The Effect of Magnetic Nonlinearity in Electrical Machines on the Transient Response of Machine Control Systems

A DISSERTATION
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CERTIFICATE

CERTIFIED that the dissertation entitled "THE EFFECT OF MAGNETIC NONLINEARITY IN ELECTRICAL MACHINES ON THE TRANSIENT RESPONSE OF MACHINE CONTROL SYSTEMS", which is being submitted by Shri SHRISH PRAKASH SRIVASTAV, in partial fulfilment for the award of the degree of MASTER OF ENGINEERING in 'POWER APPARATUS AND ELECTRIC DRIVES' of the University of Roorkee, Roorkee, is a record of student's own work carried by him under my supervision and guidance. The work embodied in this dissertation has not been submitted for the award of any other degree or diploma.

This is further to certify that he has worked for a period of 7 months from February 1976 to August 1976 for preparing dissertation for Master of Engineering Degree at this University.

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S Y N O P S I S

The objective of the present work is to investigate the effect of magnetic saturation type of nonlinearities associated with electrical machines on the transient response of a machine control system. Contrary to the approaches suggested so far, saturation effect is considered on both gain and time constant.

In the first place block diagrams of an amplidyne voltage regulating system, are developed for the cases (a) when d-axis saturation of amplidyne affects only the d to q axis gain and (b) when it affects both the gain and field time constant. Next block diagrams of the system are developed including the d.c. machine saturation as well.

The block diagrams developed are used for the study of transient response of the system. The techniques employed are operational mathematics, numerical integration and solution of two or more algebraic relationships. The experimental results obtained from a practical system are compared with those of analytical methods.

Headings of chapters?

CONTENTS

LIST OF SYMBOLS

K_f = Quadrature axis generated voltage per ampere of direct axis field current.

K_g = Voltage gain of the d.c. generator in volts per ampere.

K_q = Direct axis generated voltage per ampere of quadrature axis circuit current.

T_f = Time constant of amplidyne field winding in seconds.

T_g = Time constant of the d.c. generator field winding in seconds.

T_q = Time constant of the quadrature axis circuit of amplidyne in seconds.

N_f = Number of turns per pole on amplidyne field.

α = Main feedback ratio

w = frequency in radians per second

p = d/dt

In general

R_x = Resistance of winding x in ohms

L_x = Self-inductance of winding X in Henrys

M_{xy} = Mutual inductance between winding X and y in Henrys

G_{xy} = Rotational voltage coefficient between windings x and y (speed voltage induced in winding x per unit current in winding y at unit speed)

J = Moment of Inertia

INTRODUCTION

The science of control engineering has made rapid progress in recent years. As the need for more accurate and reliable control grew, demands arose for machines that would possess characteristics suitable for use in control systems. One aspect of development in d.c. machines which normally constitute the power amplifying stage of a control system emphasises the design of machines capable of responding very fast to signals of small magnitude. These dynamoelectric amplifiers, often known by trade name as amplidyne, have been successfully employed in many control systems[1 to 5].

The steady state and transient performance of such systems are usually studied by assuming that there are no saturation and hysteresis effects associated with amplidyne[4,6]. For analysis, the steady state[7,5] and dynamic equations[8 to 11] of electrical machine which are derived neglecting saturation and hysteresis effects are used.

The saturation of the magnetic circuit of machine has two effects : (i) It causes a reduction in the direct and quadrature axes circuit inductance, and (ii) It decreases the voltages generated in the quadrature and direct axes armature circuit.

Transient analysis of any automatic control system is mostly carried out assuming the components of the system to be linear. This involves solving the linear differential equations with constant coefficients obtained for such system. Amplidyne, which forms the component of most the control system is subjected to magnetic saturation a nd hence exhibits nonlinear characteristics. The effect of this should also be included in transient response studies of such system.

The mathematical theory available for the treatment of such problems is in an unsatisfactory state. There is no standard method by which all nonlinear differential equation can be solved. A limited number of these equations can be solved exactly[12] and a variety of approximate analytical, numerical and graphical methods are available for the rest. These methods are not generally interchangeable and each has its advantages and disadvantages for particular purposes.

The method suggested by Stout[13] for transient analysis of feedback system containing one nonlinear element has the advantage of simplicity when it is applied to systems having one input, one output and one nonlinear element which can be characterised by a relation between its instantaneous input and output, say $y = \phi(x)$. Such systems are represented by the standard block diagrams[14] and using these the transient response is carried out.

In the present work, the effect of amplidyne d-axis saturation and d.c. generator saturation on the transient response of the d.c. voltage regulating system is studied.

The system response to a step reference input is plotted for the following cases :

(i) Assuming all the components of the system to be linear.

(ii) Considering the effect of amplodyne d-axis saturation on d to q-axis gain only.

(iii) Considering the effect of amplidyne d-axis saturation on d to q axis gain and field time constant.

(iv) Considering the effect of amplidyne d-axis saturation and d.c. generator saturation on gains only.

(v) Considering the effect of amplidyne d-axis saturation and d.c. generator saturation on both gains and time constants.

A comparative study of the five cases is made and the effect of considering saturation on both gains and time constants is discussed. The experimental results obtained on a practical system are compared with the analytical results.

The analysis is carried out with the following assumptions regarding amplidyne and d.c. generators - (i) Eddy current and hysteresis effects are neglected, (ii) The brushes are located in neutral zones. Commutation is assumed to be linear and the effects of coils undergoing commutation are ignored. (iii) Both the machines are driven at constant speeds.

CHAPTER - 2

In this chapter block diagrams of an amplidyne voltage regulating system are developed for the following case - (1) assuming all the components of the system are linear, (2) Considering D-axis saturation of amplodyne on d to q axis gain only, (3) Considering the axis saturation of amplidyne on both d-q axis gain and field time constant, (4) Considering the axis saturation of amplidyno and d.c. generator situation on gains only, (v) Considering the d-axis saturation of amplidyne and d.c. generator sityation on both gains and time constant.

2.1 Linear Case

The dynamic equation shown in fig. 2(a) can be described as follows -

Assuming linear magnetic circuit and an exact componsation in amplidyne, the transient process in the field circuit can be expressed by an equation of the form

$$V_f = (R_f + L_f.p)\, i_f \quad \ldots \quad \ldots \qquad (2.1)$$

where Vf is the net applied voltage to the field winding. The rotational voltage induced in the quad-rature ax-ca armature circuit because of current IF in the field winding is

$$V_q = K_f \, i_f \qquad \ldots \quad (2.2)$$

The voltage balance equation for the q axis circuit is given by

$$V_q = (R_Q + R_s) i_q + (L_Q + L_s + 2 M_{Qs}) \frac{di_q}{dt} \qquad \ldots \quad (2.3)$$

$$\text{or } V_q = R_q \, i_q + L_q \frac{di_q}{dt} \qquad \ldots \quad (2.4)$$

where $Rq = R_Q + R_s$ and $L_q = L_Q + L_s + 2 M_{Qs}$.

The rotational voltage across the d-axis brushes is

$$Vd = K_q i_q \qquad \ldots \quad (2.5)$$

Neglecting the resistance of the armature and compensating winding of the amplidyne as they are very small compared to the field winding resitance of the d.c. generator, the following equation is obtained for its d-axis armature circuit.

$$Vd = Rg i_g + L_g \times di_g/dt \qquad \ldots \quad (2.6)$$

where i_g is the current through the generator field winding.

The rotational voltage induced across the bruses of the d.c. generator is

$$V_g = K_g \, i_g \qquad \ldots \quad (2.7)$$

The net applied voltage to the field winding of the amplidyne is

$$V_f = V_R - \alpha\, V_g \qquad \ldots \qquad (2.8)$$

Applying Laplace transformation to equation (2.1) to (2.8) and assuming initial conditions, one obtains the following transformed equation for the system.

$$I_f(s) = \frac{V_f(s)}{(R_f + sL_f)} = \frac{V_f(s)}{R_f(1 + sT_f)} \qquad \ldots \qquad (2.9)$$

$$V_q(s) = K_f I_f(s) \qquad \ldots \qquad (2.10)$$

$$I_q(s) = \frac{V_q(s)}{R_q + sL_q} = \frac{V_q(s)}{R_q(1 + s\,T_q)} \qquad \ldots \qquad (2.11)$$

$$V_d(s) = K_q I_q(s) \qquad \ldots \qquad (2.12)$$

$$I_g(s) = \frac{V_d(s)}{R_g + sL_g} = \frac{V_d(s)}{R_g(1 + sT_g)} \qquad \ldots \qquad (2.13)$$

$$V_g(s) = K_g I_g(s) \qquad \ldots \qquad (2.14)$$

$$V_f(s) = V_R(s) - \alpha\, V_g(s) \qquad \ldots \qquad (2.15)$$

Using equations (2.9) to (2.15), the block diagram of the system is drawn as shown in Fig. 2(a). For the analysis all the power blocks can be combined into a single block as

$$G(s) = \frac{K_f K_g K_q}{R_f R_g R_q (1 + sT_f)(1 + sT_g)(1+ sT_q)} \quad \ldots (2.16)$$

2.2) <u>The effect of amplidyne d-axis saturation on gain only</u>

The open circuit curve showing the re lation between the output voltage and control field current flattens off more sharply compared to t he saturation curve of an ordinary d.c. generator because of the interection between the m.m.fs. of the two axes under saturation conditions.Hence instead of determining the d-axis saturation curve from the voltage induced across the q-axis brushes for different values of field current, the following experimental producer is adopted which takes into account the effect of interaction of both the d and q axes mmm m.m.fs..

The open circuit voltage across the d-axis brushes and the current in the q-axis circuit (I_q) are measured for different values of field current (I_f). The variation of q-axis circuit resistance with q-axis current is also determined and plotted as shown im figure 4(c), for a given field current and the product of the corresponding q axis circuit current and resistance gives the value of the induced voltage; V_q across the q-axis brushes. This procedure is represented for differant values of field current and the variation of V_q with I_f is plotted as shown in Fig. 4(c).

The d-axis saturation curve can be approximated by two straight lines OA and AB, where the slope of OA gives the value of the linear voltage gain K_f. In Fig. 4(c), it is seen that as the field current exceeds I_{fo}, the gain also changes. Presently considering the saturation effect on gain only and assuming the field inductance to be constant, the following dynamic equations for amplidyne are obtained.

For the field circuit

$$V_f = R_f i_f + L_f di_f/dt \qquad \ldots \qquad (2.17)$$

The useful flux per pole along the direct axis is given by

$$\phi = N_f i_f SP_1 \qquad \ldots \qquad (2.18)$$

where, S and P_1 are the saturation factors and the performance of unsaturated magnetic circuit respectively. The factor S depends upon the field current i_f. For values of $i_f \leq I_{f0}$ it has a value equal to unity and for $i_f > I_{f0}$ it goes on decreasing

The voltage across the q-axis brushes if given by

$$V_q = K\phi = K N_f i_f S P_1 \qquad \ldots \qquad (2.19)$$

Since $K N_f P_1 = K_f$ - linear gain, the above equation can be written as

$$V_q = S K_f i_f \qquad \ldots \qquad (2.20)$$

also $V_{q0} = K_f I_{f0}$ $\qquad \ldots \qquad (2.21)$

From equation (2.20) and (2.21) it can easily be seen that the value of the saturation factor for a field current i_f is simply the ratio of (V_q/V_{q0}) corresponding to the value of (i_f/I_{f0}) to the value of (i_f/I_{f0}) itself. This can be determined using Fig. 4(c).

Equation (2.20) can also be written as

$$V_q = S\, V_{q1} \qquad \ldots \quad (2.22)$$

where V_{q1} is the voltage induced in the quadrature axis for the same current i_f with a linear magnetisation curve. Referring to Fig. 4(C) it is seen that

$$I_f / I_{f0} = V_{q1}/V_{q0} \qquad \ldots \quad (2.23)$$

Using the transform of equations (2.17), (2.20), (2.22) and (2.23) and assuming the other part of the system to be linear the block diagram given in 3(a) is obtained, where A is a nonlinear block with a gain S whose value depends on the input signal to it i.e. V_{q1}/V_{q0}

2.3 The effect of amplidyne d-axis saturation on d-axis gain and field time constant

If V_f is the net applied voltage to the field winding of amplidyne, then the following differential equation can be written, applicable to the field circuit:

$$V_f = R_f i_f + m \sigma N_f \times d\phi/dt \quad \ldots \quad (2.24)$$

where m, σ, N_f and ϕ are the number of poles, leakage coefficient, number of turns per pole and useful flux per pole respectively. Although the leakage coefficient varies with the level of saturation of the magnetic circuit, for simplicity it has been assumed to be constant in the analysis.

The useful flux per pole as given in Art. 2.2 is

$$\phi = N_f i_f S P_1 \quad \ldots \quad (2.25)$$

The voltage across the q-axis brushes is given by

$$V_q = K\phi = K N_f i_f S P_1 \quad \ldots \quad (2.26)$$

Multiplying (2.24) by N_f and substituting (2.26) in equation (2.24)

$$V_f N_f = R_f N_f i_f + \frac{m \sigma N^2_f}{K} \times \frac{dV_q}{dt} \quad \ldots (2.27)$$

Substituting the v lue of $N_f i_f$ from (2.26) in (2.27) and substituting, the following equation is obtained.

$$V_f\, K\, N_f\, S\, P_1 = V_q\, R_f + m\sigma N^2_f\, P_1 S\, \frac{dV_q}{dt} \quad \ldots (2.28)$$

Since in equation (2.28),

$$m\sigma N^2_f\, P_1 = L_f \quad \text{(linear value)}$$

and $$K\, N_f\, P_1 = K_f$$

$$V_f * K_f S = (R_f + S\, L_f\, d/dt)\, V_q \quad \ldots (2.29)$$

or $$V_f . K_f / R_f = (S^{-1} + T_f\, P)\, V_q \quad \ldots (2.30)$$

The corresponding block diagram showing the relation between the induced voltage in the quadrative circuit and the applied voltage to the field winding is shown in Fig. 3(c), where S^{-1} is the inverse saturation factor and is the ratio of (i_f/I_{f0}) to (V_q/V_{q0}). The effect of the inverse saturation factor can be taken into account by representing it in the form of a nonlinearity as shown in Fig. 8 . The block diagram of the complete system is shown in Fig. 5(a).

2.4 The effect of d-axis saturation of amplidyne and d.c. generator saturation on gains only

The amplidyne saturation effects on gain only is already derived. Here the effects of generator saturation also is considered. The voltage developed in q-axis brushes due to field winding of amplidyne is same for q-axis field winding. This winding developed a voltage in d-axis brushes of amplidyne which is same for field winding of generator. Neglecting the saturation of q - axis winding the different equation is written as :

$$V_q = i_q R_q + L_q \; di_q/dt \quad \ldots \quad \ldots \quad (2.31.)$$

or

$$V_q = R_q \, (1 + T_q \, p) \, i_q \quad \ldots \quad \ldots \quad (2.32)$$

The voltage across the d-axis brushes of g is given by

$$V_d = K_q \, i_q \quad \ldots \quad (2.33)$$

where K_q = linear gain, the above equation can be written as

$$V_d = \frac{K_q}{R_q (1 + T_q \, p)} \, V_q \quad \ldots \quad (2.34)$$

For the field circuit of generator

$$V_d = R_g \, i_g + L_g \; di_g/dt \quad \ldots \quad (2.35)$$

The useful flux per pole due to generator field is given by

$$\phi_G = N_g \, i_G \, S_g \, P_g \quad \ldots \quad (2.36)$$

where S_g and P_g are the saturation factor and the permeance of the unsaturated magnetic circuit of generator respectively. The factor S_g depends upon the field current i_g. For values of $i_g \leq I_{g0}$, it has a value equal to unity and for $I_g > I_{g0}$ it goes on decreasing.

The voltage across the generator brushes is given by

$$V_g = K \phi_g = K N_g i_g S_g P_g \qquad \ldots (2.37)$$

Since $K N_g P_g = K_g$ - the linear gain, the above equation can be written as

$$V_g = K_g S_g i_g \qquad \ldots \quad (2.38)$$

and $$V_{g0} = K_g I_{g0} \qquad \ldots \quad (2.39)$$

From equation (2.38) and (2.39) it can easily be seen that the value of the saturation factor for a field current (i_g) is simply the ratio of (V_g/V_{g0}) corresponding to the value of i_g/I_{g0} to the value of (i_g/I_{g0}) itself, these can be determined using normalised generator saturation characteristics as shown in Fig. 4.1. Equation (2.38) can also be written as

$$V_g = S_g V_{g1} \qquad \ldots \quad (2.40)$$

where V_{g1} is the voltage induced across generator brushes for the same current i_g with a linear magnetisation curve. Refering to figure (4.2) it is seen that

$$\frac{i_g}{I_{g0}} = \frac{V_{g1}}{V_{g0}} \quad \ldots \quad (2.41)$$

Using the transform of equation (2.17), (2.20), (2.22), (2.34), (2.35), (2.38) and (2.41) the block diagram given in Fig. 4(a) is obtained, where A is non-linear block of amplidyne with gain S and B is nonlinear block of generator with gain S_g whose value depends on the input signal to it i.e. V_{g1}/V_{g0} and V_{q1}/V_{q0}.

2.5 The effect of amplidyne d-axis saturation and d-c generator saturation on both gains and field time constants

The expression for the effect of amplidyne saturation on the gain and field time constant is derived in section (2.3). Here, the effect of generator saturation is also considered. If V_d is the net applied voltage to the field winding of generator, then the following differential equation can be written as applicable to the field circuit.

$$V_d = R_g i_g + m.\sigma_g N_g \frac{d\phi_g}{dt} \quad \ldots \quad (2.42)$$

where, m, σ_g, N_g and ϕ_g are the number of poles, leakage coefficient, number of turns per pole and useful flux per pole of generator respectively. Although the leakage coefficient varies with the level of saturation of the magnetic circuit of generator for simplicity, it has been assumed to be constant in the analysis.

The useful flux per pole as given in Art. 2.4.
is

$$\phi_g = N_g \, i_g \, S_g \, P_g \qquad \ldots \quad (2.43)$$

The voltage across the generator brushes is given by

$$V_g = K \phi_g = K N_g \, i_g \, S_g \, P_g \qquad \ldots \quad (2.44)$$

Multiplying (2.42) by N_g and substituting (2.44) in equation (2.42),

$$V_d \, N_g = R_g \, N_g \, i_g + \frac{m \, \sigma_g \, N^2_g}{K} \, dV_g/dt. \qquad \ldots (2.45)$$

Substituting the value of $N_g \, i_g$ from (2.44) in (2-45) and simplifying the following equation is obtained:

$$V_d \, K \, N_g \, S_g \, P_g = V_g \, R_g + m \cdot \sigma_g \cdot N^2_g \cdot P_g \cdot S_g \cdot \frac{dV_g}{dt} \qquad \ldots \quad (2.46)$$

Since in equation (2.46), $m \, \sigma_g \, N^2_g \, P_g = L_g$ (linear value)

and $K \, N_g \, P_g = K_g$

$$V_d \, K_g \, S_g = (R_g + S_g \, L_g \frac{d}{dt}) \, V_g \qquad \ldots \quad (2.47)$$

or $$V_d \quad K_g/R_g = (S_g^{-1} + T_g \, p) \, V_g \qquad \ldots \quad (2.48)$$

Using the transformation of equation (2.30), (2.34) and (2.48) and equation (2.15) the block diagram given in Fig. 6(a) is obtained. S^{-1} is the inverse saturation factor of amplidyne and is the ratio of (i_f/I_{f0}) to (V_q/V_{q0}) and S^{-1}_g is the inverse saturation factor of amplidyne and is the ratio of (i_g/I_{g0}) to (V_g/V_{g0}).

CHAPTER - 3

In this chapter the transient analysis of the d.c. voltage regulating system is carried out using the block diagrams developed in Chapter 2. All the componants of a practical system have been experimentally determined. The transient response curves for a step reference input for the cases considered in Chapter 2 are ~~gixnn~~ given.

3.1.1 Linear Case :

Assuming that all the components of the system are linear, the dynamic equations have been obtained in Art. 2.1 using the transformed equation (2.9) to (2.15) the block diagram is shown in Fig. 2(a). The closed loop transfer ~~system~~ function of the system is obtained as

$$\frac{C(s)}{R(s)} = \frac{K_f\, K_g\, K_q}{R_f\, R_g\, R_q(1 + s\,T_f)(1 + s\,T_g)(1 + s\,T_G) + K_g\, K_q\, K_f} \quad \ldots (3.1$$

3.2.2 The effect of amplidyne d-axis saturation on gain only

The d-axis saturation curve of amplidyne is given in Fig. 4(c) which can be approximated by two straight lines OA and AB. The slope of the line OA gives the value of linear d to q-axis gain K_f. The block diagram of the system developed for such a case in Art. 2.2 is shown in Fig. 3(a).

In the figure ϕ is a nonlinear block whose gain depends on the input signal to it i.e. V_{q1}/V_{q0}. It contains the straight line approximated normalised saturation characteristic shown in Fig. 4.1.

3.1.3 The effect of d-axis saturation of amplidyne on gain and time constant

The block diagram shown in Fig. 5(a) for such a case is developed in Art. 2.3 of Chapter 2. In the figure block contains the inverse of the straight lines approximated normalised saturation characteristic of amplidyne.

3.1.4 The Effect of d-axis saturation of amplidyne and d.c generator saturation on gains only

The d-axis saturation curve of amplidyne is approximated by two straight line OA and AB. Similarly saturation curve of generator can be approximated by two straight line OA and AB. The slope OA gives the value of voltage gain K_g and AB gives the nonlinear voltage gain. The block diagram shown in figure 4(a) is developed in Art. 2.4. In the figure block ϕ_d is a nonlinear block of amplidyne whose gain depends on the input signal to it i.e V_{q1}/V_{q0} and block ϕ_g is nonlinear block of generator whose gain depends on the input signal to it i.e. V_{g1}/V_{g0}

3.1.5 The effect of amplidyne d-axis saturation and d.c. generator saturation on both gains a nd time constants

The block diagram shown in fig. 6(a) for such a caso is developed in Art. 2.5. In this figure, Ψ_a is the block for amplidyne contains the inverse of the straight lines approximated normalised saturation characteristic and Ψ_g is the block for generator contains the inverse of the straight lines qpproximated normalised saturation characteristic.

3.2 Standard Block Diagram

It is shown by Stout that the original block diagram for any nonlinear system can always be reduced to the standard forms shown in figure 7(a) and 7(b). In these diagrams, linear dynamic relations are indicated by the transfer function G_1, G_2, G_3 and H, while the nonlinear relati ons are expressed by $y = \emptyset(X)$ and $X = \Psi(y)$. It is also shown that these diagrams are interchangeable description of the same system if $G = 1/H$ and Ψ is a function ~~within~~ which is the inverse of $\emptyset$.

The block diagram pertaining to the case discussed in Art. 3.1.2, 3.1.3, 3.14 and 3.1.5 can be reduced to the standard form shown in Fig. 3(b), 5(c), 4(b) and 6(b) by simple block diagram reduction technique.

3.3 Description of the Anal-ytical Method

Refering to Fig. 7(a) since the input block G_1 is linear its output U(t) can be calculated for any given input r(t) by the following laplace transform method

$$U(t) = L^{-1} (G_1(s) \; R(s))$$

where $R(s) = L (r(t))$

The method can be used to find B(t) from r(t) and a(t) from y(t). However, it should be noted that y(t) is the output of a nonlinear feedback system and is not available in analytical form because of the appr oximate calculation procedure involved. For this reason, it will be necessary to use approximate methods even in the linear part of the system Stout has described two similar procedures, one a general procedure applicable to the fig. 7(a) and other an alternative procedure applicable to figure 7(b)

3.4 General Procedure

Refering to fig. 7(a) the nonlinear feedback system may be described by the equations

$$X(t) = U(t) - V(t) \quad \ldots \quad (3.2)$$

$$y(t) = \emptyset(X(t)) \quad \ldots \quad (3.3)$$

$$V(t) = \int_0^t h(t - T) \, y(T)dT \quad \ldots \quad (3.4)$$

Equation (3.1) due to first summing point, equation (3.3) due to nonlinear block and last equation due to approximation.

Equation (3.4) is entirely in the time d omain and take advantages of the fact that the output of a linoar system can be expressed as a weighted sum of its present and past inputs The weighted function is

$$h(t) = L^{-1} (H(s)) \quad \ldots \quad \ldots \quad (3.5)$$

This weighing function is the inpulse response of the feedback block and may be calculated in advance. By solving above equation the following can be obtained.

$$x(t) = U(t) - \int_0^t h(t-T)\phi(X(T))\, dT \quad \ldots \quad (3.6)$$

In above equation x(t) is the only unknown when x(t) is found y(t) is automatically available from equation (3.3). Now equation (3.6) is a nonlinear integral equation. Solution of this equation can be found by iteration method or by approximation method, using U(t) as a first approximation to x(t) which in turn is used to find second approximation and so on. This procedure requires an analytical expression for $\phi(x)$ and the integrands increase rapidly complexity, even under the best conditions.

An approximate solution can be found by step by step method which permit use of $\phi'(x)$ in graphical term and lead directly to numerical results.

By numerical method, the various values of system variable can be calculated at interval $\Delta(t) = T$. These values will be denoted by

$$V_n = V(nT)$$

h_n = $h(nT)$ and so on. If Trapezoidal role is used then the approximate value of $V(nT)$ from equation (3.4) becomes

$$V_n = T\left(\frac{1}{2} h_n y_0 + h_{n-1} y_1 + \; \cdots\cdots \; + h_1 y_{n-1} + \frac{1}{2} h_0 y_n\right) \quad \cdots \quad \cdots \quad (3.7)$$

If we denote T h_n as B_n then equation (3.7) can be regarded as the product of the two sequence

$$\begin{matrix} y_0/2, & y_1 & \cdots & \cdots & y_n & \cdots\cdots \\ \beta_0/2, & \beta_1 & \cdots & \cdots & \beta_n & \cdots \end{matrix} \qquad \cdots \; (3.8)$$

The first value of $y(t)$, $y(0)$ is found from the initial condition of the problem,the other values are determined step by step. When $\beta 0$ is 0 then V_n depends only on past values of y upto y_{n-1} and can be directly found at each stage of the calculation with V_n unknown, x_n is immediately available and y_n can be read from the curve.

If $B_o \neq 0$ then it will be necessary to use a graphical solution of two algebric equation at each step in order to determine V_n, X_{n_1} and y_n. This complication is introduced by the necessity of satisfying the equation.

$$y_n = \phi(x_n) \qquad \ldots \qquad (3.9)$$

$$x_n = U_n - V_n \qquad \ldots \qquad (3.10)$$

Let S_n be the sum of all terms of equation (3.7) except last one. The equation (3.7) becomes,

$$V_n = \rho y_n + S_n \qquad \ldots \qquad (3.11)$$

where $\rho = \beta 0/2 \qquad \ldots \qquad (3.12)$

and $S_n = y0/2\ \beta_n + y_1\ \beta_{n-1} + \ldots + y_{n-1}\ \beta_1 \ \ldots \ (3.13)$

From equation (3.11) one can get

$$x_n = U_n - \rho y_n - S_n \qquad \ldots \qquad (3.14)$$

$$= \bar{S}_n - \rho Y_n \qquad \ldots \qquad (3.15)$$

where $\bar{S}_n = U_n - S_n \qquad \ldots \qquad (3.16)$

Since U_n is already calculated and S_n involves only past values of y_0 upto y_{n-1}. $\bar{S}_n$ is available at each stage. The only unknwon quantities are present galue of x and y namely x_n and y_n and these can be found by simultaneous solution of equation (3.9) and (3.15) usi ng the graphical procedure. If the order of denominator is greater than the order of numerator then the procrdure is very ~~xighx~~ straightforward, the inverse transform h(t) can be found out by partial fraction. If the order ofdenominator and numer tor is same then firstly remove the constant term and then use above method.

Now if the order of the numerator exceeds the order of the denominator, then the inverse transform would contain impulsive components which would cause trouble in analysis. This difficulty can be avoided by reversing the osition of the linear a nd nonlinear blocks, putting the reci rocal of H(s) in the forward block and the inverse function for the nonlinearity into the feedback path as shwon in Fig. 7(b). ~~Since~~ Sometime feed back path is automatically contain nonlinear block for this case following procedure is applied which is slightly different from above prodedure.

3.5 Alternative Method

For the block diagram of fig. 7(b) the equations are

$$V(t) = U(t) - X(t) \quad \ldots \quad (3.17)$$

$$X(t) = \Psi(y(t)) \quad \ldots \quad (3.18)$$

where Ψ is inverse function of $\emptyset$

$$y(t) = \int_0^t V(t - T)g(T)\, dT \quad \ldots \quad (3.19)$$

where $g(t)$ is the reciprocal of H(t) block as shown in fig. 7(b).

$$G(t) = L^{-1} (G(s)) \quad --- \quad (3.20)$$

An approximate value of $y(t)$ for $t = nT$ is

$$y_n = T(\frac{g_n}{2} V_o + g_{n-1} V_1 + \ldots + \frac{g_0}{2} V_n) \quad \ldots \quad \ldots (3.21)$$

Let $\alpha_n = Tg_n$

Equation (3.21) may be regarded as the product of two sequence

$$V_0/2,\ V_1,\ \ldots\ldots\ldots\ldots\ V_n$$

$$\ldots \quad (3.22)$$

and $\alpha_0/2,\ \alpha_1,\ \ldots\ \ldots\ \alpha_m$

For graphical solution equation (3.21) may be written as

$$y_n = \mu V_n + Q_n \quad \ldots \quad \ldots \quad (3.23)$$

where $\mu = \alpha_0/2 \quad \ldots \quad (3.24)$

$$Q_n = V_0/2.\alpha_n + \cdots + V_{n-1}\alpha_1 \ldots \quad (3.25)$$

From equation (3.17) and (3.23)

$$Y_n = \mu (U_n - X_n) + Q_n \quad \ldots$$

$$Y_n = \bar{Q}_n - \mu x_n \quad \ldots \quad (3.26)$$

where $\bar{Q}_n = Q_n + \mu U_n \quad \ldots \quad (3.27)$

Equation (3.18) and (3.27) constitute a pair of simultaneous equation in x and y which may be solved by graphical process.

The various constant of 1.5 kw, 125 V, 12 amp., 1800 rpm, 60 Hz amplidyne and 10, kw, 220 V, 1430 rpm d.c. generator has been experimental ly determined and comes as

R_f = 955	T_f = 0.0318 sec.	K_f = 558.3 V/A
R_q = 1.75	T_q = 0.0774 sec.	K_q = 38.0 V/A
R_g = 128.8	T_g = 0.0742 sec.	K_g = 320 V/A
V_{g0} = 202 V.	V_{q0} = 6.7 V.	I_{f0} = 12 m.amp.

3.6 Transient Response with the system components assumed to be linear

The maximum value of α for a system to be stable can be obtained with the help of R.H. criteria as follows-

The characteristic equation of the system, shown in fig2(b) is given by

$$1 + G(s)\,H(s) = 0 \qquad \ldots \quad (3.28)$$

or

$$1 + \frac{K_f\,K_g\,K_q\,\alpha}{R_f\,R_g\,R_q\,(1 + s\,T_g)(1 + sT_q)(1 + s\,T_f)} = 0 \qquad \ldots \quad (3.29)$$

$$(1 + s\,T_g)(1 + s\,T_q)(1 + s\,T_f) + \frac{\alpha K_f\,K_g\,K_q}{R_f\,R_g\,R_q} = 0 \quad \ldots \quad (3.30)$$

Substituting the various values in above equation one can get

$$S^3 + 57.8\,S^2 + 1004\,S + \left(\frac{1+31.56 * \alpha}{1.827}\right) \times 10^4 = 0 \qquad \ldots \quad (3.31)$$

Using R.H. criteria for stability

$$\begin{array}{l|ll} s^3 & 1 & 1004 \\ s^2 & 57.8 & \left(\frac{1 + 31.56\alpha}{1.827}\right) 10^4 \\ s & \left[\dfrac{\frac{57.8 \times 1004}{1} - \frac{(1+31.56\alpha)}{1.827}10^4}{57.8}\right] & 0 \\ s^0 & \frac{1+31.56\alpha}{1.827}\cdot 10^4 & \end{array}$$

For the system to be stable, the first column's elements must be positive or zero. The marginal value of α is obtained by equating first term of S row to zero.

$$\frac{(1 + 31.56\alpha)10^4}{1.827} = 57.8 \times 1004$$

$$\alpha = \frac{57.8 \times 1004 \times 1.827 \times 10^{-4} - 1}{31.56}$$

$$= \frac{10.6 - 1}{31.56} = \frac{9.6}{31.56}$$

$$= 0.304$$

Therefore the value of α is assumed to 0.25.

Substituting the value of the various constants of the system in equation (3.1) and assuming $\alpha = 0.25$, the variation of output with time for a step function input magnitude V volts is given by

$$C(t) = V(3.55486 - 0.81367\, e^{-55.52t} - e^{-1.14t}(2.7411 \text{ Cos } 29.58\, t$$

$$+ 1.50486 \text{ Sin } 29.58\, t))$$

Assuming V = 50 volts and $\Delta T = T = 0.0025$ Sec.

the different value of C(t) is

C_o = 0.0045

C_1 = 0.4965

C_2 = 1.1070 and so on

3.7 Transient Response Considering the Effect of Amplidyne D-axis Saturation on d to q Axis Gain only

Referring to block diagram shown in Fig. 3(b) if the input R(t) is a step function of magnitudes V volts, the output U(t) would be given by

$$U(t) = 0.585\, V\,(1 - e^{-31.45\, t}) \quad \ldots \quad (3.32)$$

For a given value of V = 50 V, with a time interval T = 0.0025 Sec the value of U_o, U_1, U_2 etc., corresponding to 0, T, 2T and so on can be calculated and given below :

U_o = 0.00

U_1 = 2.21148

U_2 = 4.25575 and so on

The weighing function of block H with $\alpha = 0.25$ is given by :

$$h(t) = 107.6\ e^{-31.45t} + 4180.0\ e^{-12,92\ t}$$

$$- 4287.6\ e^{-13.48t}$$

Corresponding to the assumed time interval, the values of h_o h_1 and h_2 can be calculated by above equation. The values are

$$h_o = 0.00$$

$$h_1 = 0.00480$$

$$h_2 = 0.1200 \quad \text{and so on.}$$

The weighting function for block G is given by

$$g(t) = (1 - e^{-31.45\ t}) \times 16876.0 \quad \ldots \quad \ldots \quad (3.33)$$

The different value of g(t) from above equation by putting different value of T are 0.00, 12.834, 24.12 etc, xx

The different value of function β can be calculated from equation

$$\beta_n = T\ h_n$$

$$\beta_0 = 0.00$$

$$\beta_1 = 0.00001$$

$$\beta_2 = 0.00003 \quad \text{and so on}$$

The initial conditions give $y_0 = 0$ and $E_0 = 0$

At $t = 0.0025$, Sec. $n = 1$, using expression (3.13) and (3.16)

$$S_1 = \frac{Y_0}{2} \beta_1 = 0$$

$$\bar{S}_1 = U_1 - S_1 = 2.21148$$

Since $\beta_0 = 0$ The value of y can be directly read from the graph, but in general, the following procedure is adopted.

$$X_1 = \bar{S}_1 - \rho(y_1/K_f) = 2.21148$$

Here, $\rho = \beta_0/2 = 0$

Corresponding to this value of X_1 the value of y_1 is found out using the normalized saturation characteristic. For the block Ø, the following equations are used relating the input X' to the output y'.

$$y_n = x_n \quad \text{for} \quad x_n \leq 1 \quad \ldots \quad \ldots \quad (3.34)$$

and $y_n = 5.25 + 122.5\, x_n$ for $x_n > 1$ ... (3.35)

Or by solving above equation with equation (3.15) following equation can be obtained

$$y_n = \bar{S}_n/(1 + \rho) \quad \text{for} \quad x_n \leq 1 \quad \ldots \quad (3.36)$$

$$\text{and} \quad y_n = \frac{(5.25 + 122.5 \times \bar{S}_n / 550.3)}{(1.0 + 122.5 \times \rho / 550.3)} \quad \ldots \quad (3.37)$$

for $x_n > 1$

For this case,

$$y_1 = 2.21148$$

Then,

$$E_1 = T\left(\frac{g_1}{2} y_0 + \frac{g_0}{2} y_1\right) = 0$$

Since $y_0 = g_0 = 0.0$

At t = 0.005 Sec. or n = 2

$$S_2 = \frac{y_0}{2} \beta_2 + \beta_1 y_1 = \beta_1 y_1$$

$$= 2.21 \times 0.00001 = 0$$

so that $\overline{S}_2 = U_2 - S_2 = 4.25575$

The output $y_2 = 4.25575$

The output voltage

$$E_2 = T\left(\frac{g_2}{2} y_0 + g_1 y_1 + \frac{g_0}{2} y_2\right) = 0.07$$

Thus the value of the output voltage is calculated for different instants of time, the difference in time between consecutive instants being 0.0025 Sec.

The method of calculation of transient response has been computerized. The flow chart is shown in fig. 9, and programme is given in Appendix.

3.8 Transient Response of the system considering D-axis Saturation of amplidyne on both gain and field time constant

Referring to figure 5(a) for a given step input voltage V, the output from block G is given by

$$U(t) = 0.585\ V \qquad \ldots \qquad (3.38)$$

For $\alpha = 0.25$, block H is found to be unstable. On splitting up the nonlinearity into a linear and a nonlinear function figure 3(b) is obtained. In this figure, the transfer function for block H is given by

$$H(s) = \frac{R_f\ R_g\ R_q\ (1 + S\ T_g)(1 + S\ T_q)}{R_f\ R_g\ R_q(1+ ST_f)(1+ST_g)(1+ST_q) + \alpha\ K_f\ K_g\ K_q} \qquad \ldots \qquad (3.39)$$

On substituting the values of various constants and taking $\alpha = 0.25$, the weighting function of block H is found out to be

$$h(t) = 14.54\ e^{-55.55t} + e^{-1.15t}\ (15.91\ \mathrm{Cos}(29.586\ t) - 3.64\ \mathrm{Sin}\ (29.586\ t)) \qquad \ldots \qquad (3.40)$$

with a time interval of $\Delta t = T = 0.0025$ Sec. the values of h_0, h_1, h_2 etc. are calculated.

The weighting function for block G is given by

$$g(t) = 16876\,(e^{-12.92t} - e^{-13.48t}) \quad \text{-- ---} \qquad (3.41)$$

and the values of g_0, g_1, g_2 etc., can be calculated

Transient Solution

The initial conditions give $y_0 = 0$, and $E_0 = 0$. The values of U_0, U_1, U_2 etc., remain constant 29.25 for the step reference input of 50 volts. The values of h_0, h_1, h_2 etc., are 31.45, 31.20, 31.06 etc. The values of g_0, g_1, g_2 etc., are 0, 23.65, 42.128 etc. The values of β_0, β_1, β_2 etc., are 0.0786, 0.078, 0.07787 respectively. For t = 0.0025 Sec. or n = 1 . Refering to Art. 3.5

$$Q_1 = \left(\frac{V_0\,\beta_1}{2} \right) = 29.25 \times 0.039 = 1.14$$

so that
$$\bar{Q}_1 = Q_1 + \rho\,U_1$$
$$= = 1.14 + 29.25 \times 0.0393 = 2.29$$

$$y_1 = \bar{Q}_1 - \rho X_1 = 2.29 - 0.0393\,X_1 \qquad \text{...}\ ((3.42)$$

In this case the output depends not only on the fast value of X but also on the present value of X. In Fig. 5(b) the non-linear block is in the feedback path...Corresponding to the output y_1, the input to the block Ψ is y'. Depending upon the region of operation, th e output from block Ψ is given by the following equation.

$$X' = 0 \qquad \text{for } 0 \leq y' \leq 1 \qquad \text{...} \quad (3.43)$$

and $x' = 3.65\,y' - 3.65$ for $y' > 1$ ... (3.44)

Once the point of operation on the nonlinear block is known a relation between y_1 and x_1 can be found out using the nonlinear feedback path. Thus two simultaneous equations are obtained in x_1 and y_1 and the solution of these equations give the values of X_1 and y_1. The point of operation on the nonlinear block is found out as follows:

From equation(3.42) on dividing by V_{q0}, one obtains

$$Y'_1 = \frac{\overline{Q}_1}{6.7} - \frac{\rho}{6.7} X_1$$

$$= \frac{\overline{Q}_1}{6.7} - \rho X'_1 \qquad \ldots (3.45)$$

which is the equation of straight line having an interest on the y' axis equal to $\frac{\overline{Q}_1}{6.7}$. If this value is less than or equal to unity than the point of operation is on the line O.A. and the output is given by $\overline{X}'_1 = 0$

and if it greater than unity then the point of operation is on the lime A.B. and the relation between $\overline{X}'$ and Y' is given by $X' = 3.65\,y' - 3.65$ .. (3.4 six)

For the case under consdaration $X'_1 = 0$ Hence

$$Y_1 = V_{q0} \times y'_1 = \overline{Q}_1 = 2.29 \cdots (3.47)$$

$$x_1 = 0 \text{ and } V_1 = U_1 - X_1 = 29.25 \cdots (3.48)$$

The output E_1 is given by

$$E_1 = 0.0025 \left(\frac{g_1 \, y_0}{2} + g_0 \, \frac{y_1}{2} \right) = 0 \quad \ldots (3.49)$$

<u>For t = 0.005 Sec. or n = 2</u>

The constant $Q_2 = (V_0 \, \beta_2/2 + V_1 \, \beta_1)$

$= 29.25(0.0389 + 0.078)$

$= 3.42$

so that $\overline{Q}_2 = Q_2 + \rho U_2 = 3.42 + 1.15 = 4.57$

Hence, $y_2 = 4.57 - 0.0393 \, X_2 \quad \ldots \quad \ldots \quad (3.50)$

For this case $\frac{4.57}{6.7}$ is less than unit hence $X'_2 = 0$

Therefore $y_2 = 4.57 \quad \ldots \quad \ldots \quad (3.51)$

and $V_2 = U_2 - X_2 = 29.25 \quad \ldots \quad \ldots. \quad \ldots \quad (3.52)$

The output $E_2 = 0.0025 \times 23.65 \times 2.29$

$= 0.135 \quad \ldots \quad \ldots \quad (3.53)$

The method used in this case has been computerized. The flow chart is given in Fig. 11 and programme is given in the Appendix.

3.9 <u>Transient Response of the system considering D-axix Saturation of amplidyne and D.C. generator saturation on gains only</u>.

In above case only D-axis saturation of amplidyne is considered. Here the same procedure with D.C. generator saturation to be considered. Referring to Fig. 4(b) the transfer function of block G_1 is given by

$$G_1(S) = \frac{K_f}{R_f(1 + S\,T_f)} = \frac{558.3}{955 \times 0.0318\left(s + \frac{1}{0.0318}\right)}$$

If the input is a step function of magnitude 50 V. then

$$U(s) = \frac{558.3 \times 50}{955 \times 0.0318 \times s(s + 31.45)}$$

Taking inverse laplace transform and simplifying

$$U(t) = 29.25\,(1 - e^{-31.45\,t}) \quad \ldots \quad \ldots (3.54)$$

With $\alpha = 0.25$, the weighting function of feedback block, which is the inverse laplace transform of H(s) is given by

$$h(t) = 0.14625\, e^{-31.45t} \times 202 \quad \ldots \quad (3.55)$$

In the similar manner, the ew weighting function for block G and function B is given by

$$g(t) = 16876\,(e^{-12.92\,t} - e^{-13.48t})$$

$$\beta(t) = 0.0025\, h(t)$$

<u>Transient Solution</u> - The different values of U(t), g(t) h(t) and $\beta(t)$ are calculated by above equation, considering the time interval $\Delta T = 0.0025$ Sec.

$U_0 = 0.0000$ $g_0 = 0.000$ $h_0 = 29.5425$ $\beta_0 = 0.73856$

$U_1 = 1.594$ $g_1 = 23.652$ $h_1 = 13.4532$ $\beta_1 = 0.33633$

$U_2 = 2.316$ $g_2 = 42.128$ $h_2 = 6.1408$ $\beta_2 = 0.15352$

The initial conditions give $y_0 = 0$, and $E_0 = 0$. Adopting same procedure as discussed in Art. 3.4 for t = 0.0025 Sec.

$$S_1 = \frac{y_0}{2} \beta_1 = 0$$

so that $\bar{S}_1 = U_1 - S_1 = 1.594$

In this case forward path contains two nonlinear blocks. So both nonlinear blocks should be considered side by side. The output of first block is the input of, second nonlinear block by multiplying a time function. Referring the figure 4(b)

$$X_n = \bar{S}_n - \rho Y_n$$

where $\rho = \beta 0/2 = 0.36928$

The above equation is the relation between input signal of first nonliear block and output of second nonlinear block. Now considering the first nonlinear block, the input of first non-linear block can be transformed into the output of first nonlinear block (by following equation)

$$\bar{X}_n = (\bar{\bar{Z}}_n - 0.725)/0.275 \quad \text{for } \bar{X}_n > 1 \quad (3,56)$$

$$\bar{X}_n = \bar{\bar{Z}}_n \quad \text{for } \bar{X}_n \leq 1 \quad \ldots (3.57)$$

where, $\bar{\bar{Z}}_n$ is the output of first nonlinear block

$$\bar{\bar{Z}}_n = \bar{Z}_n / V_{q0} \qquad ,\ldots \quad (3.58)$$

$$\text{and} \quad \bar{X}_n = X_n / V_{q0} \qquad \ldots \quad (3.59)$$

$$\bar{Z}_n = \bar{S}_n - y_n \cdot \rho \quad \text{for} \quad \bar{X}_n \leq 1 \qquad ,,, \quad (3.60)$$

$$\text{and} \quad \frac{\bar{Z}_n - 0.725 \times V_{q0}}{0.275} = \bar{S}_n - \rho\, y_n \quad \text{for } \bar{X}_n > 1 \quad \ldots \quad (3.61)$$

$$\text{or} \quad \bar{Z}_n = (\bar{S}_n \times 0.275 + 0.725 \times V_{q0}) - \rho \times 0.275\, y_n \quad \text{for } \bar{X}_n > 1$$

The input of second nonlinear block can be obtained by following equation:

$$Z_n = G_n \times \bar{Z}_n$$

$$= G_n \times (\bar{S}_n \times 0.275 + 0.725 \times V_{q0})$$

$$- G_n \times \rho \times 0.275\, y_n \quad \text{for } \bar{X}_n > 1 \quad \ldots \quad (3.62)$$

$$\text{and} \quad Z_n = G_n \; (\bar{S}_n - y_n) \quad \text{for} \quad \bar{x}_n \leq 1 \quad \ldots \quad (3.63)$$

The above expression is the relation between the output of second nonlinear block and input of same block. By solving above expression with nonlinear block's equation, the following equation gives the output of second nonlinear block.

The nonlinear block's equation is

$$\frac{Z_n}{V_{g0}} = y_n \quad \text{for} \quad \frac{Z_n}{V_{g0}} \leqslant 1 \quad \ldots (3.64)$$

and $y_n = 0.225 \dfrac{Z_n}{V_{g0}} + 0.775$ for $\dfrac{Z_n}{V_{g0}} > 1$, ... (3.65)

The output voltage of second nonlinear block is

$$y_n = \frac{G_n(\bar{S}_n \times 0.275 + 0.725 \times V_{q0}) \times 0.225 + 0.775\, V_{g0}}{(V_{g0} + 0.275 \times 0.225 \times G_n\, \rho\,)} \quad \ldots (3.66$$

for $\dfrac{Z_n}{V_{g0}} > 1$ and $\bar{X}_n > 1$, ...

$$y_n = \frac{\bar{S}_n \times G_n}{(V_{g0} + \rho\, G_n)} \quad \text{for} \quad \frac{Z_n}{V_{g0}} \leqslant 1 \text{ and } \bar{X}_n \leqslant 1 \text{ ,} \ldots (3.67)$$

$$y_n = \frac{(\bar{S}_n \times 0.275 + 0.725 \times V_{q0}) \times G_n}{(V_{g0} + \rho \times 0.275 \times G_n)}$$

for $\dfrac{Z_n}{V_{g0}} \leqslant 1$ and $\bar{X}_n > 1$ ... (3.68)

and $y_n = \dfrac{(\bar{S}_n \times 0.225 \times G_n + 0.775 \times V_{g0})}{(V_{g0} + 0.225 * \rho * G_n)}$

for $\dfrac{Z_n}{V_{g0}} > 1$ and $\bar{X}_n \leqslant 1$ ... (3.69)

for n = L, or $T = \dfrac{0.0025}{1}$ Sec.

$\bar{S}_1 = 1.594$

Considering the output equation of second nonlinear block for $X_1 \leq 1$ and $Z_1/V_{g0} \leq 1$. The value of Y_1 is

$$Y_1 = \frac{1.594 \times 23.652}{(202.0 + 0.369 \times 23.652)}$$

$$= 0.167 \quad \ldots \quad \ldots \quad (3.70)$$

The value of y_1 is less than unity. It means the equation which is considered, is correct. The output voltage E_1

$$E_1 = T(\frac{202}{2} \times y_1)$$

$$= 0.0025 \times 101 \times 0.167 = 0.04 \quad \ldots (3.71)$$

for $T = 0.005$ or $n = 2$. The value of S_2 is

$$S_2 = \frac{y_0}{2} \beta_2 + y_1 \beta_1 = 0.0561$$

so that $\bar{S}_2 = U_2 - S_2$

$$= 2.260 \quad \ldots \quad (3.72)$$

The output of a second nonlinear block y_2 by considering output equation for $X_2 \leq 1$ and $Z_n / V_{g0} \leq 1$ is obtained as

$$Y_2 = \frac{2.26 \times 42.128}{(202 + 0.369 \times 42.128)}$$

$$= 0.44 \quad \ldots (3.73)$$

The output voltage E_2

$$E_2 = 0.0025(101 \times 0.44 + 202 \times 0.167)$$

$$= 0.1954 \qquad \ldots \quad (3.74)$$

The method used in case of above article, has been computerised. The flow chart of which is given in Figs. Ammn 10 and programme is given in Appendix.

3.9 Transient Response of the system considering the axis saturation of amplidyne and generator saturation on both gains and field time constant.

Referring to figure 6(b) for a given step input voltage V, the output from block G_1 is given by

$$U(t) = 0.585\ V \quad \ldots \qquad \ldots \quad (3.75)$$

On splitting up the nonlinearity into a linear and non-linear function figure 6(c) is obtained. The transfer function for block H_a and H_b are given by

$$H_a(s) = \frac{\frac{1}{s\,T_f}}{1 + \frac{1}{sT_f}} = \frac{1}{(1 + sT_f)} \quad \ldots \quad (3.76)$$

1

$$\text{and} \qquad H_b(s) = \frac{\frac{1}{sT_g}}{1 + \frac{1}{sT_g}} = \frac{1}{(1 + s\,T_g)} \quad \ldots \quad (3.77)$$

2

On substituting the values of various constants and taking

α = 0.25, the weighting function of blocks H_a, H_b and H_c are found out to be

$$h_a(t) = 31.45 \, e^{-31.45 \, t} \quad \ldots \quad (3.78)$$

$$h_b(t) = 13.48 \, e^{-13.48 \, t} \quad \ldots \quad (3.79)$$

and $$h_c(t) = 0.585/4 \quad \ldots \quad (3.80)$$

with a time interval of $\Delta t = T = 0.0025$ Sec., the values of h_{a0}, h_{a1}, h_{a2} ...., h_{b0}, h_{b1}, hb_2... h_{c0}, h_{c1}, h_{c2} etc., are calculated

The weighting function for block G is given by

$$g(t) = 696.2 \, e^{-12.92 \, t} \quad \ldots \quad \ldots \quad (3.81)$$

and the values of g_0, g_1, g_2 etc., can be calculated

Transient Solution

The initial conditions give $y_0 = 0$, $z_0 = 0$ and $E_0 = 0$. The values of U_0, U_1, U_2 .. etc. remain constant 29.25 for the step reference input of 50 volts. The values of h_{a0}, h_{a1}, h_{a2} ..., h_{b0}, h_{b1}, h_{b2} ... h_{c0}, h_{c1}, h_{c2} .... etc., are 31.45, 29.1, 26.9,...., 13.48, 12.9, 12.3 ..., .01146, .01146, .01146, ~~the value of~~ etc. respectively. From different values of H, the value of β_a, β_b, β_c are calculated. The values of β_{a0}, β_{a1}, β_{a2} ... etc., are 0.07883, 0.07275, 0.06725, .. etc. The values of β_{b0}, β_{b1}, β_{b2} ... etc., are 0.033

0.03225, 0.03075 .. etc. The values of β_{o0}, β_{c1}, β_{c2} ... etc. remain constant i.e. 0.00036,.

In this case there are three feed back blocks. Two are nonlinear blocks and other is linear block. So all the three blocks should be considered side by side. The feed back path H_c gives a relation between the output of second nonlinear block H_b and the output of H_c feedback block. The relation can be obtained with the help of Trapezoidal rules as expained in Art. 3.3.

$$X_{cn} = \frac{y_0 \beta_{cn}}{2} + \frac{y_1 \beta_{c(n-v)}}{1} + \qquad + \frac{y_n \beta_{c0}}{2} \quad \ldots (3.82)$$

$$X_{cn} = S_n + \frac{y_n \beta_{c0}}{2} \quad \ldots \quad \ldots (3.83)$$

where $S_n = \frac{y_0 \beta_{cn}}{2} + y_1 \beta_{c(n-1)} + \ldots$ except last term

... (3.84)

Therefore,

$$U_{an} = U_n - X_{cn} \quad \ldots \quad \ldots (3.85)$$

Substituting equation (3.83) in equation (3.85), one can obtain,

$$U_{an} = U_n - S_n - \frac{y_n \beta_{c0}}{2} \quad \ldots \quad \ldots (3.86)$$

$$= \bar{S}_n - \frac{\beta_{c0}}{2} y_n \quad \ldots \quad \ldots (.387)$$

where $\bar{S}_n = U_n - S_n \quad \ldots \quad \ldots (3.88)$

The equation (3.87) requires not only the past value of y but also on the present value of y. In figure 6(c) the first nonlinear block is in the feedback path. Corresponding to the output z of block H_a, the input to the block ψ_a is z'. Depending upon the region of operation the output from block ψ_a is given by the following equation:

$$X'_a = 0 \quad \text{for} \quad 0 \leq z' \leq 1 \quad \ldots \quad (3.89)$$

and $$X'_a = 3.65\, z' - 3.65 \quad \text{for} \quad z' > 1 \ \ldots \ (3.90)$$

Once the point of operation on the first nonlinear block is known a relation between z and X_a can be found out using the first nonlinear feddback path. Thus two simultaneous equations are obtained in X_a and z and the solution of these equations gives the values of X_a and z in terms of output y of second block H_b. The relations are found out as follows. Referring to the Art. (3.5) for a nonlinear feed back system the output of H_b block can be obtained.

$$z_n = \frac{V_{a0}\ \beta_{an}}{2} + V_{a1}\ \beta_{a(n-1)} + \ldots$$

$$+ \frac{V_{an}\ \beta_{a0}}{2} \quad \ldots \quad \ldots \quad (3.91)$$

$$= Q_n + \frac{V_{an}\ \beta_{a0}}{2}$$

where Q_n is the summation of all values except last one

$$\text{or } Q_n = \frac{V_{a0}\,\beta_{an}}{2} + \quad \dots \quad \dots + V_{a(n-1)}\ \beta_{a1} \qquad \dots (3.92)$$

The input of block Π_b is

$$V_{an} = U_{an} - X_{an} \qquad \dots (3.93)$$

Substituting equation (3.93) in (3.91), one can obtain

$$z_n = Q_n + \frac{\beta_{a0}}{2}(U_{an} - X_{an})$$

$$z_n = Q_n + \frac{\beta_{a0}}{2} U_{an} - \frac{X_{an}\,\beta_{a0}}{2} \qquad \dots (3.94)$$

Multiplying equation (3.89) and (390) by 6.7 and substituting in (3.94) the following equations come

$$z_n = Q_n + \frac{\beta_{a0}}{2}\left(\bar{S}_n - \frac{\beta_{c0}}{2} y_n\right) - \quad \text{for } z' \leq 1 \qquad \dots (3.95)$$

$$\text{or } z_n = Q_n + \frac{\beta_{a0}}{2}\left(\bar{S}_n - \frac{\beta_{c0}}{2} y_n\right) - \frac{\beta_{a0}}{2} 3.65 \times 6.7\, z'_n$$

$$+ 3.65 \times 6.7 \times \frac{\beta_{a0}}{2}$$

$$\text{or } z_n = \frac{\left(\bar{Q}_n + S_n\,\beta_{a0}/2 - \frac{\beta_{a0}}{2}\frac{\beta_{c0}}{2} y_n + 3.65 \times 6.7)\ \frac{\beta_{a0}}{2}\right)}{(1 + 3.65 \times \beta_{a0}/2)}$$

$$\text{for } z' > 1 \qquad \dots (3.96)$$

Hence,

$$U_{bn} = G_n \times Q_n + \bar{S}_n \frac{\beta_{a0}}{2} G_n - \frac{\beta_{a0}}{2}\frac{\beta_{c0}}{2} G_n \times y_n$$

$$\text{for } z' \leq 1 \qquad \dots (3.97)$$

$$\text{or} \quad U_{bn} = \frac{G_n \times Q_n + \bar{S}_n \frac{B_{a0}}{2} G_n - \frac{B_{a0}}{2} \frac{B_{c0}}{2} G_n \times y_n + 3.65 \times 6.7 \times \frac{B_{a0}}{2} G_n}{\left(1 + 3.65 \times \frac{B_{a0}}{2}\right)}$$

$$\text{for} \quad z' > 1 \qquad \ldots \qquad \ldots \qquad (3.98)$$

Above equations are the relation between the input of second summing point and output of second block H_b. The input of the block H_b is

$$V_{bn} = U_{bn} - X_{bn} \qquad \ldots \qquad \ldots \qquad \ldots \qquad (3.99)$$

If the output of block H_b is y and input is V_b then with the help of Art. 3.5, the relation between these values can be obtained as

$$y_n = \frac{\beta_{b0}}{2} V_{bn} + \frac{\beta_{b1} V_{b(n-1)}}{1} \ldots\ldots \frac{\beta_{bn} V_{b0}}{2} \qquad \ldots (3.100)$$

$$= R_n + \frac{\beta_{b0} V_{bn}}{2} \qquad \ldots \qquad \ldots. \qquad (3.101)$$

where Q_n is the summation of all values except first one of equation (3.100)

$$\text{or} \quad R_n = \frac{\beta_{bn} V_{b0}}{2} + \frac{V_{b1} \beta_{b(n-1)}}{1} + \ldots$$

$$+ \frac{V_{b(n-1)} \beta_{b1}}{1} \qquad \ldots \qquad \ldots \qquad (3.102$$

The second nonlinear block of fig. 6(c) is also in feedback path corresponding to the output y of block H_b, the input to the block ψ_b is y'. Depending upon the region of operation the output from block ψ_b is given by the following equation

$$X'_b = 0 \quad \text{for} \quad 0 \leq y' \leq 1 \quad \ldots \quad (3.103)$$

or $$X'_b = 2.367\, y' - 2.367 \quad \text{for} \quad y' > 1 \quad \ldots \quad (3.104)$$

Once the point of operation on the second nonlinear block is known, a relation between y and X_b can be found out using the second nonlinear feedback path. Thus two simultaneous equations are obtained in X_b and y and the solution of these equations ~~are obtained in X_b and y and th~~ gives the values of X_b and y. The only required value is y, and can be obtained as follows:

Multiply by $V_{g0} = 202$ to equation(3.103)and (3.104) the following equations can be obtained:

$$X_b = 0 \quad \text{for} \quad 0 \leq y' \leq 1 \quad \ldots \quad (3.105)$$

or $$X_b = 2.367\ y - 2.367 \times 202 \text{ for } y' > 1 \ \ldots \quad (3.106)$$

Solving equations (3.99), (3.101), (3.105) and (3.106), one can obtain,

$$y_n = R_n + \frac{\beta_{b0}}{2} U_{bn} \quad \text{for } 0 \leq y' \leq 1 \qquad \ldots (3.107)$$

$$\text{or } y_n = R_n + \frac{\beta_{b0}}{2} U_{bn} - \frac{\beta_{b0}}{2} 2.367\, y_n$$

$$+ \frac{\beta_{b0}}{2} 2.367 \times 202$$

$$\text{or } y_n = \frac{R_n + \frac{\beta_{b0}}{2} \times 2.367 \times 202 + \frac{\beta_{b0}}{2} U_{bn}}{\left(1 + \frac{\beta_{b0}}{2} \times 2.367\right)}$$

$$\text{for } y' > 1 \qquad \ldots (3.108)$$

Substituting the value of V_{bn} in above equation, the following equation with condition can be obtained :

$$y_n = R_n + \frac{\beta_{b0}}{2}(G_n \times Q_n + \bar{S}_n \quad \frac{\beta_{a0}}{2} G_n - \frac{\beta_{a0}}{2} \frac{\beta_{c0}}{2} G_n Y_n)$$

$$\text{for } 0 \leq z' \leq 1 \text{ and } 0 \leq y' \leq 1 \qquad \ldots (3.109)$$

$$\text{or } y_n = \frac{R_n + \frac{\beta_{b0}}{2}\left(Q_n + \bar{S}_n \times \frac{\beta_{a0}}{2} - \frac{\beta_{a0}}{2} \times \frac{\beta_{c0}}{2} y_n + \frac{3.65 \times 6.7 \times \beta_{a0}}{2}\right) G_n}{\left(1 + 3.65 \times \frac{\beta_{a0}}{2}\right)} \qquad 3.1$$

$$\text{or } y_n = \frac{R_n + \frac{\beta_{b0} \times 2.367 \times 202}{2} + \frac{\beta_{b0}}{2}(Q_n + S_n \frac{\beta_{a0}}{2} - \frac{\beta_{a0}}{2} \frac{\beta_{c0}}{2}) G_n}{(1 + \frac{\beta_{b0}}{2} \times 2.367)}$$

For $0 \leq z' \leq 1$ & $Y' > 1$ ... (3.111)

$$= \frac{R_n + \frac{\beta_{b0} \times 2.367 \times 202}{2} + \frac{\beta_{b0}}{2}(Q_n + \frac{\bar{S}_n \beta_{a0}}{2} \; \frac{- \frac{\beta_{a0}}{2} \times \frac{\beta_{c0}}{2} y_n + 3.65 \times 6.7 \times \frac{\beta_{a0}}{2}) G_n}{(1 + 3.65 \times \frac{\beta_{a0}}{2})}}{(1 + \frac{\beta_{b0}}{2} \times 2.367)}$$

For $z' > 1$ & $y' > 1$ ... (3.112)

Rearranging the equation (3.109), (3.110), (3.111) (3.112) in a suitable form by substituting $\frac{\beta_{a0}}{2}$, $\frac{\beta_{b0}}{2}$, $\frac{\beta_{c0}}{2}$ as p_a, p_b, p_c respectively. The above equation can be written as

$$y_n = \frac{R_n + \beta_b G_n (Q_n + \bar{S}_n \times p_a)}{(1 + p_a \cdot p_b p_c \cdot G_n)} \quad \text{...(3.113)}$$

$$y_n = \frac{R_n(1 + 3.65 \times \rho_a) + \rho_b G_n(Q_n + \bar{S}_n \rho_a + 3.65 \times 6.7 \times \rho_a)}{(1 + 3.65 \times \rho_a + \rho_a \rho_b \rho_c G_n)}$$

for $0 \leq y \leq 202$ and $z > 6.7$ ... (3.114)

$$\text{or} \quad y_n = \frac{R_n \pm 202 \times 2.367 \times \rho_b + \rho_b \times G_n (Q_n + \bar{S}_n \rho_a)}{(1 + \rho_b \times 2.367 + \rho_a \cdot \rho_b \cdot \rho_c G_n)}$$

... (3.115)

for $0 \leq z \leq 6.7$ and $y > 202$

$$\text{or } y_n = \frac{(R_n + 202 \times 2.367 \times \rho_b)(1 + 3.65 \times \rho_b) + \rho_b(Q_n + \bar{S}_n \rho_a + 3.65 \times 6.7 \times \rho_a) G_n}{((1 + \rho_b \times 2.367)(1 + 3.65 \times \rho_a) + \rho_a \cdot \rho_b \cdot \rho_c G_n)}$$

for $z > 6.7$ and $y > 202$ ... (3,116)

Similarly for negative case can also be derived

For $\Delta T = T = 0.0025$ Sec. or $n = 1$. The values of $\bar{S}_1$, R_1 and Q_1 can be obtained using equation (3.84), (3.88), (3.93) and (3.102) as follows :

$$\bar{S}_1 = U_1 - y_0 \frac{\beta_{c1}}{2}$$

$$= 29.25 \quad \ldots \quad \ldots (3.117$$

$$Q_1 = V_{a0} \times \frac{\beta_{a1}}{2} = 29.25 \times 0.03637$$

$$= 1.06 \quad \ldots (3.118)$$

and $X_1 = V_{b0} \frac{\beta_{b1}}{2} = 0$ ... (3.119)

From equation (3.113) the value of y_1, can be obtained as

$$y_1 = \frac{(1.06+29.25 \times 0.0393) \times 0.0169 \times 674.2 + 0}{1 + 0.03932 \times 0.01605 \times 0.000207 \times 674.0}$$

$$= 13.8 \qquad \ldots \qquad (3.120$$

This is less than 202. Hence the equation, which is taken, is correct.

The output E_1 is given by

$$E_1 = 0.0025 \left(\frac{y_0}{2} + \frac{y_1}{2}\right) \qquad \ldots \qquad (3.121)$$

$$= 0.0025 \times \frac{13.8}{2}$$

$$= 0.01730$$

<u>For T = 0.005 or n = 2</u>

The values of S_2, R_2 and θ_2 can be obtained using some equation as

$$\bar{S}_2 = U_2 - y_0 \frac{\beta_{c2}}{2} - y_1 \beta_{c1} \qquad \ldots \qquad (3.122)$$

$$= 29.25 - 13.8 \times 0.0004$$

$$= 29.25 - 0.00552$$

$$= 29.244$$

$$Q_2 = V_{a0} \frac{\beta_{a2}}{2} + V_{a1} \beta_{a0} \quad \ldots \quad (3.123)$$

$$= 29.25(0.0386 + 0.07863)$$

$$= 29.25 \times .11723$$

$$= 3.43$$

and $$R_2 = V_{b0} \frac{\beta_{b2}}{2} + V_{b1} \beta_{b1} \quad \ldots \quad (3.124)$$

From equation (3.99) by substituting $X_{b1} = 0$

$$V_{b1} = U_{b1} - X_{b1} = U_{b1}$$

$$V_{b1} = U_{b1} \quad \ldots \quad (3.125)$$

and from (3.97), U_{b1} can be obtained as

$$U_{b1} = G_1 \times Q_1 + \overline{S}_1 \times \frac{\beta_{a0}}{2} G_1 - \frac{\beta_{a0}}{2} \frac{\beta_{c0}}{2} G_1 y_1 \quad \ldots (3.126)$$

$$= 674.2 \, (1.06 + 29.25 \times 0.0303 - 0.0393 \times 0.0169 \times 13.8)$$

$$= 674.2 \, (1.06 + 1.15 - 0.00920)$$

$$= 674.2 \, (2.201)$$

$$U_{b1} = 1632. \quad \ldots \quad (3.127)$$

Substituting equation (3.127) in (3.125), V_{b1} can be obtained as

$$V_{b1} = U_{b1} = 1632 \quad \ldots. \quad (3.128)$$

Substituting equation (3.128) in equation (3.124), the value of R_2 can be obtained as,

$$R_2 = 1632 \times 0.03225$$

$$R_2 = 52.7 \quad \ldots \quad (3.129)$$

Substituting equation (3.129), (3.127), (3.123) and (3.122) in equation (3.113), the value of y_2 can be obtained as

$$y_2 = \frac{R_2 + \rho_2 Q_2 (Q_2 + S_2 \rho_a)}{(1 + \rho_a \cdot \rho_b \cdot \rho_c\, Q_n)}$$

$$= \frac{52.7 + 652.8 \times 0.0169 \times (3.43 + 29.244 \times 0.0393)}{(1 + 0.03932 \times 0.01685 \times 0.000207 \times 652.8)}$$

$$= \frac{52.7 \times 11.02 \times (3.43 + 1.11)}{1.0}$$

$$= \frac{52.7 + 11.02 \times 4.54}{1}$$

$$= 52.7 + 50$$

$$= 102.7 \qquad \ldots \qquad (3.130)$$

The output E_2 is given by

$$E_2 = 0.0025 \left(\frac{y_o}{2} + y_1 + \frac{y_2}{2} \right)$$

$$= 0.0025\ (13.8 + 51.35)$$

$$= 0.0025 \times 65.15$$

$$= 0.1629$$

The method used in this case has been computorised. The flow chart is shown in figure 12 and programme is given in the Appendix.

CHAPTER - 4

RESULTS, DISCUSSION AND CONCLUSION

With a feedback ratio α = 0.25, the transient response curves of the d.c. voltage regulating system to step reference input of 50 volts was calculated using methods given in Art. 36, 3.7, 3.8, 3.9 and 3.10 and plotted in Fig. 13 . In Fig. 13 , curves (2) and (3) pertain to cases when only the d-axis saturation of amplidyne is considered. The overshoot is reduced appreciably in both the cases compared to the linear case. From the two curves, it is also evident that the effect of saturation is more pronounced on gain than on time constant.

Curves (4) and (5) pertain to cases wherein apart from d-axis of saturation of amplidyne, the d.c. generator saturation is also accounted for. The response is a-periodic and like the previous case saturation effect on time constant is only marginal.

Curve (6) obtained from oscillographic record (shown in Plate 1) taken on the system with α = 0.25 and V_R = 50 volts is very close to the curves (4) and (5), indicating that the saturation effects in both the machines are being felt on the response.

The discrepancy between the calculated and experimental results may be due to the following :-

(i) Errors in the measurement of constants of the system

(ii) Not accounting the variation of resistance and time constant of the quadrature axis circuit of amplidyne with the current in that axis.

(iii) Neglecting the effect of magnetic hysteresis in amplidyne

and (iv) Ignoring the effect of resistance in the feedback circuit.

Thus the effect of saturation in electrical machines on the transient response of a machine control system is to reduce the overshoot and settling time. Although saturation affects both the gain a nd time constant, its effect is more dominant on gain only.

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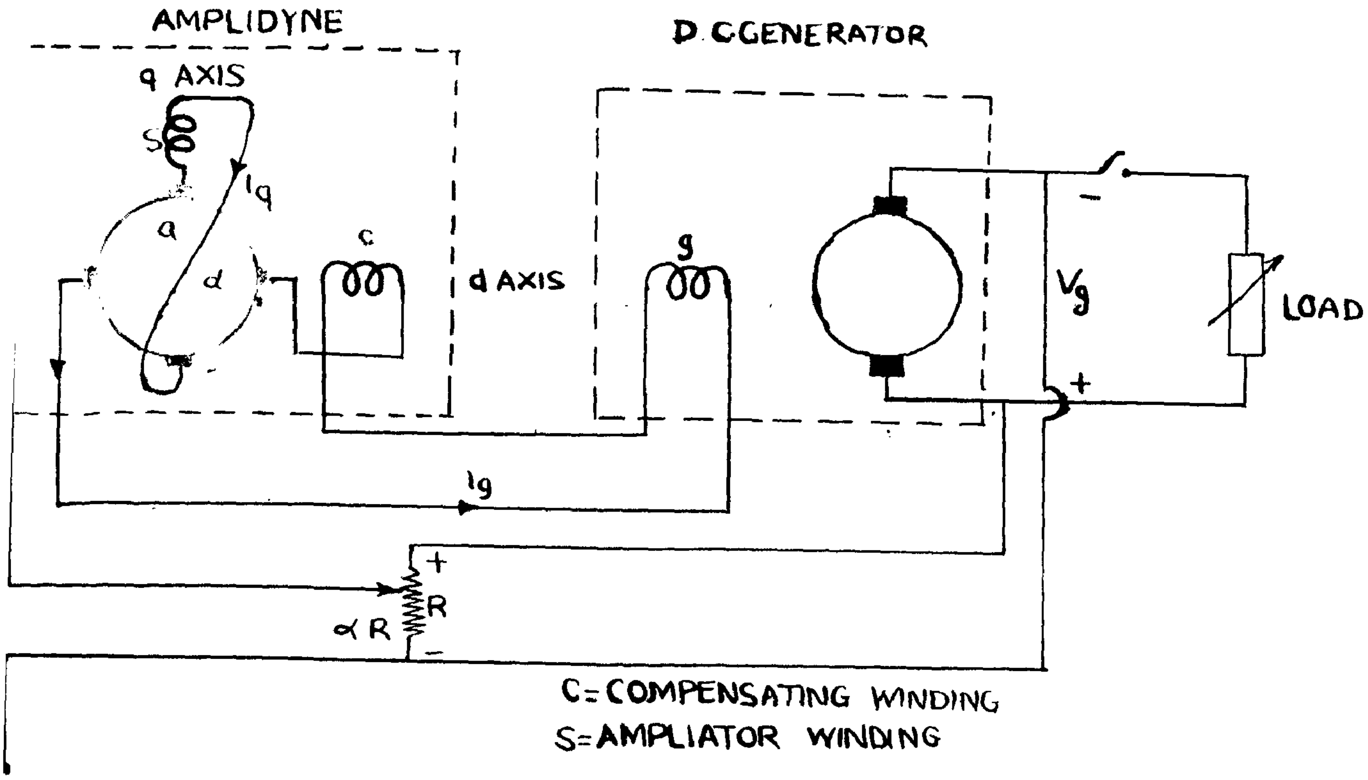


FIG. 1. D.C. VOLTAGE REGULATING SYSTEM

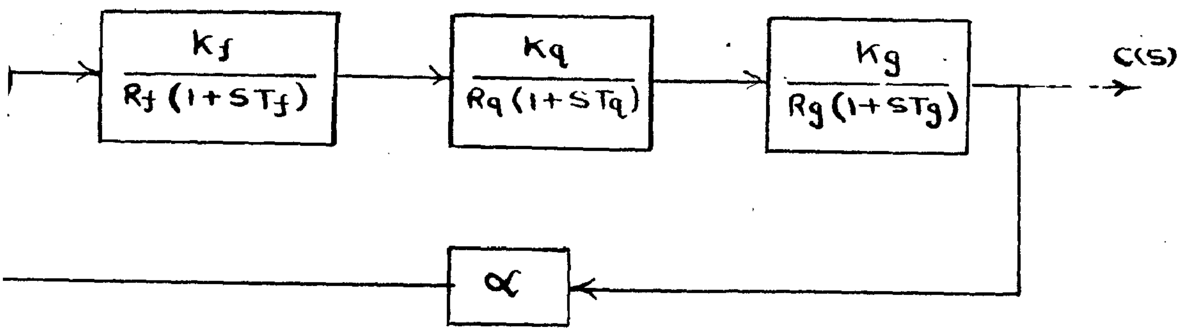
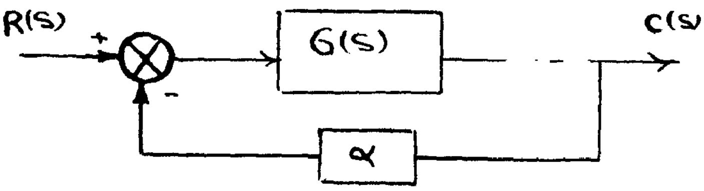
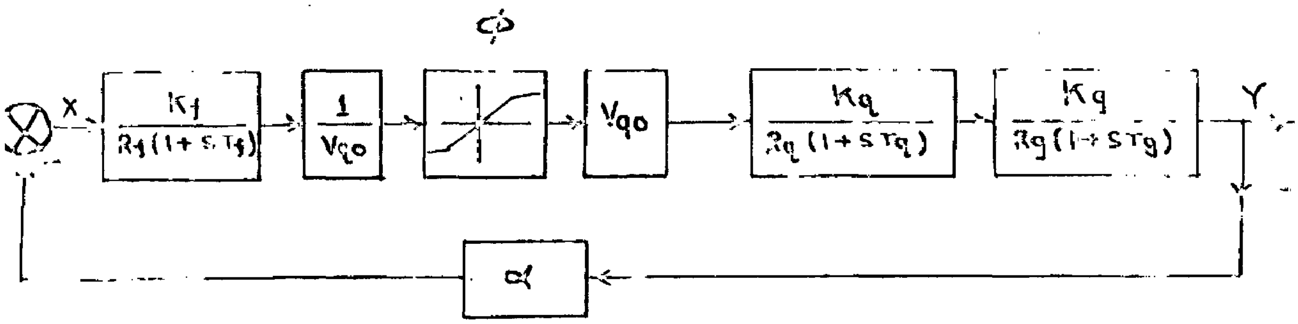


FIG. 2(a) BLOCK DIAGRAM OF THE SYSTEM

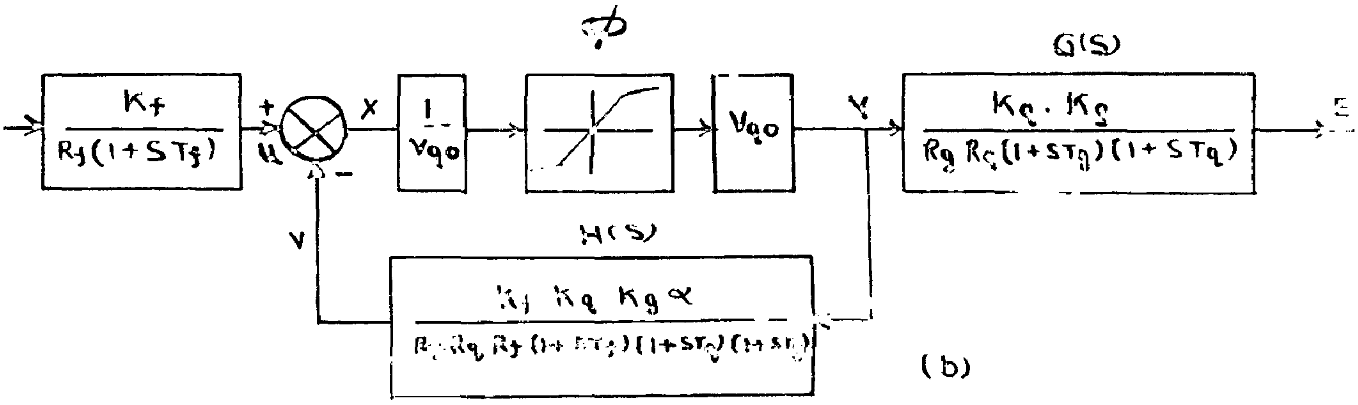


(b) REDUCED BLOCK DIAGRAM



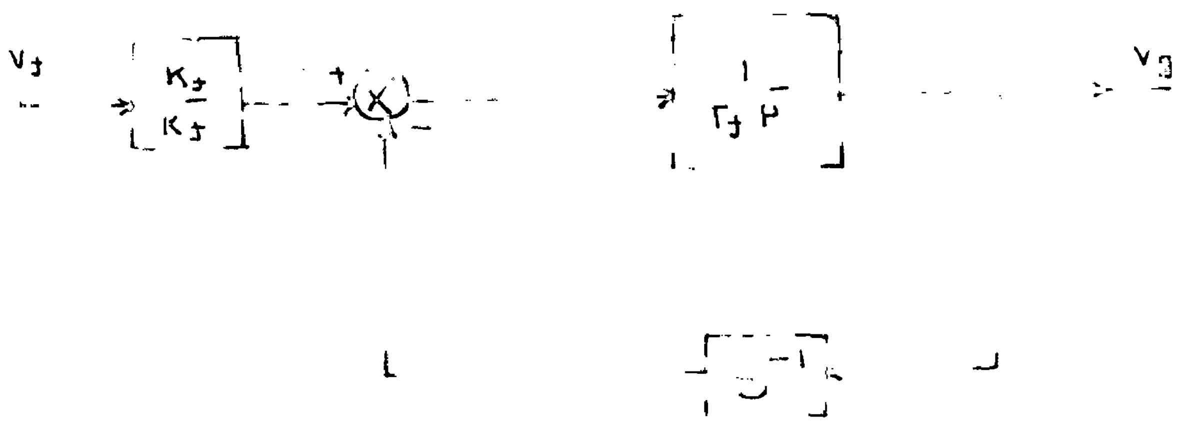
(a)

(a). BLOCK DIAGRAM OF AMPLIDYNE D AXIS SATURATION ONLY

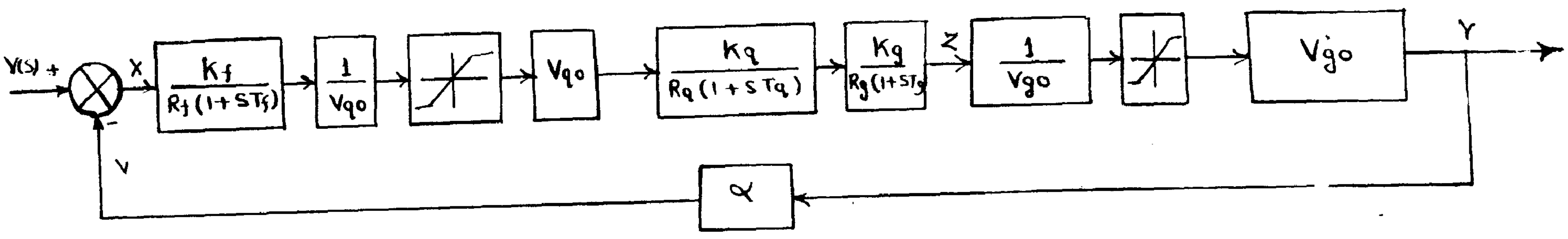


(b)

(b) BLOCK DIAGRAM OF FIG 3(a) REDUCED TO THE STANDARD FORM

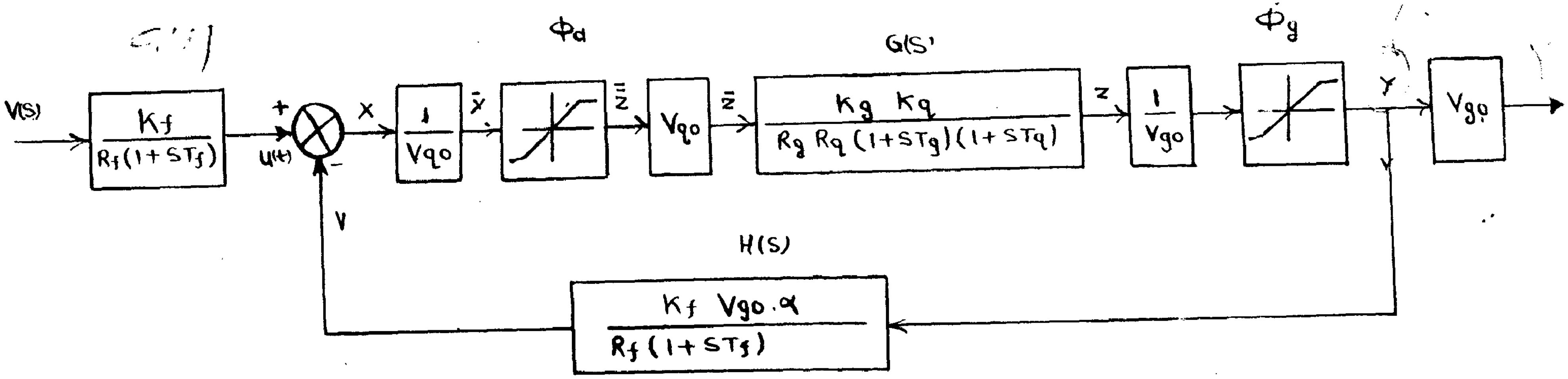


BLOCK DIAGRAM WITH INVERSE



(a)

FIG. 4(a) BLOCK DIAGRAM OF AMPLIDYNE D-AXIS AND GEN. AXIS SATURATION ON GAIN ONLY



(b)

FIG. 4(b) BLOCK DIAGRAM OF FIG 4(a) REDUCED TO STANDARD FORM

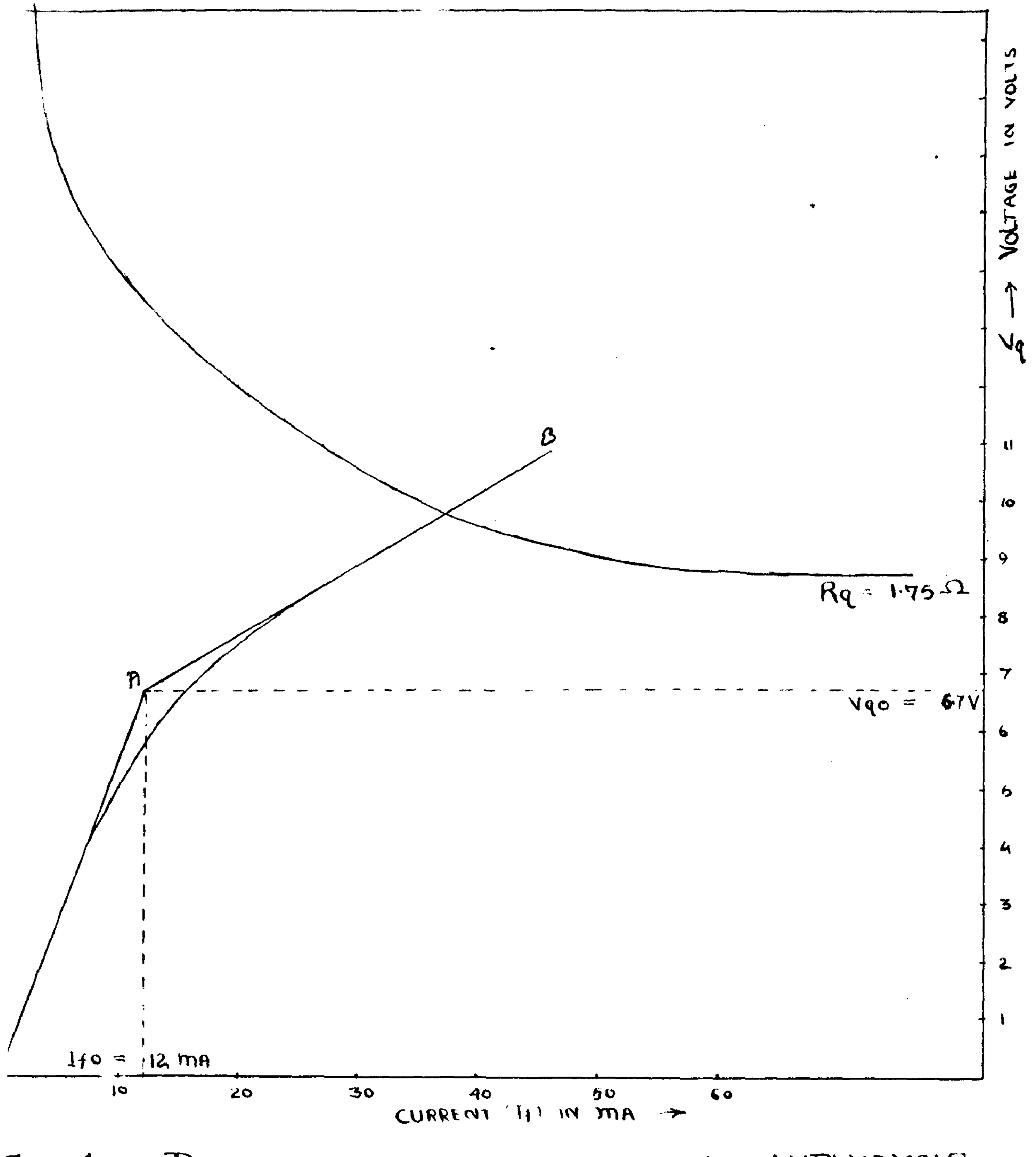


FIG. 4 (c) D-AXIS SATURATION CURVE OF AMPLYDYNE

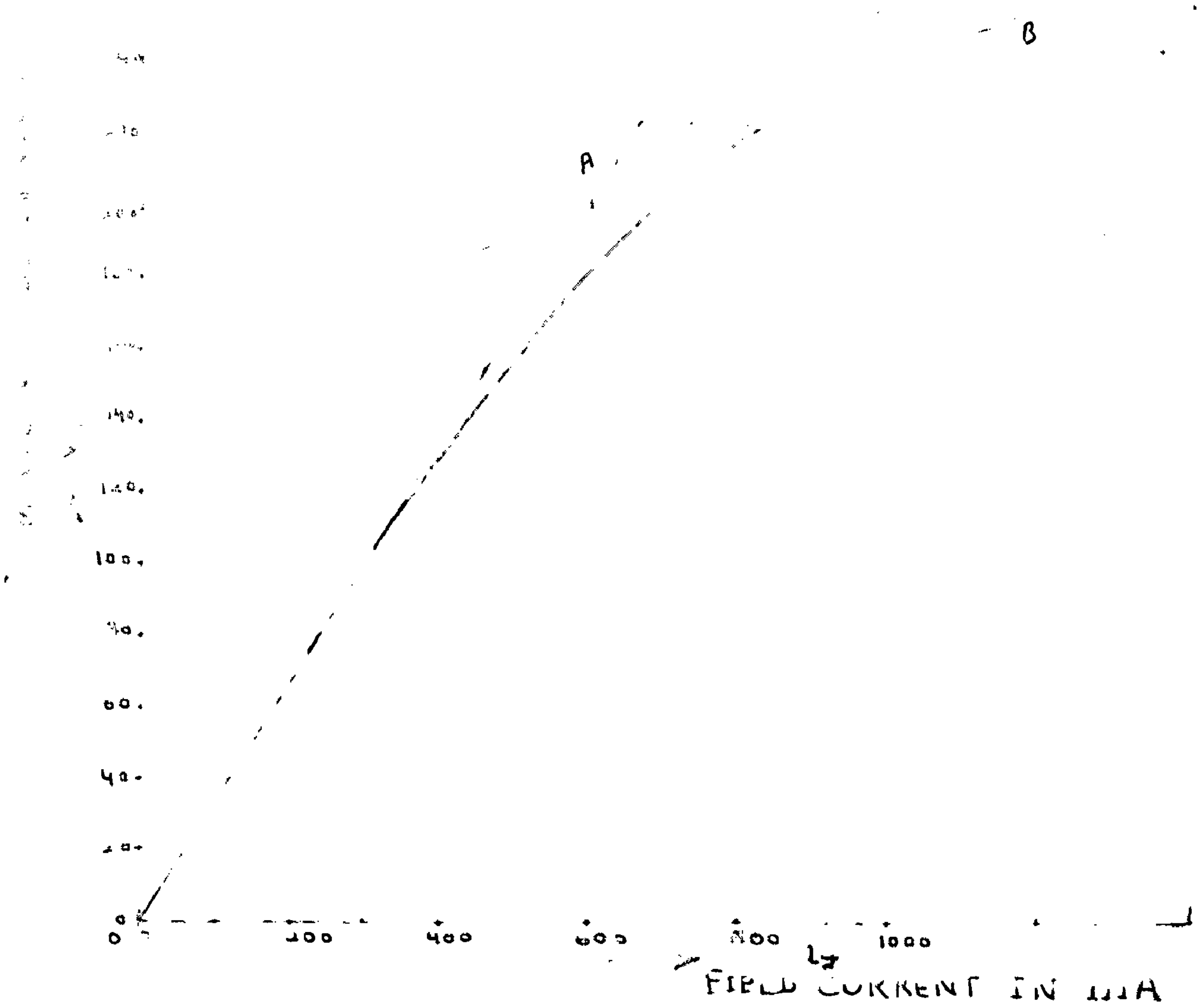
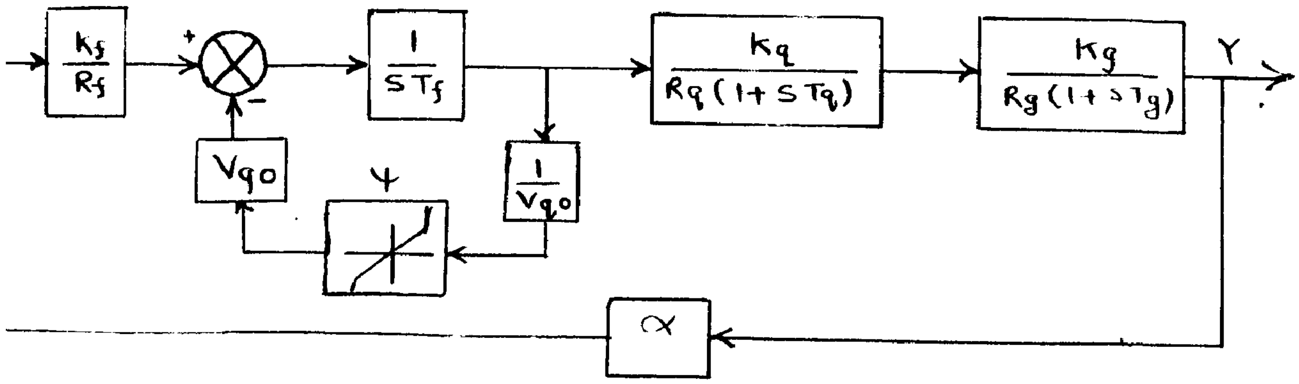
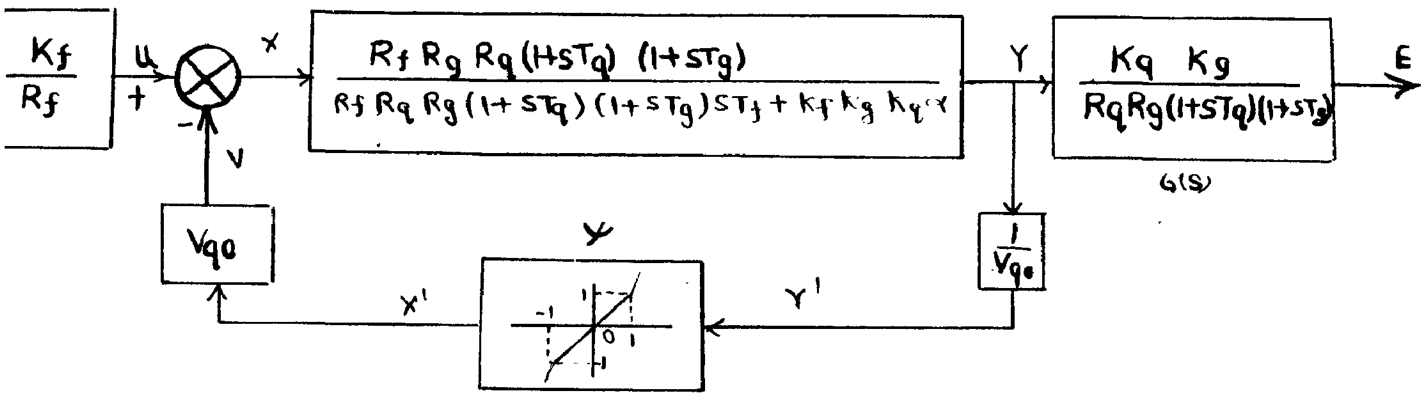


Fig. 4. OPEN CKT CHARACTERISTIC OF GENERATOR.

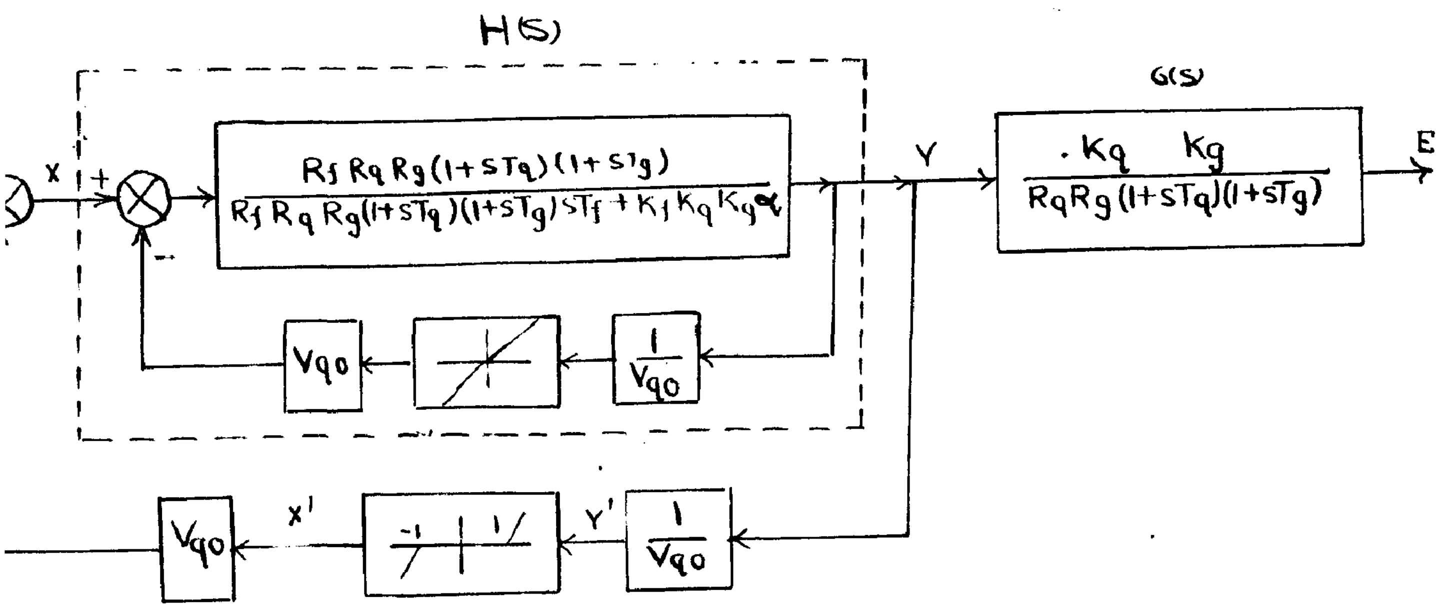
Fig. 4. NORMALISED SATURATION CURVE



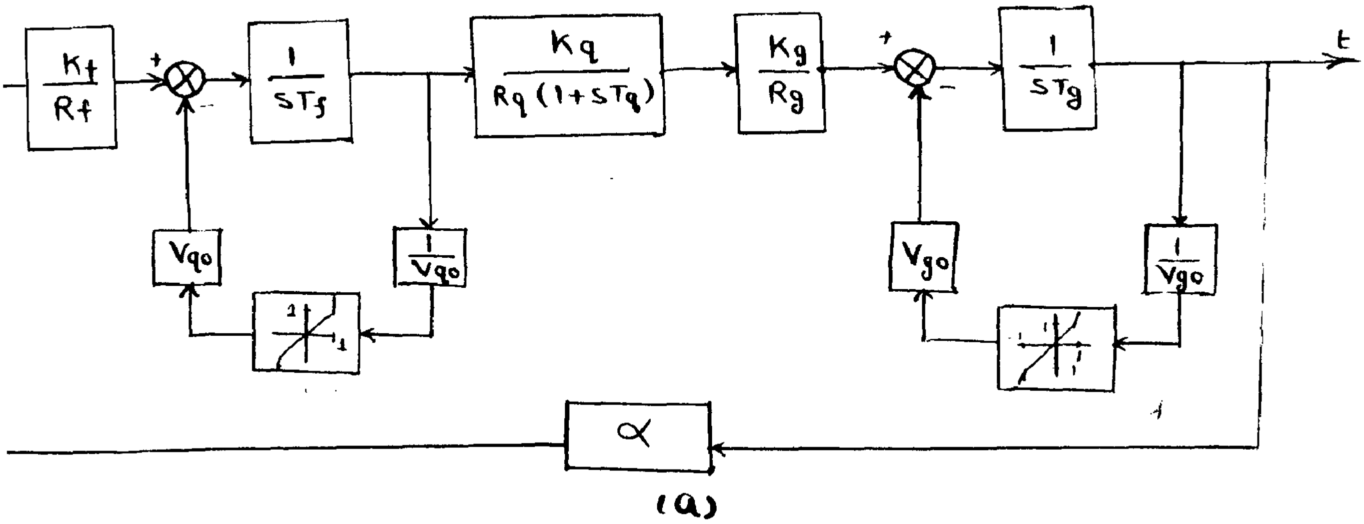
›CK DIAGRAM CONSIDERING AMPLIDYNE D AXIS SATURATION ON BOTH GAIN & FIELD TIME CONSTANT



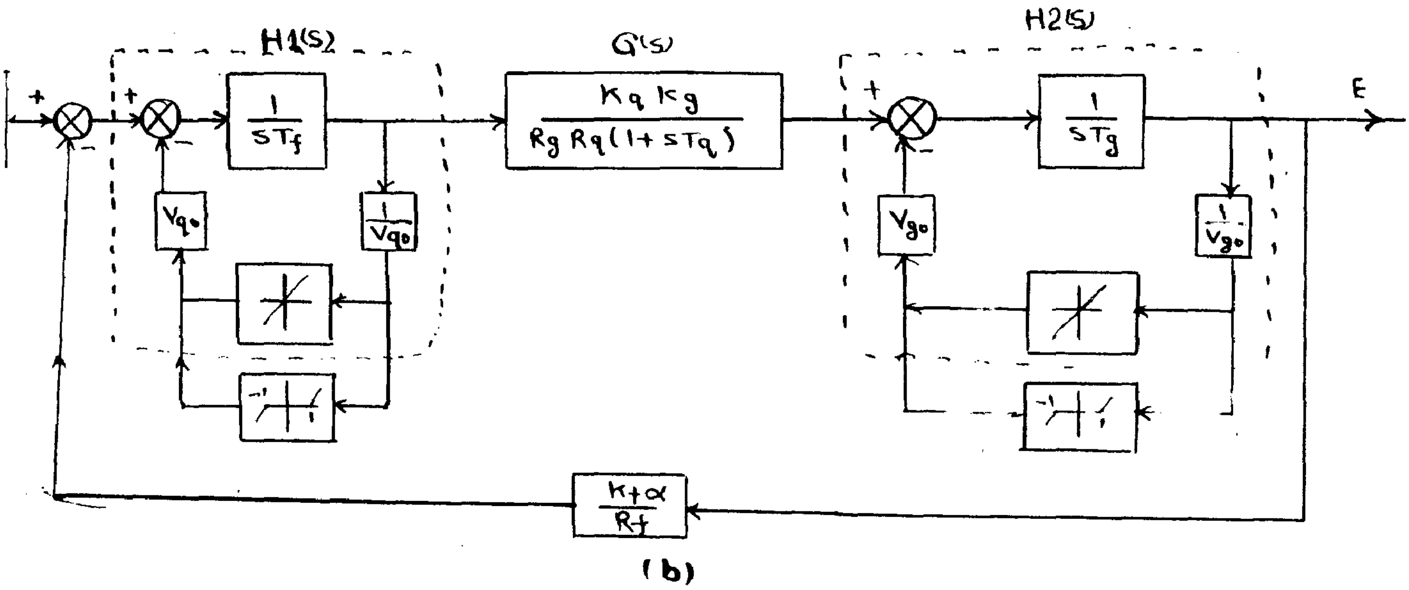
BLOCK DIAGRAM OF FIG 5(a) REDUCED TO STANDARD FORM.



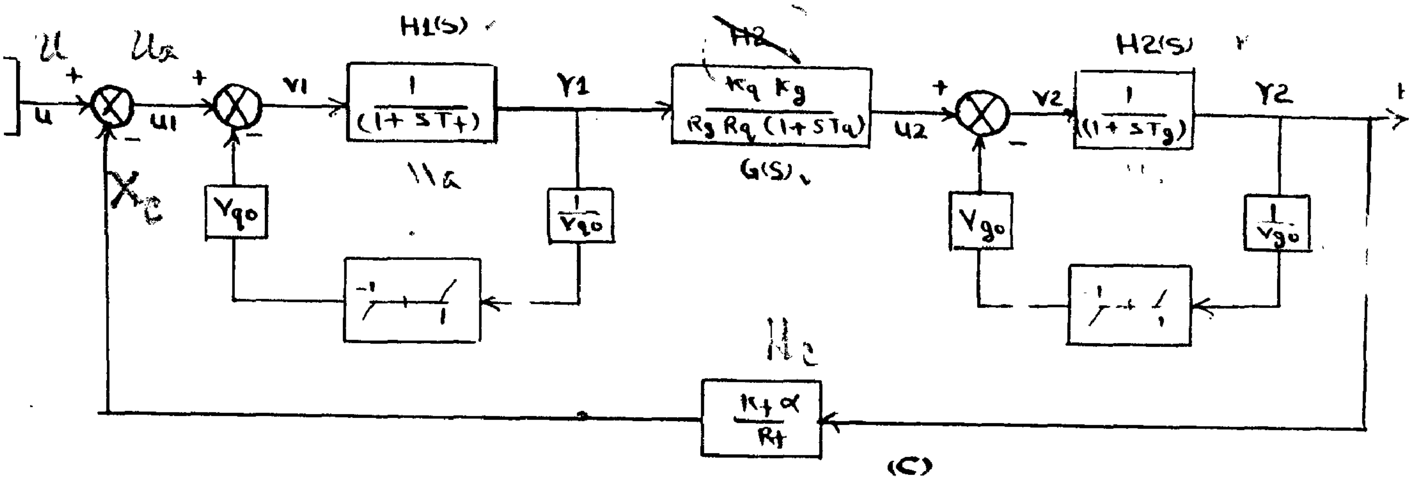
G. 5(C) MODIFIED BLOCK DIAGRAM OF FIG. 5(b)



6(a) BLOCK DIAGRAM CONSIDERING AMPLIDYNE D-AXIS AND GEN AXIS SATURATION ON BOTH GAIN & FIELD T. CONTT.



6(b) MODIFIED BLOCK DIAGRAM OF FIG 6(a)



6(c) SIMPLIFIED BLOCK DIAGRAM OF FIG 6(b)

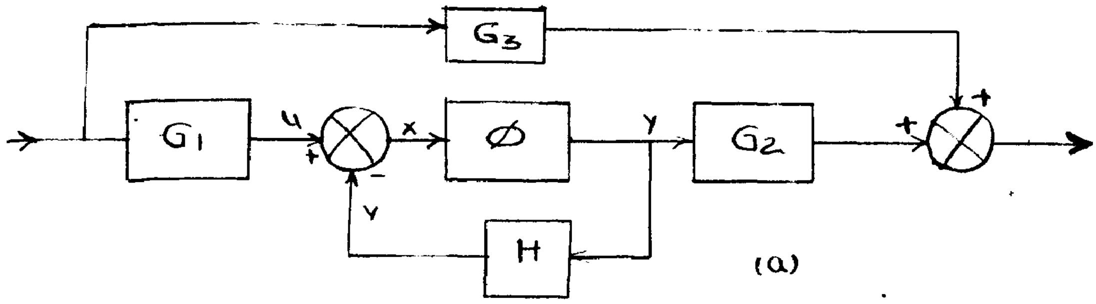


FIG. 7(a) STANDARD BLOCK DIAGRAM

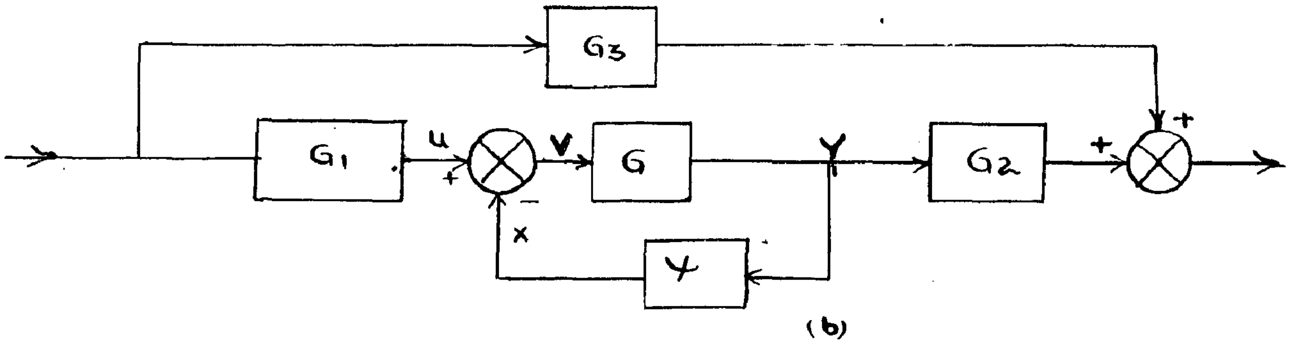


FIG. 7(b) STANDARD BLOCK DIAGRAM

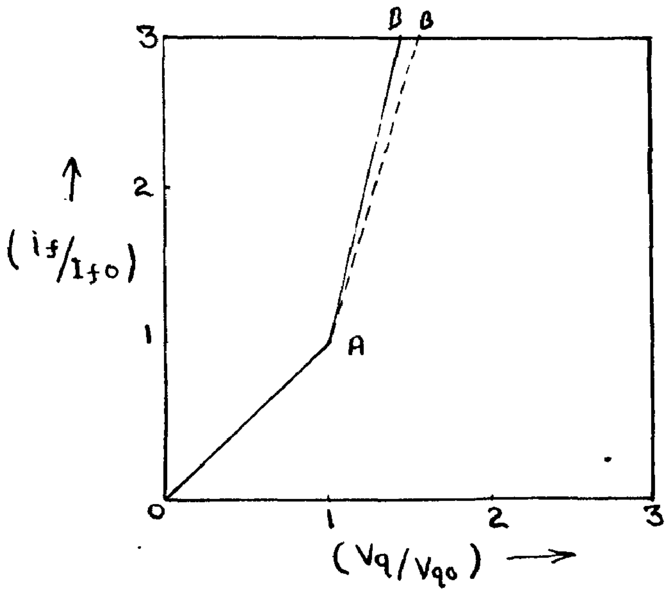


FIG. 8. INVERSE NORMALISED SATURATION CHAR.

(- - - - - -) FOR D.C GENARATOR
(——) FOR AMPLIDYNE

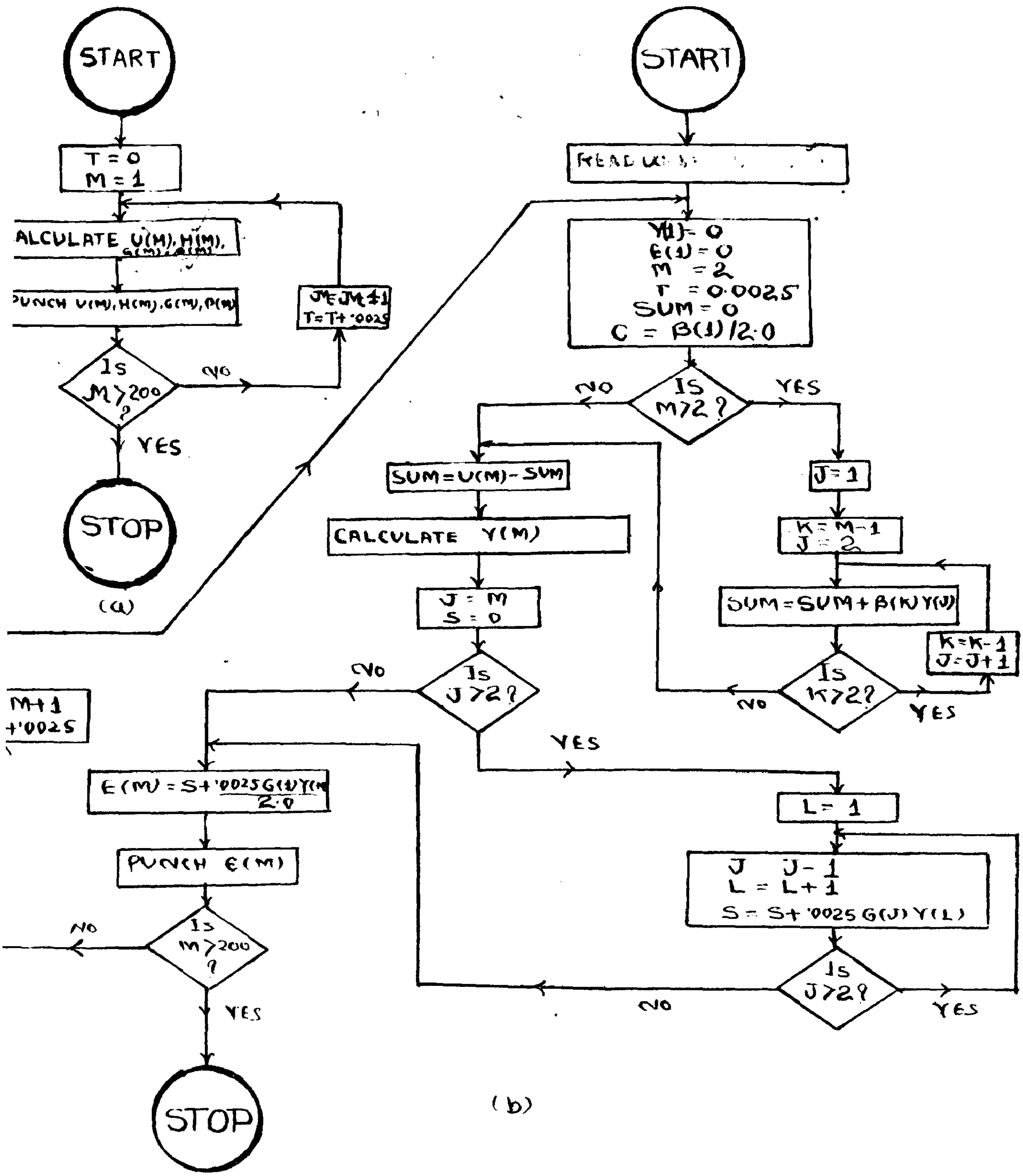


FIG 9. FLOW CHART FOR CALCULATING THE TRANSIENT RESPONSE BY CONSIDERING THE EFFECT OF D AXIS SATURATION ON GAIN ONLY

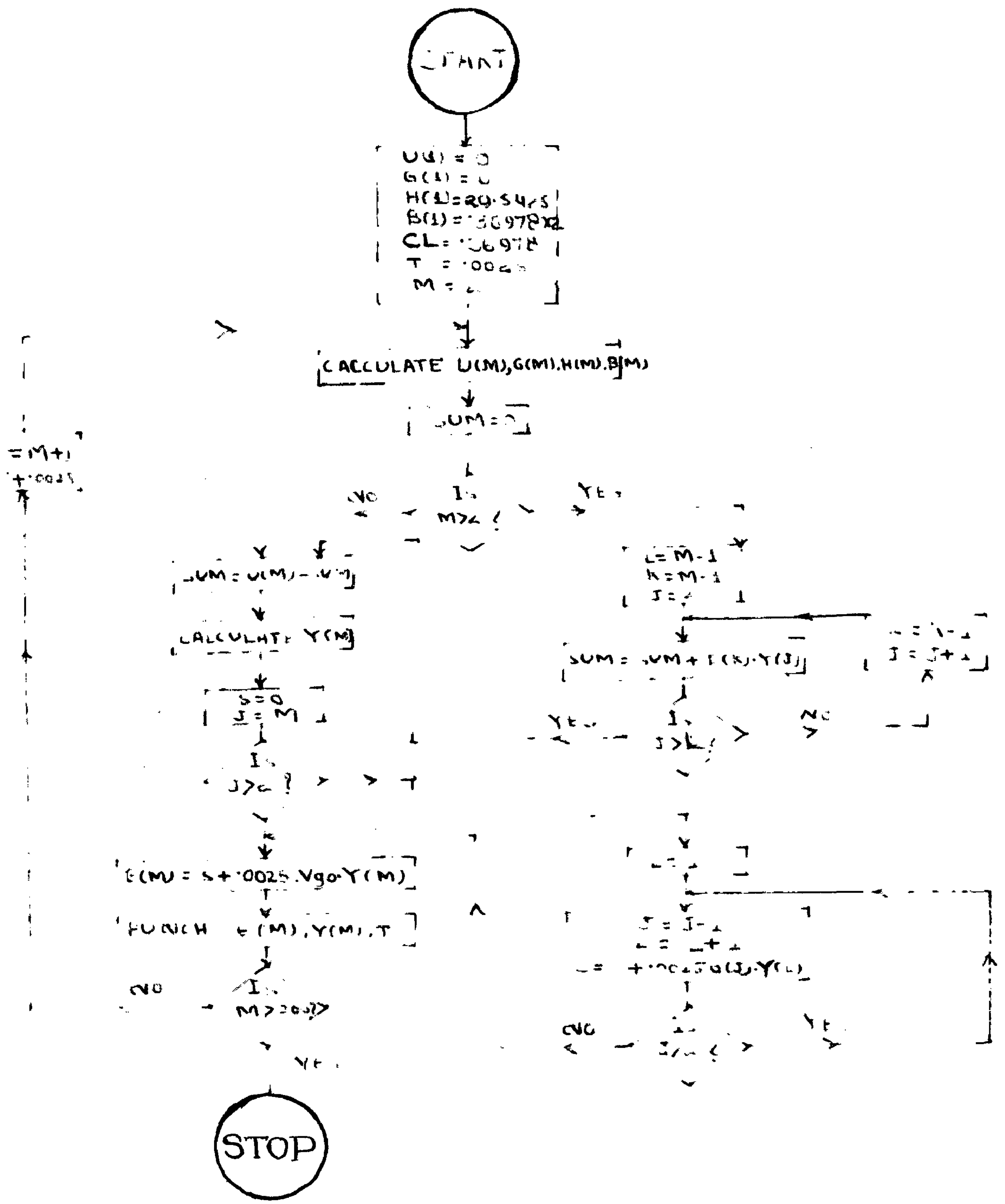


FIG. 10. FLOW CHART FOR CALCULATION OF TRANSIENT RESPONSE CONSIDERING D AXIS AND GENERATOR SATURATION ON GAIN ONLY.

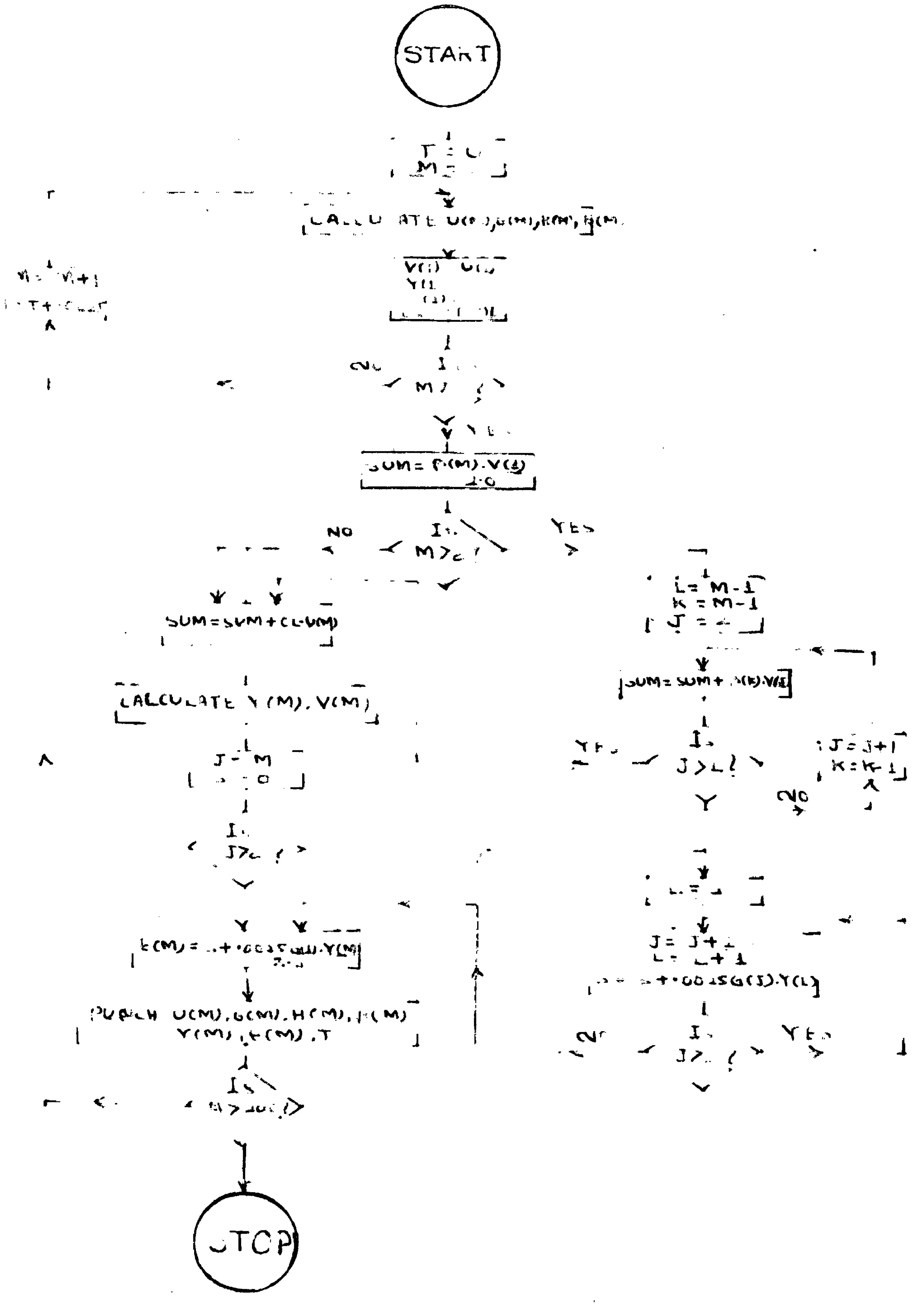
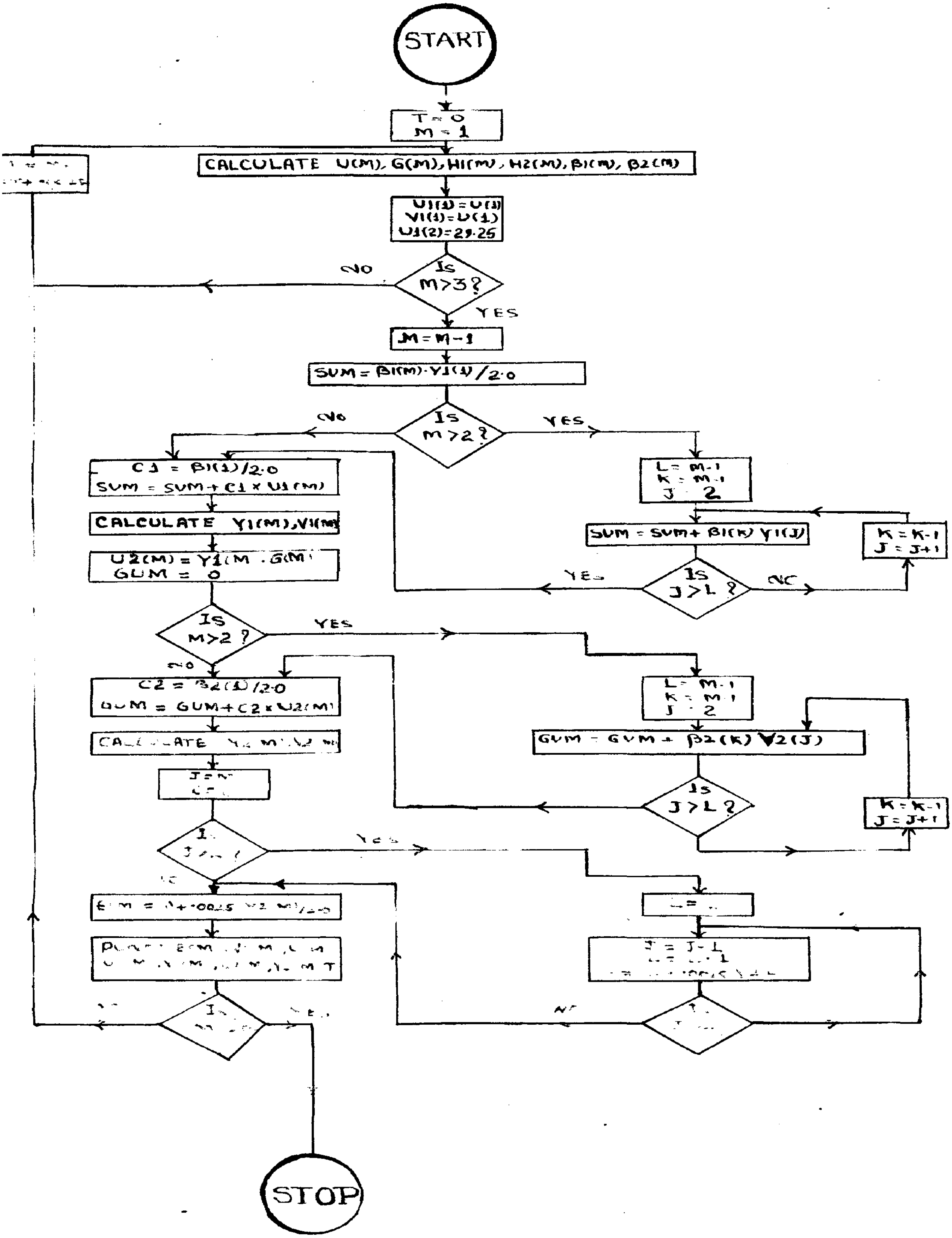


FIG. 11 FLOW CHART FOR CALCULATION OF [illegible]
CONSIDERING THE EFFECT OF [illegible] SATURATION [illegible]
[illegible] GAIN AND TIME CONSTANT



[illegible]G. 12. FLOW CHART FOR CALCULATION OF TRANSIENT RESPONSE CONSIDERING D-AXIS AND [illegible] SATURATION IN [illegible] AND TIME [illegible]

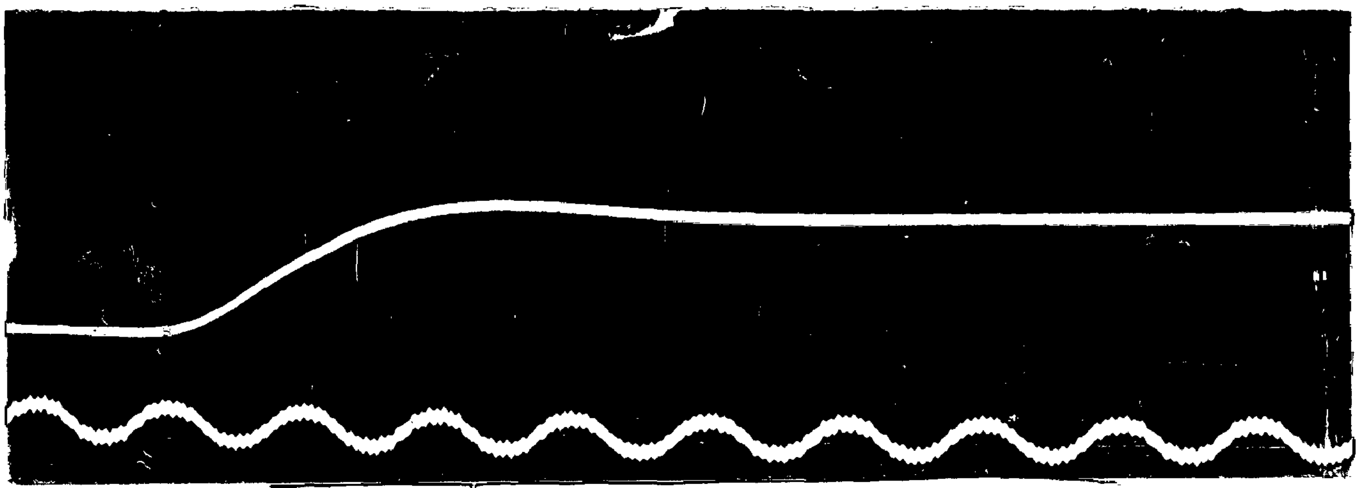
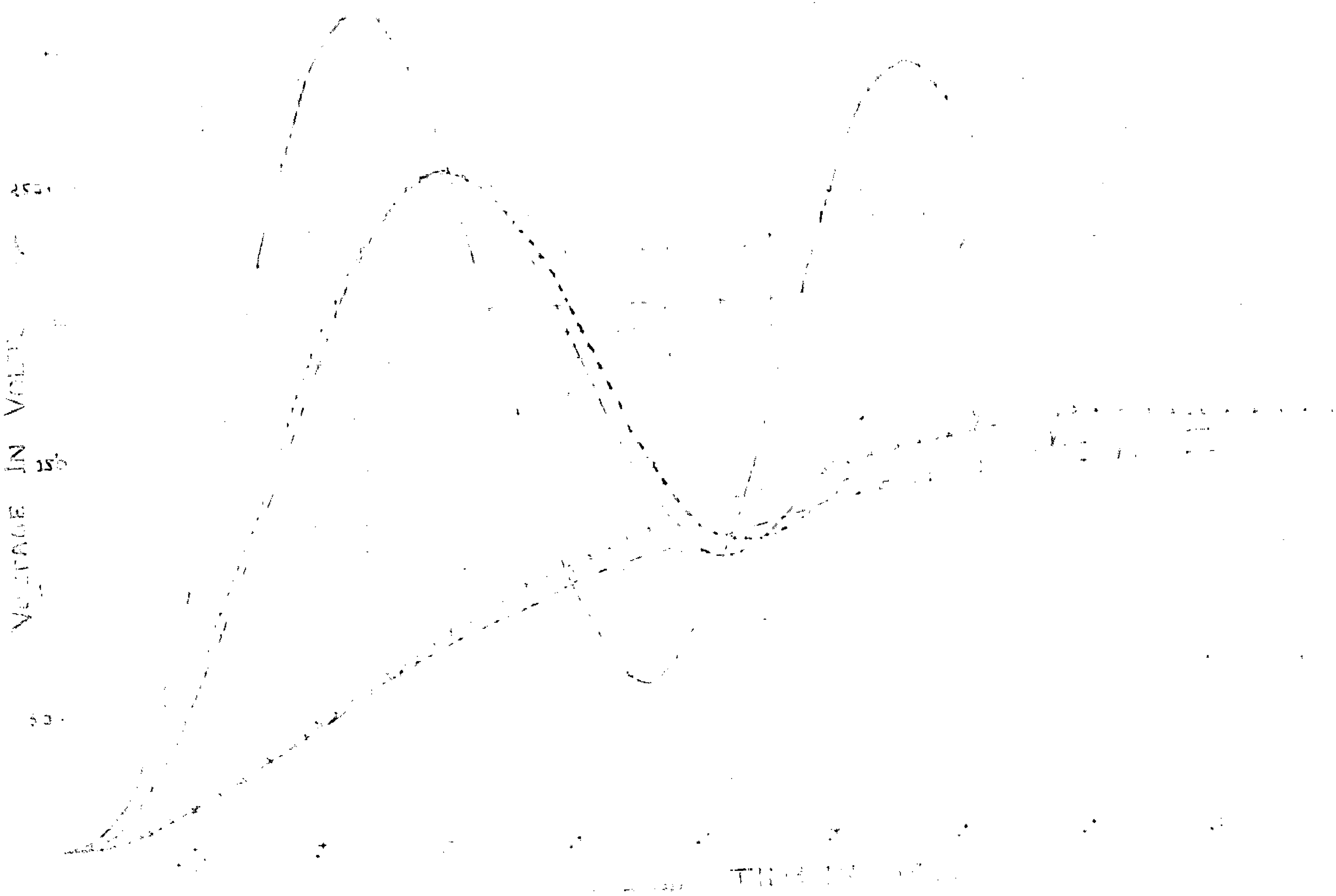


Plate – 1

(A) OUTPUT VOLTAGE RECORD FOR 50 V STEP REFERENCE

(B) 6 C/S TIMING WAVE

STEADY OUTPUT VOLTAGE = 146 V.



13

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**************************)**********************************************

**
C   C    S P SRIVASTAV TRANSIENT ANALYSIS
C        AMPL.D AXIS SATURATION ON GAIN ONLY
         DIMENSION U(200),H(200),G(200),B(200),Y(200),E(200)
         T=0.0
         DO 510 M=1,200
         U(M)=29.25*(1.0-2.718**(-31.45*T))
         H(M)= 239.237*(.56*(2.718**(-31.45*T))+17.97*(2.718**(-12.92*T))-
        11(.53*(2.718**(-13.48*T)))
         G(M)= 16876.0*(2.718**(-12.92*T)- 2.718**(-13.48*T))
         B(M)=0.0025*H(M)
         IF (M-2) 555,556,556
556      SUM=0.0
         IF(M-2) 20,20,11
11       L=M-1
         K=M-1
         DO 51 J=2,L
         SUM=SUM+B(K)*Y(J)
         K=K-1
51       CONTINUE
20       SUM=U(M)-SUM
         C=B(1)/2.0
         Y(M)=SUM/((1.0+C)*6.7)
         IF (Y(M)-1.0) 30 , 30 , 31
30       Y(M)=6.7*Y(M)
         GO TO 35
31       Y(M)=(5.25+122.5*SUM/550.3)/(1.0+122.5*C/550.3)
35       J=M
         S=0.0
         IF(J-2) 110,110,111
111      L=1
100      J=J-1
         L=L+1
         S=S+.0025*G(J)*Y(L)
         IF (J-2) 110,110,112
112      GO TO 100
110      E(M)=S+0.0025*G(1)*Y(M)/2.0
         PUNCH 3, U(M),H(M),G(M),Y(M),E(M),T
3        FORMAT (6F10.4)
555      T=T+0.0025
510      CONTINUE
         STOP
         END
```

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C  C  S.P.SRIVASTAV TRANSIENT ANALYSIS
C     CONSIDERING D ASIS AND GENRATOR SATURATION ON GAIN ONLY
       DIMENSION U(200),G(200),H(200),B(200),Y(200),Z(200),E(200)
      U(1)=0.00
      G(1)=0.00
      H(1)=29.5425
      B(1)=0.73856
      T=0.0025
      DO 510 M=2,200
      U(M)=29.25*(1.0-2.718**(-31.45*T))
      G(M)= 9381.6*(2.718**(-12.92*T)-2.718**(-13.48*T))
      H(M)=0.14625*(2.718**(-31.45*T))*202.0
      B(M)=0.0025*H(M)
      SUM=0.0
      IF (M-2) 20,20,11
11    L=M-1
      K=M-1
      DO 51 J=2,L
      SUM=SUM+B(K)*Y(J)
      K=K-1
51    CONTINUE
20    SUM=U(M)-SUM
      CL=B(1)/2.0
       Y(M)=SUM*G(M)/(202.0+CL*G(M))
       Z(M)=Y(M)*202.0/(6.7*G(M))
      IF (Z(M)) 10,21,21
21    IF (Z(M)-1.0) 30,30,31
30    IF (Y(M)-1.0) 40,40,41
31    Y(M)= (SUM*.225+.775*6.7)*G(M)/(202.0+CL*.225*G(M))
      IF (Y(M)-1.0) 40,40,45
45    Y(M)=((SUM*.225+.775*6.7)*.275*G(M)+.725*202.0)/(202.0+.275*CL*
     1.225*G(M))
      GO TO 40
41    Y(M)=(SUM*.275*G(M)+.725*202.0)/(202.0+.275*CL*G(M))
      GO TO 40
10    Z1=SQRTF (Z(M)*Z(M))
      Y1=SQRTF (Y(M)*Y(M) )
      IF (Z1-1.0) 1,1,32
1     IF (Y1-1.0) 40,40,42
32    Y(M)= (SUM*.225-.775*6.7)*G(M)/(202.0+CL*.225*G(M))
      Y1=SQRTF (Y(M)*Y(M))
      IF (Y1-1.0) 40,40,46
46    Y(M)=((SUM*.225-.775*6.7)*.275*G(M)-.725*202.0)/(202.0+.275*CL*
     1.225*G(M))
      GO TO 40
42    Y(M)=(SUM*.275*G(M)-.725*202.0)/(202.0+.275*CL*G(M))
40    Y(M)=Y(M)
      J=M
      S=0.0
      IF(J-2) 110,110,111
111   L=1
100   J=J-1
      L=L+1
      S=S+0.0025*202.0*Y(L)
      IF(J-2)110,110,112
112   GO TO 100
110   E(M)=S+.0025*101.0*Y(M)
      PUNCH3,U(M),G(M),H(M),B(M),Y(M),E(M),T
3     FORMAT (7F10.3)
      T=T+.0025
```

```
510   CONTINUE
      STOP
      END
```

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****************:.*******)*************************************************
**
C  C   S P SRIVASTAV TRANSIENT ANALYSIS
C      AMPL.D AXIS SATURATION ON BOTH GAIN AND TIME CONSTANT
       DIMENSION U(200),G(200),H(200),B(200),V(200),Y(200),E(200)
       T=0.0
       DO 510 M=1,200
       U(M)=29.25
       G(M)= 16876.0*(2.718**(-12.92*T)- 2.718**(-13.48*T))
       H(M)= 14.54*(2.718**(-55.55*T))+(2.718**(-1.15*T))*(15.91*COSF(T*
      129.566)- 3.64*SINF(T*29.586))
       B(M)=0.0025*H(M)
       E(1)=0.0
       Y(1)=0.0
       V(1)=U(1)
       IF (M-2) 555,556,556
556    SUM=B(M)*V(1)/2.0
       IF (M-2) 20,20,11
11     L= 4-1
       K=M-1
       DC 51 J=2,L
       SL 4=SUM+B(K)*V(J)
       K= <-1
51     CC ITINUE
20     CL=B(1)/2.0
       SUM=SUM+CL*U(M)
       PSUM=SUM/6.7
       PSUM1= SQRTF (PSUM*PSUM)
       IF (PSUM1-1.0) 30,30,32
 30    V(4)=U(M)
       Y(M)=SUM
       GO TO 35
32     IF (PSUM-1.0) 29,29,31
29     ZSUM= (PSUM-3.65*CL)/(1.0+CL*3.65)
       Y(M)=6.7*ZSUM
       V(M)=U(M)-3.65*6.7-3.65*6.7*ZSUM
       GO TO 35
31     ZSUM=(PSUM+3.65*CL)/(1.0+CL*3.65)
       Y(M)=6.7*ZSUM
       V(M)=U(M)-^.65*6.7*ZSUM+3.65*6.7
35     J=M
       S=J.0
       IF(J-2) 110,110,111
111    L=1
100    J=J-1
       L=L+1
       S=S+C.0025*G(J)*Y(L)
       IF (J-2) 110,110,112
112    GO TO 100
110    E(M)=S+.0025*G(1)*Y(M)/2.0
       PUNCH 3,  U(M),H(M),G(M),B(M),V(M),Y(M),E(M)
3      FORMAT (4F10.5,2F15.5,F10.5)
555    T=T+0.0025
510    CONTINUE
       STOP
       END
```

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*********************************)*********************************************************

**
C  C    S.P.SRIVASTAV TRANSIENT ANALYSIS
C       AMPLIDYNE D AXIS AND GENR. SATURATION ON BOTH GAINS AND TIME CONS
        DIMENSION U(200),G(200),H1(200),B1(200),H2(200),B2(200), B(200),
       1 Y1(200),Y2(200),V1(200),V2(200),E(200)
        T=0.00
        DO 510 M=1,200
        U(M)=29.25
        G(M)=696.2*2.718**(-12.92*T)
        H1(M)=31.45*2.718**(-31.45*T)
        B1(M)=0.0025*H1(M)
        H2(M)=13.48*2.718**(-13.48*T)
        B2(M)=0.0025*H2(M)
        B(M)=0.00146
        V1(1)=U(1)
        IF (M-2) 555,556,556
 556    SUM=B(M)*U(1)/2.0
        GUM=B1(M)*V1(1)/2.0
        RUM=0.0
        IF(M-2) 20,20,11
11      L=M-1
        K=M-1
        DO 51 J=2,L
        SUM= SUM+B(K)*U(J)
        GUM=GUM+B1(K)*V1(J)
        RUM= RUM+B2(K)*V2(J)
        K=K-1
51      CONTINUE
20      C1=B1(1)/2.0
        C2= B2(1)/2.0
        CL=B(1)/2.0
        Y2(M)= (RUM+C2*GUM*G(M)+C2*C1*G(M)*SUM)/(1.0+C2*C1*CL*G(M))
        Y1(M)= GUM+C1*SUM-C1*CL*Y2(M)
        IF (Y1(M)) 10,9,9
9       IF (Y1(M)-1.0) 12,12,13
12      IF (Y2(M)) 14,15,15
 15     IF (Y2(M)-1.0) 16,16,17
17      Y2(M)= (RUM+C2*GUM*G(M)+C2*C1*G(M)*SUM+C2*2.367*202.0)/(1.+C2*C1*
       1CL*G(M)+C2*2.367)
        Y1(M)= GUM+C1*SUM-C1*CL*Y2(M)
        V1(M)=SUM -CL*Y2(M)
        V2(M)= Y1(M)*G(M) +2.367*202.0-2.367*Y2(M)
        GO TO 75
14      IF (Y2(M)+1.0) 18,16,16
18      Y2(M)= (RUM+C2*GUM*G(M)+C2*C1*G(M)*SUM-C2*2.367*202.0)/(1.+C2*C1*
       1CL*G(M)+C2*2.367)
        Y1(M)= GUM+C1*SUM-C1*CL*Y2(M)
        V1(M)=SUM -CL*Y2(M)
        V2(M)= Y1(M)*G(M) -2.367*202.0-2.367*Y2(M)
        GO TO 75
13      Y2(M)= (RUM*(1.0+C1*3.65)+C2*GUM*G(M)+C2*C1*SUM*G(M)+C2*C1*G(M)*
       13.65*6.7) /(1.0+C1*3.65+C1*CL*C2*G(M))
        Y1(M)=(GUM+C1*SUM-C1*CL*Y2(M)+C1*3.65*6.7)/(1.0+C1*3.65)
        IF (Y2(M)) 19,21,21
21      IF (Y2(M)-1.0) 22,22,23
22      V1(M)=SUM -CL*Y2(M)+3.65*6.7-3.65*Y1(M)
        V2(M)= Y1(M)*G(M)
        GO TO 75
23      Y2(M)= (RUM*(1.0+C1*3.65)+C2*GUM*G(M)+C2*C1*SUM*G(M)+C2*C1*G(M)*
```

```
     13.65*6.7+C2*(1.0+C1*3.65)*2.367*202.0)/ ((1.0+C1*3.65)+C1*C2*CL *
     2G(M)+C2*2.367*(1.0+C1*3.65))
      Y1(M)=(GUM+C1*SUM-C1*CL*Y2(M)+C1*3.65*6.7)/(1.0+C1*3.65)
      V1(M)=SUM -CL*Y2(M)+3.65*6.7-3.65*Y1(M)
      V2(M)= Y1(M)*G(M) +2.367*202.0-2.367*Y2(M)
      GO TO 75
19    IF (Y2(M)+1.0) 24,22,22
24    Y2(M)= (RUM*(1.0+C1*3.65)+C2*GUM*G(M)+C2*C1*SUM*G(M)+C2*C1*G(M)*
     13.65*6.7+C2*(1.0+C1*3.65)*2.367*202.0) / ((1.0+C1*3.65)*(1.0+C2*2
     2.367)+C2*C1*CL*G(M))
      Y1(M)=(GUM+C1*SUM-C1*CL*Y2(M)+C1*3.65*6.7)/(1.0+C1*3.65)
      V1(M)=SUM -CL*Y2(M)+3.65*6.7-3.65*Y1(M)
      V2(M)= Y1(M)*G(M) -2.367*202.0-2.367*Y2(M)
      GO TO 75
10    IF (Y1(M)+1.0) 26,12,12
26    Y2(M)= (RUM*(1.0+C1*3.65)+C2*GUM*G(M)+C2*C1*SUM*G(M)-C2*C1*G(M)*
     13.65*6.7) / (1.0+C1*3.65+C1*C2*CL*G(M))
      Y1(M)=(GUM+C1*SUM-C1*CL*Y2(M)-C1*3.65*6.7)/(1.0+C1*3.65)
      IF (Y2(M)) 34,35,35
35    IF (Y2(M)-1.0) 36,36,37
36    V1(M)=SUM -CL*Y2(M)-3.65*6.7-3.65*Y1(M)
      V2(M)= Y1(M)*G(M)
      GO TO 75
37    Y2(M)= (RUM*(1.0+C1*3.65)+C2*GUM*G(M)+C2*C1*SUM*G(M)-C2*C1*G(M)*
     13.65*6.7+C2*(1.0+C1*3.65)*2.367*202.0)/ ((1.0+C1*3.65)+C1*C2*CL*
     2G(M)+C2*2.367*(1.0+C1*3.65))
      Y1(M)=(GUM+C1*SUM-C1*CL*Y2(M)-C1*3.65*6.7)/(1.0+C1*3.65)
      V1(M)=SUM -CL*Y2(M)-3.65*6.7-3.65*Y1(M)
      V2(M)= Y1(M)*G(M) +2.367*202.0-2.367*Y2(M)
      GO TO 75
34    IF (Y2(M)+1.0) 38,36,36
38    Y2(M)= (RUM*(1.0+C1*3.65)+C2*GUM*G(M)+C2*C1*SUM*G(M)-C2*C1*G(M)*
     13.65*6.7-C2*(1.0+C1*3.65)*2.367*202.0)/ ((1.0+C1*3.65)+C1*C2*CL*
     2G(M)+C2*2.367*(1.0+C1*3.65))
      Y1(M)=(GUM+C1*SUM-C1*CL*Y2(M)-C1*3.65*6.7)/(1.0+C1*3.65)
      V1(M)=SUM -CL*Y2(M)-3.65*6.7-3.65*Y1(M)
      V2(M)= Y1(M)*G(M) -2.367*202.0-2.367*Y2(M)
      GO TO 75
16    V1(M)=SUM -CL*Y2(M)
      V2(M)= Y1(M)*G(M)
75    J=M
      Y2(M)=Y2(M)
      Y1(M)=Y1(M)
      V1(M)=V1(M)
      V2(M)=V2(M)
      W=0.0
      IF (J-2) 220,220,222
222   L=1
200   J=J-1
      L=L+1
      W=W+.0025*Y2(L)
      IF (J-2) 220,220,224
224   GO TO 200
220   E(M)= W+0.0025*Y2(M) /2.0
      PUNCH 3, T,E(M),Y1(M),V1(M),Y2(M),V2(M)
3     FORMAT (6F10.4)
555   T=T+0.0025
510   CONTINUE
      STOP
      END
```