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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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2. Transient performance of system with four different fast models, when disturbance is generated by connecting and disconnecting the load.
LIST OF VARIABLES

A = actuation signal (output from controller)

AF = input to model

A$_{\text{max}}$ = upper boundary for possible values of A

A$_{\text{min}}$ = lower boundary for possible values of A

C = output voltage after filtering away high frequency noise

D = derivative of output voltage

C$_{\text{m}}$ = output from fast model

D$_{\text{m}}$ = derivative of model output

C$_{\text{n}}$ = output voltage with high frequency noise from generator

D = system error

D$_{\text{m}}$ = derivative of system error

D$_{\text{m}}$ = model error

D$_{\text{m}}$ = derivative of model error

(d$_1$, d$_1$) = state of system just prior to i'th run of model

D$_{\text{f}}$ = final error of ideal predictive control system

D$_{\text{m,0}}$ = model error when D$_{\text{m}}$ = 0

D$_{\text{ss}}$ = steady state error

ΔD = change in error between successive runs of model

GAIN = estimated gain of generating system at steady state

I$_{\text{f}}$ = field current of the exciter (input to generating system)

K = steady state gain of generating system
\[ N = \text{noise from communication lines between power lab and simulation lab} \]

\[ \text{ref} = \text{desired output voltage} \]

\[ T_g = \text{time constant of the generator} \]

\[ T_{\text{ex}} = \text{time constant of the exciter} \]

\[ \text{TIMEC} = \text{estimated time constant of the equivalent first order system} \]

\[ X, Y = \text{constants} \]
REAL TIME PREDICTIVE CONTROL OF GENERATING SYSTEM USING HYBRID COMPUTER AND A FAST TIME ADAPTIVE MODEL

1. 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.](image)

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
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

![Block Diagram of Control System](image)

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

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 $1.5 \Omega$ 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.

<table>
<thead>
<tr>
<th>Description</th>
<th>Manufacturer</th>
<th>Serial No.</th>
<th>Function</th>
<th>Power</th>
<th>Voltage</th>
<th>Current</th>
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<tr>
<td>3φ Induction Motor</td>
<td>Westinghouse</td>
<td>1S5G3032</td>
<td>drives exciter</td>
<td>15 hp</td>
<td>126-220v</td>
<td>66-38A</td>
</tr>
<tr>
<td>3φ Induction Motor</td>
<td>General Electric</td>
<td>3766826</td>
<td>drives gen.</td>
<td>5 hp</td>
<td>220v</td>
<td>14.1 A</td>
</tr>
<tr>
<td>d-c Generator</td>
<td>Westinghouse*</td>
<td>1S5G3033</td>
<td>exciter</td>
<td>15 KW</td>
<td>250v</td>
<td>60 A</td>
</tr>
<tr>
<td>d-c Motor</td>
<td>General Electric</td>
<td>2027250</td>
<td>generator</td>
<td>5 hp</td>
<td>230v</td>
<td>19.6 A</td>
</tr>
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</table>

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 \( A_{\text{min}} \leq A \leq A_{\text{max}} \).

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 \( A = A_{\text{max}} \), and then let \( A \) be switched to \( A_{\text{min}} \) when the state of the system reaches S. For the state of the system to reach the origin \( c = \text{ref} \) in shortest possible time from anywhere in the phase
plane, \( A \) can only have the values \( A_{\text{max}} \) or \( A_{\text{min}} \), 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 \( A = A_{\text{min}} \) or \( A_{\text{max}} \) 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 \((d_m, 0)\) 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 \(A_{\min}\).

Figure 6. System and model trajectories.
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 $\Delta d$, and the final error be $d_f$. Then $d_f$ is bounded above by $2\Delta d$ and below by $\Delta d$ ($\Delta d \leq d_f \leq 2\Delta d$).

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

$$ A = X \cdot d + Y \cdot d^\circ $$  \hspace{1cm} (1)

Figure 7. Areas of prediction.

Since the system moves towards the origin only in the second and fourth quadrant, the switching curve $T$ 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 $A_{\text{min}}$. 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. $A_{\text{min}}$ could just be applied, and prediction start when G is reached. The model must however be used to find out on which side of T the system is. So the model is set to state E and forced with A equal to $A_{\text{min}}$. If $d_{m,0}$ is positive, A is set equal to $A_{\text{min}}$. If $d_{m,0}$ is negative, A is set equal to $A_{\text{max}}$. 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 $A_{\text{min}} < A < A_{\text{max}}$ 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.

\[ \text{Ref}(s) \rightarrow \text{D}(s) \rightarrow X + sY \rightarrow G(s) \rightarrow C(s) \]

**Figure 8. System in the linear region.**

Since the reference is a step function, the steady state error is

\[
\text{d}_{ss} = \frac{\text{ref}}{1 + \lim_{s \to 0} G(s)(X + sY)}
\]

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

\[
\text{d}_{ss} = \frac{\text{ref}}{1 + \text{GAIN} \cdot X}
\]

Since \( \text{ref} = 50 \) volts, \( X = -25.6 \) and GAIN is 1.24 at no load and 0.82 at eight ampers load, \( \text{d}_{ss} \) 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 load current 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

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

(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

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

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 $\alpha$ was added to $c_m$ whenever the error was positive. It caused the input to switch later for positive errors, and when $\alpha$ 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.
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

\[
\frac{c}{A} = \frac{\text{GAIN}}{1 + (\text{TIMEC})D}
\]  

(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 $T_{\text{ex}}$ 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 $\text{T}_{\text{MEC}}$, and gives

$$\text{T}_{\text{MEC}} = \frac{A \cdot \text{GAIN} - c}{c}, \text{ for } c \neq 0$$  \hspace{1cm} (7)

The gain of the system is given by

$$\text{GAIN} = \frac{c}{A}, \text{ at steady state conditions}$$  \hspace{1cm} (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.

$\text{T}_{\text{MEC}}$ 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 $T_{\text{ex}}$ does not quite dominate $T_g$ as assumed when Equation (7) was derived. As $\dot{c}$ increases, however, $\text{T}_{\text{MEC}}$ approaches a fairly good estimate of $T_{\text{ex}}$. To keep the erroneous values of $\text{T}_{\text{MEC}}$ from saturating the model on the analog computer, $\text{T}_{\text{MEC}}$ 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

\[
\frac{\text{TIMEC}}{GAIN} = \frac{T_{ex}}{k}
\]  \hspace{1cm} (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

START

Set initial values of TIMEC, GAIN

Read $C, C_{\text{ref}}$

d = $C - C_{\text{ref}}$

Inside lin. region?

In 1. or 3 quadrant?

Yes

AF = $A_{\text{max}}$

R = $X_d + Y_C$

If $A_{\text{min}} < R < A_{\text{max}}$

let $A = R$

If $R > A_{\text{max}}$, let

$A = A_{\text{max}}$

If $R < A_{\text{min}}$, let

$A = A_{\text{min}}$

Estimate GAIN if $|C| < 0.018 \text{v/sec}$

Apply GAIN to fast model

Estimate TIMEC if $|C| > 6.3 \text{v/sec}$

Apply TIMEC to model

Set $A$ to opposite of AF

Apply $A$ to input of generating system

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 12 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 $c_m$ 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 ($A_{\text{max}}$). 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 $A_{\text{max}}$, 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 $A_{\text{max}}$ and $A_{\text{min}}$, and has much smaller oscillations after the system has entered the linear region.

When the input switched the first time in Figure 12, $\text{TMEC}$ 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 $A = A_{\text{max}}$. When it gets close to the $d$-axis, $A$ switches to $A_{\text{min}}$, 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 $c$ is nearly eight volts when the system comes into the linear region after a negative error. The output is therefore driven erroneously with $A = A_{\text{min}}$ 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, $c$ is close to minus eight volts, and the system is driven with $A_{\text{max}}$ 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.

<table>
<thead>
<tr>
<th>Model</th>
<th>Load</th>
<th>Overshoot</th>
<th>Rise Time</th>
<th>Settling Time</th>
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<tr>
<td></td>
<td></td>
<td>Volts</td>
<td>%</td>
<td>sec</td>
</tr>
<tr>
<td>Adaptive with Offset</td>
<td>no load</td>
<td>0</td>
<td>0</td>
<td>0.5</td>
</tr>
<tr>
<td>Fixed with TIMEC = 1.6 sec GAIN = 1.0 and Offset</td>
<td>8A</td>
<td>0.5</td>
<td>3.4</td>
<td>0.5</td>
</tr>
<tr>
<td>Fixed with TIMEC = 0.4 sec GAIN = 2 and Offset</td>
<td>no load</td>
<td>1.0</td>
<td>4.5</td>
<td>0.5</td>
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<tr>
<td>Fixed with TIMEC = 1.6 sec GAIN = 1.0 without Offset</td>
<td>8A</td>
<td>2.0</td>
<td>13.4</td>
<td>0.5</td>
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</table>
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.
BIBLIOGRAPHY


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
from power lab

DAC 2

DAC 5

DAC 4

ADC 1

ADC 2

COMP

C > 5 v

TIMEC/8

TIMEC/10

DAC 1

MEC/C

AF

4.2K

12 μ =

m
APPENDIX III

Additional Circuitry
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
START OF PREDICTIVE CONTROL PROGRAM

INITIAL VALUE OF TIMECONST

INITIAL VALUE OF GAIN

MODEL IN IC

START 5 SECOND DELAY

DELAY FINISHED

DELAY FINISHED

WITHIN LINEAR REGION?

NO
LA CD
SKP TCA C SGE
J P25 YES
P15 LA D 1ST OR 3RD QUADRANT?
SKN J P100
LA CD
SKP J P8 YES
J P200 NO
P100 LA CD
SKN J P8 YES
P200 LA D SET MODEL INPUT
SKN J P11
LA AMIN STA AF AF=AMIN
J P12
P11 LA AMAX STA AF AF=AMAX
DO '145 OUTPUT AF AT DAC5
P12 LA B4000 MODEL IN IC
DF '41
LX VENT START 5MSEC DELAY
DELAY NOP
NOP
NOP
NOP
DCX 1
J DELAY
LA B4000 MODEL IN OP
DF '43
LA B2000
DF '41
P9 LA B4 READ CMD
DF '64
DI '65
STA CMD
LA CD CMD DRIVEN TO ZERO?
SKN J P40
LA CMD
SKN J P41 YES
J P9 NO
P40 LA CMD
SKN J P9 NO
B2000

MODEL IN HOLD

READ CM

DM=CM-REF

SWITCH?

YES

NO

PRESENT VALUE OF AF?

A=AF

A=AMIN

A=AMAX

ABS(CD) > LIMIT?

ESTIMATE TIME CONSTANT

SCALED BY 1/8

TIMEC=(A*GAIN-C)/CD

DAC1=TIMEC

OUTPUT A AT DAC4

1ST OR 3RD QUADRANT
LA AMIN
J P50

LA X
M D
STA R
LA Y
M CD
A R
ALS 6
STA R R=X*D+Y*CD
C AMAX
SGE
J P70
LA AMAX A=AMAX, IF R>AMAX
STA A
J P80
C AMIN
SGE
J P71
STA A
J P80 A=R
LA AMIN A=AMIN, IF R<AMIN
STA A

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
LA GAIN
DO '142 DAC 2→GAIN
LA A
J P50

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