AN ABSTRACT OF THE THESIS OF

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Title: REAL TIME PREDICTIVE CONTROL OF GENERATING SYSTEM USING HYBRID COMPUTER AND A FAST TIME ADAPTIVE MODEL

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A system consisting of two d-c generators, one exiting the other, is controlled with an EAI 690 hybrid computer in an on-line operation. The hybrid computer works as a predictive controller with an on-off actuating signal. A fast-time, second-order model is used to determine the switching time, and a small linear region is used to avoid limit-cycling.

A predictive control system of this kind has a time optimal response when the controlled system is linear, stationary and of second order. Since none of these conditions are satisfied, the response is only quasi-optimal.

To improve the system performance an adaptive second-order model was used. A parameter estimator calculates the gain and the

equivalent time constant of the system and feeds these values into the model.

The response was recorded for sudden load changes and for build-up from minimum output to normal voltage. In all cases the predictive control technique worked well, but small transient oscillations were unavoidable in the linear region. Three different second-order models with fixed parameters were used, but none of the resulting responses were as good as when the model was adaptive.

Real Time Predictive Control of Generating System Using Hybrid Computer and a Fast Time Adaptive Model

by

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LIST OF VARIABLES

A = actuation signal (output from controller)

AF = input to model

A_{max} = upper boundary for possible values of A

A_{min} = lower boundary for possible values of A

c = output voltage after filtering away high frequency noise

$\dot{c}$ = derivative of output voltage

c_m = output from fast model

$\dot{c}_m$ = derivative of model output

c_n = output voltage with high frequency noise from generator

d = system error

$\dot{d}$ = derivative of system error

d_m = model error

$\dot{d}_m$ = derivative of model error

$(d_i, \dot{d}_i)$ = state of system just prior to i'th run of model

d_f = final error of ideal predictive control system

$d_{m,0}$ = model error when $\dot{d}_m = 0$

d_{ss} = steady state error

Δd = change in error between successive runs of model

$GAIN$ = estimated gain of generating system at steady state

I_f = field current of the exciter (input to generating system)

k = steady state gain of generating system

N = noise from communication lines between power lab and simulation lab

ref = desired output voltage

T_g = time constant of the generator

T_{ex} = time constant of the exciter

TIMEC = estimated time constant of the equivalent first order system

X, Y = constants

REAL TIME PREDICTIVE CONTROL OF GENERATING SYSTEM USING HYBRID COMPUTER AND A FAST TIME ADAPTIVE MODEL

I. INTRODUCTION

It is desired to keep the output voltage from a d-c generator that is excited by another d-c generator at a predetermined reference level. The field current of the exciter is the only system input available to the controller. Therefore a control system must be built that supplies field current in such a way that the output voltage is maintained at the reference level for as much of the operating time as possible. Figure 1 shows the basic system configuration.

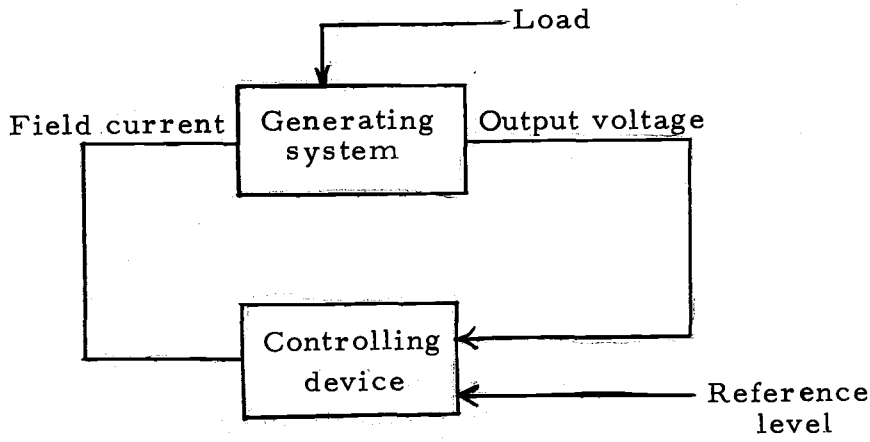

Figure 1. System configuration.

The load is the main source of disturbance for the system, and in practice it will vary randomly.

Linear feedback has been used to control output voltage of

generators (1, 2).

Fallside and Thedchanamoorthy (1967) used predictive control to regulate the output from a 3 kVA synchronous generator (3). Given any deviation from the reference, the predictive controller reduced the error to zero almost as fast as possible. The control was not quite time optimal because of imperfections in the controller and because simplifying assumptions were made about the generator when designing the control system.

The fast-time model is an essential part of a predictive control system. It simulates the controlled plant on a fast-time basis, and is used to predict the future behaviour of the plant in response to present control action.

The author also uses predictive control to regulate the system of the two d-c generators, but employs a hybrid computer. The fast model is programmed on an EAI 680 analog computer, while the rest of the control system is programmed on an EAI 640 digital computer. The author feels that this is a natural way to divide the system, and that it simplifies the design. In order to speed up the execution of the digital program and create as little delay in the controller as possible, it was written in assembler language.

The controller generates an on-off type of signal that is used to excite the exciter (the first generator). To decide whether the actuating signal should be on or off the controller considers the

state of the system itself, which is described by the output and its derivative, and the performance of the model when subjected to a test input. Since the system is assumed to be of second order, the actuating signal must be switched once to correct an error in the output. In order to find the correct switching time the fast model is used to predict where the output will end up if the switching occurs. The actuating signal is therefore switched whenever the output is predicted to go to the reference.

Since the derivative of the output cannot be found anywhere in the system, a differentiator was designed. High frequency noise generated by the differentiator was filtered out.

The predictive control technique gives time optimal control of a linear, stationary, second order system. Since the generator system considered is nonlinear, time-varying and of higher order, the control system can only give a suboptimal time response.

To compensate for the nonlinearities and the time-varying parameters of the system, the fast model was made adaptive. A parameter estimator calculates the gain and the dominating time constant of the system, and sets the gain and the highest time constant of the model to these values. This is done continuously when the system is operating. So the model should always give a good simulation of the system.

Predictive control with a fast-time adaptive model has many possible applications, other than for the voltage control of generators (4). However, the controlled system ought to be of second-order. If it is a higher order system, there should be two dominating time constants, so that it can be approximately simulated by a second order model.

A computer must also be available. It could be either a digital, an analog or a hybrid computer.

The communication channels between the hybrid computer and the generators were quite noisy, and the generators themselves created some high frequency noise. To recover the output signal a scheme of subtracting the noise from the communication channels and an RC-filter were used.

The filters create a time delay both in the output signal and its derivative. Therefore the controller did not get precise information about the state of the system, even if the system is assumed to be of second-order.

II. DESCRIPTION OF SYSTEM AND CONTROL TECHNIQUE

Block Diagram of Control System

The basic organization of the system is shown in Figure 2. The parameter estimator and the controller are contained in the digital

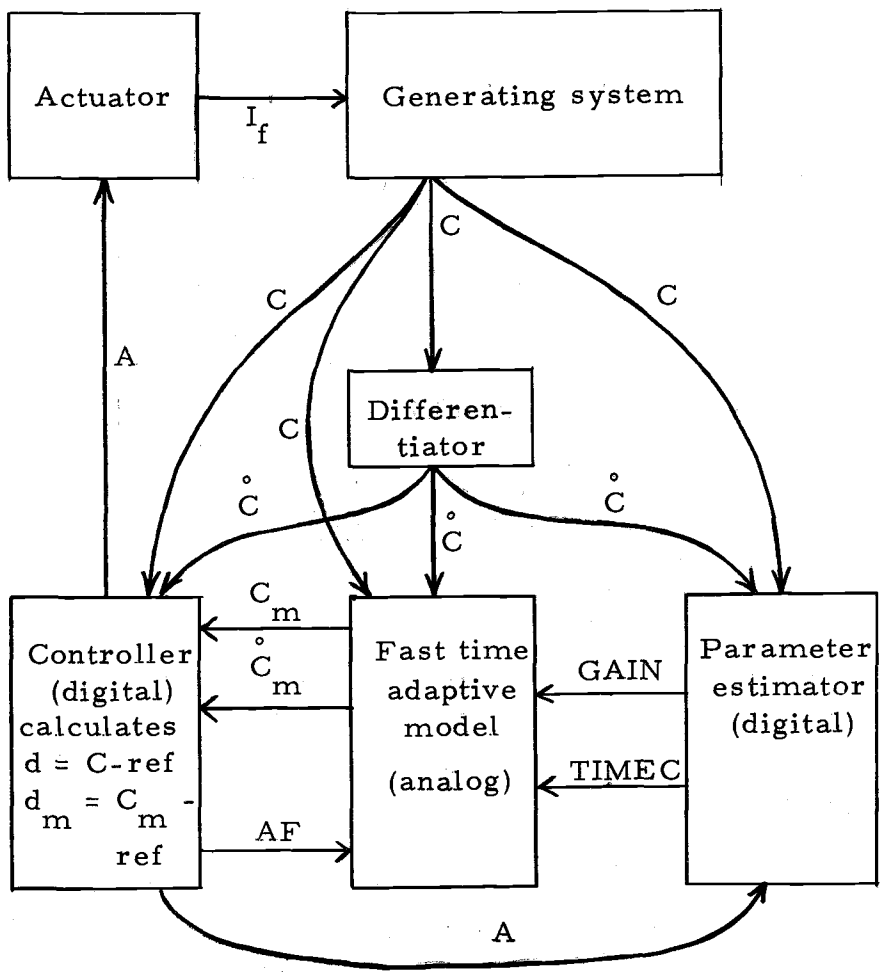

Figure 2. Block diagram of control system.

program, while the model and the differentiator are patched on the analog computer. The output is the only information transmitted from the generating system to the computer, and the actuating signal is the only instruction given by the computer via the actuator to the generating system.

Each block will be discussed in a separate section except for the differentiator that is discussed in the Appendix.

The Generating System

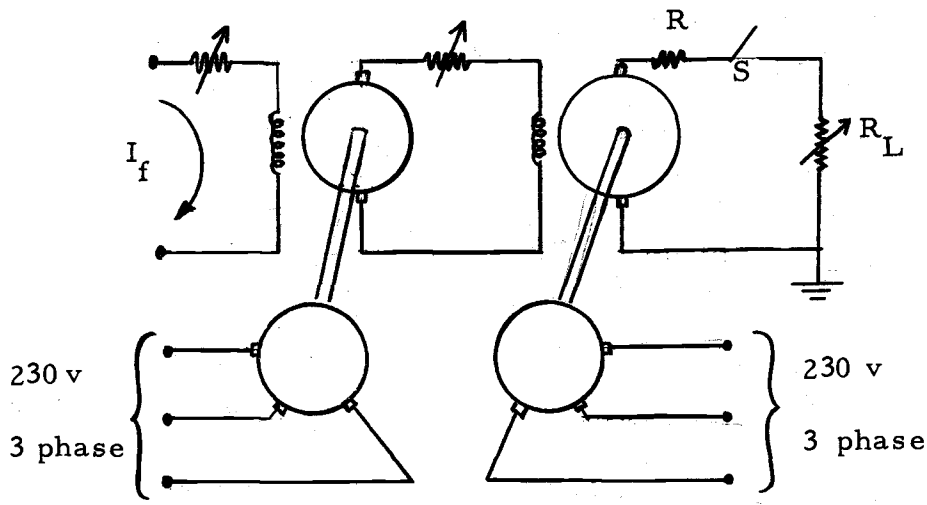

Figure 3. Generating system.

The system consists of two d-c generators, one exciting the other. They are both driven by three phase induction motors. The field current I_f is the only input variable directly available to the

controller and is restricted by $0 \leq I_f \leq 400$ ma . R_L is the loadresistance, and s is the switch that will be opened and closed during the testing of the system. R is a 1.5Ω resistor that is used to create more deviation in the output voltage and thus prevent the changes in the output signal from being buried in noise. Table I gives more detailed information about the machines.

Table I. Machine specifications.

Description	Manufacturer	Serial No.	Function	Power	Voltage	Current
3φ Induction Motor	Westinghouse	1S5G3032	drives exciter	15 hp	128-220v	66-38A
3φ Induction Motor	General Electric	3766826	drives gen.	5 hp	220v	14.1 A
d-c Generator	Westinghouse	1S5G3033	exciter	15 KW	250v	60 A
d-c Motor	General Electric	2027250	generator	5 hp	230v	19.6 A

The Actuator

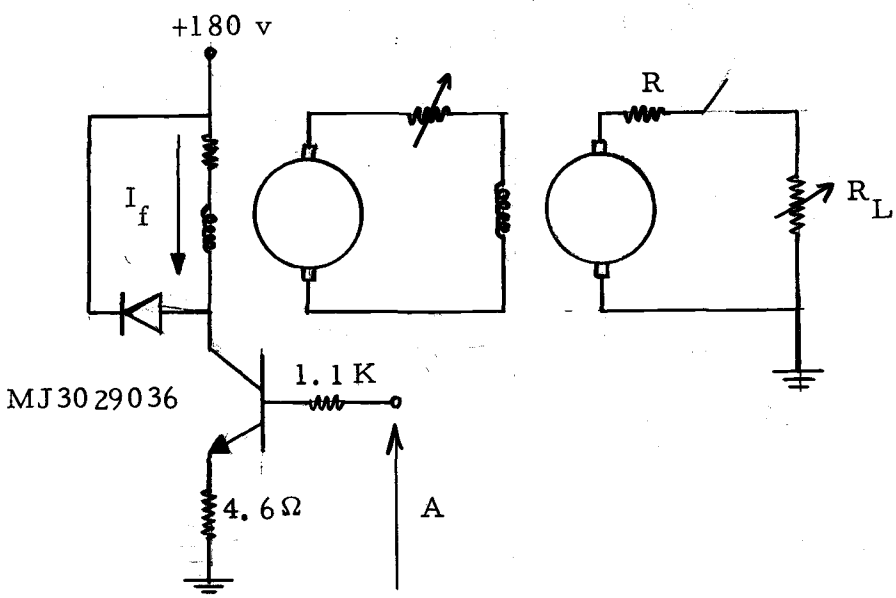

Figure 4. Actuator with exciter and generator.

The digital computer generates the actuating signal as a 16 bit binary number. This number is converted to a voltage in the analog computer and transmitted down to the power lab. The signal (A) then has a magnitude less than 12 volts and is of low power. The purpose of the actuator is to convert this signal to a current in the exiter field circuit. This was accomplished by using an NPN transistor as shown in Figure 4. In the linear region of the transistor this circuit gives a field current that is proportional to A.

The 1.1 K resistor gave the desired sensitivity to A, and the diode was used to prevent the collector voltage from exceeding 180 volts. With rapid changes in base voltage this was necessary in order to protect the transistor from secondary breakdown.

Predictive Control

Assume that the system to be controlled is linear, stationary and of second order. The state of the system is then described by the output and its derivative. As in all physical systems the input A is bounded. Let $A_{min} \leq A \leq A_{max}$.

Pontryagin's maximum principle (5) says that the fastest way to get from point B in the phase plane to 0 (see Figure 5) is to first let $A = A_{max}$, and then let A be switched to A_{min} when the state of the system reaches S. For the state of the system to reach the origin (c = ref) in shortest possible time from anywhere in the phase

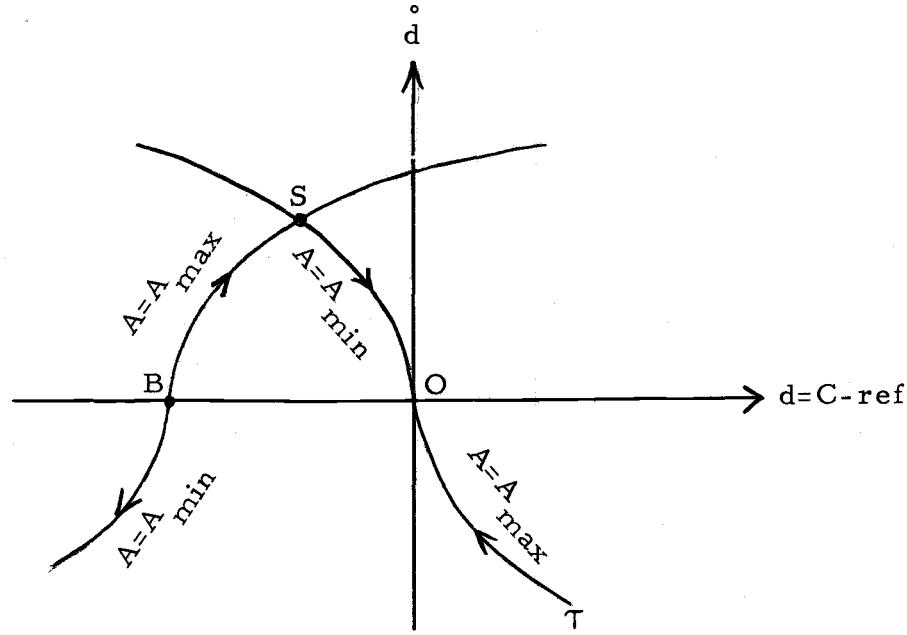

Figure 5. System trajectories in the phase plane.

plane, A can only have the values A_{max} or A_{min}, and it is only necessary to switch once between the two. To arrive at the origin the system has to approach it along T, the only trajectory with $A = A_{min}$ or A_{max} that goes through the origin.

The difficulty with this method is to find out when the system is at S and the input should be switched.

The switching curve T may be approximated by a straight line, a piecewise linear curve (6), or by various other mathematical functions.

In predictive control the switching point is found by using a fast-time model of the system. As the state of the system moves along the trajectory from B towards S, the fast model is repeatedly given

the same state as the system ($d_m = d_i$, $\dot{d}_m = \dot{d}_i$), but forced in the opposite direction (see Figure 6). The output velocity of the model

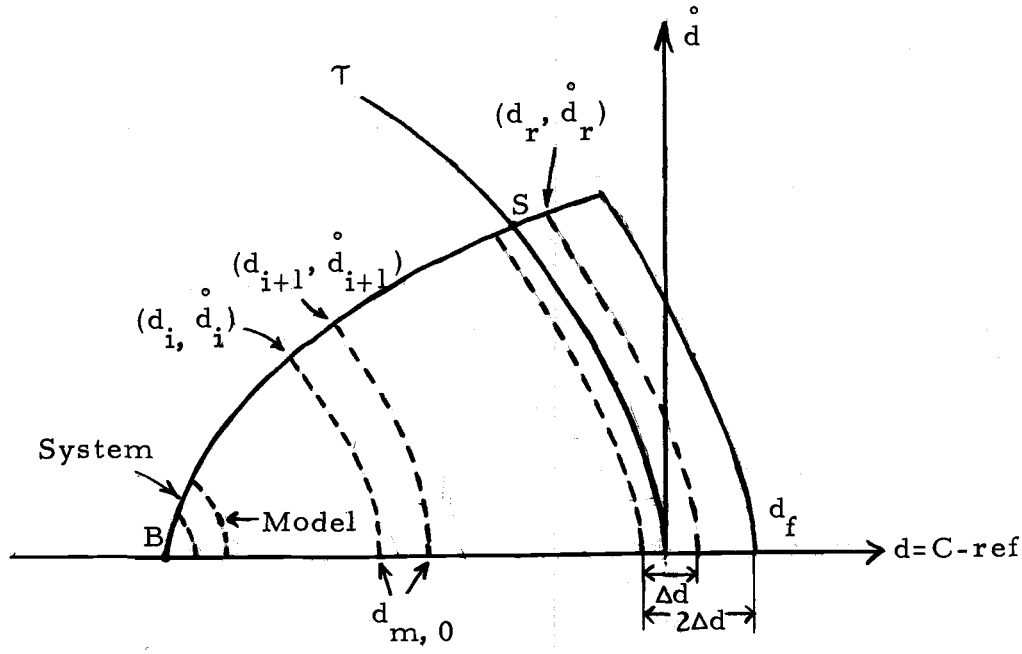

Figure 6. System and model trajectories.

$(\dot{d}_m)$ is driven to zero, and the corresponding value of the output $(d_{m,0})$ is examined. If $d_{m,0}$ has the same sign as d_i, then S has not been reached. Therefore A keeps the same value, and the model is given the same state as the system again ($d_m = d_{i+1}$, $\dot{d}_m = \dot{d}_{i+1}$). The procedure is then repeated.

At some prediction by the model, say the r'th, d_r and $d_{m,0}$ will have different signs. This means that the system passed through S between the (r-1)'th and the r'th prediction. Therefore A is switched to A_{min}.

The switching will always occur late, after the state of the system has gone through S . Let the change in error between successive runs of the model be Δd , and the final error be d_f . Then d_f is bounded above by $2\Delta d$ and below by Δd ($\Delta d \leq d_f \leq 2\Delta d$) .

In practice when a relay is used, the system never comes to rest. It ends up in a limit cycle (a closed cycle in the phase plane). To avoid this a small linear region was introduced around the origin, where

$$A = X \cdot d + Y \cdot \dot{d} \qquad (1)$$

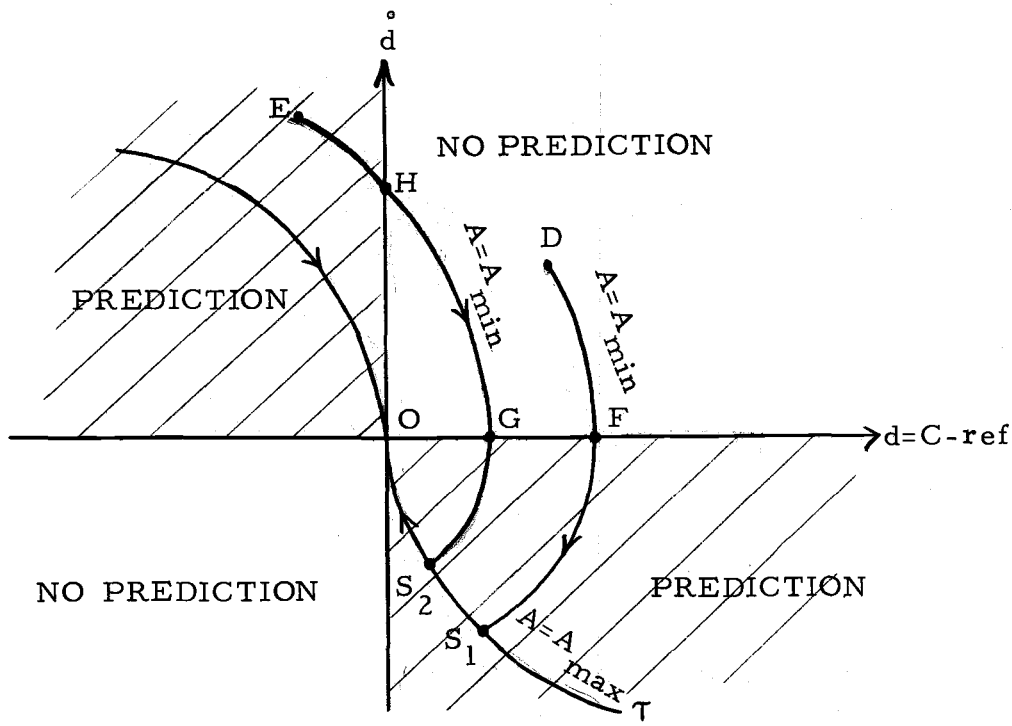

Figure 7. Areas of prediction.

Since the system moves towards the origin only in the second and fourth quadrant, the switching curve τ will always be in those

parts of the phase plane. No predictions are therefore necessary in the first and third quadrants.

If the system initially is at state D in the first quadrant (see Figure 7), A is set equal to A_{min}. The controller then waits until the system reaches F before it starts using the fast model to predict where A should be switched.

It is not necessary to start predicting at state E either. A_{min} could just be applied, and prediction start when G is reached. The model must however be used to find out on which side of τ the system is. So the model is set to state E and forced with A equal to A_{min}. If $d_{m,0}$ is positive, A is set equal to A_{min}. If $d_{m,0}$ is negative, A is set equal to A_{max}. To simplify the program no attempt was made to avoid prediction when the system moves from E to H. As long as A does not switch along that path, it does not matter if the model operates or not.

The Linear Region

The linear region was chosen to be a rectangle with a 6.24 volts width and a 15.6 volt/sec height centered around the origin in the phase plane. When the state of the system is inside this region, it has linear feedback with derivative control. The constraint $A_{min} \leq A \leq A_{max}$ must of course still be satisfied. Assuming that the generating system's transfer function exists and is G(s), the control system may be

represented by the block diagram in Figure 8.

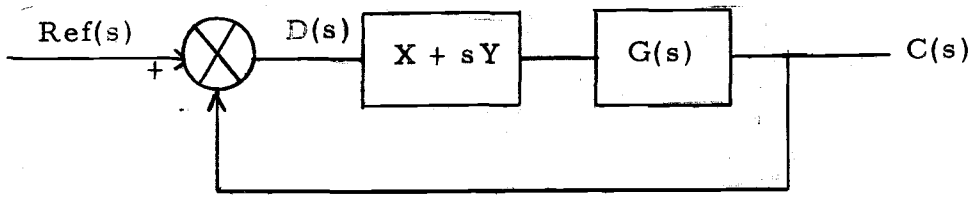

Figure 8. System in the linear region.

Since the reference is a step function, the steady state error is (7)

$$d_{ss} = \frac{ref}{1 + \lim_{s \to 0} G(s)[X + sY]} \qquad (2)$$

Assuming that G(s) has no poles or zeros on the imaginary axis, and that the gain of the generating system is GAIN, it follows that

$$d_{ss} = \frac{ref}{1 + GAIN \cdot X} \qquad (3)$$

Since ref = 50 volts, X = -25.6 and GAIN is 1.24 at no load and 0.82 at eight ampers load, d_{ss} should theoretically be -1.6 volts at no load and -2.5 volts at eight ampers load. The values for steady state error obtained in practice were -1.8 volts at no load and -2.1 volts at eight ampers loads.

It was attempted to increase the absolute value of X in order to decrease the error, but this created too much noise in the actuating signal.

Integral control was also tried, but discarded since it resulted in an oscillatory output.

The Fast-Time Adaptive Model

The generating system has two dominating time constants. They are created by the field currents of the exciter and the generator. In addition there are time constants in the armature of the generator and in the transistor that is used to supply field current to the exciter. But these are small and will be neglected.

The system is nonlinear since the magnetic fields of both exciter and generator become saturated at high field currents, and since the transistor sometimes is driven out of the region where it is linear.

The system is also time-varying. The gain is affected by the load. A high loadcurrent causes the gain to decrease, because of the voltage drop across the internal resistance in the armature of the generator. A change in the equivalent impedance of the transistor causes the time constant of the exciter field circuit to change. The time constant is large when the base voltage is high and small when the base voltage is low. The apparent time constant of the system varied between 0. 33 sec and 1. 2 sec when the transistor input was varied

between zero and ten volts. Environmental conditions like temperature and humidity will also affect the performance of the system.

Sollecito and Swann (AIEE trans. 1954, 434) worked on aircraft a-c systems and said that load and temperature variations produced maximum changes in the time constant in the order of seven to one, and changes in the gain in the order of twenty to one.

It obviously is impossible to set up an exact simulation of this system. Any model will have to be an approximation. There are several possible approaches to the problem of modeling this system. One could linearize the system about several different operating points, have one linear model for the whole operating region, or try to include the important nonlinearities using function generators.

Fallside and Thedchanamoorthy used a second order model with variable parameters for their a-c generator, and the same approach is used by the author.

Assuming that the collector voltage is proportional to the base voltage, and that T_{ex} and T_g are dominating all other time constants, the system may be described (9) by

$$\frac{c(s)}{A(s)} = \frac{k}{(1 + sT_g)(1 + sT_{ex})} \qquad (4)$$

Appendix I shows how the gain of the system is a function of the input. Hence k should be variable instead of a constant as in

Equation (4).

To compensate for the fact that the system is nonlinear, time-varying and has more than two time constants, the gain and the largest time constant are permitted to vary. The system transfer function is written

$$\frac{c(s)}{A(s)} = \frac{GAIN}{(1+sT_g)[1+s(TIMEC)]} \qquad (5)$$

The apparent gain and time constant are calculated by the parameter estimator and GAIN and TIMEC are set equal to these estimated values. Figure 9 shows the basic configuration of the model.

It was decided to run the model 100 times faster than the system. When the model was ten times faster, the time interval between each prediction became significant and sometimes the input switched much too late. When the model was 100 times faster, the switchings occurred approximately at the same place every time.

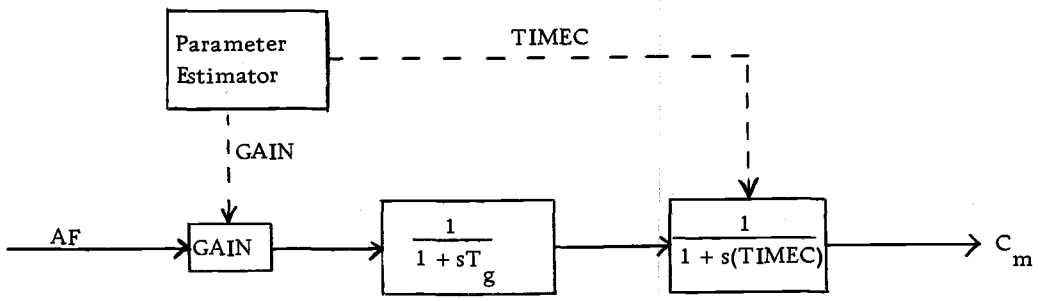

Figure 9. Block diagram of adaptive model.

When this model is used in the predictive control system, the state of the generating system will be brought to the origin of the phase plane given any initial error. Later on, however, the output drops about two volts since a steady state error is unavoidable with the kind of feedback that is used in the linear region. Because of this the model was modified slightly to make the system go to its normal operating value (the final value) after a disturbance, instead of to the reference.

The model was slowed down by increasing TIMEC. This caused the input to switch earlier and the output to end up at the final value after a negative error. It also caused the output to end up two volts higher than the reference after a positive error. To correct that a constant α was added to c_m whenever the error was positive. It caused the input to switch later for positive errors, and when α was adjusted to 3.6 volts, the output went to the final value also after a positive error. Figure 10 illustrates the effects of the modifications.

Because of time delay in the execution of the digital program, and since the controller always will decide to switch too late, it was necessary to amplify TIMEC before it was applied to the fast model. This amplification plus the one that made the output go to the final value after a negative error, made it necessary to amplify TIMEC by a factor of 16.3 before it was applied to the model.

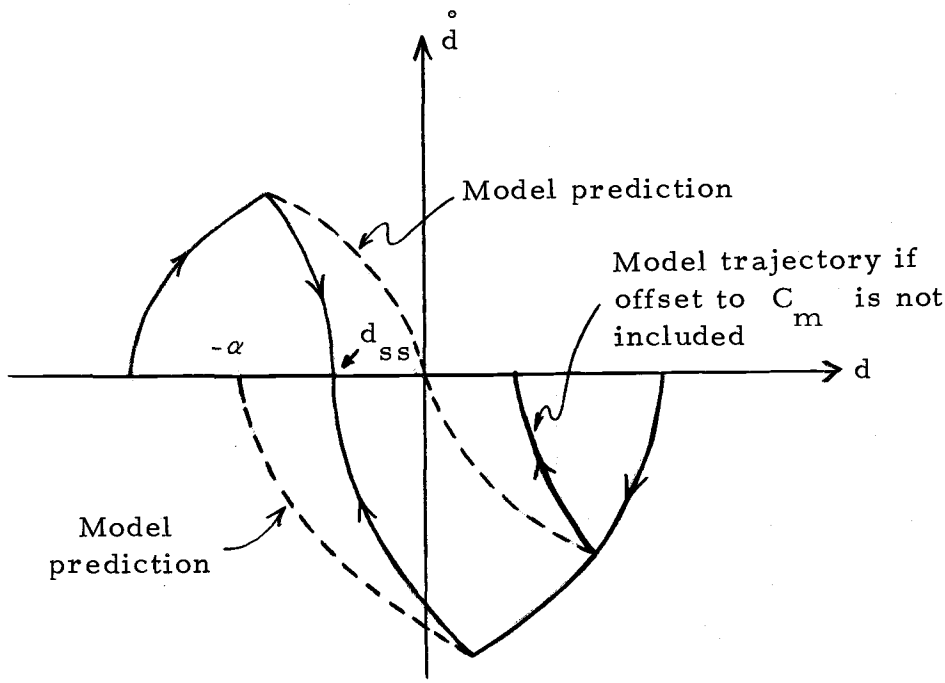

Figure 10. Effects of modifications of model.

The Parameter Estimator

When estimating the time constant of the exciter, which is the largest of the two main time constants, it is assumed that the other time constant may be neglected and the system approximated by a first order system. The equation for this first order system is

$$\frac{c}{A} = \frac{\text{GAIN}}{1 + (\text{TIMEC})D} \tag{6}$$

where D is the operator d/dt and A is constant.

Fallside and Thedchanamoorthy found the estimation scheme based on this approximation to work satisfactorily even for time

constant ratios as low as three to one. Since the ratio of T_{ex} to T_g is about three (the exact ratio depends on the equivalent impedance of the transistor), the author decided to make this approximation.

Equation (6) is then solved for TIMEC, and gives

$$TIMEC = \frac{A \cdot GAIN - c}{\dot{c}}, \text{ for } \dot{c} \neq 0 \qquad (7)$$

The gain of the system is given by

$$GAIN = \frac{c}{A}, \text{ at steady state conditions} \qquad (8)$$

It is calculated only in the linear region, and only if $|\dot{c}| < 0.018$ volts/sec to insure that it will be at steady state.

TIMEC is calculated only when the model is predicting, and only before the switching occurs. The estimate of the time constant is very much too large when $\dot{c}$ is small. This is due to the fact that T_{ex} does not quite dominate T_g as assumed when Equation (7) was derived. As $\dot{c}$ increases, however, TIMEC approaches a fairly good estimate of T_{ex}. To keep the erroneous values of TIMEC from saturating the model on the analog computer, TIMEC is only estimated if $|\dot{c}| > 6.3$ volts/sec.

High frequency noise is kept from affecting the calculation of GAIN by letting A pass through an RC-filter with a 3.3 hz corner frequency.

This scheme of estimation is best for slow drift of parameters. If sudden changes occur, as when the load is changed instantaneously, the gain will not be corrected until the system has recovered from the disturbance and settled down to steady state conditions. Before that happens the time constant will be estimated, and it will be given an incorrect value since Equation (7) contains GAIN. However the erroneous value of GAIN tends to be compensated for by an appropriate change in TIMEC from its correct value. It may be shown that during the initial part of the response

$$\frac{\text{TIMEC}}{\text{GAIN}} \approx \frac{T_{ex}}{k} \tag{9}$$

and this is the condition that gives the best switching when a fast model with incorrect parameters is used (3).

Flowchart for Control Scheme

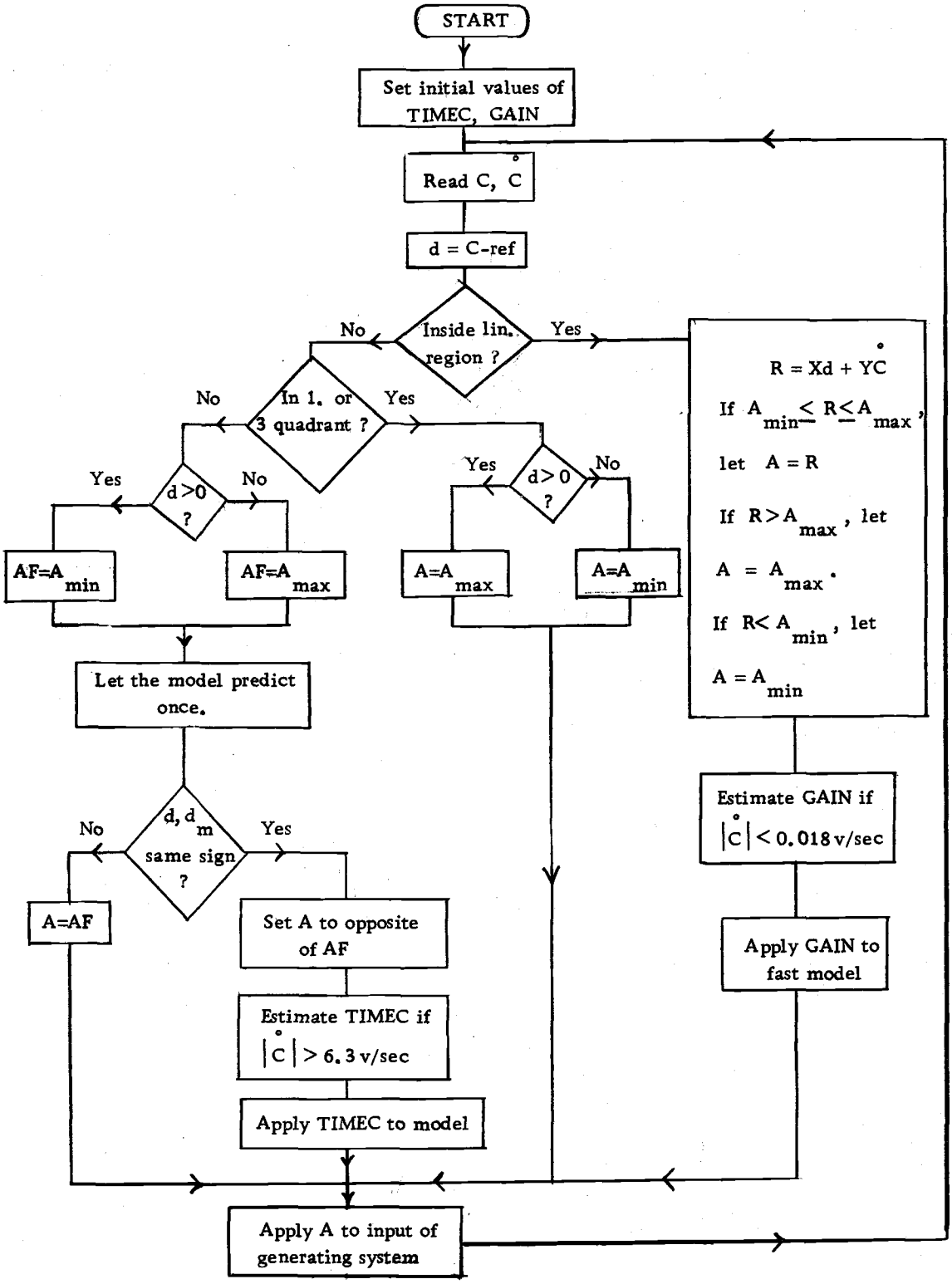

Figure 11. Flowchart for control scheme.

III. EXPERIMENTAL RESULTS

System Performance with Adaptive Model Having the Offset for Positive Errors

The system was first operated as described in the previous chapter, with an adaptive fast-time second order model that has an offset for positive errors. To test the system it was subjected to sudden changes in load. The field current was also set temporarily to zero, to let the control system build the output up from minimum voltage. Normal operating voltage at steady state was about 48 volts. The reference level was 50 volts.

In Figure 1 2 the system initially delivers an eight ampers load current. Then the switch in the armature circuit is opened and the output increases about 20 volts. The input instantaneously drops to one volt (A_{min}), and the model starts predicting 1/4 sec later when the imperfectly differentiated output goes negative, and the system enters the fourth quadrant in the phase plane. When the system predicts, the upper envelope of c_m is equal to c plus 3. 6 volts as explained on page 17. The paper speed is too slow to show each prediction separately. Instead the predictions appear as a thick line with a height that is about four volts right before the switching. The bandwidth of the strip chart recorder is too small to show that $\dot{c}_m$ is driven all the way to zero each time the model predicts. That is shown in

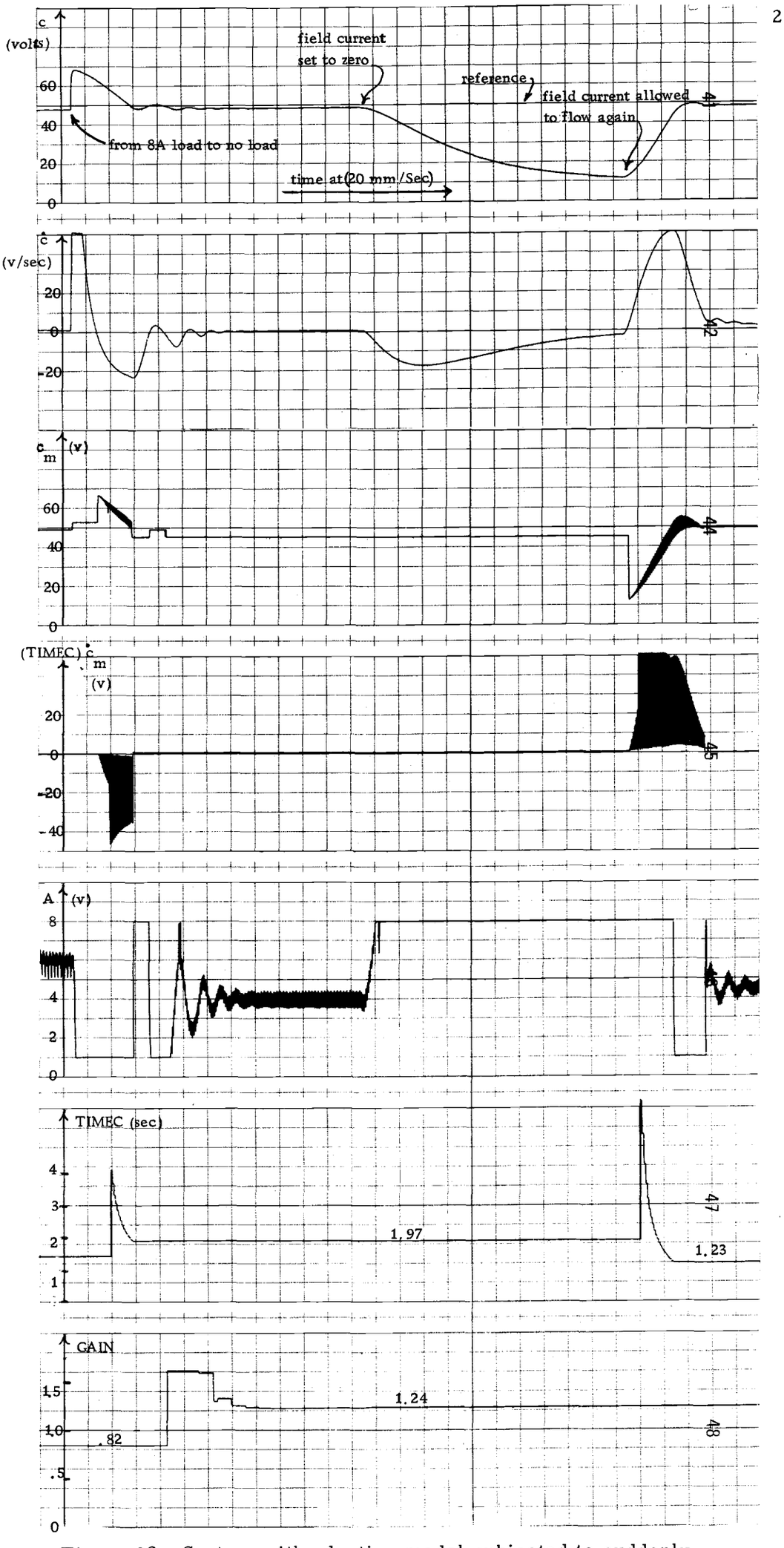

Figure 12. System with adaptive model subjected to suddenly switched off load and temporary absence of field current

Figure 13 where each prediction also is shown clearly.

At each prediction c is estimated to end up closer to the reference than where it is. When c is predicted to go to the reference, A switches to eight volts (A_{max}). The output is then brought down to the steady state value, which is about 48 volts. After the system enters the linear region, the output bounces up and oscillates a few times before it settles down to 48 volts.

The field current is then set to zero, by disconnecting the actuating signal from the generating system. The output drops slowly to about 12 volts. When the controller is disconnected, the actuating signal A is equal to A_{max}, since the controller tries to build up the output. When the controller again is connected to the generating system, the field current goes to its maximum and drives the output up to 48 volts almost without overshoot or oscillations. The model keeps predicting after the switching since the system still is in the second quadrant.

The predictions were better and the response closer to being time optimal in this case than when the armature was open circuited. That is shown by the behaviour of A. It only switches once between A_{max} and A_{min}, and has much smaller oscillations after the system has entered the linear region.

When the input switched the first time in Figure 12, TIMEC was 1.97 sec. The estimator was then using the gain at eight ampers

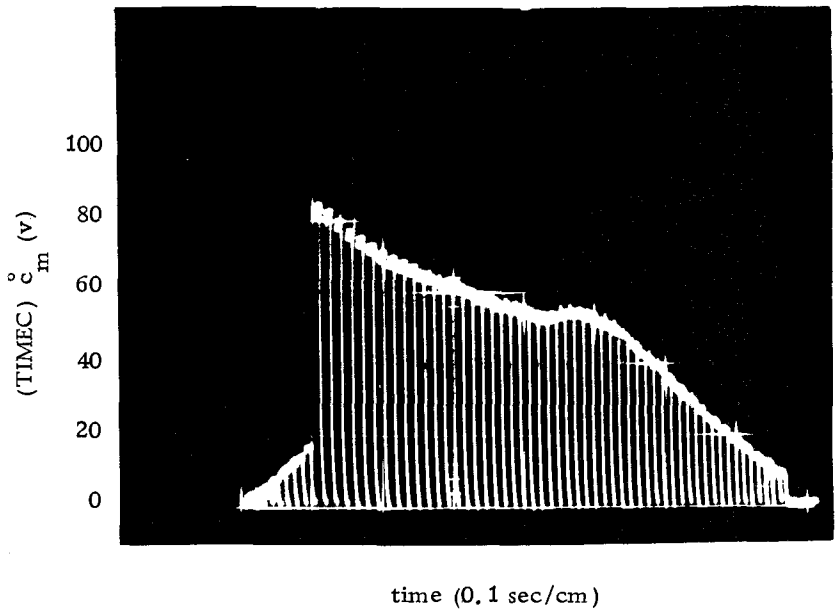

Figure 13. (TIMEC) · $\dot{c}_m$ at no load and during build-up from minimum output.

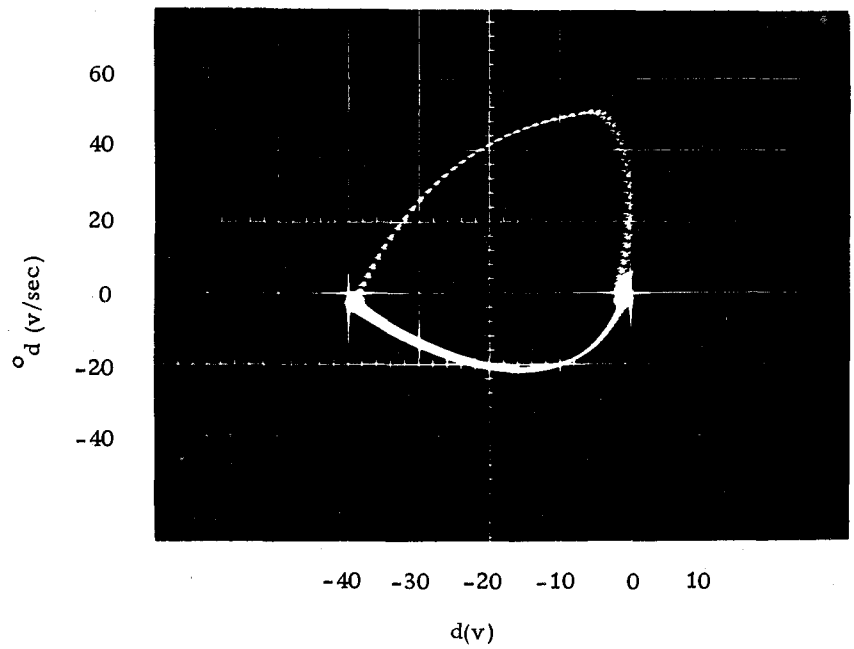

Figure 14. Phase plane trajectory when the controller is temporarily disconnected.

load which was 0.82. At the second switching in this figure the estimator used the correct gain for open circuit which is 1.24, and the correct TIMEC was estimated to 1.23 sec.

Figure 14 shows what happens in the phase plane. The system is initially at rest slightly to the left of the origin. When the controller is disconnected, the field current drops to zero, and the state of the system goes slowly through the third quadrant to a steady error of -38 volts. As the controller is connected again, the state of the system is first driven across the second quadrant with $A = A_{max}$. When it gets close to the $\overset{\circ}{d}$-axis, A switches to A_{min}, and the system is driven towards the origin. Close to the origin the system enters the linear region and settles down to its final value. The trajectory in Figure 14 is seen to be very similar to those in Figures 5, 6 and 7.

In Figure 15 the system is first suddenly subjected to a load. After the controller has corrected the error, the field current is temporarily set to zero, and the output built up from a minimum of about ten volts. All the variables show the same general pattern as in Figure 12. Only in this case both errors are corrected very well with small oscillations in both c and A.

The controller worked very good in the prediction region. After every disturbance in Figures 12 and 15 the output was driven back to its normal operating level of 48 volts. The system entered the linear region immediately after being brought to 48 volts, and since it levels

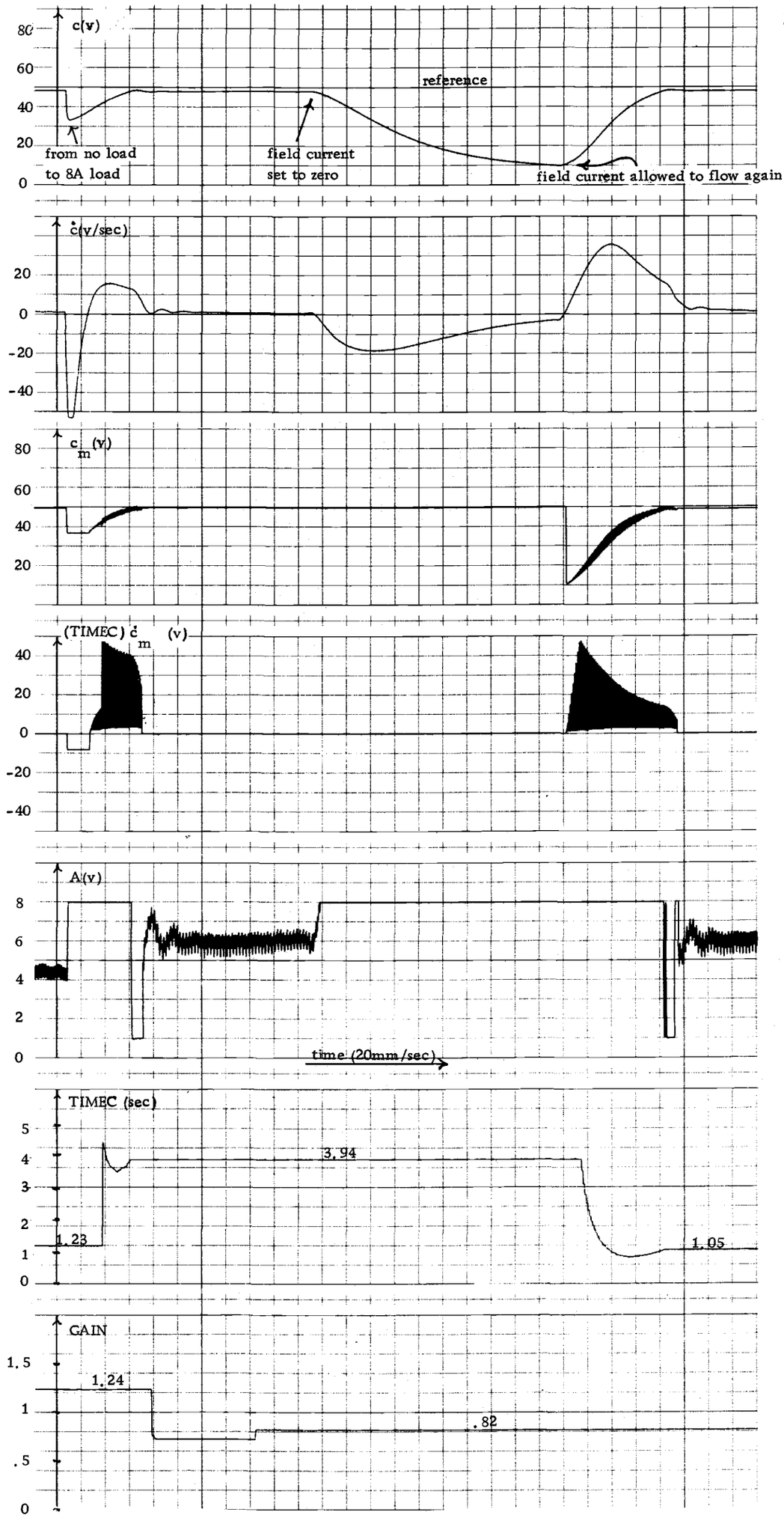

Figure 15. System with model subjected to suddenly applied load and temporary absence of field current

out there, its derivative is obviously close to zero and no oscillations should be necessary.

The differentiator does however have a time delay that tends to decrease the stability of the system. It creates oscillations as the system enters the linear region. Instead of being close to zero $\dot{c}$ is nearly eight volts when the system comes into the linear region after a negative error. The output is therefore driven erroneously with $A = A_{min}$ for about 1/20 sec, and a few small oscillations result before the output becomes steady. When the system enters the linear region after a positive error, $\dot{c}$ is close to minus eight volts, and the system is driven with A_{max} for about 1/10 sec. The resulting oscillations are therefore larger than after negative errors.

System Performance with Various Fixed Models

The system was also operated with fixed second order models, in order to see if it was necessary to use an adaptive model.

First the parameters of the fixed model were adjusted for best possible results. TIMEC was set to 1.6 sec and GAIN to 1.0. With these parameter values the response to loading and unloading is basically the same as when the adaptive model was used, as shown in Figure 16. The only difference is that the oscillations are a little larger after the load has been applied. This happens because the switching is too late.

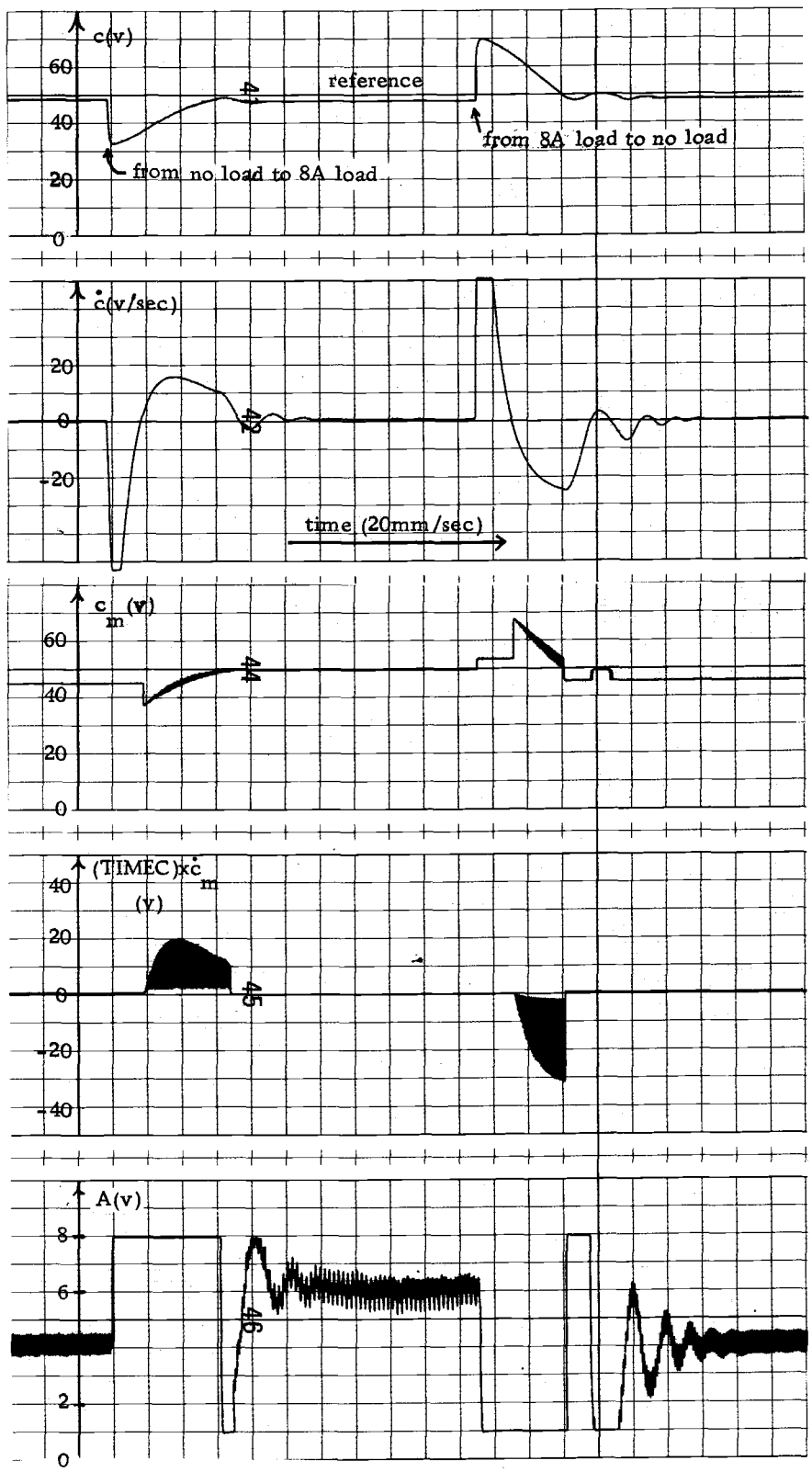

Figure 16. System with fixed model. TIMEC = 1.6 sec, GAIN = 1.0.

In Figure 17 the fixed model has TIMEC = 0.4 sec and GAIN = 2. The resulting response has more overshoot after both loading and unloading than when the model was adaptive. The switching is too late in both cases, because it switches after entering the linear region. Since it never takes advantage of the predictions, it really cannot be called a predictive control system.

Figure 16 and 17 show that the system works good with a fixed model that has carefully adjusted parameters, but if the parameters are not well adjusted, the response becomes bad.

In Figure 18 a fixed model with TIMEC = 1.6 sec and GAIN = 1.0 was used, but the offset for positive errors was not included. The system is then switching too early for positive errors, and the output shoots up before it gets down to its normal operating level. The system is even driven out of the linear region the first time it gets in, and it takes three switchings before it enters the linear region for good.

In order to better compare the four different systems, measurements of overshoot, rise time and settling time were taken. The rise time is the time it takes for the response to rise from 10% to 90% of its final value. The settling time is the time it takes for the response to reach and stay within 5% of its final value (7). The results are displayed in Table II.

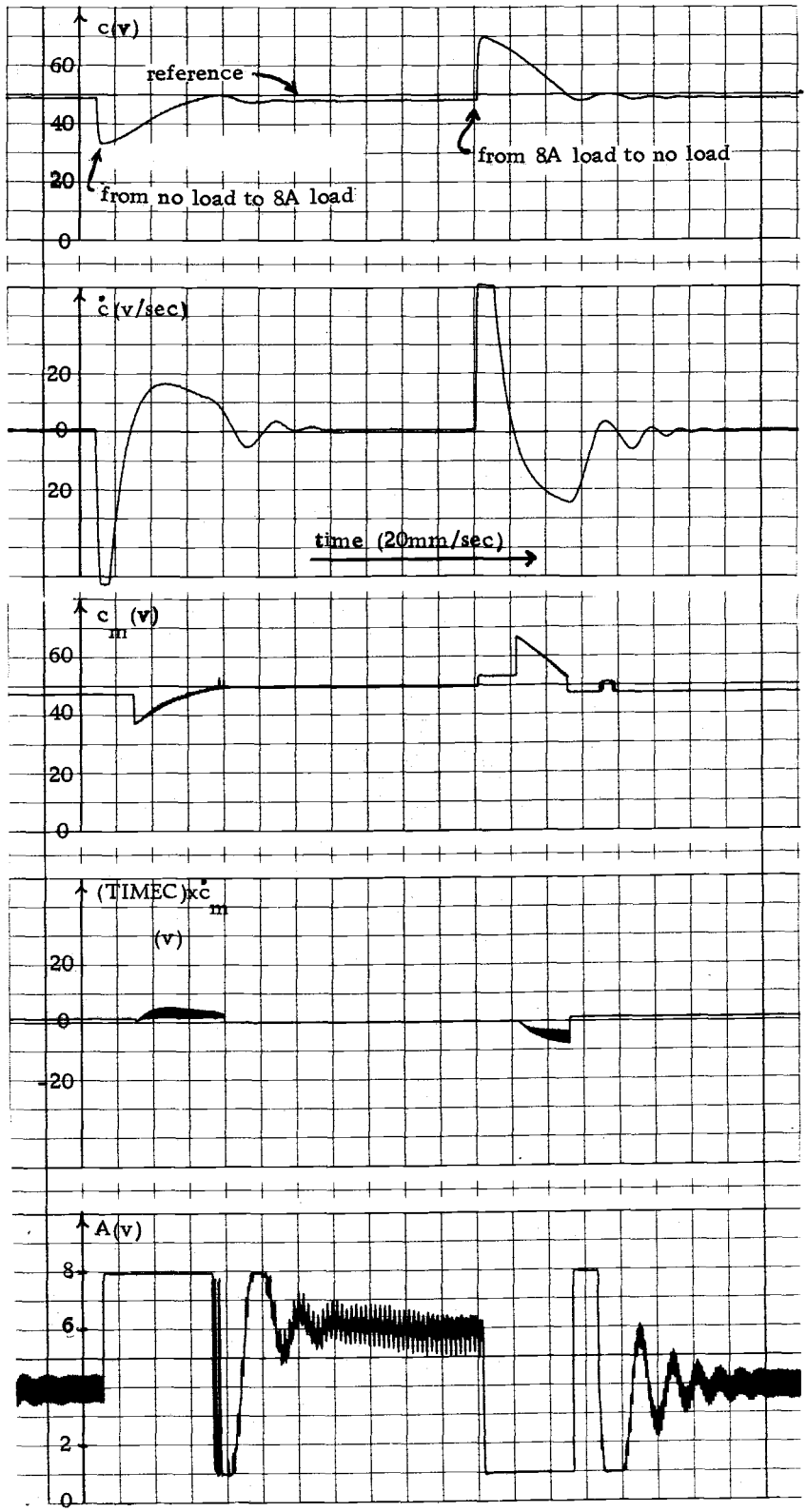

Figure 17. System with fixed model. TIMEC = 0.4 sec, GAIN = 2.0.

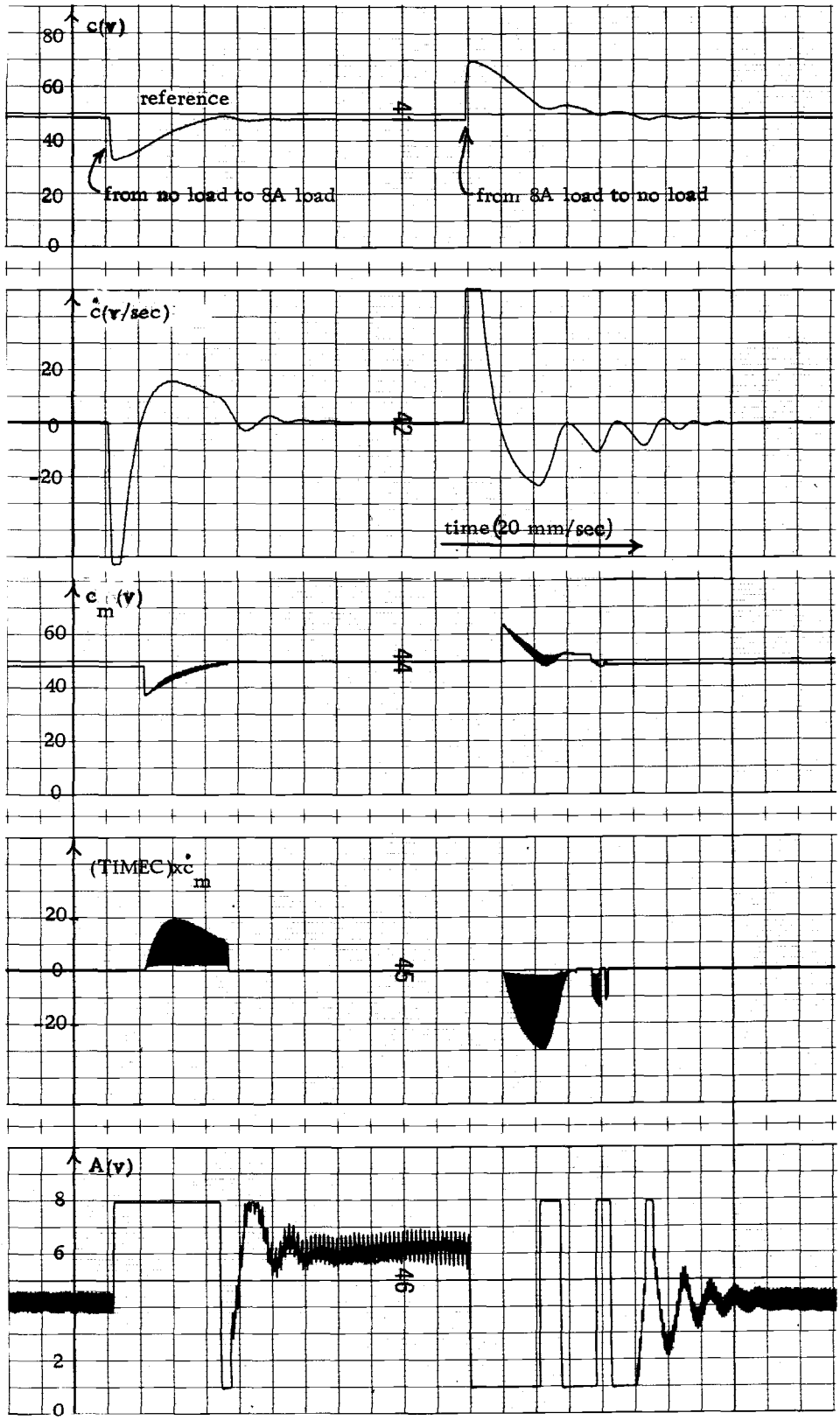

Figure 18. System with fixed model, but without offset.
TIMEC = 1.6 sec, GAIN = 1.0.

Table 2. Transient performance of system with four different fast models, when disturbances are generated by connecting and disconnecting the load.

Model	Load	Overshoot Volts	Overshoot %	Rise Time sec	Settling Time sec
Adaptive with Offset	no load	0	0	0.5	1.0
	8A	0.5	3.4	0.5	0.5
Fixed with TIMEC = 1.6 sec GAIN = 1.0 and Offset	no load	0.5	2.3	0.5	1.0
	8A	1.0	6.7	0.5	0.6
Fixed with TIMEC = 0.4 sec GAIN = 2 and Offset	no load	1.0	4.5	0.5	1.0
	8A	2.0	13.4	0.5	0.9
Fixed with TIMEC = 1.6 sec GAIN = 1.0 without Offset	no load	-4	-18.2	0.9	1.3
	8A	1.0	6.7	0.5	0.6

IV. CONCLUSIONS

It has been shown that a predictive control system using an adaptive model with an offset voltage for positive errors gives best response. The adaptive model was best suited for slow parameter changes, but will also perform well for rapid variations like when the load of the generators suddenly changes.

A fixed model may be used if the parameters are well adjusted. However, in a system with large parameter variations during the operations it is desirable to have an adaptive model.

Excessive noise from the generators and from the communication lines between the generators and the computer made it necessary to filter the output and its derivative. The resulting time delay in the differentiator caused the output to have some transient oscillations when the system entered the linear region. The oscillations after negative errors were smaller than those after positive errors.

Because of time delays in the controller and because the steady state error made it desirable to switch early, best results were obtained when the model was made to simulate a system slower than the generating system.

An advantage of predictive control is that any disturbance outside the linear region is being subjected to the maximum power capabilities of the system. And when a linear region is used, there

does not seem to be any problems with stability.

After any error the state of the system is always driven towards the reference along the same trajectory in the phase plane. The overshoot does therefore not seem to be a function of the magnitude of the error, but only of the adjustment of the model parameters.

The performance of the system depends most upon the speed of the computer, the accuracy of the sensing of the state of the system, and the model accuracy.

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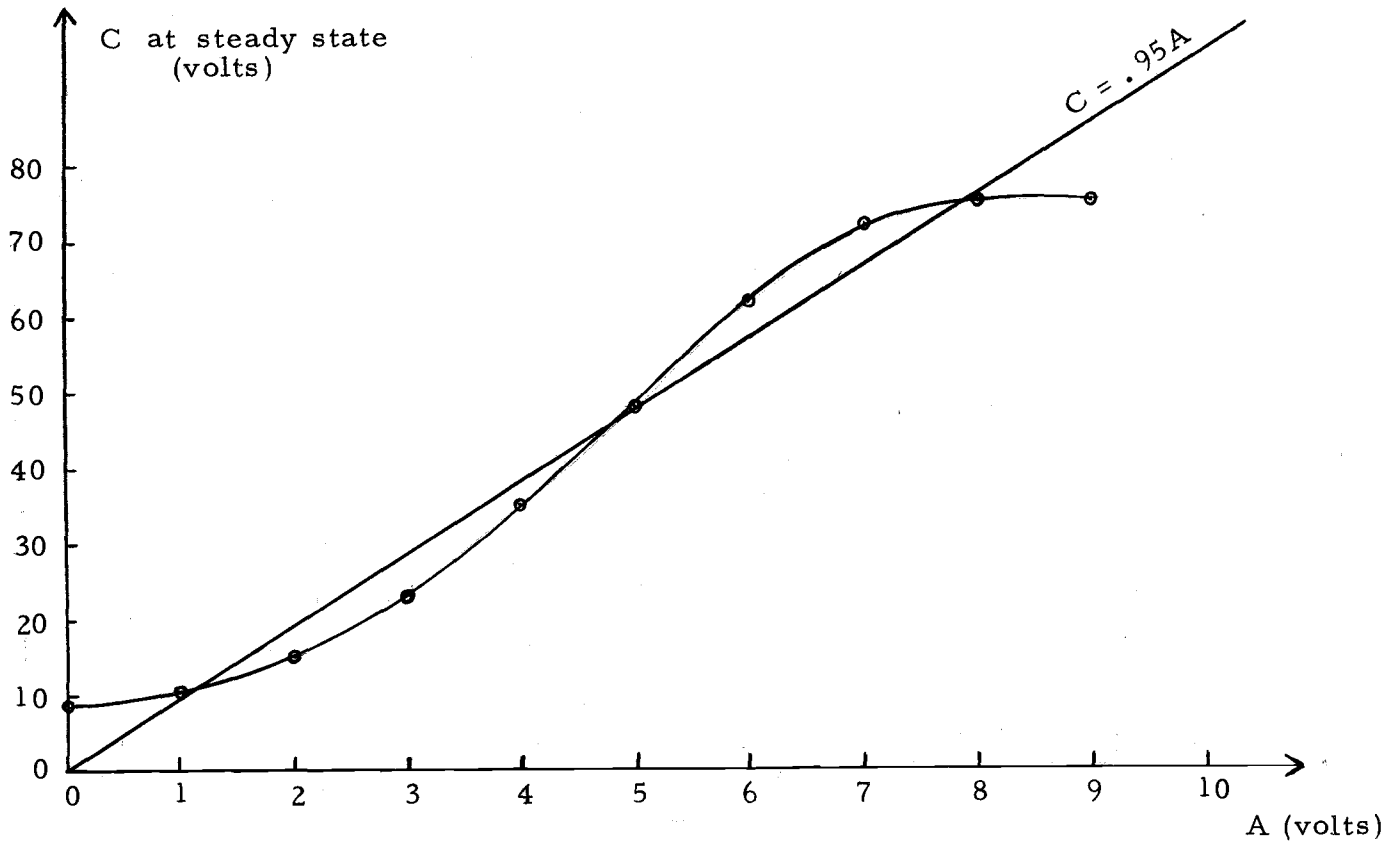
APPENDICES

APPENDIX I

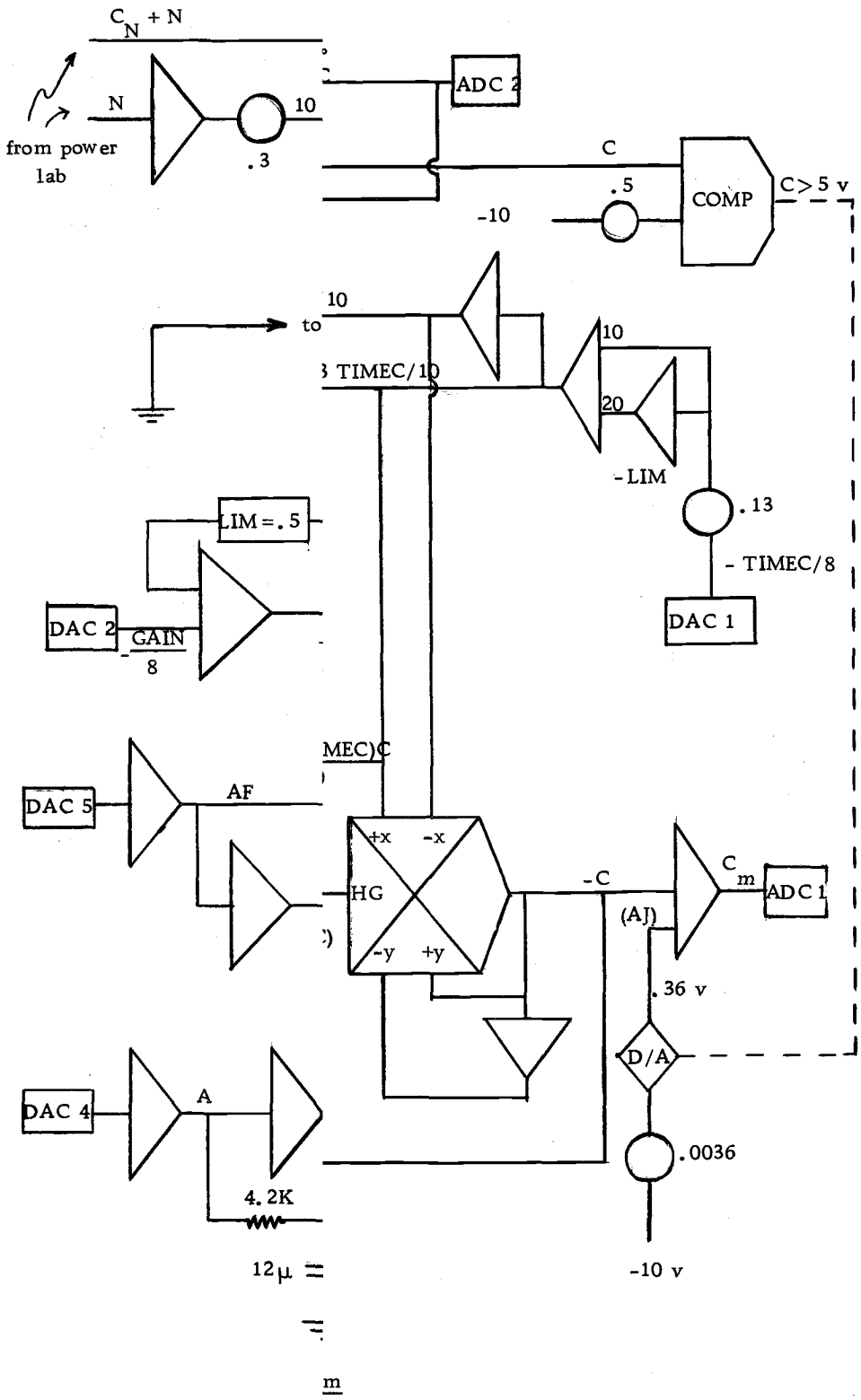
Calibration Curve for Generating System and the Straight Line Approximation used in the Fast Model



Calibration curve for generating system and the straight line approximation used in the fast adaptive model.

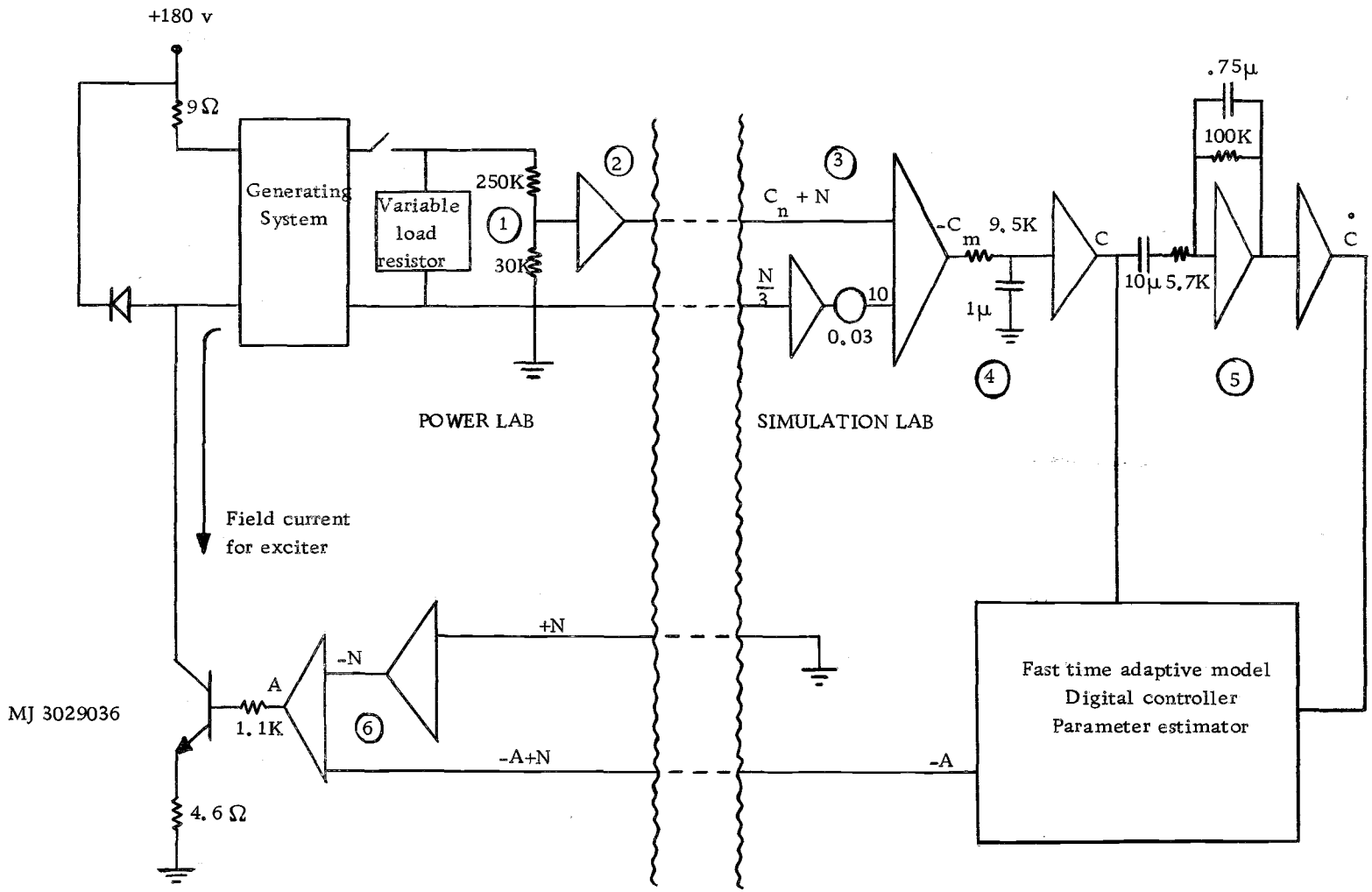
APPENDIX II

Patching on Analog Computer


C_N + N
N
10
.3
from power lab
ADC 2
C
.5
COMP
C > 5 v
-10
10
to
10
TIMEC/10
20
-LIM
.13
- TIMEC/8
DAC 1
LIM = .5
DAC 2
GAIN
8
MEC)C
DAC 5
AF
+x
-x
HG
-y
+y
-C
C_m
ADC 1
(AJ)
.36 v
D/A
DAC 4
A
.0036
4.2K
-10 v

APPENDIX III

Additional Circuitry


+180 v
9Ω
Generating System
Variable load resistor
250K
30K
1
2
3
$C_n + N$
$\frac{N}{3}$
10
0.03
$-C_m$
9.5K
1μ
C
4
5
.75μ
100K
10μ
5.7K
C
POWER LAB
SIMULATION LAB
Field current for exciter
MJ 3029036
A
1.1K
4.6Ω
-N
+N
6
-A+N
-A
Fast time adaptive model
Digital controller
Parameter estimator

A discussion of the additional circuitry that was needed to make the whole system work properly follows. The numbers correspond to the numbers in the figure on the previous page and were used to identify the various items.

1. The high resistance voltage divider attenuates the output voltage by a factor of 0.107. At the reference voltage, which is 50Ω, it only draws a current of 0.18 ma.
2. The inverter has an input resistance of 90 K and could therefore be used to pick up the output from the voltage divider.
3. To all signals transmitted through the lines going from the power lab to the simulation lab there is added some noise. This noise has the shape of a 60 cycle sinewave, 0.60 v peak to peak, plus some of its higher harmonics. To suppress this noise, it was generated separately on another channel and subtracted from the noisy signal. For best results the separately generated noise was amplified by a factor of three.
4. The signal still contains noise. This is mainly coming from the generating system itself and is filtered out with an RC-filter having a corner frequency at 16.9 hz.
5. The differentiator has a gain of one and its two RC-filters have corner frequencies at 2.12 hz and 2.8 hz.

6. Since A , the input to the transistor also contains the noise from the communication channels, the same method of subtracting the noise is used as in 3.

APPENDIX IV

The Digital Program Which Implements the Control Scheme and the Parameter Estimation

```
GNOM    DF      '61     START OF PREDICTIVE CONTROL PROGRAM
        LA      TIMEC   INITIAL VALUE OF TIMECONST
        DO      '141
        LA      GAIN    INITIAL VALUE OF GAIN
        DO      '142
        LA      AMAX
        A       AMIN
        ARS     1
        STA     AMED    AMED=(AMAX+AMIN)/2
        LA      B3000   IC
        DO      '47
        LA      B4000   MODEL IN IC
        DF      '41
        LA      B2000
        DF      '43
        LX      VENT1   START 5 SECOND DELAY
DLAY1   NOP
        NOP
        NOP
        NOP
        DCX     1
        J       DLAY2
        J       CONT    DELAY FINISHED
DLAY2   STX     INDEX
        LX      VENT2
LOOP2   NOP
        NOP
        NOP
        NOP
        DCX     1
        J       LOOP2
        LX      INDEX
        J       DLAY1
CONT    LA      B2000   OP
        DO      '47
P20     LA      B3      READ C
        DF      '64
        DI      '65
        STA     C
        S       REF
        STA     D       D=C-REF
        DO      '143    OUTPUT D AT DAC3
        LA      B2      READ CD
        DF      '64
        DI      '65
        STA     CD
        LA      D       WITHIN LINEAR REGION?
        SKP
        TCA
        C       E
        SL
        J       P15     NO
```

```
        LA      CD
        SKP
        TCA
        C       F
        SGE
        J       P25         YES
P15     LA      D           1ST OR 3RD QUADRANT?
        SKN
        J       P1ØØ
        LA      CD
        SKP
        J       P8          YES
        J       P2ØØ        NO
P1ØØ    LA      CD
        SKN
        J       P8          YES
P2ØØ    LA      D           SET MODEL INPUT
        SKN
        J       P11
        LA      AMIN
        STA     AF          AF=AMIN
        J       P12
P11     LA      AMAX        AF=AMAX
        STA     AF
P12     DO      '145        OUTPUT AF AT DAC5
        LA      B4ØØØ       MODEL IN IC
        DF      '41
        LX      VENT        START 5MSEC DELAY
DELAY   NOP
        NOP
        NOP
        NOP
        DCX     1
        J       DELAY
        LA      B4ØØØ       MODEL IN OP
        DF      '43
        LA      B2ØØØ
        DF      '41
P9      LA      B4          READ CMD
        DF      '64
        DI      '65
        STA     CMD
        LA      CD          CMD DRIVEN TO ZERO?
        SKN
        J       P4Ø
        LA      CMD
        SKN
        J       P41         YES
        J       P9          NO
P4Ø     LA      CMD
        SKN
        J       P9          NO
```

```
P41     LA      B2ØØØ       MODEL IN HOLD
        DF      '43
        LA      B1          READ CM
        DF      '64
        DI      '65
        S       REF
        STA     DM          DM=CM-REF
        LA      D           SWITCH?
        SKN
        J       P42
        LA      DM
        SKN
        J       P43         YES
        J       P44         NO
P42     LA      DM
        SKN
        J       P44         NO
P43     LA      AF          A=AF
        J       P5Ø
P44     LA      AMED        PRESENT VALUE OF AF?
        C       AF
        SLE
        J       P45
        LA      AMIN        A=AMIN
        STA     A
        J       P48
P45     LA      AMAX        A=AMAX
        STA     A
P48     LA      CD          ABS(CD) >LIMT?
        SKP
        TCA
        C       LIMT
        SGE
        J       P49
        LA      C           ESTIMATE TIMECONSTANT
        ARS     3           SCALED BY 1/8
        STA     C
        LA      A
        M       GAIN
        S       C
        D       CD
        STA     TIMEC       TIMEC=(A*GAIN-C)/CD
P49     LA      TIMEC
        DO      '141        DAC1←TIMEC
        LA      A
P5Ø     DO      '144        OUTPUT A AT DAC4
        J       P2Ø
P8      LA      D           1ST OR 3RD QUADRANT
        SKN
        J       P51
        LA      AMAX
        J       P5Ø
```

```
P51     LA      AMIN
        J       P5Ø
P25     LA      X       LINEAR REGION
        M       D
        STA     R
        LA      Y
        M       CD
        A       R
        ALS     6
        STA     R       R=X*D+Y*CD
        C       AMAX
        SGE
        J       P7Ø
        LA      AMAX    A=AMAX, IF R≥AMAX
        STA     A
        J       P8Ø
P7Ø     C       AMIN
        SGE
        J       P71
        STA     A
        J       P8Ø     A=R
P71     LA      AMIN    A=AMIN, IF R< AMIN
        STA     A
P8Ø     LA      B5      READ AF IL T
        DF      '64
        DI      '65
        STA     AFILT
        LA      CD      ABS(CD)< LIMG?
        SKP
        TCA
        C       LIMG
        SLE
        J       P82
        LA      C       ESTIMATE GAIN
        ARS     3       SCALED BY 1/8
        D       AFILT
        STA     GAIN    GAIN=C/A
P82     LA      GAIN
        DO      '142    DAC 2 ←GAIN
        LA      A
        J       P5Ø
INDEX   BSS     1
A       BSS     1
C       BSS     1
D       BSS     1
CD      BSS     1
AF      BSS     1
DM      BSS     1
CMD     BSS     1
R       BSS     1
B4ØØØ   OCT     4ØØØ
B3ØØØ   OCT     3ØØØ
```

```
B2000   OCT     2000
VENT    OCT     764
VENT1   OCT     11
VENT2   OCT     177777
B1      OCT     1
B2      OCT     2
B3      OCT     3
B4      OCT     4
B5      OCT     5
AMAX    OCT     63000
AMIN    OCT     6300
AMED    BSS     1
REF     OCT     40000
E       OCT     2000
F       OCT     5000
X       OCT     137777
Y       OCT     177677
GAIN    OCT     4000
TIMEC   OCT     70000
AFILT   BSS     1
LIMG    OCT     6
LIMT    OCT     10000
        END     GNOM
```