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ANALOG COMPUTER SIMULATION OF A PARASITICALLY LOADED ROTATING ELECTRICAL POWER GENERATING SYSTEM

by Leonard J. Gilbert

Lewis Research Center

Cleveland, Ohio 44135

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16. Abstract

An analog computer simulation of a parasitically loaded rotating electrical power generating system was developed to facilitate study of the dynamic performance of the system. System equations are expressed in terms of direct and quadrature axis variables in order to simplify the analysis. Identity of the system components is retained in the simulation so that component parameters can be readily varied and the effects observed. The simulation is applicable to the analytical study of paralleled systems.

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SUMMARY

An analog computer representation was developed to simulate an alternator with a parasitically loaded speed controller. The simulation permits the study of the dynamic and steady-state behavior of the average values of the electrical characteristics of the power generating system. A detailed simulation of the electrical performance of a parasitically loaded power generator had not been developed previously.

The discussion describes a balanced three-phase electrical generating system with balanced loads. The computer representations for all of the electrical components are presented. The identity of the components is retained in the simulation. Speed regulation, voltage regulation, load power factor, saturation effects, and amortisseur damping are factors included in the representation. A good correspondence between computer and theoretical performance results, indicating that the simplifying assumptions are acceptable.

The simulation is designed specifically to accommodate the study of paralleled parasitically loaded alternators. A transformation to direct and quadrature reference axes is used in the analysis.

INTRODUCTION

An analog computer simulation was developed to simulate an electrical generating system consisting of an alternator with a parasitically loading speed controller. The simulation described provides a means of studying the dynamic performance of such an electrical power system. The computer output signals are proportional to average values of the electrical quantities simulated. Analog computer simulations of a parasitically loaded alternator have been reported by Tew (ref. 1) and Holt (ref. 2). But the detailed simulation described here has not been developed previously. In particular the

simulation is designed to be useful for studying the performance of paralleled parasitically loaded generating systems.

Several power generating systems are being developed for space applications (refs. 3 to 5). The systems operate with constant total electrical loads provided by means of parasitic loads. Parasitic loading is an operational mode resorted to when the energy in the system energy source is relatively unlimited. As a consequence of its unlimited energy, the source can be used to control the generating system as well as to supply the electrical requirements of a useful load.

In these parasitically loaded equipments the parasitic load is used to complement the operational or useful load of the alternator so that the sum of all loads on the alternator is constant, as illustrated in figure 1. By thus limiting the load torque on the tur-
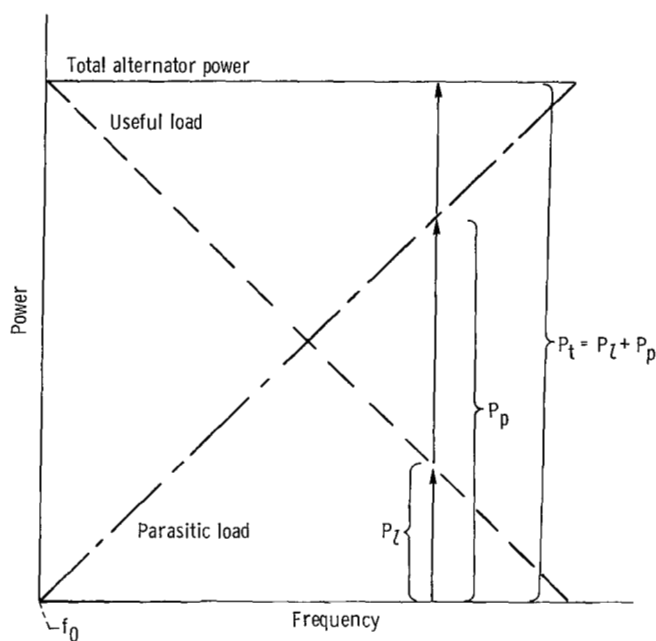

Figure 1. - Schematic diagram of ideal load distribution of parasitically loaded alternator.

bine drive, the turbine speed is also limited. The magnitude of the parasitic load required to balance a particular useful load is determined by a controller which senses the electrical frequency of the alternator output. This frequency varies inversely with the useful load applied to the alternator. By appropriate design of the sensing and loading circuits, the parasitic load and its control is made to serve as a speed control.

The parasitic loading control approach is resorted to in closed-cycle space power generating systems in order to avoid rapid control of source energy and precise flow control of the working fluid in the system. Such controls are necessary if the working

fluid flow is used to regulate the turbine speed. However, high operating temperatures, the fast reaction speeds required, and the corrosive nature of some working fluids make it undesirable to vary flows continuously for turbine regulation.

In a series of studies for the U. S. Air Force in 1957 the Energy Conversion Group at the Massachusetts Institute of Technology developed a simulation of aircraft electrical power generating systems (ref. 6). The approach used here is modeled after that development. However, in the aircraft systems simulations parasitic loading of the alternator is not a factor, whereas it is an integral part of some space power systems.

The discussion which follows describes a balanced three-phase alternator with balanced loads. The computer representations for all of the electrical subsystem components are presented, followed by a sample set of displays of characteristic electrical signals from the simulation.

The specific system simulated is comprised of the following principal components:
(1) Turbine driven alternator
(2) Voltage regulator and exciter
(3) Parasitic load speed controller
(4) Useful load
The identification of each component of the system described is retained in the simulation. Physical parameters which determine the characteristics of the system components are identifiable. Speed regulation, voltage regulation, load power factor, saturation effects, amortisseur damping, and saliency are factors included in the representation. The simulation is flexible enough so that it can be augmented to include the dynamics of the drive, and startup and shutdown operation, although this is not done here.

MATHEMATICAL REPRESENTATION OF ELECTRICAL SYSTEM COMPONENTS

System Configuration

The program described simulates the electrical system illustrated in figure 2. A three-phase synchronous alternator is turbine driven with constant power. The electrical output of the alternator is applied to (1) a load representing the desired output, termed the useful load, and to (2) a parallel load, termed the parasitic load. Because of the user's varying demands, the useful load varies. The parasitic load is used to keep the total load constant by balancing it with the input. By keeping the total load power constant the parasitic load functions as a speed control. A voltage regulator-exciter energizes the alternator field and regulates the terminal voltage of the alternator as the volt-ampere demand varies.
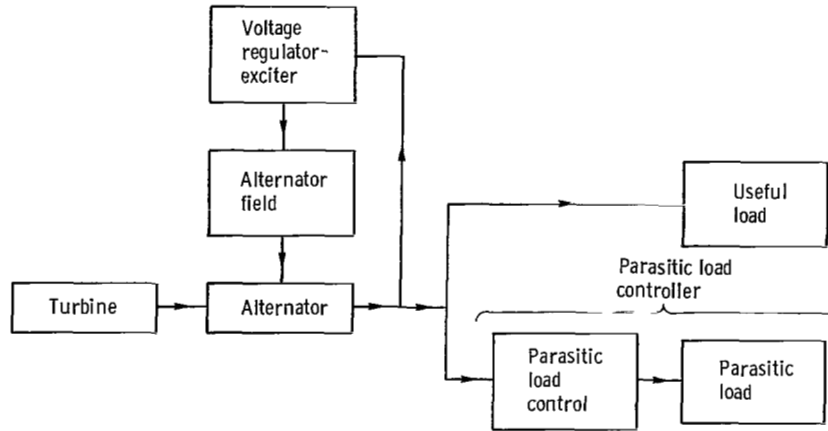
Figure 2. - Electrical power generating system block diagram.

Analytical Approach

In order to study the dynamic performance of the electrical quantities of the system the set of simultaneous differential equations which describe the system must be solved. The solution of these equations is extremely complicated unless use is made of a transformation suggested by Blondel's "two-reaction method" and developed by Park (ref. 7). The equations described in this report have been simplified by resolving the variables into components along direct and quadrature axes. This is a standard analytical approach, and discussions of this approach are widely available in modern literature on synchronous machines (ref. 5). However, the use of quadrature reference axes for the variables is a significant feature of this simulation, and the feature which differentiates it from previous simulations of parasitically loaded generating systems.

The simulation was undertaken for use ultimately in studying the dynamic behavior of paralleled parasitically loaded alternators. For paralleled systems information with respect to the relation between voltage and current and rotor is necessary for a complete understanding of performance. The use of the dq transformation not only greatly simplifies the solution of the system equations, but also facilitiates the determination of voltage-current phase relations.

When used for the study of two paralleled systems, duplicate equipments described here are required, in addition to transformation and load sharing networks.

Assumptions

The following assumptions have been made to facilitate and simplify the analysis:

(1) There is sinusoidal air gap flux distribution and sinusoidal winding distribution; that is, the magnetomotive forces in the armature are sinusoidally distributed.

(2) Phase loads are balanced.

(3) Eddy current and hysteresis losses can be neglected.

(4) Saturation effects take place only in the direct axis circuits.

(5) Rotor damping can be represented by including two windings, one in the direct axis and one in the quadrature axis.

(6) Friction and windage losses are neglected.

(7) Turbine output power is constant.

Assumptions (1) to (3) are basic assumptions made by R. H. Park (ref. 7) in the development of his synchronous machine analysis. That analysis provides the basic circuit equations used to describe the alternator. Assumption (4) reduces the complexity of the simulation. This reduction is desirable and, in view of the alternator performance data usually available, is warranted. The usefulness of the simulation is not substantially reduced by this simplification. Assumption (5) is made because it is not possible to define a current path through a solid rotor. A fictitious set of damper windings is assumed. The windings are represented in the analysis by one winding in each of the quadrature axes.

Alternator

The conventional generator equations, in terms of direct and quadrature components, as developed by R. H. Park, are listed in this section. They describe the functioning of the circuits shown in figure 3. These equations are expressed in a per unit system chosen to make all the mutual reactances in any axis, d or q equal (ref. 8). (All symbols are defined in the appendix.)

$$v_f = R_f i_f + p\psi_f$$

$$v_d = -R_a i_{td} + p\psi_d - \omega\psi_q$$

$$v_q = -R_a i_{tq} + p\psi_q + \omega\psi_d$$

$$0 = R_{kd} i_{kd} + p\psi_{kd}$$

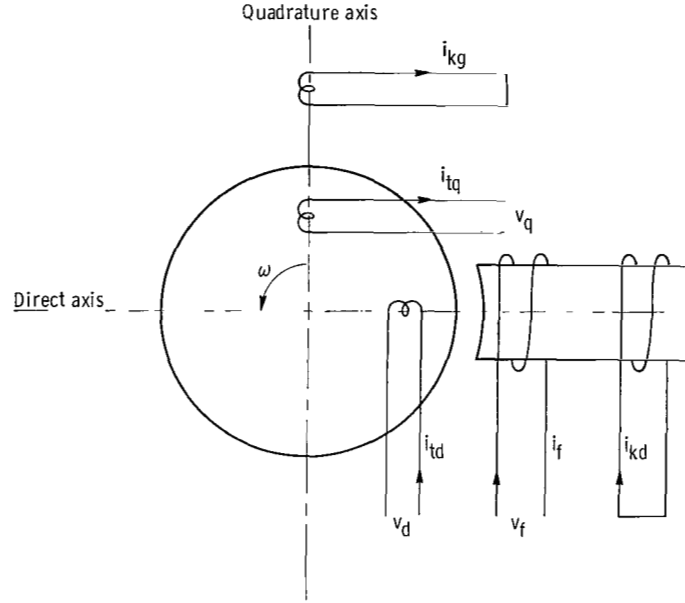$$0 = R_{kq} i_{kq} + p\psi_{kq}$$

Figure 3. – Schematic diagram of synchronous generator with two damper windings.

The flux linkages in the preceding voltage equations are as follows:

$$\psi_f = \psi_{md} + \psi_{fL} = \psi_{md} + X_{fL} i_f$$

$$\psi_d = \psi_{md} + \psi_{dL} = \psi_{md} - X_{aL} i_{td}$$

$$\psi_q = \psi_{mq} + \psi_{qL} = \psi_{mq} - X_{aL} i_{tq}$$

$$\psi_{kd} = \psi_{md} + \psi_{kdL} = \psi_{md} + X_{kd} i_{kd}$$

$$\psi_{kq} = \psi_{mq} + \psi_{kqL} = \psi_{mq} + X_{kq} i_{kq}$$

The mutual flux linkages are

$$\psi_{md} = X_{md}(i_f - i_{td} + i_{kd})$$

$$\psi_{mq} = X_{mq}(-i_{tq} + i_{kq})$$

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The active and reactive power generated at the terminals of the alternator and the electromagnetic torque developed are given by

$$P_t = v_d i_{td} + v_q i_{tq}$$

$$Q_t = -v_d i_{tq} + v_q i_{td}$$

$$T_l = \psi_d i_{tq} - \psi_q i_{td}$$

Useful Load

The useful loads applied to the alternator consist of series resistance and inductance as illustrated in figure 4. In terms of the direct and quadrature components of current, the load voltages are expressed as

$$v_d = R_l i_{ld} + X_l (p i_{ld}) - X_l \omega i_{lq}$$

$$v_q = R_l i_{lq} + X_l (p i_{lq}) + X_l \omega i_{ld}$$

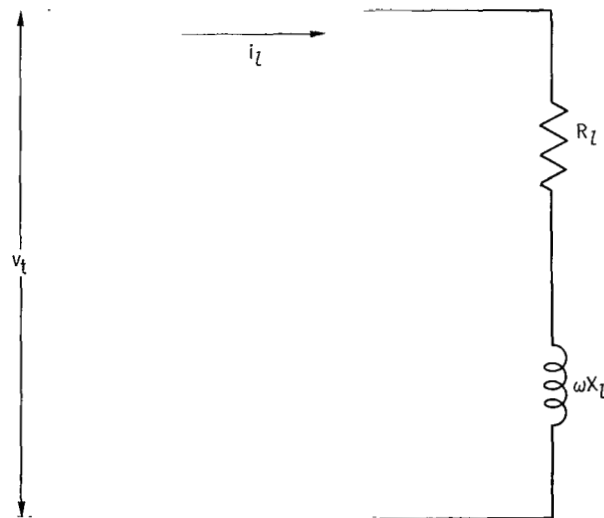These equations can be rewritten to eliminate the requirement of an explicit X_l.

Figure 4. – Schematic of useful load.

(This elimination simplifies the application of varied loads in the simulation.) Dividing each side of the equation by R_l gives

$$\frac{v_d}{R_l} = i_{ld} + \tan\theta_l (pi_{ld}) - \omega \tan\theta_l \, i_{lq}$$

$$\frac{v_q}{R_l} = i_{lq} + \tan\theta_l (pi_{lq}) + \omega \tan\theta_l \, i_{ld}$$

For a given power factor useful load, only R_l need be varied to vary the magnitude of the load.

The currents i_{dl} and i_{ql} are components of the total current components i_{td} and i_{tq} which are determined from the alternator equations. Since the useful load current and the parasitic load current are assumed to comprise the total alternator current,

$$i_{td} = i_{ld} + i_{pd}$$

$$i_{tq} = i_{lq} + i_{pq}$$

The power dissipated in the useful load is equal to

$$P_l = v_d i_{ld} + v_q i_{lq}$$

Speed Controller

The parasitic load speed controller is a control feature which distinguishes this electrical generating system from conventional turboalternator electrical generating systems. Figure 5 is a functional block diagram of the controller. The controller sim-
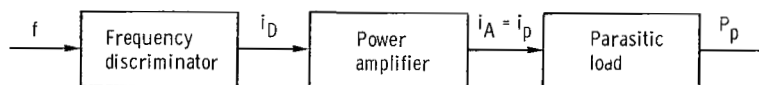
Figure 5. - Block diagram of parasitically loading speed controller.

ulated is a proportional control: output load current is proportional to the deviation of the input signal frequency from a nominal value Ω_0.

When the controller is operating, the frequency deviation is detected and measured by the frequency discriminator. The output of the discriminator, amplified, determines the magnitude of the alternator current through the parasitic load resistor.

In existing developmental parasitic load speed controllers (SNAP-2, SNAP-8, Brayton Power Systems) the control of the current through the load resistor is performed by phase control with saturable reactors or silicon controlled rectifiers (refs. 3 to 5, and 9). Such a phase-controlled current is illustrated in figure 6. Varying the firing angle
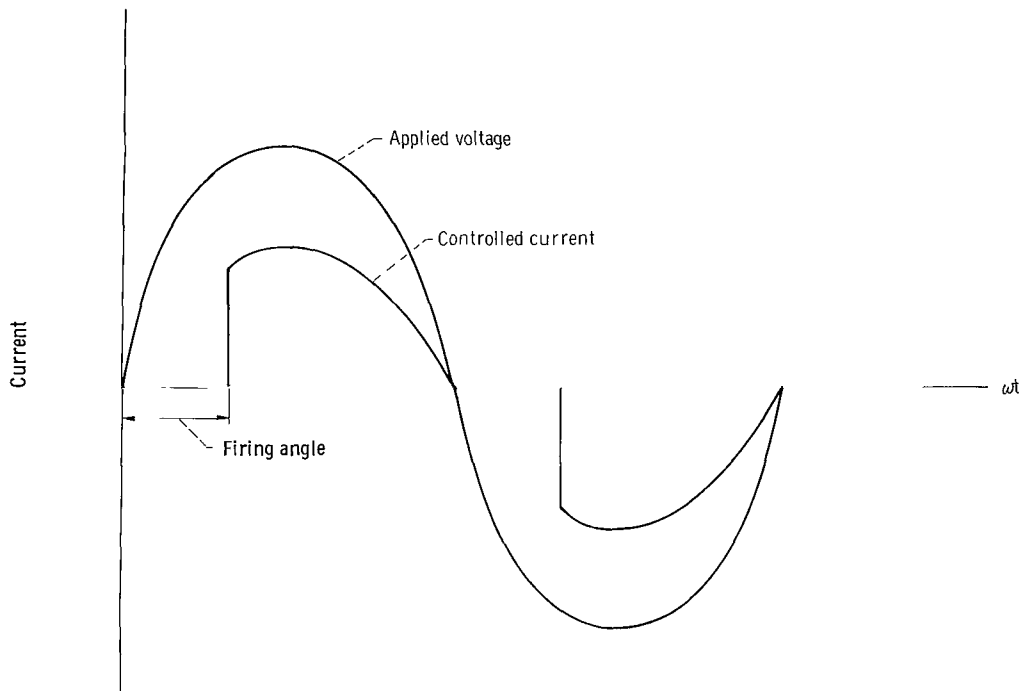
Figure 6. - Waveshape of phase-controlled current.

(fig. 6) changes the effective value of this nonsinusoidal current. But in addition to changing the value of the current, varying the firing angle also has the effect of changing the phase angle between the applied voltage and the fundamental component of the nonsinusoidal current. The current fundamental lags the voltage as in an inductive circuit. It is this fundamental component of parasitic load current which is the power producing component. Thus, in effect, the variation of parasitic power is the result of a variable inductance. This effect is fully analyzed in reference 10.

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The computer simulation of the speed controller is based upon this variable inductive effect of phase-controlled current.

Frequency discriminator. - The frequency discriminator is represented in the simulation as a first degree lag network whose transfer function (ref. 11) is

$$i'_D = \frac{K_D \, \Delta f}{\tau_D p + 1}$$

where

$$\Delta f = f - f_0 = \frac{\Omega - \Omega_0}{2\pi} \geq 0$$

(The zero limitation is imposed because a frequency less than f_0 implies a negative useful load, a nonrealistic quantity. See fig. 1.) The steady-state characteristic of the discriminator is illustrated in figure 7(a) where i_{D0} is the output current of the discriminator at a frequency f_0. Thus

$$i_D = i'_D + i_{D0}$$

Power amplifier. - The power amplifier has also been represented as a first degree lag network (ref. 11) whose transfer function is
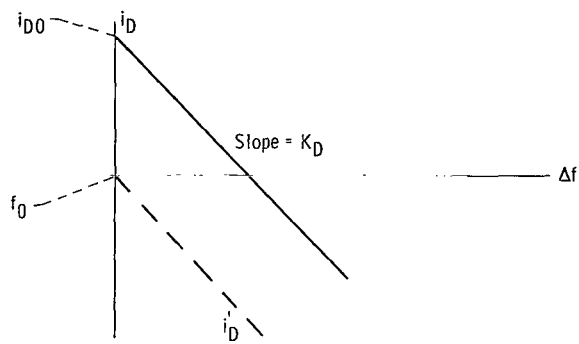
$$i'_A = \frac{K_A i_D}{\tau_A p + 1}$$

The steady-state characteristic of this amplifier is illustrated in figure 7(b); thus
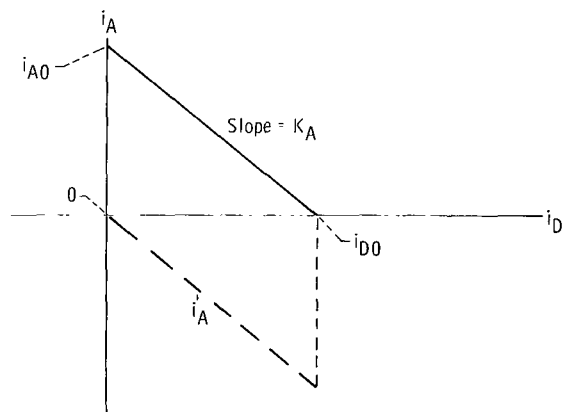
$$i_A = i'_A + i_{A0}$$

where i_{A0} is the amplifier output current when $i_D = 0$, and is such a value that
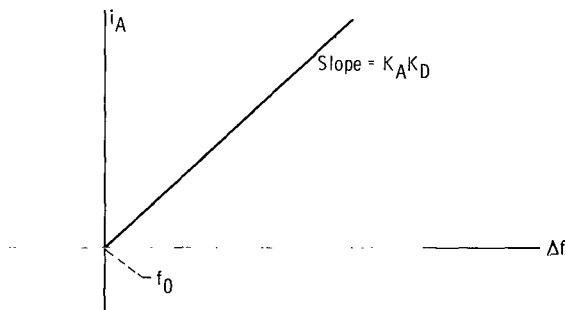
$$i_{A0} = -K_A i_{D0}$$

The combined steady-state characteristic for the discriminator and amplifier is as shown in figure 7(c).

(a) Characteristic of frequency discriminator.

(b) Characteristic of power amplifier.

(c) Combined characteristic of discriminator and amplifier.

Figure 7. - Form of steady-state characteristics of simulated speed
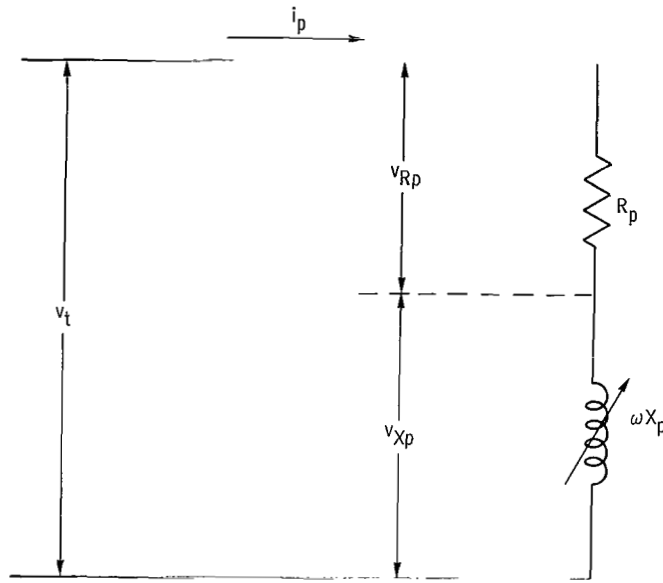controller components.

Figure 8. - Schematic of equivalent parasitic load.

Parasitic load. - In order to simulate the effect of current phase control, the parasitic load impedance is represented as a series fixed resistance and a variable inductance as in figure 8.

Calculation of parasitic power. - The computer is programmed to balance the input and output powers of the alternator. The power provided by the turbine is presumed to be constant and is so set. The power is assumed to be completely transferred across the alternator air gap and dissipated in the field, the armature windings, and the useful and parasitic loads; that is,

$$P_{In} = P_f + P_a + P_l + P_p$$

(For convenience P_f and P_a may be considered part of P_l.)

In demonstrating the performance of the generating system a purposeful change is made in the useful load, producing a load torque change in the system. The resulting turbine and load torque unbalance produces a speed change. The rotary speed becomes

$$\omega = \frac{1}{p} \frac{T_T - T_l}{J}$$

The parasitic load speed controller reacts to the speed change until the parasitic load change compensates for the useful load change and the turbine and load torques balance.

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The power dissipated in the parasitic load resistor is

$$P_p = i_p^2 R_p$$

Since R_p is fixed, in order that the current indicated in this equation equal the parasitic current generated by the speed control amplifier, the inductance value must vary. The analytical expression used to compute the reactance required to balance the system is

$$X_p = \frac{v_{Xp}}{\omega i_p} = \frac{\left(v_t^2 - i_p^2 R_p^2\right)^{1/2}}{\omega i_p}$$

In terms of the direct and quadrature components, the parasitic current becomes

$$i_{pd} = \frac{1}{X_p} \frac{1}{p} v_d - \frac{R_p}{X_p} \frac{1}{p} i_{pd} + \omega \frac{1}{p} i_{pq}$$

$$i_{pq} = \frac{1}{X_p} \frac{1}{p} v_q - \frac{R_p}{X_p} \frac{1}{p} i_{pq} - \omega \frac{1}{p} i_{pd}$$

and the power dissipated in the parasitic load resistor is

$$P_p = v_d i_{pd} + v_q i_{pq}$$

Voltage Regulator-Exciter

The model used for the voltage regulator is represented by a lead-lag network whose transfer function is given as

$$v_f = \frac{K(1 + \tau_1 p)}{1 + \tau_1 p} v_e$$

where the error signal

$$v_e = v_{Ref} - K_1 v_t \omega$$

This model was selected as a representative voltage regulator because it is the voltage control scheme used in an operating developmental generating system, the 400-hertz Brayton Power System (ref. 12). A block diagram illustrating such a regulator is shown in figure 9. It represents a stabilized shunt field exciter, sensitive to changes in generator terminal voltage and frequency.
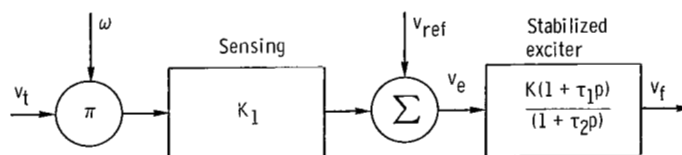

Figure 9. - Simulated voltage regulator-exciter block diagram.

COMPUTER REPRESENTATION OF GENERATING SYSTEM

Computer Equations

The equations presented in the preceding discussion were scaled and converted to a form convenient for application to a PACE 231R analog computer. The simulation involved 82 amplifiers, 32 multipliers, and two function generators.

The parameter values used in the simulation are tabulated in table I. The values of this table were obtained from component test results - where available (refs. 13 and 14) - design goals (ref. 15), and estimates of the parameters of a 400-hertz developmental Brayton Power System.

Block diagrams of the complete generating system as simulated are included as figures 10 to 12.

Saturation Approximation

The nonlinearity of the flux linkage function due to saturation can be approximated by a scheme discussed in reference 16. This scheme approximates the saturation by means of the assumptions that (1) only the direct axis mutual reactance varies with flux, and (2) the direct axis mutual flux is reduced as a result of a fictitious "saturation current" i_s. This current is described in the following paragraphs.

The alternator no load saturation curve (which is a measurable characteristic)

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TABLE I. - PARAMETER VALUES[a]

[These values were used in simulation runs for
which transient traces are shown in fig. 14.]

Alternator	
Total inertia, J	7.28
Armature resistance, R_a	0.0183
Field resistance, R_f	0.00224
Direct-axis damper resistance, R_{kd}	0.1450
Quadrature-axis damper resistance, R_{kq}	0.1450
Armature leakage reactance, X_{aL}	0.1280
Field leakage reactance, X_{fL}	0.5770
Direct-axis damper reactance, X_{kd}	0.1158
Quadrature-axis damper reactance, X_{kq}	0.1680
Direct-axis mutual reactance, X_{md}	1.0000
Quadrature-axis mutual reactance, X_{mq}	0.6230
Speed control	
Discriminator current at f_0, i_{D0}	0.9550×10^{-3}
Amplifier gain, K_A	1.8500×10^{3}
Discriminator gain, K_D	0.0464×10^{-3}
Parasitic load resistance, R_p	0.5556
Amplifier time constant, τ_A, sec	0.0310
Discriminator time constant, τ_D, sec	0.0050
Voltage regulator-exciter	
Gain, K_1	0.0975
Gain, K	73.9
Reference voltage, v_{Ref}	0.0996
Time constant, τ_1, sec	0.095
Time constant, τ_2, sec	1.540
Base values	
Field current, i_{f0}, A	2.6
Field voltage, v_{f0}, V	5760
Frequency, f, Hz	400
Phase current, i_{t0}, A	41.6
Power, P_{In0}, kW	5
Phase voltage, v_{t0}, V	120
Time base, α	100

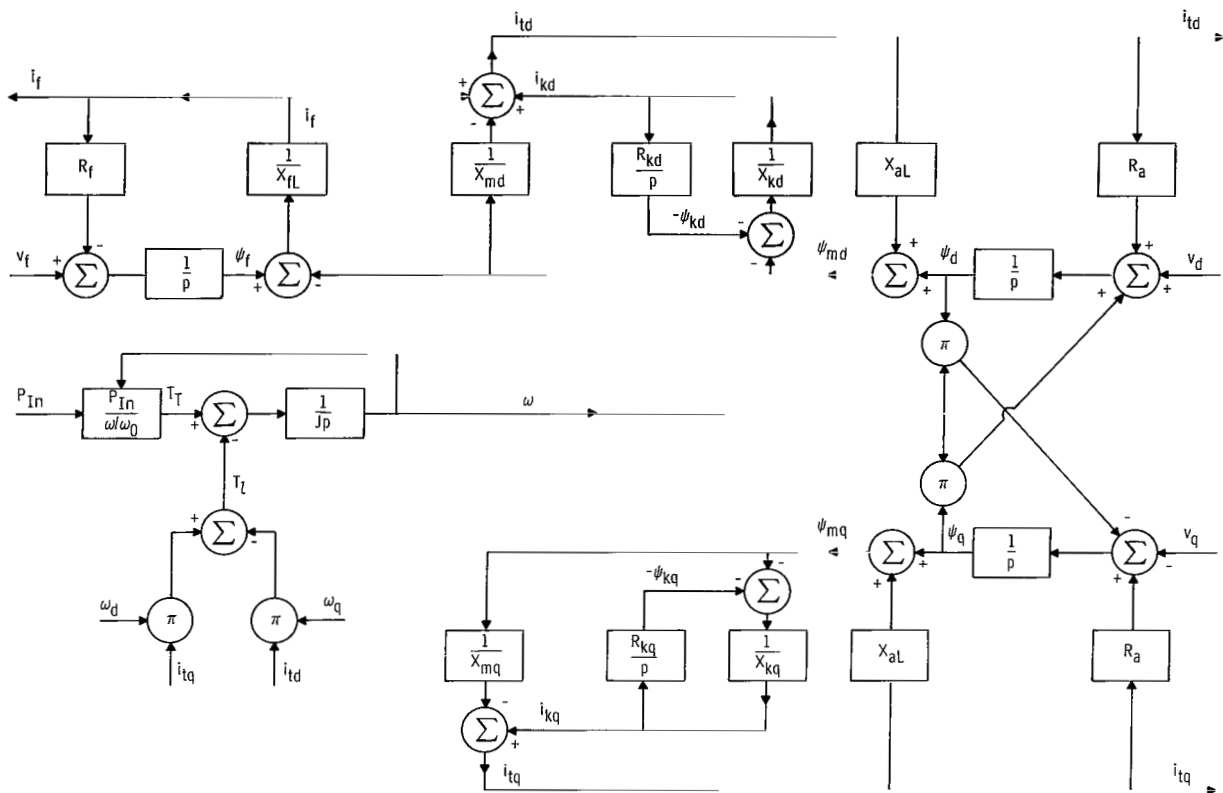[a]Per unit values unless otherwise indicated.
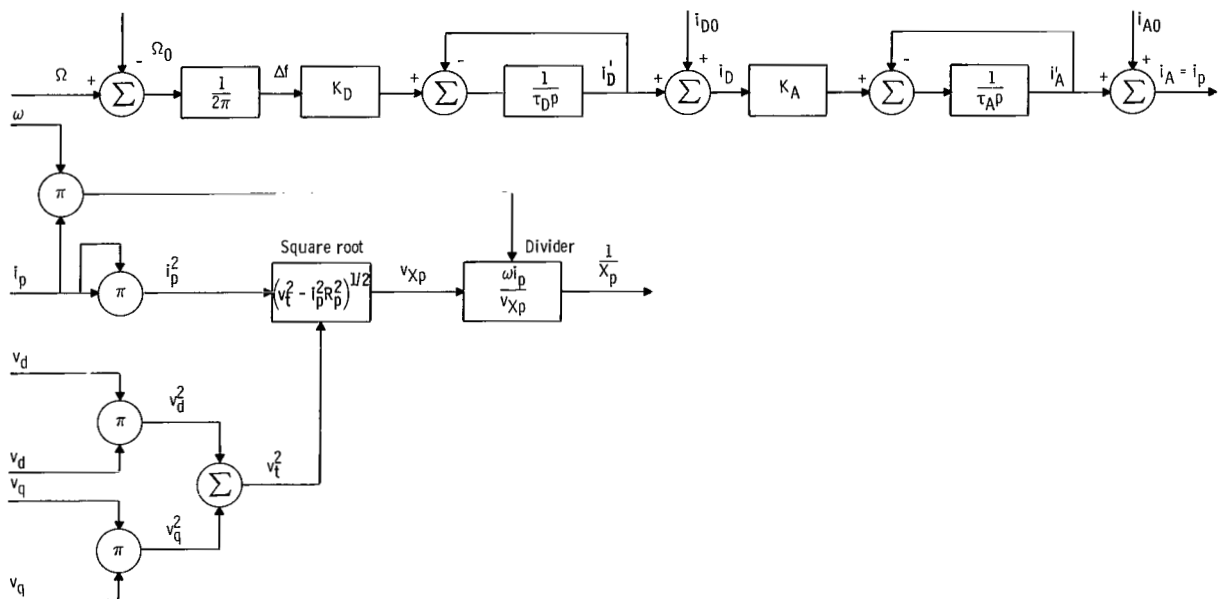
Figure 10. - Block diagram of alternator.

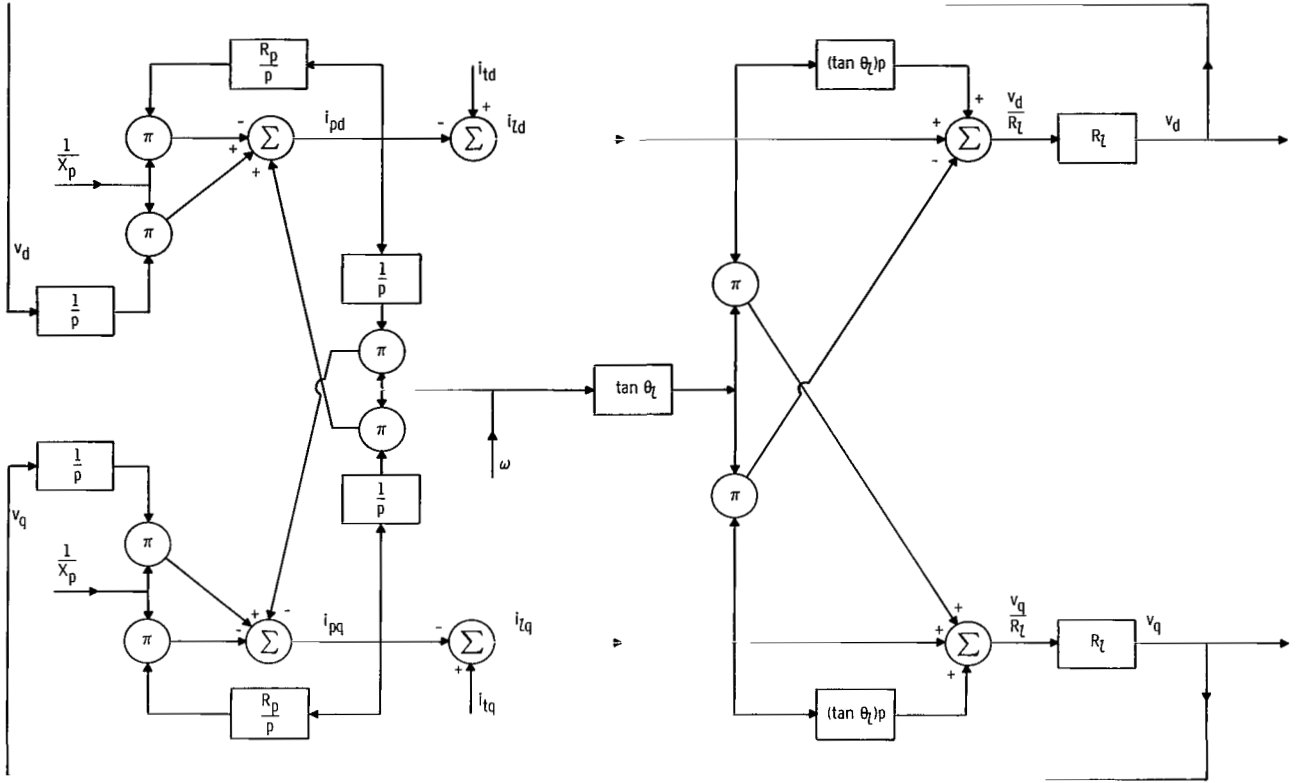Figure 11. - Block diagram of frequency discriminator and amplifier.

Figure 12. – Block diagram of useful and parasitic loads.

shows that the terminal voltage is a nonlinear function of field current (fig. 13(a)); that is,
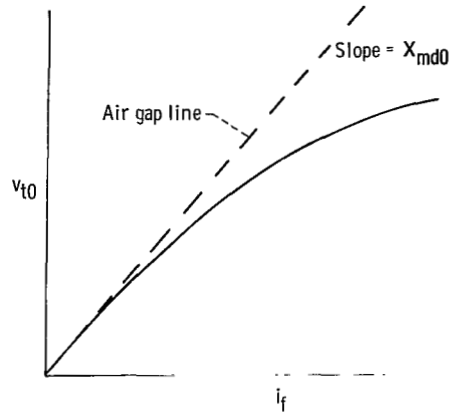
$$v_{t0} = \psi_{md0} = \left[X_{md}(i_f)\right](i_f)$$

where $X_{md}(i_f)$ is the nonlinear factor. The assumption that under load the same functional relation exists between current and reactance makes
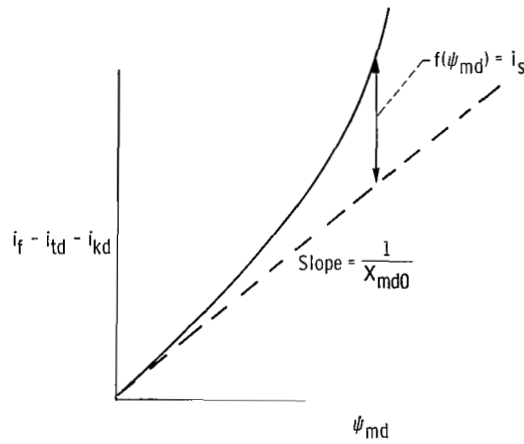
$$\psi_{md} = \left[X_{md}(i)\right](i_f - i_{td} + i_{kd})$$

If the saturation curve under load is plotted as shown in figure 13(b), then

$$(i_f - i_{td} + i_{kd}) = \frac{\psi_{md}}{X_{md0}} + f(\psi_{md})$$

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(a) Alternator no load characteristic.

(b) Saturation curve replotted to show i_s.

Figure 13. – Use of saturation curves to determine saturation current.

where the nonlinearity is included in the term $f(\psi_{md})$. This term is called the saturation current i_s. Its value can be determined from the saturation curve as follows:

$$ i_s = (i_f - i_{td} + i_{kd}) - \frac{\psi_{md}}{X_{md0}} $$

Then

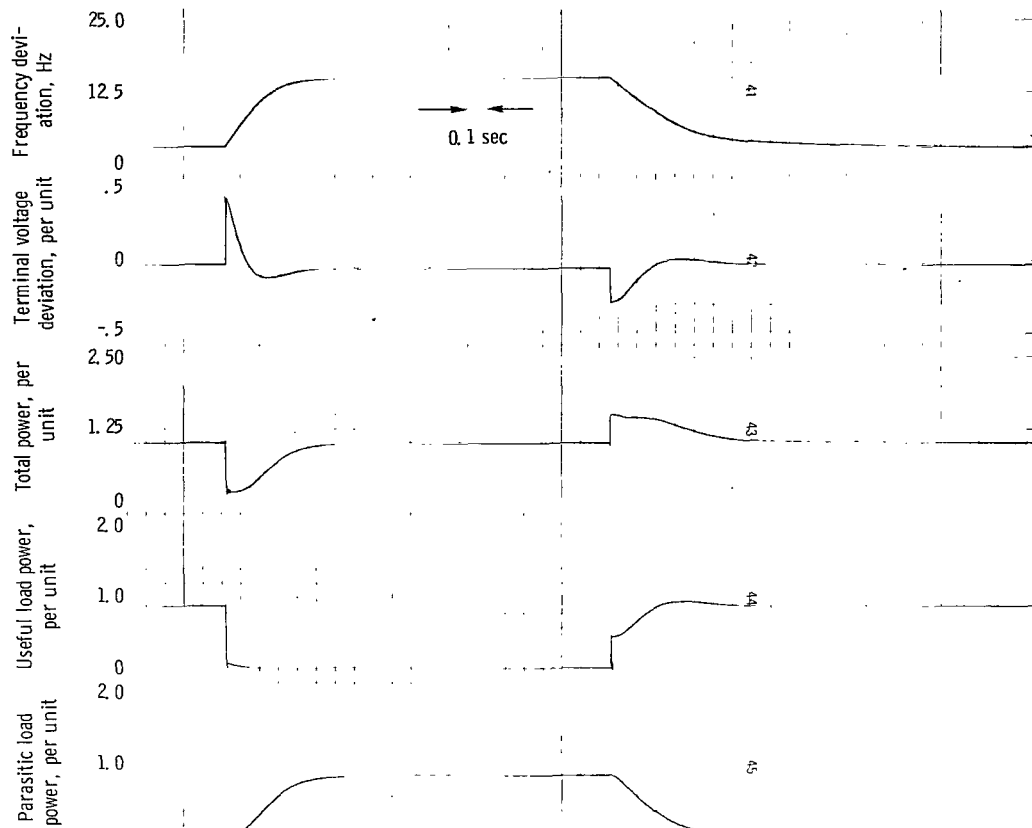$$ \psi_{md} = X_{md0} \, (i_f - i_{td} + i_{kd} - i_s) $$

Figure 14. - Simulation transient characteristics resulting from step changes in useful load. Useful load power factor = 0. 7 (lagging).

In the simulation this saturation effect is included by using a nonlinear function generator to generate i_s as a function of ψ_{md}.

Simulation Performance

In order to demonstrate the performance of the simulation, recorder traces of several sample characteristics resulting from step changes in useful load are presented in figure 14.

The characteristics display the expected theoretical performance of parasitically loaded electrical power generating system. Upon the step removal of the useful load the terminal voltage increases suddenly, returning to a steady-state value with a transient typical of a lead-lag regulator characteristic. The slight increase in the useful load power immediately following the step change is the result of the voltage pulse from unloading of the alternator. The frequency increases exponentially to a steady-state

value, and displays the characteristic of an over-damped system. Similarly, the parasitic load power increases in an exponential manner governed by the inductive nature of the parasitic load controller. The total power load (which in this case includes the armature and field losses), after its transient dip, returns to its fixed steady-state value.

When this load change is reversed, that is, upon the step application of essentially a per unit useful load, the displayed characteristics change in the opposite direction. There is one significant difference because (in this instance) the added useful load is inductive (0.7 lagging power factor). The additional impedance to current change is evident in the transient characteristics.

CONCLUDING REMARKS

The simulation developed herein permits dynamic analysis of parasitically loaded electrical power generating systems. Analysis of such regulated power systems without resort to computers is prohibitive because of the complexity of the equations describing the systems. Used properly the simulation can be a valuable tool in the analysis of contemplated designs or the improvement of existing designs. With the computer, steady-state and transient stability can be observed as system conditions and parameters are changed.

The simulation described can be altered and expanded to include additional operational factors (such as variable turbine power) and more refined models of the components. With the addition of load-sharing circuits the simulation can be used for the study of paralleled alternators.

Lewis Research Center,
    National Aeronautics and Space Administration,
        Cleveland, Ohio, June 30, 1970,
            120-27.

APPENDIX - SYMBOLS

(Unless otherwise indicated, all quantities are expressed as per unit.)

f	frequency, Hz (also functional notation)		Subscripts:	
		A	amplifier
i	current	a	armature
i'	current (variable component)	D	discriminator
J	total inertia	d	direct axis
K	gain	e	error
P	power	f	field
p	differential operator d/dt	In	input
Q	reactive volt-amperes	k	damper
R	resistance	L	leakage
T	torque	l	useful load
v	voltage	m	mutual
X	reactance (inductive)	p	parasitic load
α	time base	q	quadrature axis
θ	power factor angle	Ref	reference
τ	time constant	s	saturation
ψ	flux linkage	T	turbine
Ω	electrical frequency, rad/sec	t	total or terminal
ω	electrical frequency	0	(zero) base or nominal value

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