OPTIMUM CHOPPING CYCLE FOR DC MOTOR STARTING

by

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TABLE OF CONTENTS

CHAPTER Page

I INTRODUCTION 1

II DYNAMIC BEHAVIOR OF DC MOTOR

A. Nomenclature 3
B. Dynamic Equivalent Circuit of Motor ... 3
C. Block Diagram of Motor 4
D. Optimizing System Response 5

III CHOPPER DC MOTOR SPEED CONTROL

A. Introduction 8
B. Definitions 9
C. Principle of Operation 9
D. Time Ratio Control 10
E. Pulse Width Control 10
F. Off-frequency Control 11

IV COMPUTER PROGRAM

A. Introduction 13
B. The Mathematical Model of the System .. 13
C. The Numerical Values of the Parameters . 14
D. The Simulation Program 15

V SIMULATION

A. Introduction 21
B. Definitions 24
C. Simulation Procedure 25
D. Simulation Results 31
E. Summary 42

VI CONCLUSIONS 50

APPENDIX A SIMULATION PROGRAM 52

APPENDIX B PART OF LIBRARY OF CSMP III FUNCTION BLOCKS 53

APPENDIX C GRAPH FOR CURRENT AND SPEED RESPONSE OF OPTIMUM CHOPPING CYCLE FOR DC MOTOR STARTING .. 54

APPENDIX D IBM CONTINUOUS SYSTEM MODELING PROGRAM III 55

BIBLIOGRAPHY 62

ACKNOWLEDGMENT 64

THIS BOOK CONTAINS NUMEROUS PAGES WITH DIAGRAMS THAT ARE CROOKED COMPARED TO THE REST OF THE INFORMATION ON THE PAGE.

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LIST OF FIGURES

Figure	Title	Page
1	Representation of DC Motor	6
2	Dynamic Equivalent Circuit of Motor	7
3	Block Diagram of Separately Excited Motor with Torque Loading from Simultaneous Equations	7
4	Waveforms of Chopper Speed Control at Low Speed	12
5	Waveforms of Chopper Speed Control at High Speed	12
6	Detailed System Block Diagram of Separately Excited Motor with Constant Torque Loading for Simulation	19
7	Flow Chart Illustrating the DC Motor System Simulation Program	20
8	Graph for Two Time-intervals	22
9	Graph for Three Time-intervals	22
10	Graph for Simulation No. 1 (t2=100%): (A) Maximum Current vs. Various Values of t1; (B) Maximum Speed vs. Various Values of t1	44
11	Graph for Simulation No. 2 (p2=100%): (A) Maximum Current vs. Various Values of p1; (B) Maximum Speed vs. Various Values of p1	44
12	Graph for Simulation No. 3 (r2=25%, r3=100%): (A) Maximum Current vs. Various Values of r1; (B) Maximum Speed vs. Various Values of r1	45
13	Graph for Simulation No. 4 (r2=50%, r3=100%): (A) Maximum Current vs. Various Values of r1; (B) Maximum Speed vs. Various Values of r1	45
14	Graph for Simulation No. 5 (r2=75%, r3=100%): (A) Maximum Current vs. Various Values of r1; (B) Maximum Speed vs. Various Values of r1	45
15	Graph for Simulation No. 6 (r2=100%, r3=100%): (A) Maximum Current vs. Various Values of r1; (B) Maximum Speed vs. Various Values of r1	46

16 Graph for Simulation No. 7 (r2=25%, r3=100%):
(A) Maximum Current vs. Various Values of r1;
(B) Maximum Speed vs. Various Values of r1 46

17 Graph for Simulation No. 8 (r2=50%, r3=100%):
(A) Maximum Current vs. Various Values of r1;
(B) Maximum Speed vs. Various Values of r1 46

18 Graph for Simulation No. 9 (r2=75%, r3=100%):
(A) Maximum Current vs. Various Values of r1;
(B) Maximum Speed vs. Various Values of r1 47

19 Graph for Simulation No. 10 (r2=100%, r3=100%):
(A) Maximum Current vs. Various Values of r1;
(B) Maximum Speed vs. Various Values of r1 47

20 Graph for Simulation No. 11 (r1=40%, r2=60%):
(A) Maximum Current vs. Various Values of r3;
(B) Maximum Speed vs. Various Values of r3;
(C) Rise Time vs. Various Values of r3 47

21 Graph for Simulation No. 12 (r1=40%, r3=75%):
(A) Maximum Current vs. Various Values of r2;
(B) Maximum Speed vs. Various Values of r2;
(C) Rise Time vs. Various Values of r2 48

22 Graph for Simulation No. 13 (r2=80%, r3=75%):
(A) Maximum Current vs. Various Values of r1;
(B) Maximum Speed vs. Various Values of r1;
(C) Rise Time vs. Various Values of r1 48

23 Graph for Simulation No. 14 (r2=75%, r3=75%):
(A) Maximum Current vs. Various Values of r1;
(B) Maximum Speed vs. Various Values of r1;
(C) Rise Time vs. Various Values of r1 48

24 Graph for Simulation No. 15 (r1=50%, r3=75%):
(A) Maximum Current vs. Various Values of r2;
(B) Maximum Speed vs. Various Values of r2;
(C) Rise Time vs. Various Values of r2 49

25 Graph for Simulation No. 16 (Fr1=200 Hz, Fr3=2.5 Hz):
(A) Maximum Current vs. Various Values of Fr2;
(B) Maximum Speed vs. Various Values of Fr2;
(C) Rise Time vs. Various Values of Fr2 49

26 Graph for Simulation No. 17 (Fr2=200 Hz, Fr3=2.5 Hz):
(A) Maximum Current vs. Various Values of Fr1;
(B) Maximum Speed vs. Various Values of Fr1;
(C) Rise Time vs. Various Values of Fr1 49

27 Graph for Current and Speed Response of Optimum
Chopping Cycle for DC Motor Starting 54

LIST OF TABLES

Table	Title	Page
1	Units and Magnitudes for the DC Motor Parameters and Variables	15
2	Simulation No. 1 (Graph as shown in Fig. 10)	32
3	Simulation No. 2 (Graph as shown in Fig. 11)	33
4	Simulation No. 3 (Graph as shown in Fig. 12)	34
5	Simulation No. 4 (Graph as shown in Fig. 13)	34
6	Simulation No. 5 (Graph as shown in Fig. 14)	35
7	Simulation No. 6 (Graph as shown in Fig. 15)	35
8	Simulation No. 7 (Graph as shown in Fig. 16)	36
9	Simulation No. 8 (Graph as shown in Fig. 17)	36
10	Simulation No. 9 (Graph as shown in Fig. 18)	37
11	Simulation No. 10 (Graph as shown in Fig. 19)	37
12	Simulation No. 11 (Graph as shown in Fig. 20)	38
13	Simulation No. 12 (Graph as shown in Fig. 21)	38
14	Simulation No. 13 (Graph as shown in Fig. 22)	39
15	Simulation No. 14 (Graph as shown in Fig. 23)	39
16	Simulation No. 15 (Graph as shown in Fig. 24)	40
17	Simulation No. 16 (Graph as shown in Fig. 25)	40
18	Simulation No. 17 (Graph as shown in Fig. 26)	41
19	Part of Library of CSMP III Function Blocks	53

CHAPTER I

INTRODUCTION

The chopper-controlled dc separately and series excited motor has been widely used recently in traction and many other industry applications. Although many motor applications require constant speed, such as pumps, fans, presses, and generators, there are many applications that require the speed of the motor to be changed. Examples are: traction, hoisting, and machine tools. Motors are divided into three classifications as follows:

A. A constant speed motor is one that operates at a single speed essentially independent of load (e.g. induction motors and shunt dc motors).

B. An adjustable speed motor is one whose speed may be 'adjusted' or changed to different values. For each setting its speed is essentially independent of load (e.g. dc shunt motors).

C. A variable speed motor is one whose speed changes or varies over wide values as the load is changed.

The motors being used in modern industrial systems are becoming increasingly large in size. Starting these large motor, especially across-the-line, produces a transient voltage depression that can substantially reduce the motor output torque while severely influencing the operation of any locally connected load, as well as loads served by buses electrically remote from the point of motor starting. This also causes overheating of the motor. Certain computer-aided motor starting studies can provide an instant-by-instant shaft output torque tabulation (for comparison to the allowable torque limits of the equipment), and accurate values of motor acceleration current and rise time.

This paper is concerned with the determination of the optimum chopping cycle for dc motor starting, by using Continuous System Modeling Program III (CSMP III). The objective is to obtain a minimum starting current and a minimum rise time for motor starting. In order to optimize the dc motor response, the analysis of such a motor will be briefly reviewed. The performances of the dc chopper for three types of control -- time ratio control (TRC), pulse width control (PWC), and off-frequency control (OFC) -- are introduced in Chapter III. When a wide range of control is needed, a suitable combination of variable and constant controls is employed.

The dynamic behavior of a dc motor is, in general, highly nonlinear. Consequently, it is inadequate to approximate its performance by linear models. One of the methods of obtaining realistic solutions to the analysis and design of dc motors is computer simulation. Table 19 lists part of the library of CSMP III function blocks. Some of them are used to generate the pulses for simulating the output from the chopper, which controls the speed of the dc motor. The search for the minimum starting current and the minimum rise time by using variable 'on'-pulsewidth-to-chopping-rate ratios in certain predefined time-intervals is explored in simulation procedures. Finally, conclusions are made in Chapter VI.

CHAPTER II

DYNAMIC BEHAVIOR OF DC MOTOR

A. Nomenclature

E	Source voltage
Em	Average voltage in armature
Eb	Induced armature EMF
Ia	Average current in armature
ia	Instantaneous current in armature
Jm	The combined rotational inertia of the motor armature
Ke	EMF constant
Kt	Torque constant
La	Inductance of armature winding
Ra	Resistance of armature winding
Tm	Armature torque
TL	External load torque
W	Angular velocity (motor speed)

B. Dynamic Equivalent Circuit of Motor

The dynamic behavior of a motor is governed by its energy storage properties. Energy is stored in two ways: by a magnetic field in the magnetic circuit, and by mechanical velocity in the inertia of the armature. Of course, energy is also stored in the inertia of the load and in the magnetic fields of the electrical sources, and must be included in the consideration of the dynamics.

The energy storage property of the magnetic field is measured by inductance.

The dc motor representation is shown in Fig. 1. The dynamic equivalent circuit of the motor is shown in Fig. 2. The resistance Ra includes all of the windings in the armature circuit. The armature itself is the generator of the voltage Eb and the torque Tm.

The differential equations which describe the dynamic behavior for armature voltage control at constant field are:

For the armature circuit:

$$E = IaRa + La\frac{dIa}{dt} + Eb$$

$$Eb = Ke \cdot W$$

For the mechanical system:

$$Tm = Jm\frac{dW}{dt} + TL$$

$$Tm = Kt \cdot Ia$$

C. <u>Block Diagram of Motor</u>

The dynamic properties are conventionally shown by means of a block diagram which shows the relationship of the differential equations for small amplitudes of the variables. The variables used are the transforms of the variables in the differential equations. The block diagram for the motor is shown in Fig. 3.

D. Optimizing System Response

With reference to Fig. 1, the dynamic equation describing the approximate behavior of an armature-controlled motor is

$$E = IaRa + La\frac{dIa}{dt} + KeW \tag{1}$$

which is Kirchhoff's voltage law for the armature loop, neglecting the voltage drop across the brushes. Ke is the motor torque constant Ra and La are the armature winding resistance and inductance, respectively. The mechanical torque is

$$Tm = Jm\frac{dW}{dt} + TL \tag{2}$$

where Tm is the torque delivered by the motor, TL is the load constant torque, and Jm is the combined rotational inertia of the motor armature and the load. Motor friction is neglected.
The electromagnetic torque is

$$Tm = Kt \cdot Ia \tag{3}$$

which expresses the proportionality between torque and armature current for a separately-excited dc motor.

These equations can be combined and put in state variable form.

$$\frac{dIa}{dt} = \frac{1}{La}(E - IaRa - KeW) \tag{4}$$

$$\frac{dW}{dt} = \frac{1}{Jm}(KtIa - TL) \tag{5}$$

These equations have been modeled by means of a FORTRAN program using a trapezoidal rule of integration and a variety of system parameters to study their effect on the dynamic response.

These dynamic equations can be analyzed by using the Laplace transform technique.

$$(La.s + Ra)\ Ia(s) = E(s) - Eb(s) \tag{6}$$

$$Eb(s) = Ke \ . \ W(s) \tag{7}$$

$$Kt\ Ia(s) - TL = Jm \cdot s \cdot W(s) \tag{8}$$

which implies,

$$Ia(s) = \frac{E(s) - Eb(s)}{La \cdot s + Ra} \tag{9}$$

$$Eb(s) = Ke \cdot W(s) \tag{10}$$

$$W(s) = \frac{1}{Jm \cdot s}[Kt\ Ia(s) - TL] \tag{11}$$

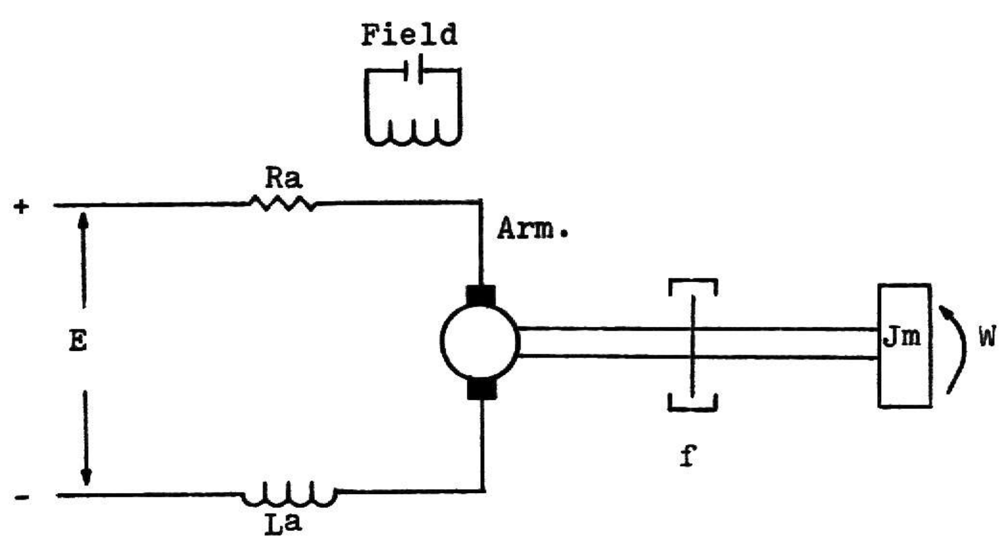


Figure 1. Representation of DC Motor.

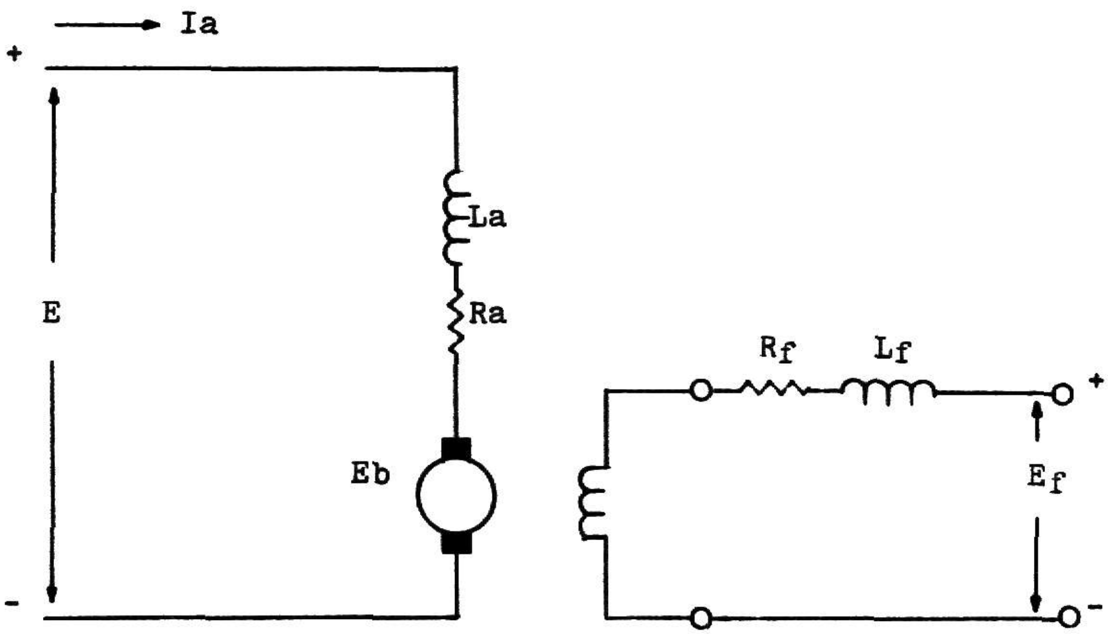


Figure 2. Dynamic Equivalent Circuit of Motor.

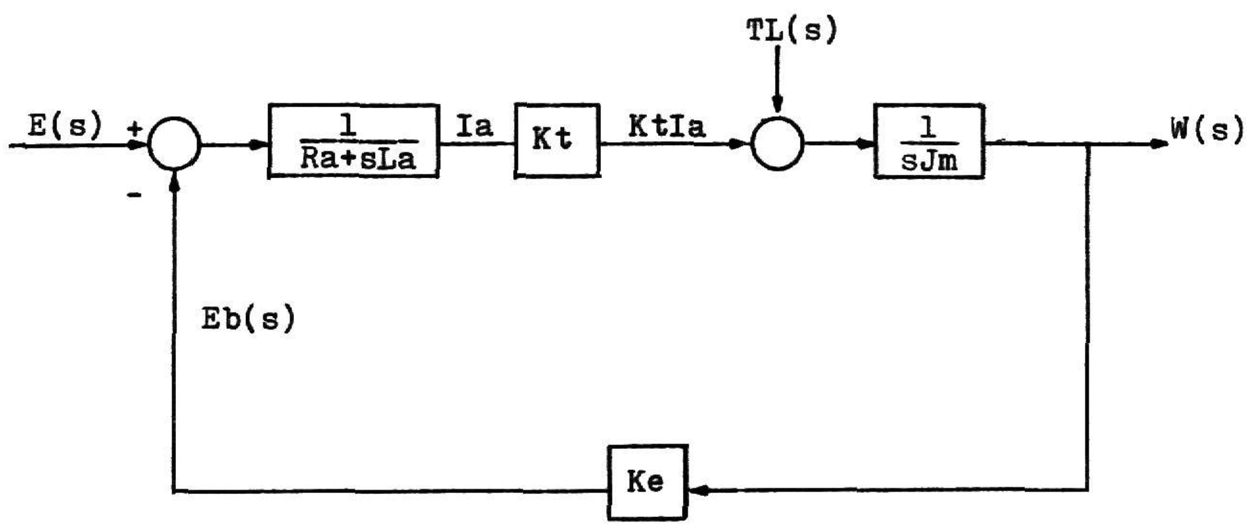


Figure 3. Block Diagram of Separately Excited Motor with Torque Loading from Simultaneous Equations.

CHAPTER III

CHOPPER DC MOTOR SPEED CONTROL

A. Introduction

The flexibility of the dc motor for speed control, its overload capability, and its reliability make it the dominant means of providing a controllable source of mechanical rotating power in industry. The steady-state characteristics of the motor determine how the motor can be controlled; the dynamic characteristics determine how the control system must be designed to obtain the required response.

A chopper is a dc-to-ac converter which produces low frequency square waves at the chopping frequency (or chopping rate) with an amplitude proportional to the applied direct voltage. A thyristor is used to connect and disconnect the motor from the source, that is, to chop the source voltage. The drive signal for the chopper may be obtained from a low voltage transformer connected to the power line, in which case chopping will occur at the power line frequency (60 Hz in North America). For reasons which are related to the noise generated by active devices, it is frequently desirable to use a higher chopping rate (such as 100 to 200 Hz), and in such cases suitable oscillators must be provided to drive the chopper. For example, those associated with servo equipment in aircraft systems use 400 Hz supplies which provide a suitable chopper drive.

B. Definitions

In order to fully understand what follows, certain definitions are important. These relate to time segments in chopping.

TAU: "on-pulse" pulsewidth. It represents a source voltage applied to the dc motor.

T: "off-pulse" pulsewidth. It represents no source voltage applied to the motor.

TAU1: time of first pulse.

TAU2: chopping rate. It represents the repetition rate of switch closure.

r: "on-pulse" pulsewidth-to-chopping-rate ratio. It represents the percentage of supplied voltage the dc motor receives.

C. Principle of Operation

The principle of operation is that the motor is supplied with pulses of source voltage whose value is controlled by the ratio of on-to-period time of the pulses. For example, if the ratio is 0.8, the motor receives an average of 0.8 E and behaves as though it were connected to a continuous source of this value. Hence, at constant torque load, the motor speed will be proportional to the pulse ratio.

The waveforms for two speeds at the same current and torque are shown in Fig. 4 and Fig. 5. For slow-speed operation, the pulse ratio and average motor voltage Em are low. The average current Ia is determined by the torque requirement. The motor can receive energy from the source only during the on-time TAU. During this time the voltage (E - Eb) is applied to the Ra, La armature circuit and the current ia increases exponentially. During the off-time, the current ia decreases exponentially under the voltage -Eb applied to the same Ra, La circuit. For high-speed operation, since the current ia falls only a small amount during the off-time T, the voltage difference (E - Eb) should be small to increase the current during the on-time TAU. The speed of the motor thus rises to bring the voltage Eb closed to E.

D. Time Ratio Control

In chopper circuits, the supply voltage is repeatedly connected to and disconnected from the load by means of a switch. The output voltage can be controlled by time ratio control, with the average voltage on the load regulated by varying the repetition rate of switch closure. In this case, as shown in Fig. 5, the pulsewidth TAU is constant, and variation of the cycle (1/TAU2) may result in a transition from a continuous to an intermittent armature current region.

E. Pulse Width Control

This is well-known as pulsewidth modulation, with the average voltage on the load regulated by varying the time during each interval that the switch is closed. In this mode the cycle 1/TAU2 is constant, and the variation of the pulsewidth may result in a transition from a continuous to an intermittent armature current region. A maximum TAU2 can be calculated, ensuring current continuity irrespective of the pulsewidth, but the resulting switching frequency is generally too high for convenient practical application. Consider a load connected to a constant voltage supply by a switch. If the switch is operated so as to be closed for 50% of the time, then when it is closed the load will receive the supply voltage. However, on a time interval of several cycles, the mean load voltage will only be 50% of the supply voltage. If the percentage of on-to-period time is varied or "modulated", the mean load voltage can be correspondingly controlled.

F. Off-frequency Control

Since neither of the above modes ensures the continuity of the armature current, the so called "off-frequency control", was proposed by Z. Zabar and A. Alexandrovitz for maintaining armature current continuity. This method is based on a constant turn-off time (TAU2 - TAU = constant) for the working thyristor, ensuring that the exponentially-suppressed armature current does not decay during this interval. In these circumstances, variation of TAU2 results in variation of TAU, and the average on the load is regulated by varying the repetition rate of switch opening.

As an additional advantage, the proposed technique permits $TAU/TAU2 \approx 1$, that is,

$$r = \frac{TAU2 - T}{TAU2} = 1 - \frac{T}{TAU2}$$

and $T = TAU2 - TAU =$ constant, so that TAU2 may be increased to give $T/TAU2 \ll 1$; i.e., all of the supply voltage is fed to the armature, and the motor can be utilized at the rated level.

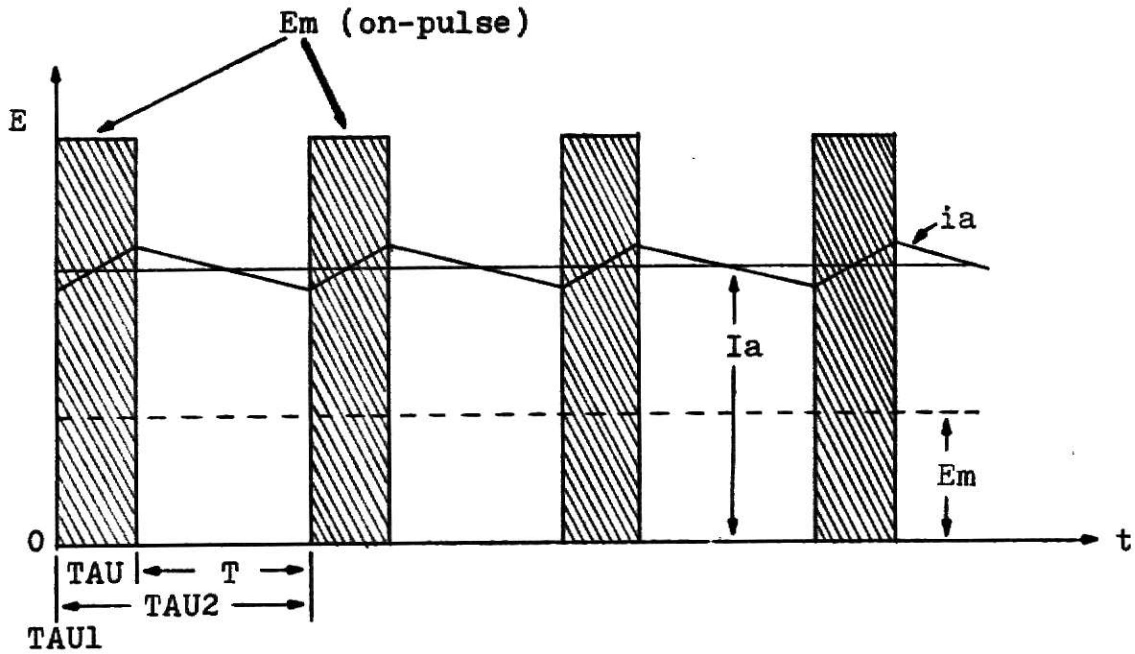


Figure 4. Waveforms of Chopper Speed Control at Low Speed.

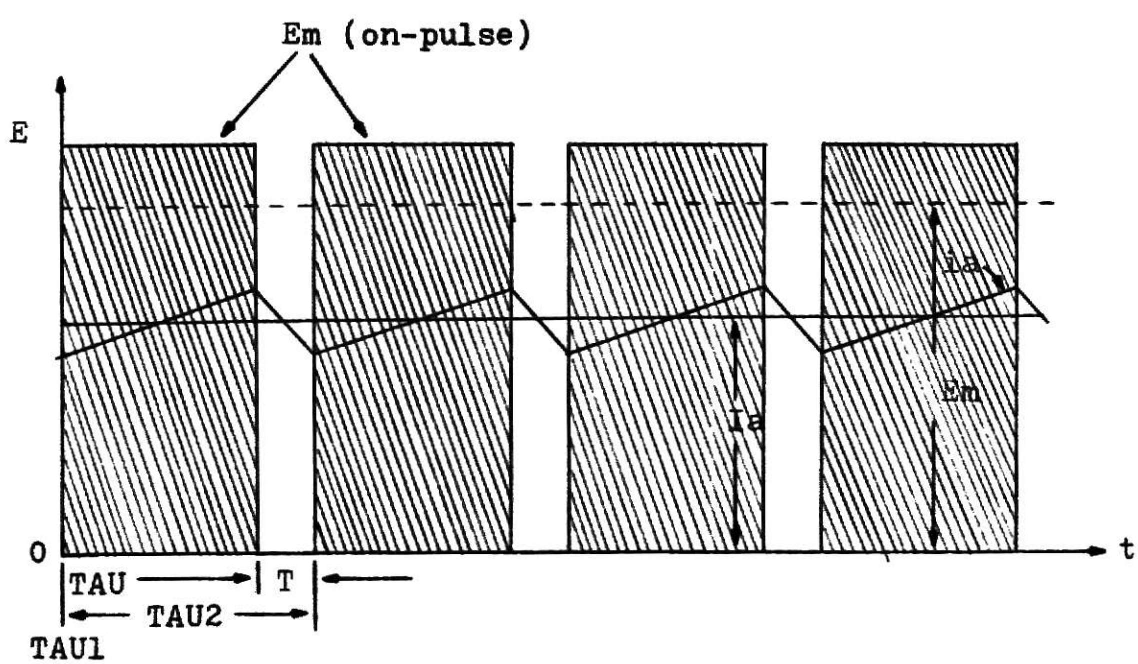


Figure 5. Waveforms of Chopper Speed Control at High Speed.

CHAPTER IV

COMPUTER PROGRAM

A. Introduction

In the past, analog computer simulations of dc motors have been conducted. The advantage of using an analog computer is that the change in the performance of the motor can be investigated while the motor parameters are being changed continuously on line. On the other hand, digital computer simulation offers a great deal of flexibility. The computer can be used for both analysis and design. Standard FORTRAN or a simulation language like the Continuous System Modeling Program (CSMP) III may be used.

In this paper, the use of CSMP III, as shown in Appendix D, is emphasized. A programmer who understands a simulation program written in FORTRAN can generally modify it for use with CSMP, but the reverse is usually not true. Before any dc motor system can be simulated, some basic information regarding the system and the simulation procedure is needed.

B. The Mathematical Model of the System

The mathematical model of a dc motor consists of a system of differential equations which describe the dynamic behavior of the dc motor system. These are generally first-order differential equations. It is important that these differential equations accurately represent the system to be simulated, since the simulation results are only as valid as the model which is used to generate them. In this case, the dc motor is used in traction connected to a constant load. Neglecting inertia and friction, these equations are

$$\frac{dIa}{dt} = \frac{1}{La}(E - Ia\ Ra - Ke\ W) \tag{12}$$

$$Eb = Ke \cdot W \tag{13}$$

$$\frac{dW}{dt} = \frac{1}{Jm}(Kt\ Ia - TL) \tag{14}$$

By using the Laplace transform technique, these equations become

$$Ia(s) = \frac{1}{La \cdot s + Ra}[E(s) - Eb(s)] \tag{15}$$

$$Eb(s) = Ke \cdot W(s) \tag{16}$$

$$W(s) = \frac{1}{Jm \cdot s}[Kt\ Ia(s) - TL] \tag{17}$$

The detailed system block diagram of a separately excited dc motor with constant torque loading for simulation is shown in Fig. 6.

C. The Numerical Values of the Parameters

It is important that the actual numerical values of all the parameters of the system be accurately obtained, since the simulation results will be directly dependent on them. All of the numerical values should be consistently represented in one system of units. This will insure proper magnitudes of the variables and output quantities. Table 1 shows the units and magnitudes for all of the dc motor parameters and variables appearing in Eqs. 12 through 17, in the MKS system.

Table 1. Units and Magnitudes for the DC Motor Parameters and Variables

Variable	Units-MKS system	Magnitudes
W	radians/sec.	
Ia	Amperes	
E, Eb	Volts	
Ra	Ohms	4.98
La	Henrys	0.0524
Jm	kg-m^2	0.0087
TL	kg-m	3.0
Ke	Volts/radians/sec.	1.212
Kt	kg-m/Ampere	0.83

D. The Simulation Program

The actual simulation program can be considered, after all of the information that is necessary to perform the simulation has been collected. Figure 7 shows the basic flow chart of a computer program for simulating a dc motor system. The exact CSMP III program for the simulation is given in Appendix A.

In order to fully understand the simulation program, an explanation about the program is necessary. The system parameters and the initial conditions are first set in the program. With reference to Appendix B, the combination of two function blocks, Y = IMPULS (P1,P2) and Y = PULSE (P,X), is used to generate the pulses for simulating the chopper output from the system. P1 is the time of the first pulse, P2 is the interval between pulses, P is the minimum pulse width, and X must be greater than zero as the trigger. For example, Fig. 4 represents the chopper output waveform at low speed motor control and Fig. 5 represents the chopper output waveform at high speed motor control. In this case, P1 is TAU1, P2 is TAU2, P is TAU, and X is X1.

The function block Y = REALPL (IC,P,X) simulates a first order differential equation. IC is the initial value of the variable X, P is the ratio of La to Ra, and X is the variable of integration. In this case, IC is zero; the ratio of La to Ra is 0.0105; and X is YONE.

The function block Y = INTGRL (IC,X) is used to integrate the dynamic equation of the system. IC is the initial condition and X is the variable of integration. In this case, IC is zero, and X is YFIVE.

The SPEED (variable) is obtained by multipling the OUT (variable) with a constant coefficient after the successful completion of each integration step. The information is printed or plotted according to the output format requirements.

The OUTPUT statement may list up to 55 symbolic names for scalar output variables or array elements. Each case may, however, include a number of OUTPUT statements, each of which will produce a separate output document. Note that the OUTPUT statement is intended only for real variables. If the value of an integer variable must be documented, a real variable should be set equal to the integer variable, and the real variable listed on the OUTPUT statement.

The LABEL statement allows the user to specify the heading to appear at the top of each page of an output document. The text of the heading is entered between the statement label, LABEL, and card column 72. One continuation card is allowed for a LABEL statement. A page width of up to 120 characters is allowed. A maximum of five LABELs may be specified for one OUTPUT statement.

The PAGE statement is used to override the standard format of the output document. A multitude of variations is possible, such as continuous graphs if an x-y plotter is available. Each of the format options is specified by a parameter of the PAGE statement. The XYPLOT parameter is used if the output document is to be produced by an x-y plotter rather than a line printer.

The TIMER statement allows the user to specify the values of certain system variables. The current value of the specified system variable is replaced by the corresponding real number. If there is more than one value for a TIMER reserved-word for a simulation run, the last value given will be used. User specifications are automatically adjusted by the program, as necessary, to ensure a consistent relationship between integration interval, run time, and output intervals. The system variables that may be set are:

System Variable Name	Description
FINTIM	Finish time for terminating a particular simulation (that is, the maximum simulation value for the independent variable). This must be specified for each simulation. FINTIM is adjusted, as necessary,

to be the highest multiple of the most frequent output that occurs within the originally specified FINTIM

DELT — Integration interval or step size for the independent variable. If DELT is specified, the program adjusts it, as necessary, to be a submultiple of OUTDEL. If OUTDEL has not been specified, DELT is adjusted, as necessary, to be a submultiple of (FINTIM - start time)/100. If DELT is not specified, the program assigns it a value equal to 1/16 of OUTDEL.

OUTDEL — Print increment for the OUTPUT printing and preparation of a data tape for plotting program. If an OUTDEL is required but has not been specified, it is set equal to (FINTIM - start time)/100.

The END CONTINUE statement is used when a run is to be interrupted to allow a data or control statement to be changed during the simulation. When restarted after data or control statement input, the program does not reset initial conditions or the independent variable (TIME), but continues from the point at which the interruption occured. Run control by means of a multiple-valued parameter on a CONSTANT statement should not be used in conjunction with the END CONTINUE statement. Output document generation occurs only at the end of the case (that is, when an END statement is encountered without an operand). The portion of the output document up to the END CONTINUE statement is therefore not printed out until the end of the case. The last use of the END statement must be followed by the STOP statement.

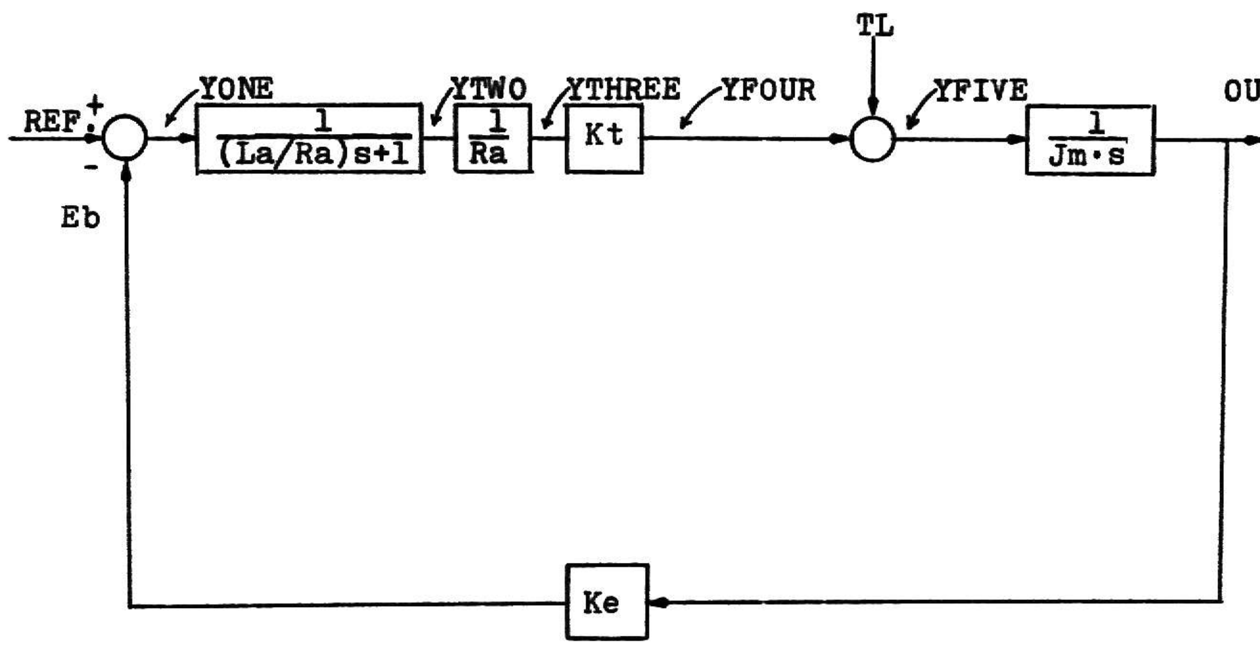


Figure 6. Detailed Syatem Block Diagram of Separately Excited Motor with Constant Torque Loading for Simulation.

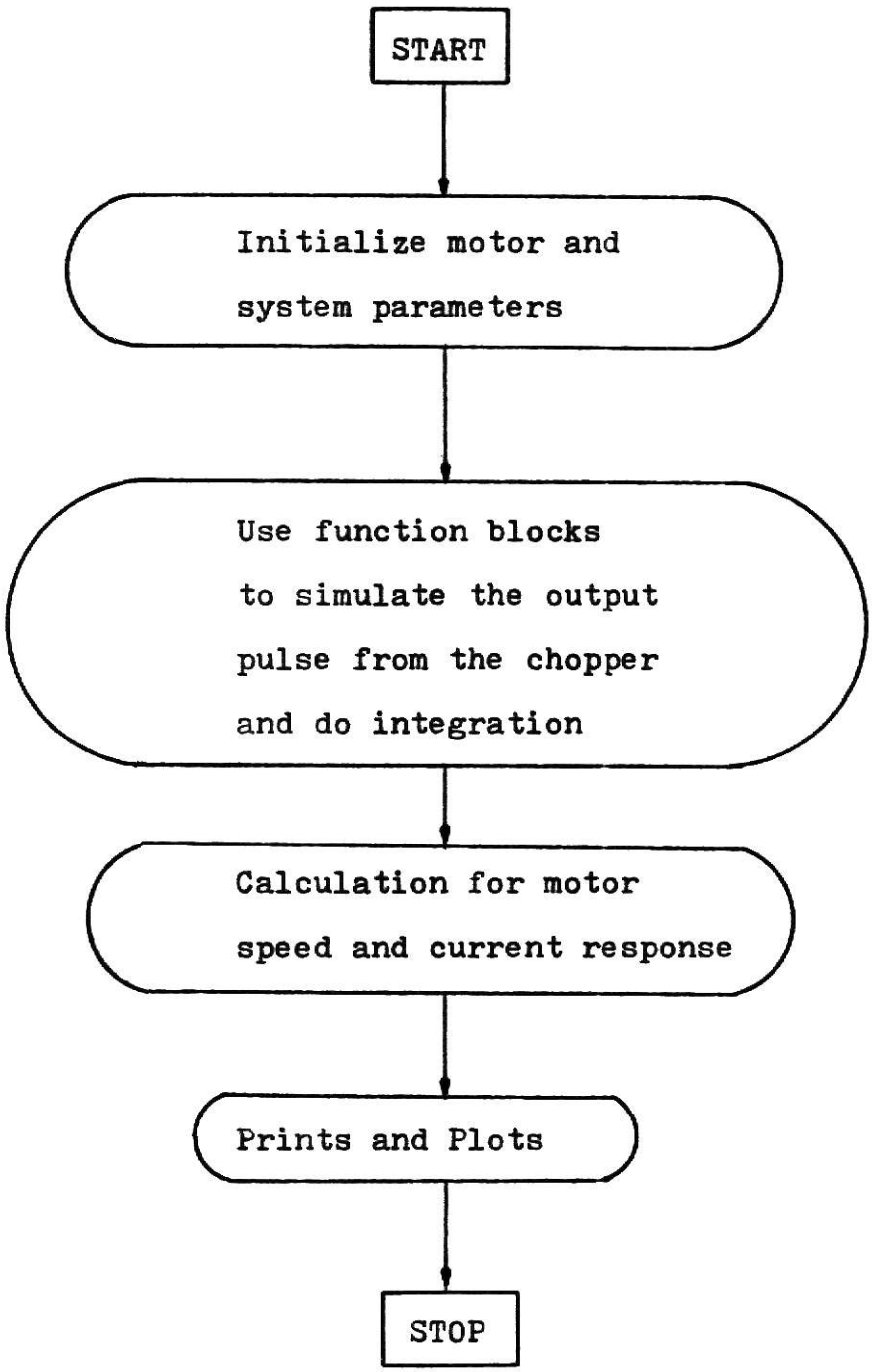


Figure 7. Flow Chart Illustrating the DC Motor System Simulation Program.

CHAPTER V

SIMULATION

A. Introduction

The basic principles of a chopper dc motor speed control were introduced in Chapter III. The implementation of these principles for investigating the starting current and speed acceleration of a separately excited dc motor (from 0 to 0.2 second) will be introduced in the following simulation procedures. The motor used for the simulation is a separately excited 240 volt dc motor rated 1 hp at 1750 rpm. It requires 3.6 amperes full load current.

The simulation process is divided into either two or three time intervals, and make use of the following modulation methods. The modulation methods are (1) time ratio control, (2) pulse width control, and (3) a combination of the two. Figure 8 illustrates the two time-intervals, and Figure 9 illustrates the three time-intervals.

In order to understand the purpose and the procedures of this simulation, an explanation about different time-intervals and simulation processes is given below:

1. Two time-intervals:

   The motor transient response occurs in a very short time and then rapidly goes to steady-state (about 0.2 second). In the first simulation, the motor's performance is explored in two time-intervals. These time-intervals are

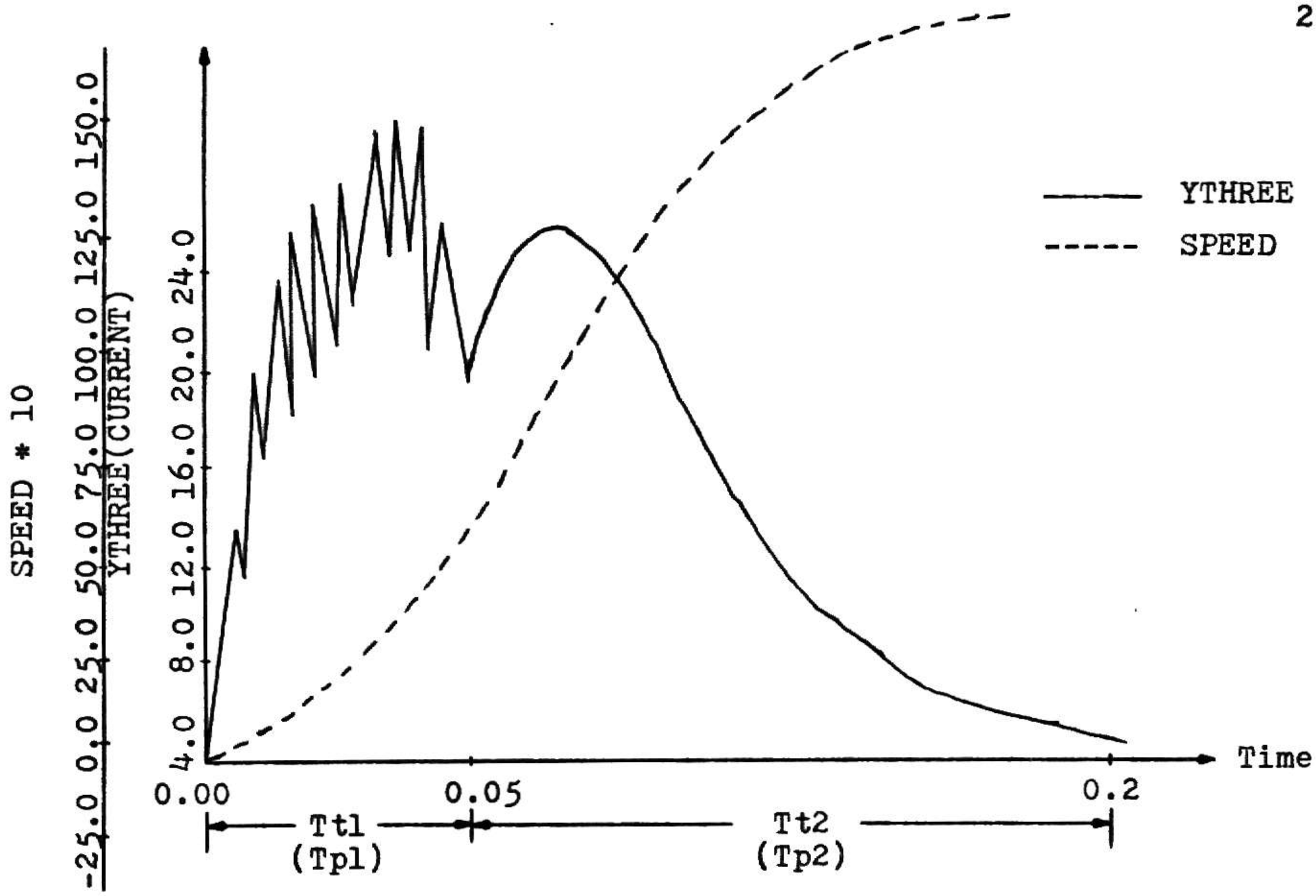


Figure 8. Graph for Two Time-intervals.

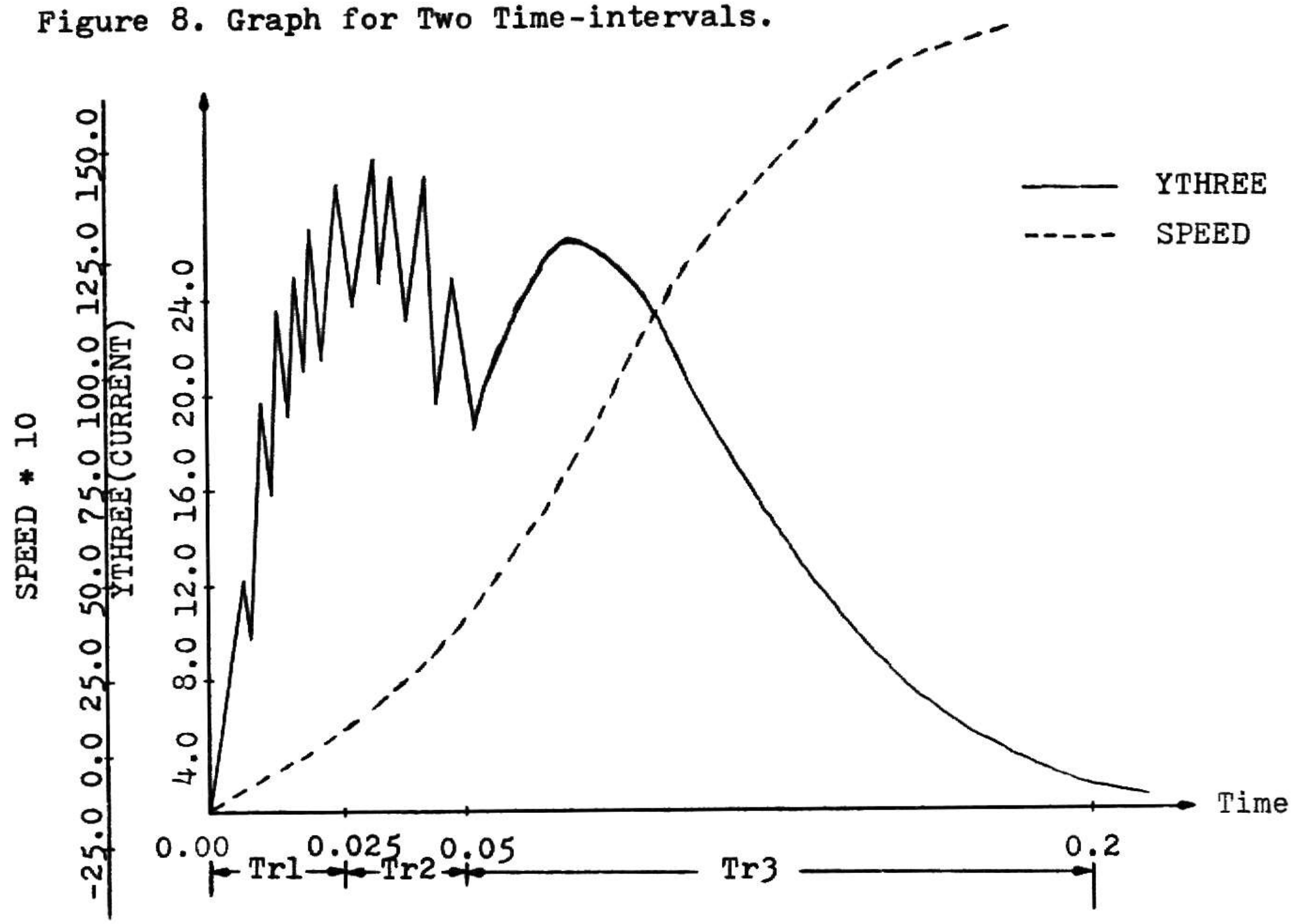


Figure 9. Graph for Three Time-intervals.

Tt1 = 0.0 - 0.05 second and

Tt2 = 0.05 - 0.2 second [using Time Ratio Control (TRC)];

also

Tp1 = 0.0 - 0.05 second and

Tp2 = 0.05 - 0.2 second [using Pulse Width Control (PWC)].

With reference to Figure 8, the TRC method and the PWC method are used in these two time-intervals for the following simulation.

2. Three time-intervals:

With reference to Table 2 and Table 3, the maximum speed of the motor is 1252.58 rpm for the two time-intervals simulation process. Apparently the motor's acceleration is poor because the motor is rated 1 hp at 1750 rpm. In the second simulation, the motor's performance is explored in three time-intervals. These time-intervals are

Tr1 = 0.0 - 0.025 second,

Tr2 = 0.025 - 0.05 second, and

Tr3 = 0.05 - 0.2 second.

With reference to Figure 9, the TRC method, the PWC method, and a combination of the two are used in these three time-intervals for the following simulation.

Finally, from the analysis of the motor response using variable on-pulse pulsewidth and variable chopping rates in three time-intervals step by step, an optimum on-pulse pulsewidth-over-chopping-rate is searched for in the Tr1, Tr2, and Tr3 time-interval The minimum starting current and the minimum rise time (the shortest time to get the maximum speed) can be found by applying these voltages to the motor.

B. Definitions

In order to fully understand the following simulation procedure, certain definitions are important. These relate to time and frequency values in chopping. These also relate to the ratio of on-pulse pulsewidth-to-chopping-rate.

TAU = "on-pulse" pulsewidth

TAU1 = 0.0, time of first pulse

TAU2 = chopping rate

YTHREE (ia) = instantaneous armature current

TAU/TAU2 = "on-pulse" pulsewidth-to-chopping-rate ratio

Tt1 = Tp1 = 0.0 - 0.05 second, the first time-interval in two time-intervals

t1 or p1 = TAU/TAU2 in the Tt1 or Tp1 time-interval, respectively

Tt2 = Tp2 = 0.05 - 0.2 second, the second time-interval in two time-intervals

t2 or p2 = TAU/TAU2 in the Tt2 or Tp2 time-interval, respectively

Tr1 = 0.0 - 0.025 second, the first time-interval in three time-intervals

r1 = TAU/TAU2 in the Tr1 time-interval

Tr2 = 0.025 - 0.05 second, the second time-interval in three time-intervals

r2 = TAU/TAU2 in the Tr2 time-interval

Tr3 = 0.05 - 0.2 second, the third time-interval in three time-intervals

r3 = TAU/TAU2 in the Tr3 time-interval

Fr1 = 180 - 220 Hz (chopping cycle) in the Tr1 time-interval

Fr2 = 180 - 220 Hz (chopping cycle) in the Tr2 time-interval

Fr3 = 2.5 Hz (chopping cycle) in the Tr3 time-interval

C. Simulation Procedure

Before proceeding with the simulation, it is necessary to note a few points in regard to the selection of parameters. In general, the chopping frequency for driving the dc motor is from few Hertz to hundreds of Hertz. In fact, chopping frequencies from 150 Hz to 300 Hz have been used for simulations of motor performance in many papers. Now, 50% - 70% of the supplied voltage is applied to the dc motor when it is to be started. This partial source voltage guarantees that the starting current is not too high, and gives better acceleration at the same time. Because the motor's transient response occurs in a short time, the time-interval from 0.0 to 0.2 second is usually divided into two or three time-intervals.

The simulation procedure for obtaining the optimum chopping cycle for dc motor starting is given below:

1. The time-ratio control method is used to investigate the motor starting current and the speed acceleration in two time-intervals. In the case of simulation No. 1, these two time-intervals are Tt1 (from 0 to 0.05 second) and Tt2 (from 0.05 to 0.2 second). In the Tt1 time-interval, chopping rate TAU2 is variable (TAU2 = 0.03 - 0.003 second). In the Tt2 time-interval, chopping rate TAU2 is fixed (TAU2 = 0.003 second). With reference to Table 2 and Figure 10, the highest maximum motor speed is 1252.58 rpm with maximum starting current of

34.2656 amperes. The lowest maximum starting current is 16.5709 amperes with a maximum speed of 799.94 rpm. Because the result must be the lowest maximum starting current with highest maximum speed, this conclusion may be made for simulation No. 1: the result is poor.

2. The pulse-width control method is used to investigate the motor starting current and the speed acceleration in two time-intervals. In the case of simulation No. 2, these two time-intervals are Tp1 (from 0 to 0.05 second) and Tp2 (from 0.05 to 0.2 second). In the Tp1 time-interval, pulsewidth TAU is variable (TAU = 0.0005 - 0.005 second). In the Tp2 time-interval, pulsewidth TAU is fixed (TAU2 = 0.005 second). With reference to Table 3 and Figure 11, the highest maximum speed is 1163.47 rpm with maximum starting current of 33.795 amperes. The lowest maximum starting current is 19.102 amperes with a maximum speed of 808.007 rpm. Because the result must be the lowest maximum starting current with the highest maximum speed, this conclusion may be made for simulation No. 2: the result is also poor. From the above simulation results, neither the time-ratio control method nor the pulse-width control method can obtain the optimum motor response.

3. The time ratio control method is used to investigate the motor starting current and speed acceleration in three time-intervals In the cases of simulations No. 3, 4, 5, and 6, these three time-intervals are Tr1 (from 0 to 0.025 second), Tr2 (from 0.025 to 0.05 second) and Tr3 (from 0.05 to 0.2 second). In the Tr1 time-interval, chopping rate is variable (TAU = 0.012 - 0.003 second). In the Tr2 time-interval, chopping rate is fixed

(TAU = 0.012, 0.006, 0.004 and 0.003 second, respectively). In the Tr3 time-interval, chopping rate is fixed (TAU = 0.003 second). With reference to Tables 4, 5, 6, and 7, and also Figures 12, 13, 14, and 15, the lowest maximum starting current is 17.44 amperes with maximum speed of 798.697 rpm. The highest maximum speed is 1275.59 rpm with maximum starting current of 29.2931 amperes. The former can be found in Table 4 and Figure 12 where r1 = 25%, r2 = 25%, and r3 = 100%; the latter can be found in Table 6 and Figure 14 where r1 = 75%, r2 = 75%, and r3 = 100%.

4. The pulse-width control method is used to investigate the motor starting current and the motor acceleration in three time-intervals. In the cases of simulations No. 7, 8, 9, and 10, these three time-intervals are the same as simulations No. 3, 4, 5, and 6. In the Tr1 time interval, pulse width is variable (TAU = 0.00125 - 0.003 second). In the Tr2 time-interval, pulse width is fixed (TAU = 0.00125, 0.0025, 0.00375, and 0.005 respectively). In the Tr3 time-interval, pulse width is fixed (TAU = 0.005 second). With reference to Tables 8, 9, 10, and 11, and also Figures 16, 17, 18, and 19, the lowest maximum starting current is 19.77 amperes with maximum speed of 806.56 rpm as given in Table 8 and Figure 16 where r1 = 25%, r2 = 25% and r3 = 100%. The highest maximum speed is 1041.04 rpm with maximum starting current of 31.054 amperes as given in Table 10 and Figure 18 where r1 = 75%, r2 = 75%, and r3 = 100%.
5. A combination of the time-ratio control method and the pulse-width control method is used to investigate the motor starting current and the motor acceleration in three time-intervals.

In the cases of simulation No. 11, 12, 13, 14, 15, 16, and 17, these three time-intervals are Tr1 (from 0 to 0.025 second), Tr2 (from 0.025 to 0.05 second), and Tr3 (from 0.05 to 0.2 second). As shown in simulation No. 11, pulse width (TAU = 0.002 second) and chopping rate (TAU2 = 0.005 second) are fixed in the Tr1 time-interval. Pulse width (TAU = 0.003 second) and chopping rate (TAU = 0.005 second) are also fixed in the Tr2 time-interval. Pulse width (TAU = 0.025, 0.1, 0.225, and 0.4 second respectively) and chopping rate (TAU2 = 0.1, 0.2, 0.3, and 0.4 second respectively) are variable in the Tr3 time-interval. With reference to Table 12 and Figure 20, the lowest maximum starting current is 26.973 amperes and the highest maximum speed is 1740.8 rpm where r1 = 40%, r2 = 60%, and r3 = 100%. As shown in simulation No. 12, pulse width (TAU = 0.002 second) and chopping rate (TAU2 = 0.005 second) are fixed in the Tr1 time-interval; pulse width (TAU = 0.0035, 0.004, 0.0045, and 0.005 second respectively) is variable with fixed chopping rate (TAU2 = 0.005 second) in the Tr2 time-interval; pulse width (TAU = 0.3 second) and chopping rate (TAU2 = 0.4 second) are fixed in the Tr3 time-interval. With reference to Table 13 and Figure 21, the lowest maximum starting current is 26.432 amperes with the highest maximum speed of 1741.52 rpm, and the rise time is 0.0935 second where r1 = 40%, r2 = 75%, and r3 = 75%. As shown in simulation No.13, pulse width is variable (TAU = 0.0025, 0.003, 0.0035, and 0.004 second respectively) with fixed chopping rate (TAU2 = 0.005 second) in the Tr1 time-interval; pulse width (TAU = 0.004

second) and chopping rate (TAU2 = 0.005 second) are fixed in the Tr2 time-interval; pulse width (TAU = 0.3 second) and chopping rate (TAU2 = 0.4 second) are fixed in the Tr3 time-interval. With reference to Table 14 and Figure 22, the lowest maximum current is 26.938 amperes with maximum speed of 1743.20 rpm and rise time 0.093 second where r1 = 60%, r2 = 80%, and r3 = 75%. As shown in simulation No. 14, pulse width is variable (TAU = 0.0025, 0.003, 0.0035, and 0.004 second respectively) with fixed chopping rate (TAU2 = 0.005 second) in the Tr1 time-interval; pulse width (TAU = 0.0035 second) and chopping rate (TAU2 = 0.005 second) are fixed in the Tr2 time-interval; pulse width (TAU = 0.3 second) and chopping rate (TAU2 = 0.4 second) are fixed in the Tr3 time-interval. With reference to Table 15 and Figure 23, the lowest maximum current is 25.048 amperes with the highest maximum speed of 1743.89 rpm and minimum rise time 0.096 second where r1 = 50%, r2 = 70%, and r3 = 75%. As shown in simulation No. 15, pulse width (TAU = 0.0025 second) and chopping rate (TAU2 = 0.005 second) are fixed in the Tr1 time-interval; pulse width is variable (TAU = 0.00275, 0.003, 0.00325, and 0.0035 second respectively) with fixed chopping rate (TAU2 = 0.005 second) in the Tr2 time-interval; pulse width (TAU = 0.3 second) and chopping rate (TAU2 = 0.4 second) are fixed in the Tr3 time-interval. With reference to Table 16 and Figure 24, the lowest maximum current is 25.048 amperes with the highest maximum speed of 1743.89 rpm and minimum rise time 0.096 second where r1 = 50%, r2 = 70%, and r3 = 75%. From the above simulation results, this conclusion may be made: the minimum starting current is 25.048 amperes and the minimum rise time is 0.096 second.

6. The minimum starting current and minimum rise time have been found in simulation No. 14. The following two simulations are based on the result of simulation No. 14, but the chopping frequency is changed from 180 Hz to 220 Hz in either the Tr1 time-interval or the Tr2 time-interval. The purpose is to see if the result will be better. As shown in simulation No. 16, pulse width (TAU = 0.0025 second) and chopping frequency (Fr1 = 200 Hz) are fixed in the Tr1 time-interval; pulse width is variable (TAU = 0.00389, 0.00368, 0.0035, 0.0033, and 0.00318 second respectively) with variable chopping frequency (Fr2 = 180, 190, 200, 210, and 220 Hz) in the Tr2 time-interval; pulse width (TAU = 0.3 second) and chopping frequency (Fr3 = 2.5 Hz) are fixed in the Tr3 time-interval. With reference to Table 17 and Figure 25, the lowest maximum current is 25.048 amperes with maximum speed of 1743.63 rpm and minimum rise time 0.096 second where r1 = 50%, r2 = 70%, and r3 = 75%. As shown in simulation No. 17, pulse width is variable (TAU = 0.00278, 0.00263, 0.0025, 0.00238, and 0.00227 second respectively) with variable chopping frequency (Fr1 = 180, 190, 200, 210, and 220 Hz) in the Tr1 time-interval; pulse width (TAU = 0.0035 second) and chopping frequency (Fr2 = 200 Hz) are fixed in the Tr2 time-interval; pulse width (TAU = 0.3 second) and chopping frequency (Fr3 = 2.5 Hz) are fixed in the Tr3 time-interval. With reference to Table 18 and Figure 26, the lowest maximum current is 25.048 amperes with maximum speed of 1743.89

rpm and minimum rise time 0.096 second where r1 = 50%, r2 = 70%, and r3 = 75%.

7. Finally, for the optimum chopping cycle found in simulation No. 14, dc motor starting current and speed response are plotted by X-Y Plotter as shown in Appendix C.

D. Simulation Results

The chopping frequency, percentage of supplied voltage, and time-interval were varied using computer simulation, and the results were printed out by either line printer or X-Y Plotter. In this case, the simulation process is divided into either two or three time-intervals, and makes use of three kinds of modulation methods (time-ratio control, pulse-width control, and a combination of the two). The simulation results (printed by line printer) are given in the following tables.

1. Two time-intervals:

a. Time-Ratio Control method (Table 2)

Pulse width fixed: TAU = 0.003 and
Chopping rate variable: TAU2 = 0.03 - 0.003 in Tt1
Pulse width fixed: TAU = 0.003 and
Chopping rate fixed: TAU2 = 0.003 in Tt2

Simulation No. 1 (graph as shown in Fig. 10)

Table 2

TIMER		TAU	TAU1	TAU2	MAX. CURRENT	MAX. SPEED
FROM	TO					
0.0	0.05	0.003	0.0	0.03		
0.05	0.2	0.003	0.0	0.003	21.8114	795.069
0.0	0.05	0.003	0.0	0.015		
0.05	0.2	0.003	0.0	0.003	18.8196	797.461
0.0	0.05	0.003	0.0	0.01		
0.05	0.2	0.003	0.0	0.003	16.5709	799.941
0.0	0.05	0.003	0.0	0.0075		
0.05	0.2	0.003	0.0	0.003	19.2409	804.040
0.0	0.05	0.003	0.0	0.006		
0.05	0.2	0.003	0.0	0.003	22.1677	804.941
0.0	0.05	0.003	0.0	0.005		
0.05	0.2	0.003	0.0	0.003	24.9747	841.409
0.0	0.05	0.003	0.0	0.004		
0.05	0.2	0.003	0.0	0.003	28.0639	935.858
0.0	0.05	0.003	0.0	0.00375		
0.05	0.2	0.003	0.0	0.003	31.6378	1109.960
0.0	0.05	0.003	0.0	0.00333		
0.05	0.2	0.003	0.0	0.003	34.2656	1252.580
0.0	0.05	0.003	0.0	0.003		
0.05	0.2	0.003	0.0	0.003	22.1677	804.941

b. Pulse-Width Control method (Table 3)

Pulse width variable: TAU = 0.0005 - 0.005 and
Chopping rate fixed: TAU2 = 0.005 in Tp1
Pulse width fixed: TAU = 0.005 and
Chopping rate fixed: TAU2 = 0.005 in Tp2

Simulation No. 2 (graph as shown in Fig. 11)

Table 3

TIMER FROM	TIMER TO	TAU	TAU1	TAU2	MAX. CURRENT	MAX. SPEED
0.0 0.05	0.05 0.2	0.0005 0.005	0.0 0.0	0.005 0.005	24.039	803.799
0.0 0.05	0.05 0.2	0.001 0.005	0.0 0.0	0.005 0.005	21.884	805.160
0.0 0.05	0.05 0.2	0.0015 0.005	0.0 0.0	0.005 0.005	19.772	806.567
0.0 0.05	0.05 0.2	0.002 0.005	0.0 0.0	0.005 0.005	19.102	808.007
0.0 0.05	0.05 0.2	0.0025 0.005	0.0 0.0	0.005 0.005	21.592	809.499
0.0 0.05	0.05 0.2	0.003 0.005	0.0 0.0	0.005 0.005	24.975	828.958
0.0 0.05	0.05 0.2	0.0035 0.005	0.0 0.0	0.005 0.005	28.125	920.729
0.0 0.05	0.05 0.2	0.004 0.005	0.0 0.0	0.005 0.005	31.054	1041.040
0.0 0.05	0.05 0.2	0.0045 0.005	0.0 0.0	0.005 0.005	33.795	1163.470
0.0 0.05	0.05 0.2	0.005 0.005	0.0 0.0	0.005 0.005	24.056	809.135

2. Three time-intervals:

a. Time-Ratio Control method

(1) Pulse width fixed: TAU = 0.003 in Tr1, Tr2, and Tr3
Chopping rate variable: TAU2 = 0.012 - 0.003 in Tr1
Chopping rate fixed: TAU2 = 0.012 in Tr2
Chopping rate fixed: TAU2 = 0.003 in Tr3 (Table 4)

<u>Simulation No. 3 (graph as shown in Fig. 12)</u>

<u>Table 4</u>

TIMER		TAU	TAU1	TAU2	MAX. CURRENT	MAX. SPEED
FROM	TO					
0.0	0.025	0.003	0.0	0.012		
0.025	0.05	0.003	0.0	0.012		
0.05	0.2	0.003	0.0	0.003	17.443	798.697
0.0	0.025	0.003	0.0	0.006		
0.025	0.05	0.003	0.0	0.012		
0.05	0.2	0.003	0.0	0.003	22.186	790.152
0.0	0.025	0.003	0.0	0.004		
0.025	0.05	0.003	0.0	0.012		
0.05	0.2	0.003	0.0	0.003	29.292	763.079
0.0	0.025	0.003	0.0	0.003		
0.025	0.05	0.003	0.0	0.012		
0.05	0.2	0.003	0.0	0.003	23.885	700.545

(2) Pulse width fixed: TAU = 0.003 in Tr1, Tr2, and Tr3
Chopping rate variable: TAU2 = 0.012 - 0.003 in Tr1
Chopping rate fixed: TAU2 = 0.006 in Tr2
Chopping rate fixed: TAU2 = 0.003 in Tr3 (Table 5)

<u>Simulation No. 4 (graph as shown in Fig. 13)</u>

<u>Table 5</u>

TIMER		TAU	TAU1	TAU2	MAX. CURRENT	MAX. SPEED
FROM	TO					
0.0	0.025	0.003	0.0	0.012		
0.025	0.05	0.003	0.0	0.006		
0.05	0.2	0.003	0.0	0.003	19.001	802.886
0.0	0.025	0.003	0.0	0.006		
0.025	0.05	0.003	0.0	0.006		
0.05	0.2	0.003	0.0	0.003	22.168	804.941
0.0	0.025	0.003	0.0	0.004		
0.025	0.05	0.003	0.0	0.006		
0.05	0.2	0.003	0.0	0.003	29.293	803.009
0.0	0.025	0.003	0.0	0.003		
0.025	0.05	0.003	0.0	0.006		
0.05	0.2	0.003	0.0	0.003	22.168	796.505

(3) Pulse width fixed: TAU = 0.003 in Tr1, Tr2, and Tr3
Chopping rate variable: TAU2 = 0.012 - 0.003 in Tr1
Chopping rate fixed: TAU2 = 0.004 in Tr2
Chopping rate fixed: TAU2 = 0.003 in Tr3 (Table 6)

Simulation No. 5 (graph as shown in Fig. 14)

Table 6

TIMER		TAU	TAU1	TAU2	MAX. CURRENT	MAX. SPEED
FROM	TO					
0.0	0.025	0.003	0.0	0.012		
0.025	0.05	0.003	0.0	0.004		
0.05	0.2	0.003	0.0	0.003	26.119	1271.923
0.0	0.025	0.003	0.0	0.006		
0.025	0.05	0.003	0.0	0.004		
0.05	0.2	0.003	0.0	0.003	22.508	1273.765
0.0	0.025	0.003	0.0	0.004		
0.025	0.005	0.003	0.0	0.004		
0.05	0.2	0.003	0.0	0.003	29.293	1257.593
0.0	0.025	0.003	0.0	0.003		
0.025	0.05	0.003	0.0	0.004		
0.05	0.2	0.003	0.0	0.003	22.721	1271.717

(4) Pulse width fixed: TAU = 0.003 in Tr1, Tr2, and Tr3
Chopping rate variable: TAU2 = 0.012 - 0.003 in Tr1
Chopping rate fixed: TAU2 = 0.003 in Tr2
Chopping rate fixed: TAU2 = 0.003 in Tr3 (Table 7)

Simulation No. 6 (graph as shown in Fig. 15)

Table 7

TIMER		TAU	TAU1	TAU2	MAX. CURRENT	MAX. SPEED
FROM	TO					
0.0	0.025	0.003	0.0	0.012		
0.025	0.05	0.003	0.0	0.003		
0.05	0.2	0.003	0.0	0.003	19.000	802.866
0.0	0.025	0.003	0.0	0.006		
0.025	0.05	0.003	0.0	0.003		
0.05	0.2	0.003	0.0	0.003	22.167	804.941
0.0	0.025	0.003	0.0	0.004		
0.025	0.05	0.003	0.0	0.003		
0.05	0.2	0.003	0.0	0.003	29.293	816.936
0.0	0.025	0.003	0.0	0.003		
0.025	0.05	0.003	0.0	0.003		
0.05	0.2	0.003	0.0	0.003	22.167	804.941

b. Pulse-Width Control method

(1) Pulse width variable: TAU = 0.00125 - 0.005 in Tr1 (Table 8)
Pulse width fixed: TAU = 0.00125 in Tr2
Pulse width fixed: TAU = 0.005 in Tr3
Chopping rate fixed: TAU2 = 0.005 in Tr1, Tr2, and Tr3

Simulation No. 7 (graph as shown in Fig. 16)

Table 8

TIMER		TAU	TAU1	TAU2	MAX. CURRENT	MAX. SPEED
FROM	TO					
0.0	0.025	0.00125	0.0	0.005		
0.025	0.05	0.00125	0.0	0.005		
0.05	0.2	0.005	0.0	0.005	19.771	806.566
0.0	0.025	0.0025	0.0	0.005		
0.025	0.05	0.00125	0.0	0.005		
0.05	0.2	0.005	0.0	0.005	21.592	807.362
0.0	0.025	0.00375	0.0	0.005		
0.025	0.05	0.00125	0.0	0.005		
0.05	0.2	0.005	0.0	0.005	31.058	808.634
0.0	0.025	0.005	0.0	0.005		
0.025	0.05	0.00125	0.0	0.005		
0.05	0.2	0.005	0.0	0.005	24.066	807.504

(2) Pulse width variable: TAU = 0.00125 - 0.005 in Tr1 (Table 9)
Pulse width fixed: TAU = 0.0025 in Tr2
Pulse width fixed: TAU = 0.005 in Tr3
Chopping rate fixed: TAU2 = 0.005 in Tr1, Tr2, and Tr3

Simulation No. 8 (graph as shown in Fig. 17)

Table 9

TIMER		TAU	TAU1	TAU2	MAX. CURRENT	MAX. SPEED
FROM	TO					
0.0	0.025	0.00125	0.0	0.005		
0.025	0.05	0.0025	0.0	0.005		
0.05	0.2	0.005	0.0	0.005	21.959	808.685
0.0	0.025	0.0025	0.0	0.005		
0.025	0.05	0.0025	0.0	0.005		
0.05	0.2	0.005	0.0	0.005	21.593	809.507
0.0	0.025	0.00375	0.0	0.005		
0.025	0.05	0.0025	0.0	0.005		
0.05	0.2	0.005	0.0	0.005	31.054	827.968
0.0	0.025	0.005	0.0	0.005		
0.025	0.05	0.0025	0.0	0.005		
0.05	0.2	0.005	0.0	0.005	24.056	809.366

(3) Pulse width variable: TAU = 0.00125 - 0.005 in Tr1 (Table 10)
Pulse width fixed: TAU = 0.00375 in Tr2
Pulse width fixed: TAU = 0.005 in Tr3
Chopping rate fixed: TAU2= 0.005 in Tr1, Tr2, and Tr3

Simulation No. 9 (graph as shown in Fig. 18)

Table 10

TIMER		TAU	TAU1	TAU2	MAX. CURRENT	MAX. SPEED
FROM	TO					
0.0	0.025	0.00125	0.0	0.005		
0.025	0.05	0.00375	0.0	0.005		
0.05	0.2	0.005	0.0	0.005	28.930	860.601
0.0	0.025	0.0025	0.0	0.005		
0.025	0.05	0.00375	0.0	0.005		
0.05	0.2	0.005	0.0	0.005	27.273	918.357
0.0	0.025	0.00375	0.0	0.005		
0.025	0.05	0.00375	0.0	0.005		
0.05	0.2	0.005	0.0	0.005	31.054	1041.040
0.0	0.025	0.005	0.0	0.005		
0.025	0.05	0.00375	0.0	0.005		
0.05	0.2	0.005	0.0	0.005	25.128	880.007

(4) Pulse width variable: TAU = 0.00125 - 0.005 in Tr1 (Table 11)
Pulse width fixed: TAU = 0.005 in Tr2
Pulse width fixed: TAU = 0.005 in Tr3
Chopping rate fixed: TAU2 = 0.005 in Tr1, Tr2, and Tr3

Simulation No. 10 (graph as shown in Fig. 19)

Table 11

TIMER		TAU	TAU1	TAU2	MAX. CURRENT	MAX. SPEED
FROM	TO					
0.0	0.025	0.00125	0.0	0.005		
0.025	0.05	0.005	0.0	0.005		
0.05	0.2	0.005	0.0	0.005	22.896	808.055
0.0	0.025	0.0025	0.0	0.005		
0.025	0.05	0.005	0.0	0.005		
0.05	0.2	0.005	0.0	0.005	25.160	809.041
0.0	0.025	0.00375	0.0	0.005		
0.025	0.05	0.005	0.0	0.005		
0.05	0.2	0.005	0.0	0.005	31.054	819.642
0.0	0.025	0.005	0.0	0.005		
0.025	0.05	0.005	0.0	0.005		
0.05	0.2	0.005	0.0	0.005	24.057	809.148

c. Combination of the TRC and PWC methods

(1) Pulse width fixed: TAU = 0.002 and
Chopping rate fixed: TAU2 = 0.005 in Tr1
Pulse width fixed: TAU = 0.003 and
Chopping rate fixed: TAU2 = 0.005 in Tr2
Pulse width variable: TAU = 0.025 - 0.4 and
Chopping rate variable: TAU2 = 0.1 - 0.4 in Tr3 (Table 12)

Simulation No. 11 (graph as shown in Fig. 20)

Table 12

TIMER FROM	TIMER TO	TAU	TAU1	TAU2	MAXIMUM CURRENT	MAXIMUM SPEED	RISE TIME
0.0	0.025	0.002	0.0	0.005			
0.025	0.05	0.003	0.0	0.005			
0.05	0.2	0.025	0.0	0.1	26.973	1063.12	-
0.0	0.025	0.002	0.0	0.005			
0.025	0.05	0.003	0.0	0.005			
0.05	0.2	0.1	0.0	0.2	26.973	1691.75	0.097
0.0	0.025	0.002	0.0	0.005			
0.025	0.05	0.003	0.0	0.005			
0.05	0.2	0.225	0.0	0.3	26.973	1740.59	0.097
0.0	0.025	0.002	0.0	0.005			
0.025	0.05	0.003	0.0	0.005			
0.05	0.2	0.4	0.0	0.4	26.973	1740.53	0.097

(2) Pulse width fixed: TAU = 0.002 and
Chopping rate fixed: TAU2 = 0.005 in Tr1
Pulse width variable: TAU = 0.0035 - 0.005 and
Chopping rate fixed: TAU2 = 0.005 in Tr2
Pulse width fixed: TAU = 0.3 and
Chopping rate fixed: TAU2 = 0.4 in Tr3 (Table 13)

Simulation No. 12 (graph as shown in Fig. 21)

Table 13

TIMER FROM	TIMER TO	TAU	TAU1	TAU2	MAXIMUM CURRENT	MAXIMUM SPEED	RISE TIME
0.0	0.025	0.002	0.0	0.005			
0.025	0.05	0.0035	0.0	0.005			
0.05	0.2	0.3	0.0	0.4	26.432	1741.52	0.0935
0.0	0.025	0.002	0.0	0.005			
0.025	0.05	0.004	0.0	0.005			
0.05	0.2	0.3	0.0	0.4	27.852	1742.52	0.0900
0.0	0.025	0.002	0.0	0.005			
0.025	0.05	0.0045	0.0	0.005			
0.05	0.2	0.3	0.0	0.4	30.537	1743.58	0.0855
0.0	0.025	0.002	0.0	0.005			
0.025	0.05	0.005	0.0	0.005			
0.05	0.2	0.3	0.0	0.4	28.334	1740.82	0.0960

(3) Pulse width variable: TAU = 0.0025 - 0.004 and
Chopping rate fixed: TAU2 = 0.005 in Tr1
Pulse width fixed: TAU = 0.004 and
Chopping rate fixed: TAU2 = 0.005 in Tr2
Pulse width fixed: TAU = 0.3 and
Chopping rate fixed: TAU2 = 0.4 in Tr3 (Table 14)

Simulation No. 13 (graph as shown in Fig. 22)

Table 14

TIMER		TAU	TAU1	TAU2	MAXIMUM CURRENT	MAXIMUM SPEED	RISE TIME
FROM	TO						
0.0	0.025	0.0025	0.0	0.005			
0.025	0.05	0.004	0.0	0.005			
0.05	0.2	0.3	0.0	0.4	27.273	1742.90	0.0850
0.0	0.025	0.003	0.0	0.005			
0.025	0.05	0.004	0.0	0.005			
0.05	0.2	0.3	0.0	0.4	26.938	1743.20	0.0930
0.0	0.025	0.0035	0.0	0.005			
0.025	0.05	0.004	0.0	0.005			
0.05	0.2	0.3	0.0	0.4	28.125	1743.99	0.0925
0.0	0.025	0.004	0.0	0.005			
0.025	0.05	0.004	0.0	0.005			
0.05	0.2	0.3	0.0	0.4	31.054	1744.05	0.0920

(4) Pulse width variable: TAU = 0.0025 - 0.004 and
Chopping rate fixed: TAU2 = 0.005 in Tr1
Pulse width fixed: TAU = 0.0035 and
Chopping rate fixed: TAU2 = 0.005 in Tr2
Pulse width fixed: TAU = 0.3 and
Chopping rate fixed: TAU2 = 0.4 in Tr3 (Table 15)

Simulation No. 14 (graph as shown in Fig. 23)

Table 15

TIMER		TAU	TAU1	TAU2	MAXIMUM CURRENT	MAXIMUM SPEED	RISE TIME
FROM	TO						
0.0	0.025	0.0025	0.0	0.005			
0.025	0.05	0.0035	0.0	0.005			
0.05	0.2	0.3	0.0	0.4	25.048	1741.89	0.0960
0.0	0.025	0.003	0.0	0.005			
0.025	0.05	0.0035	0.0	0.005			
0.05	0.2	0.3	0.0	0.4	25.079	1742.26	0.0970
0.0	0.025	0.0035	0.0	0.005			
0.025	0.05	0.0035	0.0	0.005			
0.05	0.2	0.3	0.0	0.4	28.125	1742.63	0.0970
0.0	0.025	0.004	0.0	0.005			
0.025	0.05	0.0035	0.0	0.005			
0.05	0.2	0.3	0.0	0.4	31.054	1743.02	0.0960

(5) Pulse width fixed: TAU = 0.0025 and
Chopping rate fixed: TAU2 = 0.005 in Tr1
Pulse width variable: TAU = 0.00275 - 0.00375 and
Chopping rate fixed: TAU2 = 0.005 in Tr2
Pulse width fixed: TAU = 0.3 and
Chopping rate fixed: TAU2 = 0.4 in Tr3 (Table 16)

Simulation No. 15 (graph as shown in Fig. 24)

Table 16

TIMER FROM	TIMER TO	TAU	TAU1	TAU2	MAXIMUM CURRENT	MAXIMUM SPEED	RISE TIME
0.0	0.025	0.0025	0.0	0.005			
0.025	0.05	0.00275	0.0	0.005			
0.05	0.2	0.3	0.0	0.4	25.636	1740.89	0.099
0.0	0.025	0.0025	0.0	0.005			
0.025	0.05	0.003	0.0	0.005			
0.05	0.2	0.3	0.0	0.4	25.636	1740.89	0.099
0.0	0.025	0.0025	0.0	0.005			
0.025	0.05	0.00325	0.0	0.005			
0.05	0.2	0.3	0.0	0.4	25.048	1741.89	0.096
0.0	0.025	0.0025	0.0	0.005			
0.025	0.05	0.0035	0.0	0.005			
0.05	0.2	0.3	0.0	0.4	25.048	1741.89	0.096
0.0	0.025	0.0025	0.0	0.005			
0.025	0.05	0.00375	0.0	0.005			
0.05	0.2	0.3	0.0	0.4	27.273	1742.91	0.093

(6) Pulse width fixed: TAU = 0.0025 and (Table 17)
Chopping rate fixed: TAU2 = 0.005 (Fr1 = 200 Hz) in Tr1
Pulse width variable: TAU = 0.00389 - 0.00318 and
Chopping rate variable: TAU2 = 0.00556 - 0.00455 (Fr2 = 180 - 220 Hz) in Tr2
Pulse width fixed: TAU = 0.3 and
Chopping rate fixed: TAU2 = 0.4 (Fr3 = 2.5 Hz) in Tr3

Simulation No. 16 (graph as shown in Fig. 25)

Table 17

TIMER FROM	TIMER TO	TAU	TAU1	TAU2	MAXIMUM CURRENT	MAXIMUM SPEED	RISE TIME
0.0	0.025	0.0025	0.0	0.005			
0.025	0.05	0.00389	0.0	0.00556	26.470	1741.33	0.098
0.05	0.2	0.3	0.0	0.4			
0.0	0.025	0.0025	0.0	0.005			
0.025	0.05	0.00368	0.0	0.00526			
0.05	0.2	0.3	0.0	0.4	26.233	1742.17	0.096
0.0	0.025	0.0025	0.0	0.005			
0.025	0.05	0.0035	0.0	0.005			
0.05	0.2	0.3	0.0	0.4	25.057	1741.89	0.097
0.0	0.025	0.0025	0.0	0.005			
0.025	0.05	0.00333	0.0	0.00476			
0.05	0.2	0.3	0.0	0.4	26.583	1741.63	0.098
0.0	0.025	0.0025	0.0	0.005			
0.025	0.05	0.00318	0.0	0.00455			
0.05	0.2	0.3	0.0	0.4	25.861	1741.37	0.098

(7) Pulse width variable: TAU = 0.00278 - 0.00227 and (Table 18)
Chopping rate variable: TAU2 = 0.00556 - 0.00455 (Fr1 = 180 - 220 Hz) in Tr1
Pulse width fixed: TAU = 0.0035 and
Chopping rate fixed: TAU2 = 0.005 (Fr2 = 200 Hz) in Tr2
Pulse width fixed: TAU = 0.3 and
Chopping rate fixed: TAU2 = 0.4 (Fr3 = 2.5 Hz) in Tr3

<u>Simulation No. 17 (graph as shown in Fig. 26)</u>

<u>Table 18</u>

TIMER		TAU	TAU1	TAU2	MAXIMUM CURRENT	MAXIMUM SPEED	RISE TIME
FROM	TO						
0.0	0.025	0.00278	0.0	0.00556			
0.025	0.05	0.0035	0.0	0.005			
0.05	0.2	0.3	0.0	0.4	25.351	1741.54	0.0985
0.0	0.025	0.00263	0.0	0.00526			
0.025	0.05	0.0035	0.0	0.005			
0.05	0.2	0.3	0.0	0.4	26.288	1741.11	0.0955
0.0	0.025	0.0025	0.0	0.005			
0.025	0.05	0.0035	0.0	0.005			
0.05	0.2	0.3	0.0	0.4	25.056	1741.89	0.0960
0.0	0.025	0.00238	0.0	0.00476			
0.025	0.05	0.0035	0.0	0.005			
0.05	0.2	0.3	0.0	0.4	25.866	1741.77	0.0971
0.0	0.025	0.00227	0.0	0.00455			
0.025	0.05	0.0035	0.0	0.005			
0.05	0.2	0.3	0.0	0.4	26.935	1741.67	0.0987

E. Summary

From the above simulation results, the conclusion will contain the following comments:

1. In most thysistor applications, the chopper frequency is from few Hz to hundreds of Hz. It is quite common to operate the chopper from 150 Hz to 300 Hz.
2. The program using the CSMP III language to simulate the motor's dynamic performance is shown in Appendix A. The graph for current and speed response of the optimum chopping cycle for dc motor starting is shown in Appendix C, as plotted by X-Y plotter.
3. For the sake of insuring that the optimum chopping frequency had been found, simulations No. 16 and 17 were processed by varying the chopping frequency around the 200 Hz point in the Tr1 or the Tr2 time-intervals. As shown in simulation No. 16, changing the chopping frequency Fr2 from 180 to 220 Hz in the Tr2 time-interval (chopping frequency is fixed in the Tr1 (Fr1 = 200 Hz) and Tr3 (Fr3 = 2.5 Hz) time-intervals), it does not improve the response of the motor. As shown in simulation No. 17, changing the chopping frequency Fr1 from 180 to 220 Hz in the Tr1 time-interval (chopping frequency is fixed in the Tr2 (Fr2 = 200 Hz) and Tr3 (Fr3 = 2.5 Hz) time-intervals) does not improve results either.
4. Finally, the optimum chopping cycle for starting this dc motor is as follows:

From 0.0 to 0.025 second,

Chopping frequency: Fr1 = 200 Hz

"on-pulse" pulsewidth is 50% of chopping rate (TAU2)

From 0.025 to 0.05 second,

Chopping frequency: Fr2 = 200 Hz

"on-pulse" pulsewidth is 70% of chopping rate (TAU2)

From 0.05 to 0.2 second,

Chopping frequency: Fr3 = 2.5 Hz

"on-pulse" pulsewidth is 75% of chopping rate (TAU2)

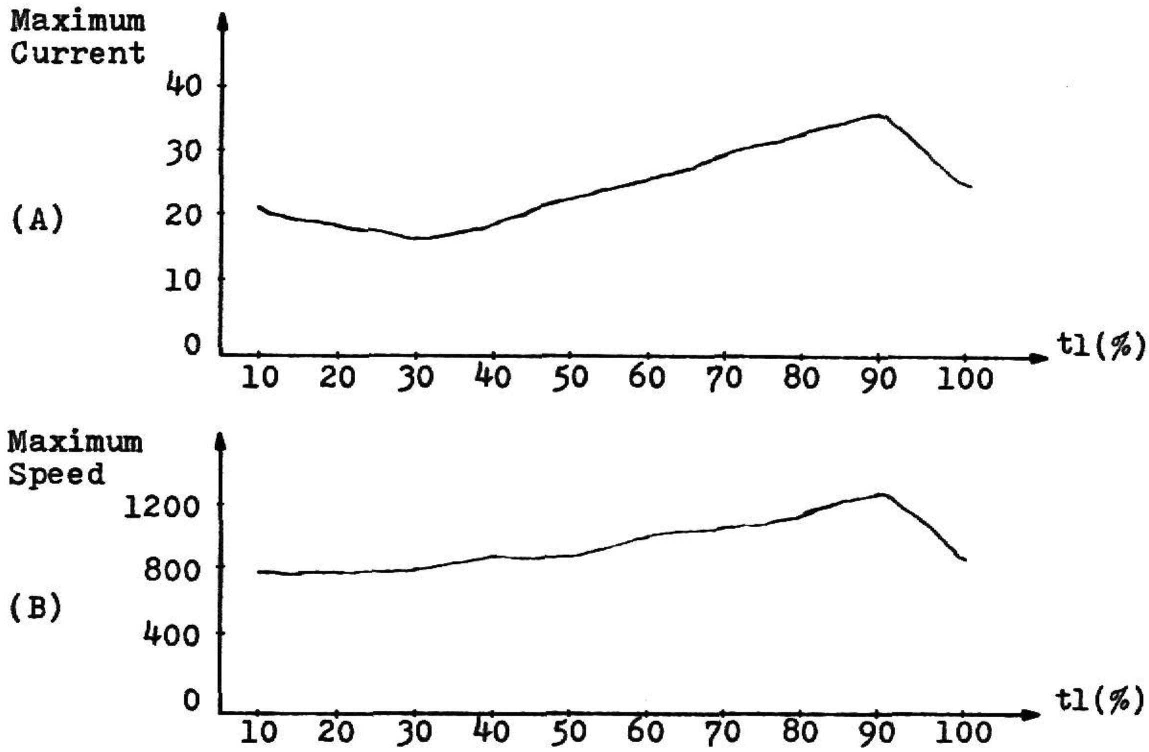


Figure 10. Graph for simulation No. 1 (t2 = 100%):
(A) maximum current vs. various values of tl;
(B) maximum speed vs. various values of tl.

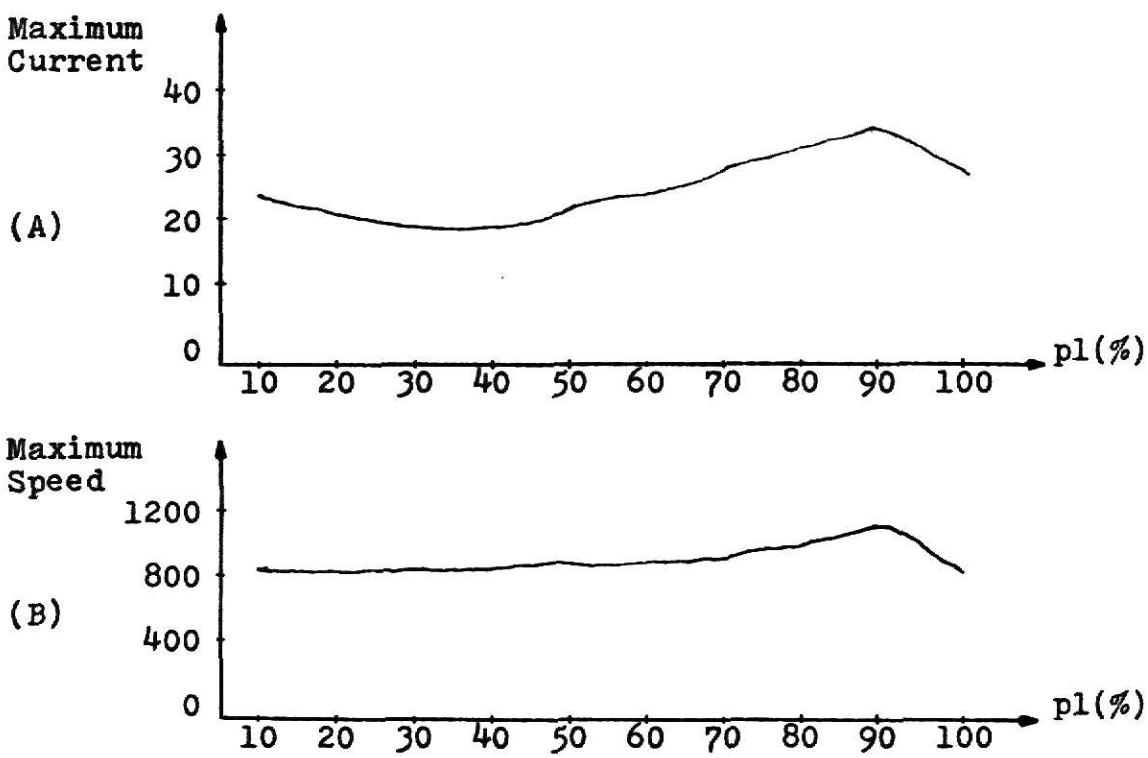


Figure 11. Graph for simulation No. 2 (p2 = 100%):
(A) maximum current vs. various values of pl;
(B) maximum speed vs. various values of pl.

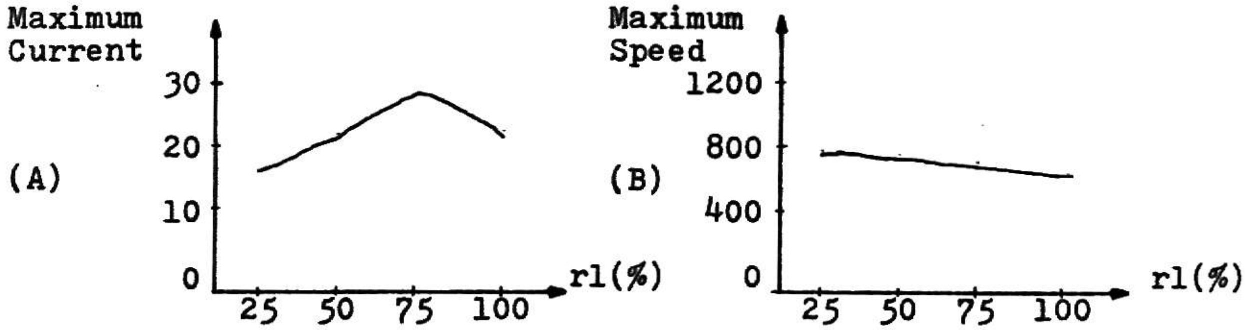


Figure 12. Graph for simulation No. 3 (r2 = 25%, r3 = 100%):
(A) maximum current vs. various values of rl;
(B) maximum speed vs. various values of rl.

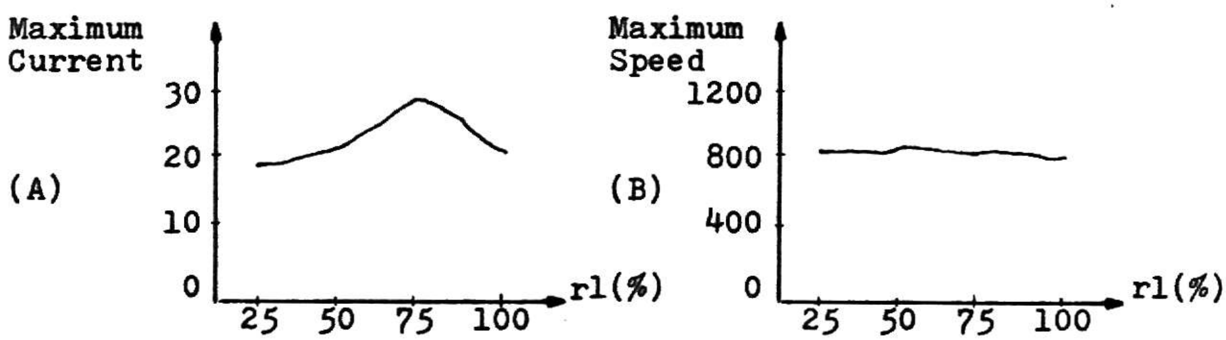


Figure 13. Graph for simulation No. 4 (r2 = 50%, r3 = 100%):
(A) maximum current vs. various values of rl;
(B) maximum speed vs. various values of rl.

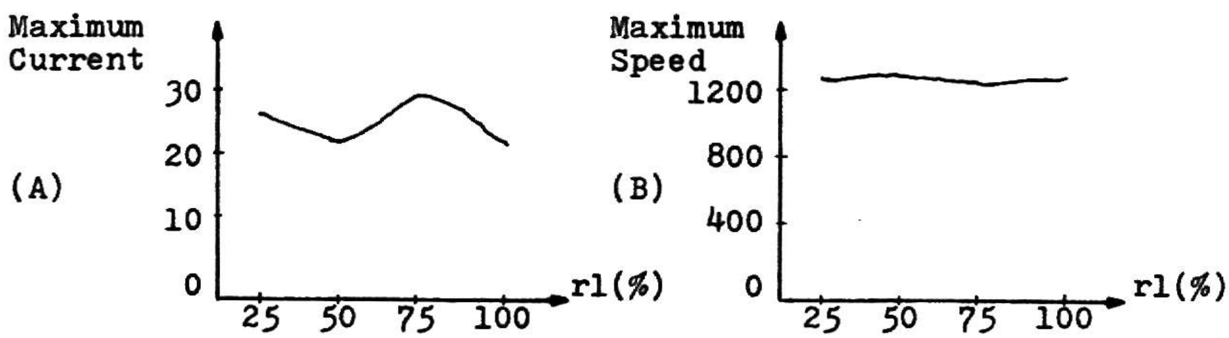


Figure 14. Graph for simulation No. 5 (r2 = 75%, r3 = 100%):
(A) maximum current vs. various values of rl;
(B) maximum speed vs. various values of rl.

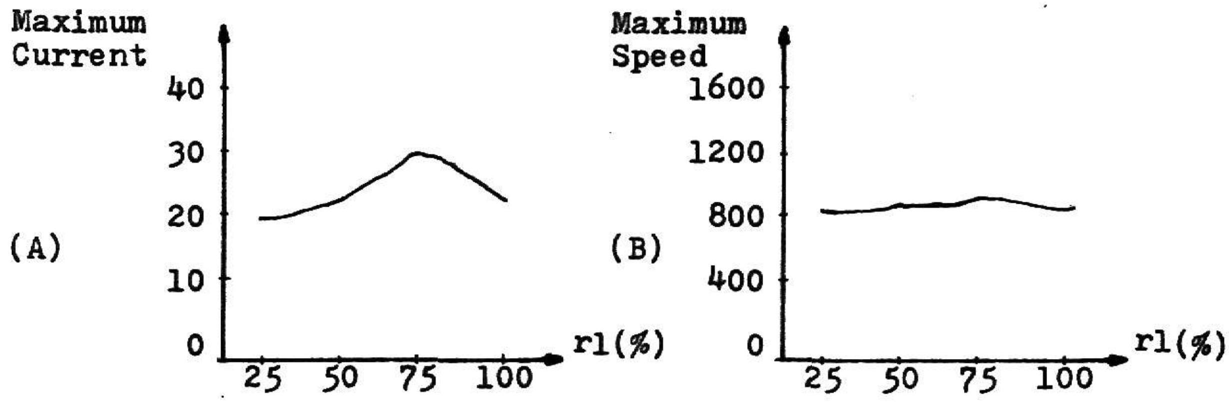


Figure 15. Graph for simulation No. 6 (r2 = 100%, r3 = 100%):
(A) maximum current vs. various values of rl;
(B) maximum speed vs. various values of rl.

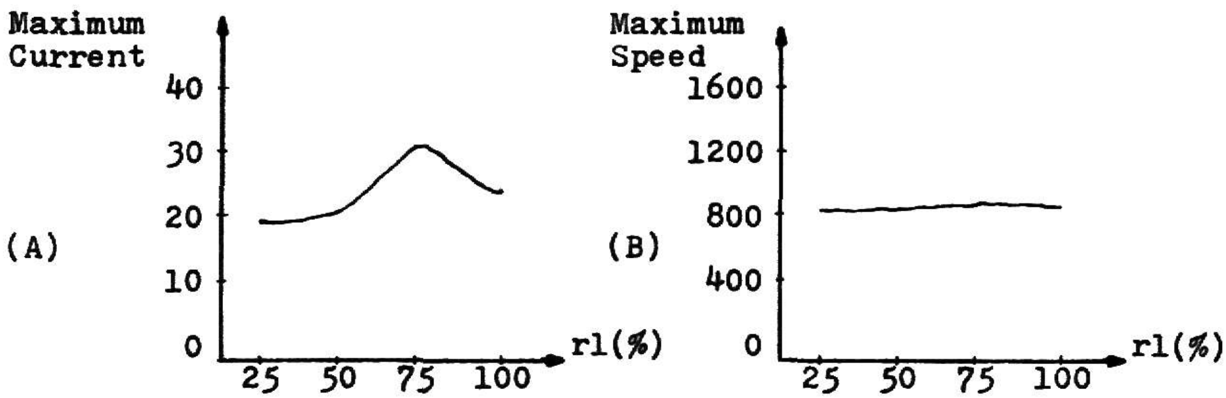


Figure 16. Graph for simulation No. 7 (r2 = 25%, r3 = 100%):
(A) maximum current vs. various values of rl;
(B) maximum speed vs. various values of rl.

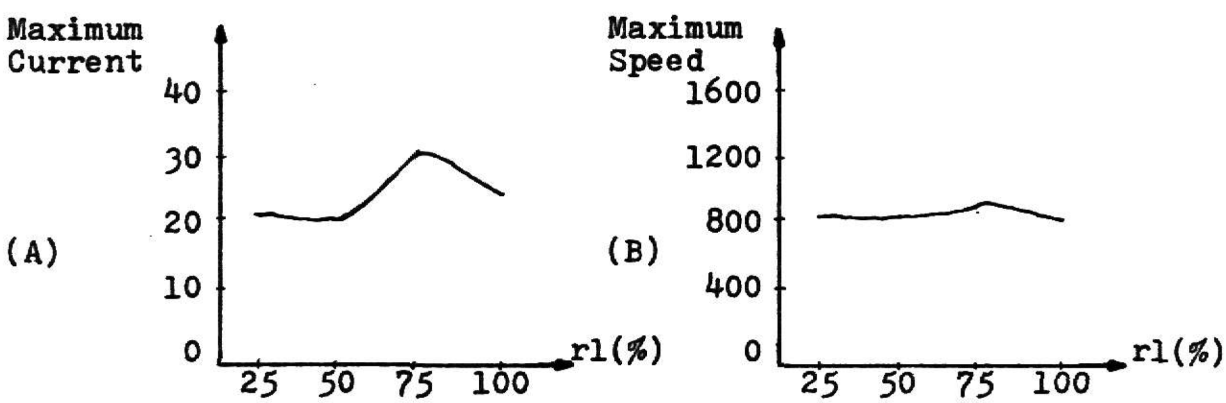


Figure 17. Graph for simulation No. 8 (r2 = 50%, r3 = 100%):
(A) maximum current vs. various values of rl;
(B) maximum speed vs. various values of rl.

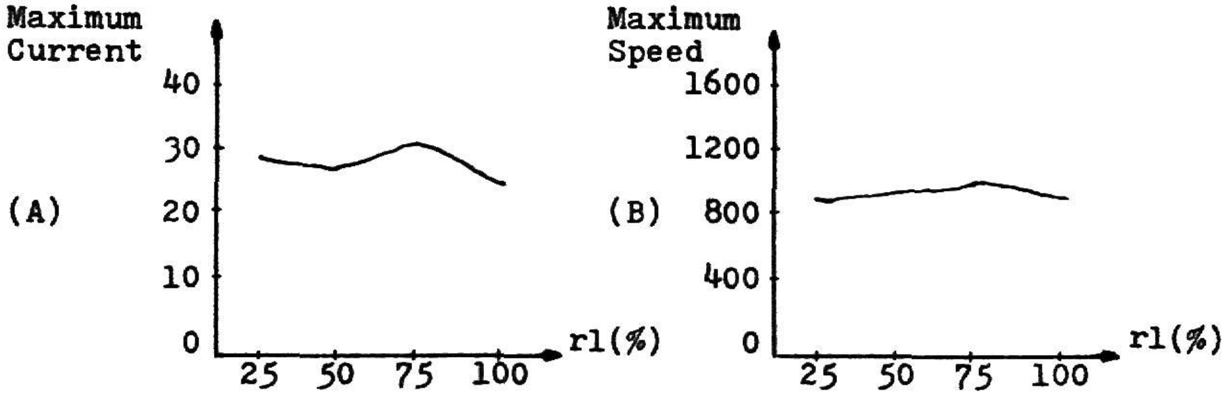


Figure 18. Graph for simulation No. 9 (r2 = 75%, r3 = 100%):
(A) maximum current vs. various values of r1;
(B) maximum speed vs. various values of r1.

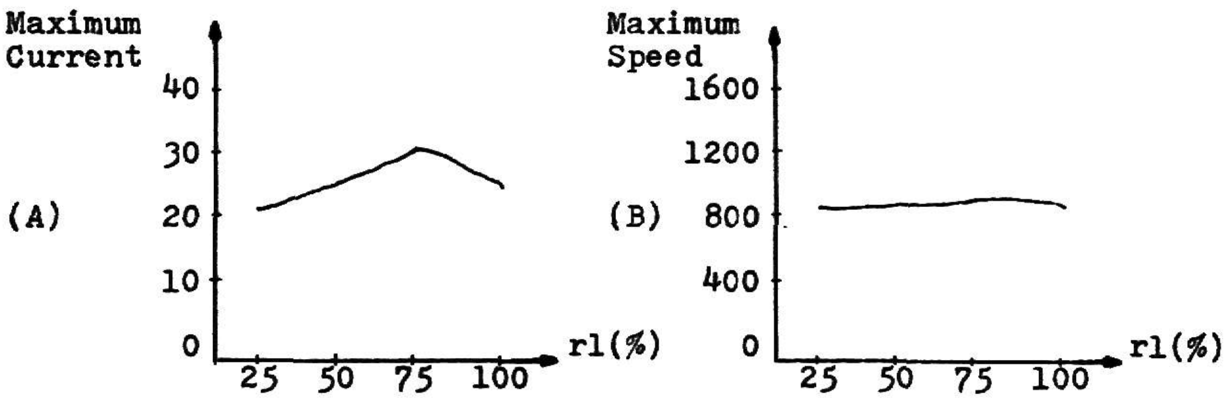


Figure 19. Graph for simulation No. 10 (r2 = 100%, r3 = 100%):
(A) maximum current vs. various values of r1;
(B) maximum speed vs. various values of r1.

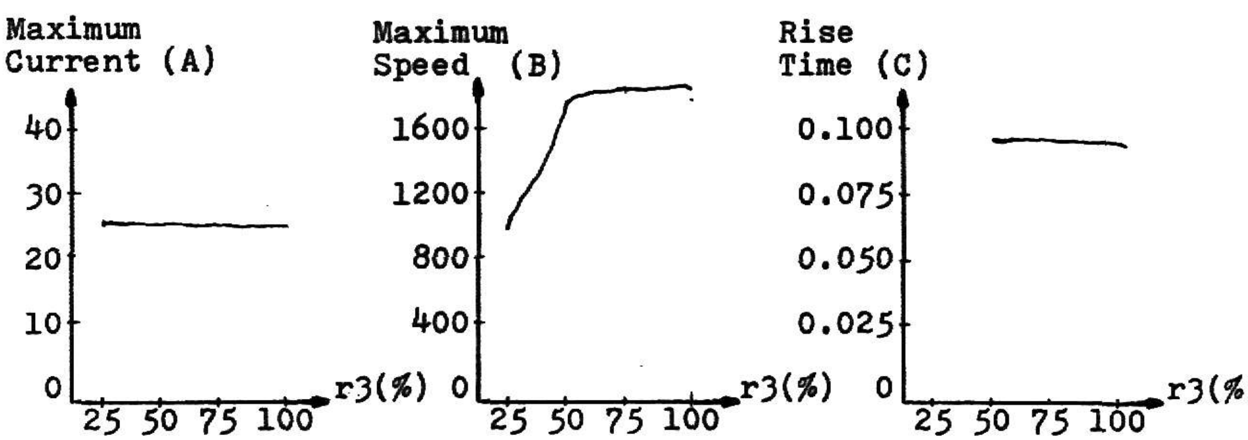


Figure 20. Graph for simulation No. 11 (r1 = 40%, r2 = 60%):
(A) maximum current vs. various values of r3;
(B) maximum speed vs. various values of r3;
(C) rise time vs. various values of r3.

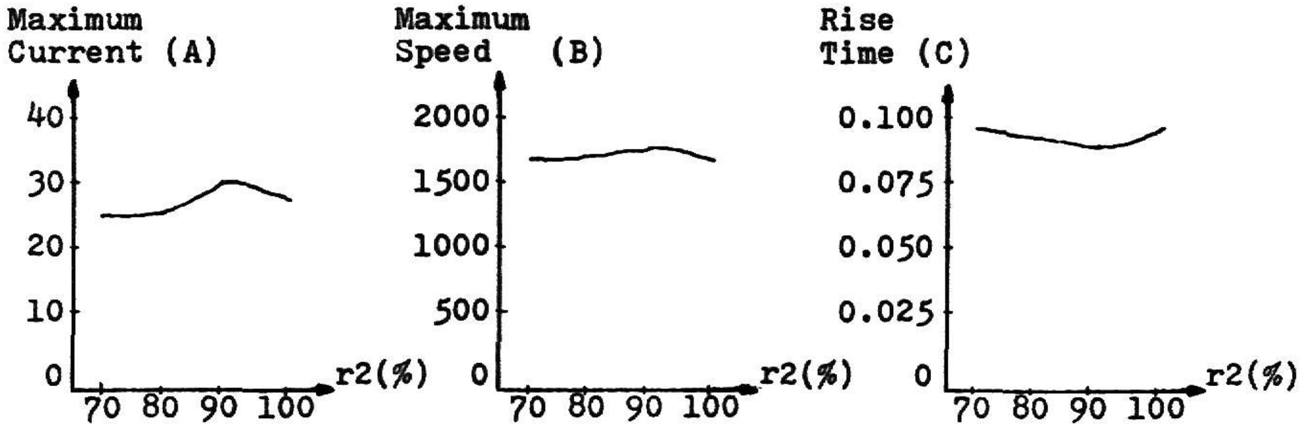


Figure 21. Graph for simulation No. 12 (r1 = 40%, r3 = 75%):
(A) maximum current vs. various values of r2;
(B) maximum speed vs. various values of r2;
(C) rise time vs. various values of r2.

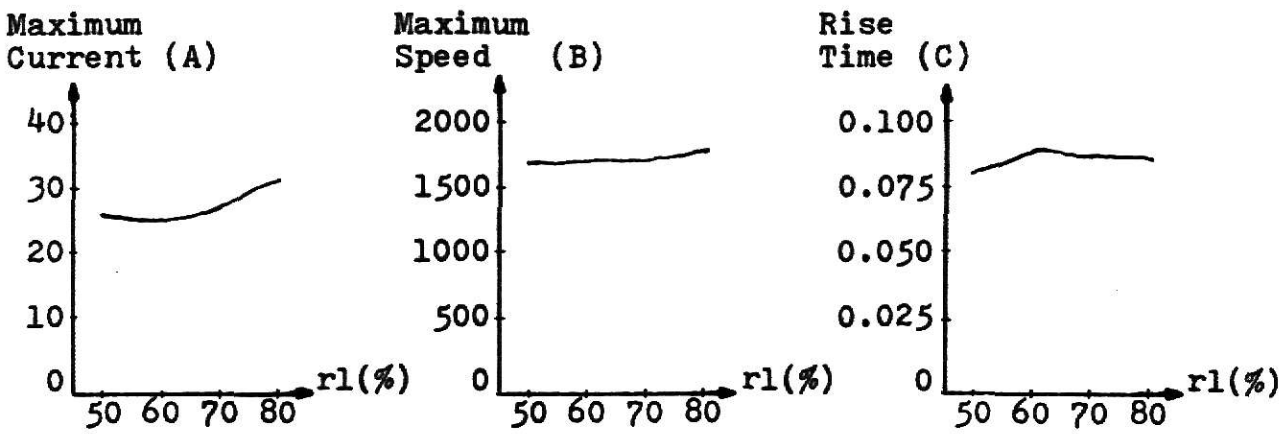


Figure 22. Graph for simulation No. 13 (r2 = 80%, r3 = 75%):
(A) maximum current vs. various values of r1;
(B) maximum speed vs. various values of r1;
(C) rise time vs. various values of r1.

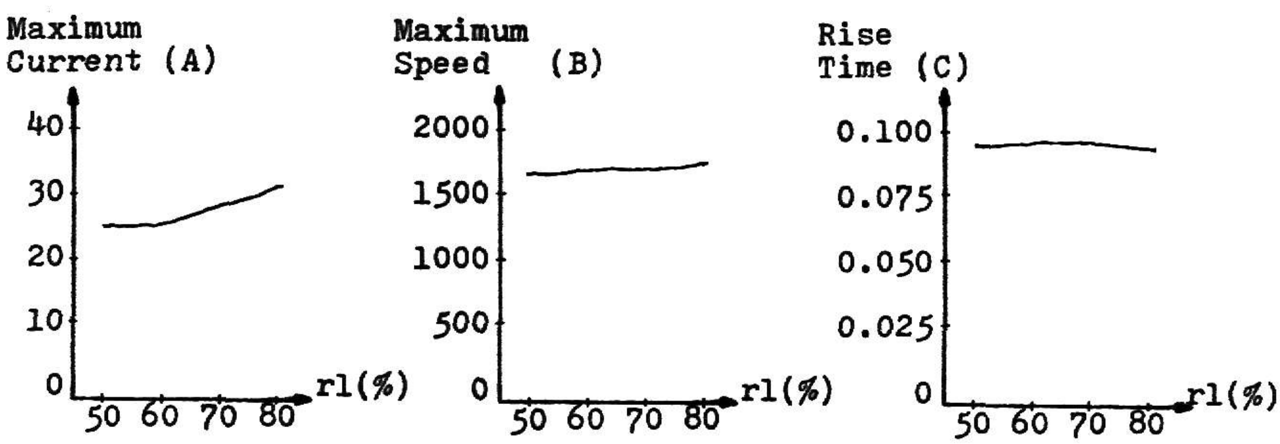


Figure 23. Graph for simulation No. 14 (r2 = 75%, r3 = 75%):
(A) maximum current vs. various values of r1;
(B) maximum speed vs. various values of r1;
(C) rise time vs. various values of r1.

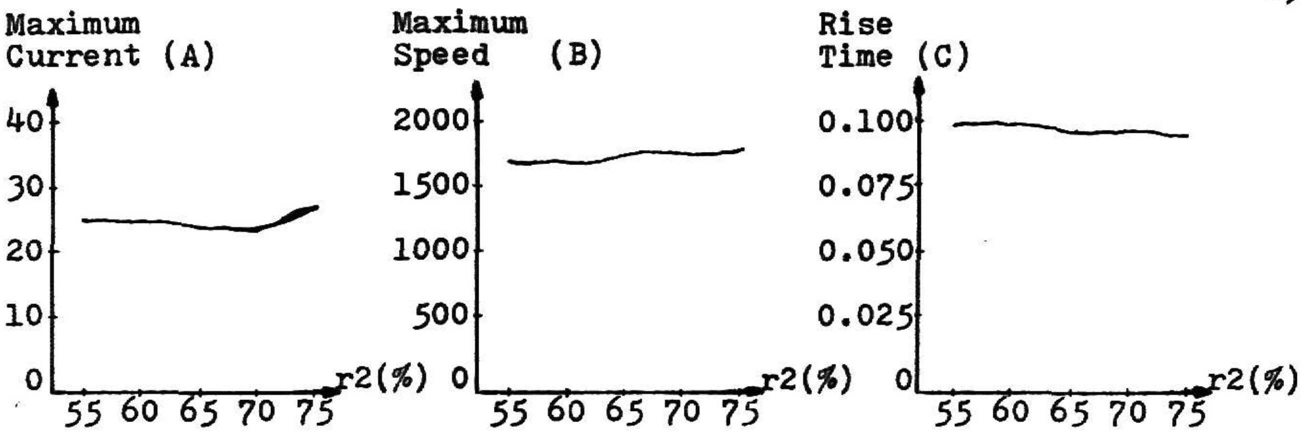


Figure 24. Graph for simulation No. 15 (r1 = 50%, r2 = 75%): (A) maximum current vs. various values of r2; (B) maximum speed vs. various values of r2; (C) rise time vs. various values of r2.

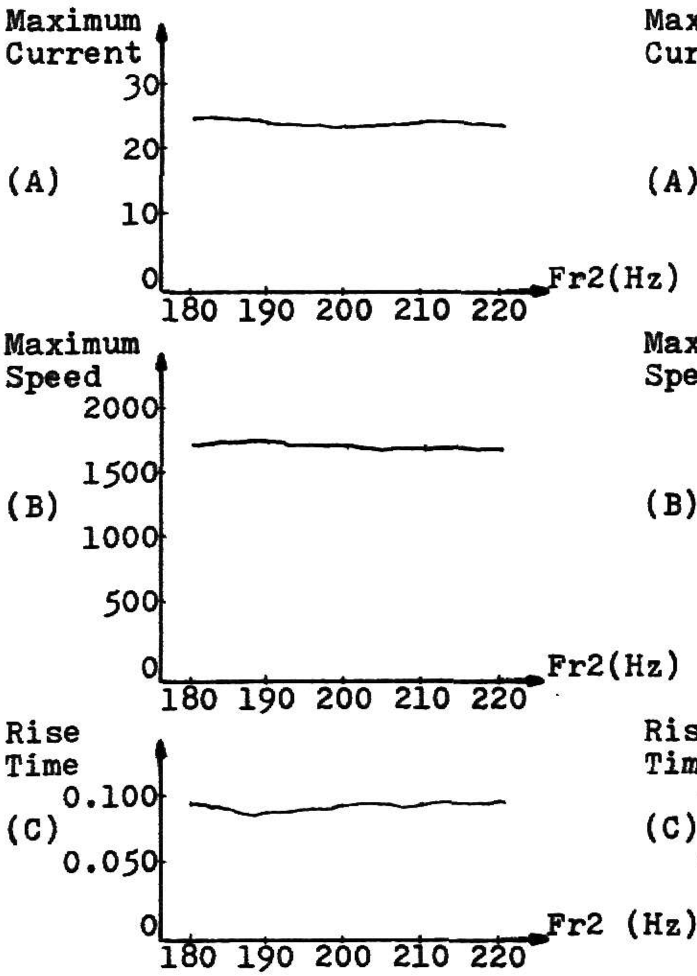


Figure 25. Graph for simulation No. 16 (Fr1 = 200 Hz, Fr3 = 2.5 Hz): (A) maximum current vs. various values of Fr2; (B) maximum speed vs. various values of Fr2; (C) rise time vs. various values of Fr2.

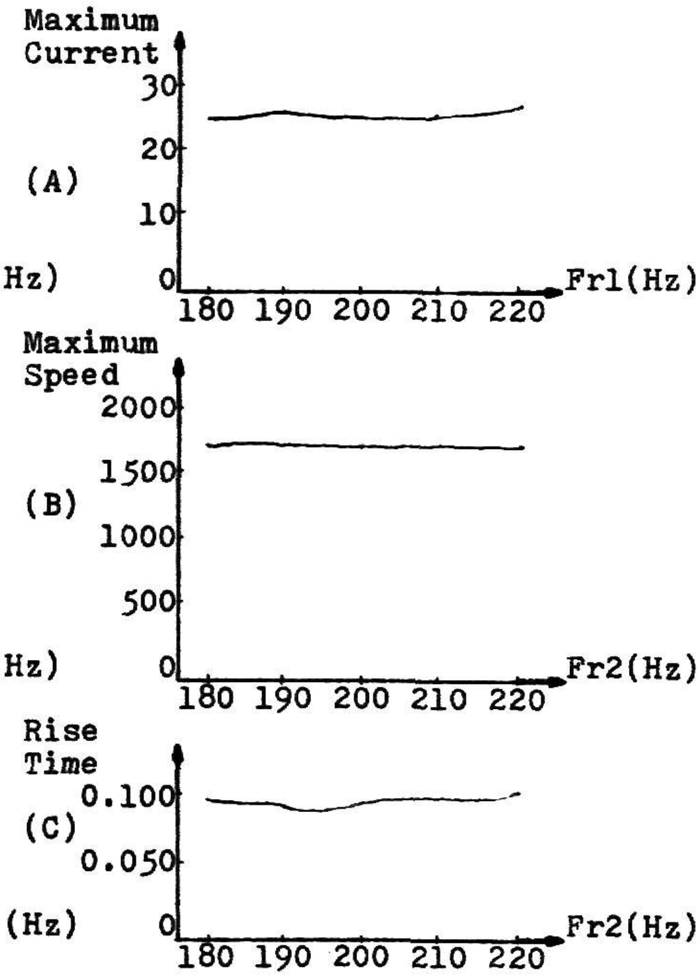


Figure 26. Graph for simulation No. 17 (Fr2 = 200 Hz, Fr3 = 2.5 Hz): (A) maximum current vs. various values of Fr1; (B) maximum speed vs. various values of Fr1; (C) rise time vs. various values of Fr1.

CHAPTER VI

CONCLUSIONS

The dynamic performance of a DC motor has been described by means of differential equations, state variables, and Laplace transforms. To optimize system response, a block diagram of a motor with constant torque loading has been developed for simulation.

The principle of chopper DC motor speed control was introduced. The methods for applying this principle are Time Ratio Control (TRC), Pulse Width Control (PWC), and a combination of these methods.

CSMP III Language combines the functional block modeling capabilities of a digital-analog simulation, with the algebraic and logical capabilities of a procedural language like FORTRAN. A system to be simulated is described to the program by a series of structure, data, and control statements.

CSMP III simulation of the thyristorized switch for DC motor starting provides insight into the behavior of the system. It eliminates analytical difficulties due to the inherent nonlinearity of the circuit, thereby permitting optimization of the switch parameters in accordance with the properties of the controlled object. It may be stated that the preliminary insight obtained through CSMP III simulation of the properties of the thyristorized switch and the behavior of the controlled motor, provides a basis for a practical model.

A simple and straightforward procedure for searching the optimum chopping cycle for dc motor starting has been presented. The simulation process is divided into either two or three time-intervals, and makes use of three kinds of modulation methods: the TRC method, the PWC method, and a combination of the two. The analysis also brings out the fact that the choice of the chopping frequency, percentage of supplied voltage, and time-intervals plays a significant role in the above simulation. The simulation results can be printed by use of a line printer or an X-Y Plotter. The former is for the purpose of analysis, the latter is for the final document. From analysis of the simulation results as shown in Tables 2 through 18, as well as in Figures 10 through 26, conclusions as to the optimum chopping cycle for dc motor starting may be made as follows:

From 0.0 to 0.025 second

Chopper frequency = 200 Hz

Chopping rate = 0.005 second

Pulse width TAU = 0.0025 second

Frpm 0.025 to 0.05 second

Chopper frequency = 200 Hz

Chopping rate = 0.005 second

Pulse width TAU = 0.0035 second

From 0.05 to 0.2 second

Chopper frequency = 2.5 Hz

Chopping rate = 0.4 second

Pulse width TAU = 0.3 second

The minimum starting current is 25.048 amperes, and the minimum rise time is 0.096 second.

APPENDIX A

CSMP III PROGRAM

```
TITLE                    MOTOR RESPONSE
INITIAL
  CONSTANT RA=4.98, LA=0.0524, KT=0.83, KE=1.212, JM=0.0087, ...
           TL=3.0, TAU=0.0025, TAU1=0.0, TAU2=0.005
DYNAMIC
  X1 = IMPULS (TAU1, TAU2)
  X2 = PULSE (TAU, X1)
  REF = 240.0 * X2
  EB = KE * OUT
  YONE = REF - EB
  YTWO = REALPL (0.0, 0.0105, YONE)
  YTHREE = YTWO / RA
  YFOUR = KT * YTHREE
  YFIVE = YFOUR - TL
  OUT = (1.0/JM) * INTGRL (0.0, YFIVE)
  SPEED = OUT * 60.0 / (2.0 * 3.14159)
OUTPUT TIME, YTHREE, SPEED
LABEL MOTOR CURRENT (YTHREE) AND SPEED AS A FUNCTION OF TIME
PAGE XYPLOT
TIMER FINTIM = 0.025, DELT = 0.25 E-05, OUTDEL = 0.0005
  END CONTINUE
  CONSTANT TAU = 0.0035
  TIMER FINTIM = 0.05
  END CONTINUE
  CONSTANT TAU = 0.3, TAU2 = 0.4
TIMER FINTIM = 0.2
END
STOP
```

APPENDIX B

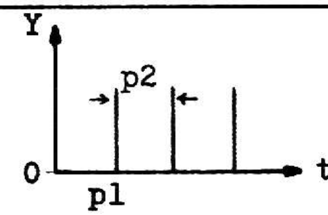
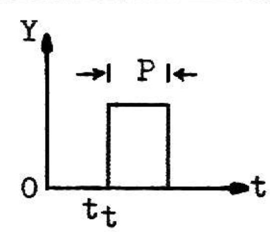
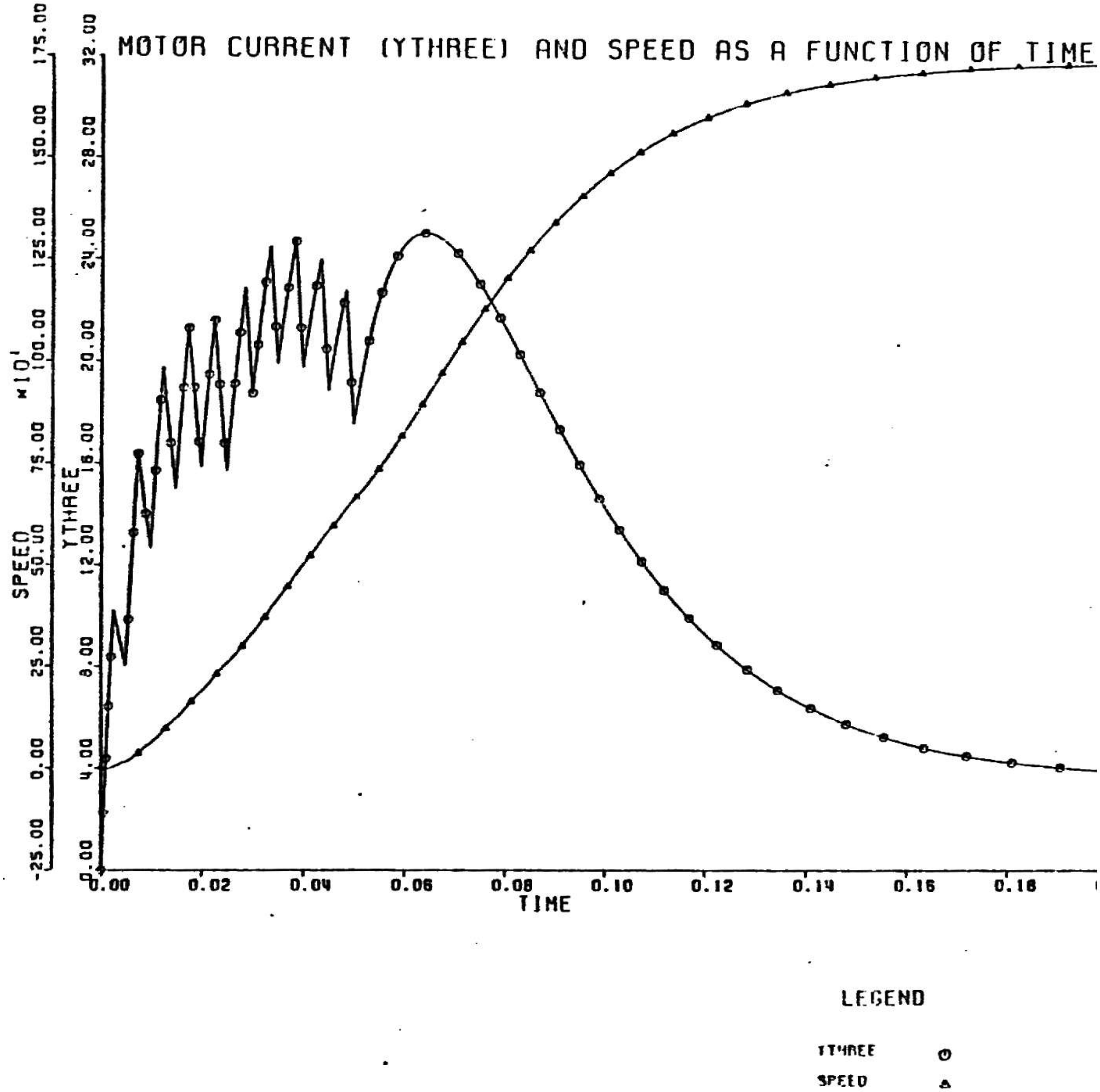
CSMP III Statement	Equivalent Mathemetical Expression
INTEGRATOR Y = INTGRL(IC,X) where: Y = output IC = initial condition X = integrand	$y(t) = \int_{ts}^{t} x\, dt + y(ts)$ where: ts = start time t = time Equivalent Laplace Transfer Function : $\frac{Y(s)}{X(s)} = \frac{1}{s}$
1ST ORDER LAG(REAL POLE) Y = REALPL(IC,P,X) where: IC = $y\big\|_{t=ts}$	$p \frac{dy}{dt} + y = x$ Equivalent Laplace Transfer Function : $\frac{Y(s)}{X(s)} = \frac{1}{ps + 1}$
IMPULSE GENERATOR Y = IMPULS(P1,P2) where: P1 = time of first pulse P2 = interval between pulses	$y = 0;\ t < p1$ $y = 1;\ (t-p1) = kp2$ $y = 0;\ (t-p1) \neq kp2$ where: k = 0, 1, 2,... 
PULSE GENERATOR (WITH X > 0 AS TRIGGER) Y = PULSE(P,X) where: P = minimum pulse width	$y = 1;\ t_t < t < (t_t + p)$ or $x > 0$ $y = 0;$ otherwise where: t_t = time of trigger 

Table 19. Part of Library of CSMP III Function Blocks

APPENDIX C

GRAPH FOR CURRENT AND SPEED RESPONSE OF OPTIMUM CHOPPING CYCLE FOR DC MOTOR STARTING



APPENDIX D

CONTINUOUS SYSTEM MODELING PROGRAM III *

A. Introduction

Continuous System Modeling Program III is an IBM program product designed to meet the needs of engineers and scientists engaged in modeling systems involving continuous behavior, and in simulating such behavior to test their models, or engaged in continuous system simulation. CSMP III Language is a Continuous System Simulation Language (CSSL), which means that it combines the functional block modeling capabilities of a digital-analog simulator, with the algebraic and logical capabilities of a procedural language like FORTRAN. To use CSMP III one must prepare, in CSMP III Language, a system description and additional specifications as required by the model and the exercises to be conducted.

B. Statement Classification in CSMP III

1. Structure statement

Used to describe the structure and properties of the system to be simulated. For example:

Y = INTGRL (ICY,U)

which states that Y is the output of an integrator whose input is U. At the beginning of each simulation run, Y will be set to its initial condition ICY.

---

* The following material is directly out of bibliography [16] IBM Continuous System Modeling Program III (CSMP III), Program Reference Manual for reference only.

2. Data statement

Used to give values to parameters, constants, initial conditions, tables, and other data characterizing the specific situation to be simulated. For example:

INCON ICY = 1.0

begin with the label INCON identifying it as one of the Data statements. INCON statements have only one function: they are used to specify initial conditions where these are given symbolic names in the model.

3. Execution control statement

Used to request particular simulation runs and specify, in particular, their integration stepping and conditions of termination. For example:

TIMER FINTIM = 6.0, PRDEL = 0.1

This is a TIMER statement which specifies, besides FINTIM just described, a "TIME-interval" to control the frequency of tabulation of simulation results. PRDEL may be changed between or during runs if desired.

4. Output control statement

Used for tabulation of selected model variables at PRDEL intervals starting at run start time, or to request particular printed or machine-readable documents. For example:

PRINT U,Y

5. Translation control statement

Used to impose structure on the models, to extend modeling facilities, to separate models, and to provide additional capacity in the simulation vehicles produced. For example:

END

a simple END statement is both a Translation control statement and an Execution control statement: it marks the end of the collection of statements specifying structure, data, execution control, and output control for one simulation case.

6. FORTRAN statement

Used to supplement any of the above types of statements. For example:

Y = EXP (X)

which is both a CSMP III statement and a FORTRAN statement.

C. Elements of the CSMP III Language

1. Numeric constants

There are two types of constants: integer and real. An integer constant may be positive, zero, or negative. If unsigned, it is assumed to be positive. The following are valid integer constants:

0 -91 -3468 24691

A real (floating-point) constant is a number written with from one to seven significant decimal digits with a decimal point. It may be positive or negative. If unsigned, it is assumed to be positive.

A real constant may be followed by a decimal exponent written as the letter E, followed by a signed or unsigned one-or-two-digit integer constant. The following are valid real constants:

0. -97.345 5934.75 -24.951E9 -83.625E-05

2. Symbolic names

A symbolic name contains from one to six alphabetic characters--that is, numeric 0 through 9, or alphabetic A through Z. The first character must be alphabetic. Symbolic names must not contain embedded blanks or any of the special characters + / ($ -) , * . ' and may not be a word reserved by CSMP III as a FORTRAN IV keyword. The following are valid symbolic names:

RATE SR915 A41B

All variables that are represented by symbolic names are normally treated within the simulation as being real--that is, having floating-point values. Integer variables must be specified with a FIXED translation control statement. Note that this convention differs from FORTRAN, which automatically treats as an integer any variable that has as the first character of its name the letter I, J, K, L, M, or N.

3. Operators

Operators are used instead of functional blocks to indicate basic arithmetical functions or relationships. As in FORTRAN, these operators are:

Symbol	Function
+	addition
-	subtraction
*	multiplication
/	division
**	exponentiation
=	replacement
( )	grouping of variables and/or constants

As in algebra and FORTRAN, parentheses may be used in arithmetic expressions to specify the order in which the arithmetic operations are to be performed. Expressions within parentheses are always evaluated first. When parentheses are omitted, or when an entire arithmetic or functional expression is enclosed within a single pair of parentheses, the order in which the operations are performed is as follows:

Operation	Hierarchy
Evaluation of functions	1st (highest)
Exponentiation (**)	2nd
Multiplication and division (* and /)	3rd
Addition and subtraction (+ and -)	4th (lowest)

For operators of the same hierarchy, except exponentiation, the component operations of the expression are performed from left to the right. Thus, the arithmetic expression, A/B*C, is evaluated as (A/B)*C. For exponentiation, the evaluation is from right to left. Thus, the expression A**B**C is evaluated as A**(B**C).

For example:

```
RATE = DIST / TIME
Y = A*X**2 + B
A = (B*C) + (D*E)
```

4. Functions

Functional blocks (functions) are used for more complex mathematical operations such as integration, time delay, quantization, and limiting. The basic CSMP III system library includes all the standard functions found in analog computers plus a complement of special-purpose functions often used in simulation problems. In appendix B, table 19 lists part of the library of functional blocks. All the functions available in the FORTRAN IV library can be treated as functional blocks. Illustrations of the most useful functions are shown in CSMP III Program Reference Manual in their functional block notation.

5. Labels

The first word of CSMP III data and control statements is a label that tells the program the purpose of the statement. Some statements contain only the label, such as INITIAL, NOSORT, and ENDMAC. Others contain an interval and the "finish time" for a run. One would use the TIMER statement as follows:

```
TIMER   DELT = 0.025,   FINTIM = 450.
```

The label must be separated from the data by at least one blank column.

D. Summary

A system to be simulated is described to the program by a series of structure, data, and control statements. Structure statements describe the functional relationships between the variables of the model and, taken together, define the network to be simulated. Data statements assign numeric values to the parameters, constants, initial conditions, and table entries associated with the problem. Control statements specify options relating to the translation, execution, and output phases of the CSMP III program (such as run time, integration interval, and type of output). The basic elements in the preparation of these three types of statements are numeric constants, symbolic names, operators, functions, and labels.

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OPTIMUM CHOPPING CYCLE FOR DC MOTOR STARTING

by

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Diploma, Taipei Institute of Technology, 1971

AN ABSTRACT OF A MASTER'S REPORT

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Electrical Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1979

ABSTRACT

Experimental procedures are developed for determining the optimum chopping cycle for dc motor starting, by using Continuous System Modeling Program III (CSMP III). The objective is to obtain a minimum starting current and a minimum rise time for motor starting.

In order to optimize the dc motor response, the analysis of such a motor is briefly reviewed. The performances of the dc choppe for three types of control -- time ratio control (TRC), pulse width control (PWC), and off-frequency control (OFC) -- are introduced. When a wide range of control is needed, a suitable combination of variable and constant controls is employed.

The dynamic behavior of a dc motor is nonlinear. Consequently, it is inadequate to approximate its performance by linear models. One of the methods of obtaining realistic solutions to the analysis and design of dc motors is computer simulation. The simulation process is divided into either two or three time-intervals, and makes use of three kinds of modulation methods (time ratio control, pulse width control, and a combination of the two).

The search for the minimum starting current and the minimum rise time by using variable "on-pulsewidth-to-chopping-rate" ratios in certain predefined time-intervals is explored in simulation procedures. In other words, the chopping frequency, percentage of supplied voltage, and time-interval were varied using computer simulation. The results were printed out by either line printer or X-Y Plotter.