PARAMETER IDENTIFICATION AND CONTROL OF DC MOTOR USING CURVE FITTING TECHNIQUE

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CERTIFICATE

I hereby certify that the work which is being presented in the dissertation entitled, **"Parameter Identification and Control of DC motor using Curve Fitting Technique"**, in partial fulfillment of the requirements for the award of degree of Master of Engineering in Power system and electrical drives submitted in Electrical and instrumentation Engineering Department of Thapar University, Patiala, is an authentic record of my own work carried out under the supervision of Mr. Souvik Ganguli, Assistant Professor, EIED

The matter presented in the dissertation has not been submitted for award of any other degree of this or any other University.

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This is to certify that the above statement made by the candidate is correct and true to the best of my knowledge.

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ABSTRACT

In this work we have employed curve fitting technique for identification of dc motor parameters and control. A dc motor is modeled using armature control method. The block diagram generated from the dynamic equation is used for obtaining the transfer functions. Here we have used transfer function approach for finding the parameters of separately excited dc motor viz. armature resistance, armature inductance, back emf constant, moment of inertia, viscous friction. The mechanical parameters are obtained using curve fitting technique. Thereafter we have controlled the dc motor using PI controller for improvement in its response. There are different classical tuning methods to control the parameters of controller but here we have applied Zeigler Nichols method for tuning the open loop parameters.

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CHAPTER 1
INTRODUCTION

1.1 Background of Work

Separately excited dc motors are mainly used as actuators in industrial applications. These motors have the advantage of having low friction, small size, high speed, low construction cost and high torque. The mathematical modeling is one of the most important and often the most difficult step towards understanding physically a DC motor, an accurate model is required for developing the motor equations, transfer function that relates the input & output data. There are few parameters of the DC motor that are complicated to determine using measurements. Hence we need parameter estimation techniques [8].

Parameter identification was first introduced by Zadeh (1956) as a generic expression problem of “determining the input-output relationships of a black box by experimental data. With the advancement in control engineering dynamic model identification has been a major topic of interest and has many industrial and military applications. So parameter identification is emerging as a topic of great importance, because for almost every servo control design a mathematical model is needed and parameter identification is often the only means of obtaining mathematical models of most physical systems because most systems are usually so complex that, unlike dc motors, there is no easy way to derive their models based on the physical laws. Earlier techniques used for DC motor parameter identification viz. Recursive least estimation techniques [9], least square [1], moment method [16], pasek algebraic parameter identification technique [25] and steepest descent gradient method etc. Due to some limitation in classical methods, the recent trend is to use intelligent method algorithm for DC motor identification viz. curve fitting technique [28], Adaptive Tabu Search Method, Radial Basis Function Neural Network (RBF), Genetic Algorithm (GA) [21].

1.2 Objective of Work

The dissertation fulfills the following objectives:

- Measuring the electrical parameters Ra ,La using LCR meter

- Calculating Back emf constant
- Obtaining mechanical parameters viz. moment of inertia and viscous friction coefficient employing curve fitting technique considering step response data.
- Designing Controller for D.C motor by using Ziegler Nicolas’s method using curve fitting technique

1.3 Organization of the Dissertation

Chapter 1 discuss the introduction & need of system identification and Background of work done in the field of parameter identification and control of D.C motor.

Chapter 2 discuss the Literature survey including past techniques and researches that are chronologically surveyed that can help in developing new technologies used for parameter identification purposes.

Chapter 3 discuss some of the popular parameter identification techniques, highlighting their merits and demerits as well. Several D.C motor parameter identification techniques viz, curve fitting technique, least square method, recursive least square technique, inverse methodology, neural network, genetic algorithm etc, are discussed and compared.

Chapter 4 discuss the basic model of a separately excited DC motor drive. In this chapter Transfer functions and state space models are derived for position and speed control applications**.** An introduction about curve fitting technique & controller design is given for obtaining the mechanical results.

Chapter 5 presented the results obtained using curve fitting technique to identify the motor parameters. The control results using PI controller & the controller parameters obtained using Zeigler Nicolas method are shown.

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CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In this chapter a review of existing literature is carried to support the study undertaken in this thesis. The past techniques and researches are chronologically surveyed that can help in developing new technologies used for parameter identification purposes. So prior to presenting the framework, this chapter will provide a brief overview of the literature on parameter identification.

2.2 Literature survey

Bodson *et al.* [1] introduced a method in which parameters were identified through a least-squares algorithm. Stochastic analysis that assume bounded noise, and a sensitivity analysis were also reviewed. After the analysis predicted results were compared with the results of experimental data obtained on a DC motor. The uncertainty estimation method is justified in the context of adaptive control, requiring robustness and transient performance was namely flight control. This new method of adaptive algorithm both provided parameters and estimated uncertainty affecting these parameters.

Restrepo *et al.* [2] proposed the use of least square method to determine drive chain parameters of robot joints such as drive gain parameters composed of amplifier gain, bandwidth, motor torque constant and friction coefficients. Two methods can be used either by determining the motor torque constant Kt, and amplifier gain Ga separately or by global identification of Gt and friction parameters.

Saab *et al.* [11] introduced a method to estimate the parameters of a DC motor experimentally employing discrete measurements of an integrated dynamometer. Discrete measurements using integrated dynamometer was used for determining the parameters of a DC motor. The main advantage of this method was that it could identify the parameters of a DC motor without the use of a D/A converter and a power amplifier.

Eker *et al.* [4] introduced discrete-time on-line identification of a permanent-magnet DC motor under open-loop conditions. The data in discrete form was obtained from experimental results on PMDC motor. For matching the actual and predicted results then root mean square error criterion was employed used. The linear difference equations obtained from I/O data was used for motor modeling.

Omar *et al*. [5] designed a controller based on gain-scheduling feedback to move a load on a gantry crane from point to point within one oscillation cycle and without inducing large swings. This controller could effectively reduce load oscillations and take reasonable time for load transferring. A mathematical model was taken and an offline identification based on least square method was used. The settling period was considered equal to the oscillation period. The unknown parameters such as friction coefficients were obtained and validated.

Zhu *et al*. [6] provided a new insight into least squares regression and immediately applied it for estimating the parameters of nonlinear rational models. From the beginning the ordinary explicit expression for linear in the parameters model was expanded into an implicit expression. Then a generic algorithm in terms of least squares error was developed for the model parameter estimation. It also proved that a nonlinear rational model can be expressed as an implicit linear in the parameters model, therefore, the developed algorithm could be comfortably revised for estimating the parameters of the rational models.

Soliman *et al*. [11] proposed the application of the least square error parameter identification algorithm for obtaining the parameters of separately excited DC motor. The unknown parameters considered were the resistance and inductance of the armature windings (Ra. La), the motor inertia, the damping constant, the torque and back emf constant (K) and load torque constant. The least squares error estimation algorithm was utilized in identifying the parameters of separately excited dc motor.

Kapun *et al.* [8] Stated an off-line identification method developed on the basis of least-squares approximation technique and a closed-loop method was used for identifying the parameters of a BLDC motor model .This method was used for determining data such as back-EMF harmonics and mechanical parameters (torque constant, viscous friction coefficient, and Coulomb friction coefficient). The initial parameters used were phase currents, position of rotor and speed of rotor. The effectiveness of method was verified by experimental results performed on a low-power BLDC motor.

Arshad *et al.* [9] proposed a method for finding the parameters of a simple DC motor using the two basic algorithms ordinary Least Squares (OLS) and Recursive Least Squares (RLS). For a simple SISO DC motor input and output in the form of voltage and rotation were applied to the parameter estimator. Algorithms like LS and RLS were there upon applied and the results obtained after using them were compared. The accuracy of the results obtained depends on the algorithm that is applied inside estimator block.

Salah *et al.* [25] stated a method for parameters identification of a permanent magnet dc motor .In this method the rotor voltage, current and speed of rotor were obtained experimentally using the NIDAQ USB-6008 data acquisition module. Required data signals were obtained using DAQ toolbox and Simulink in MATLAB signals. For identification of parameters nonlinear least square method was applied.

Moetezuma *et al.* [11] proposed parameter identification methodology based on a discrete-time least square Algorithm. The parameterization was obtained using operational calculus employing AIM (Algebric identification method). The operational calculus was combined with least square algorithm applying AIM eliminated disturbances using operational calculus to the model of a DC motor and also filter out high frequency noise.

Nassef *et al.* [12] presented a procedure for short time identification of feed drive systems using non linear least square algorithm. First of all system Response was measured and then the system transfer function coefficients could be obtained using LS algorithm. For induction motor non linear least square has been used.

Turner *et al.* [13] presented the utilization of least square technique to determine parameters for mathematical model employing LabView. Using least square method the system model parameters were determined and the method was utilized to filter noise from data. The mathematical model of dc motor was used for LS parameter estimation .The response of system after simulation was compared with the measured response of the plant. A filtered signal is used for LS algorithm and filtering software was obtained in NI LabView. Measured analog voltage was used with LS algorithm to generate motor model parameters.

Garrido *et al.* [14] proposed a closed loop identification method for position controlled dc servomechanisms. A Proportional Derivative (PD) controller was used for servo model control .The error between output and estimated parameters was used in identification of motor parameters.

Hadef *et al.* [24] proposed a parameter identification method using inverse problem methodology. The objective function w.r.t desired vector was minimized and the unknown parameters were estimated using conjugate gradient method. The end results were verified using Tikhonov's regularization method.

Wei Wu *et al.* [16] proposed a method based on Taylor series for DC motor parameter identification. A constant voltage was applied and motor speed response was sampled these samples were fitted in the coefficients of Taylor series .The motor mechanical and electrical constant can be obtained through these coefficients .This method required only a speed sensor ,No current measurements was required. For curve fitting least square method was used.

Colorado *et al.* [17] introduced the method of parameter estimates for a closed loop identification applied to DC servomechanism with bounded signal and a PD controller. The parameters such as controller gain which may appear in identification algorithm were taken into account on performing identification based on closed loop condition. In applications like servo mechanism if the model is not BIBO stable then it could lead to undesired effects. Hence for Robotic applications and for better security closed loop parameter identification was used.

Wei *et al.* [18] introduced application of adaptive Kalman filtering to system identification to acquire the accurate model of a brushless DC motor, the identification method for the motor based on adaptive Kalman filtering algorithm was proposed by computing the maximum likelihood estimation of the innovation variance and was used to modify the filter gain, the influence of variable measurement noise was restrained and the parameters was estimated accurately.

Kaed Bey et *al.* [19] introduced a discrete measurement of an integrated dynamometer for estimating the parameters of a DC motor .The unknown parameters involved were motor armature winding resistance and inductance, back e.m.f. constant, motor torque constant, moment of inertia, and the viscous friction. For filtering purpose a Kalman filter was implemented, to estimate the angular acceleration and the derivative of the armature current. An I/P dc signal was used and DC parameters were decoupled from AC parameters and these dc parameters were then used for obtaining the AC parameters.

Muhammad *et al.* [20] provided identification and control of a DC motor using Parametric Estimation Method (PEM) and an LQR optimal controller was designed to control the position and speed of the motor. System identification was used which provided more brief results than obtained from mathematical modeling. For a multilayer perceptron network artificial neural network was employed. For identification input and output signals were directly measured and mathematical model was used for estimating the DC motor parameters.

Wang *et al.* [29] introduced the Parameters identification based on the voltage drop of double fed wind generator .The DC component was separated from AC component and curve fitting technique was used within motor parameters .Least square method was used for identification of vector control motor parameters.

2.3 Conclusion

In the next chapter some of the popular parameter identification techniques are discussed. Chapter also highlight their merits and demerits as well .From the review it is found that several parameter identification techniques viz curve fitting technique, least square method, recursive least square technique, inverse methodology, neural network, genetic algorithm etc, are already being employed to identify the parameters of a dc motor.

CHAPTER 3

PARAMETER IDENTIFICATION PROCESS

3.1 Introduction

With the advancement in technology the new methods are being suggested by engineers for better operation and improved control in industries e.g. in mechanical and other type of production industries. The other application areas of system identification includes task for studying the performance of aerospace vehicles, in biological researches like controlling body parts movement such as Arm and Leg, Heart rate control etc. Parameter identification is important especially for dc motors as for their precise control their mathematical model is required and that can be obtained only after knowing the motor parameters. Even if initially the mathematical model is available but as parameters changes with time that mathematical model may not remain accurate at a later time. Hence a dynamic modeling is required

3.2 Parameter Identification Process

The main aim of parameter identification is to design a control strategy by formulating accurate mathematical models, designing precise controllers, predicting the closed loop behavior of the plant. The data obtain from researches can be used to validate the manufacture supplied parameters and specify missing information. For system requiring Accurate and Adequate information system identification is the only mean for obtaining mathematical models of such systems.

Each identification process requires a series of basic steps. The quality of results obtained depends on the proper implementation of these steps otherwise it can leads to poor results. In each process the following steps should be taken:

- Collecting system information
- Selecting a control strategy & model structure for the system.
- Selecting model parameters that best fit the model
- Measurements: selection of a "goodness of fit" criterion.
- Validating the selected model.

The Parameter Identification Method has following advantages

- Time and money that is involved in testing process is saved as no mechanical coupling necessary
- Entire system information: it provide full information about characteristic curve and values of any motor

3.3 Parameter identification techniques

3.3.1 Curve fitting
3.3.2 Least square method
3.3.3 Recursive Least square method
3.3.4 Inverse methodology
3.3.5 Moments method
3.3.6 Genetic algorithm

3.3.1 Curve Fitting

Curve fitting technique now a days is the most popular and useful technique in various fields for analysis work. The main aim is to find out the best curve for any Mathematical function that best fit to a sequence of data points. It basically examines the relationship between given set of independent and dependent variables. Fitted curves obtained can be used in data visualization, finding relationships among two or more variables [30].

Different type of curve fitting

3.3.1.1 Linear Fitting

This type of fitting is generally used for linear equations or for first degree polynomial like

$$y = ax + b$$

The given line has slope a. A line will connect any two points, so a first degree polynomial equation is an exact fit through any two points with distinct x coordinates. If the order of the equation is increased to a second degree polynomial then polynomial fitting can be used.

3.3.1.2 Polynomial Fitting

If the order of the equation is increased to higher degree polynomial, the following equation is obtained

$$y = ax^2 + bx + c$$

And for these type of equations polynomial fitting can be used.

3.3.1.3 Apparent Fitting

Many types of curves, such as conic sections (circular, elliptical, parabolic, and hyperbolic arcs) or trigonometric functions (such as sine and cosine), sinusoidal patterns require apparent fitting. In these cases, trajectories data is taken & this trajectory data is matched points to a parabolic curve for finding best fitting data.

3.3.1.4 Algebric Fitting and Geometric Fitting

For algebraic analysis of data, "fitting" usually means trying to find the curve that minimizes the vertical (y-axis) displacement of a point from the curve (e.g., ordinary least squares). However for graphical and image applications geometric fitting seeks to provide the best visual fit; which usually means trying to minimize the orthogonal distance to the curve (e.g., total least squares), or to otherwise include both axes of displacement of a point from the curve. Geometric fits are not popular because they usually require non-linear and/or iterative calculations, although they have the advantage of a more aesthetic and geometrically accurate result [31].

3.3.2 Least square method

One of the most popular techniques for Parameter identification is the least square method (LSM). The various reasons for the popularity of method is firstly it works well with simple linear models secondly it make use of squares that make LSM tractable because according to the Pythagorean theorem if the error is independent of an estimated quantity, a squared error or the squared quantity can be added . Also the mathematical formulations and algorithms involved in LSM such as derivatives, eigen decomposition, singular value decomposition are easy and well known to use.

The LSM is basically used for finding the numerical values of parameters that best fit the curve data . It states that the most accurate value for the unknown quantities will be those for which the sum of the squares of the differences between the observed and the computed values is minimum" and this difference between the estimated and calculated values is termed as residual .It uses the sum of squared of the difference b/w the obtained and predicted results.

$$Y_i = a + bX$$

$$E = \sum (Y_i - Y_i)^2 = \sum [Y_i - (a + Bx_i)^2] \tag{3.1}$$

There are several type of LSM. The simple form of Least square method is known as Ordinary Least square method (OLS), And another version is called weighted least squares (WLS) and has better performance than OLS as it can modulate the final observation at the end of result .Some other variation in the least square method are alternating least squares (ALS) type and partial least squares (PLS) type [1].

3.3.3 Recursive Least Squares

Recursive least squares is used for the parameters identification from recurring (in time) linear algebraic equations. It is more robust and efficient than least square method .Since it does not make use of squares it is not sensitive to outranges as compared to least square method. Consider

A simple linear algebraic equation for a given set of time t

$$a_1(t)x_1 + a_2(t)x_2 + \ldots a_n(t)x_n = b(t) \tag{3.2}$$

Where $a_j(t)$ (j = 1, 2, ... , n) and b(t) = known data values x_j (j = 1, 2, ... , n) = unknown parameters (to be calculated) .

Writing this equation in matrix-vector form, we get

$$A_0\mathbf{x}_0 = \mathbf{b}_0 \tag{3.3}$$

$\mathbf{A}_0$ represents $a_{ij} = a_i(t_j)$, (i = 1, 2, ..., n; j = 1, 2, ..., m), $\mathbf{x}_0$ includes x_j (j = 1, 2, ..., n), and $\mathbf{b}_0$ represents b_i (i = 1, 2, ..., m). The solution after applying least square method to Eq. (2) is

$$\mathbf{x}_0 = (A_0^T A_0)^{-1} A_0^T \mathbf{b}_0 \tag{3.4}$$

Let after time t_{m+1} the equation changes to

$$a_1(t_{m+1})x_1 + a_2(t_{m+1})x_2 + \ldots a_n(t_{m+1})x_n = b(t_{m+1}) \tag{3.5}$$

Representing in matrix form

$$\mathbf{a}^T\mathbf{x} = b \tag{3.6}$$

in which $b = b(t_{m+1})$. The new equation can be added in the previous equation (3.3) (3.7)

$$A = \begin{bmatrix} A_0 \\ \mathbf{a}^T \end{bmatrix}, b = \begin{bmatrix} \mathbf{b}_0 \\ b \end{bmatrix} \tag{3.7}$$

The least squares solution to Eq. (3.6) is

$$\mathbf{x} = (A^T A)^{-1} A^T \mathbf{b} \tag{3.8}$$

This procedure is lengthy as every time new equation has to be added to the previous equation and steps are repeated and original equation (3.4) is not utilized. So here recursive technique is used

from Eqs. (3.7)

$$\begin{aligned} A^T A &= A_0^T A_0 + \mathbf{a}\mathbf{a}^T , \\ A^T \mathbf{b} &= A_0^T \mathbf{b}_0 + \mathbf{a}b \end{aligned} \tag{3.9a,b}$$

Now the inverse of a matrix from adding the identity matrix I to any rank one matrix ($\mathbf{de}^T$) identity plus a multiple of the rank one matrix, shown as

$$\left[I + \mathbf{de}^T\right]^{-1} = I + c\mathbf{de}^T \tag{3.10}$$

Verifying eq (3.10):

$$\begin{aligned} \left[I + \mathbf{de}^T\right]\left[I + c\mathbf{de}^T\right] &= I + c\mathbf{de}^T + \mathbf{de}^T + \mathbf{de}^T c\mathbf{de}^T \\ &= I + c\mathbf{de}^T + \mathbf{de}^T + c\mathbf{d}(\mathbf{e}^T\mathbf{d})\mathbf{e}^T \\ &= I + [c(1 + \mathbf{e}^T\mathbf{d}) + 1]\mathbf{de}^T \end{aligned} \tag{3.11}$$

Eq. (3.11) will provide the identity matrix, if Equation (9) is the inverse of the constructed matrix, Assuming

$$c = -\frac{1}{1 + \mathbf{e}^T\mathbf{d}} \tag{3.12}$$

Multiplying Eq. (9) by the non-singular matrix B^{-1}

$$\begin{aligned} B^{-1}[I + \mathbf{de}^T]^{-1} &= [[I + \mathbf{de}^T]B]^{-1} = [B + \mathbf{de}^T B]^{-1} \\ &= B^{-1}[I + c\mathbf{de}^T] = B^{-1} + cB^{-1}\mathbf{de}^T \end{aligned} \tag{3.13}$$

$$A(Z)^{-1} = 1 + a_1z^{-1} + a_2z^2 + \text{\_\_\_\_\_\_\_\_\_\_\_} + a_{na}z^{-n}$$

$$B(Z)^{-1} = 1 + b_1z^{-1} + b_2z^{-2} + \text{\_\_\_\_\_\_\_\_\_\_\_} + b_{nb}z^{-nb}$$

$$Y(t) = X^T\theta$$

$$\theta^T = [-a_{1\text{--------}}, -a_{na}, b_{0\text{--------}}, b_{nb})$$

Hence it can be shown that the recursive least squares solution is robust as well as efficient[9].

3.3.4 Inverse problem methodology

Inverse problem methodology involves defining an objective function. The objective function for the inverse problem can be written as the squared sum of errors between measured and calculated values of the rotor angular speed of the separately excited dc motor. Identification inverse problems found its application in finding defects in materials and structures and in propagation phenomena, radiation, and measurement of static response, steady state and transient response and Eigen frequencies. The main aim is to minimize the objective function. Consider an objective function F_x defined as

$$F_x = \frac{1}{2}\sum_{i=1}^{n}(w_i^c - w_i^0)^2 \tag{3.14}$$

The most accurate values are those for which objective function is minimum. The minimization of the objective function with respect to the desired vector is the most important procedure in solving the inverse problem and then conjugate gradient method is used to determine the unknown parameters [24].

3.3.5 Method of moments

The Method of Moments is used for finding unknown parameters of a system by relating these parameters to the moments of the distribution and then empirical moments is applied to back up the unknown distribution parameters. It provides estimate of parameters that are consistent but is not as efficient as Maximum Likelihood (ML). They are generally used because of simple calculation procedure than ML method.

The main steps required are:

1 To find the true functional form of the distribution of outcomes

2 To represent the distribution parameters in terms of the data

Suppose a sample of size n is drawn, resulting in the values w_1…….w_n For j=1,……,k, let

$$u_j = \frac{1}{n}\sum_{i=1}^{n} W_i \tag{3.15}$$

be the jth sample moment, an estimate of u_j . The method of moments estimator for θ_1, $\theta_{2\ldots\ldots}$ θ_k denoted by θ_1, $\theta_{2,\ldots\ldots,}$ θ_k is defined as the solution (if there is one) to the equations.[9]

3.3.6 Genetic algorithm (GA)

The genetic algorithm has its evolution from the theory of natural selection and genetic evolution .The GA based parameter estimation algorithm is used to find the unknown parameters, using the sum of squared difference between errors, compared to the previous traditional method GA perform well for systems with complexity and discontinuity. The basic steps included in the algorithm are

1) Optimization of fitness function or objective function
2) Selection of population size at each generation
3) Selecting individual with better fitness value.
4) Applying GA to obtain the results
5) Validating the obtained result

For the better performance of a numerical model optimizations of computational and Physical parameters are essential for improving model performance.

The advantage of using GA is that it can obtain global optimum solution rather than just providing local minima. It can also handle non linear models.GA has its main application in image processing, system identification, and fuzzy logic controller design. Compared to old methods of parameter identification, the GA is more appropriate when the function includes some complexities or discontinuities [21].

3.4 CONCLUSION

In the next chapter dc motor modeling & control is discussed .The dynamic equations are used for constructing the block diagram & obtaining transfer function required for finding DC motor parameters. PID controller that can provide control action design for specific process requirements is also discuss.

CHAPTER 4

DC MOTOR MODELING AND CONTROL

4.1 Introduction

DC motors are widely used in applications requiring adjustable speed, good speed regulation and frequent starting, braking and reversing operations. Some important applications are rolling mills, paper mills, mine winders, hoists, machine tools, traction, printing presses, textile mills and cranes. Fractional horsepower DC motors are widely used as servo motors for positioning and tracking. Although, it is being predicted that AC drives will replace DC drives, however, even today the variable speed applications are dominated by DC drives because of its reliability and ease of control. In this chapter, the basic model of a separately excited DC motor is discussed. Transfer functions are derived from the block diagram of the dc motor. For dc motor control controller design is discussed along with its transient response specifications [8].

4.2 Motor Modeling and Simulation

In armature control of DC motor, it is assumed that demagnetizing effect of armature reaction is neglected, magnetic circuit is assumed to be linear and the field voltage is constant. This method is used to obtain the speed below the rated speed. Fig 4.1 shows the equivalent model of armature controlled DC motor.

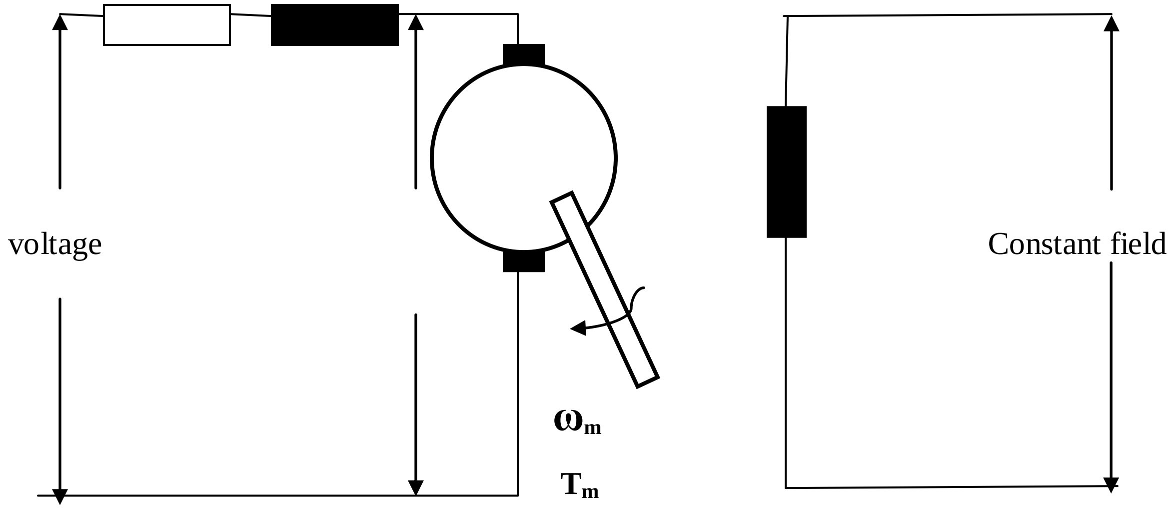

Fig 4.1 Model of Separately Excited DC motor

A common actuator in control systems is the DC motor. It directly provides rotary motion and, coupled with wheels or drums and cables, can provide, transitional motion. The model of the armature is shown in above Fig 4.1[24].

4.3 Separately Excited DC Motor dynamic Equations

The DC machine as dynamic system, including the interactions of the electromagnetic and the mechanical effect, is dealing within the following section. The equivalent circuit of the separately exited dc machine can be represented in schematic from as shown in Fig. 4.1. The electrical equation of a DC motor is derived from the simple motor circuit illustrated in Fig 4.1. The relation between these variables is given by equations (4.1-4.6) where e_b, the internally generated voltage, is proportional to the motor velocity.

The motor back emf constant K, is a measure of the voltage per unit speed generated when the rotor is turning. The magnitude and polarity of K are functions of the shaft angular velocity, ω_r, and direction of rotation respectively. Also K is the motor torque constant that is a measure of the torque-per-unit-current produced by the motor. The motor torque T, is related to the armature current, ia, by a constant factor K_t. The back emf e_b, is related to the rotational velocity by the constant factor K_e [24].

The dynamic of the dc motor may be expressed by the following equations

$$V_t = R_a I_a + L_a \frac{di_a}{dt} + e_b \tag{4.1}$$

$$T_m(s) - T_L(s) = J\frac{d\omega}{dt} + B\omega \tag{4.2}$$

$$T_m = K_t i_a \tag{4.3}$$

$$e_b = k_b \omega \tag{4.4}$$

Taking laplace transform of equations 4.1 to 4.4 we get,

$$V_t(s) = R_a I_a(s) + sL_a I_a(s) + K_b \omega(s) \tag{4.5}$$

$$K_t I_a(s) = sJ_m \omega(s) + B_m \omega(s) + T_L(s) \tag{4.6}$$

where the algebraic symbols used represent the following:

V_t= Terminal voltage

I_a= Armature current

ω= Rotor speed

R_a= Armature Resistance

K_t= Torque constant

L_a= Armature inductance

J_m= Moment of inertia

K_b= Voltage constant

B_m = Viscous friction

4.4 Block Diagram of a Separately Excited DC Motor

To determine the relationship between output and input voltage it is necessary to consider the block diagram of dc motor. The above mentioned dynamic equations are used for constructing the block diagram for the motor. From the block diagram we can determine the transfer function required for finding DC motor parameters.

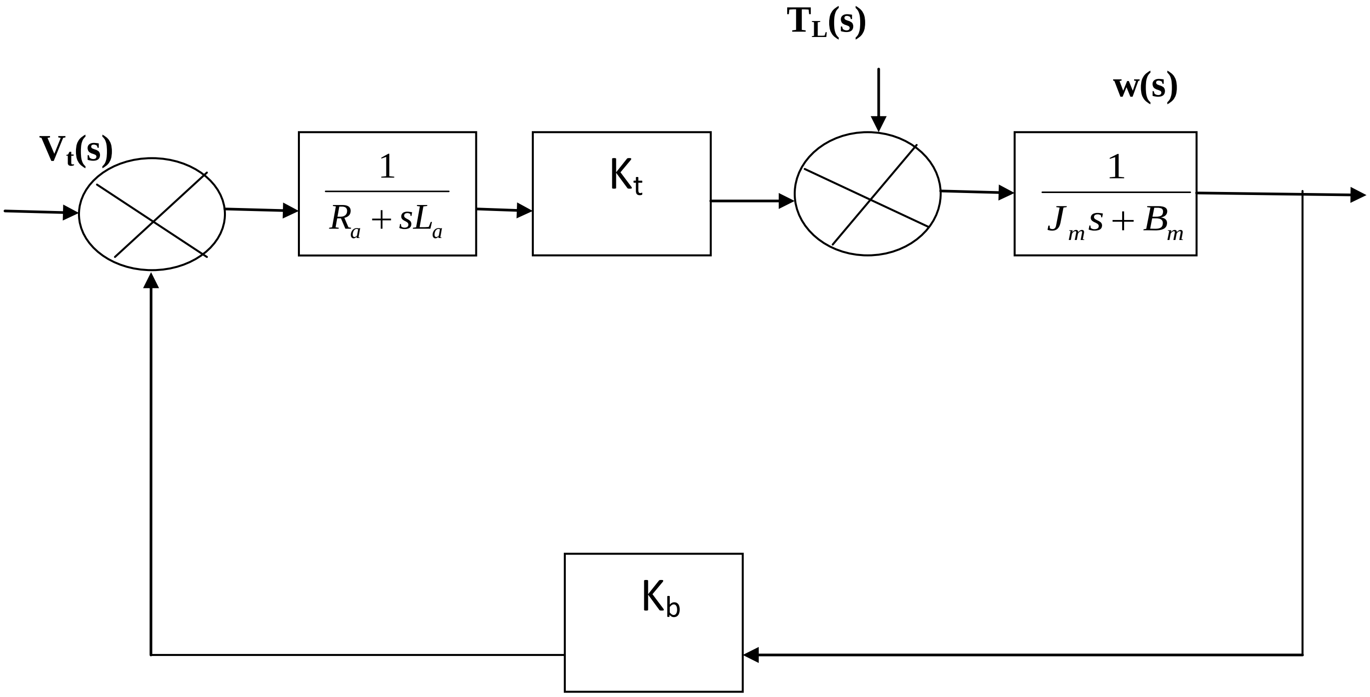

Fig 4.2 Block diagram of separately excited DC motor

There are two possible cases:

(1) When T_L=0

The output follows the input signal and the corresponding response so obtained known as servo response of the system. Fig 4.3 shows the block diagram of servo model of the DC motor when load torque is zero.

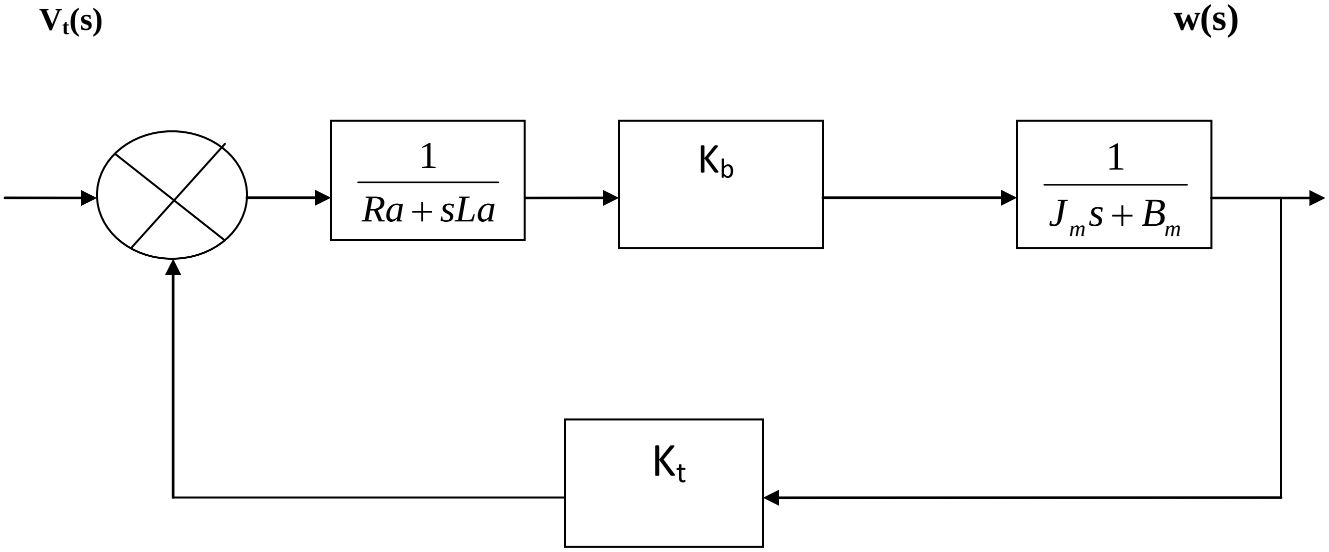

Fig 4.3 Block diagram of separately excited DC motor when T_L=0

After identifying all the major components in the block diagram, the transfer functions of all parts in the diagram have been defined. An open loop represents the single direction of flow in a system with no knowledge of the response. But as we have a closed loop system the output of the system is being measured and fed back to the input to form a close loop system. Transfer function is thus a brief representation of the above mentioned steps. The closed loop function for Fig 4.3 is given as

$$\frac{\omega(s)}{V_t(s)}=\frac{k_t}{s^2L_aJ_m+(R_aJ_m+B_mL_a)s+(k_t{}^2+B_mR_a)} \tag{4.7}$$

Considering step change of voltage the laplace inverse for the above equation is

$$\omega(t) = V_t(t) \times \frac{2}{\sqrt{(b^2 - 4ac)}e^{(-\frac{1}{2}\times\frac{t}{ab})} \times Sinh(\frac{1}{2} \times \frac{t}{a\sqrt{(b^2 - 4ac)}})} \tag{4.8}$$

The coefficients a, b, c are given as

$$a = \frac{L_a J_m}{K} \tag{4.9}$$

$$b = \frac{R_a J_m + B_m L_a}{K} \tag{4.10}$$

$$c = \frac{K^2 + B_m R_a}{K} \tag{4.11}$$

(2) When V_t=0

This gives the regulatory response of the system. Fig 4.4 shows the block diagram of regulatory model of the DC motor when V_t=0.

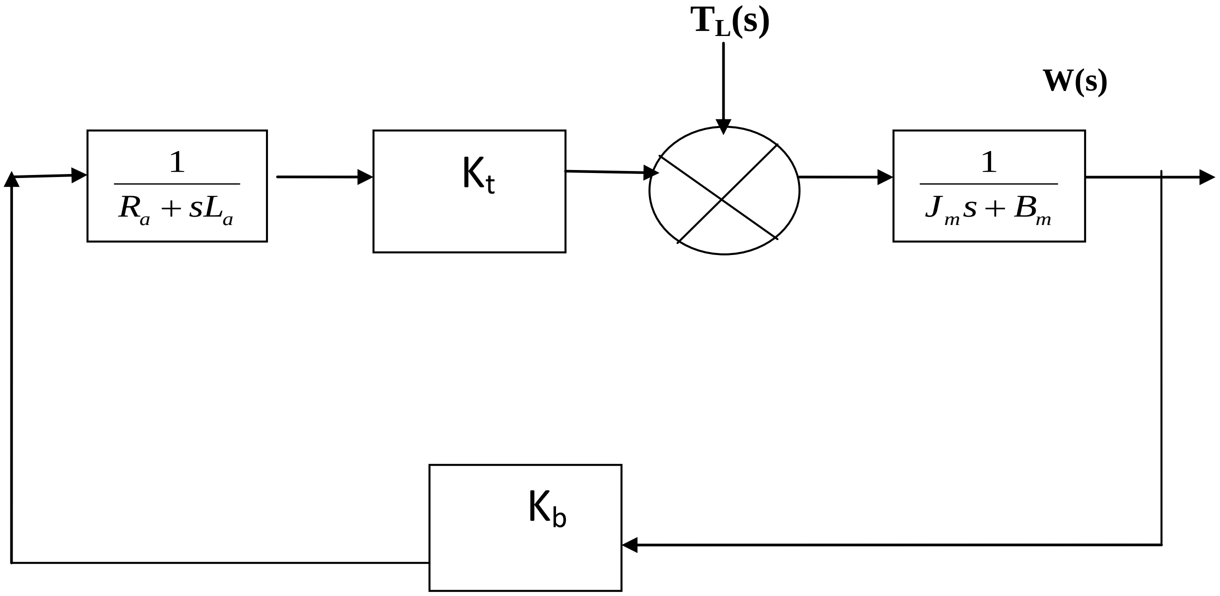

Fig 4.4 Block diagram of separately excited DC motor when V_t=0

The transfer function for Fig. 4.4 is given as

$$\frac{\omega(s)}{T_L(s)} = -\frac{(R_a + L_a s)}{s^2 L_a J_m + (R_a J_m + B_m L_a)s + (k_t{}^2 + B_m R_a)} \tag{4.12}$$

4.5 Curve fitting technique

Curve fitting technique now a days is the most popular and useful technique in various fields for analysis work. The main aim is to find out the best curve or any mathematical function that best fit to a sequence of data points. It basically examines the relationship between given set of independent and dependent variables. Fitted curves obtained can be used in data visualization, finding relationships among two or more variables [29].

Linear Fitting

This type of fitting is generally used for linear equations or for first degree polynomial like

$$y = ax + b \tag{4.13}$$

The given line has slope a. A line will connect any two points, so a first degree polynomial equation is an exact fit through any two points with distinct x coordinates. If the order of the equation is increased to a second degree polynomial then polynomial fitting can be used.

Polynomial Fitting

If the order of the equation is increased to higher degree polynomial, the following equation is obtained

$$y = ax^2 + bx + c \tag{4.14}$$

And for these type of equations polynomial fitting can be used.

Apparent Fitting

Many types of curves, such as conic sections (circular, elliptical, parabolic, and hyperbolic arcs) or trigonometric functions (such as sine and cosine), sinusoidal patterns require apparent fitting. In these cases, trajectories data is taken and this trajectory data is matched to a parabolic curve for finding best fitting data.

Algebric Fitting and Geometric Fitting

For algebraic analysis of data, "fitting" usually means trying to find the curve that minimizes the vertical (y-axis) displacement of a point from the curve (e.g. ordinary least squares). However for graphical and image applications geometric fitting seeks to provide the best visual fit; which usually means trying to minimize the orthogonal distance to the curve (e.g. total least squares), or to otherwise include both axes of displacement of a point from the curve. Geometric fits are not popular because they usually require non-linear and/or iterative calculations, although they have the advantage of a more aesthetic and geometrically accurate result [31].

4.6 CONTROLLER DESIGN

PID controller is one of the most commonly used controllers found used in Industrial Process today. A PID controller calculates an "error" value as the difference between a measured process variable and a desired ‘set point’. PID controller is also known as three term control:- the proportional (P), integral (I) and derivative (D). By tuning these three parameters in the PID controller algorithm, the controller can provide control action designed for specific process requirements.

4.7 PID CONTROLLER

A PID controller is a combination (sum) of P, I and D controller, so now we must also discuss the function of each.

Proportional (P) controller calculates the term proportional to the ‘error’.

Integral (I) controller calculates a term proportional to integral of ‘error’.

An integral controller gives zero SSE (Steady State Error) for a step input but reduces the speed of a system.

Derivative (D) controller calculates a term proportional to derivative of error. A derivative control terms often produces faster response [28].

4.7.1 Proportional (P) term:

The proportional term makes a change to the output that is proportional to the current error value. The proportional response can be adjusted by multiplying the error by a constant K_p, called the proportional gain. The proportional term is given by:

$$P_{out} = K_p e(t) \tag{4.15}$$

$$u = K_p e + K_i \int edt + K_d \frac{de}{dt} \tag{4.16}$$

Where K_P - Proportional gain

K_i - Integral gain

K_d - Derivative gain.

The signal u will be sent to the plant and the new output Y will be obtained and sent back to the sensor again to find the new error signal e. The controller takes e and computes its derivative and it's integral again. This process goes on and on. By adjusting the weighting constants K_P, K_i and K_d , the PID controller can be set to give the desired performance.

Taking Laplace Transform of equation (4.14)

$$K(s) = \frac{U(s)}{E(s)} = K_p + \frac{K_i}{s} + K_d s \qquad (4.17)$$

4.7.2 Integral (I) term:

The contribution from the integral term is proportional to both the magnitude of the error and the duration of the error. The integral in a PID controller is the sum of the instantaneous error over time and gives the accumulated offset that should have been corrected previously. The accumulated error is then multiplied by the integral gain (K_i) and added to the controller output. The integral term is given by

$$I_{out} = K_i \int_0^t e(\tau)d\tau \qquad (4.18)$$

4.7.3 Derivative (D) term:

The derivative of the process error is calculated by determining the slope of the error over time and multiplying this rate of change by the derivative gain K_d. The magnitude of the contribution of the derivative term to the overall control action is termed the derivative gain, K_d [32].

The derivative term is given by:

$$D_{out} = K_d \frac{d}{dt} e(t) \qquad (4.19)$$

4.7.4 PID Term:-

The PID controller output can be obtained by adding the three terms

Where K_p= Proportional gain

K_i= integration coefficient

K_d= derivative coefficient

T_i= integral action time

T_d= derivative action time

The block diagram of PID controller is shown in Fig 4. 5

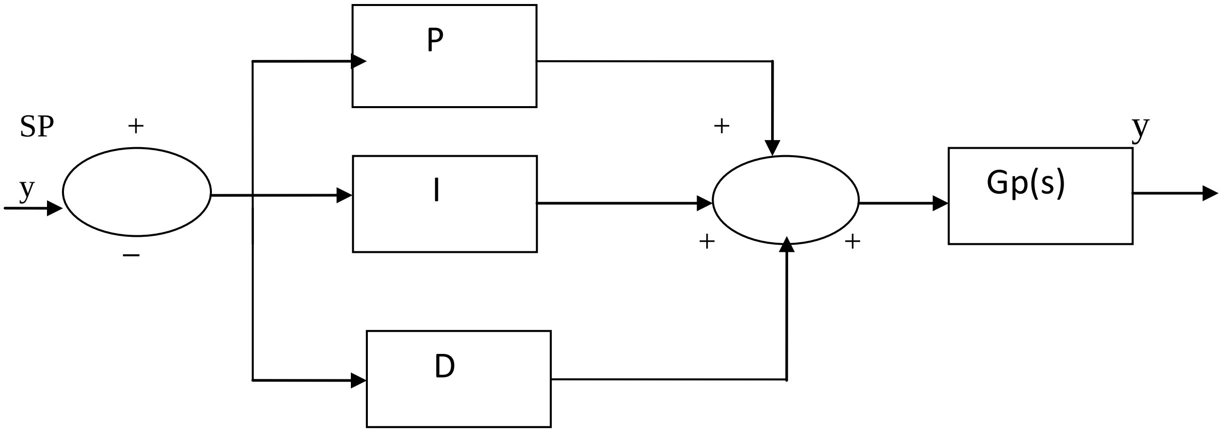

Fig 4.5 Block diagram of PID controller

Transfer function for PID controller

$$\frac{X(s)}{F(s)} = \frac{K_d s^2 + K_p s + K_i}{s^3 + (b + K_d)s^2 + (k + K_p)s + K_i} \tag{4.20}$$

4.8 OPEN LOOP PID TUNING METHODS

Open loop tuning methods are those where the feedback controller is disconnected and the experimenter excites the plant and measures the response. The key point here is that since the controller is disconnected, clearly the plant is no longer strictly under control. If the loop is critical, then this test could be hazardous. Indeed if the process is open-loop unstable, then we will be in trouble before we begin. Notwithstanding for many process control applications, open loop type experiments are usually quick to perform, and deliver informative results. If the system is steady at set point, and remains so, then we have no new information about how the process behaves.

There are various tuning strategies based on an open-loop step response. While they all follow the same basic idea, they differ slightly in how they extract the model parameters from the recorded response and relate appropriate tuning constants to the model parameters. There are four different methods, the classic Ziegler-Nichols open loop method, the Cohen-Coon method, Internal Model Control (IMC) method and Approximate M-constrained

Integral Gain Optimization (AMIGO) method. Naturally if the response is not sigmoidal or'S' shaped and exhibits overshoot, or an integrator, then this tuning method is not applicable. This method implicitly assumes the plant can be adequately approximated by a first order transfer function with time delay [22].

$$G_p = \frac{Ke^{-\theta s}}{Ts+1} \tag{4.21}$$

Where: K- is gain,

T_d -is the dead time or time delay, and

T- is the open loop process time constant.

4.9 Transient-Response Specifications

The transient response of a practical control system often exhibits damped oscillations before reaching a steady state. In specifying the transient-response characteristics of a control system to a unit-step input, it is common to use the following terms:

Delay Time: The delay time t_d is the time needed for the response to reach half (50%) of its final value. Delay time can be calculated from this formula

$$Td = \frac{1+0.7\zeta}{\omega_n} \tag{4.22}$$

Rise Time: The rise time t_r is the time required for the response to rise from 10% to 90%. Or the time required to rise from 0% to 100% of its final value. Rise time can be calculated from this formula

$$T_r = \frac{1}{\omega_d}\tan^{-1}\left(-\frac{\sqrt{1-\zeta^2}}{\zeta}\right) \tag{4.21}$$

Peak Time: The peak time t_p is the time required for the response to reach the first peak of the overshoot. For the first peak overshoot, $t_p\omega_d = \pi$

$$T_p = \frac{\pi}{\omega_d} = \frac{\pi}{\omega_n\sqrt{1-\zeta^2}} \tag{4.22}$$

Maximum Peak Overshoot: The maximum peak overshoot Mp is the maximum peak value of the response curve, the maximum percent overshoot is Mp × 100.The maximum overshoot occurs at the peak time and can be calculated from the given formula.

$$M_p = e^{\frac{-\pi\zeta}{\sqrt{1-\zeta^2}}} \tag{4.23}$$

Settling Time: The settling time t_s is the time required for the response curve to reach and stay within ± 2% of the final value. In some cases, 5% instead of 2% is used as the percentage of the final value. The settling time is the largest time constant of the system. The settling time corresponding to ± 2% or ± 5% tolerance band may be measured in terms of the time constant [15].

Based on 2% criteria, it is found that $T_s = 4T$

$$T_s = \frac{4}{\zeta\omega_n} \tag{4.24}$$

Based on 5% criteria, it is found that Ts = 3T

$$T_s = \frac{3}{\zeta\omega_n} \tag{4.25}$$

4.10 CONCLUSION

In the next chapter, the results are presented and discussed. The electrical parameters are measured and calculated whereas the mechanical parameters are obtained using curve fitting technique. The motor speeds at different armature voltages are determined from the experimental setup and are used in the parameter identification process to obtain unknown parameters by using curve fitting technique. For the speed control of a DC motor a PI controller is employed. The controller parameters are tuned using Ziegler Nicols method.

CHAPTER 5

RESULTS AND DISCUSSIONS

5.1 INTRODUCTION

The electrical parameters of DC motor can be determined from the experimental set up used for speed control of DC motor. However, it is difficult to find some of the mechanical parameters viz. moment of inertia (J), viscous friction (B) from the experimental setup. Therefore, in this chapter, we have presented the curve fitting technique to identify the mechanical motor parameters of the motor. The motor speeds at different armature voltage are determined from the experimental setup and are used in the identification process. The speed vs armature voltage curve is fitted with the experimental data and thus the mechanical parameters are obtained employing curve fitting technique .Then the transfer function coefficients are obtained and the DC motor model is developed. Finally, we will control the motor model developed using PI controller. The controller parameters are tuned using open loop method of Zeigler Nicols utilizing curve fitting to express the DC motor model with the help of a first order time delay system.

5.2 Experimental Results

From the experimental set up different speed values of dc motor are obtained by varying armature voltage and the back emf (e_b) and hence back emf constant (K) is calculated. The value of L_a and R_a measured from LCR meter are obtained as 99.4 mH and 8.9 ohm respectively. The experimental results are shown in Table 5.1 given below.

Table 5.1 Experimental Data Results and Calculations

Speed (rpm)	Speed (rps)	ArmatureVoltage (V)	Back emf (V)	Back emf constant (V-s/rad)
1518	158.88	230	225.55	1.42
1478	154.70	225	220.55	1.43
1447	151.45	220	215.55	1.42

Speed (rpm)	Speed (rps)	ArmatureVoltage (V)	Back emf (V)	Back emf constant (V-s/rad)
1413	147.89	215	210.55	1.42
1381	144.54	210	205.55	1.42
1347	140.99	205	200.55	1.42
1322	138.37	200	195.55	1.41
1291	135.12	195	190.55	1.41
1255	131.36	190	185.55	1.41
1213	126.96	185	180.55	1.42
1184	123.93	180	175.55	1.42
1152	120.58	175	170.55	1.41
1108	115.97	170	165.55	1.43
1099	115.03	166	161.55	1.40
1056	110.53	160	155.55	1.41
1023	107.07	155	150.55	1.41
981	102.68	150	145.55	1.42
934	97.76	143	138.55	1.42
912	95.46	139	134.55	1.41
856	89.59	131	126.55	1.41
814	85.20	125	120.55	1.41
799	83.63	120	115.55	1.38
748	78.29	115	110.55	1.41
720	75.36	110	105.55	1.40
670	70.13	105	100.55	1.43
656	68.66	100	95.55	1.39
610	63.85	95	90.55	1.42
583	61.02	89	84.55	1.39
555	58.09	85	80.55	1.39
520	54.43	80	75.55	1.39

The average value of back emf constant (K) taken from reading is obtained as 1.41. The graph showing the fitted curve and experimental data obtained from MATLAB program is shown in Fig 5.1.

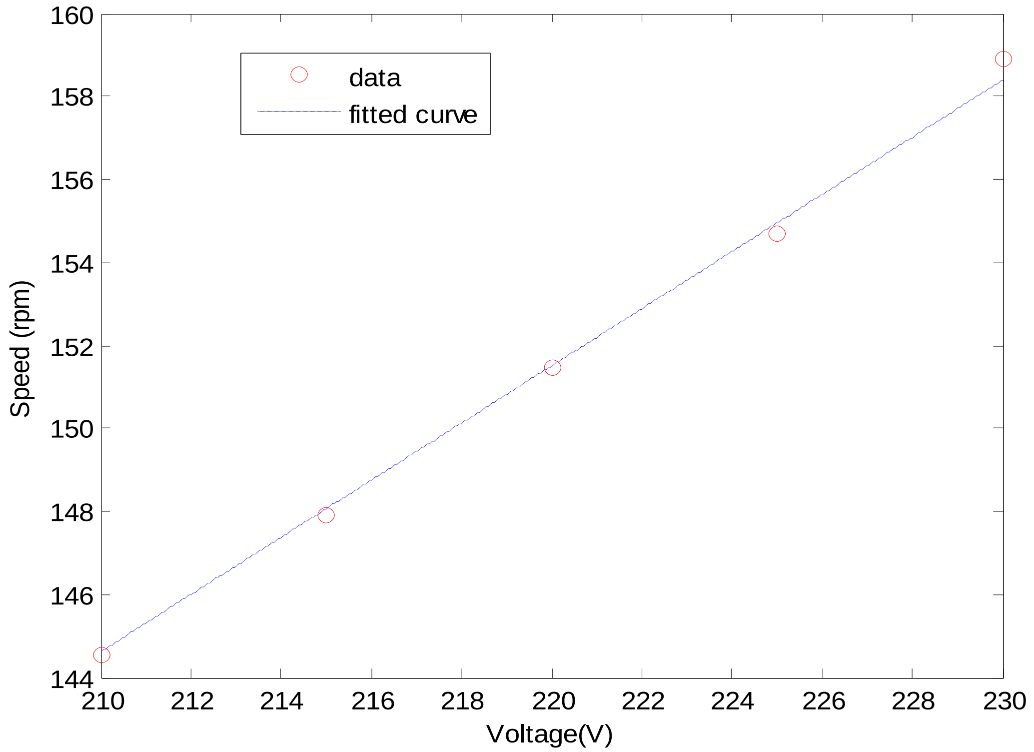

Fig 5.1 Graph showing the fitting of experimental data with theoretical equation

The unknown mechanical parameters obtained are

- J=0.002 Kg/ m^2
- B=0.003 Nm/Rad/sec

The final DC motor electrical and mechanical parameters are tabulated below:

Table 5.2: DC Motor Machine Parameters

Parameters	Values
Armature Resistance	8.9 ohms
Armature Inductance	99.4 mH
Viscous Friction Constant	0.003 Nm-sec/rad
Moment of Inertia	0.002 kg-m^2
Back emf constant	1.41

5.3 OPEN LOOP TRANSFER FUNCTION

The open loop transfer function of the armature circuit is given by

$$\frac{1}{0.994\,s + 8.9}$$

Step response corresponding to the open loop transfer function is shown in Fig 5.2.

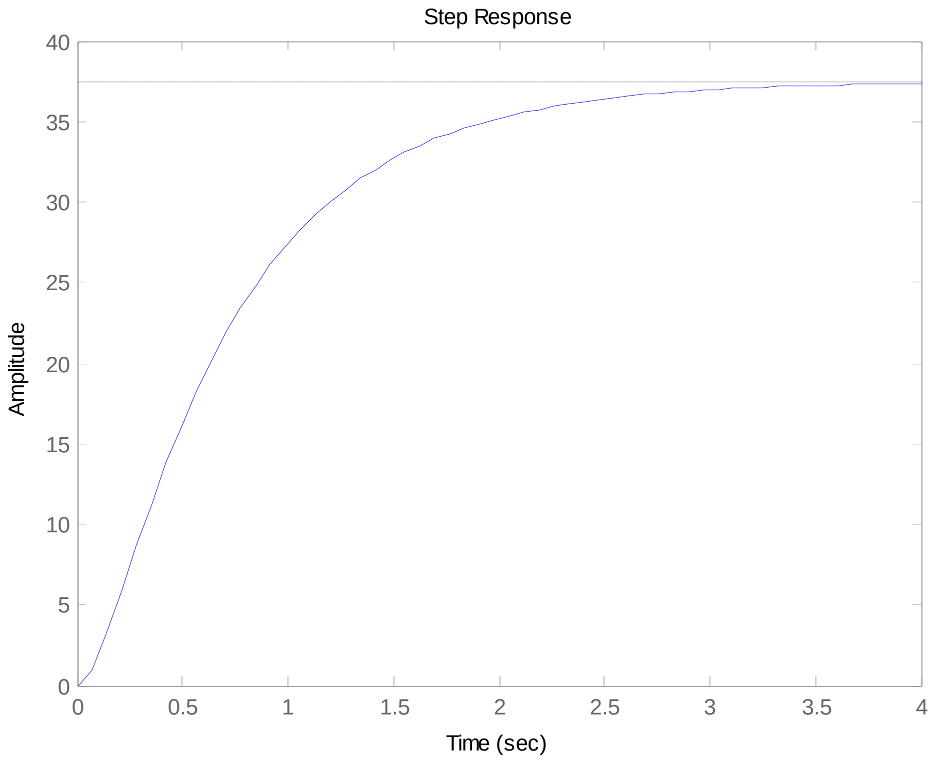

Fig 5.2 Step response for uncontrolled DC motor model (Armature Circuit)

Similar responses can also be obtained for the mechanical circuit, servo model, regulatory model as well as the entire system combining servo and regulatory models. Only servo model has been taken up for controlling the speed of the DC motor. Table 5.2 shows the time domain results obtained for the DC motor models developed.

Table 5.3: Time domain analysis of Servo and Regulatory Models

Time Domain Parameters →	Peak Time (s)	Rise time (s)	Settling time (s)	Maximum Peak Overshoot (%)	Undershoot
Servo Model	1.437	0.0546	0.7382	47.5643	0
Regulatory Model	0.0803	0.0145	0.8168	165.9964	0

The servo speed and the regulatory response is obtained below in Fig 5.3.

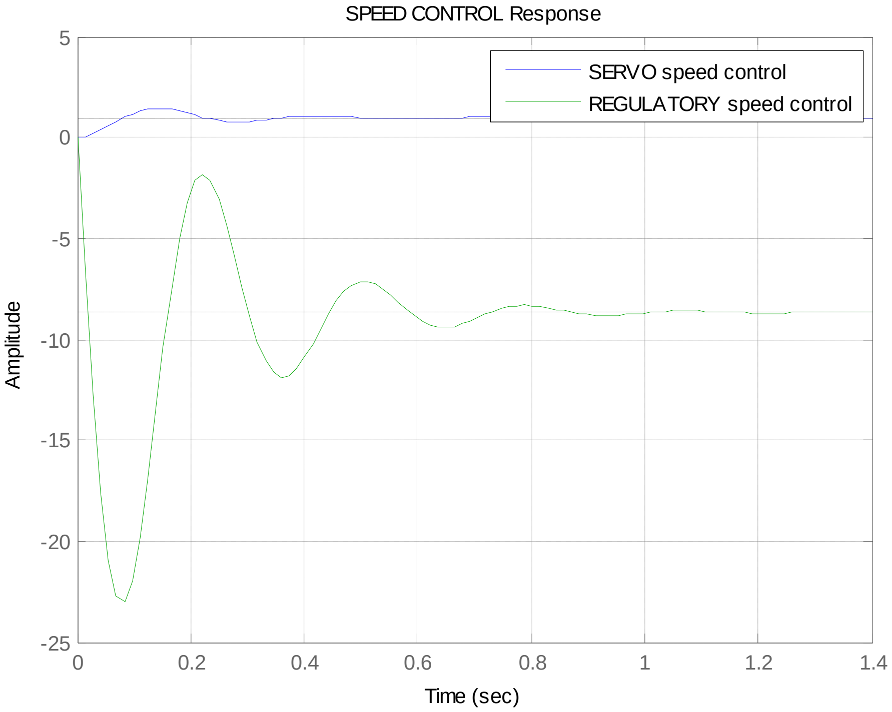

Fig 5.3 Step Responses of Servo and Regulatory Models

The transfer function of the DC motor can be represented by an equivalent first order time delay form using curve fitting technique. The time delay form of DC motor open loop transfer function is represented as follows:

$$\exp(-1.28*s) * \frac{37.3}{0.6563\,s + 1}$$

From the above first order time delay form we obtain the parameters given below:

Gain, **K** = 37.3026

Dead time or time delay, **theta (** θ **)** =1.2774

Open loop process time constant, **tau (** τ **)** =0.6563

These parameters are used in Ziegler-Nichols open loop PID tuning method to obtain the controller parameters discussed in the next section.

5.4 CONTROLLER DESIGN: ZIEGLER-NICHOLS (ZN) METHOD

Ziegler-Nichols open loop tuning method is one of the most popular and most widely used classical tuning methods. The Ziegler-Nichols open-loop method is also referred to as a process reaction method, because it tests the open-loop reaction of the process to a change in the control variable output. The PI tuning parameters as a function of the open loop model parameters K, T and from equation (4.6) as derived by Ziegler-Nichols are given in table below:

The value of ZN case =K =37.3026

Transfer function:

$$\frac{0.05273s + 0.0124}{0.008456s^3 + 0.0884s^2 + 0.1663s + 0.0124}$$

The controller parameters obtained by ZN method are tabulated below:

Table 5.4 Controller Parameters tuned by ZN Method

Design Method	**Controller**	**Kp**	**Ki**	**Kd**
Ziegler-Nichols Method (Open loop)	**PI**	0.0124	4.2537	0

The time domain results for PID tuned DC motor is shown in Table 5.5.

Table 5.5 Time domain analysis of Z-N PI tuned system

Controller		**T_r**	**Ts**	**Tp**	**overshoot**	**undershoot**
Ziegler-Nichols Method (Open loop)	**PI**	24.7494	45.7265	100.3525	0	0

The frequency domain as well as the robustness parameters are also obtained and shown in Table 5.6

Table 5.6 Open loop PI tuning method frequency domain & robustness analysis

Method	**Frequency domain analysis**		**Robustness analysis**	
Ziegler-Nichols Method (Open loop)	Gain margin	Phase margin	Modulus Margin(in db)	Delay margin(in sec)
	inf	-180	3.755	inf

The other results are

Mod Marg oploop = 3.755

Settling Min: 0.9002

Settling Max: 0.9997

Peak: 0.9997

The step response of DC motor model (with speed controller) controlled by Ziegler-Nichols open loop PI controller is shown in Fig 5.4 below:

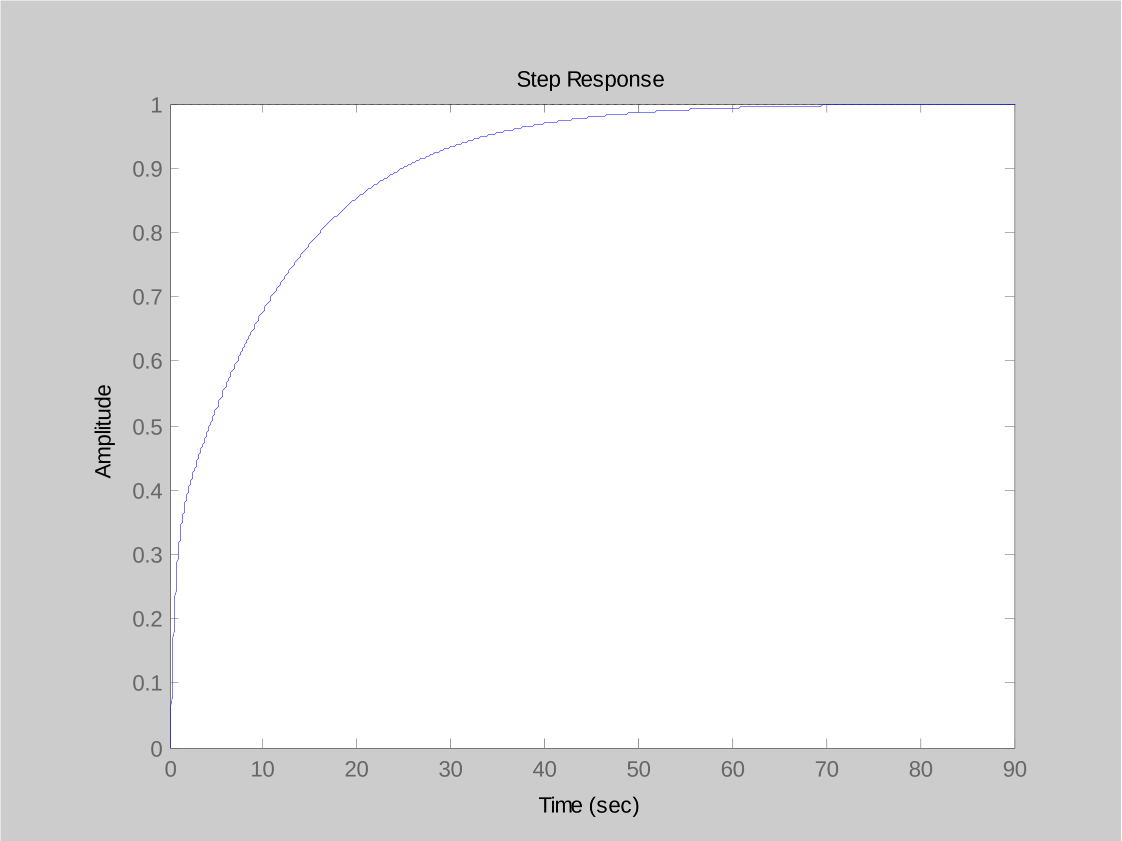

Fig 5.4 Step Response of ZN open loop PI tuning method

5.5 CONCLUSION

DC motor model is developed considering voltage and disturbance torque as inputs. Experiment has been carried out to obtain the relation between speed and armature voltage. Even armature resistance and inductances have been measured. Back emf constant has been calculated. The mechanical parameters viz. viscous friction and rotor inertia has been evaluated using curve fitting technique considering step change of armature voltage. Finally the servo model is represented as a first order time delay system and controlled by open loop Ziegler-Nichols method. The time domain, frequency domain and robustness parameters are also determined for the controlled DC motor model. Overshoot is reduced but frequency domain and robust parameters are not within acceptable range which has to be improved.

5.6 FUTURE SCOPE OF THE WORK

The effect of disturbance load torque can be incorporated for parameter identification of dc motor. We can also consider the impulse input of the DC motor input to identify the model parameters. Intelligent algorithms can also be applied for parameter identification. A comparative study can also be carried out with the existing methods available in the literature. Robust issues can also been taken up for the DC motor model.

REFERENCES

[1] Marquardt D. W., “An Algorithm for Least-Squares Estimation of Nonlinear Parameters,” *Journal of the Society for Industrial and Applied Mathematics,* vol. 11, No. 2, pp. 431-441, 1963.

[2] Raol J. R., Girija G. and Singh J., “Modeling and Parameter Estimation of Dynamic Systems”, *The Institution of Engineering and Technology*, London, United Kingdom Phillips, C. and Nagle, H. 1995.

[3] Hiziroglu H. R. and Qureshi A. H. "Dynamic Analysis of DC motors Operating with Different Types of Mechanical Drives", *Proceeding of Electric Power System in the Fast Developing Countries,* pp. 430-433, 1987.

[4] El-Sharkawi M. A., "Advanced Control Techniques for Higb Performance Electric Drives" *Analysis and Control System Tecbniques for Electric Power Systems*.(Control and Dynamics Systems Edited by C. T. Leondes) Vol. 44, pp. 89 -130, 1991.

[5] Weerasooriya S. and EI-Sharkawi M. A., "Identification and Control of a DC Motor Using Back-Propagation Neural Networks" *IEEE Trans. on Energy Conversion*, Vol. 6. No.4, pp. 663-669, 1991.

[6] Oldak S., Baril C. and Gutman P. O. “Quantitative design of a class of nonlinear systems with parameter uncertainty”, *International Journal of Robust and Nonlinear Control,* Vol 4, pp. 101-107, 1994.

[7] Baek S.M. and Kuc T-Y., “An Adaptive PID Learning Control of DC Motors,” *IEEE International Conf. on Systems*, Man, Cybernetics, vol.3, pp.2877-2882, 1997.

[8] Chapman S. J., “Electric machinery fundamentals”. *Boston: McGraw-Hill,* 1999.

[9] Ljung Lennart, “System Identification Theory for the User”, *Prentice Hall PTR*, 1999.

[10] Rubaai A. and Kotaru R., "Online identification and control of a DC motor using learning adaptation of neural networks," Industry Applications, *IEEE Transactions on online identification*, vol. 36, pp. 935-942, 2000.

[11] Saab S. S. and Kaed-Bey R. A., “Parameter Identification of a DC Motor: An Experimental Approach,” *IEEE International Conf. on Elec. Circuit and Systems*. (ICECS), vol.4, pp. 981-984, 2001.

[12] Pintelon Rik, Schoukens Johan, System Identification. “A Frequency Domain Approach”, *IEEE* Press, NJ, 2001.

[13] Robertson D. G. and Lee J. H., “On the use of constraints in least squares estimation and control”, *Automatica*, Vol. 38, pp 1113-1123, 2002.

[14] Puangdownreong D., Areerak K-N., Srikaew A., Sujitjorn S. and Totarong P., “System Identification via Adaptive Tabu Search,” *Proc. IEEE International Conf. on Ind. Tech.* (ICIT02), pp. 915-920, 2002.

[15] Hussein Ahmed Mustafa “Transient response analysis”, pp. 10-20, 2003.

[16] “A New Experimental Application of Least-Squares Techniques for the Estimation of the Induction Motor Parameters”, *IEEE Transactions on Industry Applications*, Vol. 39, No. 5, 2003.

[17] Dupuis A., Ghribi M. and Kaddouri A., “Multiobjective Genetic Estimation of DC Motor Parameters and Load Torque,” *IEEE International Conf. on Ind. Tech. (ICIT)*, pp 1511-1514, 2004.

[18] Kim M. S., and Chung S. C., “A systematic approach to design high performance feed drive system,” *International Journal of Machine tools and Manufacture*, vol. 45, pp.1421-1435, 2005.

[19] Rao, G. and Unbehauen, H., “Identification of continuous time systems” *IEEE Process-Control Theory*, vol. 153, pp. 185-220, 2006.

[20] Rubaai A. and Kotaru R., "Online identification and control of a DC motor using learning adaptation of neural networks", *IEEE Trans on Industry Applications*, vol. 36, pp. 935-942, 2000.

[21] Lankarany M and Rezazade A., “Parameter Estimation Optimization Based on Genetic Algorithm Applied to DC Motor”, *IEEE International Conf. on Electrical Engineering.* (ICEE), pp.1-6, 2007.

[22] Dorf R.C. and Bishop R. H., “Modern Control System”. *Massachussetts: Pearson Education,* 2008.

[23] El-Sharkawi M. A., "Advanced Control Techniques for Higb Performance Electric Drives" *Analysis and Control System Tecbniques for Electric Power Systems*.(Control and Dynamics Systems Edited by C. T. Leondes) Vol. 44, pp. 89 -130, 2009.

[24] Hadef Mounir and Mekideche Mohamed Rachid “Inverse Problem Methodology for Parameter Identification of a Separately Excited DC Motor”, *Journal of Electrical Engineering and Technology,* Vol. 4, No. 3, pp. 365~369, 2009.

[25] Salah M. and Abdelati M., “Parameters identification of a permanent magnet DC motor Modeling” , *Identification and Control MIC,* 675-085, 2010.

[26] Galijašević, S., Mašić, Š., Smaka S., Akšamović, A., Balić, D.”Parameter identification and digital control of speed of a permanent magnet DC motors” *23rd International Symposium on Information, Communication and Automation Technologies* 2011.

[27] Wu Wei, "DC Motor Parameter Identification Using Speed Step Responses" *Modelling and Simulation in Engineering* vol. 2012, 5 pages, 2012.

[28] Ahn, H.-J., Shim, “System modeling and controller design using time series data” *International Conference on Control, Automation and Systems,* pp. 1144-1147, 2012.

[29] Xiao, J., Hou, L., Wang, H., Zhang, W. “Modeling of DC motor and its controller optimization design” *International Conference on Advanced Mechatronic Systems,* pp. 163-167, 2013.

[30] Sandra Lach Arlinghaus, PHB Practical Handbook of Curve Fitting. *CRC Press*, 1994.

[31] Kolb William M.. "Curve Fitting for Programmable Calculators" *Syntec*, *Incorporated*, 1984.

[32] Aidan O'Dwyer "Handbook of PI and PID controller tuning rules", *Imperial College Press 2nd Edition*, pp.30-40, 2006.