflag=HIGH; }
if (digitalRead(PIN_INPUT)==LOW && kflag==HIGH) {
kount++, kflag=LOW; }
currentTime = millis()- startTime; }
int sped = int(60000./float(sampleTime)/7)*kount;
// current measurement loop...........................
RawValue = ACSoffset - analogRead(analogIn);
Voltage = (RawValue / 1024.0) * 5000; // Gets you mV
Amps = ((Voltage) / mVperAmp);
//......................................................
Input = sped;
myPID.Compute();
Input01 = Output;
myPID01.Compute();
pwmWrite(PIN_OUTPUT,Output01);
// output display....................
Serial.println(sped);
//Serial.print(" ");
//Serial.println(Setpoint);}}
//}
```

Appendix-C: The Java Code of Eclipse Program

```
package osamacon;
import java.awt.BorderLayout;
import java.awt.event.ActionEvent;
import java.awt.event.ActionListener;
import java.util.Scanner;
import javax.swing.JButton;
import javax.swing.JComboBox;
import javax.swing.JFrame;
import javax.swing.JPanel;
import org.jfree.chart.ChartFactory;
import org.jfree.chart.ChartPanel;
import org.jfree.chart.JFreeChart;
import org.jfree.chart.plot.PlotOrientation;
import org.jfree.data.xy.XYSeries;
import org.jfree.data.xy.XYSeriesCollection;
import com.fazecast.jSerialComm.SerialPort;
public class osamacon {
	static SerialPort chosenPort;
	static int x = 0;
	public static void main(String[] args) {
		// create and configure the window
		JFrame window = new JFrame();
```

```
			window.setTitle("osamacon GUI");
			window.setSize(600, 400);
			window.setLayout(new BorderLayout());
			window.setDefaultCloseOperation(JFrame.EXIT_ON_CLOSE);
			// create a drop-down box and connect button, then place them at the
top
			JComboBox<String> portList = new JComboBox<String>();
			JButton connectButton = new JButton("Connect");
			JPanel topPanel = new JPanel();
			topPanel.add(portList);
			topPanel.add(connectButton);
			window.add(topPanel, BorderLayout.NORTH);
			// populate the drop-down box
			SerialPort[] portNames = SerialPort.getCommPorts();
			for(int i = 0; i < portNames.length; i++)
				portList.addItem(portNames[i].getSystemPortName());
			// create the line graph
			XYSeries series = new XYSeries("capacitance");
			XYSeriesCollection dataset = new XYSeriesCollection(series);
			JFreeChart xyLineChart = ChartFactory.createXYLineChart("",
"Time(sec)", "Speed(rpm)", dataset,PlotOrientation.VERTICAL, true, true, false);
			window.add(new ChartPanel(xyLineChart), BorderLayout.CENTER);
			// configure the connect button and use another thread to listen for
data
			connectButton.addActionListener(new ActionListener(){
				@Override public void actionPerformed(ActionEvent arg0) {
					if(connectButton.getText().equals("Connect")) {
				// attempt to connect to the serial port
			chosenPort =
SerialPort.getCommPort(portList.getSelectedItem().toString());
		chosenPort.setComPortTimeouts(SerialPort.TIMEOUT_SCANNER, 0, 0);
						if(chosenPort.openPort()) {
```

```
connectButton.setText("Disconnect");
portList.setEnabled(false); }

// create a new thread that listens for incoming text and populates the graph
Thread thread = new Thread(){
@Override public void run() {
Scanner scanner = new Scanner(chosenPort.getInputStream());
while(scanner.hasNextLine()) {
try {String line = scanner.nextLine();
int number = Integer.parseInt(line);
series.add(x++, number);
window.repaint();
} catch(Exception e) {}}
scanner.close();}};
thread.start();  } else {
// disconnect from the serial port
chosenPort.closePort();
portList.set Enabled (true);
connectButton.setText("Connect");
series.clear();
x = 0;  }}});
// show the window
window.setVisible(true);}}
```

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