AN ABSTRACT OF THE THESIS OF

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Title: DIGITAL MODEL OF A SYNCHRONOUS GENERATOR EXCITATION SYSTEM

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This thesis develops a simplified and logical simulation model for an amplidyne excitation system for a synchronous generator with an automatic voltage regulator.

The non-transfer function representation using field determined parameters including variable inductance and machine saturation was used to reduce the computing time for the stability analysis.

The simulation of the above model was programmed in Fortran. The simulation results are compared with actual data taken in the laboratory.

From the results it was observed that steady state voltage for the model and the actual system was within 3.0%. But the transient response of the model and actual system did not agree.

Digital Model of a Synchronous Generator Excitation System

by

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TABLE OF CONTENTS

LIST OF GRAPHS

LIST OF FIGURES

DIGITAL MODEL OF A SYNCHRONOUS GENERATOR EXCITATION SYSTEM

I. INTRODUCTION

The stability of a power system is of vital importance in the operation of large interconnected electrical systems. This subject has been the concern of the industry for the past 50 years.

In recent years it has attracted more attention due to bulk power generation and transmission. The transmission systems are designed to operate at higher loads and emphasis is given to large scale interconnections, DC tie lines, EHV lines and underground cables.

As the power industry pursues the goal of reliable systems with minimum cost, the problem of stability can be a limiting design factor and therefore deserves careful evaluation.

The stability of the system is greatly influenced by its excitation. Therefore in recent years considerable attention has been given to the analysis and design of the excitation system.

The reinforcement of power system interconnections and the non-linearity of the system characteristics increase the difficulty of testing the system stability by simulation. Even the present computers are not capable of representing major power systems in sufficient detail to produce an accurate stability study in a reasonable time with minimum cost. One possible solution is to have a simplified representation of the original system. However, the equivalent representation should be such as to give acceptably accurate stability results. In mathematical terms, this means reducing the number of differential equations that represent the system.

The object of this thesis is to develop a simple and logical model to represent an excitation system for a synchronous generator with an automatic regulator and amplidyne.

To accomplish this object, the system is divided into four main parts, namely:

1. DC machine (excitor),
2. Amplidyne,
3. AC machine (generator), and
4. Regulating system.

Each component is modeled separately and its simulation response is compared with the actual response data. The steady state and transient response of the complete system due to a sudden change in the field resistance of the synchronous generator is also investigated. The model response is compared with the actual system response as recorded in the laboratory.

II THEORY OF OPERATION

The field rheostat of the direct current exciter was adjusted to provide a required voltage output from the AC generator. In this condition, the amplidyne voltage will be zero. However, if at any time the generator voltage tends to rise due to a change in load, the regulator detects this rise, and causes the amplidyne to increase its voltage in the "Buck" direction. As a result, the current in the exciter field decreases. This will then reduce the output voltage of the exciter, which in turn will reduce the generator output voltage. Thus the voltage error is reduced toward zero.

The error cannot be reduced entirely to zero or this would also reduce the amplidyne output to zero allowing the terminal voltage to return to the off-reference value that originally caused the error. The amplidyne acts as an amplifier for the error signal. The amplification has to be maintained within reasonable limits to avoid instability.

On the other hand, if the generator voltage decreases the regulator will detect this difference and it will cause the amplidyne voltage to increase in the "Boost" direction which in turn causes the generator output voltage to rise toward normal.

Description of Experiment Set-Up

An AC generator excited by a self-excited DC machine is shown in Figure 1. The excitation level is controlled by the shunt field rheostat of the DC generator. When the amplidyne is connected in series with the shunt field winding, as shown, the AC generator voltage can be controlled automatically by the voltage regulator.

The regulator consists of two main sections: a linear and a non-linear circuit. A silverstat regulator was used to supply the non-linear output, which was compared with a fixed reference voltage and the difference was applied to the amplidyne. The amplidyne amplifies this error signal and converts it to "Buck" or "Boost" voltage according to the polarity of the error.

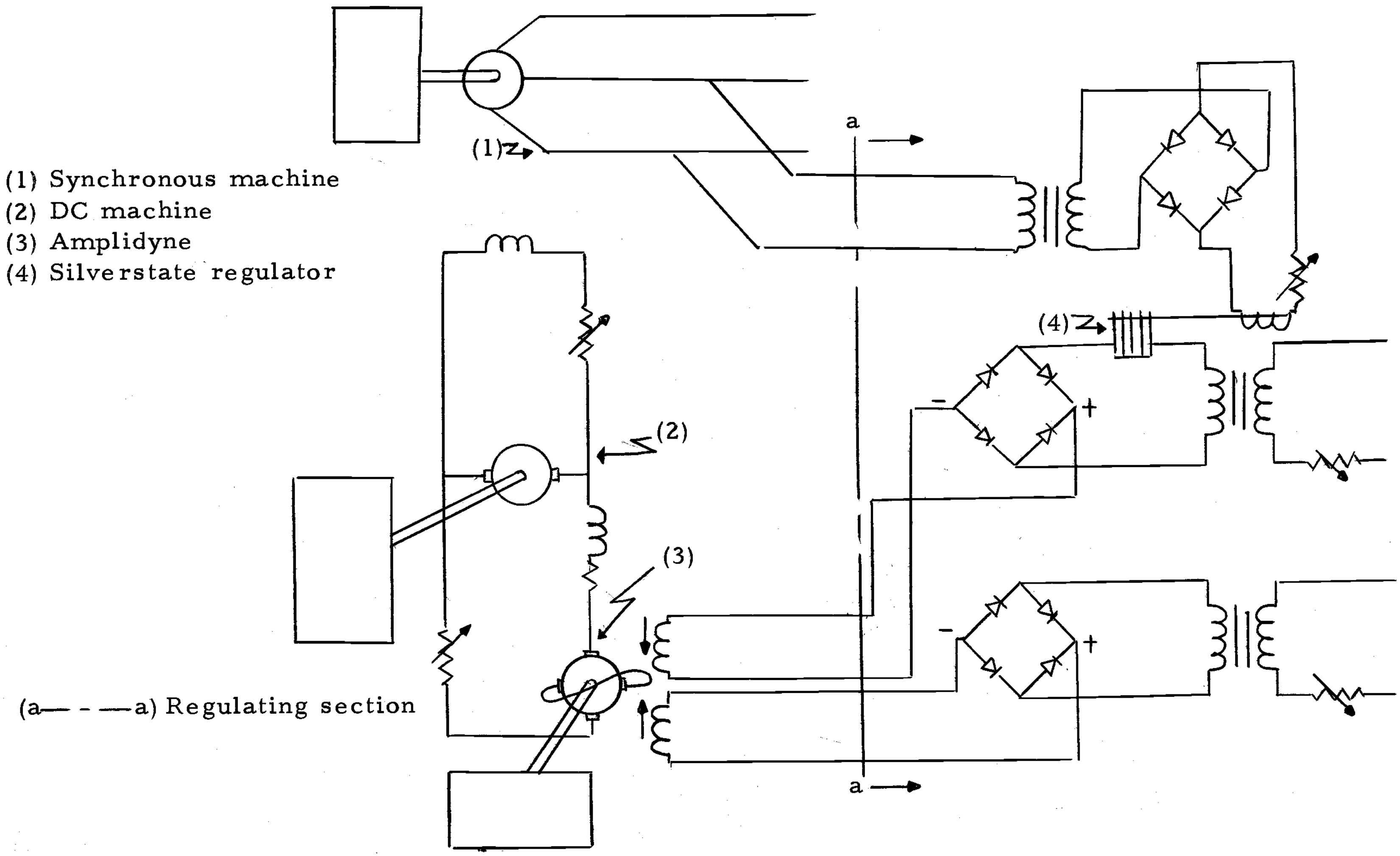


Figure 1. A synchronous generator excitation system.

III DEVELOPMENT OF THE MODEL

The system as shown in Figure 1 was subdivided into the following four parts to facilitate the model building:

(a) Direct current machine with and without load.

(b) Amplidyne.

(c) Open circuited alternating current machine.

(d) Regulating system.

In the next chapter the models for the above components are derived and their performances are compared with the actual physical device time responses.

Model of an Open-Circuited Direct Current Machine

Figure 2 shows a simple representation of a self-excited generator.

The equation for the no-load condition can be written:

$$E_{TD} = I_{FD} * R_D + N_{FD} \frac{dQ_{FD}}{dt} \qquad (1)$$

where $R_D = R_{VD} + R_{FD}$

$E_{GD} = E_{TD}$ (neglecting the armature drop as $R_A < R_D$)

$E_{GD} = f\,(I_{FD})$

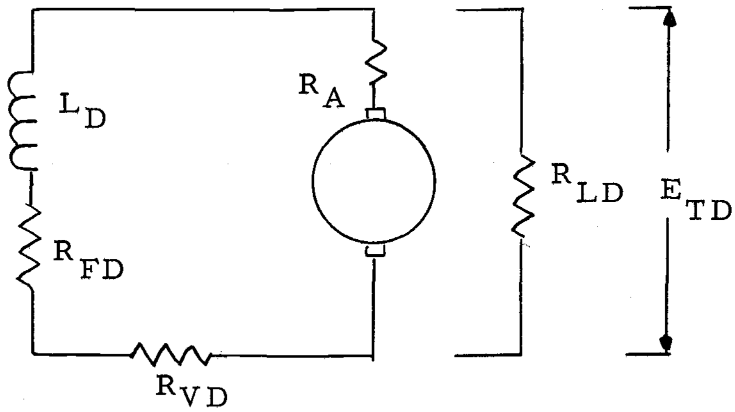


Figure 2. A self excited generator.

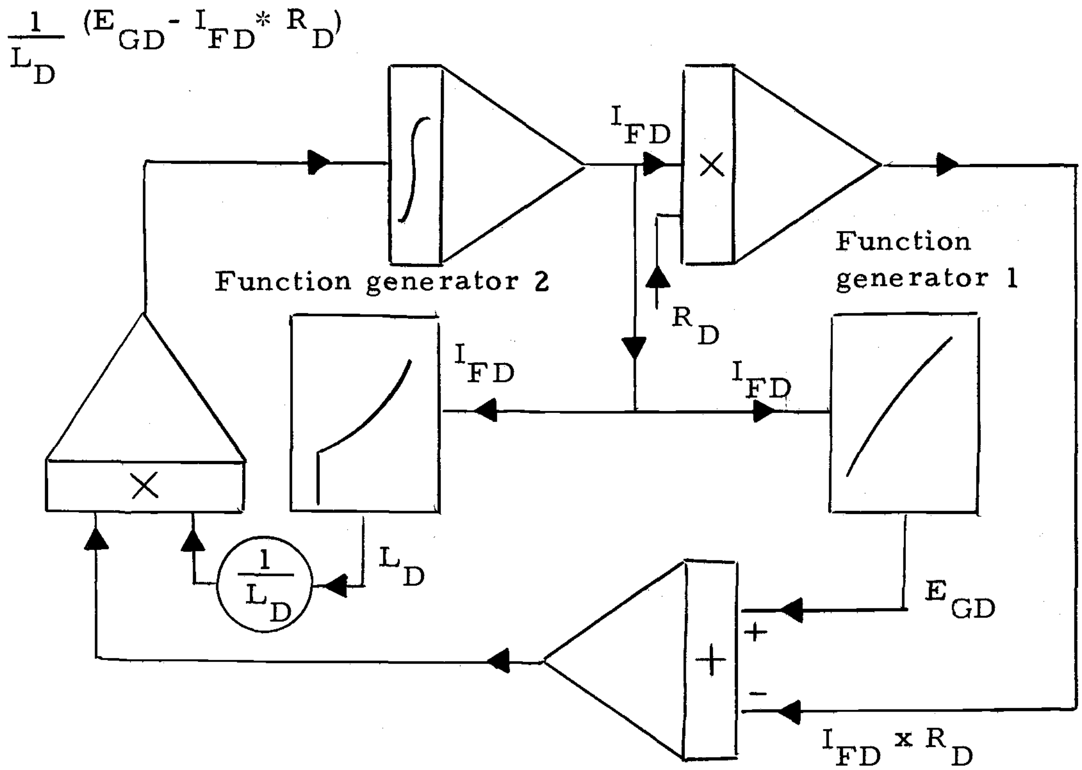


Figure 4. Functional model of a self excited DC machine.

The eddy currents in the solid parts of the magnetizing circuits are very small. Therefore, equation (1) can be written as

$$E_{TD} = I_{FD} * R_D + L_D * \frac{dI_{FD}}{dt} \qquad (2)$$

where E_{TD} is a non-linear function of I_{FD}. Their functional relationship is given by the magnetizing characteristic. The inductance (L_D) is proportional to $\frac{dE_{TD}}{dI_{FD}}$.

The steady-state terminal voltage (build up voltage) can be predicted by a graphical method. In this method the shunt field resistance line is drawn on the magnetizing curve of the machine for a specific speed. The no-load terminal voltage is given by the ordinate of the intersection of the saturation curve and the field resistance as shown in Figure 3. The build-up voltage can be found by solving the non-linear equation (2). This type of equation can be solved by numerical methods.

From equation (2)

$$I_{FD} = \int \frac{1}{L_D} (E_{TD} - I_{FD} * R_D)\, dt \qquad (2a)$$

The current I_{FD} is obtained by solving equation 2a. This is achieved by integrating the terms on the right-hand side of the above equation which are shown as the input to the integrator (Fig. 4).

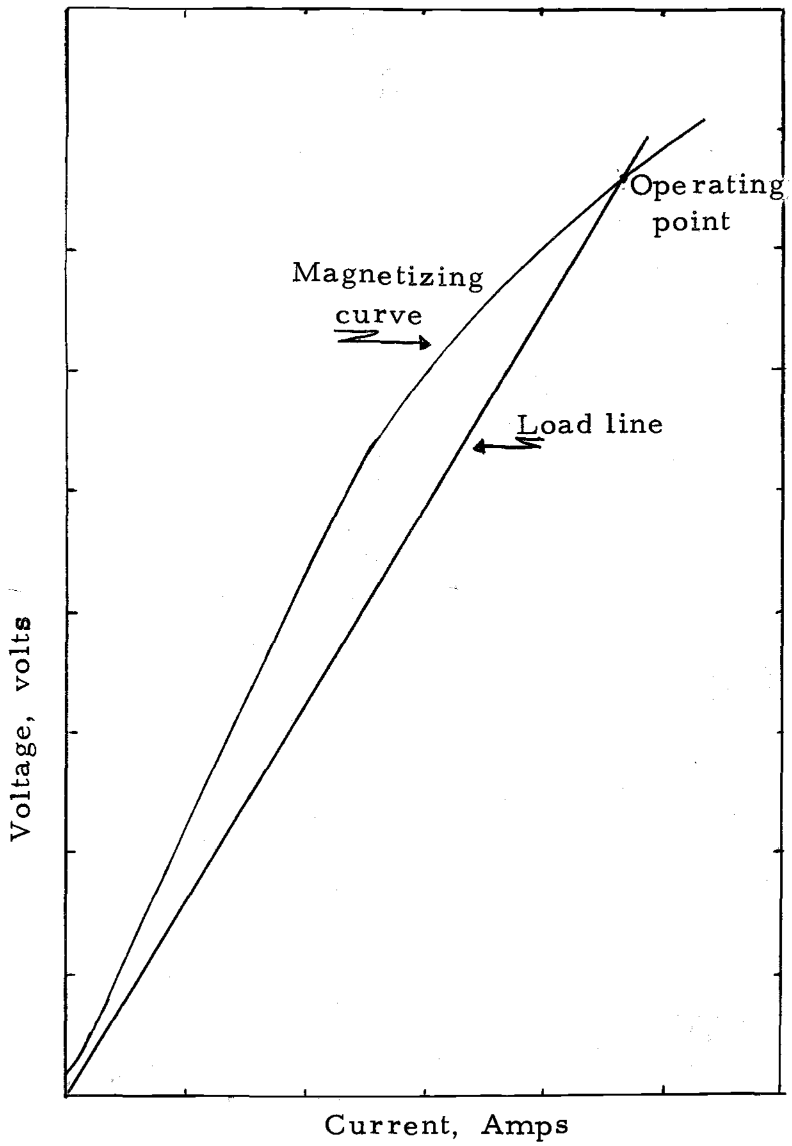


Figure 3. Graphical method to show the build up voltage of a DC machine.

The values of the generated voltage and the inductance L_D are obtained as follows:

The function generator (1) in Figure 4, represents the magnetizing character of the machine which gives the relationship between the I_{FD} and E_{GD}. For the particular values of the I_{FD} the corresponding value of the E_{GD} is obtained from the function generator.

The inductance L_D of the field winding is a function of the field current I_{FD} the method of obtaining the values of the inductance is described in Appendix A. The function generator 2 represents the relationship between I_{FD} and L_D. From this function generator, values of the L_D corresponding to I_{FD} are obtained.

The reciprocal of the L_D is multiplied by the difference between the generator voltage E_{GD} and the voltage drop across the total field circuit resistance to obtain the input to the integrator as shown in Figure 4. This defines the complete model of the machine. To implement the model, various values of the parameters were found experimentally for a particular machine.

Determination of Machine Variables and Parameters

Specifications of the machine: General Electric Company,

direct current generator	No. 1227362	Comp'd wound
	Amp 24	Volts 112/125
	3 K. W.	speed 1800 r. p. m.

The following characteristics were found experimentally:

1. Saturation characteristics (graph 1).
2. Inductance vs. field current shown in graph 2.

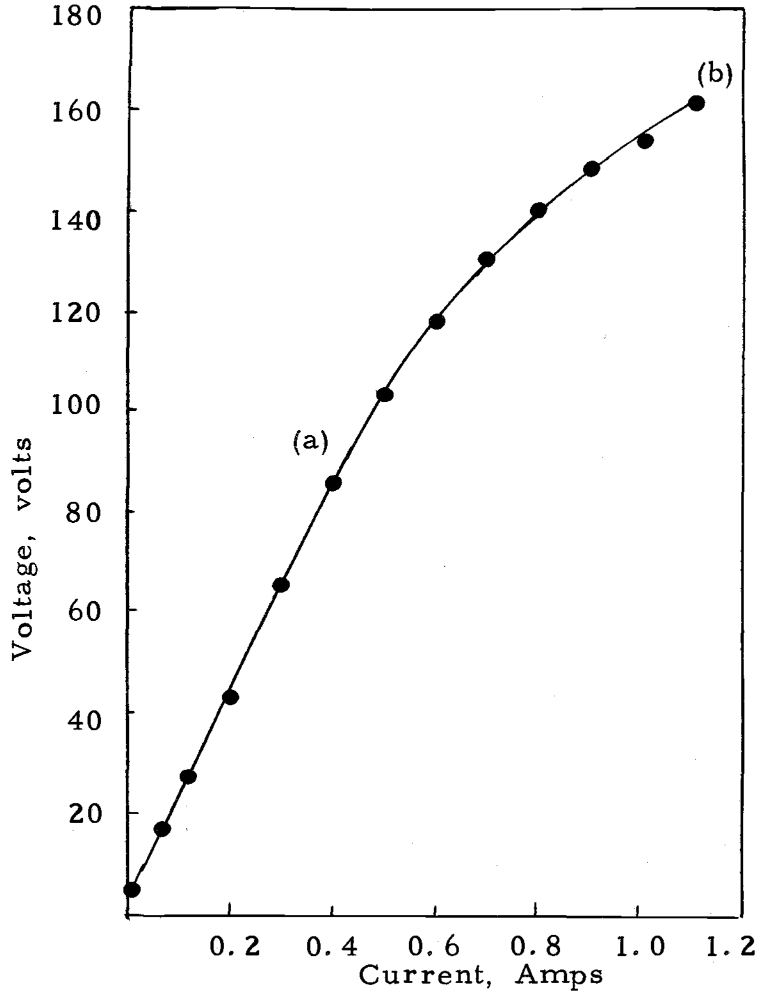
The procedure and results of the experiment are given in Appendix A.

The resistance of the field circuit was evaluated for the build-up voltage under consideration.

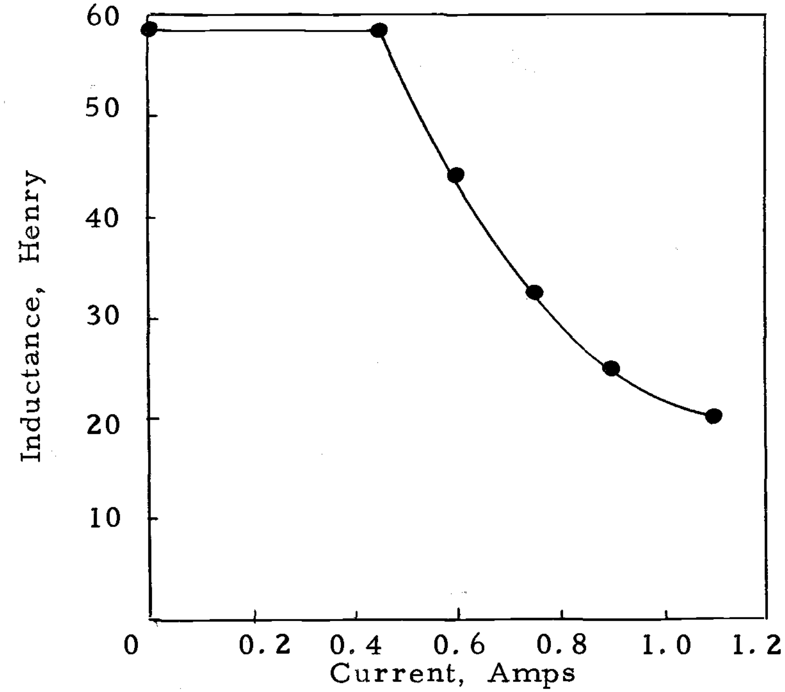
Digital Model of the DC Machine

The digital program for the DC machine was developed from the functional model shown in Figure 4. The program was written in Fortran. The integration scheme used was the modified Euler method. This method is simple to program and its accuracy is comparable to the second order Runge-Kutta method. Since the accuracy in measurement is only one-tenth of one percent, this method was found suitable for the machine model.

Aiken Neville repeated (Iterated) linear interpolation method



Graph 1. Magnetizing curve of a DC machine.



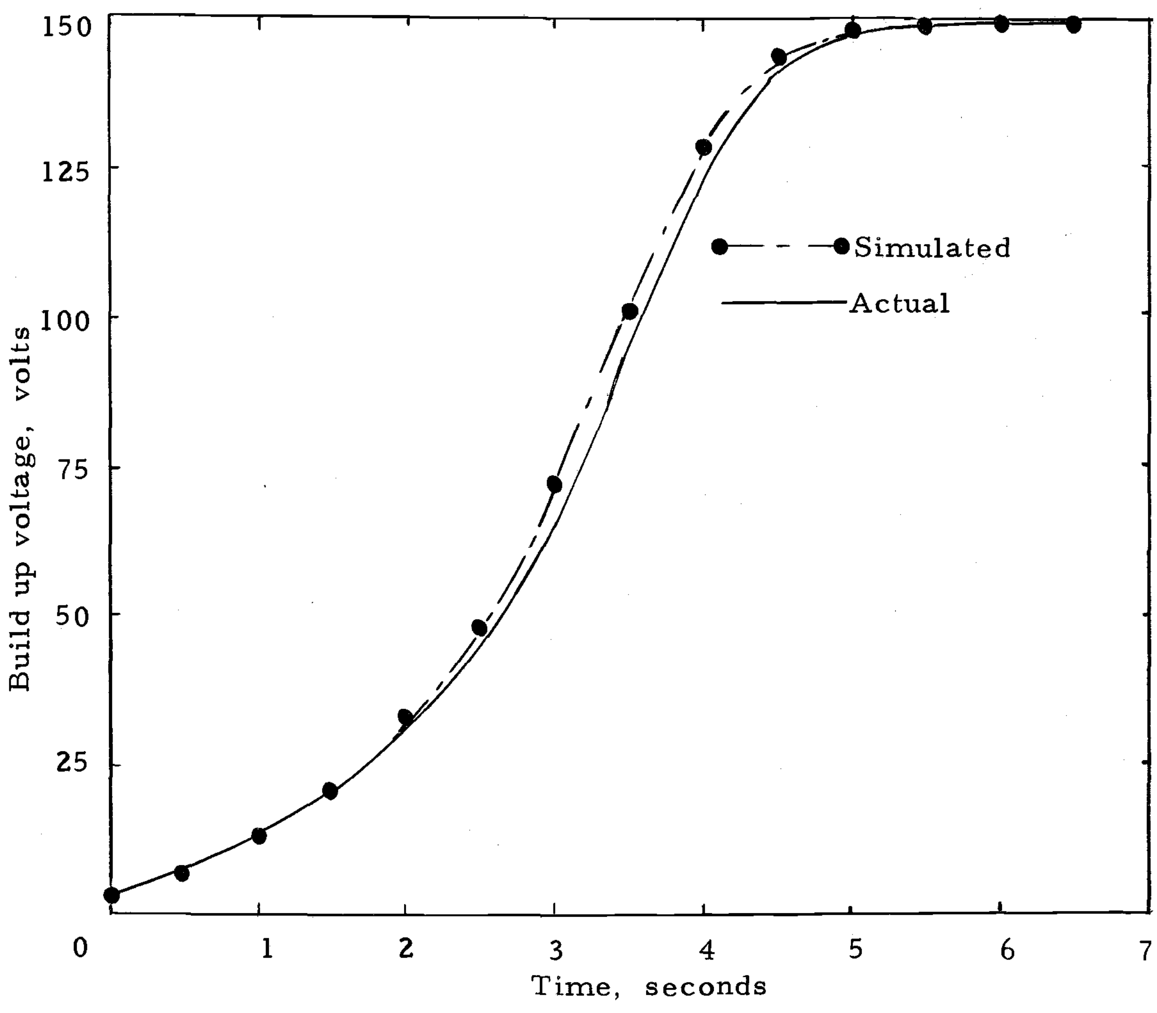
Graph 2. Inductance of a DC machine.

was used to determine the intermediate points for the function generator. This method has a better accuracy than ordinary linear interpolation, but it needs four points to perform the interpolation. Therefore, values between the initial two points and the last two points were interpolated by the linear method.

The listing of the program, block diagram and result, are given in Appendix B.

Comparison of Experimental and Computer Results:

The experimentally obtained build-up voltage of the open-circuited DC machine and the results of the simulation are shown on graph 3. As can be seen from the graph, the computer results show good agreement with the experimental values. The maximum error in the simulation is 3.56% in build-up voltage which occurs at 3.5 seconds.



Graph 3. Build up voltage of an open circuited self excited DC machine.

Model of the DC Machine With Load

Figure 2 represents the DC machine with the load. The voltage equations around the circuit can be written as follows:'

$$E_{TD} = R_D * I_{FD} + N_D * (dQ_{FD}/dt) \quad (3)$$

$$E_{TD} = E_{GD} - R_A * I_{AD} \quad (5)$$

$$I_{AD} = I_{LD} + I_{FD} \quad (6)$$

$$E_{GD} = f\ (I_{FD}) \quad (7)$$

$$I_{LD} = E_{TD}/R_{LD} \quad (8)$$

Neglecting the eddy current losses in the magnetic circuit, equation (3) becomes

$$E_{TD} = R_D * I_{FD} + L_D * dI_{FD}/dt \quad (4)$$

The functional model of the DC machine with load is obtained on the same basis as in the case of the open circuited DC machine. The only difference is in the calculation of the terminal voltage E_{TD}. This is due to the fact that armature resistance drop has a significant effect on the build-up voltage. Now E_{TD} is the difference between the generated voltage E_{GD} and drop across armature resistance $(R_A X I_{AD})$. The armature current I_{AD} is the sum of the load current I_{LD} and the field current I_{FD}. The load current is obtained by dividing the terminal voltage by the load resistance.

Initially it is assumed that the terminal voltage is the same as the generated voltage which is equal to the residual voltage.

Figure 5 shows the complete functional model of the DC machine with load. The magnetizing curve and the graph of inductance vs. current are the same as for the open circuited case. The remaining parameters, the resistance of the field winding and the load, are calculated for a specified build-up voltage and load.

The machine equation (4-8) were simulated on a digital computer. The block-diagram, program listing and results are given in Appendix B.

Graphs 4 and 5 show the comparison between the build-up voltage of the DC machine taken in the laboratory and the results of the simulation. The above two graphs are for load currents of 4.85 amps and 10.1 amps, respectively.

The above values of the load current are considerably higher than the operating current which is about 3 Amps. (Maximum value of the excitation current for the AC machine is 5 Amps.) The maximum error was found to be about 4.5% for a load current of 4.85 Amps which occurs at 4 seconds. For a load current of 10.1 Amps a maximum error of 6.5% occurs at 3.5 seconds. Therefore, as in the open circuit case the computer results for the DC machine with load are in close agreement with the experimental results.

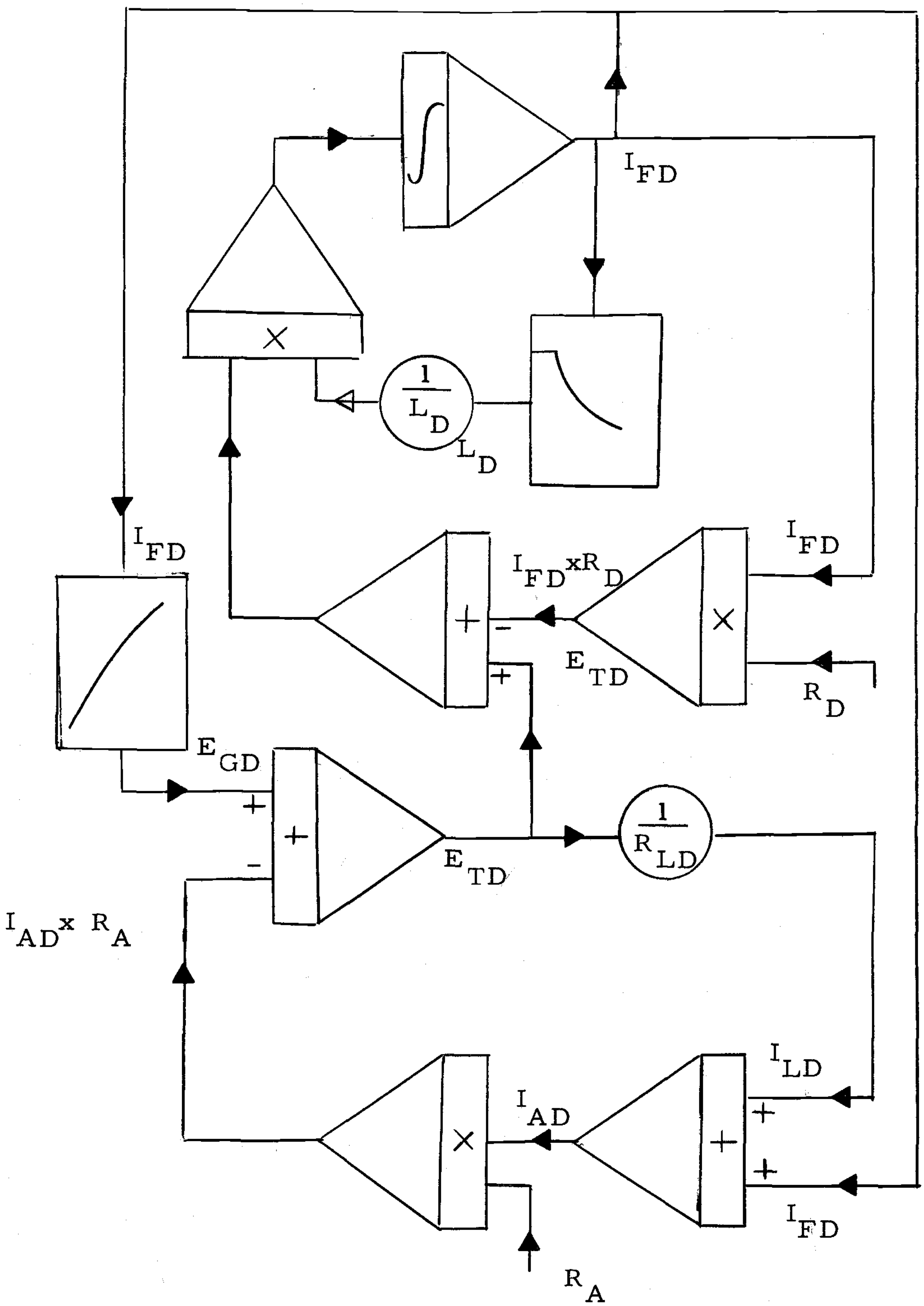
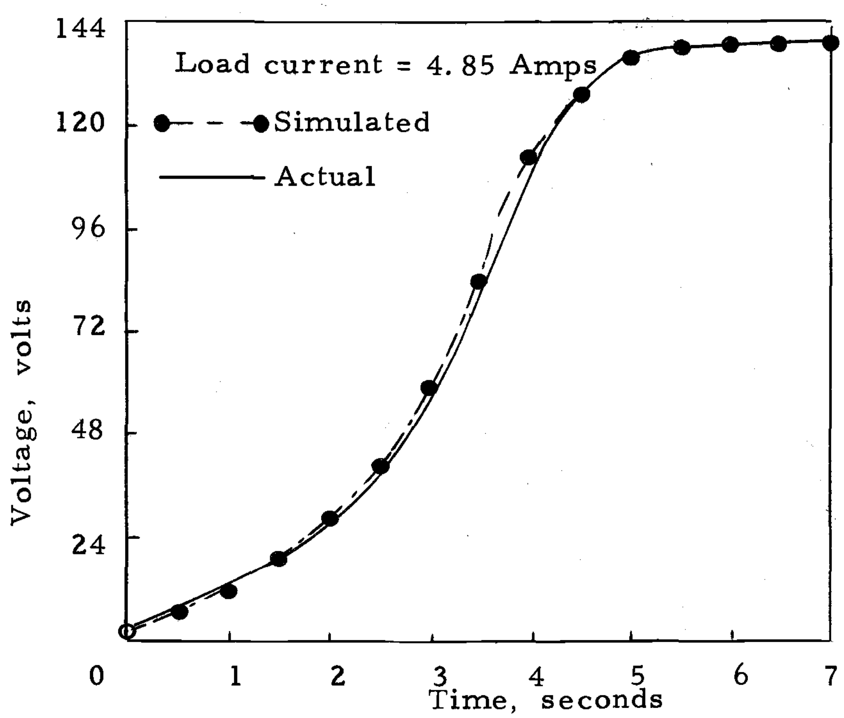
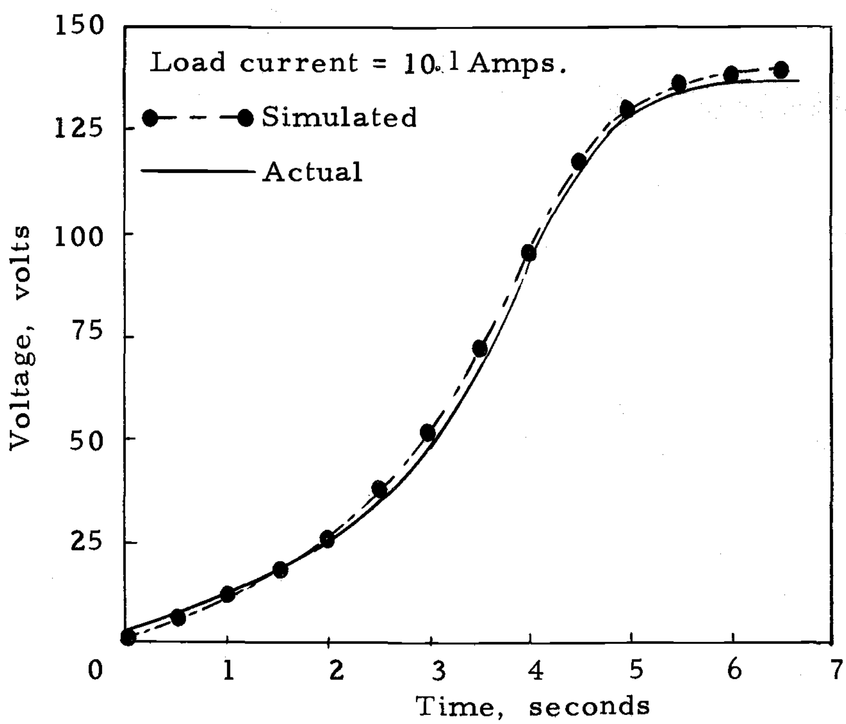


Figure 5. Functional model of a DC machine with load.



Graph 4.



Graph 5. Build up voltage of a DC machine with load.

Model of the Amplidyne

The theory of the amplidyne has been described in detail in the literature (1, 3, 6, 7). It is necessary to discuss briefly some of the amplidynes' important features.

The amplidyne is a two-pole, DC generator with two pairs of brushes in quadrature as shown in Figure 6.

A voltage E_{TAM1} applied across the direct axis control field produces a current I_{AM}. This current creates a flux in the direct axis. The rotation of armature in this flux generates a voltage E_{GAM1} in the quadrature axis which causes a current I_{AM1} to flow. The flow of armature current I_{AM1} develops a magnetic field in the quadrature axis. The rotation of the armature in this field generates the voltage E_{GAM2} at the direct axis brushes. If a load resistance is connected across the brushes, current I_L flows in the load circuit. However, this load current causes a new magnetomotive force in the armature which opposes the magnetomotive force of the control field winding. To overcome this so called "load axis armature reaction", there is a distributed compensating field in series with the load axis brushes which neutralises the armature magnetomotive force due to I_L. Hence, only a small current is required in the control field to generate the required output voltage at the load terminals.

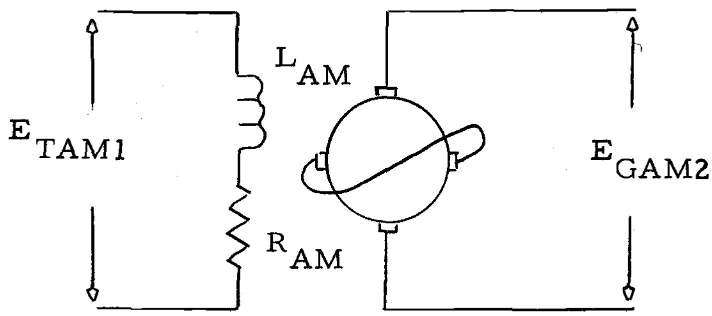


Figure 6. Electrical representation of an amplidyne.

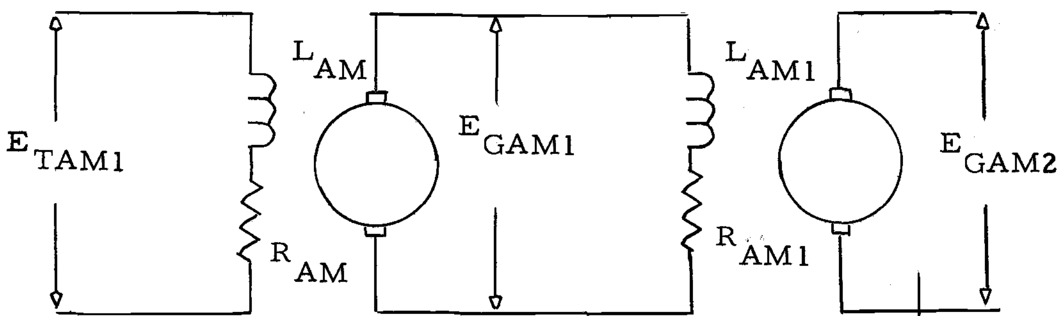


Figure 7. Representation of an amplidyne as two DC machine in series.

From the above discussion it can be seen that the amplidyne is a machine with two stages of amplification. The first stage is from control field to quadrature axis and second stage is from quadrature axis to the load terminals. For modeling purpose this can be represented as two DC generators in series, as shown in Figure 7.

The voltage equations of the amplidyne are the following:

$$E_{TAM1} = I_{AM} * R_{AM} + L_{AM} (dI_{AM}/dt) \quad (9)$$

$$E_{GAM1} = f (I_{AM})$$

$$E_{GAM1} = I_{AM1} * R_{AM1} + L_{AM1} * (dI_{AM1}/dt) \quad (10)$$

$$E_{GAM2} = f(I_{AM1})$$

$$R_{AM} = R_{VAMD} + R_{FAMD}$$

$$R_{AM1} = R_{VAMQ} + R_{FAMQ}.$$

Equations (9) and (10) can be written as follows:

$$I_{AM} = \int [(E_{TAM1} - I_{AM} * R_{AM})/L_{AM}] \, dt \quad (9a)$$

$$I_{AM1} = \int [(E_{GAM1} - I_{AM1} * R_{AM1})/LAM1] \, dt \quad (10a)$$

The functional model for the amplidyne is obtained as follows: The currents I_{AM1} and I_{AM} are obtained by solving equations 10a and 9a. These currents are shown as outputs of the integrators in the functional model (Fig. 8). The generator voltages E_{GAM2} and E_{GAM1} corresponding to the respective currents are obtained from

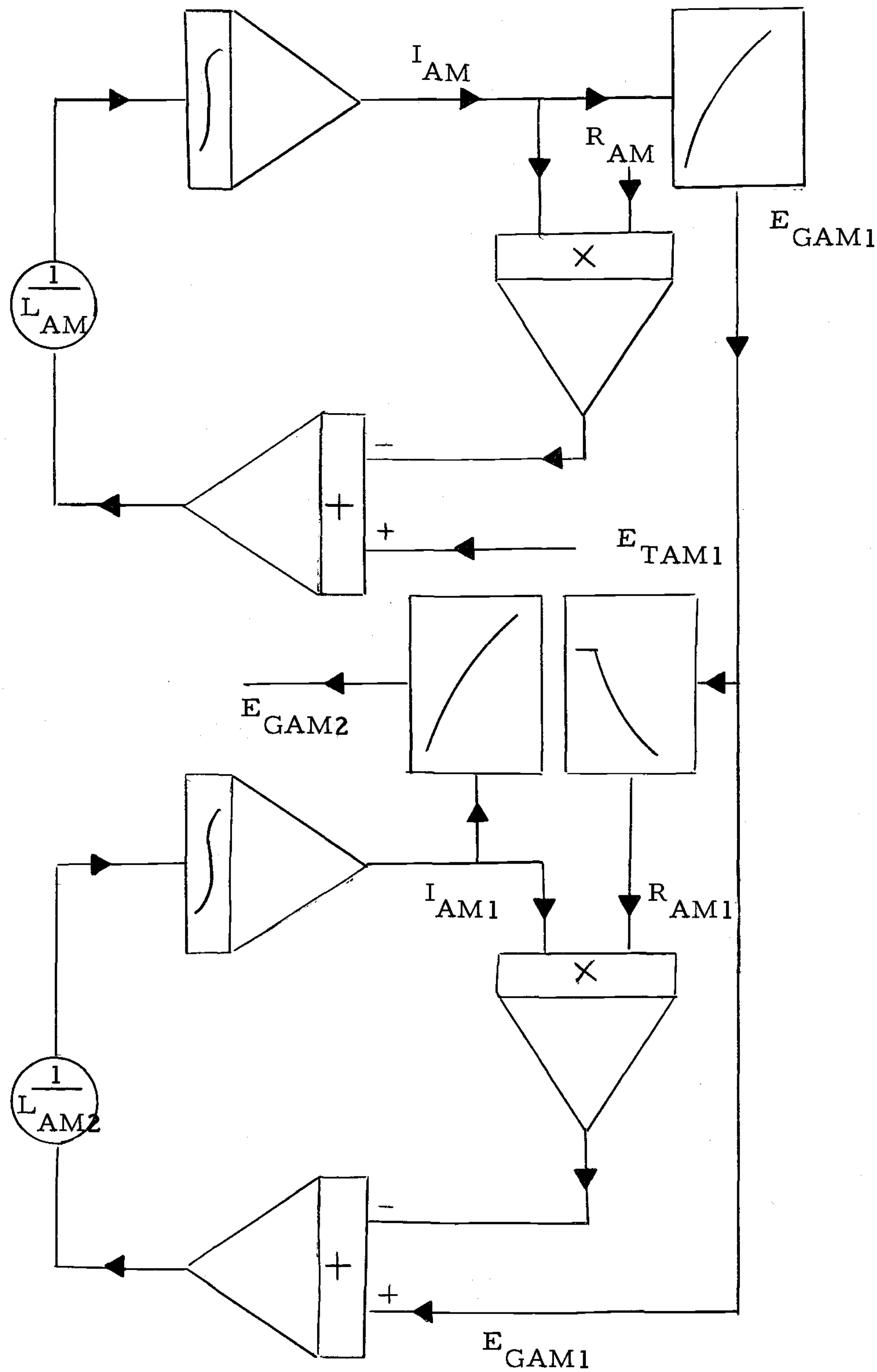
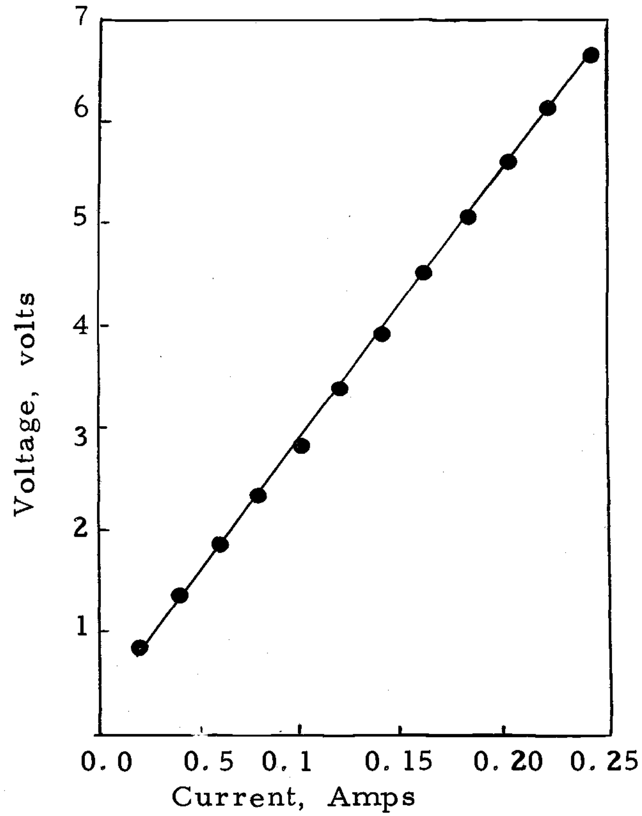
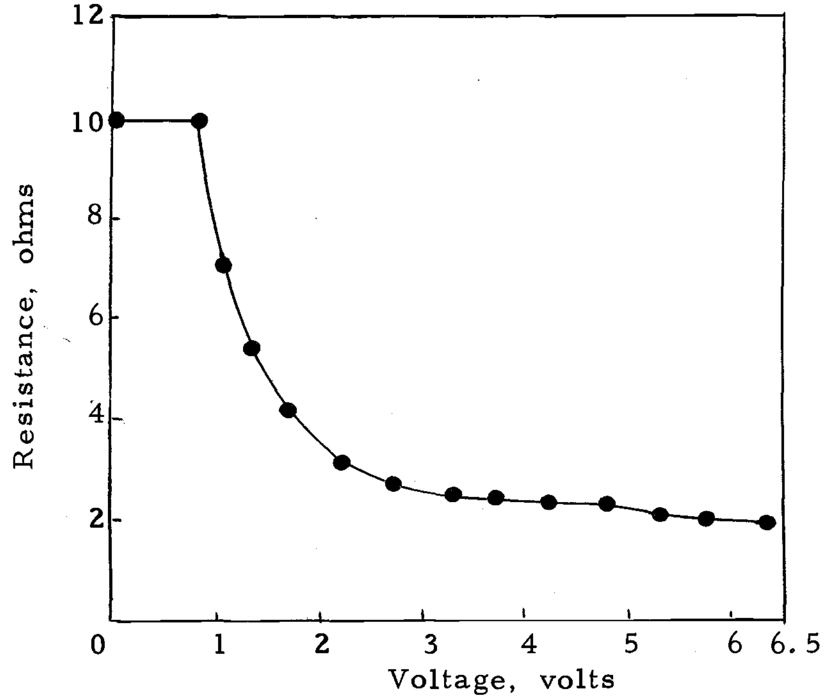


Figure 8. Functional model of an amplidyne.



Graph 6. Magnetizing curve of a control winding of an amplidyne.



Graph 7. Resistance of the quadrature winding of an amplidyne.

the function generators 1 and 2. The quadrature axis equivalent resistance which was found to be a function of the generator voltage E_{GAM1} is obtained from function generator 3. To implement the model the values of the constants and non-linear data were evaluated for the amplidyne through laboratory tests. The quadrature field winding resistance was found as follows:

The voltage was applied across the quadrature field winding of the amplidyne running at the constant speed. The current in the quadrature winding was recorded. The quadrature winding resistance was found by dividing the voltage by the current. The resistance was found to be the non-linear function of the voltage across quadrature winding as shown by graph 7 . This non-linear nature of the resistance is assumed to be caused by the commutator and brushes.

Determination of the amplidyne variables and parameters:

Specifications of the machine: General Electric Co.

Model 5AM 79AB 182

Control Field	Ohms $25^{o}C$	Max amp.
F1-F2	980	0.12
F3-F4	980	0.12
F5-F6	43	0.59
F7-F8	43	0.59

Input V 220
A 7.2 Cy 60
PH 3 WND IND

Output	KW 3.5		
	V 125	A	12

The following variables and parameters were found experimentally.

(1) The saturation characteristic for the control field winding which is shown on graph 6.

(2) Equivalent resistance of the quadrature winding vs. voltage across quadrature winding as shown on graph 7.

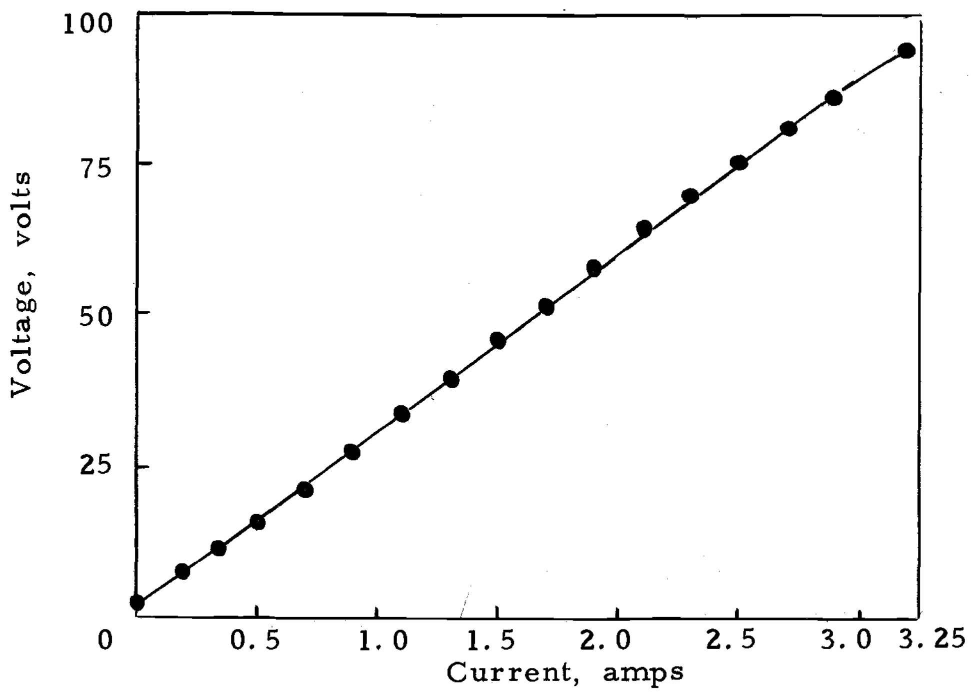
(3) The saturation characteristic of the quadrature winding as shown on graph 8.

The procedure for finding the saturation curve, inductance of the control field winding and quadrature winding is the same as discussed for the DC exciter. The resistance of the control field circuit was found by the ratio of field voltage to control field current.

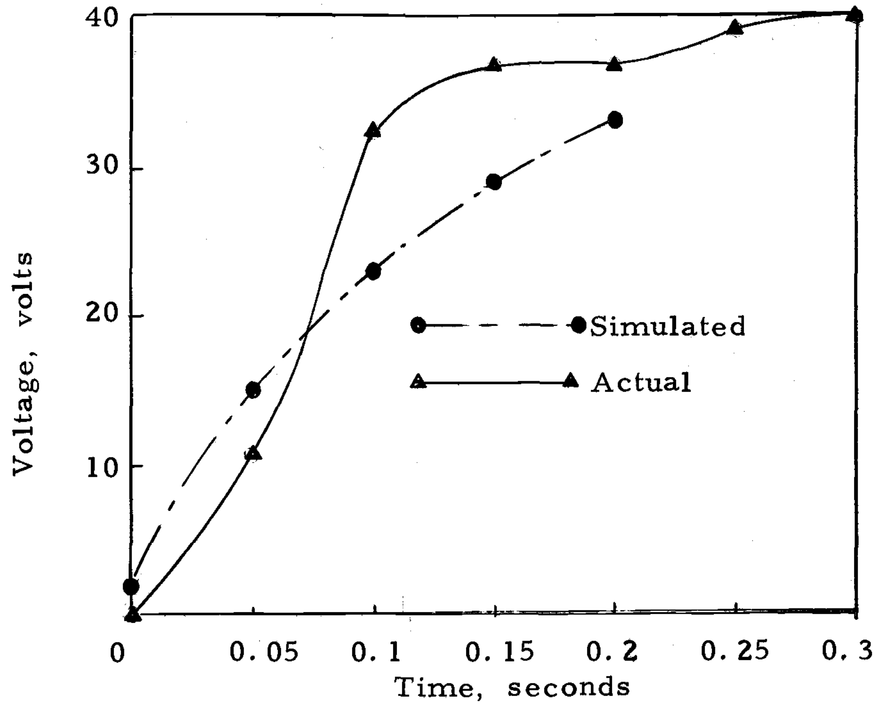
Digital Model of the Amplidyne

The digital model for the amplidyne was developed from the functional model shown in Figure 8. The flow chart and the listing of the program are given in Appendix B.

Graph 9 compares the actual build-up voltage of the amplidyne to the results of the simulation. It is observed from the graph that there is a significant difference between the simulated and



Graph 8. Magnetizing characteristics of an amplidyne (quadrature winding).



Graph 9. Build up voltage of an amplidyne.

actual response of the machine. This may be due to the following reasons:

In the derivation of the model the effects of the direct-axis compensating and commutative winding were neglected

Errors in the laboratory measurements of the equivalent resistance of the quadrature winding.

Operation of the amplidyne at the knee of the magnetising curve. (Note: In modeling the above system, the value of the quadrature winding inductance was increased from 0.1 to 0.2 to compensate for the error in the measurement of the inductance.)

Model of the AC Machine

Figure 9 schematically represents an open-circuited synchronous generator. The field circuit equations for an open-circuited AC generator are:

$$E_{TAC} = I_{AC} * R_{AC} + L_{AC}\left(\frac{dI_{AC}}{dt}\right)$$

where $R_{AC} = R_{VAC} + R_{FAC}$

Constant generator speed is assumed.

$$V_T = f\,(I_{AC})$$

$$L_{AC} = f(I_{AC})$$

In the above equations the r.m.s. value of voltage (V_T) is used and this function is shown on graph 10.

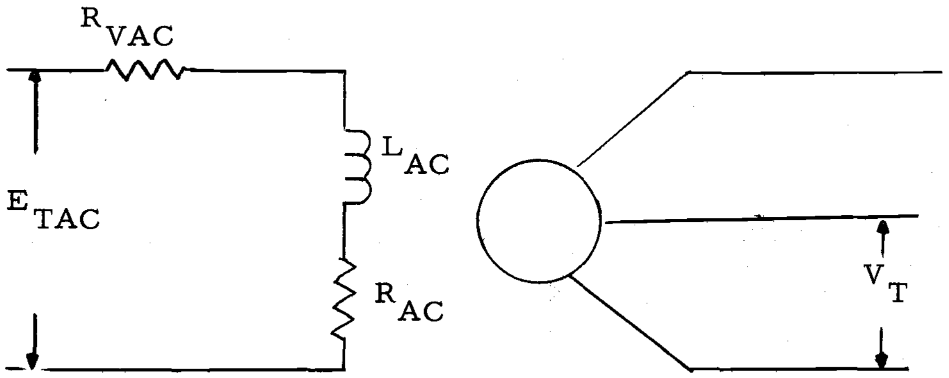


Figure 9. An open circuited synchronous generator.

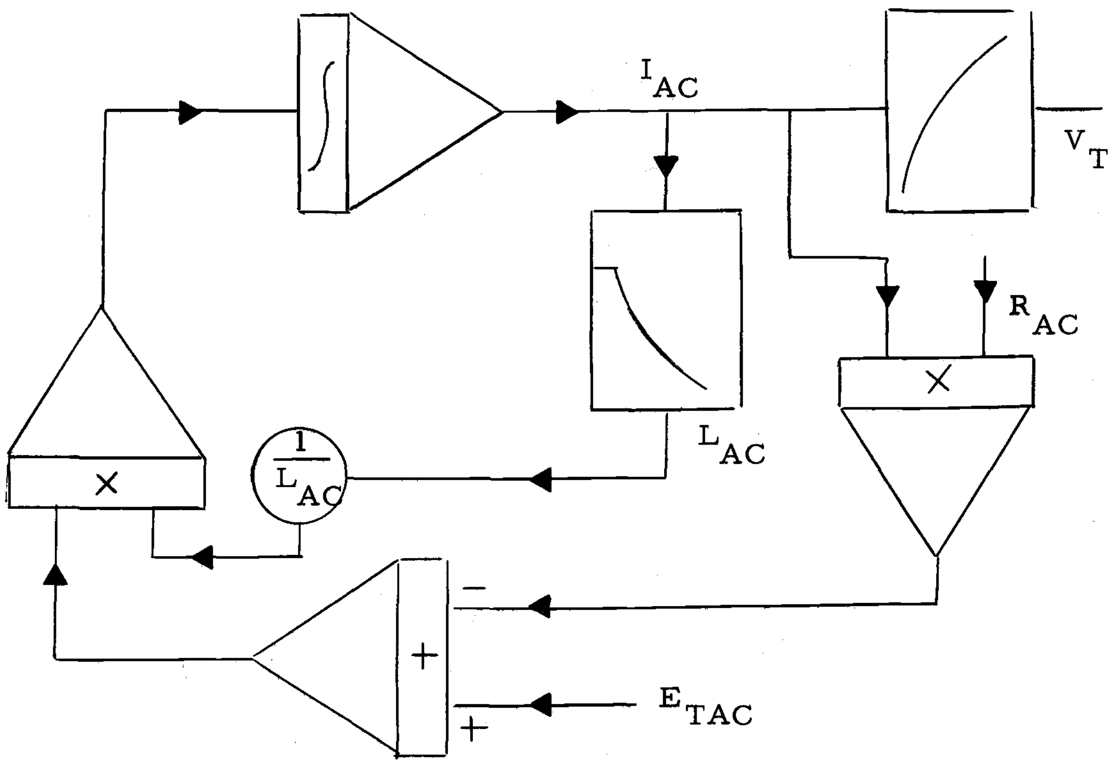


Figure 10. Functional model of a synchronous generator.

From the above equations we observe that the mathematical representation of the open circuited AC generator is equivalent to the separately excited DC generator. Hence, the functional model shown in Figure 10, is derived in the same manner as that of the DC machine.

Determination of the machine variables:

Specifications: General Electric Company. Alternating current generator. Model 12 G 688. Phase 3 Cycles 60 KVA 18.75 Volts 240 Amps 45 Speed 1200 r.p.m. Excitation volts 125 Amps 4.7 15 KW 0.8 Pf

The following variables were found experimentally:

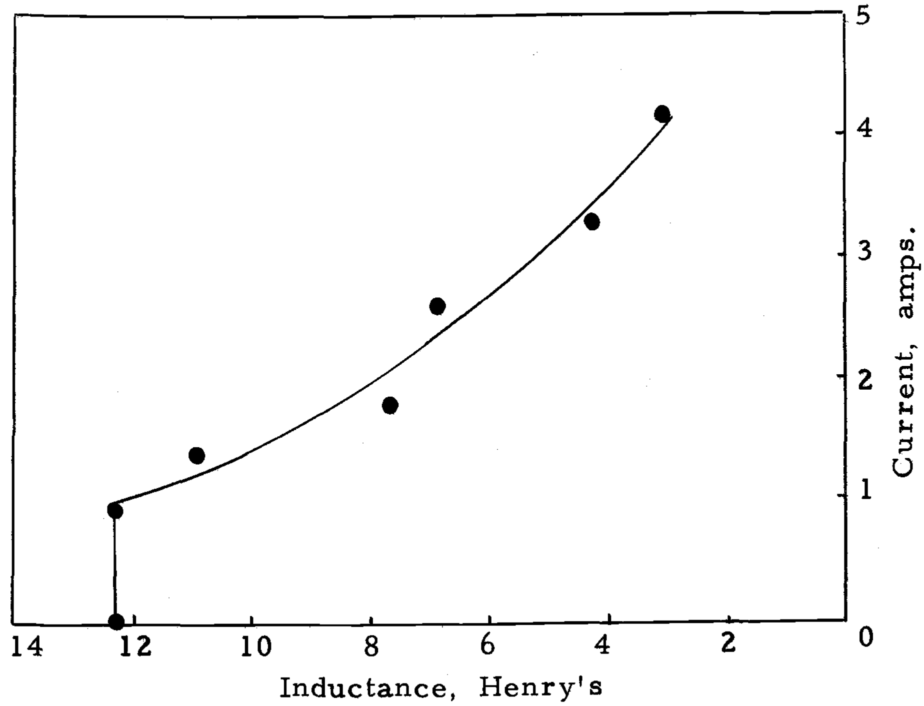
(1) Saturation characteristics shown on graph 10.

(2) Inductance vs. field current shown on graph 11.

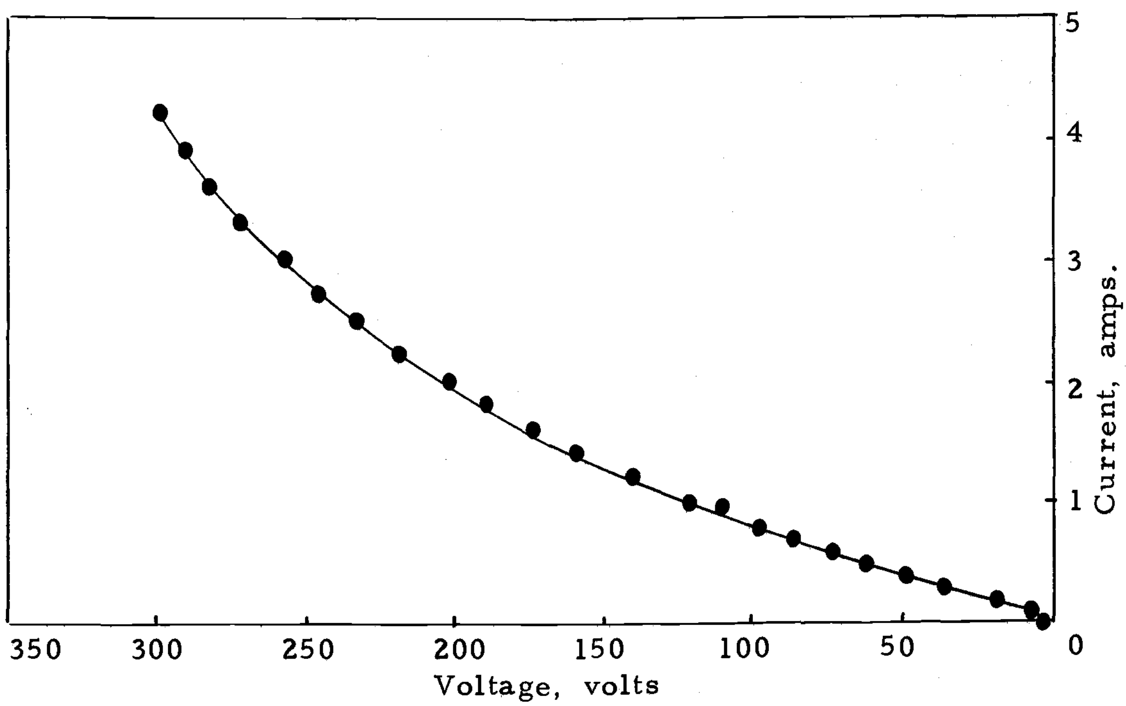
The resistance was evaluated for the particular voltage build up under consideration.

The Fortran program and block diagram for this model are given in Appendix B.

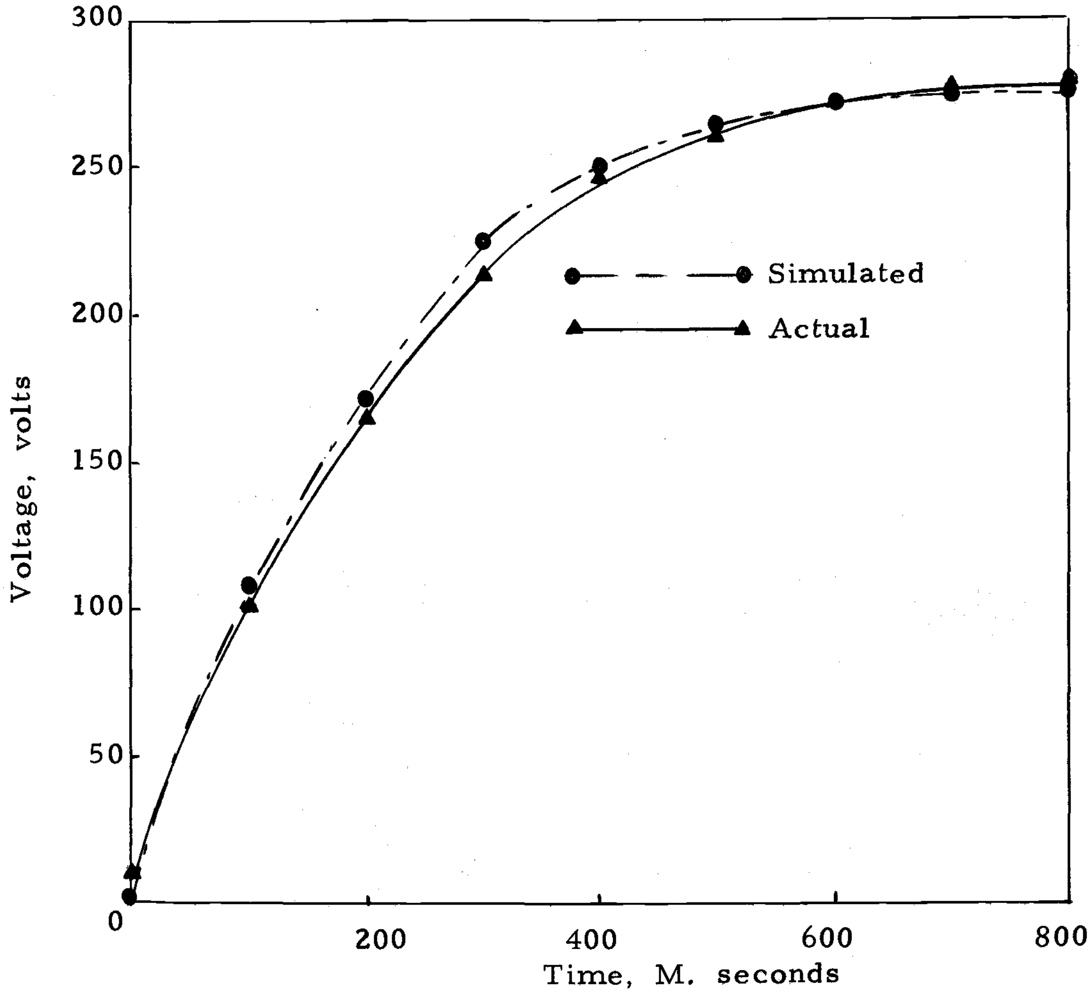
Graph 12 compares the results obtained from the digital model and from the experiment. The maximum percentage error for the simulated build-up voltage was found to be 6.9 which occurs at 100 msec. The difference between the curves in graph 12 may be due to the following:



Graph 11. Inductance of a synchronous machine.



Graph 10. Magnetizing curve of a synchronous machine.



Graph 12. Build up voltage of an open circuited AC machine.

(1) The leakage current loss was not taken into account in the model.

(2) Error in the inductance values due to the difficulty of digitizing the oscillogram.

Model of the Regulating System

Figure 1 shows the regulating section of the excitation system. This is the section where the output voltage of the AC generator is converted to a direct voltage. This direct voltage is applied to the magnetic coil of the silverstat regulator. The output resistance of the regulator is a non-linear function of the current in the magnetizing coil. Thus, direct voltage from rectifier 1 is a non-linear function of the output voltage of the AC machine. This rectified voltage is applied to one of the control field winding of the amplidyne in such a way that the mmf produced by this coil opposes the mmf produced by the other control field winding. The mmf in the latter is directly proportional to the reference voltage. The difference between the two mmf values produced the flux which is proportional to the error signal.

The inductance of the regulating section is very small in comparison to its resistance. So it was assumed that there is no time delay in this section of the system.

The model of the above system is developed in the following manner.

(a) The transformer and rectifier combination supplies a direct voltage to the silverstat regulator:

The output voltage from this rectifier is a non-linear function of the AC generator terminal voltage. This is represented by the function generator shown on graph 13.

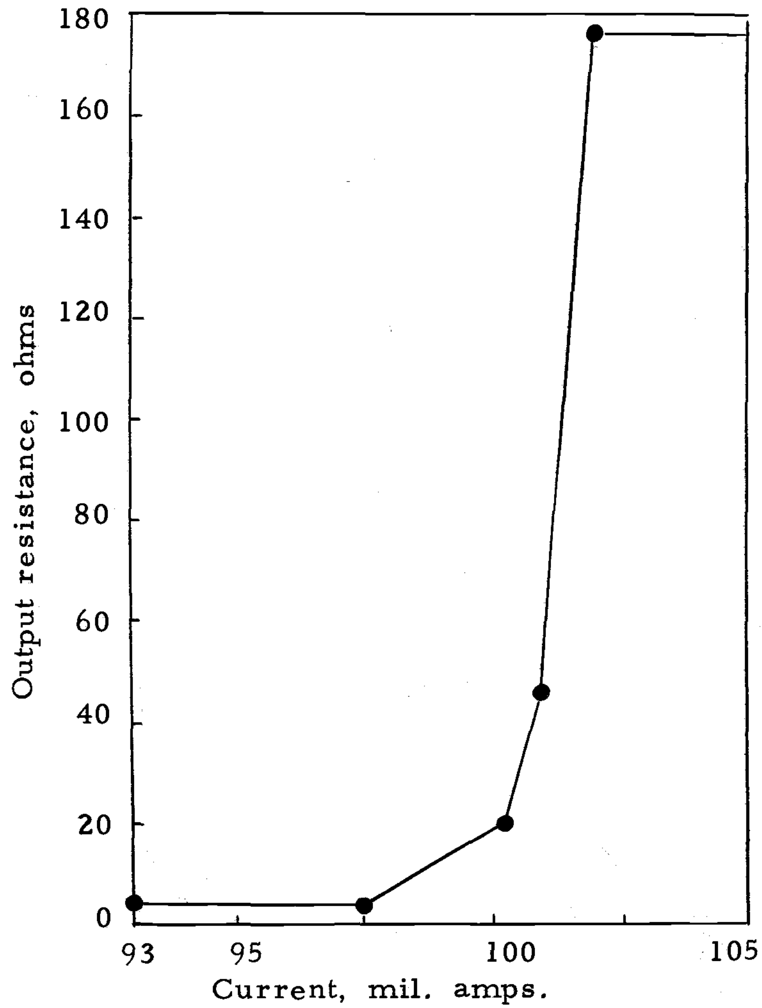
This function was generated by experimentally varying the input voltage from 100 volts to 300 volts of steps of 10 volts. Intermediate values can be determined by interpolation.

(b) The silver-state regulator:

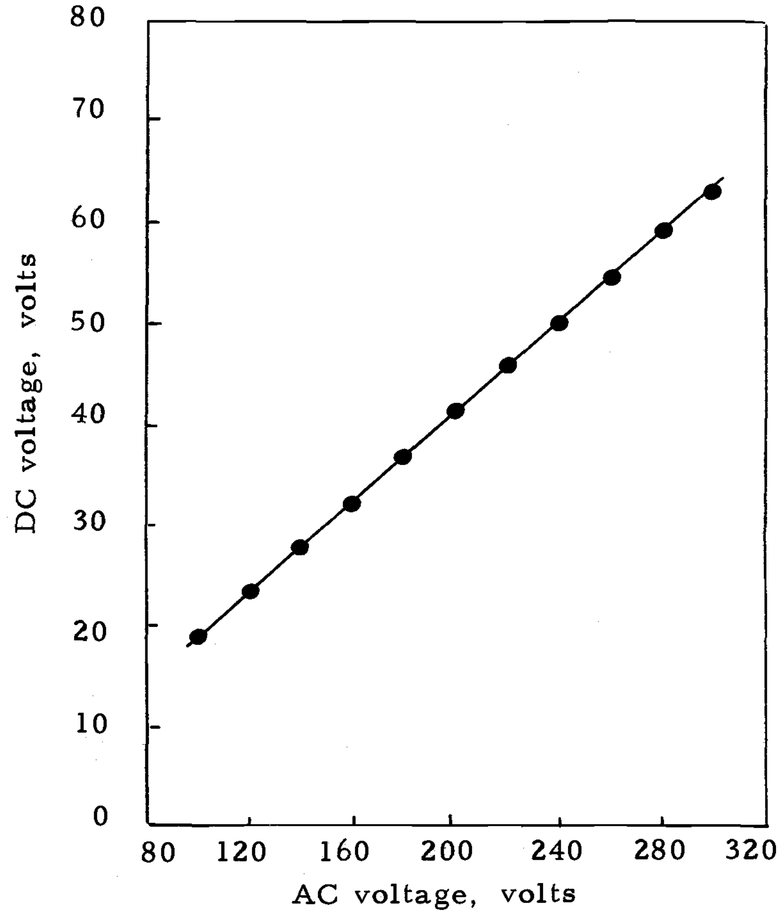
The output resistance of the regulator is non-linearily proportional to the input current of the magnetic coil. The variable resistor in series with the magnetic coil is adjusted to provide 98 ma in the circuit for the desired value of the terminal voltage. With reference to graph 14, this provides an operating point midway between the output resistance limits. In the model this is represented by a function generator.

(c) Rectifiers connected to the control field winding of the amplidyne.

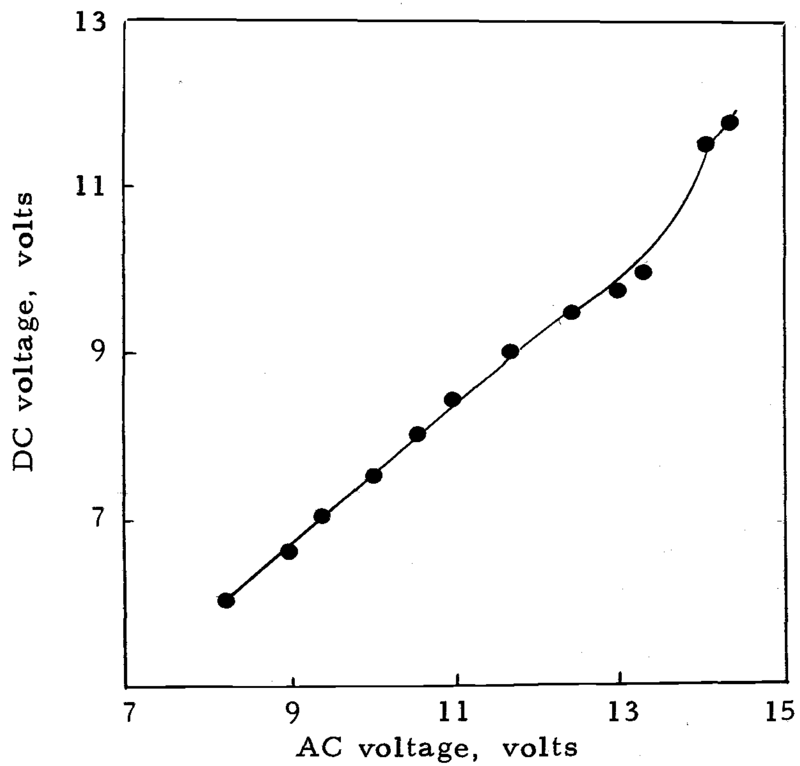
The function generator shown on graphs 15 and 16 represent the models of the rectifiers. It was observed in the experiment that load affects the rectifier output voltage. Therefore the output



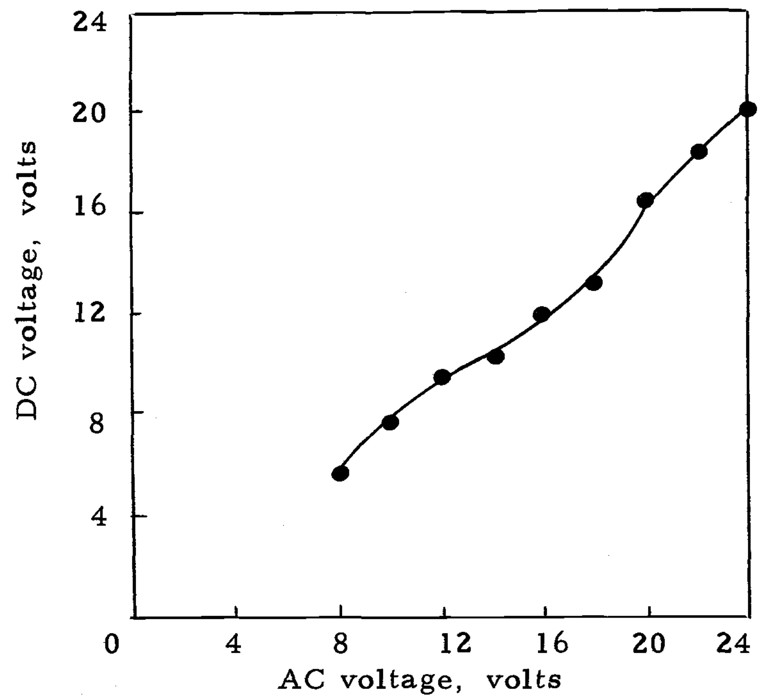
Graph 14. Function generator to represent a silverstat regulator.



Graph 13. Function generator for a rectifier and transformer combination.



Graph 15. Rectifier 1



Graph 16. Rectifier 2.

Function generator to represent the rectifiers.

voltage of the rectifier was recorded under a load of one ampere.

Model of the Complete Excitation System

The functional model of the complete excitation system is shown in Figure 11. This is obtained by combining the functional model of the DC machine, AC machine, amplidyne and the regulating system.

The Fortran program corresponding to this functional model of the system was run on the CDC 3300 computer at Oregon State University. The Fortran program for the model is given in Appendix B.

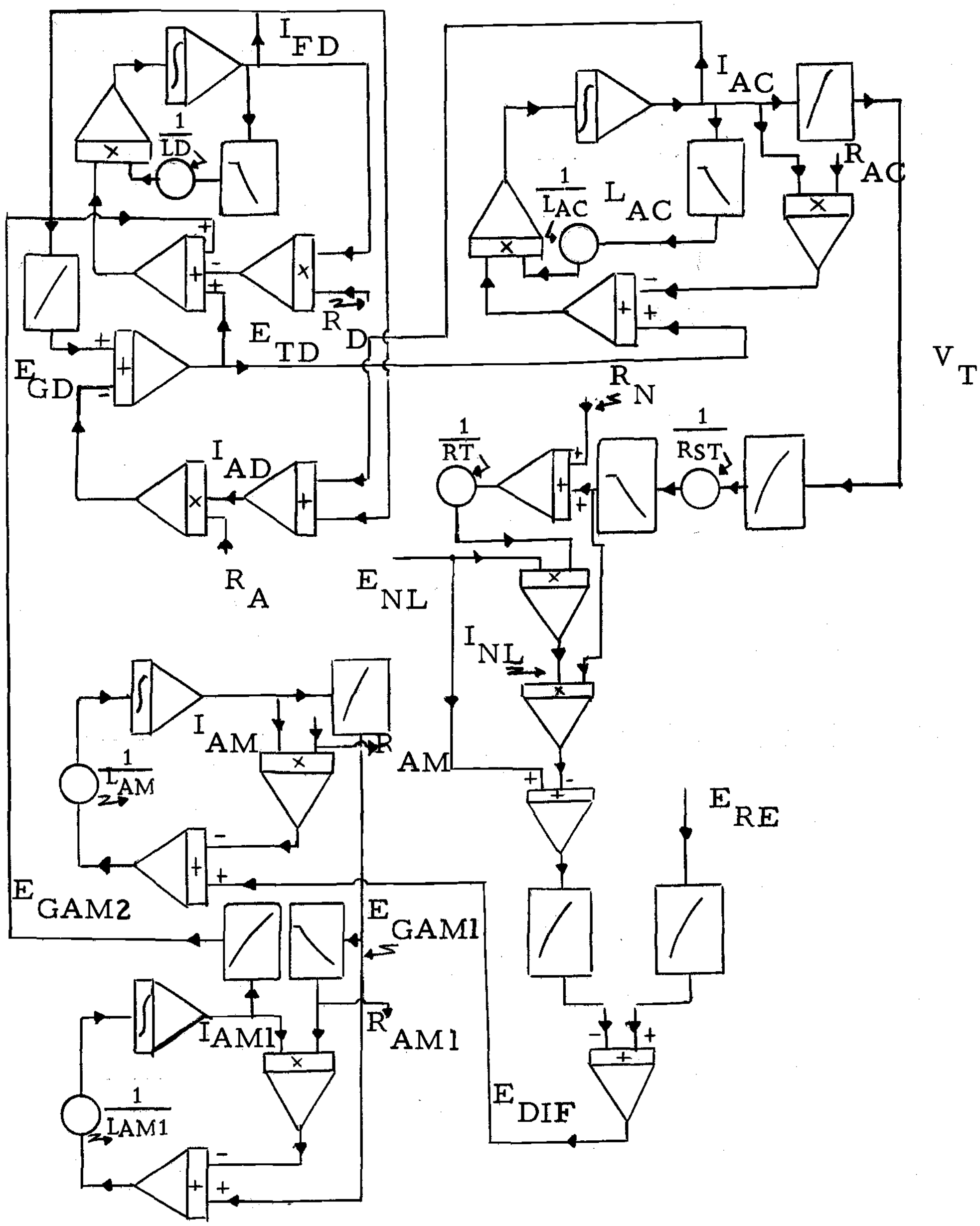


Figure 11. Functional model of an excitation system.

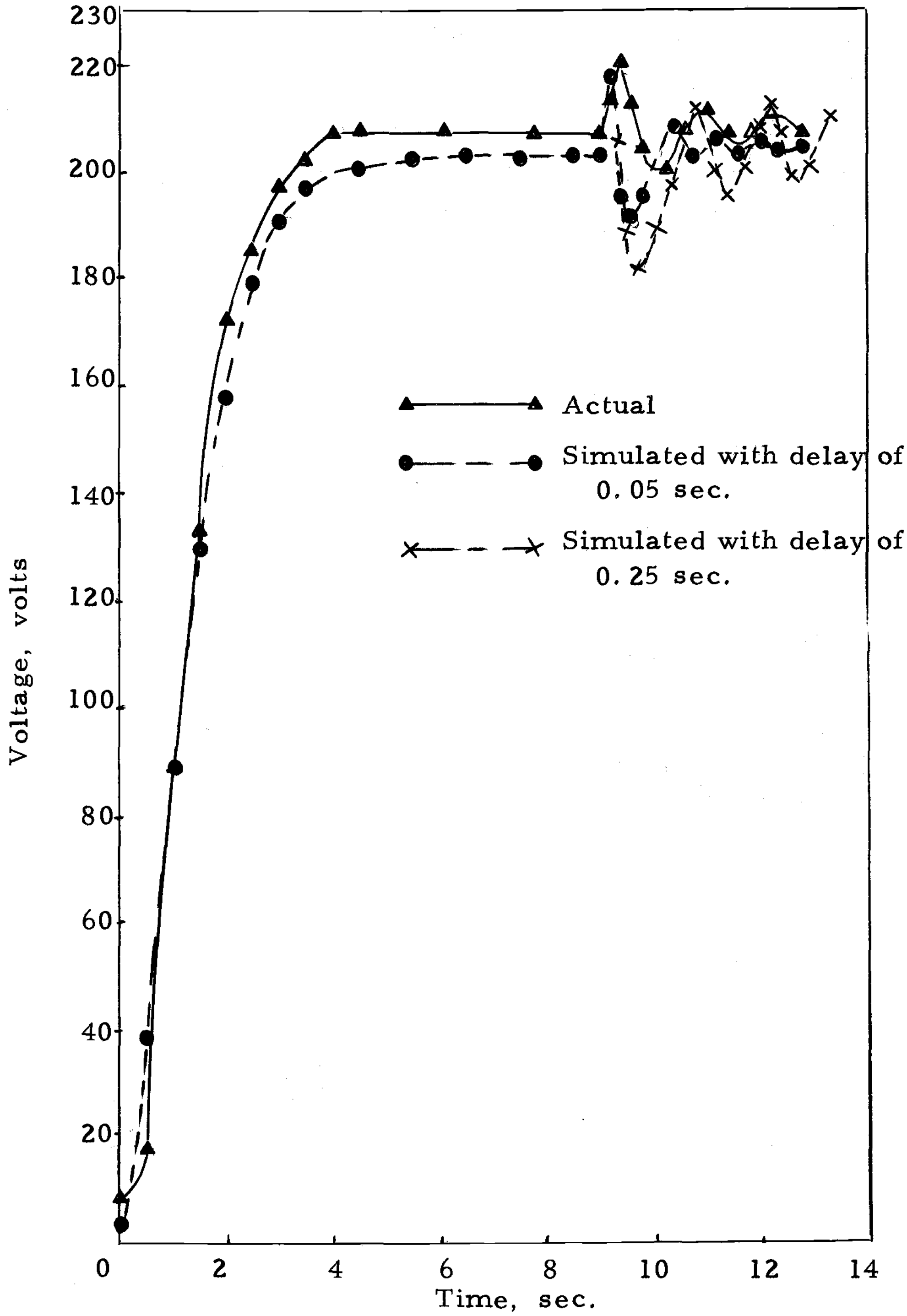
IV COMPARISON OF THE EXPERIMENTAL AND COMPUTER RESULTS OF THE COMPLETE EXCITATION SYSTEM

Graph 17 shows the steady state and transient response of the AC machine terminal voltage due to sudden change in the field resistance.

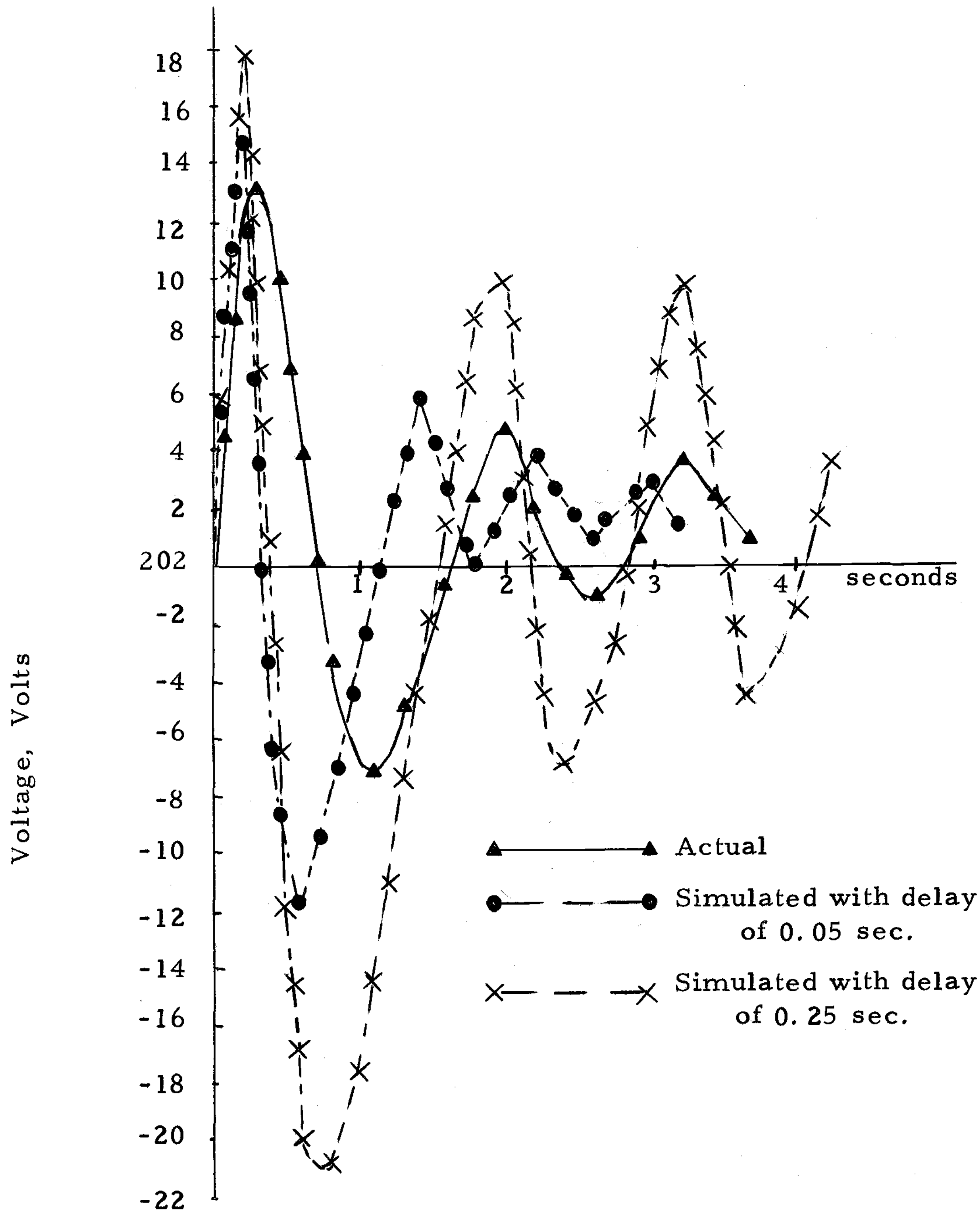
The digital model and the experimental system were both allowed to build up to a steady state terminal condition when started from initial or residual condition. A comparison of the final voltages indicated an error of 2.42% in the digital model output: the above error could have been caused by the small errors in the build-up voltages of the components of the system. The errors are amplified due to the numerical integration. The transient response of the model is noticeably different from the actual system. Graph 18 shows the transient response of the system assuming the steady state voltage is the same for the model and the actual system.

The difference in the transient response is due to the following reasons:

(1) In modeling the system it was assumed that the delay in the regulating components would not affect the response of the system. But from the results it was observed that any small delay can change the response of the system considerably, as shown in graph 18. The delay was added to the model of the silverstat



Graph 17. Response of complete AC excitation system (AC machine buildup voltage).



Graph 18. Transient response of the complete AC excitation system.

regulator. Even the incorporation of this delay did not produce the response in agreement with the actual response. The reason for this may be due to the fact that the regulator is a complicated electro-mechanical device, which even in its simplest form is a second order system with damping action. So, the exact model of this system is quite involved.

(2) In modeling the system the loading effects were neglected by assuming that the output voltages of the transformers and rectifiers remain constant. In the actual system the load currents change the output voltages which then affects the model response.

(3) It was also assumed that the input of the components is not affected by its own output. But in the physical system there is a feed-back from output to the input. This affects the performance of the components, which in turn affects the response of the system.

The errors due to the assumptions made in the model are small compared to the measurements taken in the laboratory. But the amplidyne, being an error sensitive device amplifies the small error considerably. The overall effect of all the above errors on the transient response of the digital models is also intensified considerably due to the amplidyne models whose transient response was shown to be considerably different.

V CONCLUSION

In this thesis an investigation has been made as to the feasibility of developing a simple digital model for an excitation system of a synchronous generator. The components in the excitation system are non-linear and their exact modeling is quite complicated and tedious. So, an attempt has been made to simplify the model of the individual conponents in order to study the overall performance of the system.

A laboratory experiment was set up to study the actual performance of the system. The experimental results are compared with those obtained from the model.

The steady-state response of the digital model of the excitation system are found to be in close agreement with actual system. However, due to certain assumptions made in the modeling, the transient response of the model is found to be quite different from the actual response. The model can be improved by taking into account the effects due to load and feed-back currents. Also, by incorporating a more elaborate model for the regulating system, the overall performance of the digital model can still be improved.

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APPENDIX

APPENDIX A

EXPERIMENT TO FIND MAGNETIZING CHARACTERISTIC AND FIELD RESISTANCE

Figure 12 shows the experimental schematic diagram to find the magnetizing characteristic and the field resistance of a DC machine.

A voltage is applied through a rheostat to the field of the DC machine which is run at constant speed. The resistance R is changed to obtain values of the voltages and current tabulated on pages 50 and 51.

Graph 1 shows the magnetizing curve. The shunt field resistance is equal to the voltage across shunt field winding divided by the shunt field current. The values are tabulated on page 51. The average value of the resistance is found to be 100.5 ohms.

EXPERIMENT TO MEASURE THE INITIAL VALUE OF THE INDUCTANCE

In an inductive circuit, when terminals are suddenly short circuited, the current is given by

$$i = I * e^{-(R/L)t}$$

where I = initial value of the current

L = inductance

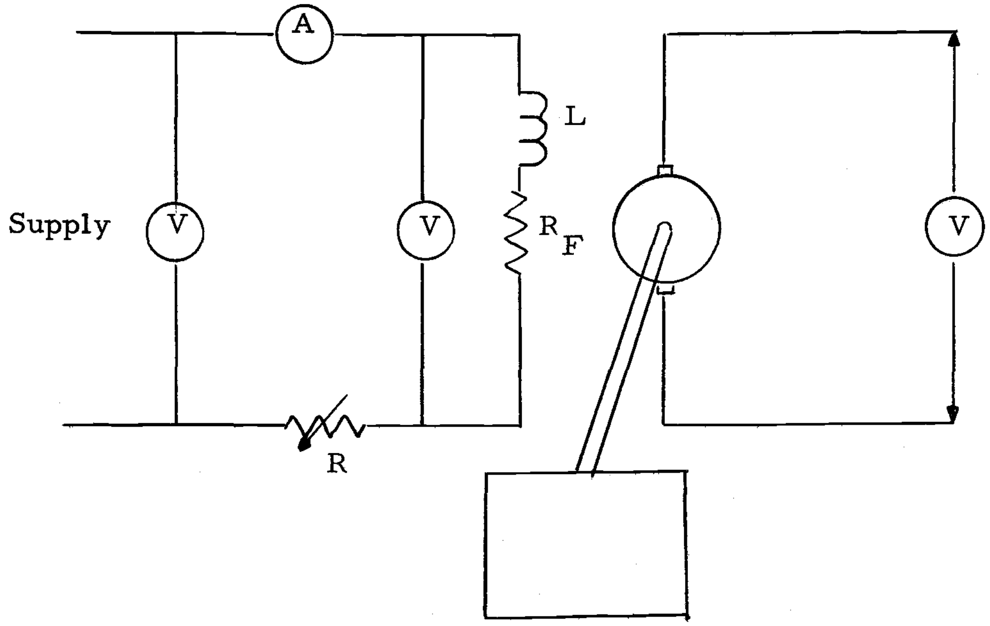


Figure 12. Experiment set up to find the magnetizing characteristic of a DC machine.

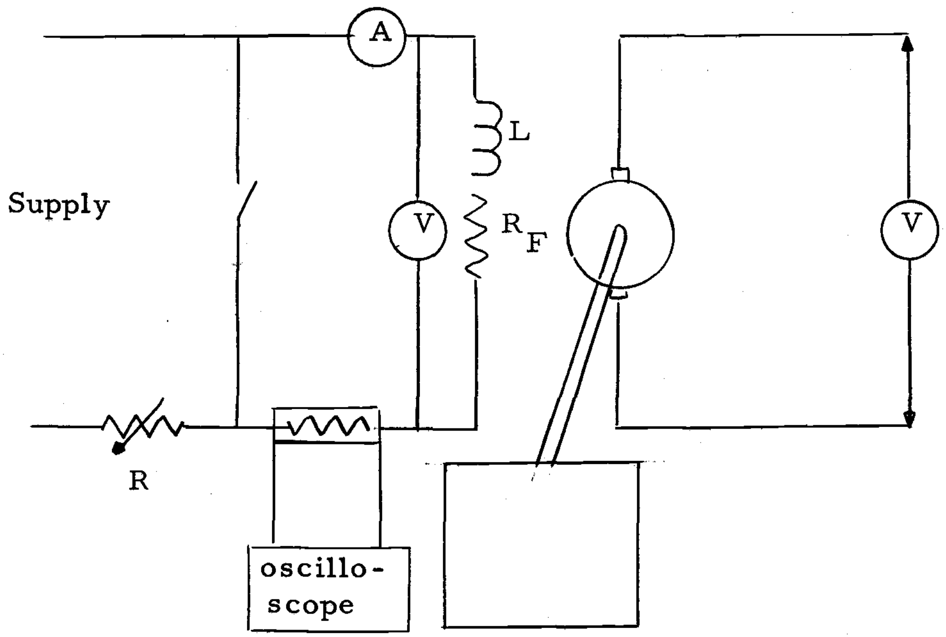


Figure 13. Experiment set up to find the inductance of a DC machine.

R = resistance

t = time

At the end of one time constant, i.e., $t=L/R$, the current decays to 36.8% of its initial value. If log i is plotted against time, the exponential curve becomes a straight line and from which the time constant of the circuit can be determined.

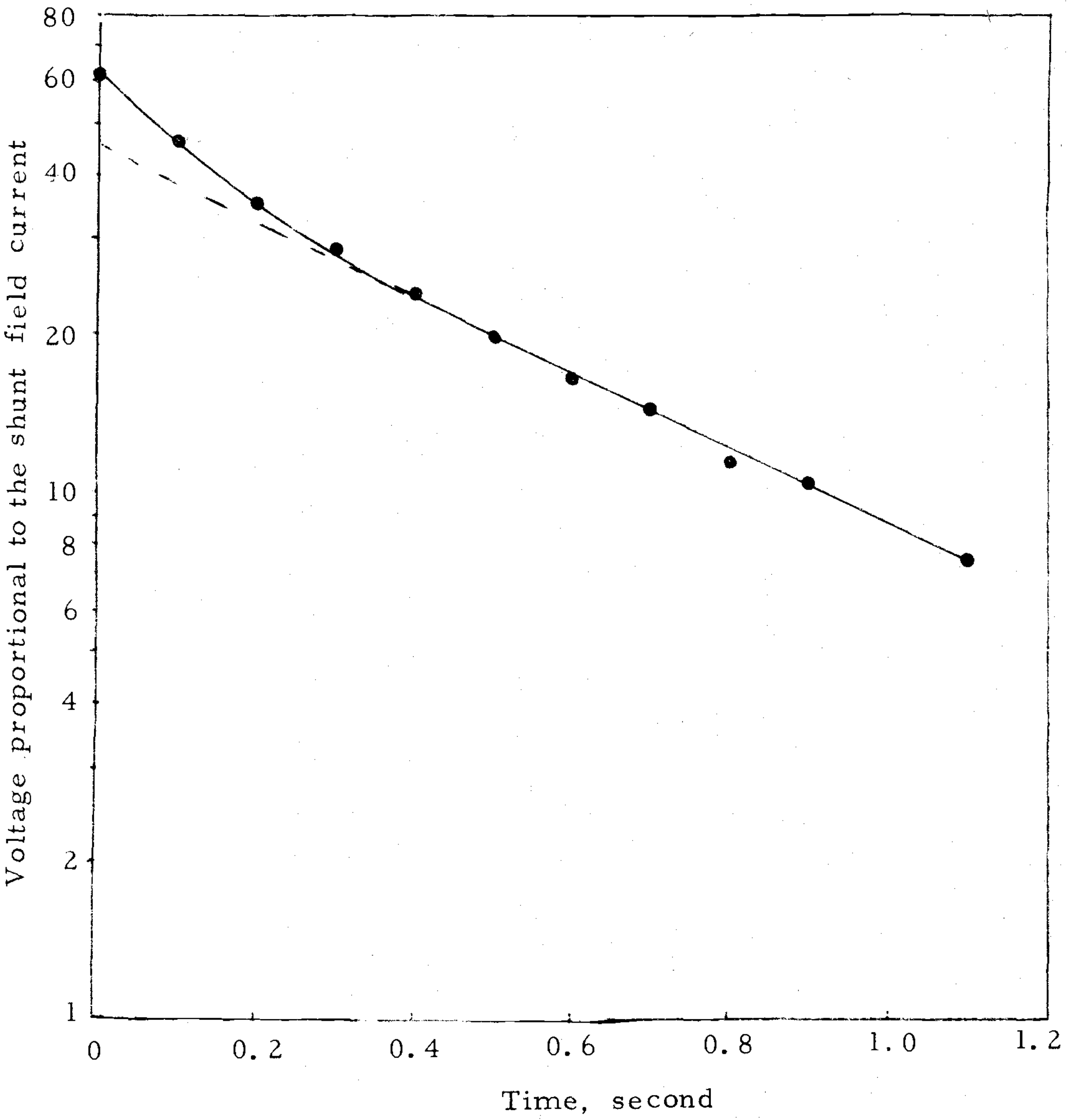
Figure 13 gives the experimental diagram to determine the decay of the current in the field winding of the DC machine.

When the switch is closed, the current starts to decay to zero. This was recorded on an oscilloscope and a picture of the decay was taken.

The value of the current vs. time was plotted on the semilog paper (graph 19). From the graph the time required for the current to decay to 36.8% of its initial value was found to be 0.61 seconds.

Using the formula $L=T/R$ value of the inductance was found to be 58.5 henrys.

This value of the inductance remain constant up to point (a) on the magnetising curve (graph 1). On the saturation part of the curve from point (a) to point (b) it is proportional to the slope of the curve, i.e., de/di*. Graph 2 gives the plot of the inductance vs. current.



Graph 19. Decay of the shunt field current.

*For a magnetic circuit we know

$$L = N \frac{d\phi}{di}$$

$$L \; \alpha \; \frac{d\phi}{di}$$

$$e \; \alpha \; \phi$$

$$L \; \alpha \; \frac{de}{di}$$

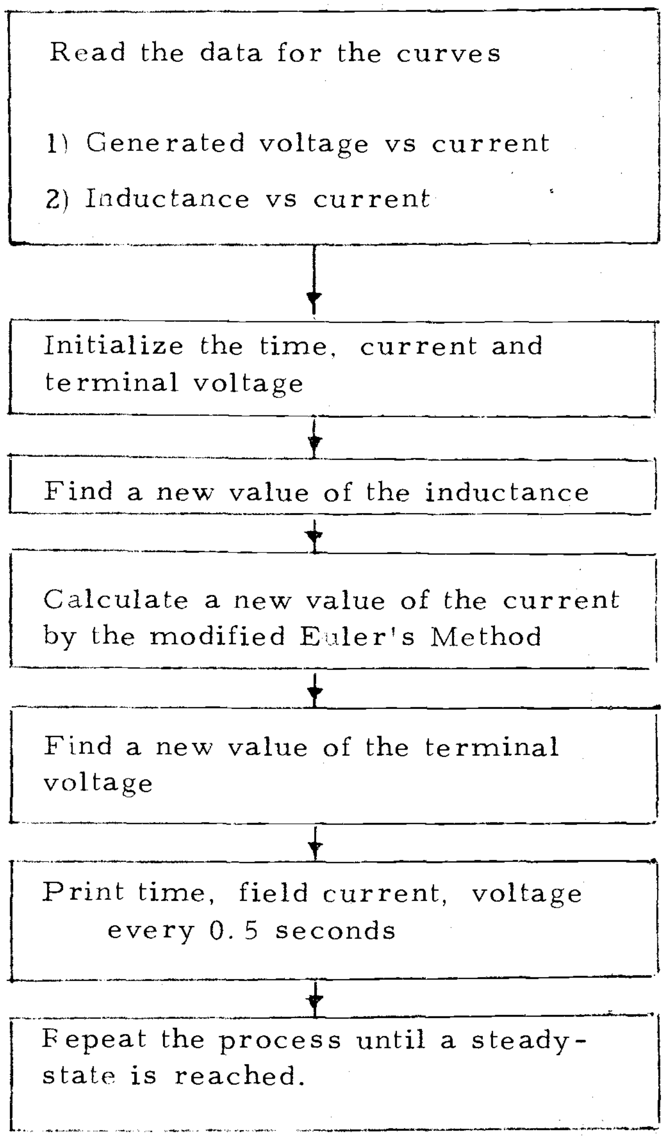
MAGNETIZING CHARACTERISTIC OF THE DIRECT CURRENT MACHINE

Shunt field current (amps)	Terminal voltage (volts)
0.0	3.5000
.0036	4.0500
.0104	4.7500
.0179	5.8000
.0240	6.7500
.0400	10.3000
.0600	14.2000
.0700	16.5000
.0900	20.7000
.1100	24.5000
.1200	27.0000
.1500	33.0000
.2000	43.0000
.2500	54.5000
.3000	65.2000
.3500	75.5000
.4000	86.0000
.4500	95.0000
.5000	103.5000
.5500	115.1000
.6000	118.0000
.6500	124.3000
.7000	130.2000
.7500	135.7000
.8000	140.5000
.8500	144.7000
.9000	148.5000
.9500	151.5000
1.0000	154.5000
1.1000	162.0000

SHUNT FIELD WINDING RESISTANCE

Voltage across shunt field winding (volts)	Shunt field current (amps)	Shunt field resistance (ohms)
15	0.15	100
19.5	0.2	97.5
29.8	0.3	99.3
40.3	0.4	100.75
50.5	0.5	101.25
61.2	0.6	102.0
71.0	0.7	101.5
80.0	0.8	100
90.5	0.9	100.5
101.0	1.0	101.0
112.5	1.1	102.3
	Average	100.5

BLOCK DIAGRAM FOR OPEN-CIRCUITED DIRECT-CURRENT MACHINE



```
OS3 FORTRAN  VERSION 3.0                04/27/72  1110
      PROGRAM DCMCL
      DIMENSION W(60),Z(60),A(60),F(15)
      DIMENSION DCC(60),DCL(60)
C     DIGITAL MODEL OF A OPEN CIRCUIT SELF-EXCITED
C     DIRECT CURRENT MACHINE
      READ 600,(W(I),Z(I),I=1,30)
  600 FORMAT(2F8.4)
      READ 610,(DCC(I),DCL(I),I=1,6)
  610 FORMAT(2F8.5)
      T=0.05
      LO=14
      LI=10
      NC=29
      NL=5
      ER=3.5
      D=0.0
      EG=ER
      FLX=D
      TT=0.0
      R=146.2/0.858
      PRINT 800,R
  800 FORMAT(2X,≠RESISTANCE OF FIELD WINDING =  ≠,
     3F7.3,≠ OHMS≠,///)
      PRINT 355
  355 FORMAT(5X,≠TIME≠,6X,≠FIELD≠,5X,≠BUILD-UP≠/
     15X,≠IN≠,8X,≠CURRENT≠,3X,≠VOLTAGE≠/
     25X,≠SECONDS≠,3X,≠IN AMPS≠,3X,≠IN VOLTS≠,///)
      PRINT 100,TT,D,EG
      DO 25 K=1,LO
      TT=TT+0.5
      DO 20 J=1,LI
      CALL FUNC (NL,DCC,DCL,D,FL)
      DY1=(EG-D*R)/FL
      D=FLX+DY1*T
      DO 10 I=1,10
      CALL FUNC(NL,DCC,DCL,D,FL)
      CALL FUNC(NC,Z,W,D,EG)
      DY2=(EG-D*R)/FL
      F(I)=FLX+(DY1+DY2)*T/2.0
      D=F(I)
      IF(I.LT.2)  GO TO 10
      IF(ABS(F(I)-F(I-1)).LT.0.001) GO TO 15
   10 CONTINUE
   15 FLX=D
      CALL FUNC(NC,Z,W,D,EG)
   20 CONTINUE
      PRINT 100,TT,D,EG
  100 FORMAT(5X,F4.1,6X,F6.4,4X,F7.3,/)
   25 CONTINUE
      END
```

Fortran Program for the open circuited DC machine

RESISTANCE OF FIELD WINDING = 170.396 OHMS

TIME IN SECONDS	FIELD CURRENT IN AMPS	BUILD-UP VOLTAGE IN VOLTS
0	0	3.500
.5	.0253	7.000
1.0	.0533	12.855
1.5	.0925	21.151
2.0	.1465	32.375
2.5	.2180	47.095
3.0	.3257	70.514
3.5	.4734	98.826
4.0	.6576	125.220
4.5	.7880	139.410
5.0	.8355	143.529
5.5	.8460	144.380
6.0	.8480	144.543
6.5	.8484	144.573
7.0	.8485	144.579

Results of Computer Simulation for the open circuited DC machine

BLOCK DIAGRAM FOR THE DC MACHINE WITH LOAD

Read the data for the curves

1) Generated voltage vs field current
2) Inductance vs field current

↓

Initialize time, currents, voltages and counters

↓

Print load resistance, field resistance and headings

↓

Calculate a new load current and the armature current

↓

Find a new value of the inductance

↓

Calculate a new value of the field current by the modified Euler Method

↓

Find a new value of the terminal voltage

↓

Print time, field current, terminal voltage and load current every 0.5 seconds

↓

Repeat the process until a steady-state is reached

↓

Repeat the above process for two different values of the field resistance.

```
      OS3 FORTRAN VERSION 3.0                    04/27/72  2136
            PROGRAM DCMCL
            REAL IA,IL
            DIMENSION W(30),Z(30),A(30) ,F(15)
            DIMENSION RS(5),DCC(10),DCL(10),RM(5)
      C     DIGITAL MODEL OF DIRECT CURRENT MACHINE WITH LOAD
            READ 600,(W(I),Z(I),I=1,30)
        600 FORMAT(2F8.4)
            READ 610,(DCC(I),DCL(I),I=1,6)
        610 FORMAT(2F8.5)
            T=0.05
            LI=10
            LO=14
            NC=29
            NL=5
            RA=0.42
            RS(1)=140.5/0.823
            RM(1)=140.5/4.85
            RS(2)=132.5/0.773
            RM(2)=132.5/10.1
            ER=3.5
            DO 900 MS=1,2
            R=RS(MS)
            RL=RM(MS)
            PRINT 800,R,RL
        800 FORMAT(2X,≠RESISTANCE OF FIELD WINDING  = ≠,
           3F7.3,≠ OHMS≠/ 2X,≠LOAD RESISTANCE  =≠,13X,F7.3,≠ OHMS≠,///)
            PRINT 355
        355 FORMAT(5X,≠TIME≠,6X,≠FIELD≠,5X,≠BUILD-UP≠,3X,≠LOAD≠/
           15X,≠IN≠,6X,≠CURRENT≠,3X,≠VOLTAGE≠,4X,≠CURRENT≠/
           25X,≠SECONDS≠,3X,≠IN AMPS≠,3X,≠IN VOLTS≠,3X,≠IN AMPS≠,///)
            IL=0.0
            IA=0
            TT=0.0
            D=0.0
            FLX=D
            EG=ER
            ET=EG
            PRINT 100,TT,D,ET,IL
            DO 25 K=1,LO
            TT=TT+0.5
            DO 20 J=1,LI
            IL=ET/RL
            IA=D+IL
            CALL FUNC(NL,DCC,DCL,D,FL)
            DY1=(EG-IA*RA-R*D)/FL
            D=FLX+DY1*T
            DO 10 I=1,10
            CALL FUNC(NL,DCC,DCL,D,FL)
            CALL FUNC(NC,Z,W,D,EG)
            ET=EG-IA*RA
            IL=ET/RL
            IA=D+IL
            DY2=(EG-IA*RA-R*D)/FL
            F(I)=FLX+(DY1+DY2)*T/2.0
            D=F(I)
            IF(I.LT.2)  GO TO 10
            IF(ABS(F(I)-F(I-1)).LT.0.001) GO TO 15
         10 CONTINUE
         15 FLX=D
            IF(D.GT.1.1) GO TO 950
            CALL FUNC(NC,Z,W,D,EG)
            ET=EG-IA*RA
         20 CONTINUE
            PRINT100 ,TT,D,ET,IL
        100 FORMAT(5X,F4.1,6X,F6.4,4X,F7.3,4X,F6.3,/)
         25 CONTINUE
        950 PRINT 360
        360 FORMAT(1H1)
        900 CONTINUE
            END
```

Fortran Program for the DC machine with load

RESISTANCE OF FIELD WINDING = 170.717 OHMS
LOAD RESISTANCE = 28.969 OHMS

TIME IN SECONDS	FIELD CURRENT IN AMPS	BUILD-UP VOLTAGE IN VOLTS	LOAD CURRENT IN AMPS
0	0	3.500	0
.5	.0247	6.764	.234
1.0	.0508	12.168	.420
1.5	.0861	19.590	.676
2.0	.1332	29.367	1.014
2.5	.1947	41.225	1.423
3.0	.2802	60.037	2.072
3.5	.4015	84.881	2.930
4.0	.5560	113.790	3.928
4.5	.7032	128.410	4.433
5.0	.7842	136.737	4.720
5.5	.8105	139.065	4.800
6.0	.8168	139.603	4.819
6.5	.8182	139.722	4.823
7.0	.8185	139.748	4.824

Results of Computer Simulation for the DC machine with load of 4.85 Amps

RESISTANCE OF FIELD WINDING = 171.410 OHMS
LOAD RESISTANCE = 13.119 OHMS

TIME IN SECONDS	FIELD CURRENT IN AMPS	BUILD-UP VOLTAGE IN VOLTS	LOAD CURRENT IN AMPS
0	0	3.500	0
.5	.0239	6.518	.497
1.0	.0480	11.455	.873
1.5	.0793	17.897	1.364
2.0	.1195	25.990	1.981
2.5	.1721	36.120	2.753
3.0	.2370	49.799	3.796
3.5	.3306	69.157	5.271
4.0	.4504	91.925	7.007
4.5	.5952	113.869	8.679
5.0	.7014	126.028	9.606
5.5	.7567	131.845	10.050
6.0	.7764	133.710	10.192
6.5	.7821	134.230	10.232
7.0	.7836	134.370	10.243

Results of Computer Simulation for the DC machine with load of 10.1 Amps

BLOCK-DIAGRAM FOR THE AMPLIDYNE

Read data for the curves

1) Terminal voltage of the quadrature winding vs current in the control field winding
2) Terminal voltage of the armature vs quadrature winding current
3) Terminal voltage of the quadrature winding vs resistance

↓

Initialize currents, voltages and counters

↓

Calculate the current in the control field winding by the modified Euler Method

↓

Find the terminal voltage of the quadrature winding
Find the resistance of the quadrature winding

↓

Calculate the current in the quadrature winding by the modified Euler Method

↓

Find the terminal voltage of the amplidyne

↓

Print time, control field winding resistance, terminal voltage of quadrature winding, quadrature winding current and terminal voltage of amplidyne

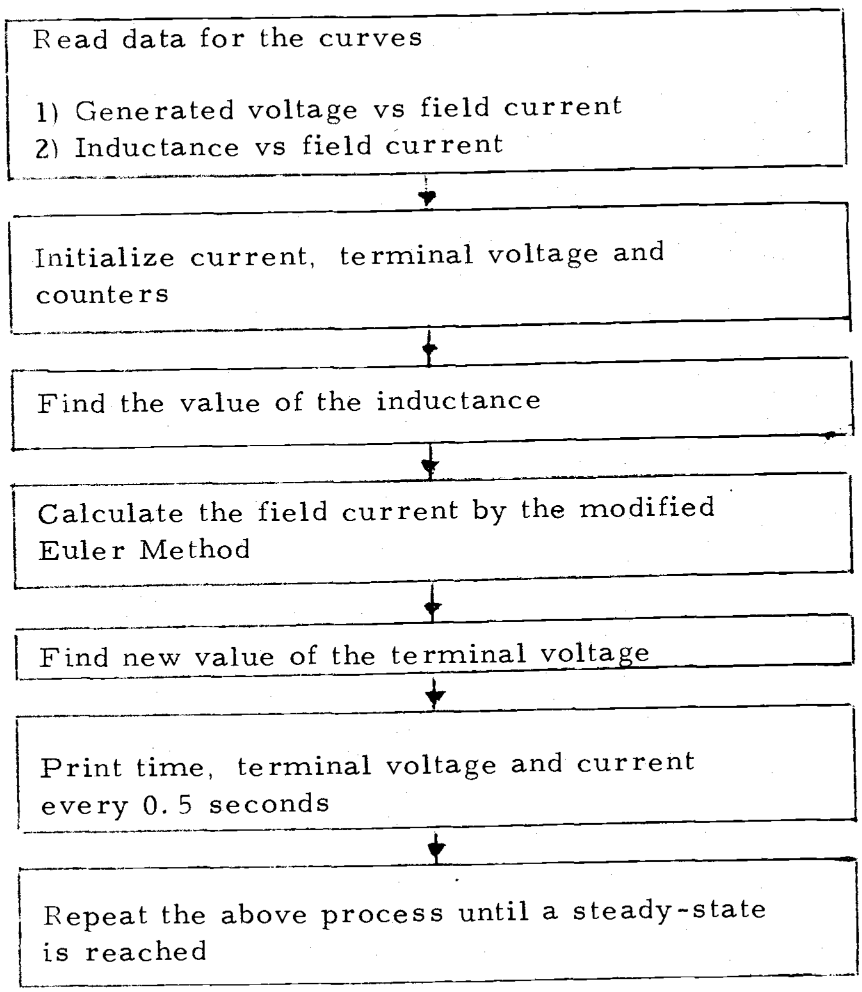
↓

Repeat the process until a steady-state is reached.

```
OS3 FORTRAN  VERSION 3.0               08/09/72  2122
      PROGRAM AMDYN
      DIMENSION ACO(60),AVO(60),FAM(60),A(60)
      DIMENSION ACQ(60),AVQ(60),AET(60),R(60)
      READ 305,(ACO(K),AVO(K),K=1,29)
      READ 305,(ACQ(J),AVQ(J),J=1,35)
      READ 305,(AET(N),R(N),N=1,35)
  305 FORMAT(2F5.2)
      ET1=13.8
      RAM1=ET1/0.11
      NQ=34
      NA=28
      FLAM1=0.176
      FLAM2=0.25
      CAM1=0.0
      CAM2=0.0
      DASM1=0.0
      DASM2=0.0
      TT=0.0
      T=0.0
      L4=1
      L3=1
      PRINT 322,RAM1
  322 FORMAT(5X,≠RESISTANCE OF CONTROL WINDING IS ≠,F8.4,///)
      PRINT 356
  356 FORMAT(5X,≠TIME≠,6X,≠CONTROL≠,3X,≠VOLTAGE≠,6X,≠CURRENT≠
     1,6X,≠OUTPUT≠/
     25X,≠IN≠,8X,≠FIELD≠,5X,≠ACROSS≠,7X,≠IN≠,11X,≠VOLTAGE≠/
     35X,≠SECONDS≠,3X,≠CURRENT≠,3X,≠QUADRATURE≠,3X,≠QUADRATURE≠/
     425X,≠WINDING≠,6X,≠WINGING≠,///)
      DO 265 MH=1,2
      DO 220 M=1,L4
      DO 225 N=1,L3
      CALL INT(ET1,CAM1,RAM1,FLAM1,DASM1,    T)
      CALL FUNC(NA,ACO,AVO,CAM1,ET2)
      CALL FUNC(NQ,AET,R,ET2,RAM2)
      CALL INT(ET2,CAM2,RAM2,FLAM2,DASM2,    T)
  225 CONTINUE
      CALL FUNC(NQ,ACQ,AVQ,CAM2,EBA)
      PRINT 230,TT,CAM1,ET2,CAM2,EBA
  230 FORMAT(5X,F5.3,5X,F6.4,4X,F6.3,7X,F7.4,6X,F7.3)
      TT=TT+0.05
  220 CONTINUE
      T=0.001
      L3=50
      L4=10
  265 CONTINUE
      END
```

Fortran Program for the amplidyne

BLOCK-DIAGRAM FOR THE AC MACHINE



```
OS3 FORTRAN  VERSION 3.0                05/08/72  2149
      PROGRAM ACOPC
      DIMENSION S1(50),T1(50),FA(20) ,A(60)
      DIMENSION XL(10),YL(10)
C     DIGITAL MODEL OF OPEN CIRCUIT A.C.MACHINE
      READ 700, (S1(NI),T1(NI),NI=1,43)
  700 FORMAT( 16F5.2)
      READ 710,(XL(I),YL(I),I=1,7)
  710 FORMAT(2F8.5)
      PRINT 325
  325 FORMAT(5X,≠FIELD RESISTANCE = 35.9≠,///)
      PRINT 300
  300 FORMAT(5X,≠TIME≠,6X,≠FIELD≠,5X,≠BUILD UP≠/5X,≠IN≠,8X,≠CURRENT≠,3X,
     1 ≠VOLTAGE≠/5X,≠SECONDS≠,3X,≠IN AMPS≠,3X,≠IN VOLTS≠//)
      RL=35.9
      CA=0.0
      L1=1
      L2=1
      TT=0.0
      DAS=0.0
      NC=42
      NA=6
      T=0.0
      ET=125.0
      DO 165 MY=1,2
      DO 125 N=1,L1
      DO 120 M=1,L2
      CALL FUNC(NA,XL,YL,CA,FLA)
      DYA1=(ET-CA*RL)/FLA
      CA=DAS+DYA1*T
      DO 110 L=1,10
      CALL FUNC(NA,XL,YL,CA,FLA)
      DYA2=(ET-CA*RL)/FLA
      FA(L)=DAS+(DYA1+DYA2)*T/2.0
      CA=FA(L)
      IF(L.LT.2) GO TO 110
      IF(ABS(FA(L)-FA(L-1)).LT.0.001) GO TO 115
  110 CONTINUE
  115 DAS=CA
  120 CONTINUE
      CALL FUNC(NC,S1,T1,CA,EB)
      PRINT 130,TT,CA,EB
  130 FORMAT(5X,F3.1,8X,F4.2,6X,F7.2,/)
      TT=TT+0.1
  125 CONTINUE
      L1=10
      L2=10
      T=0.01
  165 CONTINUE
      END
```

Fortran Program for the AC machine

FIELD RESISTANCE = 35.9

TIME IN SECONDS	FIELD CURRENT IN AMPS	BUILD UP VOLTAGE IN VOLTS
0	0	2.00
.1	.88	108.47
.2	1.60	175.99
.3	2.33	225.51
.4	2.81	250.49
.5	3.14	264.24
.6	3.33	273.03
.7	3.42	276.55
.8	3.46	277.71
.9	3.47	278.17
1.0	3.48	278.36

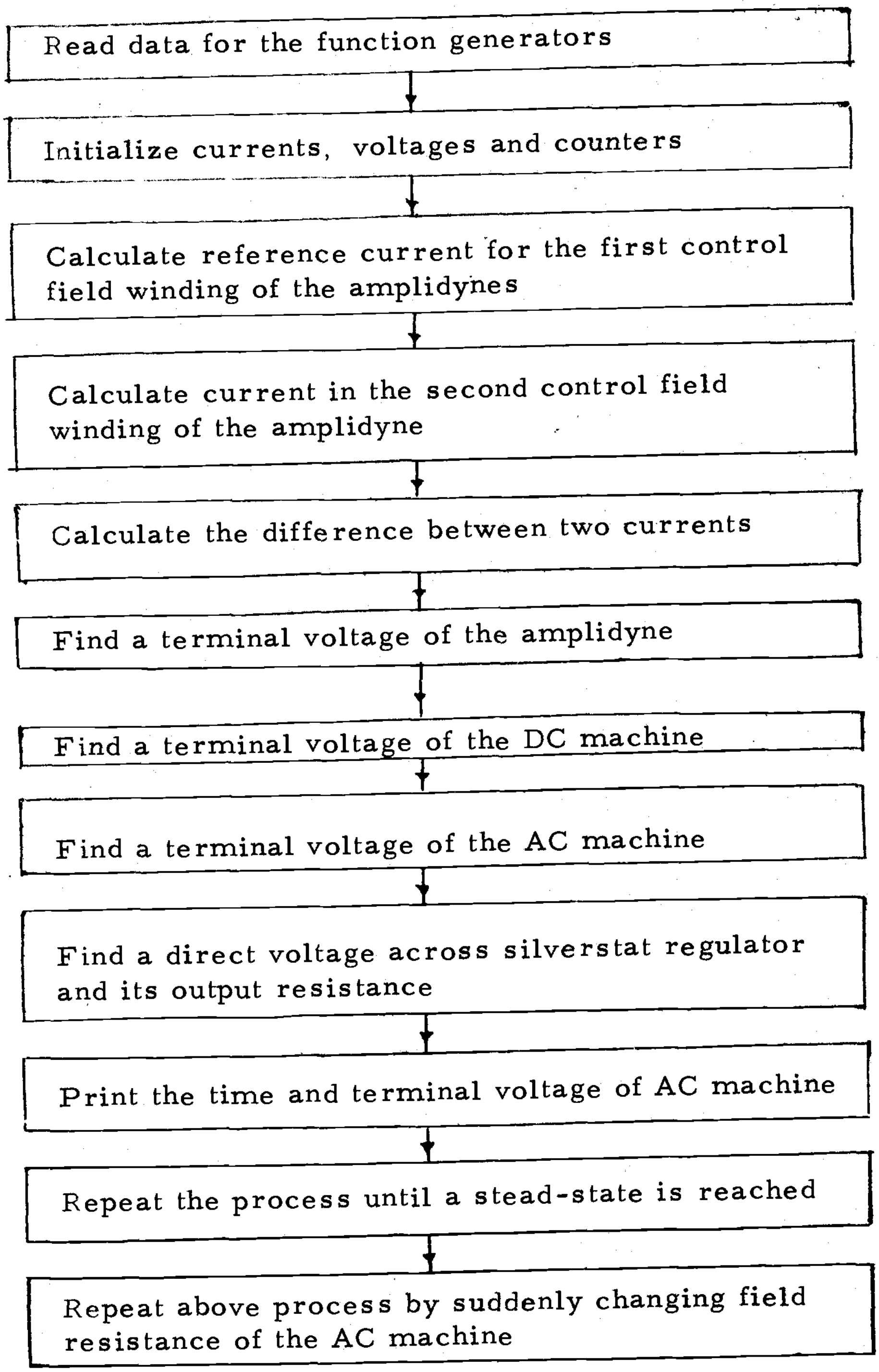
Results of Computer Simulation for the AC machine

RESISTANCE OF CONTROL WINDING IS 125.4545

TIME IN SECONDS	CONTROL FIELD CURRENT	VOLTAGE ACROSS QUADRATURE WINDING	CURRENT IN QUADRATURE WINGING	OUTPUT VOLTAGE
0	0	.460	0	2.000
.050	.1100	3.200	.4917	15.142
.100	.1100	3.200	.7956	23.078
.150	.1100	3.200	.9777	29.907
.200	.1100	3.200	1.0868	33.215
.250	.1100	3.200	1.1523	35.096
.300	.1100	3.200	1.1915	36.244
.350	.1100	3.200	1.2150	36.980
.400	.1100	3.200	1.2290	37.439
.450	.1100	3.200	1.2375	37.717
.500	.1100	3.200	1.2425	37.884

Results of Computer Simulation for the amplidyne

BLOCK-DIAGRAM FOR THE EXCITATION SYSTEM OF THE SYNCHRONOUS MACHINE



```
      PROGRAM DIMDAC
      REAL IA,IL
      EQUIVALENCE(DATA,W)
      COMMON              W,Z,DCC,DCL,S1,T1,XL,YL,ACO,AVO,ACQ,AVQ,AET,B,
     1ACFAG,DCFSR,CSRIP,RSROP,ACRENL,DCRENL,ACREL,DCREL
      DIMENSION DATA(472)
      DIMENSION W(30),Z(30)          ,F(15)
      DIMENSION RS(5),DCC( 6),DCL( 6),RM(5)
      DIMENSION S1(43),T1(43),FA(20)
      DIMENSION ACO(29),AVO(29),FAM(60),A(60)
      DIMENSION XL( 7),YL( 7)
      DIMENSION ACQ(35),AVQ(35),AET(35),B(35)
      DIMENSION ACFAG(21),DCFSR(21),ACRENL(12),DCRENL(12),ACREL(12)
      DIMENSION DCREL(12),CSRIP(6),RSROP(6)
      DIMENSION ACON(3),AVON(3)
      BUFFER IN (20,1)(DATA(1),DATA(472))
      RNLRE=93.9
      ACSFNL=25.15
      R=231.97
      RL=50.75
      RAM1=84.2
      ACL=12.7
      RAM12=52.9
      RSR=384.0
      CAM11=0.24
      DASM1=0.24
      FLRS=100.0
      DARSA=0.0
      CSR1=0.0
      ROST=4.0
      NGR=20
      NSRR=5
      NLC=11
      NNLC=11
      EB=2.0
      NC=29
      NL=5
      RA=0.42
      ER=3.5
      G=0.5
      ACON(1)=-0.050
      AVON(1)=-1.0
      ACON(2)=-0.040
      AVON(2)=-0.7
      ACON(3)=0.0
      AVON(3)= 0.0
      NNAP=2
      T=0.05
      TS=0.001
      LOT=2
      NB=42
      NA=6
      NQ=34
      NM=28
      FLAM1=0.176
      FLAM2=0.25
      L3=50
      LI=10
      LO=13
```

Fortran Program for the Complete Excitation System.

```
      TT=0.0
      EBACOM=0.0
      IL=0.0
      IA=0
      D=0.0
      FLX=0
      EG=ER
      ET=EG
      CA=0.0
      DAS=0.0
      CAM2=0.0
      DASM2=0.0
      CALL FUNC(NLC,ACREL,DCREL,ACL,DCL2)
      CAM12=DCL2/RAM12
      DO 315 JKA=1,LOT
      DO 325 JKB=1,LO
      NCD=0.0
      DO 335 JKC=1,LI
      RTNLR=RNLRE+ROST
      CUINLC=ACSFNL/RTNLR
      ACNL=ACSFNL-CUINLC*ROST
      CALL FUNC(NNLC,ACRENL,DCRENL,ACNL,DCNL)
      DO 225 N=1,L3
      ET1=DCNL
      CALL INT(ET1,CAM11,RAM1,FLAM1,DASM1,     TS)
      CAMR=CAM11-CAM12
      CAM1=ABS(CAMR)
      IF(CAMR.LT.0.0.AND.CAMR.GT.-0.05) GO TO 41
      GO TO 42
   41 CALL FUN(NNAP,ACON,AVON,CAMR,ET2)
      GO TO 43
   42 CALL FUNC(NM,ACO,AVO,CAM1,ET2)
   43 ET7=ABS(ET2)
      CALL FUNC(NQ,AET,B,ET7,RAM2)
      CALL INT(ET2,CAM2,RAM2,FLAM2,DASM2,    TS)
      IF(CAM2.LT.0.0) GO TO 44
      CALL FUNC(NQ,ACQ,AVQ,CAM2,EBA)
      GO TO 45
   44 EBA=2.0*ABS(CAM2)/0.05
   45 IF(ABS(EBACOM-EBA).LT.0.0001) GO TO 417
      EBACOM=EBA
  225 CONTINUE
  417 IF(CAMR.LT.-0.05) GO TO 415
      EBOA=EBA
      GO TO 416
  415 EBOA=-EBA
  416 IL=ET/RL
      IA=D+IL
      CALL FUNC(NL,DCC,DCL,D,FL)
      DY1=(EG-IA*RA-R*D+EBOA)/FL
      D=FLX+DY1*T
      DO 10 I=1,10
      CALL FUNC(NL,DCC,DCL,D,FL)
      CALL FUNC(NC,Z,W,D,EG)
      ET=EG-IA*RA
      IL=ET/RL
      IA=D+IL
      DY2=(EG-IA*RA-R*D+EBOA)/FL
      F(I)=FLX+(DY1+DY2)*T/2.0
      D=F(I)
      IF(I.LT.2)  GO TO 10
      IF(ABS(F(I)-F(I-1)).LT.0.001) GO TO 15
```

Fortran Program for the Complete Excitation System.

```
 10 CONTINUE
 15 FLX=0
    CALL FUNC(NC,Z,W,D,EG)
    ET=EG-IA*RA
    CALL FUNC(NA,XL,YL,CA,FLA)
    DYA1=(ET-CA*RL)/FLA
    CA=DAS+DYA1*T
    DO 110 L=1,10
    CALL FUNC(NA,XL,YL,CA,FLA)
    DYA2=(ET-CA*RL)/FLA
    FA(L)=DAS+(DYA1+DYA2)*T/2.0
    CA=FA(L)
    IF(L.LT.2) GO TO 110
    IF(ABS(FA(L)-FA(L-1)).LT.0.001) GO TO 115
110 CONTINUE
115 DAS=CA
    CALL FUNC(NB,S1,T1,CA,EB)
    CALL FUNC(NGR,ACFAG,DCFSR,EB,EBDC)
    EBDC=EBDC-4.5
    CALL INT(EBDC,CSR1,RSR,FLRS,DARSA,    T)
    CSR=CSR1*1000.0
    CALL FUN (NSRR,CSRIP,RSROP,CSR,ROST)
335 CONTINUE
    TT=TT+G
    PRINT 100,TT,EB
   1CA,EB
100 FORMAT(2X,14(F8.4,1X))
325 CONTINUE
    LI=4
    G=0.2
    TT=0.0
    LO=24
    RL=42.87
315 CONTINUE
    END
```

Fortran Program fo: the Complete Excitation System.

Time Seconds	Output of the AC Machine Volts
0	2.0
.5000	38.2166
1.0000	88.1327
1.5000	129.4137
2.0000	158.3967
2.5000	179.4290
3.0000	191.0729
3.5000	197.0527
4.0000	199.1280
4.5000	200.4563
5.0000	201.4004
5.5000	202.1816
6.0000	202.4604
6.5000	201.8012
7.0000	202.4200
7.5000	201.9917
8.0000	202.1997
8.5000	202.2262
9.0000	202.0251
.2000	220.6013
.4000	200.6492
.6000	182.6524
.8000	181.0225
1.0000	185.6453
1.2000	192.8273
1.4000	198.7910
1.6000	204.5123
1.8000	211.8981
2.0000	212.9172
2.2000	199.1131
2.4000	195.0687
2.6000	197.3308
2.8000	200.8027
3.0000	207.5515
3.2000	212.2348
3.4000	207.7924
3.6000	198.9815
3.8000	198.1587
4.0000	200.4865
4.2000	206.4110
4.4000	211.4075
4.6000	208.1822
4.8000	201.0399

Result of Computer Simulation for the complete excitation system.