Simulation of Power Systems on Analogue Computer

A Dissertation
submitted in partial fulfilment
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of

MASTER OF ENGINEERING

in

POWER SYSTEMS ENGINEERING

By
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CERTIFICATE

Certified that the dissertation entitled 'SIMULATION OF POWER SYSTEMS ON ANALOGUE COMPUTER' which is being submitted by Sri V.B.Arora in partial fulfilment for the award of Degree of MASTER OF ENGINEERING IN POWER SYSTEM ENGINEERING of University of Roorkee is a record of student's own work carried out by him under my supervision and guidance. The matter 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 8 months from January to August 1968 for preparing dissertation for Master of Engineering Degree at this University.

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CONTENTS

SYNOPSIS

Power system stability problems have been solved by various methods. In the present work for simulating the power system on the analogue computer, each component of the system is represented by its performance equation. The synchronous machine is represented with the help of the operational forms of the Park's equation. In the previous work the induction motor load is simulated with the help of $\alpha\beta0/dqo$ transformation. In this work the motor is simulated by its equation of motion and its equivalent circuit.

In carrying out the transient stability study of the power system on the occurrence of unsymmetrical faults, the method of symmetrical components is used which reduces the system to a form suitable for analogue computation.

An attempt has been made to include the contribution made by the damper winding and angle regulator towards the transient stability of the system when a major disturbance on the system takes place and finally the combined effect of voltage regulator and angle regulator upon the transient stability limit of the system.

The effect of variation of the various parameters of the system e.g. resistance damper winding, gain and time constants of the regulator and the governer can also be studied.

This thesis gives in detail the performance equations of the various elements of the power system and the computer set-ups to simulate these equations. A simpler method of representing unsymmetrical faults on the system is proposed.

This thesis also discuss briefly the various methods of simulation and study. Finally the method of simulating a multi-machine system is explained.

The assumptions made are the same as made in other studies.

NOMENCLATURE

e_a e_t e_c	voltages of phase a,b,c
ψ_d, ψ_q	d-q axis fluxes,
e_d e_q	d-q axis voltage,
i_d i_q	d-q axis current,
e_t	terminal voltage,
E_r	refrence voltage,
V_b	Busbar voltage,
E_d''	Subtransient voltage,
V_d, V_q	Components of bus voltages along d-q-axis
z	impedance,
r	resistance,
x_d	d-axis synchronous reactance,
x_d'	d-axis transient reactance,
x_q	q-axis synchronous reactance,
θ	impedance angle,
δ	rotor angle,
M	inertia constant of synchronous machine,
T_i	input torque,
T_e T_u	electrical torque,
T_1 T_2 T_3	time constants used with voltage regulator
T_4 T_5	time constants used with governer
K_{r1} K_{r2} K_{r3}	Arbitrary constants used with voltage regulator
$K_{\delta 1}$ $K_{\delta 2}$ $K_{\delta 2}$	Arbitrary constants used with governer
G_g	Governer gain.

NOMENCLATURE

e_a e_t e_c	voltages of phase a,b,c
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V_b	Busbar voltage,
E_d''	Subtransient voltage,
V_d,V_q	Components of bus voltages along d-q-axis
z	impedance,
r	resistance,
x_d	d-axis synchronous reactance,
x_d'	d-axis transient reactance,
x_q	q-axis synchronous reactance,
θ	impedance angle,
δ	rotor angle,
M	inertia constant of synchronous machine,
T_i	input torque,
T_e Tu	electrical torque,
T_1 T_2 T_3	time constants used with voltage regulator
T_4 T_5	time constants used with governer
K_{r1} K_{r2} K_{r3}	Arbitrary constants used with voltage regulator
$K_{\delta1}$ $K_{\delta2}$ $K_{\delta2}$	Arbitrary constants used with governer
G_g	Governer gain.

s	fractional slip
R_r R_s	rotor and stator resistance, of induction motor
X_r X_s	rotor and stator reactances,
T_L	load torque
I	Inertia constant of induction motor
1	used as a suffix for positive sequence,
2	used as a suffix for negative sequence,
0	used as a suffix for field
k_d k_q	used as a suffix for damper

1.1 INTRODUCTION

A power system consists of a large number of elements and these can be broadly divided into the power and the control elements. The power elements include the generators, transformers, transmission lines and the loads while the control elements include the voltage regulators and the governer, the protective equipment and the switchgear.

In normal operation of the power system all these elements react together and form one unit for the purpose of generation, transmission and distribution of electrical energy.

Effective and efficient control of the power system can be realised only when the exact nature of the transient behaviour of the system is understood. While studying the transient behaviour of the system, it must be remembered that all transients resulting from the occurrence of faults and their clearance, switching on or off the loads etc. are essentially electro-mechanical transients. Hence, it is necessary to consider all the elements of the power system as constituting an integral system. This means that the study of the electrical parts of the system should be associated closely with the study of the prime movers and their control equipment.

The characteristics of the power elements of the system are defined by the impedances, admittances and the transformation ratio, time constants, inertia of the rotating parts etc. These are known as the parameters of the system.

The stability of a system is defined as its ability to develop restoring forces between its elements equal to or greater than the disturbing forces so as to maintain a state of equilibrium between the elements.

A power system while in operation may be operating either within the steady state stability limit or within the transient stability limit. A steady state stability limit is defined as the maximum amount of power that the system can transmit without loss of synchronism when the load is increased in small steps. Accordingly the field currents of the generators and synchronous condensors increase in each step, thereby maintaining normal operating conditions. Obviously an increase in field current is necessary with the increase of loads so as to satisfy the constant voltage requirement. If the increase in the field currents can be made to increase simultaneously with the increase of load as it could be with a suitable voltage regulator, the stability limit increases appreciably. The stability limit under these conditions is known as dynamic stability limit or steady state limit with automatic devices.

A system is said to be in a transient state if the operating state of the power system is characterised by sudden changes in load or circuit conditions.

For a clear understanding of the nature of the transients, it is necessary to consider short period transient processes which may occur due to changes in the electromechanical conditions of the system or due to the occurrence of a fault in the system. If the system can withstand these disturbances without the individual machine loosing synchronism, it is said to be stable. So, it is necessary to study not only the steady state conditions but also the transient state conditions which frequently prevail in practice.

For the successful operation of the system, it is necessary to maintain the voltage and frequency within the specified limits at various points in the system. The system suffers from various disturbances such as occurrence of faults, throwing on or off of loads etc. These disturbances tend to create instability in some of the machines. The system then develops restoring forces to bring itself back to its original state or some other stable state as may happen when the faulty part of the system is switched out. The automatic devices help the system in developing the restoring forces.

Therefore, for the successful operation of the power system during the transient conditions it is necessary to know the contribution made by the automatic devices and the reaction of the system to their operation. Thus, if the designer has a clear idea about the transients occurring in the system he can make a correct assessment of the influence of the automatic devices. The design of the automatic devices can then be optimised so as to make the distinction between the transient and the steady state stability limits disappear.

Numerous approaches have been made to the system stability problems. All these are based on the operational

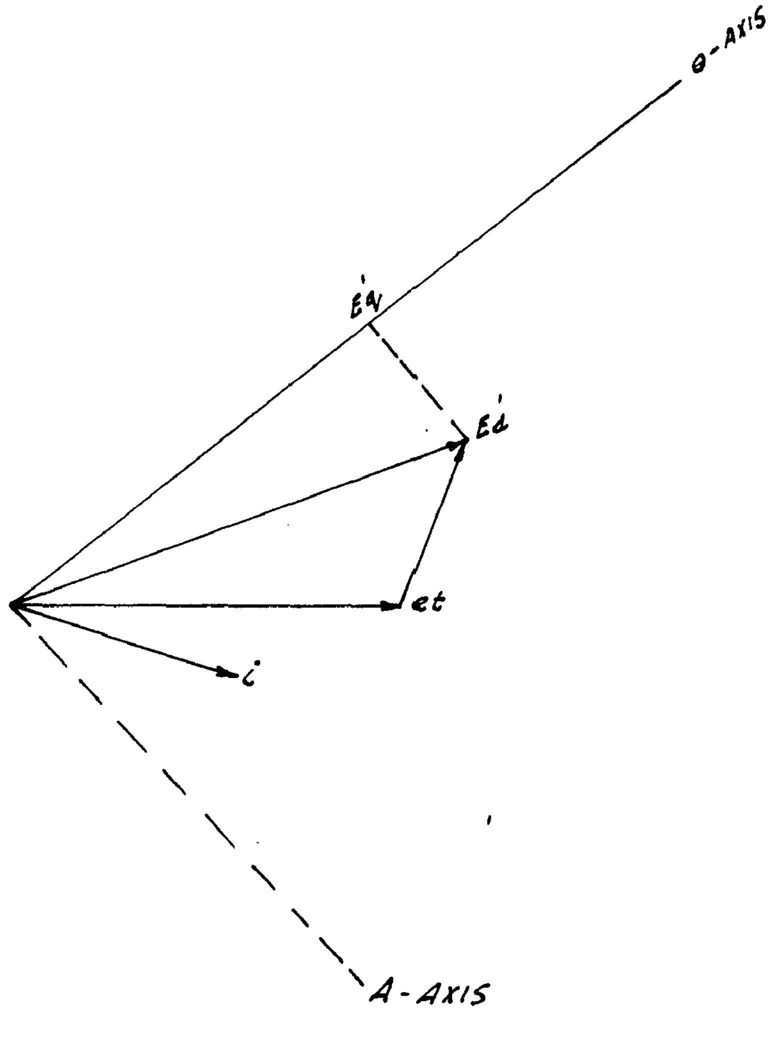


FIG. 1

form of the Park's equation written for the synchronous machines [2]. Many times certain simplifying assumptions are made. For example, the flux linkage of the field a winding is regarded as constant during the transient process. This enables one to represent the machine by the voltage E_q' defined in the phasor diagram shown in Fig.1, and the reactance x_d'. (It can be proved that E_q' represents the field flux linkage). As a result of this assumption, the equations of motion of the machine is reduced to a second order non-linear differential equation of the form,

$$M \frac{d^2\delta}{dt^2} = P_1 - P_m \sin \delta$$

This equation has been solved by methods such as the Step-by-Step method [5] and the network analyser [6,7]

Other approaches start from the Park's equation of the machine and use the equation, $T_e = \psi_d i_q - \psi_q i_d$ for the power output. Hence, the power output is expressed in terms of both the angle δ and time t during the transient process. Various assumptions are usually made in this analysis for simplicity. The following general methods are used to study the stability problem.

1. Mechanical Model Simulator,
2. Step-by-Step and graphical analysis,
3. General differential analyser application,
4. Network Analyser,

5. Digital Computer,

6. Analog Computer,

7. Combined Computer,

The effect of variation of the field flux linkages during transient disturbances has to be observed carefully for the following reasons:-

(a) To find the damping characteristic of the system to assess the validity of the assumption of constant field flux linkage.

(b) The contribution made by the modern fast acting voltage regulator towards the transient stability limit of the system.

(c) Generalised relationship between the assumptions made and the system parameters from the results of the above assumptions and associated studies.

Experiments were conducted on various computers e.g. prototype analogue computer, a combined computer, a combined electrical, electro-mechanical, electronic simulator, an electro-mechanical analogue computer and a purely electronic analogue computer |8|. The experiment concluded in the selection of a analogue computer of the d.c. electronic type because of the following.

(a) Close physical resemblance with the actual system,

(b) Easiness of varying system parameters,

(c) Direct variation of record of any quantity of the system, and

(d) Accurate representation of the system disturbances and the prediction of remedies for overcoming the harmful effect caused by these disturbances.

1.2 NECESSITY OF SIMULATION

In the past the power systems were simple, consisting of one generating station with a radial distribution system. Hence, the study of changes on the occurrence of disturbance was of little importance. With the advent of the development of the industry, the growth in the interconnections in the power system has created the necessity of improved quality and continuity of the service.

Further, the widespread application of automatic voltage regulators and fast acting governors in posing important problems for successful operation. The effect of varying the different parameters of the automatic voltage regulator and fast acting governers on the overall performance of the system is to be studied.

To arrive at qualitative and quantative results by analytical methods, particularly with complex multiloop systems the analysis involves laborious calculations. Also, in systems associated with elements having non-linear characteristics and where large number of variables are involved, for proper evaluation of performance, the calculations become very lengthy and hence curtail the scope of the study.

The use of analogue computer simplifies and shorten the work of carrying out the calculations. It is a tool which, in the hands of a competent engineer, becomes a very valuable aid in analysing the performance of the system and the apparatus. A much more complicated analysis of the power system and the performance of its component parts may be obtained from the results of the analogue computer study than by the actual system data and operating reports.

1.3 METHODS OF SIMULATION

The following methods are chiefly used in solution of the power system problems.

1.3.1 NETWORK ANALYSER

The network analyser provides an useful means for carrying out the load flow studies of complicated power systems. It provides faster solution of adequate accuracy in the analysis of the problem. In the normal operations of the system periodical checks are made which have shown important changes to be made in the system owing to the growth of loads. These checks also give same explanation for the unusual happenings in the normal operation of the power system.

The following is the brief description of the components and the operation of the network analyser.

(i) The Generator Units

The generators are represented by a variable a.c. voltage where phase shift can also be adjusted. A phase shifter and a single phase induction regulator are used in each generator unit. In addition to these there is a variable inductance and resistance to represent the generator impedance. The voltage used is usually of 400 c/s frequency or even higher [6] so as to reduce the size of the inductors.

(ii) Line Impedance Units

These units consist of variable resistors and reactors connected in series for representing the transmission lines. Shunt capacitors are also provided for representing the π and T equivalent circuit of long lines.

(iii) Load Impedance Units

These consists of variable resistors and reactors which are connected in either series or parallel combinations. These units differ from the line impedance units because of their high value of impedance.

(iv) Capacitor Units

The variable capacitors are used to represent line capacity, synchronous condenser and negative reactance occurring in the equivalent circuit of the multi-winding transformers.

(v) Auto Transformer Units

These are used to step up or step down the voltages at desired points in the network.

(vi) Mutual Transformer Units

These are used for simulating the mutual coupling between the various circuit and consists of 1:1 ratio transformers.

(vii) Instruments

Electronic instruments are used for measuring voltage current power and reactive power at various points in the system.

The principle studies that can be carried out on the network analyser are as follows:-

(a) Voltage regulation and load flow studies for normal and emergency operation.

(b) Short circuit studies to determine the circuit - breaker capacity.

(c) Steady state and transient stability studies for determining power limits of the transmission lines.

The solution of these problems is carried in the following steps.

(1) Assembling and organising the data of the power system.

(2) Conversion of these data to base values suitable for being used with the calculator voltages currents and impedances.

(3) Setting of the scaled data and adjusting the loads and the generator outputs in accordance with the requirements of the problem.

(4) Metering the network for getting the records, such as voltage, current, phase angle, watts and vars.

(5) Reconverting the values so obtained from base to system values.

The calculator is capable of giving direct records for the solution of the problem like short circuit and load flow studies simply by converting the values into system values. Transient stability study can be had by taking 'Step-by-Step' records. The calculator is capable of providing electrical conditions in each step, thus not only saving the time of lengthy calculations but also permiting the solution of the multi-machine problems.

1.3.2 MECHANICAL MODEL SIMULATOR

In recent years small scales machines have been developed [9] for representing the synchronous machine to a microscale. Such model machines have shown their performance similar to that of synchronous machine and have their outputs of the order of 20-25 kw and operate at voltages 220-400 volts. Transmission lines are represented in miniature form.

Such models have proved useful for the following,

(a) To check the basic theoretical assumptions,

(b) To check the accuracy of the formula used in the calculations.

(c) To test the operation of an installation under critical conditions.

(d) To study the general behaviour of the system when the parameters are subjected to changes.

(e) To study the electromagnetic and electro-mechanical and wave propagation transients associated with the induced overvoltage and lightning surges on the line.

These models when applied to the analysis of the operation of the power system give information which is useful for the design and operation of the system as a whole and of its component parts. These are also useful in optimising the design and operating conditions of a given system and to devise means for its proper control.

1.3.3 THE DIGITAL COMPUTER [11]

The digital computer has become a powerful tool in the solution of the power system problems. The inadequacy of representing some of the components of the power system on network analyser is fulfilled by this computer.

In making use of this computer for the power flow studies, a specified power input and voltage magnitude of real and reactive power is applied at the terminals of passive networks. The solution so obtained provides complete input and voltage information at the terminals and power flow in each branch of the network.

In preparing table for the load flow studies care should be taken so that,

(1) The algebraic sum of the components of flow at each junction of the network be zero.

(2) The algebraic sum of the voltage drop around each closed loop path of the network be zero.

For carrying analysis following information must be gathered.

(1) Configuration of the network,

(2) Impedances and suspectances of various network elements.

(3) Power and reactive demand at all load buses.

(4) Power and reactive output of all generators except the swing generator.

(5) Voltage and phase angle ratio of all transformers.

(6) Voltage and phase angle at one bus in the network this can be the reference bus.

Results obtained from the computer are as follows:-

(1) Power and reactive flow at each end of line elements.

(2) Voltage and phase angle at all buses.

(3) Power and reactive power loading of the swing generator.

For a large class of power flow studies associated with the planning and system extension, the network analyser can provide the solution of adequate accuracy, but for problems like calculation of losses and other problems where the analyser fails to provide the solution of desired accuracy, digital computer is used.

For stability studies, various techniques have been used on the digital computer. The digital computer constitutes a very versatile, flexible and economical tool for the analysis of the problems of the power system.

1.3.4 THE ANALOGUE COMPUTER

In the past utility companies have been working use of network analyser and digital computer for solving the engineering problems. For the solution of many of the problem network analyser gave lengthy and tedious solutions and hence digital computer became more popular as this could be bought or rented for use. Perhaps this was so because the analogue computer techniques were still under development. The new techniques of the analogue computer are now fully developed and are finding their best use in engineering research.

Modern computing devices can be mainly divided into two categories (a) Digital, (b) Analogue. The digital computers are basically designed to perform arithmetic calculations at a very fast rate while the analogue computer offers close physical resemblance with the actual system. Each one is having its definite advantage and its field of application. The biggest advantage of the digital computer being that it can provide solution at very fast rate and is capable of handling large amounts of data simultaneously. The disadvantage of this computer is owing of its working with numerical equations, which may in some case be a handicap. For example, in problems where the effect of variation of system parameters on the performance of the system is to be studied, such as the effect of varying the cross-section of the line conductors during load flow studies the coefficient of potentiometer settings in the analogue computer set-up can be simple changed while in the case of digital computer it may be necessary to recompute several matrices.

In the aircraft industry where most of the work is carried out with the help of computers, analogue computers are made use of for finding the approximate solution of the problems and digital computers are used for finding the solutions of the required accuracy.

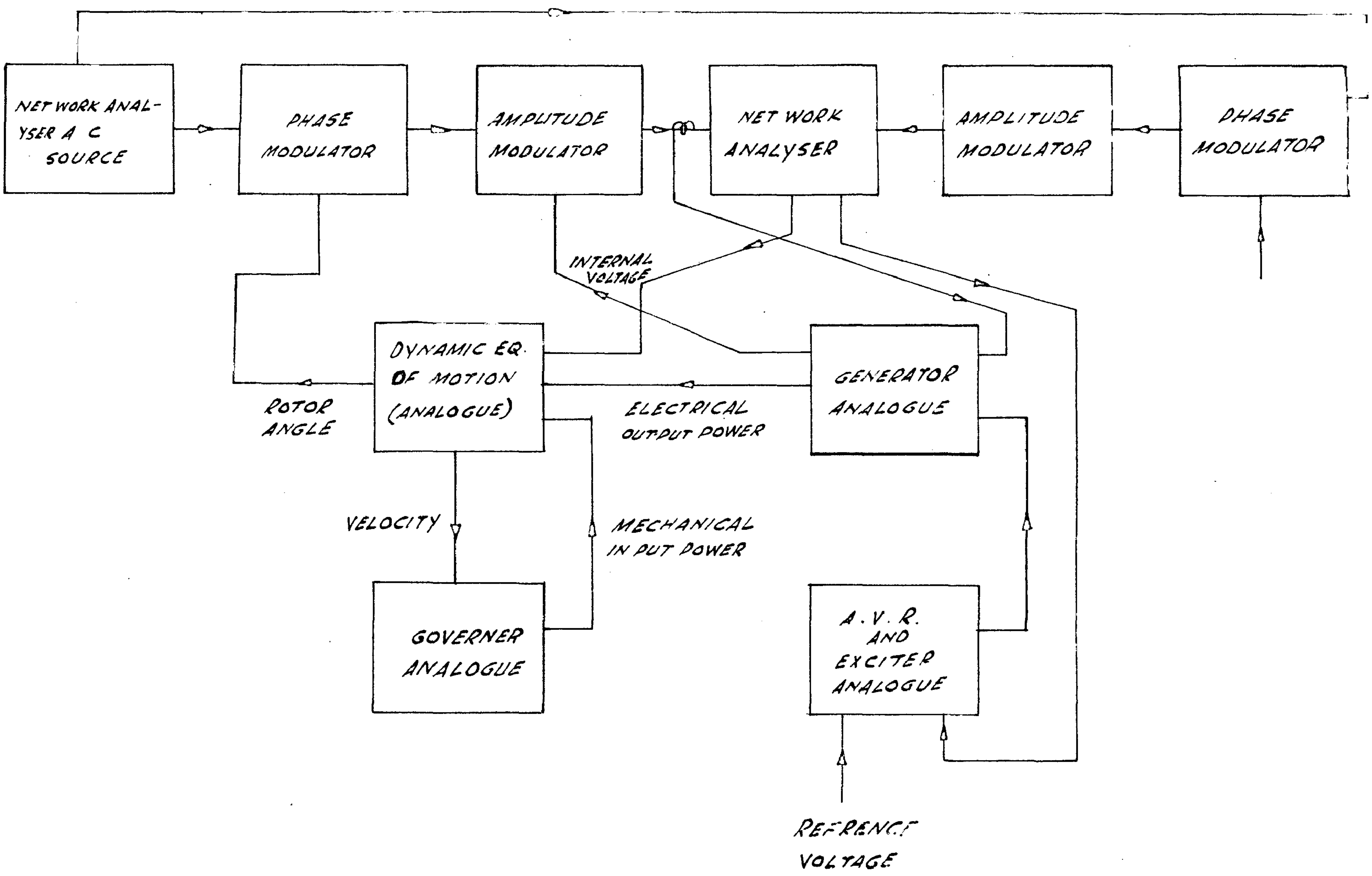
In making use of this computer to power system problems the performance equation for each component of the system are framed and suitable analogue set-up are arranged for these equations with the help of operational amplifiers which provide summation integration, multiplication and division operations.

1.3.5 THE COMBINED COMPUTER |3|

This computer consists of a combination of the analogue computer of the d.c. electronic type and the a.c. network analyser. In making use of this computer for the power system problem we proceed as follows.

The performance equation for the synchronous machine, the voltage regulator and the governer are represented on the analogue computer with the help of operational amplifiers multiplifers and coefficient setting pots. Initial conditions for the various amplifiers are calculated either by hand calculations or with the help of digital computers.

The network analyser is used for representing the transmission line by its equivalent T or π circuit. In the represehtation of transmission systems assumptions are made for neglecting the magnetizing currents, iron losses and phase



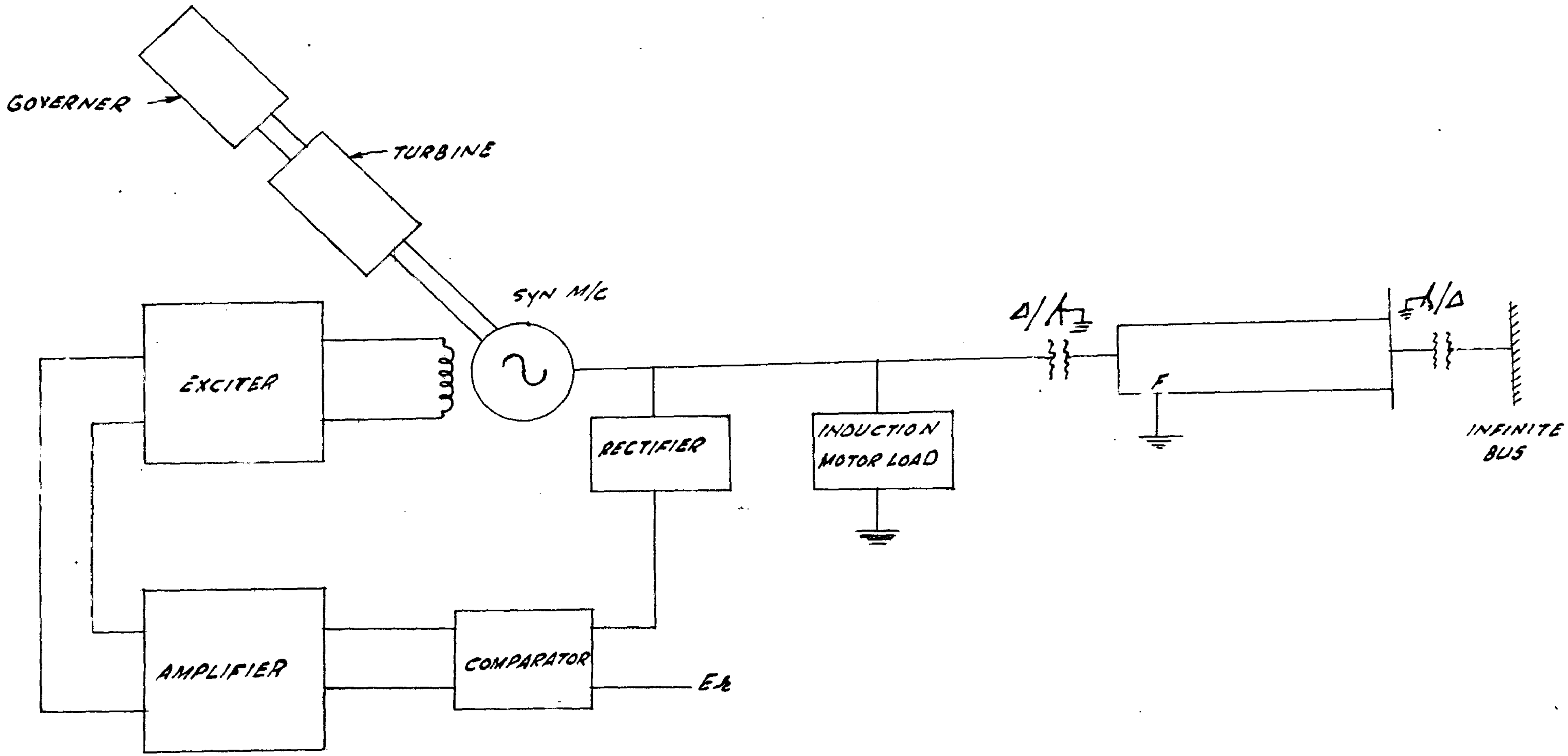
COMBAINED COMPUTER (BLOCK DIAGRAM)
FIG 1·31

shifts in transformers.

For representing the faults on the power system the sequence networks are formed on the analyser and connected with the help of high speed relays. The operation of these relays is controlled at preselected timing depending upon the specific problem.

In order to couple the analogue computer which is of d.c. type with the network analyser which is of a.c. type a converter unit is used. A block diagram of such a converter unit is shown in Fig. 1.31.

This type of computer combines the advantages of the network analyser and the flexibility of the analogue computer.



SYSTEM CONSIDERED

FIG. 1.4

1.4 SYSTEM CONSIDERED

The system consists of a synchronous generator having an Induction motor load at its terminals and is connected to an infinite busbar through a double circuit transmission line terminating at each end with $\Delta / 人$ transformer. The Δ side of the transformer is connected on the generator side and the Y side, which is solidly earthed is on the line side. The synchronous machine is provided with a fast acting automatic voltage regulator, an angle regulator, and a fast acting governer.

The parameter chosen for the synchronous machine, the voltage regulator and the goverher are listed in Table 1.

Table 1

$x_d = 1.2$	$x_q = 0.8$	1 = 0.5 sec.
$x_{afd} = 1.0$	$x_{akq} = 0.6$	2 = 0.05 sec.
$x_{akd} = 1.0$	$x_{kkq} = 0.8$	3 = 0.3 sec.
$x_{ffd} = 1.1$	$r_{kq} = 0.04$	4 = 0.1 sec.
$x_{fkd} = 1.0$	$r = 0.01$	5 = 0.5 sec.
$r_{kd} = 0.02$	$r_{fd} = 0.0011$	$R_t = 0.05$ /line
		$X_t = j0.2$ /line

$K_r = 30$ $G_g = 20$

Author's Approach to the problem and assumptions made

In simulating the power system described in section 2.1, the synchronous machine is represented by the operational form of Park's equations. The Park's equations are written only for the positive sequence components of the voltages, currents and flux linkages. The set-up simulating these equation is capable of computing the positive sequence torque, current and voltage at any instant. The negative sequence torque is computed separately and is assumed to be constant during the transient process. This is only an approximation for, actually, the negative sequence torque does vary during the transient period. However, as the negative sequence current flows only for the short duration of the fault, and the decrement in the negative sequence current is small, this assumption does not introduce any significant error in the study. On the other hand, it simplifies the representation considerably.

The equations of the machine, the voltage regulator and the governer are written in a form most suitable for simulation on the computer.

The transmission line is represented by its equivalent π circuit. The equations are derived relating the d- and q-axis componenents of the voltages and currents at the two ends (Chapter 5). The author has suggested a simple and an efficient way of representing the faults in the system. Hence, studies can be made for various values of the fault clearing time.

The induction motor load is treated in a simplified way. Instead of the conventional method of applying the α-β-0 transformation to the phase quantities [14] and computing the torque output in terms of the α,β currents and voltages, the induction motor is represented by its positive and negative sequence equivalent circuits. The positive and negative sequence torques are computed from the values of the positive and negative sequence voltages at the terminals of the machine. In this analysis the assumption that the electromechanical transient in the motor is much slower than the electrical transients, is implicit. For large loads this assumption is quite justified. The positive sequence voltages at the terminals of the machine is available from the computer set-up of the synchronous machine as $\sqrt{e_d^2+e_q^2}$. The negative sequence voltage is calculated from the sequence diagram. A computer set-up is arranged to compute the torques and use these in the equation of motion of the motor to compute the slip. This is explained in detail in section .

The following assumptions are made while deriving the equations of the synchronous machine.

1. Hystresis and eddy current losses are negligible.
2. Airgap flux is sinusoidally distributed in space. The distribution of windings in synchronous machine is such as to minimise harmonics as far as possible. The performance test conducted on some of the machines have justified this assumption with analytical calculations.
3. Armature resistance is neglected, as this being small compared with reactance of the machine.

4. D.C. component of fault current is neglected, the occurrence of this component being of very short duration.

5. $p\psi_d$, $p\psi_q$, pi_d, pi_q, pe_d, pe_q, $p\omega$ terms are neglected.

Voltages induced in the armature by rate of change of armature flux linkages are negligible compared with the voltages generated by these fluxes rotating at fundamental speed.

6. Line impedance is assumed in lumped form.

7. The transformer magnetising current, losses and phase shift are neglected.

8. Voltage regulator is an amplidyne and voltage regulator is responsive to positive sequence terminal voltage only.

9. Amplidyne feeds to the field of the main exciter.

10. Negative sequence torque remains constant during transient disturbances.

11. Torque speed characteristic of the turbine is linear under steadystate and transient conditions.

2.1 EQUATIONS OF THE SYNCHRONOUS MACHINE

With the usual assumptions made during the analysis of the synchronous machine [2] the voltage equations for the phases a,b,c the field and damper windings can be written as,

$$e_a = p\psi_a - r\, i_a$$
$$e_b = p\psi_b - r\, i_b$$
$$e_c = p\psi_c - r\, i_c$$
$$e_{fd} = p\psi_{fd} + r_{fd}\, i_{fd}$$
$$e_{kd} = 0 = p\psi_{kd} + r_{kd}\, i_{kd}$$
$$e_{kq} = 0 = p\psi_{kq} + r_{kq}\, i_{kq}$$

The sign conventions used in equation (2.11) are the same as used by Concordia i.e. generating action is considered positive and motoring action is considered negative.

Following Park's transformation [10] of the phase quantities, which is defined by the transformation matrix,

$$\left[T_{d-1-o}\right] = \begin{bmatrix} +2/3\cos\theta & +2/3\cos(\theta-120) & +2/3\cos(\theta+120) \\ -2/3\sin\theta & -2/3\sin(\theta-120) & -2/3\sin(\theta+120) \\ +1/3 & +1/3 & +1/3 \end{bmatrix} \quad .. (2.12)$$

the voltages e_a, e_b, e_c the flux linkages to ψ_a, ψ_b, ψ_c and the currents i_a, i_b, i_c are transformed into e_d e_q e_o, ψ_d ψ_q ψ_o and i_d i_q i_o.

Therefore,

$$\begin{bmatrix} e_d \\ e_q \\ e_o \end{bmatrix} = \begin{bmatrix} T_{d-1-o} \end{bmatrix} \cdot \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix}$$

$$\begin{bmatrix} \psi_d \\ \psi_q \\ \psi_o \end{bmatrix} = \begin{bmatrix} T_{d-q-o} \end{bmatrix} \cdot \begin{bmatrix} \psi_a \\ \psi_b \\ \psi_c \end{bmatrix} \qquad .. (2.13)$$

$$\begin{bmatrix} i_d \\ i_q \\ i_o \end{bmatrix} = \begin{bmatrix} T_{d-q-o} \end{bmatrix} \cdot \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

The inverse transformation is done by the $\begin{bmatrix} T_{d-q-o} \end{bmatrix}^{-1}$ which is

$$\begin{bmatrix} T_{d-q-o} \end{bmatrix}^{-1} = \begin{bmatrix} \cos\theta & -\sin\theta & 1 \\ \cos(\theta-12) & -\sin(\theta-120) & 1 \\ \cos(\theta+120) & -\sin(\theta+120) & 1 \end{bmatrix} \qquad .. (2.14)$$

Therefore,

$$\begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} = \begin{bmatrix} T_{d-q-o} \end{bmatrix}^{-1} \begin{bmatrix} e_d \\ e_q \\ e_o \end{bmatrix} \qquad .. (2.15)$$

etc.

Using equation (2.11), the transformation given in equation (2.13) and the per unit system, the following equations are derived,

$$\psi_d = -x_d\, i_d + x_{afd}\, i_{fd} + x_{akd}\, i_{kd}$$
$$\psi_q = -x_q\, i_q + x_{akq}\, i_{kq}$$
$$\psi_o = -x_o\, i_o$$
$$\psi_{fd} = -x_{afd}\, i_d + x_{ffd}\, i_{fd} + x_{fkd}\, i_{kd}$$
$$\psi_{kd} = -x_{akd}\, i_d + x_{fkd}\, i_{fd} + x_{kkd}\, i_{kd}$$
$$\psi_{kq} = -x_{akq}\, i_q + x_{kkq}\, i_{kq}$$
$$e_d = p\psi_d - \psi_q\, p\theta - r i_d$$
$$e_q = p\psi_q + \psi_d\, p\theta - r i_q$$
$$e_o = p\psi_o - r i_o$$

Using the last three equations of the set (2.11), the rotor currents i_{fd} i_{kd} i_{kq} are eliminated in the first three equations of the set (2.16). Hence,

$$\psi_d = -x_{d(p)}\, i_d + G_{(p)}\, e_{fd}$$
$$\psi_q = -x_{q(p)}\, i_q \qquad \text{.. (2.17)}$$
$$\psi_o = -x_o\, i_o.$$

where $x_{d(p)}$ $x_{q(p)}$ are operational impedances and $G_{(p)}$ is the field operator.

Considering one damper circuit in each axis,

$$G_{(p)} = \frac{p(x_{11d}x_{afd} - x_{f1d}x_{a1d}) + x_{afd}r_{1d}}{p^2(x_{11d}\, x_{ffd} - x_{f1d}^2) + p(x_{11d}\, r_{fd} + x_{ffd}\, r_{1d}) + r_{1d}r_{fd}}$$

$$xd(p) = xd - \frac{p^2(x_{11d}x^2_{afd} - 2x_{f1d}x_{a1d}x_{afd} + x_{ffd}x^2_{a1d}) + p(x^2_{afd}r_{1d} + x^2_{a1d}r_{fd})}{p^2(x_{11d}x_{ffd} - x^2_{f1d}) + p(x_{11d}r_{fd} + x_{ffd}r_{1d}) + r_{1d}r_{fd}}$$

$$xq(p) = xq - \frac{p\,x^2\,a_{1q}}{p\,x_{11q} + r_{1q}} \qquad .. (2.18)$$

The electrical torque of the machine is given by

$$T_e = \psi_d i_q - \psi_q i_d \qquad .. (2.19)$$

Equation (2.19) is valid under the transient conditions also and this equation is used in the stability analysis of the machine.

Considering the negative sequence equivalent of the machine |4| the negative sequence torque can be written as,

$$T_{e2} = -I_2^2(r_2 - r_a) \qquad .. (2.20)$$

The negative sign on the right hand side indicates that it is a braking torque. As explained in section 1.4, the d-q-o axis transformation is done only for the positive sequence component of the voltages and the currents. Hence, $e_o \psi_o$ and i_o given in set (2.16) are zero. The negative sequence and zero sequence currents and voltage are considered separately. The zero sequence current produces no torque. The torque produced by the negative sequence current, given by eq. (2.20), will be present only for the duration of the fault, after which the set-up representing the torque is disconnected from the complete analogue set-up. As already explained, this torque is assumed constant during the fault and zero after the fault is cleared.

Summarising the equations which completely represent the machine under the assumption made in section 1.4, are as follows.

$$\psi_d = -xd(p)i_d + G(p)\,e_{fd}$$
$$\psi_q = -xq(p)i_q$$
$$e_d = -\psi_q$$
$$e_q = \psi_d$$
$$T_{e1} = \psi_d i_q - \psi_q i_d$$
$$T_{e2} = -I_2^2(r_2 - r_a)$$
$$e_t = \sqrt{ed^2+eq^2}$$
$$Mp^2\delta = T_i - T_{e1} - T_{e2}$$

2.2 <u>SIMULATION OF THE MACHINE EQUATIONS</u>

The equations given in set (2.21) are to be simulated on the computer. The expression for xd(p), xq(p) G(p) are written in a form suitable for simulation as follows.

$$\left.\begin{aligned} xd(p) &= xd\,\frac{(1+T_d' p)(1+T_d'' p)}{(1+T_{do}' p)(1+T_{do}'' p)} \\ xq(p) &= xq\,\frac{(1+T_q'' p)}{(1+T_{qo}'' p)} \\ G(p) &= K\,\frac{1+T_{kd}p}{(1+T_{do}' p)(1+T_{do}'' p)} \end{aligned}\right\} \quad \ldots (2.22)$$

where the values for the time constants $T_d^{'}$ $T_d^{''}$ $T_{do}^{'}$ $T_q^{''}$ $T_{qo}^{''}$ T_{kd} and K are determined from the data of Table 1 as is shown in Appendix 1.

In appendix 2 the expression for xd(p) xq(p) and G(p) are derived as follows.

$$xd(p) = \frac{(x_d - A_7)}{(1+T_{do}^{'}p)} + A_5 - \frac{A_6}{(1+T_{do}^{''}p)}$$

where A_5 A_6 and A_7 are constants. The numerical values of these constant have been calculated by equations (a-2-10) and (a-2-11) of appendix 2, as

$A_5 = 0.209$
$A_6 = 0.064$
$A_7 = 0.145$

Substituting these values in the expression for xd(p)

$$xd(p) = \frac{1.055}{1+3.26p} + 0.209 - \frac{0.064}{1+0.029p} \quad .. \; (2.23)$$

Also from Appendix (2)

$$G(p) = K\left[\frac{A_8}{(1+T_{do}^{'}p)} + \frac{A_9}{(1+T_{do}^{''}p)}\right]$$

Where A_8 and A_9 are constants. The numerical values for these constant have been calculated in eq.(a-2-12) of Appendix 2.

$A_8 = 1.004$
$A_9 = -0.004$
$K = 910$

Substituting these values in the above expression.

$$G(p) = \left| \frac{1.004}{1+3.26p} - \frac{0.004}{1+0.029p} \right| 910 \qquad .. (2.24)$$

So complete expression for ψ_d may be written as

$$\psi_d = -xd(p)\, i_d + G(p)\, e_{fd}$$

$$= -\left| \frac{1.055}{1+3.26p} + 0.209 - \frac{0.064}{1 + 0.029p} \right| i_d$$

$$+ \left| \frac{1.004}{1+3.26p} - \frac{0.004}{1+0.029p} \right| e$$

where,

$$e = K.e_{fd}$$

or

$$\psi_d = -\frac{1.055}{1+3.26p} i_d - 0.209\, i_d + \frac{0.064}{1+0.029p} i_d + \frac{1.004}{1+3.26p} e - \frac{0.004}{1+0.029p} e \qquad .. (2.25)$$

From eq.(2.21)

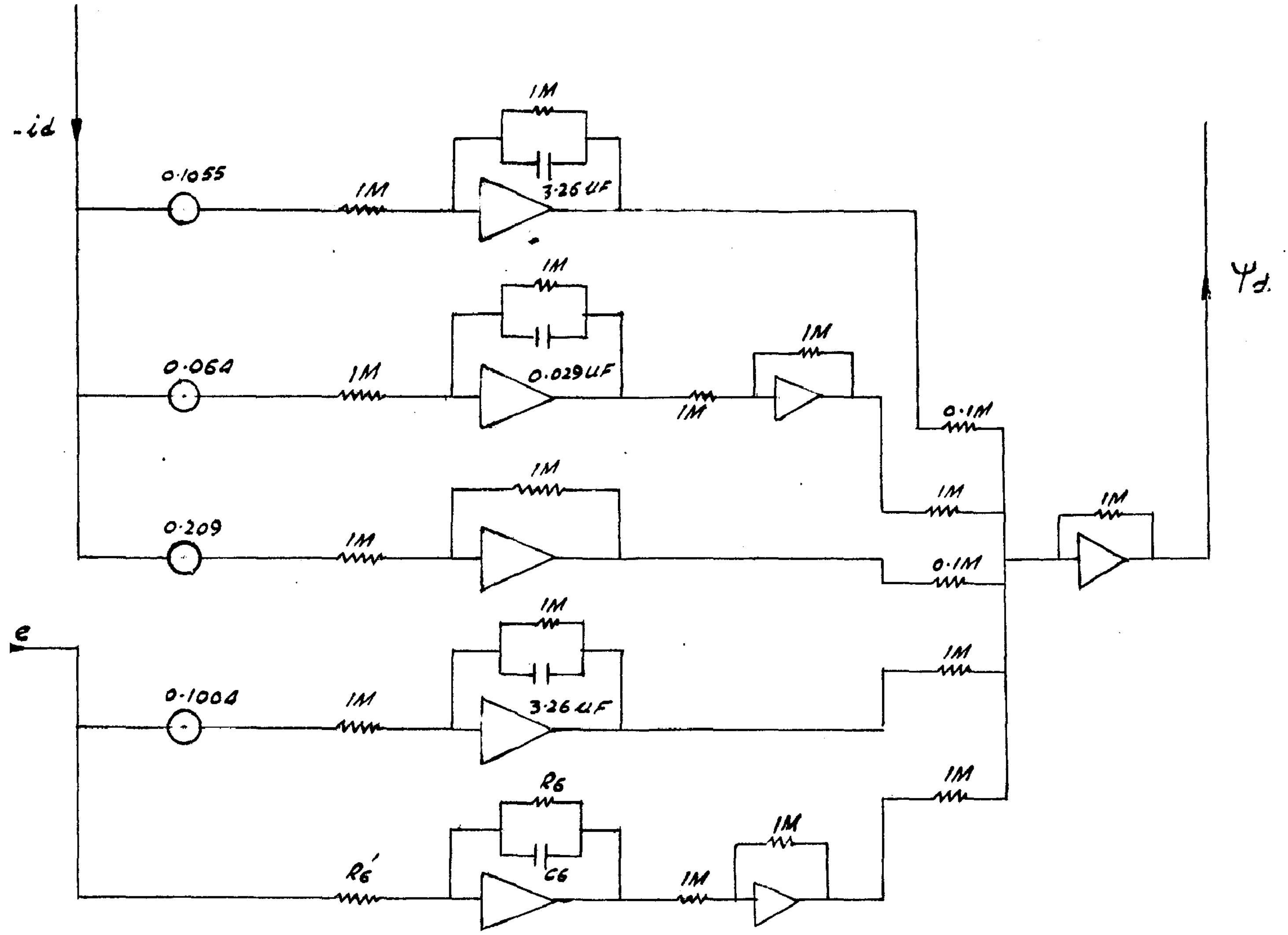
$$\psi_q = -xq(p)\, i_q$$

Substituting for xq(p) as derived in Appendix 2

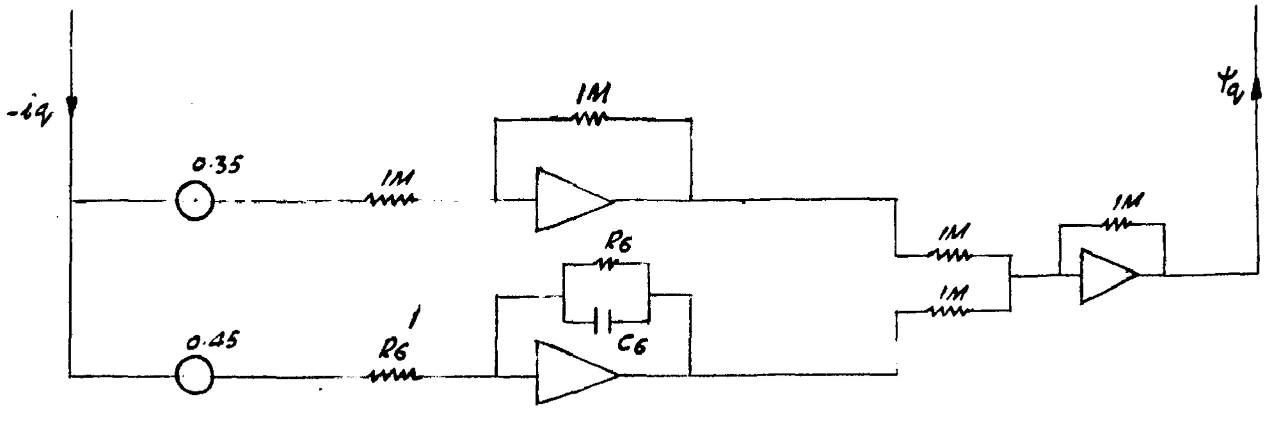
$$\psi_q = \left| \frac{1-A_{10}}{1+T''_{qo}p} + A_{10} \right| x_q i_q$$

where A_{10} as calculated by eq.(a-2-14) of Appendix 2.

$$A_{10} = 0.437$$

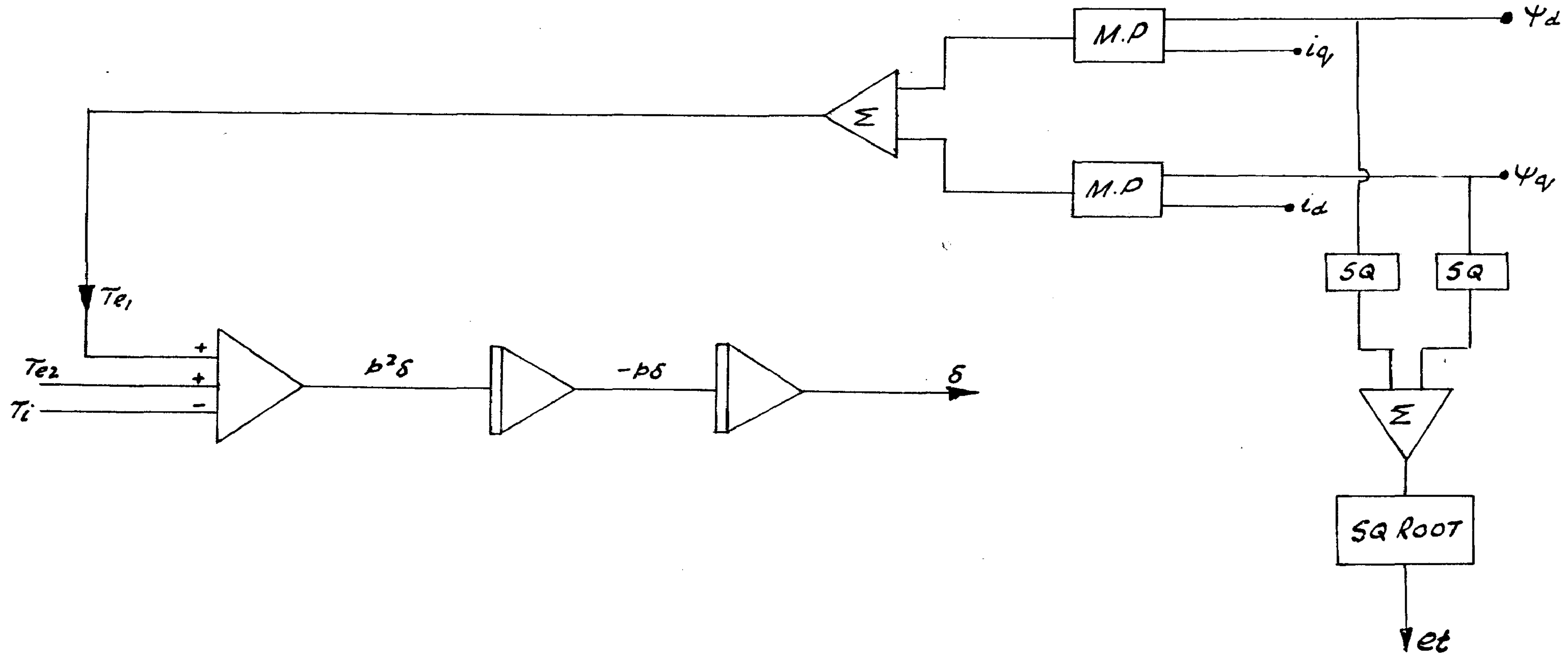


ANALOG SETUP FOR ψ_d



ANALOG SETUP FOR ψ_q

FIG. 2.22



ANALOGUE SETUP FOR LAST FOUR EQUATIONS OF SET 2·21

FIG. 2·23

Substituting in the above expression for ψ_q

$$\psi_q = - \frac{0.45\ i_q}{(1+0.0637p)} - 0.35\ i_q \qquad .. (2.26)$$

Analogue set-up representing eq. (2.25), (2.26) and last four equation of set (2.21) are shown in Fig. 2.22 and 2.23 respectively.

SATURATION IN SYNCHRONOUS MACHINE

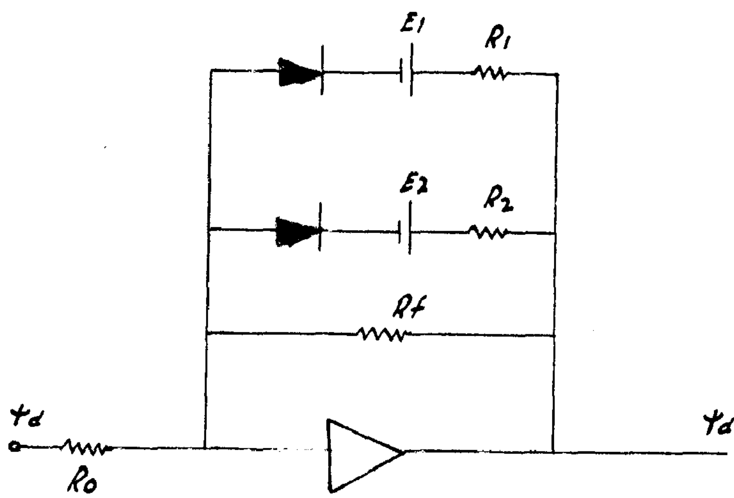
There are two methods of considering saturation in the synchronous machine.

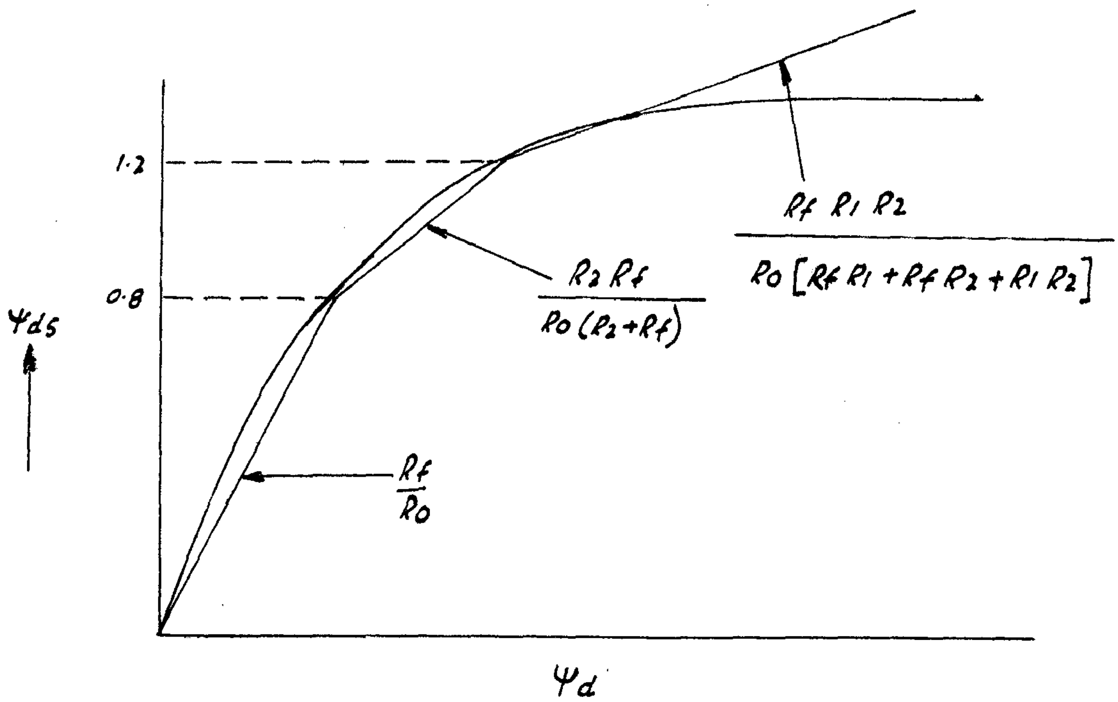
1. The saturation of armature teeth causes the air gap flux and the mutual flux linkage to be reduced by a factor K, but the armature and rotor leakage reactances are not effected by saturation.

2. That both the air gap flux linkage and the leakage reactances are effected by saturation so that total flux linkage of all the direct axis circuits are reduced by a common fraction k_d of their unsaturated value and the flux linkage of the quadrature axis circuits are reduced by a common factor k_q of their unsaturated value.

In fact the leakage reactances do saturate but to a lesser extent so that the first assumption gives a pessimistic estimate of the flux linkage while the second is optimistic.

In this analysis the saturation in the quadrature axis is neglected. Hence, only the direct axis flux linkage





FUNCTION GENERATOR SIMULATING SATURATION OF THE MACHINE

FIG. 2·24

ψ_d has to be considered for saturation. The saturated value of ψ_d is related to unsaturated value by the saturation curve shown in fig. 2.23. Hence, to connect value of ψ_d, the diode function generator shown in Fig. 2.24 is connected at the output of the set-up shown in fig. 2.21.

The operation of the function generator circuit is explained as follows. The diodes offer very high resistance so long as input voltage representing ψ_d is less than the any of the bias voltage E_1 or E_2. When the applied voltage representing ψ_d becomes more than the bias voltage the diode offers very low resistance and current flows through the resistance R_1 and R_2. The break point E_1 and E_2 occur when the output voltage of the function generator is equal to one of the bias voltage. The resistance R is equal to the parallel combination of R_f and R_1.

SIMULATION OF THE VOLTAGE AND THE ANGLE REGULATOR

3.1 THE VOLTAGE REGULATOR

The excitation system of the synchronous machine plays important part during the transient disturbance in the power system. By improving the excitation system of the machine considerable improvement can be made in the stability limit of the machine |12|. A great deal of literature has been published on the design of voltage regulator and their influence on the stability limits. Improvement in the excitation system can be achieved by providing the exciter with,

1) Quick response i.e. high rate of build up and high ceiling voltage.

2) Fast acting automatic voltage regulator.

The exciter response is defined as the rate of build up or build down of the main exciter voltage when a change in this voltage is required by the action of the voltage regulator. The ceiling voltage of the exciter varies through quite a range depending upon the particular design. Usually the ceiling voltage is 50% more than the normal exciter voltage for the rated maximum load.

A voltage regulator is a device which when used with the synchronous machine increases or decreases the excitation of the machine as the terminal voltage of the machine decreases or increases.

Voltage regulators are mainly divided into

(a) Electromechanical voltage regulator,

(b) Static voltage Regulator

Electromechanical type include,

(a) <u>Vibrating Contact Type Voltage Regulator</u>

These employ continuously vibrating contacts which alternatively insert and short circuit sections of the exciter field resistance; the opening and closing operation being controlled by a beam.

(b) <u>Rehostatic Type Regulator</u>

(i) <u>Direct Acting Regulator</u>

In this type of regulator the voltage sensitive element is an electromagnet the armature of which is balanced against a spring. The resistance element which is in the exciter field circuit is connected directly to the armature and forms a part of the regulator assembly.

As the control voltage changes the armature changes its position and adjust the resistance element in such a way so as to restore the controlled position.

<u>Indirect Acting Rehostatic Type</u>

The voltage sensitive element of this regulator is a polyphase torque motor with a phase wound stator and a squirel cage rotor. The torque is proportional to the approximate average of the three phase voltages. The torque of the motor being balance against the pull of a helical spring, so that for each value of the voltage there is a particular position.

(b) Static Voltage Regulators

(i) Impedance type regulator

It consists of linear and non-linear impedances. The three phase voltage is connected into single phase and applied to linear and non-linear impedances. If the phases are balanced then equal current passes through linear and non-linear elements and if unbalanced then different current flows in linear and non-linear impedances. The difference of two currents is applied to the control field windage to obtain the control voltage of its previous value.

(ii) Transductor Type-voltage Regulator

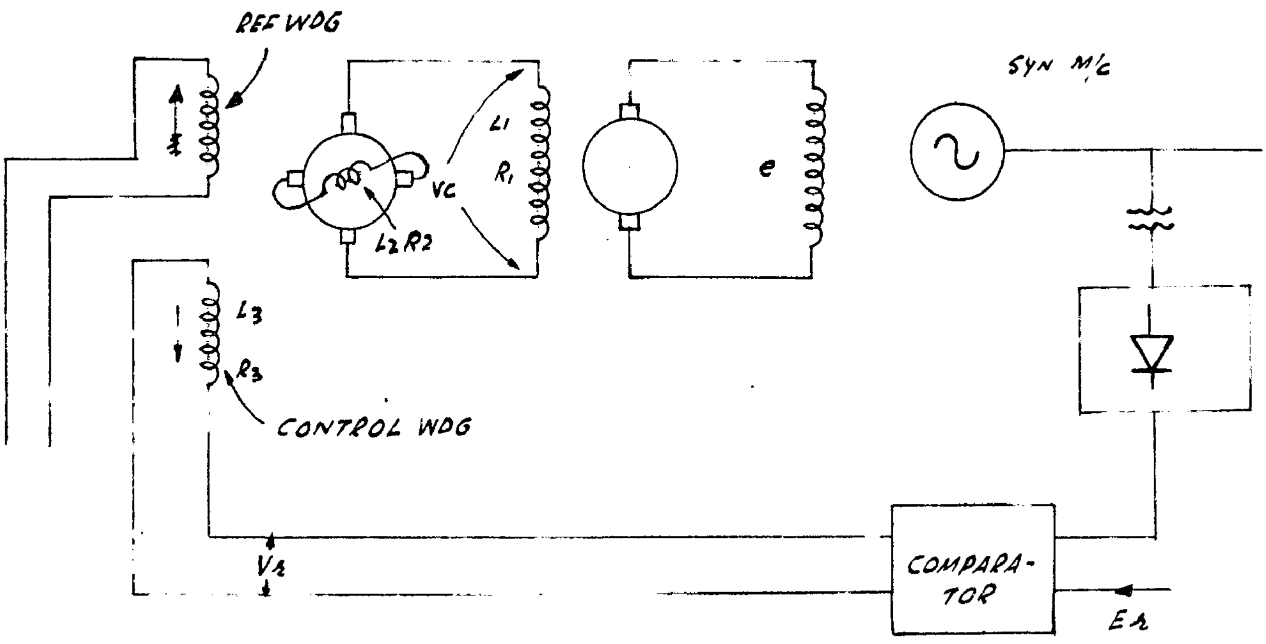
Voltage regulators using magnetic amplifiers are developed which can serve the purpose of voltage sensing and power amplification.

(iii) Electronic Type Voltage Regulator

These can be used with rotating amplifiers in an excitation system with rotating exciter or directly with an electronic exciter to control the grids of the firing tubes which in turn control the firing point of the main power tubes.

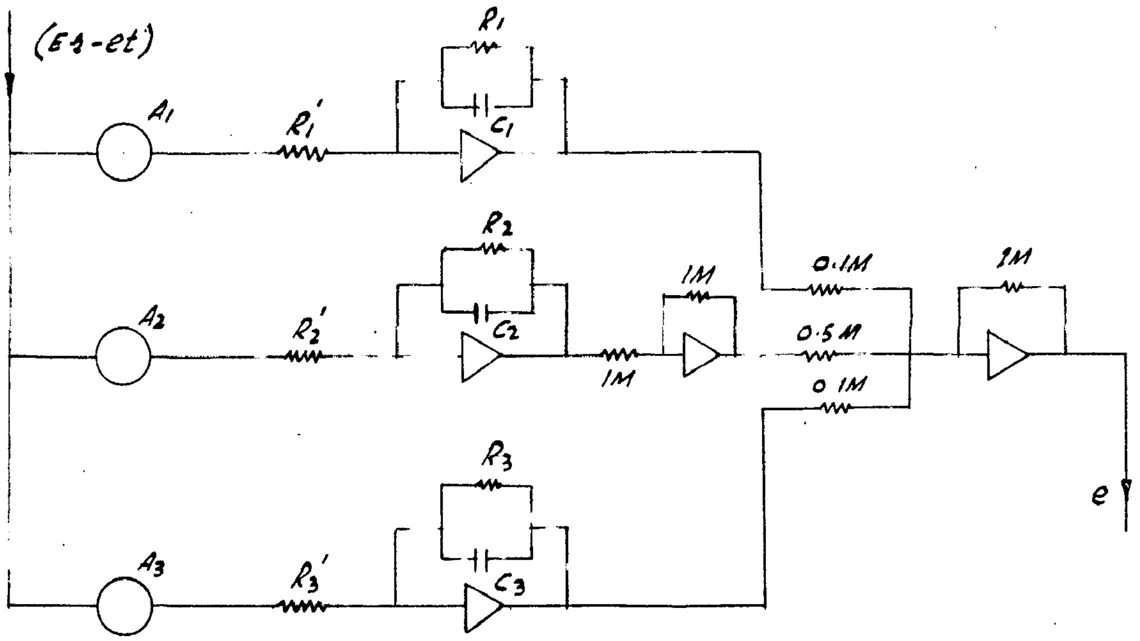
In general static regulators are better as these can provide faster and accurate control of generator exciters. In the analysis to follow amplidyne voltage regulator is considered the operation of which can be explained as follows.

The terminal voltage of the synchronous machine is tapped and applied to a potential transference, the output of which is connected to a rectifier unit. The output of the rectifier unit is applied to the comparator unit. The comparator unit compares the voltage received with the reference voltage and gives an output as the difference of the two voltages. The comparator unit may be of the non-linear bridge type which requires no separate reference voltage, a magnetic amplifier type error detector which provides amplification as well or an electronic circuit using a zero diode or a VR tube which supplies the reference voltage. The error signal so obtained is applied to the control winding of the amplidyne. This voltage produces a flux which acts in a direction opposite to that produced in the refrence winding. The difference of the two fluxes links with the short circuited winding of the amplidyne and induces some voltage in it. Since the impedance of the short circuited winding is small hence a heavy current flows which produces the flux of considerable magnitude which when linked with the output winding produces a voltage of a value equal to K_{rg} times the input voltage to the machine where $K\lambda_2$ is the voltage gain of the amplifier. This output voltage is applied across the field of the exciter the output of which controls the excitation of the field winding of the synchronous machine. Thus, any deviation in



AMPLIDYNE VOLTAGE REGULATOR

FIG. 3.11



ANALOG SETUP VOLTAGE REGULATOR

FIG. 3.12

the output voltage of the machine is conveyed to the exciter which adjusts the excitation accordingly and tries to maintain constant voltage at the terminals of the machine.

An expression for the input and output of the amplidyne is derived as follows [3].

As shown in fig.(3.11),

$$e = \frac{K_{r1}}{1+pT_1} V_c$$

$$V_c = \frac{K_{r2}}{(1+pT_2)(1+pT_3)} V_r \qquad .. (3.11)$$

$$V_r = K_{r3}(E_r - e_t)$$

From equation of set (3.11)

$$e = \frac{K_{r1}K_{r2}K_{r3}(E_r - e_t)}{(1+pT_1)(1+pT_2)(1+pT_3)} \qquad .. (3.12)$$

The equation (3.12) can be written as

$$e = \left[\frac{A_{r1}}{(1+pT_1)} + \frac{A_{r2}}{(1+pT_2)} + \frac{A_{r3}}{(1+pT_3)}\right](E_r - e_t) \qquad .. (3.13)$$

where,

$$\left.\begin{aligned} A_{r1} &= \frac{K_{r1}T_1^2}{(T_1-T_3)(T_1-T_2)} \\ A_{r2} &= -\frac{K_{r2}T_2^2}{(T_1-T_2)(T_2-T_3)} \\ A_{r3} &= \frac{K_{r3}T_3^2}{(T_2-T_3)(T_1-T_3)} \end{aligned}\right\} \qquad .. (3.14)$$

Figure (3.12) shows analogue set-up representing equation (3.13).

The parameters to be optimised in the above equations are K_r the regulator gain and T_3 the time constant of the control field winding. These parameters can be optimised simply by changing the coefficient A_1 A_2 A_3 and studying the effect of their variations. The ranges of variation of these parameters are as follows.

(1) Regulator gain K_r values from 30 to 40 in steps of 2.

(2) T_3 the time constant of the control field winding varies from 0.2 to 0.4 seconds in steps of 0.1 second.

The table no. 3 gives the values of A_{r1} A_{r2} and A_{r3} for various values of K_r and T_3.

3.2 <u>Angle Regulator</u>

It is a device which when used with the synchronous machine acts as a regulator for varying the excitation of the machine. When the load changes in the system occur, the angle between the rotor interpole axis and a synchronously rotating reference changes. The angle regulator tries to restore the rotor axis to its previous position. The various types of angle regulator and their influence on stability has been analysed by various authors. The voltage regulators are being extensively used in power system and hence it becomes necessary to compare the action of angle regulator with that of the voltage regulator.

In the normal operation of the synchronous generator it seems reasonable to maintain constant voltage over

Table No.3

S.No.	K_r	T_3	A_{r1}	A_{r2}	A_{r3}
1	30	0.2	55.5	1.11	-26.7
2	32	0.2	59.1	1185	-28.4
3	34	0.2	62.9	1.26	-30.2
4	36	0.2	66.5	1.33	-32.0
5	38	0.2	70.2	1.405	-33.8
6	40	0.2	74.0	1.48	-35.6
7	30	0.3	83.4	0.666	-54.0
8	32	0.3	89.0	0.71	-57.6
9	34	0.3	94.5	0.755	-61.2
10	36	0.3	100.0	0.8	-64.9
11	38	0.3	105.5	0.845	-68.5
12	40	0.3	111.0	0.89	-72.0
13	30	0.4	166.5	0.477	-137.0
14	32	0.4	178.0	0.509	-146.5
15	34	0.4	189.0	0.54	-155.5
16	36	0.4	200.0	0.573	-165.0
17	38	0.4	211.0	0.605	-174.0
18	40	0.4	222.0	0.635	-183.0

their entire operating range rather than constant load angle. Thus, if the angle regulator is used it has to be biased by a voltage regulator during its steadystate operation. The stability of regulator and the improvement in the stability limit of the system is found to be almost of the same value [13].

In this the feedback signal proportional to angle δ, velocity $\frac{d\delta}{dt}$ and acceleration $\frac{d^2\delta}{dt^2}$ of rotor is used for controlling the excitation of the machine. The feedback signal is given by

$$K_{1\delta}\delta + K_{2\delta}p\delta + K_{3\delta}p^2\delta$$

where,

$K_{1\delta}$, $K_{2\delta}$ $K_{3\delta}$ are constant.

This signal is applied to the amplidyne (as explained earlier), the output of which is connected to field winding of the exciter.

Therefore,

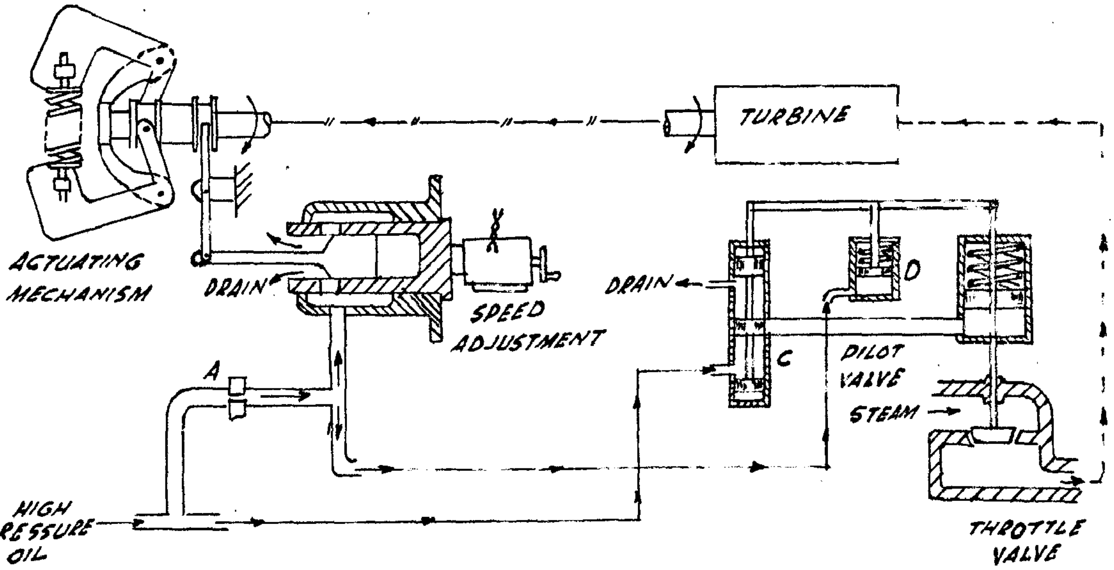
$$e_{fd} = \frac{(K_{1\delta}\delta+K_{2\delta}p\delta+K_{3\delta}p^2\delta)K}{(1+T_1p)(1+T_2p)(1+T_3p)} + e_{fdo} \qquad .. (3.21)$$

4.1 SIMULATION OF THE GOVERNER

Governers are used for regulating the speed of the prime movers of the generators i.e. the water turbines or steam turbines. The use of a fast acting automatic voltage regulator has resulted in not only an increase in the transient stability limit ~~but also an increase in the transient stability limit~~ but also an increase in the time after the occurrence of disturbance during which the governer can adjust the input power to the prime mover and make the difference between input and output. power zero. Thus, the governer plays important part in improving the transient stability limit of the system.

Earlier, the stability studies disregarded the action of the governer. The studies were based on the stability during the first swing with constant input power and the turbine assuming that if the machine is stable in the first swing it will be stable in subsequent swings too. However, such an assumption is not always justified as the governer mechanism and the turbine itself offer a certain time delay in their response. With the development of fast acting overners with a small dead-band, the performance of the turbine and the governer necessitate a rigorous treatment.

This section suggests a method of simulating the governer with its time constants and the turbine on the analogue computer. As was stated in section 1.4, the turbine characteristic is considered linear.



GOVERNING SYSTEM

FIG. 4·11

Governers are slow in action because of the time lag introduced in the movement of mechanical parts.

A typical governer used with a steam turbine is shown in the fig. (4.11) [15]. The complete system can be sub-divided into four parts.

(a) A mechanism which detects the speed change,

(b) A mechanism for transfer the change in the speed to the throttle valve mechanism,

(c) A mechanism for controlling the input to the turbine.

(d) A turbine responding to change in its input conditions by a change of speed.

Governer is connected to a shaft running at about one fifth of speed of the prime mover. A pump provides a constant high pressure oil source at A and this oil passes through the adjustable part B, to the drain. When the speed changes, the actuating mechanism either opens or closes the drain port for increased or reduced speed respectively and therefore the pressure across the pilot piston D changes. The throttle valve mechanism operated by D then reduces or increases the steam input to the turbine and thus the shaft speed is either reduced or increased. A time delay is introduced firstly because of the length of the connecting pipe between actuating and valve mechanism and secondly because of the servo-system. Hence, while considering the performance of the governer two time constants are taken into account.

Let T_4 = Time constant of oil servo system,

T_5 = Time constant of actuating mechanism and valve.

Assuming a velocity governer,

$$T_1 = T_{10} - \frac{G_g p \delta}{(1+pT_4)(1+T_5 p)} \quad .. (4.11)$$

Where,

T_{10} = Input power during steady state,

T_1 = Input power during transient state.

Let,

$$\frac{G_g}{(1+pT_4)(1+pT_5)} = \frac{A_4}{1+pT_4} + \frac{A_5}{(1+pT_5)} \quad .. (4.12)$$

Solving A_4 and A_5 in terms of T_4, T_5 and G_g where,

$$\left.\begin{aligned} A_4 &= \frac{G_g T_4}{(T_4-T_5)} \\ A_5 &= -\frac{G_g T_5}{(T_4-T_5)} \end{aligned}\right\} \quad .. (4.13)$$

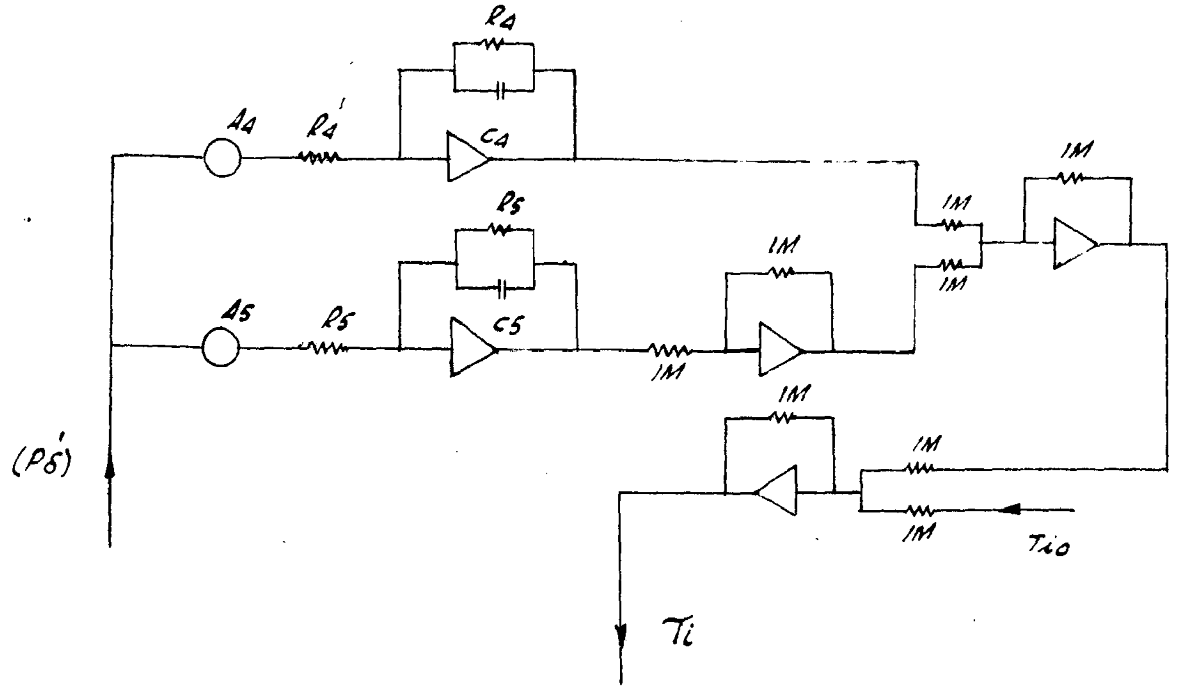
Substituting the values from table 1,

$$A_4 = -5 \qquad A_5 = 25 \quad .. (4.14)$$

So equation (4.11) reduces to

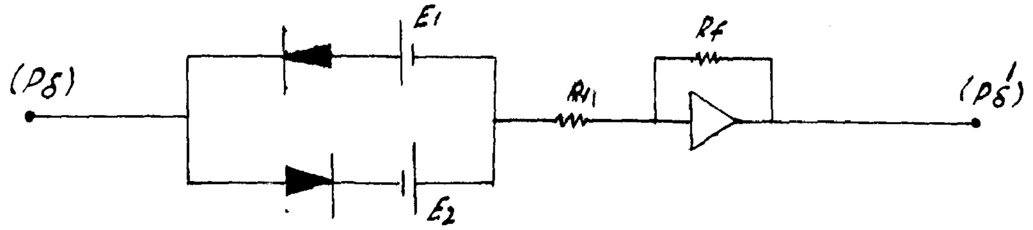
$$T_1 = T_{10} - \left[\frac{A_4}{(1+pT_4)} + \frac{A_5}{(1+pT_5)}\right] p\delta \quad .. (4.15)$$

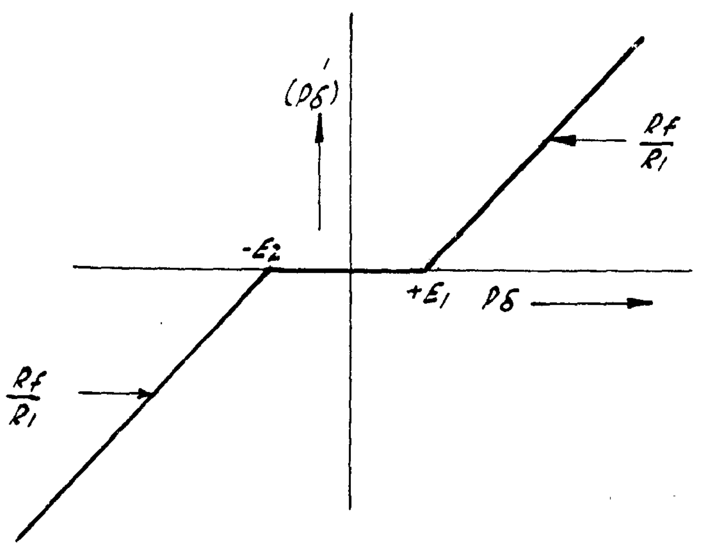
The parameter to be optimised in equation (4.11) is the governer gain. Table 4 shows the optimization scheme



ANALOG SETUP FOR GOVERNER

FIG. 4.12





DEAD BAND SIMULATION

FIG. 4.13

for the governer. Fig. 4.12 shows the analogue simulation for the equation (4.15) where,

$R_4C_4 = 0.1$ $\qquad$ $R_5C_5 = 0.5$

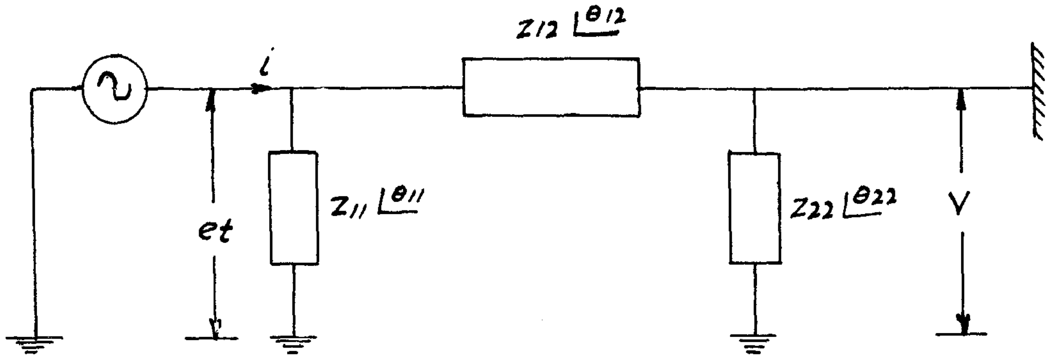
$\frac{R_4}{R_4'} = A_4^1$ $\qquad$ $\frac{R_5}{R_5'} = A_5^1$

Table 4

S.No.	G_g	A_4	A_5
1.	20	-5.0	25.0
2.	22	-5.5	27.5
3.	24	-6.0	30.0
4.	26	-6.5	32.5
5.	28	-7.0	35.0
6.	30	-7.5	37.5

4.2 DEAD BAND

The 'dead-band' applied to the governer means the region in which the governer is insensitive. Because of the friction of the moving parts and the time lag the governer cannot respond to very small changes in the speed. The dead-band of the governer may be 1% or so. In order to take account of this a diode function generator is used as shown in the fig. (4.13). This function generator is connected at the input point of the governer set-up. The characteristic of the function generator is also shown in the figure.



TRANSMISSION LINE REPRESENTATION

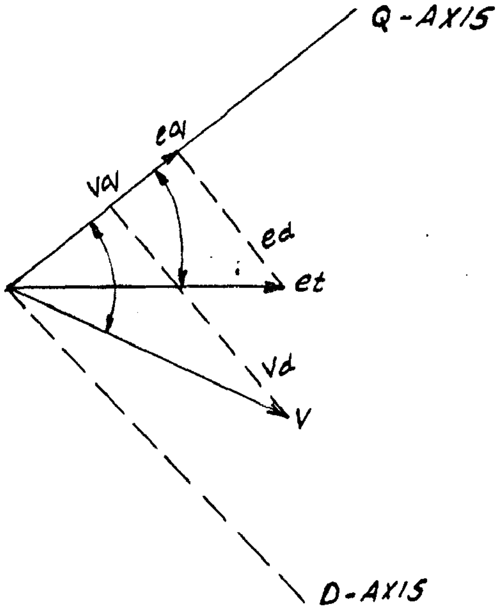
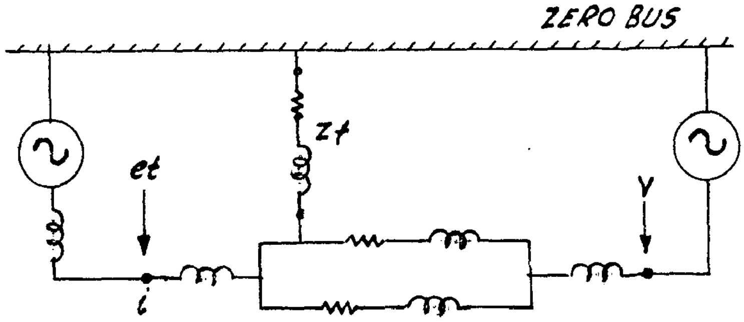


FIG. 5.1



POSITIVE SEQUENCE DIAGRAM

FIG 5.2

5.1 SIMULATION OF TRANSMISSION LINE

The transmission line is represented by a π network as shown in Fig.(5.1)

e_t and v_b represent the machine terminal voltage (positive sequence) and the busbar voltage. Hence,

$$i = \frac{e_t \lfloor -\delta_1}{z_{11} \lfloor \theta_{11}} - \frac{e_t \lfloor -\delta_1 - v_b \lfloor -\delta}{z_{12} \lfloor \theta_{12}}$$

Referring i, e_t and v_b to the direct axis and quadrature axis of the rotor of the machine we have from equation (5.1),

$$i_d = \left[\frac{\cos\theta_{11}}{|z_{11}|} + \frac{\cos\theta_{12}}{|z_{12}|} \right] e_d + \left[\frac{\sin\theta_{11}}{|z_{11}|} + \frac{\sin\theta_{12}}{|z_{12}|} \right] e_q - \frac{\cos\theta_{12}}{|z_{12}|} v_d - \frac{\sin\theta_{12}}{|z_{12}|} v_q \qquad .. (5.2)$$

$$i_q = \left[\frac{\cos\theta_{11}}{|z_{11}|} + \frac{\cos\theta_{12}}{|z_{12}|} \right] e_q - \left[\frac{\sin\theta_{11}}{|z_{11}|} + \frac{\sin\theta_{12}}{|z_{12}|} \right] e_d - \frac{\cos\theta_{12}}{|z_{12}|} v_q + \frac{\sin\theta_{12}}{|z_{12}|} v_d \qquad .. (5.3)$$

Equations (5.2) and (5.3) represent the steady state relations between i_d, i_q, e_d, e_q, v_d and v_q.

The relations are obtained only after neglecting terms containing $\frac{di_d}{dt}$, $\frac{di_q}{dt}$, $\frac{dw}{dt}$ $\frac{de_d}{dt}$ $\frac{de_q}{dt}$ $\frac{dv_d}{dt}$ and $\frac{dv_q}{dt}$ in comparison with terms containing wi_d, wi_q, we_d, we_q wv_d and wv_q.

During the unfaulted condition $z_{11} = z_{22} = \infty$ as the line is represented by its series impedance only (A long line can also be represented, in which case z_{11}, z_{22} will be finite and equal to

$$\frac{1}{y\frac{\tanh\sqrt{zy/2}}{\sqrt{zy/2}}} = \frac{2}{\sqrt{y/z}\ \tanh\frac{\sqrt{zy}}{2}}$$

where,

z = total series impedance,

y = total shunt impedance,

z_{12} will then be equal to the total series impedance between the generator bus and the infinite bus.

Under fault conditions the values of z_{11} and z_{22} can be calculated from the sequence diagram as shown in fig.(5.2) where z_f depends upon the type of fault, as shown in the following table.

Type of fault	z_f
L-G	z_2+z_0
L-L	z_2
D-L-G	$\frac{z_2 \cdot z_0}{z_2+z_0}$
3∅ fault	0

where, z_2 and z_0 are the total negative sequence and zero sequence impedance between the fault point and the neutral.

After the fault is cleared by the operation of the proper circuit breakers, z_{11}, z_{12}, z_{22} will attain new values.

In appendix 3 the values of z_{11} , z_{12}, z_{22} are cleared for the faulted, unfaulted and the fault-cleared conditions. These values are tabulated below.

Type of fault	z_{11}	z_{22}	z_{12}
Prefault	∞	∞	$0.301 \angle 85.25^\circ$
During fault			
(i) L-G	$0.405 \angle 88.95^\circ$	$0.82 \angle 81.8^\circ$	$0.40 \angle 85.6^\circ$
(ii) L-L	$0.294 \angle 86.75^\circ$	$0.59 \angle 81.45^\circ$	$0.456 \angle 86^\circ$
(iii) L-L-G	$0.171 \angle 89.6^\circ$	$0.345 \angle 82.6^\circ$	$0.725 \angle 85.7^\circ$
(iv) 3Φ fault	$0.1 \angle 90^\circ$	$0.202 \angle 82.9^\circ$	∞
Post fault	∞	∞	$0.403 \angle 82.9^\circ$

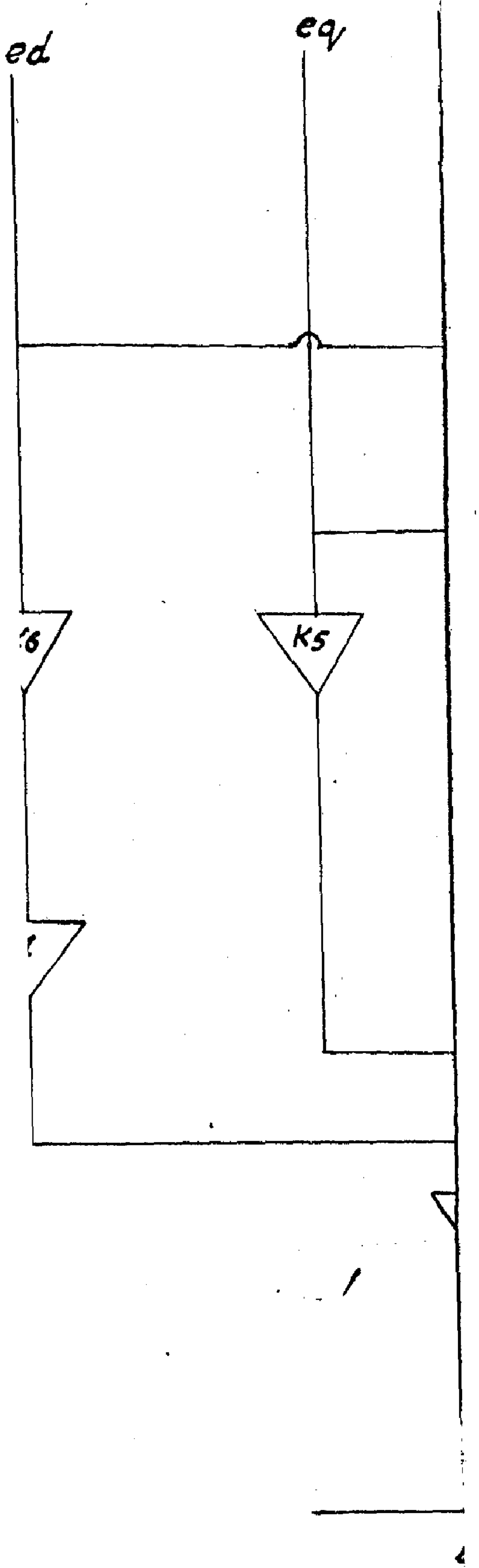
The equation (5.2) and (5.3)can be written as

$$i_d = K_1 e_d + K_2 e_q - K_3 v_d - K_4 v_q \qquad .. \ (5.4)$$

$$i_q = K_5 e_q - K_5 e_d - K_7 v_q + K_8 v_d \qquad .. \ (5.5)$$

where the constants K_1 K_2 .... K_8 are calculated in Appendix 3, and given in the table below.

Type of fault	$K_2=K_6$	$K_1=K_5$	$K_3=K_7$	$K_4=K_8$
Pre-fault	3.32	0.274	0.274	3.32
During fault				
i) L-G	4.96	0.2375	0.192	2.18
ii) L-L	5.58	0.345	0.153	2.10
iii) L-L-G	7.22	0.146	0.103	1.37
iv) 3Φ fault	10	0	0	0
Post-fault	2.46	0.306	0.306	2.46



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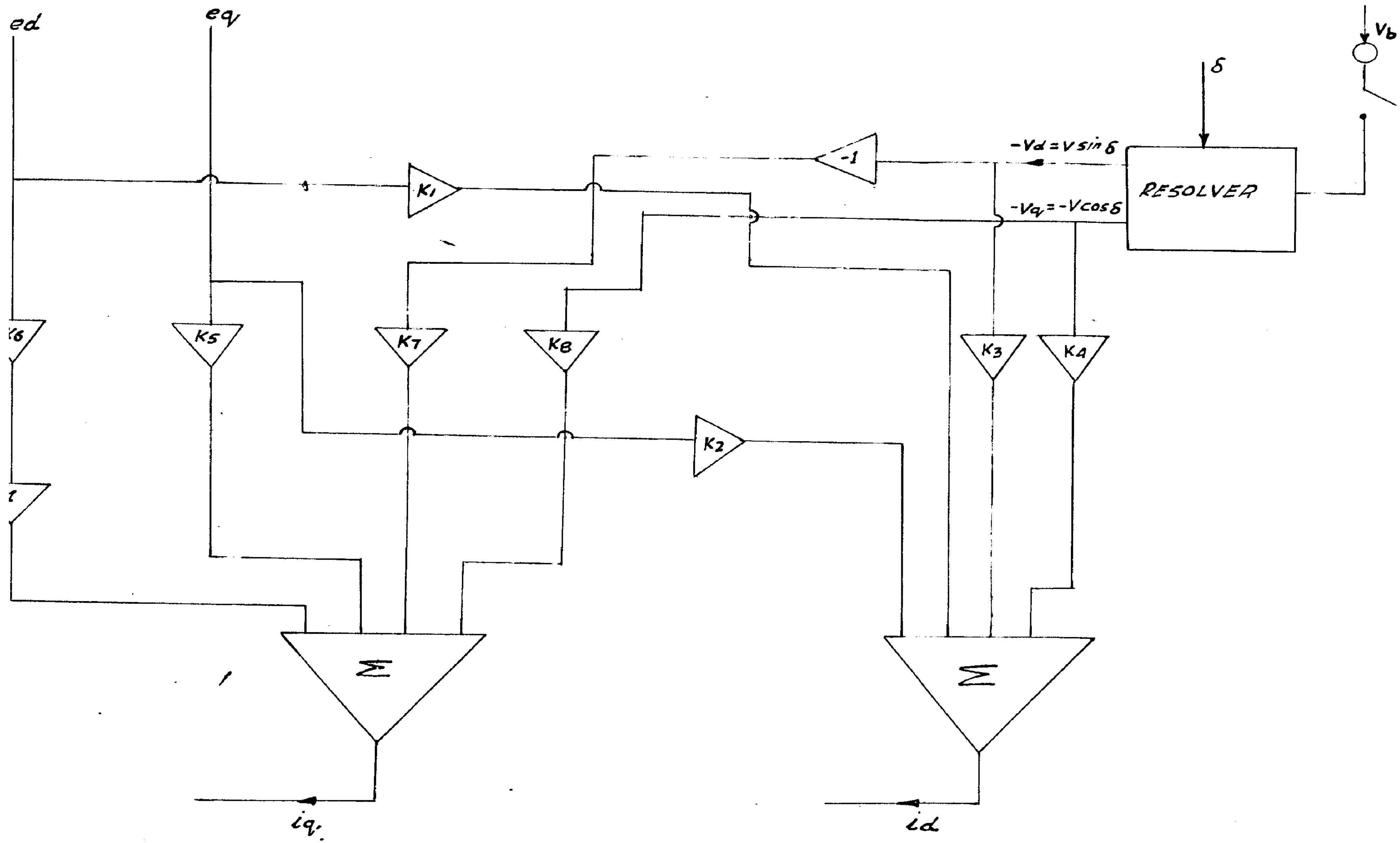


ANALOG SETUP FOR EQUATION (3.14) AND 3.15

FIG. 5.3

Equations (5.4) and (5.5) are represented on the analogue computer as shown in fig. (5.3)

5.2 FAULT REPRESENTATION

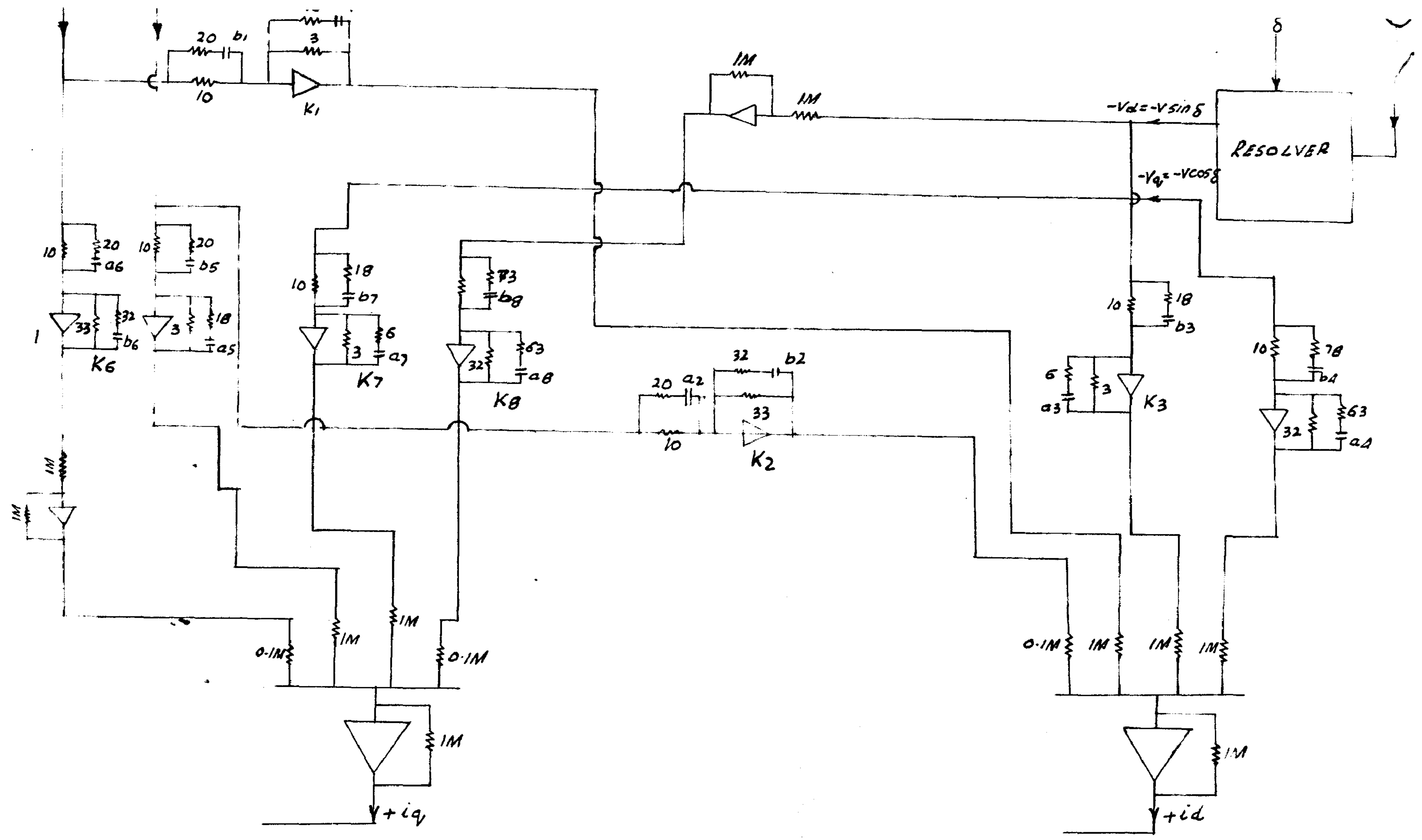
For simulating the fault on the transmission line, impedances z_{11}, z_{12} and z_{22} have to be changed twice, firstly, on the occurrence of the fault and secondly on the clearance of the fault by the opening of the circuit breakers. Evidently the line impedances have to be changed within a period depending upon the fault-clearing time.

One way of tackling this problem would be

1. To set the gain of amplifiers numbered 26 to 33 for steady-state value and record the voltage, current and power at the terminal of the machine.

2. Stop the computer and set the gain of amplifiers numbered 26 to 33 to faulted value and adjust the bus voltage and input torque till the conditions achieved are the same as that obtained at the end of prefault case. Run the computer for 1 or 2 secs and record the quantities for the faulted cases.

3. Stop the computer and change the gain of amplifier numbered 26-33 for post-fault case and readjust the busbar voltage and the input torque till the conditions achieved in the circuit are just the same as that obtained at the end of faulted case for a particular duration of the fault and record the desired quantities.



ANALOGUE SET UP FOR LINE & FAULT SIMULATION

FIG. 5-4

The procedure described above seems to be lengthy and time consuming. To the author's mind this could best be achieved by making use of relays providing a large number of contacts whereby the operation of the relay changes the gains of the amplifiers numbered 26 to 33.

To represent the fault and its subsequent clearing the values of K_1 K_2 ... K_8 have to be changed twice. This change is brought about by changing the gains of the amplifiers numbered 26 to 33 by connecting extra resistance in the feedback loop and at the input path of the amplifier as shown in fig. (5.4). The contacts a_1, a_2 ... a_8 and b_1, b_2 ...... b_7 are the contacts of the relays A and B. The relay B is operated by a time delay circuit shown in fig. (5.5). The contacts b_1, b_2...b_7 close after a pre-determined time after the a_1,a_2... a_8 contacts close. The operation of relay A is done manually.

As no time scaling is done on the computer, the computer time represents the real time. Here the time delay in the closing of contacts b_1, b_2 ... b_7 is made equal to the time of clearing of the fault. Hence, the effect of fault clearing time can be easily studied by changing the settings of the time delay circuit resistance R.

The final set-up representing the line and the fault is shown in fig. (5.4). The value of the resistances to be connected by the contacts a_1,a_2 ... a_8 and b_1, b_2 ... b_7 are calculated in Appendix 3.

Calculation for the Negative Sequence Current

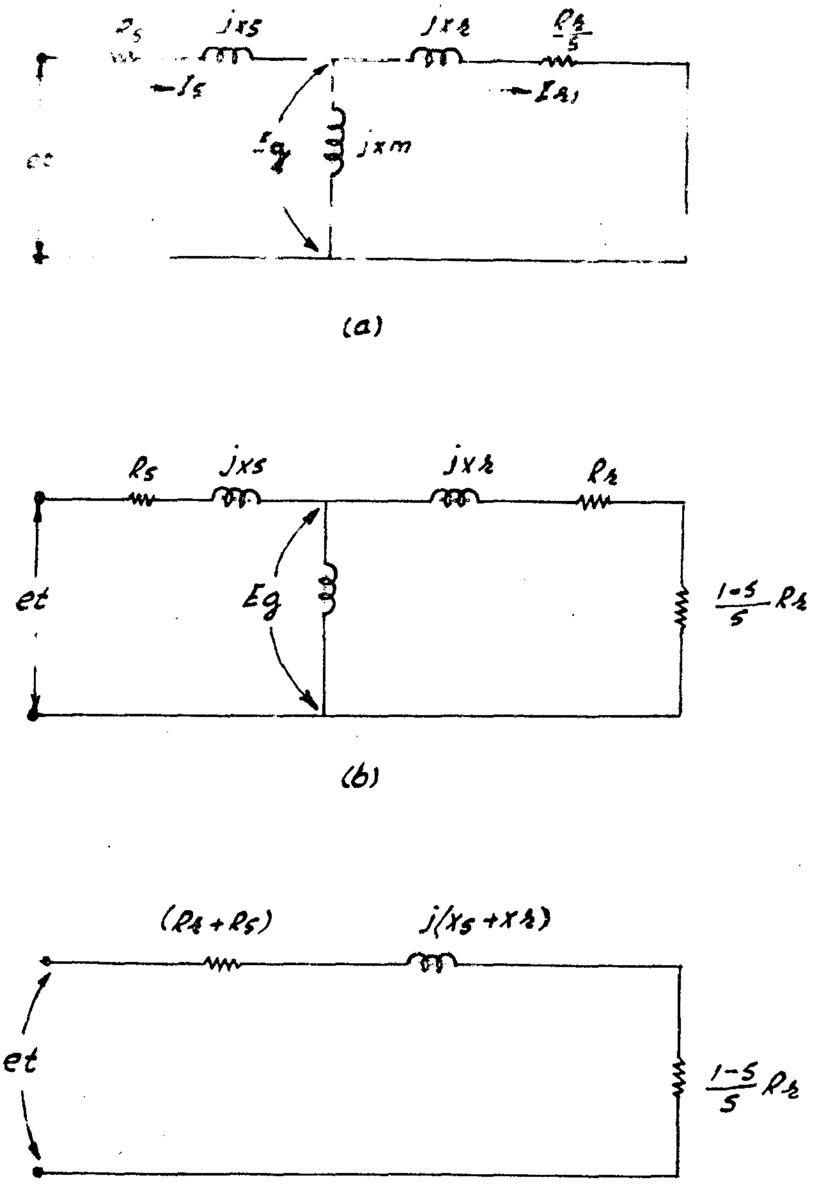
As the negative sequence current in the machine is assumed constant during the fault, it is necessary to calculate the initial value of the negative sequence current;for this the machine is represented by x_d'' and E_d''(transient voltage behind x_d''). The negative sequence current is calculated from the sequence diagram. The negative sequence torque is represented by a constant voltage on the computer.

6. SIMULATION OF LOAD (INDUCTION MOTOR)

Various methods [16] have been used for determining the transient performance of induction motor. Analogue simulation [14] is most suitable for carrying the study of any transient and unbalanced operation of the motor. Following assumptions are made in representing the motor on the computer.

1. Friction and windage losses are negligible.
2. Eddy current and hystresis losses are neglected.
3. Saturation in the motor is neglected.
4. Parameters are assumed to have constant value for all conditions.
5. Magnetizing reactance X_m is neglected.
6. Rotor has the same number of turns as the stator or has been reduced to the equivalent so that the rotor constants, currents and voltages may be expressed on the same basis as the stator.
7. As was pointed out in section 4, the positive and negative sequence torques are calculated from the equivalent circuits. Hence, it is assumed that the electrical transient in the machine are much faster than the electro-mechanical transients which change the slip.

The positive sequence torque for the motor is derived from the equivalent circuit shown in fig.(6.1).



(c)

EQUIVALENT CIRCUT OF INDUCTION MOTOR

POSITIVE SEQUENCE

FIG. 6.1

From the equivalent circuit the terminal voltage

$$e_t = E_{g1} + (R_s + jX_s)I_{s1} \qquad .. (6.1)$$

The voltage induced in rotor,

$$sE_{g1} = (R_r + j_s X_r)I_{r1}$$

or

$$E_{g1} = (R_r + \frac{1-s}{s} R_r + jX_r)I_{r1} \qquad .. (6.2)$$

The equation is represented by the equivalent circuit of Fig.(6.2) where the power absorbed in R_r represents the Cu-losses of the rotor and $\frac{1-s}{s} R_r$ represents the power output of the motor. The equivalent circuit shown in fig. (6.16) takes the form of (6.1c) by neglecting the magnetising reactance X_m which is very high in comparison with $R_r + jX_r$.

The power output of the machine is given by

$$p = 3 \frac{1-s}{s} R_r I_{r1}^2 \qquad .. (6.3)$$

and hence, the positive sequence torque output,

$$T_{1g} = K \frac{3R_r}{s} I_{r1}^2 \qquad .. (6.4)$$

where, K is a constant depending upon the unit employed.

As the field produced by the negative sequence torque rotates in a direction opposite to that of the positive so the expression for the negative sequence torque is obtained by replacing s in the expression for positive sequence torque by (2-s).

$$\therefore \quad T_{g2} = -3KR_r \frac{I_{r2}^2}{2-s} \qquad .. (6.5)$$

The negative sequence torque will be assumed to remain constant during fault period.

Considering equation (6.3)

$$P = 3\frac{1-s}{s} \; R_r I_{r1}^2$$

Substituting,

$$I_{r1} = \frac{e_t}{\left[(R_r+R_s+\frac{1-s}{s}R_r)^2+(X_s+X_r)^2\right]^{1/2}}$$

$$P = \frac{1-s}{s} R_r \frac{e_t^2}{(R_r+R_s+\frac{R_r}{s}-R_r)^2+(X_s+X_r)^2}$$

$$P = \frac{(1-s)s^2}{s} R_r \frac{e_t^2}{s^2R_s^2+R_r^2+2sR_sR_r+s^2(X_s+X_r)^2}$$

$$P = (s-s^2)R_r \frac{e_t^2}{s^2\left[R_s^2+(X_s+X_r)^2\right]+R_r^2+2sR_sR_r}$$

Neglecting s^2 term as it is very small

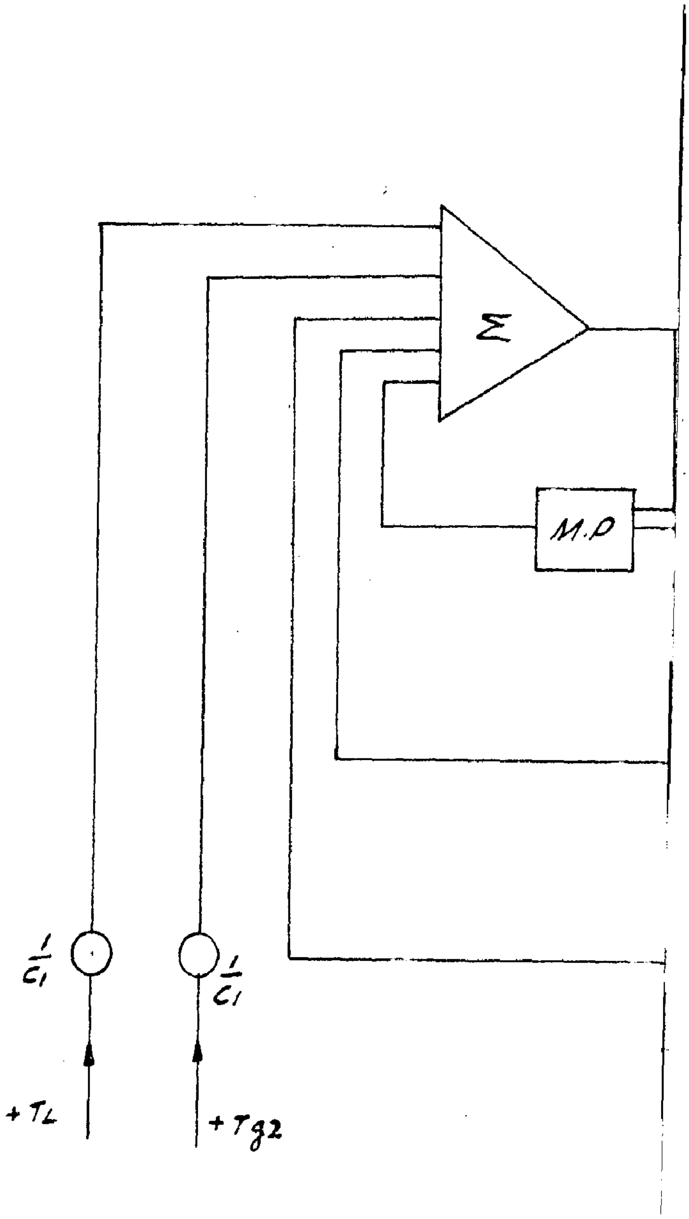
$$P = sR_r \frac{e_t^2}{R_r^2+2R_sR_rs} = \frac{e_t^2}{\frac{R_r}{s}+2R_s} \qquad .. (6.6)$$

The equation for motion of the motor can be written as

$$J\frac{d^2\theta}{dt^2} = T_L - T_{g1} + T_{g2}$$

Substituting T_{g1} from eq. (6.6)

$$J\frac{d^2\theta}{dt^2} = T_L - \frac{e_t^2}{\frac{R_r}{s}+2R_s} + T_{g2}$$



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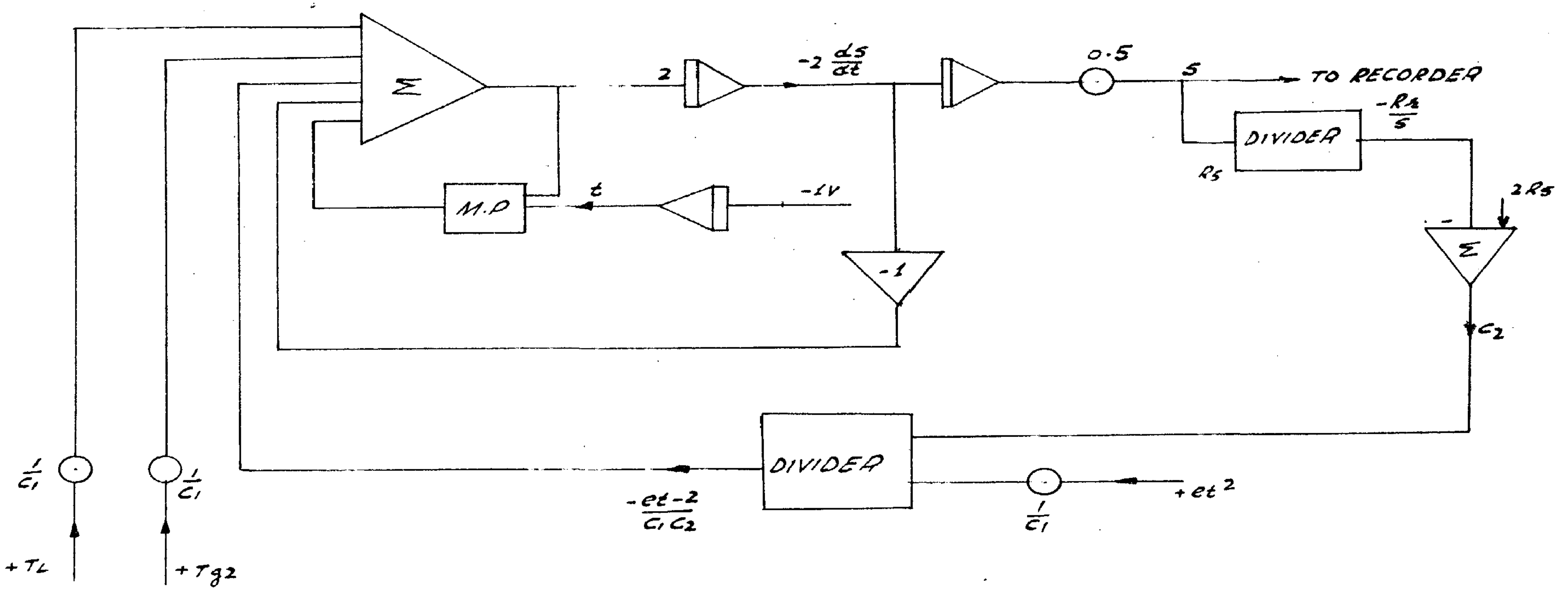
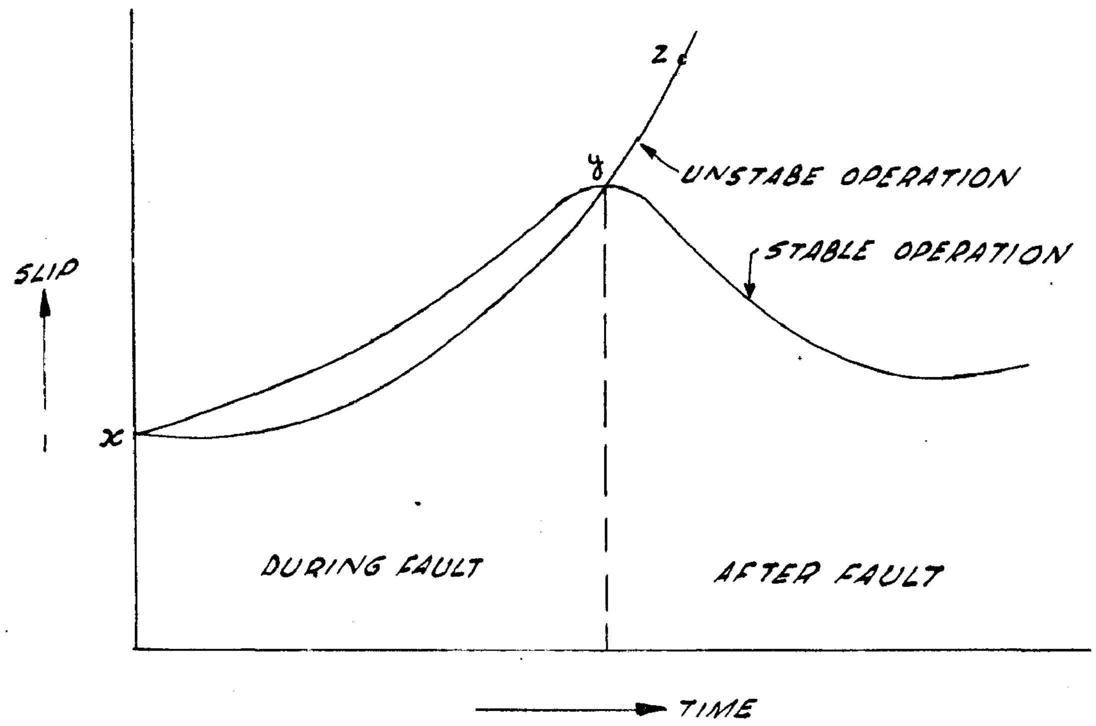


ANALOG SETUP FOR SLIP VARIATION

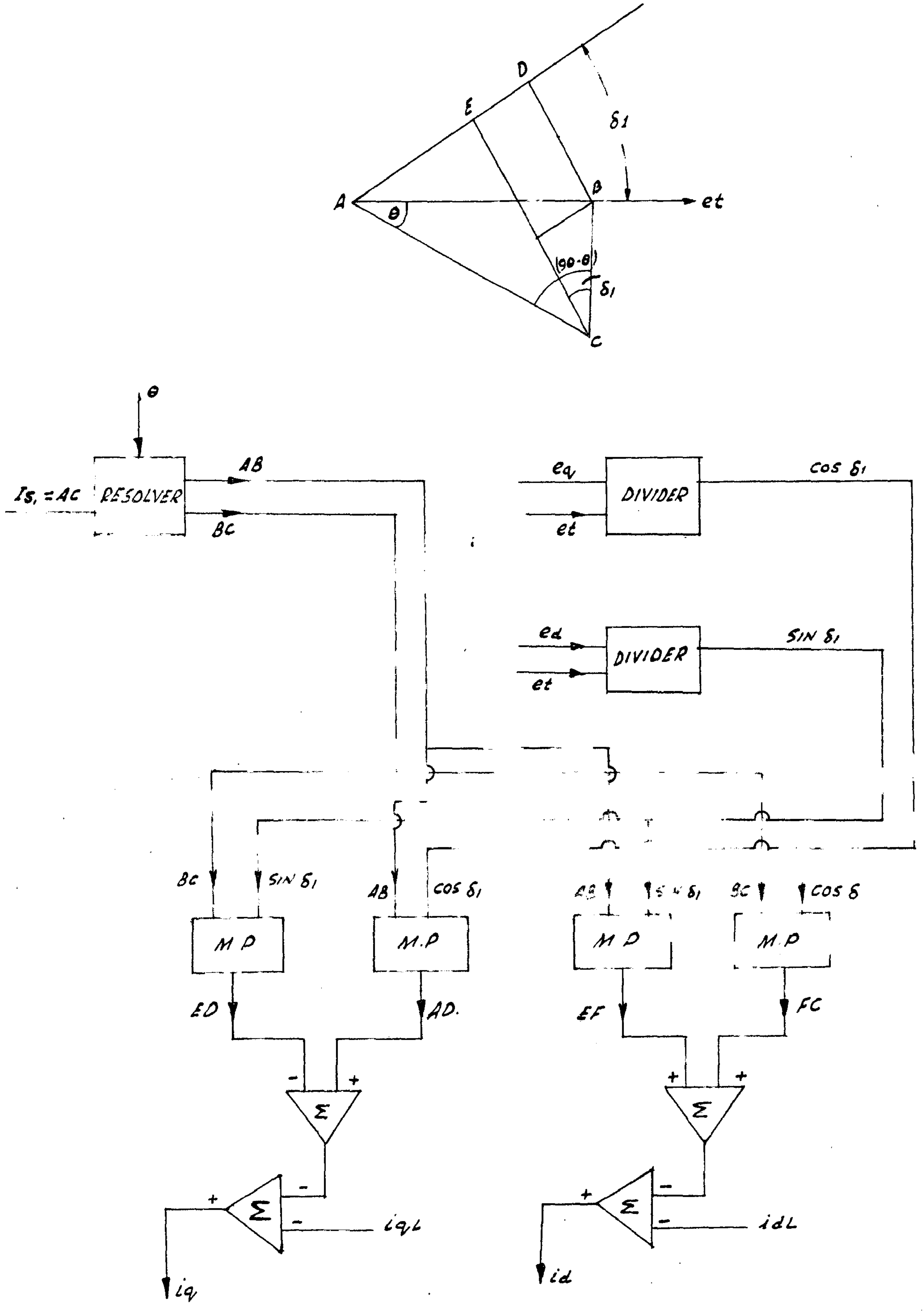
IN INDUCTION MOTOR

FIG. 6·2



SLIP VARIATION OF THE INDUCTION MOTOR DURING FAULT

FIG. 6·3



ANALOG SETUP FOR CURRENT ADDITION

FIG. 6.4

or $$-w_oJ\left[t\,\frac{d^2s}{dt^2}+2\frac{ds}{dt}\right]=T_L-\frac{e_t^{\,2}}{\frac{R_s}{s}+2R_s}+T_{g2}$$

Let,

$$w_oJ=C_1$$

$$\frac{R_r}{s}+2R_s=C_2$$

Above equation reduces to

$$-C_1\left[t\,\frac{d^2s}{dt^2}+\frac{ds}{dt}\right]=T_L-\frac{e_t^2}{C_2}+T_{g2}$$

or $$t\,\frac{d^2s}{dt^2}=-\frac{T_L}{C_1}+\frac{e_t^2}{C_1C_2}-\frac{T_{g2}}{C_1}-2\,\frac{ds}{dt} \qquad \text{.. (6.7)}$$

The analogue simulation for eq.6.7 is shown in fig. (6.2). In the stability study of the machine the slip s is applied to the recorder and the variation of the slip with time is recorded. If the slip increases upto point y as shown in fig.(6.3) and then decreases the machine is having its stable operation if slip goes on increasing upto and beyond point z then machine is unstable.

The total current drawn from the synchronous machine is equal to the sum of line current and fault current. Figure 6.4 shows the analogue set-up for adding motor current with line current to get total current.

7.2 SCALING

Because of the limitations imposed by the elements of the computer for linear operation it is necessary to relate the problem variable with the computer variable. Since the variables in each system has very real limitation on their possible magnitude and rate of change with respect to time, the corresponding variables of the system are related by mangitude and time scale factors. This can be explained as follows.

Maximum Voltage Limitations

A well designed operational amplifier has a wide dynamic range in which the output voltage varies linearly with the input voltage. Because of the saturation in the amplifier the output voltage becomes non-linear. So the operation of the amplifier beyond the linear range introduces error.

Minimum Voltage Limitation

The range of operating amplifier should not be so low that the magnitude of error voltage (random noise voltage) becomes appreciable compared with the operating signal.

Considerations for Time Scaling

Slow Speed Limitation

(a) In the problem where the variation of the actual quantities takes place more slowly than the computer time computer need to be slowed down. Since the signal voltages and error signals are integrated hence, the error tends to build up.

(b) High Speed Limitation

If the variation of the variables in the problem takes place at faster rate than the computer time, time lags occur as a result of phase shift in computing amplifier.

So, we conclude that the voltage applied to the computer should neither be too high nor too small and also time scale must neither be too fast nor too slow.

Since the frequency of the transients occurring in the system is small of the order of 2 cycles per second hence, time scaling is not necessary.

7.2 Scaling

Assuming the computer operating voltage as $\pm 10V$ and following variations in the quantities flowing in the circuit.

Quantity	Max. values
T_i	$2T_i$
T_{io}	$2T_{io}$
ψ_d	$2\psi_d$
ψ_q	$2\psi_q$
e_d	$2e_d$
e_q	$2e_q$
i_d	$10i_d$
i_q	$10i_q$

continued

Quantity	Max. values
T_{e1}	$3T_{e1}$
T_{e2}	T_{e2}
V_d	V_d
V_q	V_q
e_t	$2e_t$

We proceed for scaling as follows.

$$\psi_d = \left[\frac{1.055}{(1+3.26p)} + 0.209 - \frac{0.064}{(1+0.029p)}\right] i_d$$

$$+ \left[\frac{1.004}{(1+3.26p)} - \frac{0.04}{(1+0.029p)}\right] e$$

1 p.u. of i_d = 1 volt on computer,

1 p.u. of e = 2 volt on computer,

At $t = \infty$, $p = 0$, For 0.9925 - 1.0 p.u. of current

$$\psi_d = -0.644\left[1.055-0.064+0.209\right]x1 + 2\left[1.004 - 0.004\right]x1.547$$

$$= -0.774+3.09$$
$$= 2.316 \text{ volts}$$

Also at $p = 0$ and $t = \infty$

$$\psi_d = -x_d\ i_d + G(p)\ e$$

$$= -1.2x0.644+1.547$$
$$= 0.775$$

So, 0.775 units of ψ_d are represented by 2.318 volts on computer. Hence 1 p.u. of ψ_d is represented by $\frac{2.318}{0.775} = 2.99 \simeq 3.0$ volts.

<u>Scale for ψ_q</u>

$$\psi_q = -\frac{0.45\ i_q}{(1+0.0637p)} - 0.35\ i_q$$

1 p.u. of i_q is represented by 1 volt on the computer. Thus, at $t = \infty, p = 0$

$$\psi_q = -0.45x0.754-0.35x0.754$$
$$= -0.604 \text{ volts}$$

Therefore, 0.604 units of ψ_q are represented by 0.604 volts on computer. Hence 1 p.u. of ψ_d = 1 volt on the computer.

<u>Scale for e_d and e_q</u>

$$e_d = -\psi_q$$

$\therefore$ 1 unit of e_d is represented by -1 volt on computer,

$$e_q = +\psi_d$$

1 unit of e_q is represented by 3 volts on computer.

<u>Scale for e_t</u>

$$e_t = \sqrt{e_d^2 + e_q^2}$$

$$= \sqrt{1^2 + 3^2}$$

$$= 3.15 \text{ volts}$$

So, 1 unit of e_t is represented by 3.15 volts on computer.

Scale for i_d and i_q

$$i_d = K_1\, e_d + K_2\, e_q - K_3\, V_d - K_4\, V_q$$

$$i_q = K_5\, e_q - K_6\, e_d - K_7\, V_q + K_8\, V_d$$

For prefault case

$$K_2 = K_4 = K_6 = K_8 = 3.32,$$

$$K_1 = K_3 = K_5 = K_7 = 0.274$$

$$\therefore\ i_d = 0.274x(-1)+3.32x3-0.274x1-3.32x1.$$
$$= 2x3.32$$
$$= 6.092$$

$\therefore$ 0.664 units of i_d are represented by 6.092 volts on computer.

1 unit of i_d is represented by

$$= \frac{6.092}{0.664} = 9.19 \text{ volts}$$

This can be adjusted by reducing the gain of amplifier No.23 by a factor $\frac{1}{9.19}$ = 0.109 volts.

Scale for i_q

$$i_q = 0.274 \times 3 - 3.32 \times (-1) - 0.274 \times 1 + 3.32$$
$$= 0.548 + 6.62$$
$$= 7.168$$

0.754 p.u. of i_q are represented by 7.168 volts on computer

1 p.u. of i_q is represented by = $\frac{7.168}{0.754}$ =9.5 volts.

This can be adjusted by reducing the gain across the amplifier No.22 by 9.5 times or 0.105.

<u>Scale for T_{e1} and T_{e2}</u>

$$T_{e1} = \psi_d\, i_q - \psi_q\, i_d$$

Therefore in steady state

$$= 3.0 \times 0.754 - 1 \times 0.664$$
$$= 2.26 - 0.664$$
$$= 1.596 \text{ volts}$$

$\therefore$ p.u. of T_{e1} is represented by = 1.596 volts

$\simeq$ 1.6 volts on computer.

<u>T_{e2}</u>

For prefault $T_{e2} = 0$

During fault $= I_2^2 (R_2 - R_a)$

$= (1.075)^2 (0.1)$

$= 0.116$ volts

1 p.u. of T_{e1} = ~~0~~1.596 volts

0.116 p.u. of T_{e2} = 1.59x0.116 = 0.184 volts.

<u>Voltage Regulator</u>

$$e = \left| \frac{A_1}{(1+pT_1)} + \frac{A_2}{(1+pT_2)} + \frac{A_3}{(1+pT_3)} \right| (E_r - e_t)$$

From the optimization table for voltage regulator in Chapter 4,

At $t = \infty$ $p = 0$

Maximum value of $A_1 + A_2 + A_3 = 40$

Choosing 1 p.u. of E_r = 4 volts.

$$e = 40(4.0 - 3.15) = 40 \times 0.85 = 34 \text{ volts.}$$

From assumed data

1 p.u. of e = 2 volts.

This is adjusted by reducing the gain of amplifier No;19 by the factor $\frac{34}{2} = 17$.

Scaling for e_q

$$M p^2\delta = T_1 - T_{e1}$$

$$\text{or} \quad p^2\delta = \frac{1}{M}(T_1 - T_{e1})$$

$$\therefore \quad p^2\delta = \frac{1}{6}(5 - 1.596) = 0.635$$

The oscillations of the rotor angle can be expressed as

$$\delta = A \sin wt$$

$$\therefore p\delta = wA \sin wt$$

$$p^2\delta = w^2 A \sin wt.$$

where A = constant,
w = $2\pi f$
f = frequency of rotor angle oscillations

Assuming rotor frequency of 1 cycle/sec and A = 4

$$p\delta_{max.} = 8\pi$$

$$\therefore \quad 1 \text{ p.u. of } p\delta = \frac{8\pi}{10} = 2.52$$

$$p^2\delta_{max.} = 4\pi^2 x4$$

$$1 \text{ p.u. of } p^2\delta = 15.8 \text{ volts.}$$

This is adjusted by increasing the gain of amplifier No.21 by a factor $\frac{15.8}{0.635} = 25$.

<u>Scale for Governer</u>

$$T_1 = T_{1o} - \left[\frac{A_4}{(1+pT_4)} + \frac{A_5}{(1+pT_5)}\right]p\delta$$

During optimization $A_4 + A_5 = 30$

Also $p\delta = 2.52$

$T_{10} = 4.$

$\therefore T_1 = 4 - [30]2.52$

$T_1 = 4 - 75.5 = -71.5$

Assuming $T_1 = 4$ this is adjusted by reducing the gain of amplifier No.20 by a factor $\frac{71.5}{4} = 17.8$ times.

7.2 STUDIES

In this section the various types of stability studies defined in section 1.1 will be considered. Before carrying out the stability studies on the computer it has to be set for the normal steadystate operation of the power system. This is achieved as follows.

Patch up the diagram shown in fig. 7.1 on the computer with,

$R_1C_1 = 0.5 \qquad R_2C_2 = 0.05 \qquad R_3C_3 = 0.2$

$R_4C_4 = 0.1 \qquad R_5C_5 = 0.5 \qquad R_6C_6 = 0.029 \quad R_7C_7 = 0.0637$

$$\frac{R_1'}{R_1} = \frac{R_2'}{R_2} = \frac{R_3'}{R_3} = \frac{R_4'}{R_4} = \frac{R_5'}{R_5} = \frac{R_6'}{R_6} = \frac{R_7'}{R_7} = 1$$

and set the coefficient pot setting and perform the steps given below.

1. Open the angle regulator switches S_{61}, S_{62}, S_{63}
2. Open switch S_1 and adjust the initial value across the amplifier No.12 corresponding to $\delta=\delta_o$ calculated in Appendix .
3. Open switch S_2, S_3, S_4 and S_5 and adjust $V_b=1.0$
4. Adjust E_r to get e equal to the no load excitation voltage as calculated in Appendix 4.
5. Close switch S_2, S_3, S_4 and S_5 and measure e_t and adjust E_r so that $e_t = 1.0$.
6. Read off the value of i_d and i_q at the output of amplifier numbered 22 and 23 and verify it with that calculated theoretically in Appendix .

7. Adjust T_{io} so that $T_i = T_1$ i.e. zero voltage at the input of amplifier numbered 21.

8. Close the switch S_1.

7.4 The computer is now set for the balanced steady state operation of the system. The various studies are carried as follows.

7.4.1. Steady State Stability

For carrying out this study change the input. T_{io} gradually and record the variation of T_i with δ(Rotor angle). This is done by feeding the output of amplifier numbered 12 and 20 to a xy recorder. Go on changing T_{io} in gradual steps and record the corresponding variation of T_i versus δ. From the records the maximum value of T_i for which the system remains stable gives the steady-state stability limit.

7.4.2 Dynamic Stability

For carrying out dynamic stability study the value of T_{io} is first adjusted to some steady state value and then changed in a small step. The variation of T_i with δ is recorded. The maximum value of T_i for which the system remains stable gives the dynamic stability limit.

7.4.3 Transient Stability

For carrying out the transient stability study on the occurrence of various types of faults following adjustments are made in addition to the 8 steps described earlier for the normal operation of the system.

(a) Set the gain of the amplifier numbered 26 to 33 to a value depending upon the type of fault under consideration.

(b) Adjust the time constant of the relay circuit shown in fig. 5.5 equal to fault clearing time.

(c) Operate the relay A with the help of manual switch and feed the output of amplifier numbered 12 and 20 to xy recorder. From the records the maximum value of T_1 which the system remains stable gives the transient stability limit.

The stability of the system can be determined by recording the variation of δ with time. If the oscillations in δ die down then the system is stable and if they increase, it is unstable.

8.1 REPRESENTATION OF MULTI-MACHINE POWER SYSTEM ON ANALOGUE COMPUTER

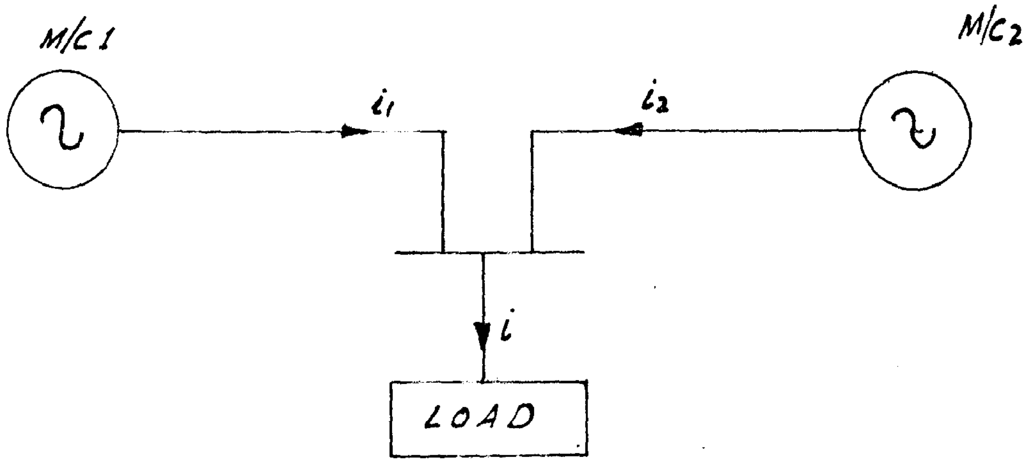
It is possible to represent the performance equation of each component of a system by a suitable analogue set-up on the computer. The individual set-up so obtained for the various components of the system are combined after their transformation into a common reference frame to obtain the overall performance of the complete system. Transformation of the various components into a common reference frame is carried out in the following steps.

(a) Establishment of the basic reference frame and representation of each component with respect to this frame. Usually the cross-field reference frame of Park's or d-q axis are chosen as the reference frame.

(b) Though there is no restriction posed by the system in selecting the reference frame it is advantageous to choose the reference frame as that of a machine with the highest rating or the machine which is most stable.

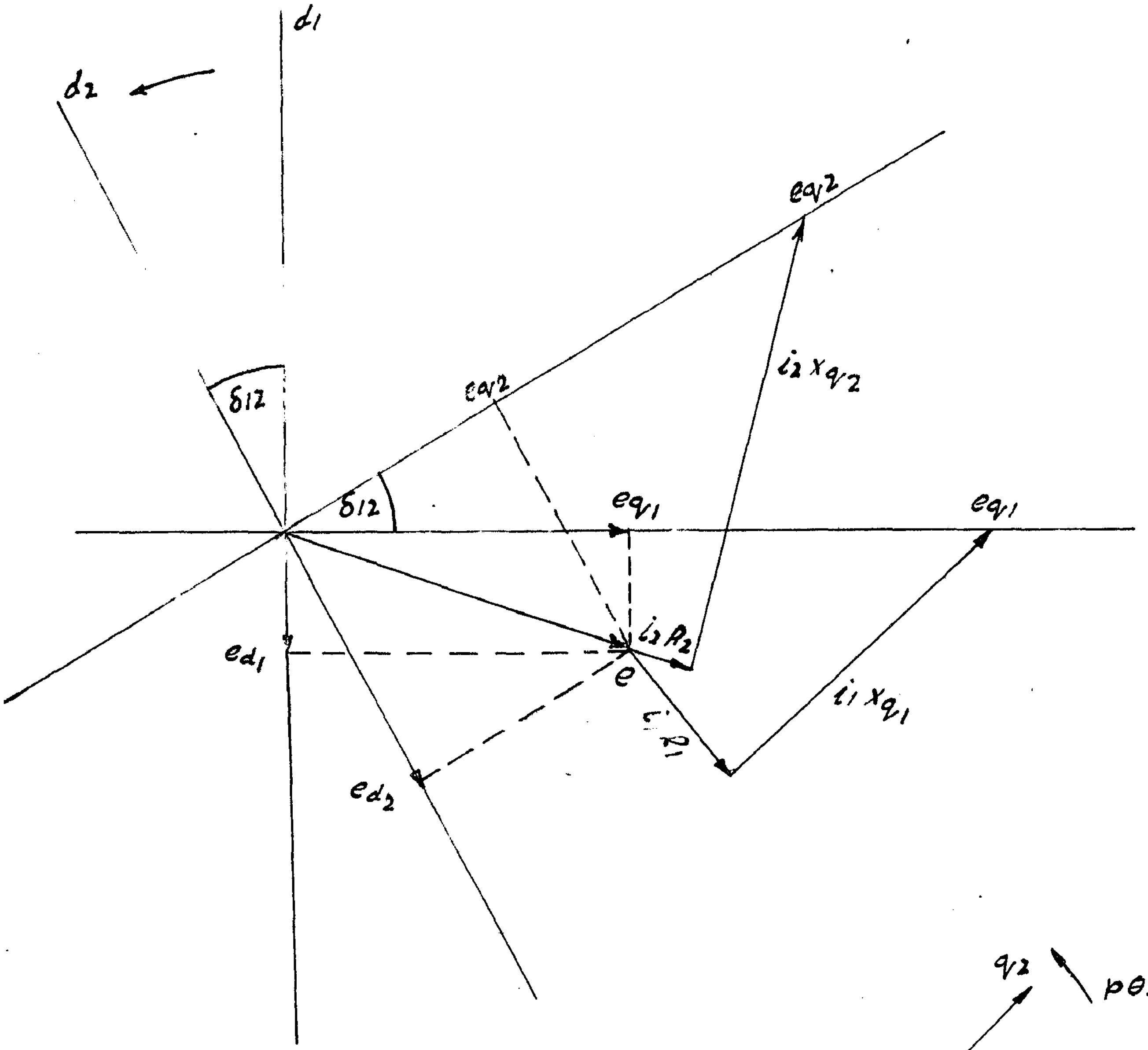
Thus, in a n machine system the frame of one machine is chosen as the reference and remaining (n-1) machines are expressed with respect to this reference frame. This transformation being necessary because of the different orientation of the rotors of the (n-1) machine in the system.

For clear understanding of the simulation of the multimachine we proceed for the analysis of the two



TWO MACHINE SYSTEM

FIG. 8·1



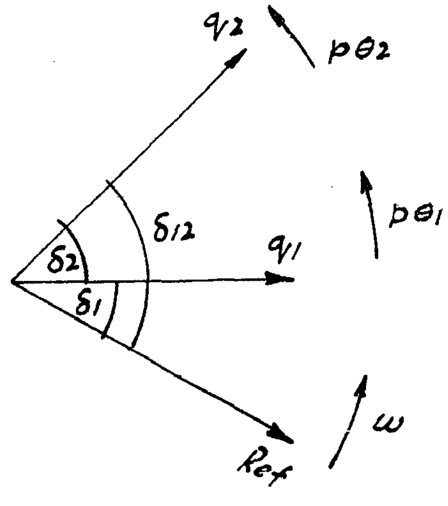
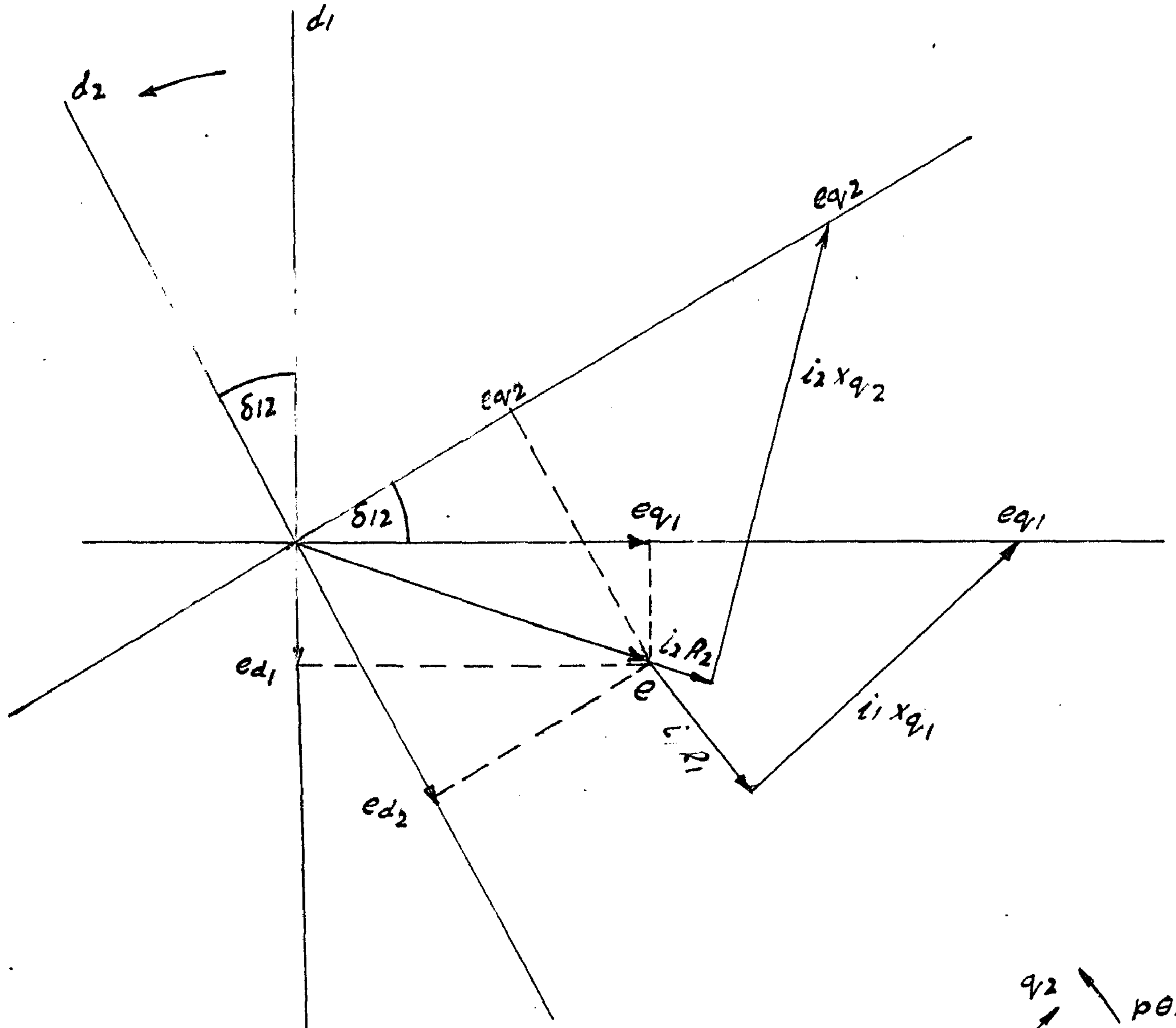


FIG. 8.2

VOLTAGE TRANSFORMATION VECTOR
<u>DIAGRAM</u>



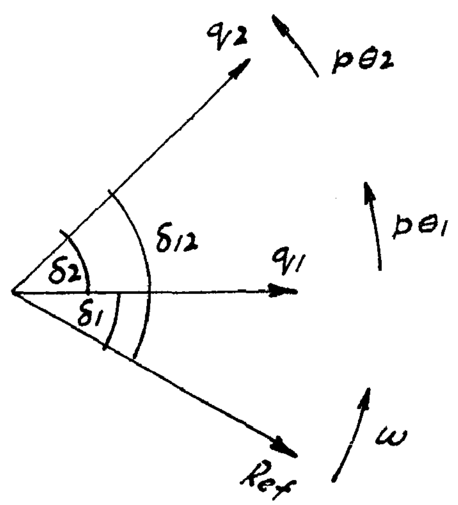


FIG. 8.2

VOLTAGE TRANSFORMATION VECTOR DIAGRAM

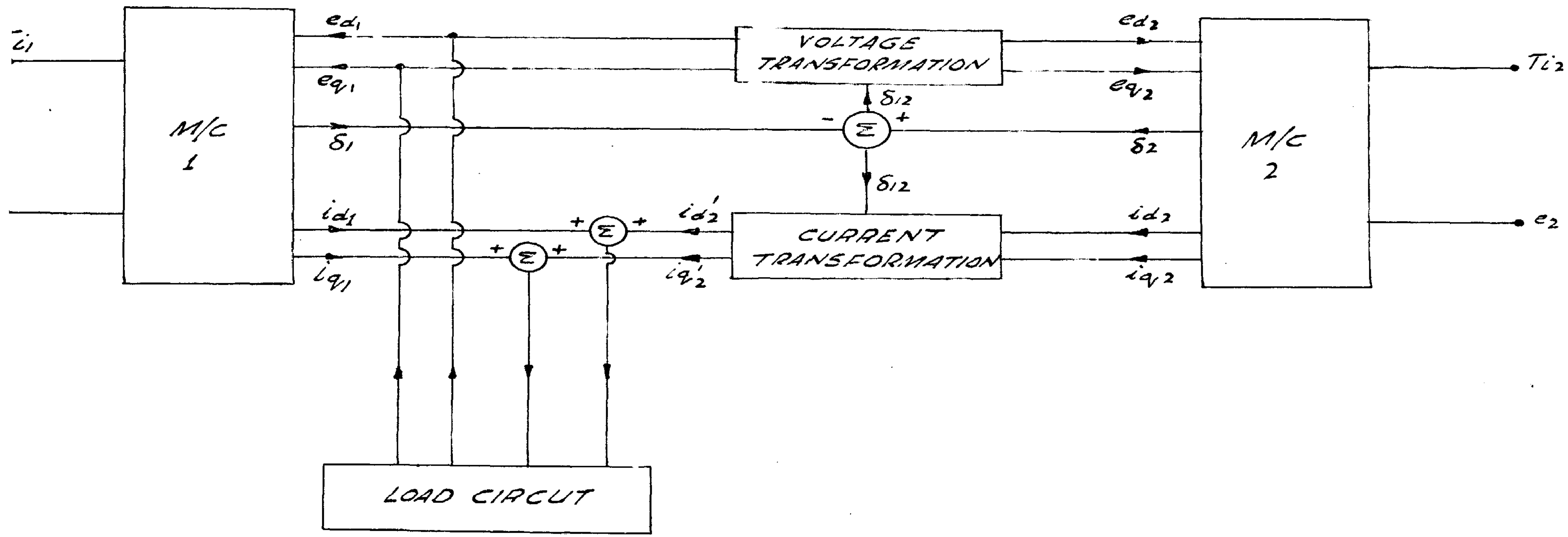


FIG. 8.3

SIMULATED TWO MACHINE SYSTEM (BLOCK DIAGRAM) machine system as shown in Fig. (8.1)

δ_1 and δ_2 being the angles between the quadrature axis of machine (1) and (2) and the rotating reference frame and δ_{12} the angle between the quadrature axis of machine (1) and (2). The voltage transformation for the two machine system is self-explanatory from the vector diagram of Fig. (8.2). In the vector diagram shown e is the common voltage at the junction of the two machine and e_{d1} e_{q1} , e_{d2} e_{q2} represents the components of the voltages e along d_1 q_1 and d_2, q_2 axis.

In the block diagram of Fig.8.3 assume some values of e_{d1} and e_{q1} and record i_{d1} and i_{q1}. e_{d2} and e_{q2} are obtained from the transformation of the e_{d1} and e_{q1} with the help of analogue set-up shown in Fig.4 and hence i_{d2} and i_{q2} are also known. i_{d2} and i_{q2} are transformed into i'_{d2} and i'_{d2} and added with i_{d1} and i_{q1} to obtain i_{dL} and i_{qL}. How i_{dL} and i_{qL} are impressed into the load circuit to get e_{d1} and e_{q1} which were assumed initially and thus the whole system works as one closed loop.

The voltage of machine (2) can be expressed in terms of the voltage of the machine (1) by the following relationship.

$$e_{d2} = e_{q1} \sin_{\delta 12} + e_{d1} \cos_{\delta 12}$$

$$e_{q2} = e_{q1} \cos_{\delta 12} - e_{d1} \sin_{\delta 12}$$

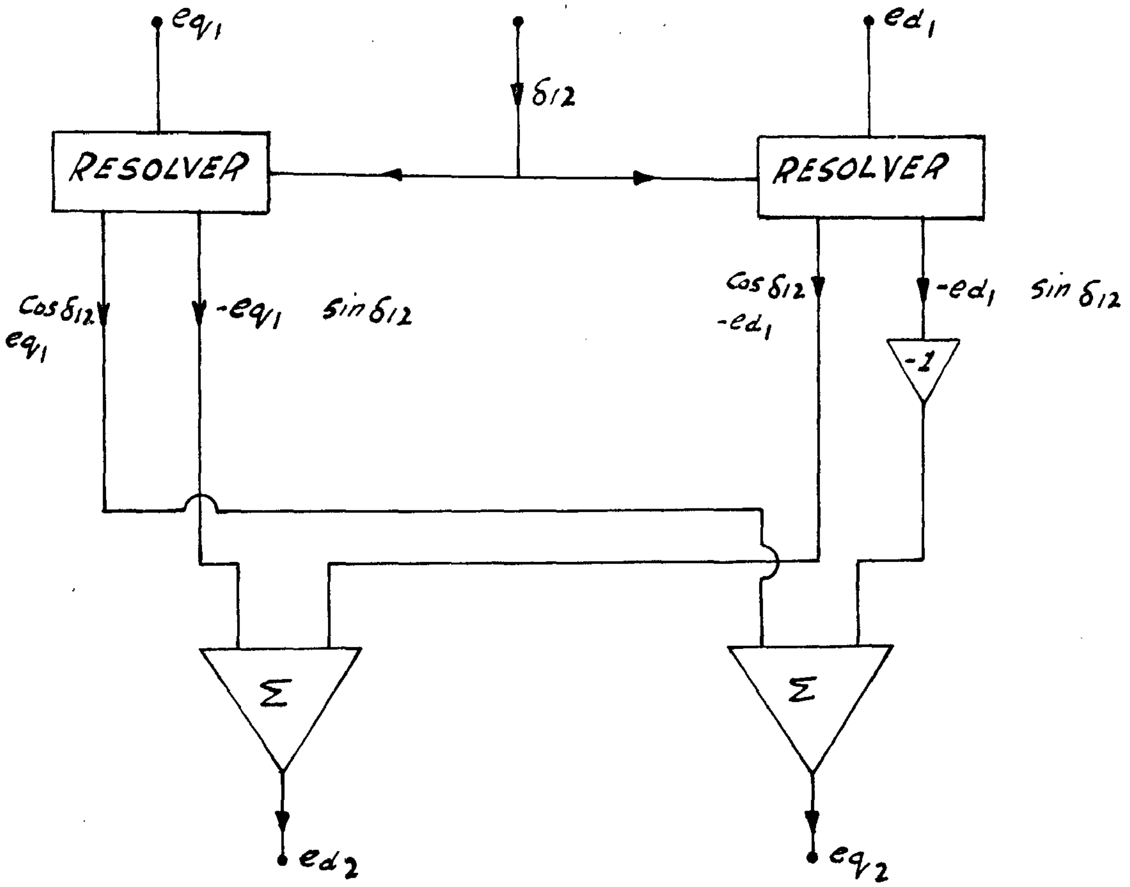
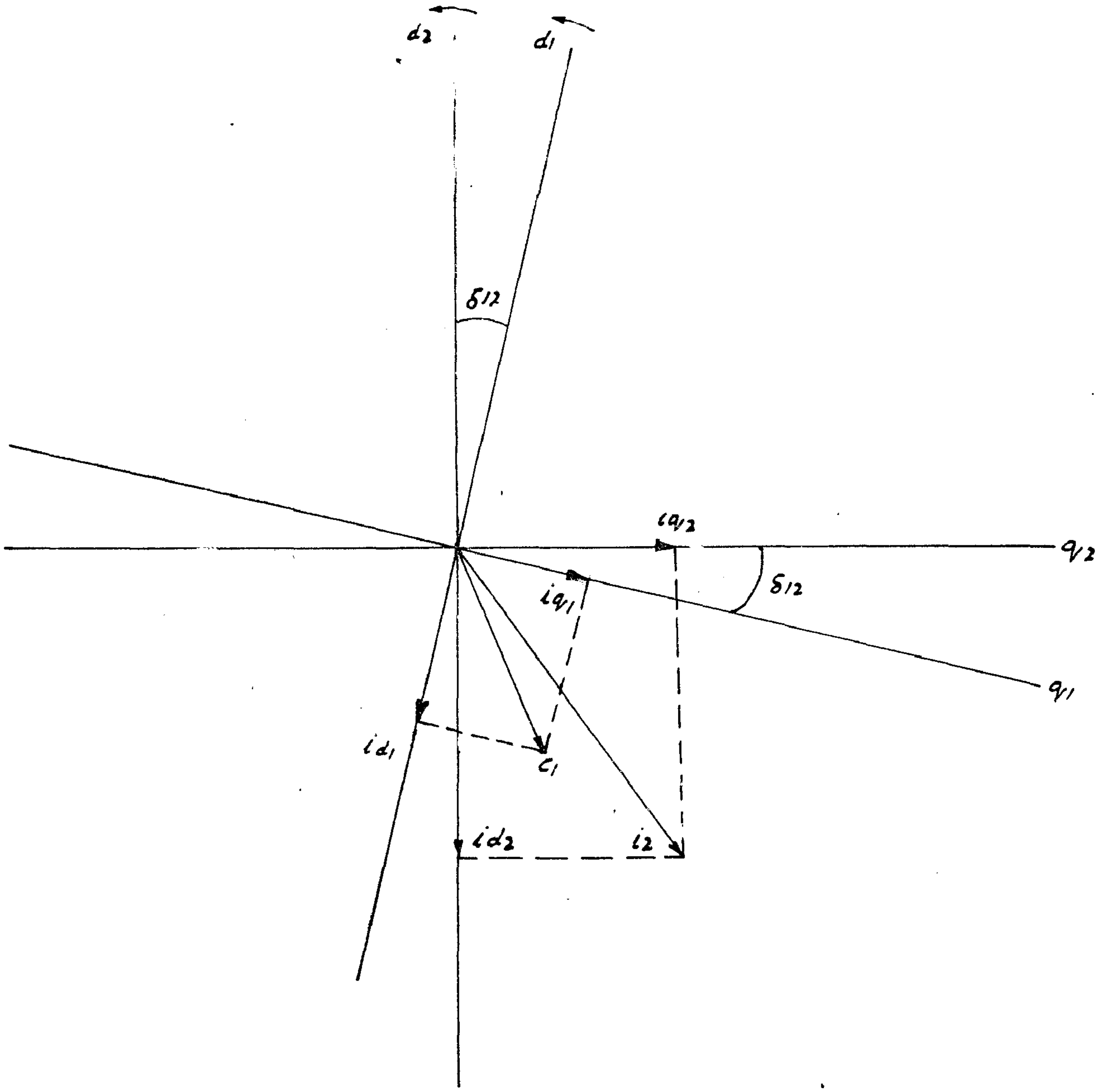


FIG. 8.4

ANAGOG SETUP FOR VOLTAGE TRANSFORMATION



CURRENT TRANSFORMATION VECTOR DIAGRAM

FIG 8·5

An analogue set-up for these equations is shown in Fig. 8.4.

Transformation of Currents.

Fig. 8.5 shows the transformation of currents. The load current i_{dL} and i_{qL} is calculated with the relationship given by the following equations.

$$i_L = i_1 + i_2$$
$$i_{qL} = i_{q1} + i'_{q2}$$
$$i_{dL} = i_{d1} + i'_{d2}$$

From the vector diagram,

$$i'_{q2} = i_{q2} \cos_{\delta 12} + i_{d2} \sin_{\delta 12}$$
$$i'_{d2} = i_{d2} \cos_{\delta 12} - i_{q2} \sin_{\delta 12}$$
$$i_{qL} = i_{q1} + i_{q2} \cos_{\delta 12} + i_{d2} \sin_{\delta 12}$$
$$i_{dL} = i_{q2} + i_{d2} \cos_{\delta 12} - i_{q2} \sin_{\delta 12}$$

8.2 SIMULATION OF MACHINE

The equation for the synchronous machine derived from Park's reference with the assumption made previously may be written as follows.

For M/C(1)

$$T_{11} = M_1 \frac{d^2\delta}{d_t^2} + T_{u1,1} + T_{u2,1} \qquad .. (1)$$

$$T_{u1,1} = \psi_{d1}\, i_{q1} - \psi_{q1} i_{d1}$$

$$T_{u2,1} = I_{21}^2 (R_{21} - R_{a1})$$

An analogue set-up for these equations is shown in Fig. 8.4.

Transformation of Currents.

Fig. 8.5 shows the transformation of currents. The load current i_{dL} and i_{qL} is calculated with the relationship given by the following equations.

$$i_L = i_1 + i_2$$
$$i_{qL} = i_{q1} + i'_{q2}$$
$$i_{dL} = i_{d1} + i'_{d2}$$

From the vector diagram,

$$i'_{q2} = i_{q2} \cos_{\delta 12} + i_{d2} \sin_{\delta 12}$$
$$i'_{d2} = i_{d2} \cos_{\delta 12} - i_{q2} \sin_{\delta 12}$$
$$i_{qL} = i_{q1} + i_{q2} \cos_{\delta 12} + i_{d2} \sin_{\delta 12}$$
$$i_{dL} = i_{q2} + i_{d2} \cos_{\delta 12} - i_{q2} \sin_{\delta 12}$$

8.2 SIMULATION OF MACHINE

The equation for the synchronous machine derived from Park's reference with the assumption made previously may be written as follows.

For M/C(1)

$$T_{i1} = M_1 \frac{d^2\delta}{d_t^2} + T_{u1,1} + T_{u2,1} \quad \text{.. (1)}$$

$$T_{u1,1} = \psi_{d1} \, i_{q1} - \psi_{q1} i_{d1}$$

$$T_{u2,1} = I_{21}^2 (R_{21} - R_{a1})$$

$$e_{d1} = p\psi_{d1} - \psi_{q1} p\theta_1$$

$$e_{q1} = p\psi_{q1} + \psi_{d1} p\theta_1$$

$$e_{q1} = p\psi_{q1} + \psi_{d1} p\theta_1$$

For M/S (2)

$$T_{12} = M_2 \frac{d^2\delta}{d_t^2} + T_{u1,2} + T_{u2,2}$$

$$T_{u12} = \psi_{d2} i_{q2} - \psi_{q2} i_{d2}$$

$$T_{u22} = T_{2,2}^2 (R_{2,2} - R_{a2})$$

$$e_{d2} = p\psi_{d2} - \psi_{q2} p\theta_2$$

$$e_{q2} = p\psi_{12} + \psi_{d2} p\theta_2$$

8.3 <u>SIMULATION OF LOAD</u>

The equations for the load circuit are written as follows.

$$e_a = p\psi_a - R_L i_b$$

$$e_b = p\psi_b - R_L i_b$$

$$e_c = p\psi_c - R_L i_c$$

where,

$$\psi_a = X_L i_a \quad \psi_b = X_L i_b \quad \psi_c = X_L i_c$$

These equations when transformed into d-q axis components give,

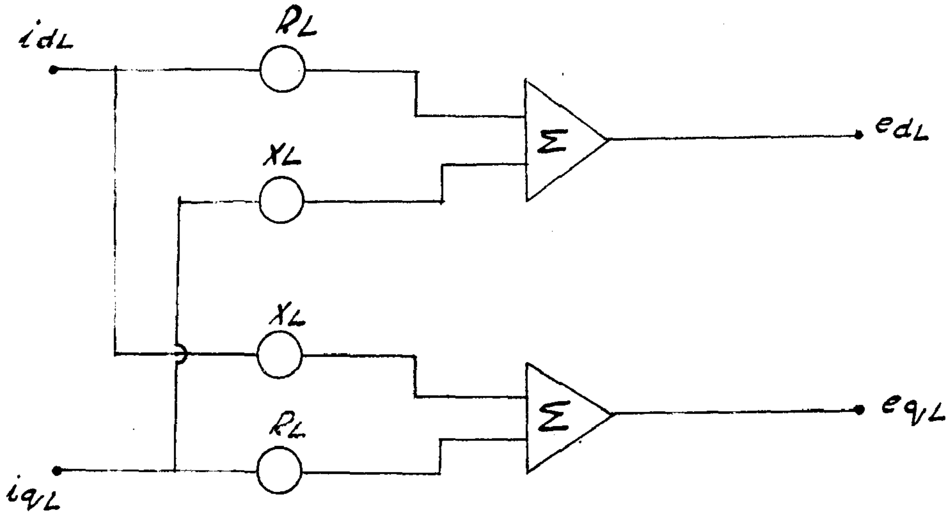


FIG. 8·6

ANALOG SETUP FOR LOAD REPRESENTAION

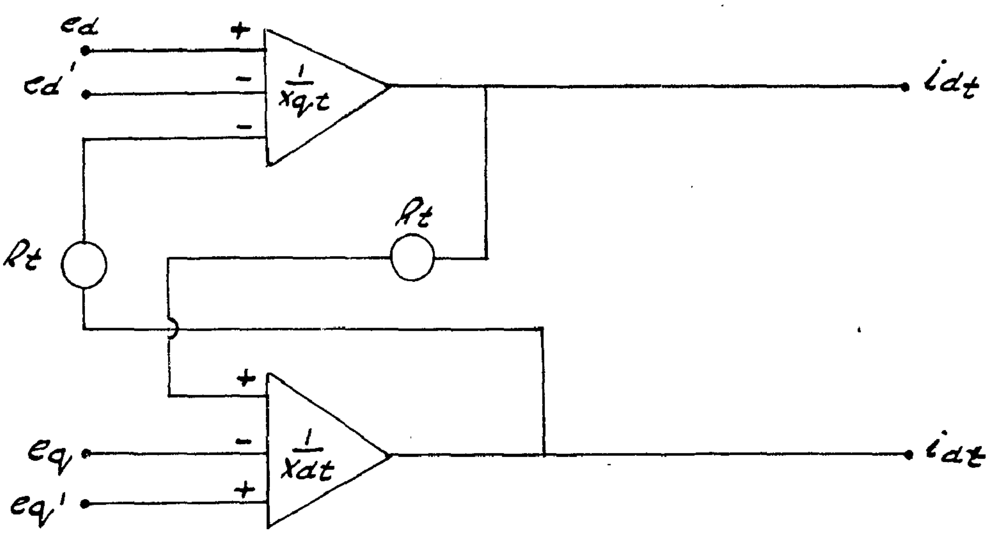


FIG. 8·7

ANAGOG SETUP FOR LINE REPRESENTATION

$$e_{dL} = X_L\, p\, i_{dL} - X_L\, i_{qL}\, p\theta - R_L\, i_{dL}$$

$$e_{qL} = X_L\, p\, i_{qL} + X_L\, i_{dL}\, p\theta - R_L\, i_{qL}$$

Neglecting the transient terms and assuming $p\theta$ equal to unity we get,

$$e_{dL} = -X_L\, i_{qL} - R_L\, i_{dL}$$

$$e_{qL} = X_L\, i_{dL} - R_L\, i_{qL}$$

A suitable analogue set-up for these equations is given in Fig. (8.6).

8.4 SIMULATION OF TRANSMISSION LINES

Transmission lines are simulated with the following equation.

$$e_a = e_a' + i_a(R_t + p\, X_t)$$

$$e_b = e_b' + i_b(R_t + p\, X_t)$$

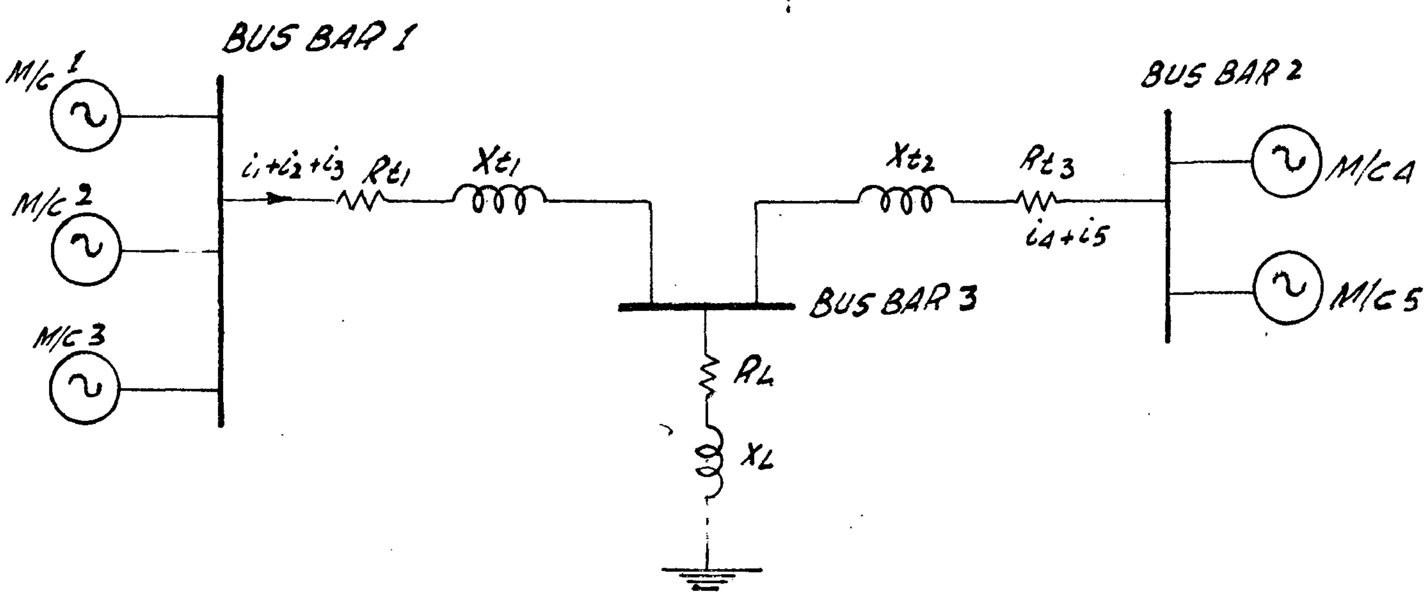
$$e_c = e_c' + i_c\,(R_t + p\, X_t)$$

where, e_a and e_a' are the voltages at each end of the transmission lines.

These equations when transformed into d-q axis yields,

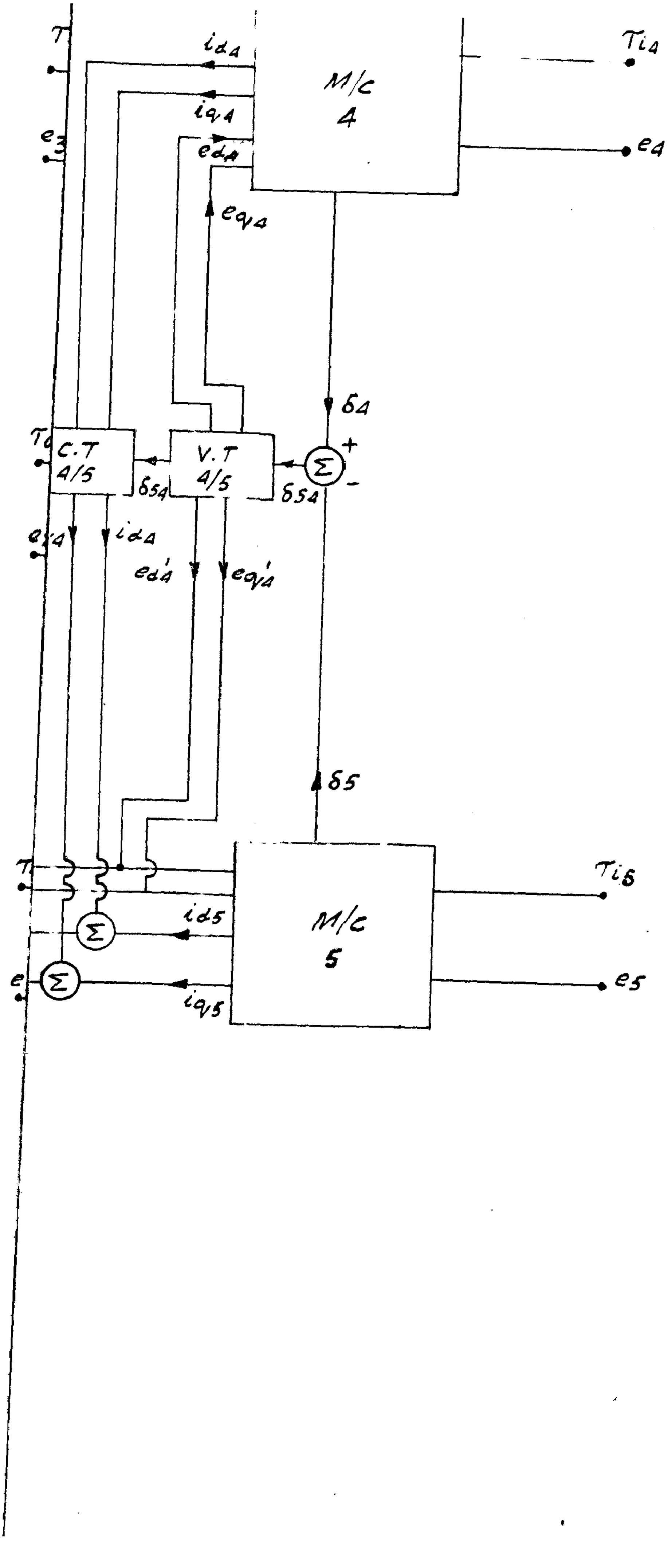
$$e_d = p\psi_{dt} - \psi_{qt}p\theta - R_t\, i_{dt} + e_d'$$

$$e_q = p\psi_{qt} + \psi_{dt}p\theta - R_t\, i_{qt} + e_q'$$



MULTIMACHINE SYSTEM

FIG. 8·8



T
i_{d4}
M/c
4
T_{i4}
i_{q4}
e_3
e_{d4}
e_4
e_{q4}
δ_4
C.T
4/5
V.T
4/5
+
-
δ_{54}
δ_{54}
i_{d4}
e_{d4}'
e_{q4}'
δ_5
T_{i5}
i_{d5}
M/c
5
e_5
i_{q5}

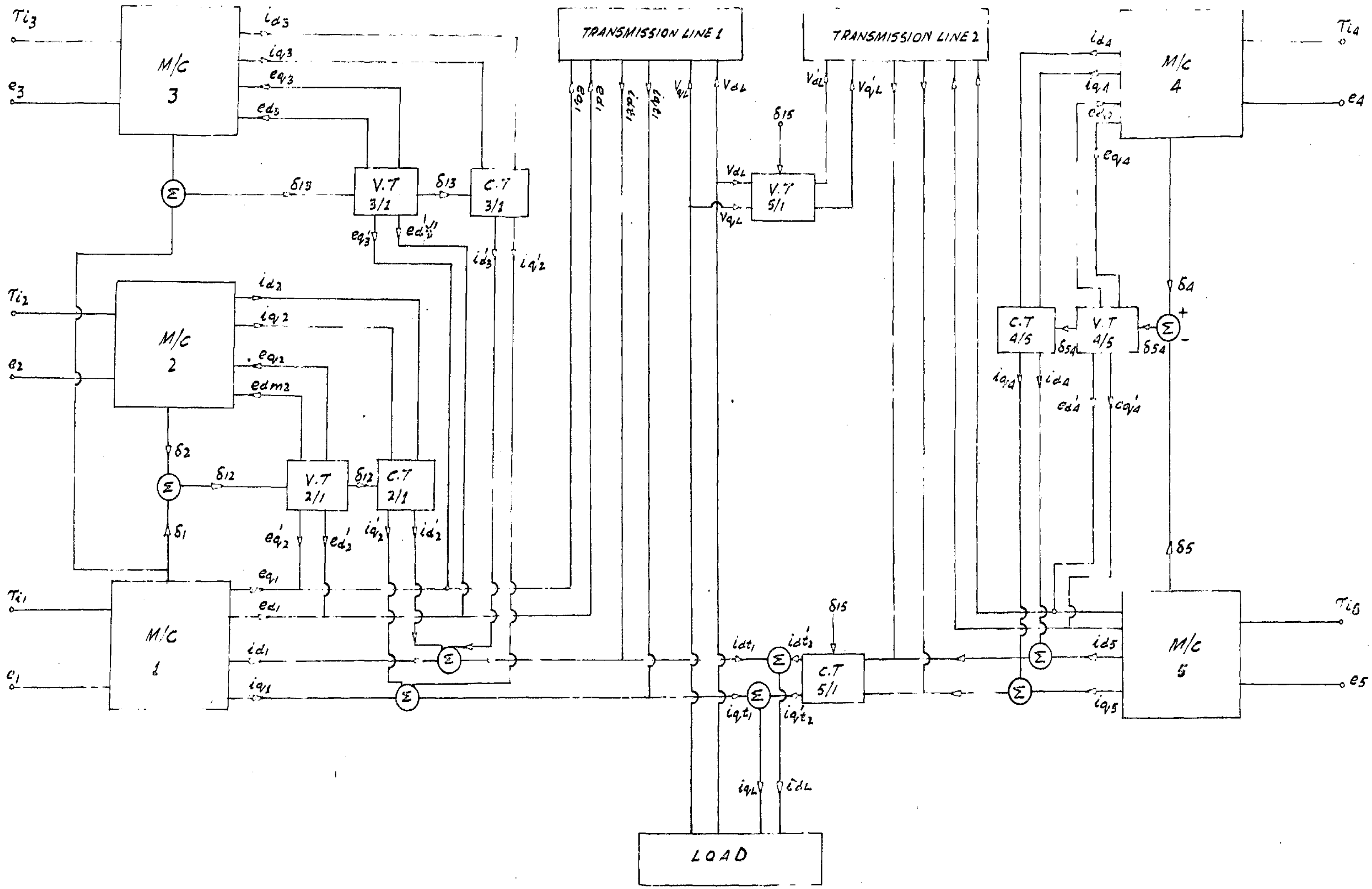


FIG. 8.9

ANALOGE BLOCK DIAGRAM OF MULTIMACHINE SYSTEM where,

$$\psi_{dt} = X_t \, i_{dt}$$

$$\psi_{qt} = X_t \, i_{qt}$$

Neglecting transient terms and putting $p\theta$ equal to unity we get,

$$e_d = e_d' + R_t \, i_{dt} - X_t \, i_{qt}$$

$$e_q = e_q' + R_t \, i_{qt} + X_q \, i_{dt}$$

A suitable analogue representing these equations is shown in Fig. 8.7.

8.5. SIMULATION OF MULTIMACHINE SYSTEM [18]

Fig. 8.9 shows the block diagram for the multi-machine system of Fig. 8.8. In the system shown in Fig.10 the frame of machine (1) is chosen as the reference frame then for representing the all other machine of the system with respect to machine (1) it is not necessary to express each machine with reference of frame of machine (1). In the system shown the machine (5) with respect to machine (4) and finally the frame of machine (4) is referred to the frame of machine (1) thus making the system more economical.

Appendix-I

Substituting the data given in Table 1 the expressions for xd(p) xq(p) and G(p) of equation (2.18)

$$xd(p) = xd - \frac{p^2(x_{11d}+x_{afd}^2-2x_{f1d}x_{a1d}x_{afd}+x_{ffd}x_{a1d}^2)+p(x_{afd}^2r_{1d}-x_{a1d}^2r_{fd}}{p^2(x_{11d}x_{ffd}-x_{f1d}^2)+p(x_{11d}r_{fd}+x_{ffd}r_{1d})r_{1d}r_{fd}}$$

$$\text{or } xd(p) = 1.2 - \frac{p^2(1.1-2+1.1)+p(0.02+0.0011)}{p^2(0.21)+p(121x10^{-5}+22x10^{-3})+22x10^{-6}}$$

$$\text{or } xd(p) = 1.2 - \frac{0.2p^2 + 0.0211p}{0.21p^2+0.02321p+21x10^{-6}}$$

$$\text{or } xd(p) = \frac{0.252p^2+0.02781p+26.4x10^{-6} - 0.2p^2-0.0211p}{0.21p^2+0.02321p + 22x10^{-6}}$$

$$\text{or } xd(p) = \frac{0.052p^2+0.00671p+26.4x10^{-6}}{0.21p^2+0.02321p + 22x10^{-6}}$$

$$xd(p) = \frac{\frac{0.052x10^6}{26.4}p^2 + \frac{0.00671x10^6}{26.4}+1}{\frac{0.21}{22}x10^6p^2 + \frac{23210}{22}p+1}1.2$$

$$xd(p) = \frac{1970p^2 + 254p + 1}{9550p^2+1055p+1}1.2$$

$$xd(p) = \frac{(1+248p)(1+8p)}{(1+1025p)(1+9.1p)} \quad 1.2 \qquad .. \text{(A-1-1)}$$

Comparing this expression for xd(p) with the one given in equation 2.22 we get,

$$T_d' = 248 \qquad T_d'' = 8$$

$T'_{do} = 1025 \qquad T''_{do} = 9.1$

$$x_q(p) = x_q - \frac{p\,x^2\,a_{1q}}{p\,x_{11q} + r_{1q}}$$

Substituting values from Table 1.

$$xp(p) = 0.8 - \frac{px0.36}{px0.8+0.04}$$

$$= \frac{0.64p + 0.032-0.36p}{0.8p+0.04}$$

$$= \frac{0.28p + 0.032}{0.8p + 0.04}$$

$$= \frac{(1+8.75p)}{(1+20p} 0.8$$

$$\psi_q = \frac{(1+8.75p)}{(1+20p)} 0.8 \qquad \text{.. (a-1-2)}$$

Comparing with equation (2.22)

$T''_q = 8.75 \qquad T''_{qo} = 20$

$$G(p) = \frac{p(x_{11d}x_{afd}-x_{f1d}x_{a1d})+x_{a1d}r_{1d}}{p^2(x_{11d}x_{ffd}-x^2_{f1d})+p(x_{11d}r_{fd}+x_{ffd}r_{1d})+r_{1d}r_{fd}}$$

Substituting values from table 1,

$$\text{or} \quad G(p) = \frac{p(1.1x1.0-1.0x1.0)+1.0x0.02}{p^2(1.1x1.1-1.0^2)+p(1.0x0.0011+1.1x0.02)+0.02x.0011}$$

$$\text{or} \quad G(p) = \frac{0.1p+0.02}{0.21p^2+0.02321p+0.000022}$$

$$\text{or} \quad G(p) = \frac{5p+1}{9550p^2+1055p+1} \left(\frac{0.02}{22} x 10^6\right)$$

$$\text{or} \quad G(p) = \frac{5p+1}{(1+1025p)(1+9.1p)} \quad [910]$$

Comparing this expression with equation (2.22) we get,

$T_{kd} = 5 \qquad T'_{do} = 1025 \qquad T''_{do} = 9.1$

$K = 910$

The values of the time constant obtained in equation (a-1-1), (a-1-2) and (a-1-3) are in radians. Converting these values in secl we get,

$$T'_d = \frac{248}{314} = 0.79 \text{ sec.}$$

$$T''_d = \frac{8}{314} = 0.0255 \text{ sec.}$$

$$T'_{do} = \frac{1025}{314} = 3.26$$

$$T''_{do} = \frac{9.1}{314} = 0.029 \text{ sec.}$$

$$T_{kd} = \frac{5}{314} = 0.0159$$

$$T''_q = \frac{8}{314} = 0.0278$$

$$T''_{qo} = \frac{20}{314} = 0.0637$$

Appendix -2

From equation (2.22)

$$xd(p) = xd \frac{(1+T_d'p)(1+T_d''p)}{(1+T_{do}'p)(1+T_{do}''p)}$$

Let $$\frac{(1+T_d'p)(1+T_d''p)}{(1+T_{do}'p)(1+T_{do}''p)} = \frac{A_1}{(1+T_{do}'p)} + \frac{A_2}{(1+T_{do}''p)}$$

or $$1+p(T_d'+T_d'')+p^2T_d'T_d'' = A_1+A_2+p(A_1T_{do}''+A_2T_{do}')$$

Let,

$$A_1 = 1+A_3p$$
$$A_2 = A_4p$$

Substituting in above equation we get,

$$1+p(T_d'+T_d'')+p^2T_d'T_d'' = 1+A_3p+A_4p+p\left[(1+A_3p)T_{do}''+A_4pT_{do}'\right]$$

or $$1+p(T_d'+T_d'')+p^2T_d'T_d'' = 1+p(A_3+A_4+T_{do}'')+p^2(A_3T_{do}''+A_4T_{do}')$$

Comparing coefficients,

$$T_d'+T_d'' = A_3+A_4+T_{do}''$$
$$T_d'\,T_d'' = A_3T_{do}''+A_4T_{do}'$$

Solving for A_3, A_4 in terms of T_d' T_d'' T_{do}' and T_{do}'' we get,

$$A_3 = T_{do}'\left[\frac{T_d'+T_d''-T_{do}''}{T_{do}'-T_{do}''}\right]$$

$$A_4 = T_d'+T_d''-T_{do}''-T_{do}'\left[\frac{T_d'+T_d''-T_{do}''}{T_{do}'-T_{do}''}\right] \qquad \text{.. (a-2-1)}$$

$$\therefore\; xd(p) = xd\left[\frac{1+A_3p}{(1+T'_{do}p)} + \frac{A_4p}{(1+T''_{do}p)}\right] \quad \text{.. (a-2-2)}$$

Also,

$$\frac{Ap}{(1+Bp)} = \frac{A}{B}\left[1-\frac{1}{(1+Bp)}\right]$$

$$\therefore\quad \frac{A_3p}{(1+T'_{do}p)} = \frac{A_3}{T'_{do}}\left[1-\frac{1}{(1+T'_{do}p)}\right]$$

$$!\;!\quad \therefore\; \frac{A_4p}{(1+T''_{do}p)} = \frac{A_4}{T''_{do}}\left[1-\frac{1}{(1+T'_{do}p)}\right]$$

Substituting in eq. (a-2-2) we get,

$$xd(p) = \frac{xd}{(1+T'_{do}p)} + xd\left[\frac{A_3}{T'_{do}} + \frac{A_4}{T''_{do}}\right] - \frac{xd\;A_3}{T'_{do}(1+T'_{do}p)} - \frac{xd\;A_4}{T''_{do}(1+T''_{do}p)}$$

Let, $xd\left[\frac{A_3}{T'_{do}} + \frac{A_4}{T''_{do}}\right] = A_5$

$xd\,\frac{A_4}{T''_{do}} = A_6$ and $xd\frac{A_3}{T'_{do}} = A_7$

$$\therefore\quad xd(p) = \frac{(xd-A_7)}{(1+T'_{do}p)} + A_5 - \frac{A_6}{(1+T''_{do}p)} \quad \text{.. (a-2-3)}$$

Also from equation (2.22)

$$G(p) = K\,\frac{1+T_{kd}p}{(1+T'_{do})(1+T''_{do})}$$

Let, $$\frac{1+T_{kd}p}{(1+T'_{do}p)(1+T''_{do}p)} = \frac{A_8}{(1+T'_{do}p)} + \frac{A_9}{(1+T''_{do}p)}$$

or $$1+T_{kd}p = A_8+A_9+p(A_8T''_{do} + A_9T'_{do})$$

Comparing coefficients

$$A_8 + A_9 = 1$$
$$A_8T''_{do}+A_9T'_{do}= T_{kd}$$

Solving A_8 A_9 in terms of T_{kd} T'_{do} and T''_{do} we get,

$$A_8 = \frac{T_{kd}-T'_{do}}{T''_{do}+T'_{do}} \qquad (a-2-4)$$

$$A_9 = \frac{T''_{do} - T_{kd}}{T''_{do}-T'_{do}}$$

$$\therefore \quad G(p) = \left[\frac{A_8}{(1+T'_{do}p)} + \frac{A_9}{(1+T''_{do}p)}\right] K \qquad (a-2-5)$$

Similarly,

$$xq(p) = \frac{(1+T''_{q}p)}{(1+T''_{qo}p)} \; xq$$

Also $$\frac{1+T''_{q}p}{(1+T''_{qo}p)} = \frac{1}{(1+T''_{qo}p)} + \frac{T''_{q}}{T''_{qo}}\left[1 + \frac{1}{(1+T''_{qo}p)}\right]$$

Let $$\frac{T''_{q}}{T''_{qo}} = A_{10}$$

$$\therefore \quad \frac{1+T''_{q}p}{(1+T''_{qo}p)} = \frac{1-A_{10}}{(1+T''_{qo}p)} + A_{10}$$

$$\therefore\ xq(p) = \left[\frac{1-A_{10}}{(1+T''_{qo}p)} + A_{10}\right] xq \qquad \text{.. (a-2-6)}$$

As desired in equation (2.17)

$$\psi_d = -xd(p)i_d + G(p)\, e_{fd}$$

Substituting xd(p) and G(p) from (a-2-3) and (a-2-5) we get,

$$\psi_d = -\left[\frac{xd - A_7}{(1+T'_{do}p)} + A_5 - \frac{A_6}{(1+T'_{do}p)}\right] i_d + \left[\frac{A_8}{(1+T'_{do}p)} + \frac{A_9}{(1+T''_{do}p)}\right] e$$

At $t = \infty$ and $p = 0$

$$xd - A_7 + A_5 - A_6 = xd$$

or $$A_5 = A_6 + A_7 \qquad \text{.. (a-2-7)}$$

Also at any other value of t

$$xd(p) = -\left[\frac{(xd-A_7)}{(1+T'_{do}p)} + A_5 - \frac{A_6}{(1+T''_{do}p}\right]$$

$$= -\frac{(1+T'_dp)(1+T''_dp)}{(1+T'_{do}p)(1+T''_{do}p)}\ xd$$

or $$-(xd-A_7)(1+T''_{do}p)+A_5(1+T'_{do}p)(1+T''_{do}p) - A_6(1+T'_{do}p) = \left[1+p(T'_d+T''_d)+p^2(T'_d\ T''_d)\right] xd$$

Comparing coefficients of p on both sides,

$$-(xd-A_7)T''_{do} + A_5(T'_{do} + T''_{do})+A_6\ T'_{do} = -xd(T'_d+T''_d) \qquad \text{.. (a-2-8)}$$

Comparing p^2 terms,

$$-B_5(T'_{do}\ T''_{do}) = -xd\ T'_d\ T''_d$$

$$B_5 = +xd\ \frac{T'_d\ T''_d}{T'_{do}\ T''_o} \qquad \text{.. (a-2-9)}$$

Substituting the numerical value in eq. (a-2-9) and (a-2-8) we get,

$$B_5 = +1.2\ \frac{0.79x0.02555}{3.26x0.029}$$

$$B_5 = +0.209$$

$$\therefore \quad B_6+B_6 = +0.209 \qquad \text{.. (a-2-10)}$$

$$-(1.2-A_7)0.029-0.209(3.26+0.029)+3.26\ A_6 = -1.2(0.79-0.0255)$$

$$\text{or} \quad 3.26A_6+0.029A_7 = -1.2x8155+0.209x3.289+0.029x1.2$$

$$= 0.98+0.688+0.0348$$

$$\text{or } 3.26A_6+0.029\ A_7 = 0.2672$$

Putting $A_7 = (0.209-A_6)$ in above equation

$$3.26A_6+0.029(0.209-A_6) = 0.2672.$$

$$\text{or} \quad 3.231A_6 = 0.2672-0.0606= 0.2066$$

$$\text{or} \quad A_6 = 0.064$$

$$\therefore \quad A_7 = 0.209-0.064 = 0.145 \qquad \text{.. (9-2-11)}$$

A_8 and A_9 are calculated by substituting the time constant from Table 1 in equation (a-2-4)

$$A_8 = \frac{T_{kd} - T'_{do}}{T''_{do} + T'_{do}} = \frac{0.0159-3.26}{0.029-3.26} = 1.004$$

$$A_9 = 1 - A_8 = 1 - 1.004 = -0.004 \qquad .. \text{(a-2-12)}$$

So complete expression for ψ_d can be written as

$$\psi_d = -\left[\frac{1.2-0.145}{(1+3.26p)} + 0.209 - \frac{0.064}{(1+0.029p)}\right] i_d + \left[\frac{1.004}{(1+3.26p)} - \frac{0.004}{(1+0.029p)}\right] e$$

or

$$\psi_d = -\frac{1.055}{(1+3.26p)} i_d - 0.209\, i_d + \frac{0.064}{(1+0.029p)} i_d + \left[\frac{1.004}{(1+3.26p)} - \frac{0.004}{(1+0.029p)}\right] \qquad \ldots \text{(a-2-13)}$$

From eq. (2.17)

$$\psi_q = -x_q(p)\, i_q$$

Substituting $x_q(p)$ from eq. (a-2-6)

$$\psi_q = -\left[\frac{1-A_{10}}{(1 + T''_{qo}p)} + A_{10}\right] x_q\, i_q$$

for A_{10} T''_{qo}

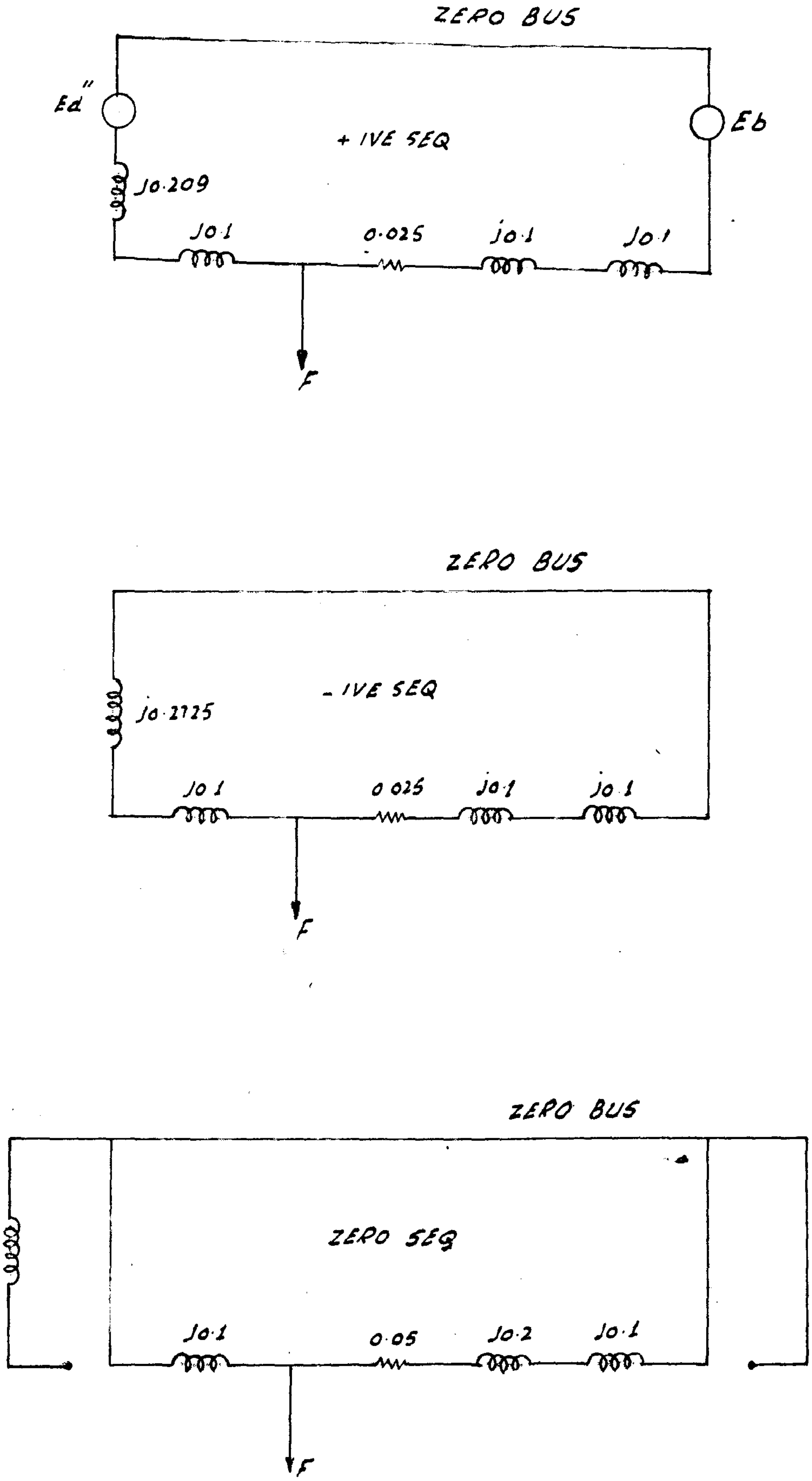
Substituting numerical values from Appendix 10,

$$A_{10} = \frac{T''_q}{T''_{qo}} = \frac{8.75}{20} = 0.437$$

$$\therefore \quad \psi_q = -\left[\frac{0.563}{(1+0.0637)} + 0.437\right] 0.8\, i_q$$

or

$$\psi_q = -\frac{0.45\, i_q}{(1+0.0637p)} - 0.35\, i_q \qquad .. \text{(a-2-14)}$$



SEQUENCE DIAGRAM

FIG.(a-3-1)

Appendix 3

Calculations for z_{11}, z_{22} z_{12}

From the calculations made in appendix 1 and the data of the problem supplied following parameters [2] can be calculated.

$$x_d'' = x_d \frac{T_d' T_d''}{T_{do}' T_{do}''} = 1.2 \frac{0.79x2.5x10^{-3}}{3.26x2.9x10^{-3}}$$

$$= 0.209$$

$$x_q'' = x_q \frac{T_q''}{T_{qo}''} = 0.8x \frac{0.0278x10^{-3}}{0.0637x10^{-3}}$$

$$= 0.336$$

$$x_2 = \frac{x_d'' + x_q''}{2} = \frac{0.209x0.306}{2}$$

$$= 0.2725$$

$$x_o = 0.3\, x_d'' = 0.3x0.209$$

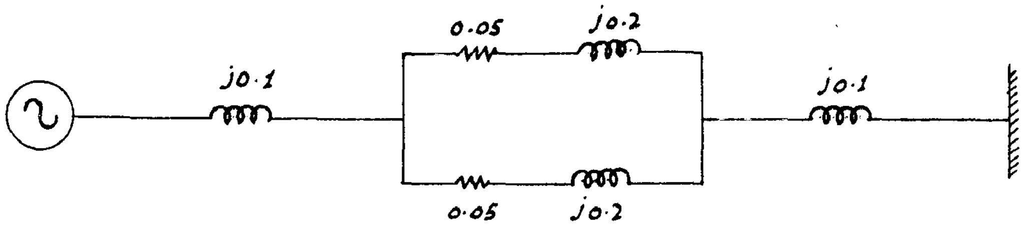
Positive , negative and zero sequence impedances of the system are calculated from the sequence diagrams shown in fig. (a-3-1)

$$z_1 = \frac{j0.309x(0.025+j0.2)}{0.025+j0.2+j0.309}$$

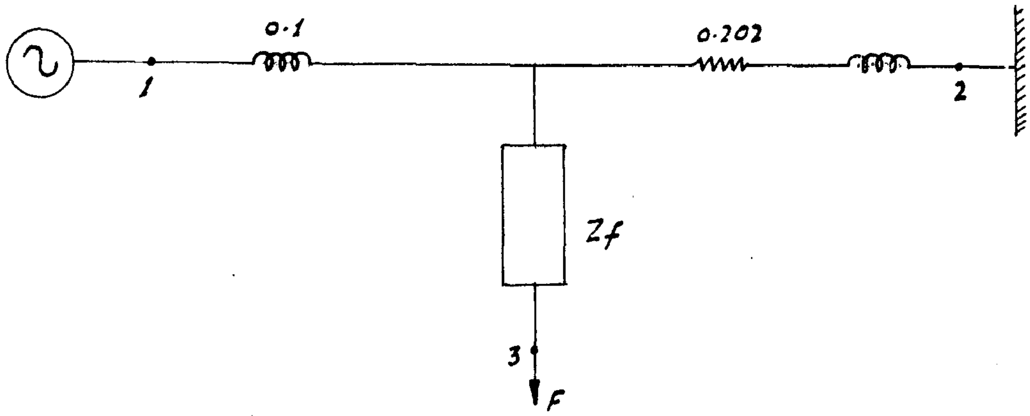
or $z_1 = 0.1225\,|\underline{85.7^o}$

$$z_2 = \frac{0.3725\,|\underline{90^o} x0.202\,|\underline{82.9^o}}{0.573\,|\underline{87.5^o}}$$

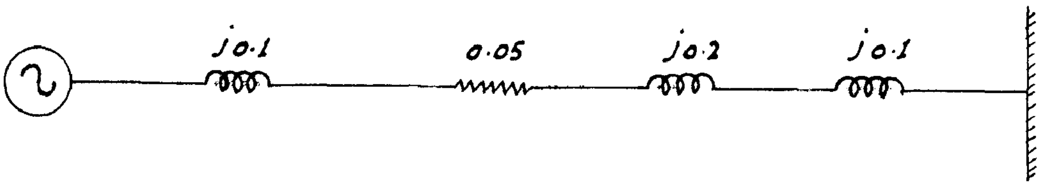
$$z_2 = 0.13\,|\underline{85.4^o}$$



PREFAUT



FAULT



POST FAULT

FIG. (a.3-2)

$$z_0 = \frac{0.1\,|\underline{90^\circ}\ (0.05+j0.3)}{j0.1+0.05+j0.3}$$

$$z_0 = 0.0753\,|\underline{87.7^\circ}$$

PREFAULT CALCULATIONS

Referring to fig. (a-3-2)

$z_{11} = \infty \qquad z_{22} = \infty$

$$z_{12} = 0.025+j0.3$$
$$= 0.301\,|\underline{85.25^\circ}$$

FAULT CALCULATIONS

L-L FAULT

$$z_{11} = z_1 + z_3 + \frac{z_1 z_3}{z_2}$$

$$= 0.1\,|\underline{90^\circ} + 0.13\,|\underline{85.4^\circ} + \frac{0.1\mathrm{x}0.13}{0.202}\ |\underline{90+85.4 - 82.9^\circ}$$

$$= 0.0166+j0.2937$$

$$= 0.294\,|\underline{86.75^\circ}$$

Similarly,

$$z_{22} = 0.59\,|\underline{81.45^\circ}$$
$$z_{12} = 0.456\,|\underline{86^\circ}$$

L-G FAULT

$$z_{11} = 0.1\,|\underline{90^\circ}+0.205\,|\underline{86.25^\circ}+\frac{0.1\mathrm{x}0.025}{0.202\,|82.9^\circ}\ |\underline{90+86.25^\circ}$$

$$= 0.00739+j0.4055$$
$$= 0.4055\,|\underline{88.95^\circ}$$

Similarly,

$$z_{22} = 0.82\,|\underline{81.8^\circ}$$

$z_{12} = 0.40\,|\underline{85.6^\circ}$

L-L-G FAULT

$$z_{11} = j0.1\,|\underline{90^\circ} + 0.0477\,|\underline{86.85^\circ} + \frac{0.1\times 0.0477}{0.202\,|\underline{82.9^\circ}}\,|\underline{90+86.85^\circ}$$

$$= 0.00118 + j0.1711$$

$$= 0.1711\,|\underline{89.6^\circ}$$

Similarly,

$z_{22} = 0.345\,|\underline{82.60}$

$z_{12} = 0.725\,|\underline{85.7^\circ}$

Post Fault Calculations

Referring to fig. (a-3-2)

$z_{11} = \infty \qquad z_{22} = \infty$

$$z_{12} = 0.05 + j0.4$$

$$= 0.403\,|\underline{82.9^\circ}$$

CALCULATIONS OF GAIN OF AMPLIFIER

In the equation (3.4) and (3.5) derived earlier,

$$K_2 = K_6 = \frac{\sin\theta_{11}}{|z_{11}|} + \frac{\sin\theta_{12}}{|z_{12}|}$$

$$K_1 = K_5 = \frac{\cos\theta_{11}}{|z_{11}|} + \frac{\cos\theta_{12}}{|z_{12}|}$$

$$K_3 = K_7 = \frac{\cos\theta_{12}}{|z_{12}|}$$

$$K_4 = K_8 = \frac{\sin\theta_{12}}{|z_{12}|}$$

Prefault

From the previous calculations

$z_{11} = \infty \qquad z_{22} = \infty \qquad z_{12} = 0.301\,|\underline{85.25^\circ}$

$$K_2 = K_6 = 0 + \frac{\sin 85.25^\circ}{0.301} = \frac{0.9965}{0.301} = 3.32$$

$$K_1 = K_5 = 0 + \frac{\cos 85.25^\circ}{0.301} = \frac{0.0825}{0.301} = 0.274$$

$$K_3 = K_7 = \frac{\cos\theta_{12}}{z_{12}} = 0.274$$

$$K_4 = K_8 = \frac{\sin\theta_{12}}{z_{12}} = 3.32$$

During Fault

L-G Fault

$z_{11} = 0.4055\,|\underline{88.95^\circ} \qquad z_{22} = 0.82\,|\underline{81.8^\circ}$

$z_{12} = 0.40\,|\underline{85.6^\circ}$

$$K_2 = K_6 = \frac{\sin 88.95^\circ}{0.4055} + \frac{\sin 85.6}{0.40}$$

$$= \frac{0.9998}{0.4055} + \frac{0.9970}{0.40}$$

$$= 2.46 + 2.5$$

$$= 4.96$$

$$K_1 = K_5 = \frac{\cos 88.95^\circ}{0.4055} + \frac{\cos 85.6^\circ}{0.40}$$

$$= \frac{0.0185}{0.4055} + \frac{0.0767}{0.4}$$

$$= 0.0455 + 0.192$$

$$= 0.2375$$

$$K_3 = K_7 = \frac{\cos\theta_{12}}{z_{12}} = \frac{0.9975}{0.456}$$

$$= 2.18$$

L-L-Fault

$$z_{11} = 0.294\underline{|86.75^\circ} \qquad z_{22} = 0.59\underline{|81.45^\circ}$$

$$z_{12} = 0.456\underline{|86^\circ}$$

$$K_2 = K_6 = \frac{\sin 86.75^\circ}{0.294} + \frac{\sin 96^\circ}{0.456}$$

$$= \frac{0.9984}{0.294} + \frac{0.9975}{0.456}$$

$$= 3.4 + 2.18$$

$$= 5.58$$

$$K_1 = K_5 = \frac{\cos 86.75^\circ}{0.294} + \frac{0.9975}{0.456}$$

$$= 3.4 + 2.18$$

$$= 5.58$$

$$K_1 = K_5 = \frac{\cos 86.75^\circ}{0.294} + \frac{\cos 86^\circ}{0.456}$$

$$= \frac{0.0565}{0.294} + \frac{0.0696}{0.456}$$

$$= 0.192 + 0.153$$

$$= 0.345$$

$$K_3 = K_7 = \frac{\cos\theta_{12}}{0.456} = \frac{0.0697}{0.456} = 0.153$$

$$K_4 = K_8 = \frac{\sin\theta_{12}}{0.475} = \frac{0.9975}{0.475} = 2.10$$

L-L-G Fault

$$z_{11} = 0.1711\underline{|89.6^\circ} \qquad z_{22} = 0.345\underline{|82.6^\circ}$$

$$z_{12} = 0.725\underline{|85.7^\circ}$$

$$K_2 = K_6 = \frac{\sin 89.6^\circ}{0.1711} + \frac{\sin 85.7^\circ}{0.725}$$

$$= \frac{0.9999}{0.1711} + \frac{0.9971}{0.725}$$

$$= 5.85 + 1.375$$

$$= 7.225$$

$$K_1 = K_5 = \frac{\cos 89.6^\circ}{0.1711} + \frac{\cos 85.7^\circ}{0.725}$$

$$= 0.043 + 0.1032$$

$$= 0.1462$$

$$K_3 = K_7 = \frac{\cos\theta_{12}}{z_{12}} = \frac{0.0749}{0.725} = 0.1032$$

$$K_4 = K_8 = \frac{\sin\theta_{12}}{z_{12}} = \frac{0.9971}{0.725} = 1.375$$

3ØFault

$$z_{11} = 0.1\,|\underline{90^\circ} \qquad z_{22} = 0.202\,|\underline{82.9^\circ} \qquad z_{12} = \infty$$

$$k_2 = K_6 = \frac{\sin 90^\circ}{0.1} = 10$$

$$K_1 = K_5 = 0$$

$$K_3 = K_7 = \frac{\cos\theta_{12}}{z_{12}} = 0$$

$$K_4 = K_8 = \frac{\sin\theta_{12}}{z_{12}} = 0$$

Post-Fault

$$z_{11} = \infty \qquad z_{22} = \infty \qquad z_{12} = 0.403\,|\underline{82.9^\circ}$$

$$K_2 = K_6 = 0 + \frac{\sin 82.9^\circ}{0.403} = \frac{0.9923}{0.403} = 2.46$$

$$K_1 = K_5 = 0 + \frac{\cos 82.9^\circ}{0.403} = \frac{0.1236}{0.403} = 0.306$$

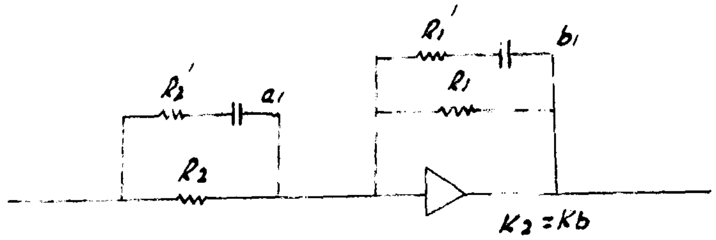


FIG. (a)

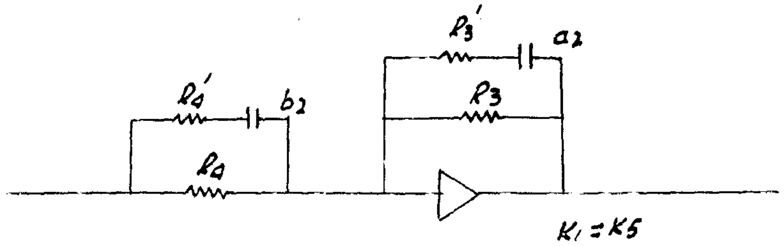


FIG. (b)

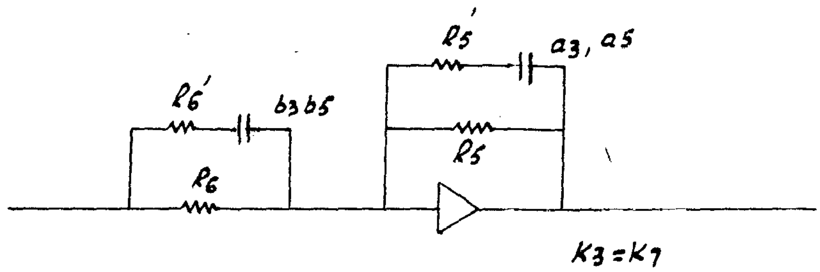


FIG. (C)

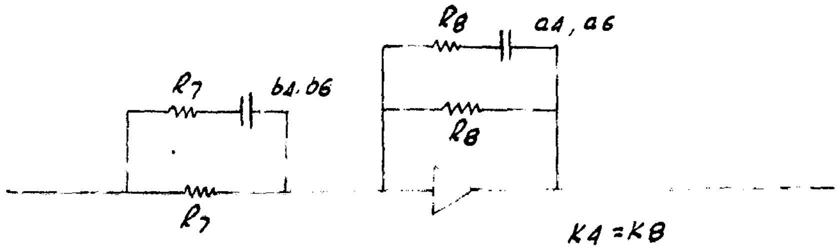


FIG. (d)

FIG (a-3-3)

$$K_3 = K_7 = \frac{\cos 82.9^\circ}{0.403} = 0.306$$

$$K_4 = K_8 = \frac{\sin 82.9^\circ}{0.403} = 2.46$$

CALCULATION FOR RESISTANCES

For S.L.G. fault case the values are calculated as follows.

For $K_2 = K_6$ Refer fig. (a-3-3)

$$\frac{r_1}{r_2} = 3.32$$

Let $r_2 = 10$ K $\therefore r_1 = 33.2$ K

$$\frac{r_1}{r_2 r_2'/r_2+r_2'} = 4.96 \quad \text{or} \quad \frac{3.32}{4.96} = \frac{r_2'}{10+r_2'}$$

$$0.67 = \frac{r_2'}{10+r_2'}$$

$$\text{or} \quad r_2'(1-0.67) = 6.7$$

$$r_2' = \frac{6.7}{0.33} = 20.3\text{K}$$

Also,
$$\frac{r_1 r_1'/r_1+r_1'}{r_2\, r_2'/r_2+r_2'} = 2.46$$

or
$$\frac{33.2 \times r_1'/33.2+r_1'}{6.7} = 2.46$$

or
$$\frac{r_1'}{33.2+r_1'} = \frac{2.46 \times 6.7}{33.2} = 0.495$$

$$r_1'(1-0.495) = 33.2 \times 0.495 = 16.5$$

or $r_1' = \frac{16.5}{0.505} = 32.6K$

<u>For $K_1 = K_5$</u> Refer fig. (a-3-3)

$$\frac{r_3}{r_4} = 0.274$$

Let, $r_4 = 10K$ $r_3 = 2.74K$

$$\frac{r_3 r_3'/(r_3+r_3')}{r_4} = 0.2375$$

or $0.274 \frac{r_3'}{2.74+r_3'} = 0.2375$

or $\frac{r_3'}{2.74+r_3'} = 0.865$

or $r_3' = 0.865(2.74+r_3')$

or $r_3'(1-0.865) = 2.37$

$$r_3' = \frac{2.37}{0.135} = 17.6K$$

$$\frac{r_3 r_3'/(r_3+r_3')}{r_4 r_4'/(r_4+r_4')} = 0.306$$

Also, $\frac{r_3 r_3'}{r_3 + r_3'} = \frac{2.74 \times 17.6}{20.34} = 2.06$

or $\frac{2.06}{10 \times 0.306} = \frac{r_4'}{10+r_4'}$

$$0.675 = \frac{r_4'}{10+r_4'}$$

$$r_4'(1-0.675) = 6.75$$

$$r_4' = 20.8$$

For $K_3 = K_7$ (Referring Fig. (a-3-3)

$$\frac{r_5}{r_6} = 0.274$$

Let $r_6 = 10K$ $\qquad r_5 = 2.74K$

$$\frac{r_5 r_5'}{r_5 + r_5'} = 0.192$$

or $$\frac{r_5'}{2.74 + r_5'} = \frac{0.192}{0.274} = 0.7$$

$$r_5'(1-.7) = 0.7 \times 2.74$$
$$r_5' = 6.4K$$

$$\frac{r_5 r_5'}{r_5 + r_5'} = \frac{2.74 \times 6.4}{2.74 + 6.4} = 1.92$$

$$\therefore \frac{1.92}{r_6 r_6' / r_6 + r_6'} = 0.306$$

or $$\frac{1.92}{10 \times 0.306} = \frac{r_6'}{10 + r_6'}$$

$$r_6'(1-0.63) = 6.3 \text{ or}$$
$$r_6' = 17K$$

For $K_4 = K_8$ Referring fig. (a-3-3)

$$\frac{r_8}{r_7} = 3.32$$

$r_7 = 10K$ $\qquad r_8 = 33.2K$

$$\frac{r_8 r_8'/(r_8+r_8')}{r_7} = 2.18$$

or $$\frac{r_8'}{33.2+r_8'} = \frac{2.18}{2.32} = 0.655$$

$$r_8'(1-0.655) = 33.2x0.655=21.8$$

$$r_8'(1-0.655) = 33.2x0.655 = 21.8$$

$$r_8' = 63.2K$$

$$\frac{r_8 r_8'}{r_8+r_8'} = 21.8$$

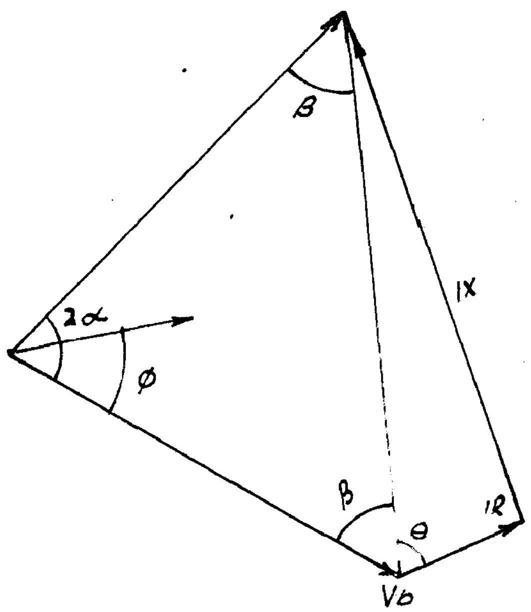
$$\frac{21.8}{10xr_7'/10+r_7'} = 2.46$$

$$\frac{r_7'}{10+r_7'} = \frac{21.8}{10x2.46}$$

or $$0.886 = \frac{r_7'}{10+r_7'}$$

$$r_7'(1-0.886) = 8.86$$

or $$r_7' = 78K$$



$2\beta = 180 - 2\alpha$

$\phi = 180 - (\beta + \theta)$

V_b = BUSBAR VOLTAGE

e_t = TERMINAL VOLTAGE

FIG. (a-4-1)

Appendix 4

Referring to Fig. (a-4-1)

For normal system current variation from 0.2 p.u. to 1.6 p.u. in steps of 0.2 prefault values are calculated as follows.

$$180-2\alpha = 2\beta$$

$$180-(\beta+\theta) = \phi$$

where,

θ = Impedance angle,

= 85.60

$z = 0.025 + j0.3 = 0.301 \angle 85.6^\circ$

For 1 p.u. of bus and terminal voltage

For $i = 0.2$ p.u.

$$\cos 2\alpha = \frac{1+1-(0.0906 \times 0.04)}{2} = 0.998$$

$\therefore\ 2\alpha = 2.6^\circ$

$\therefore\ 2\beta = 180^\circ - 2.6^\circ$

$\therefore\ \beta = 88.7^\circ$

$\therefore\ \phi = 180-(\beta+\theta) = 180-(88.7^\circ+85.6^\circ) = 5.7^\circ$

Similarly these angles are calculated for other values of currents and tabulated as shown in Table (a-4-1).

Table (a-4-1)

i	α°	β°	ϕ°
0.2	1.3	88.7	5.7
0.4	3.5	88.5	7.9
0.6	5.15	84.85	9.55
0.8	6.8	83.2	11.2
1.0	8.65	81.35	13.05
1.2	10.40	79.60	14.80
1.4	12.15	77.85	16.55
1.6	13.90	76.10	18.30

Calculations for E_d'' V_f P_i and e_q and e

For $i = 0.2$

$$E_d'' = e_t + \bar{I}\,\bar{x}_d$$

$$E_d'' = 1.0\,|\underline{2.6^\circ} + 0.2\,|\underline{5.6^\circ}(j0.209)$$

$$E_d'' = 0.997\,|\underline{50}$$

$$V_f = V + \bar{I}\,\bar{Z}$$

$$V_f = 1.0 + 0.2\,|\underline{5.7^\circ} \times 0.202\,|\underline{82.9^\circ}$$

$$V_f = 1.0\,|\underline{2.3^\circ}$$

$$P_i = \frac{E_d''^2}{z}\cos\alpha - \frac{E_d'' V_b}{z}\cos(\theta+\alpha)$$

$$P_i = \frac{(0.997)^2}{0.51} \times 0.0488 + \frac{0.997}{0.51} \times 0.0384$$

$$= 0.095 + 0.075 = 0.170$$

$$e_q = \bar{e}_t + \bar{I}\,\bar{x}_q$$

$$= \bar{e}_t + 0.2\,|\underline{5.6^\circ} \times j0.8$$

$$= 1.0\,|\underline{11.8^\circ}$$

i_d and i_q in steady state conditions may be calculated as follows.

At $i = 0.2$ $\quad \delta_o = 11.8^\circ - 5.6^\circ = 6.2$

$i_d = i \sin\delta$ $\qquad i_q = i \cos\delta = 0.2 \times 0.9941$

$= 0.2 \times 0.1080$ $\qquad i_q = 0.199882 =$

$i_d = 0.0216$

$$E = \bar{e}_q + \bar{I}_d\,(\overline{x_d - x_q})$$

$$= 1.0\,|\underline{11.8^\circ} + 0.0216 \times 0.4$$

$$= 1.00864\,|\underline{11.8^\circ}$$

Similarly above calculations are made for other values of currents and tabulated as given in Table (a-4-2)

S-L-G Fault Calculations

As calculated in Appendix 3

$z_1 = 0.1225\angle 85.7^\circ \quad z_2 = 0.13\angle 86.4^\circ$

$z_0 = 0.0753\angle 87.7^\circ$

$$z_1+z_2+z_0 = 0.1225\angle 85.7^\circ + 0.13\angle 85.4^\circ + 0.0753\angle 87.7^\circ$$

$$= 0.327\angle 86.1^\circ$$

$$I_f = \frac{V_f}{z_1+z_2+z_0}$$

$$\therefore \quad I_f = \frac{V_f}{0.327\angle 86.1^\circ}$$

$$= 3.06\angle -86.1 \times V_f$$

$$I_1 = I_f \times \frac{0.202\angle 82.9^\circ}{0.51\angle 87.2^\circ}$$

$$\therefore \quad I_1 = 3.06\ V_f\angle -86.1^\circ \times \frac{0.202\angle 82.9^\circ}{0.51\angle 87.2^\circ}$$

or $\quad I_1 = V_f \times 1.21\angle -90.4^\circ$

So for $i = 0.2$ p.u. from table (a-4-2) $V_f = 1.0\angle 2.3^\circ$

$$\therefore \quad I_1 = 1.21 \times 1.0\angle 2.3^\circ - 90.4^\circ = -88.1^\circ$$

Total current flowing from the generator

= Prefault current + fault current,

$= 0.2\angle 5.6^\circ + 1.21\angle -88.1^\circ$

$= 1.21\angle -78.6^\circ$

Table (a-4-2)

Prefault Calculations

i	ϕ	δ_o	e''_d	e_q	V_f	i_d	i_q	E	P_i
0.2	5.6°	6.2°	$0.997\angle 5^\circ$	$1.0\angle 11.8^\circ$	$1.0\angle 2.3^\circ$	0.0216	0.1988	$1.0086\angle 11.8^\circ$	0.170
0.4	7.90°	16.9°	$1.0\angle 11.7^\circ$	$1.005\angle 24.8^\circ$	$1.0\angle 4.6^\circ$	0.116	0.383	$1.0514\angle 24.8^\circ$	0.400
0.6	9.55°	26.35°	$1.005\angle 17.4^\circ$	$1.115\angle 35.8^\circ$	$1.0\angle 7.0^\circ$	0.266	0.588	$1.2214\angle 35.8^\circ$	0.5929
0.8	11.2°	34.4°	$1.02\angle 23.1^\circ$	$1.21\angle 45.6^\circ$	$1.0\angle 9.3^\circ$	0.451	0.66	$1.3904\angle 45.6^\circ$	0.7936
1.0	13.05°	41.15°	$1.035\angle 28.9^\circ$	$1.285\angle 54.2^\circ$	$1.0\angle 11.65^\circ$	0.6573	0.7524	$1.547\angle 54.2^\circ$	0.9925
1.2	14.8	46.9°	$1.05\angle 34.45^\circ$	$1.45\angle 61.7^\circ$	$0.997\angle 14^\circ$	0.877	0.819	$1.801\angle 61.7^\circ$	1.185
1.4	16.55	51.65°	$1.08\angle 39.85^\circ$	$1.6\angle 68.2^\circ$	$0.994\angle 16.4^\circ$	1.1	0.87	$2.04\angle 68.2^\circ$	1.387
1.6	18.3°	55.6°	$1.105\angle 45.6^\circ$	$1.74\angle 73.9^\circ$	$0.991\angle 18.8^\circ$	1.32	0.902	$2.268\angle 73.9^\circ$	1.6

$i_d = i_T \cos\delta_o'$ where $\delta_o' = 90.4^\circ$

$= 1.21 \times 0.9999$

$= 1.21$

$i_q = 1.21 \times (-0.0069) = -0.00835$

Referring to the negative sequence diagram of Fig. (a-3-2)

$$I_f = 3.06\ V_f \underline{|-86.1^\circ}$$

$$I_2 = I_f \frac{0.202 \underline{|82.9^\circ}}{j0.3725+0.025+j0.2}$$

$$I_2 = I_f \frac{0.202 \underline{|82.9^\circ}}{0.573 \underline{|87.5^\circ}}$$

$$= I_2 = 1.075\ V_f \underline{|-95.5^\circ}$$

$i = 0.2$

$$I_2 = 1.075 \times 1.0 \underline{|-90.5^\circ + 2.3^\circ}$$

$$= 1.075 \underline{|-88.2^\circ}$$

Similarly the values of I_1 I_2 I_d I_q are calculations for other values of currents and shown in table (a-4-3).

Table a-4-3

i	I_1	I_m	I_2	i_q	i_d
0.2	$1.21\angle{-88.1^\circ}$	$1.21\angle{-78.6^\circ}$	$1.075\angle{-88.2^\circ}$	-0.00835	1.21
0.4	$1.205\angle{-85.8^\circ}$	$1.245\angle{-67.3^\circ}$	$1.075\angle{-85.9^\circ}$	-0.0456	1.245
0.6	$1.205\angle{-83.8^\circ}$	$1.32\angle{-56.5^\circ}$	$1.075\angle{-83.5^\circ}$	-0.0530	1.319
0.8	$1.205\angle{-81^\circ}$	$1.42\angle{-46.8^\circ}$	$1.075\angle{-81.2^\circ}$	-0.0595	1.419
1.0	$1.2\angle{-78.8^\circ}$	$1.54\angle{-38.4^\circ}$	$1.075\angle{-78.85^\circ}$	-0.0698	1.539
1.2	$1.23\angle{-76.8^\circ}$	$1.73\angle{-31.2^\circ}$	$1.07\angle{-76.5^\circ}$	-0.0872	1.729
1.4	$1.192\angle{-73.8^\circ}$	$1.83\angle{-24.4^\circ}$	$1.068\angle{-74.1^\circ}$	-0.0830	1.829
1.6	$1.2\angle{-71.7^\circ}$	$2.08\angle{-18.6^\circ}$	$1.065\angle{-71.7^\circ}$	-0.0809	2.08

SUMMARY AND CONCLUSION

Analogue computer forms a versatile tool for carrying out the stability studies of power systems. By simulating the performance equation of each component on the analogue computer the study of the transient operation is greatly simplified and the solution of the problem can be obtained easily and quickly.

In simulating the synchronous machine the operational forms of Park's equations are used and the effect of field flux linkage damper winding is included which have an appreciable influence on the stability of the system. In computing the positive and negative sequence torques the negative sequence torque produced is assumed to remain constant which is justified as the decrement in the negative sequence current is small, moreover its occurrence is for very short duration.

The performance equations for voltage regulator and governer are expressed in a form suitable for analogue computation. An arrangement is shown for carrying out individual and combined study of different voltage regulators.

The induction motor load has been represented in a simplified manner with the help of its equivalent circuit where the electromechanical transients are considered much slower in comparison to the electrical transients.

The transmission line is represented in its lumped form and the method of symmetrical components is used in analysing the unsymmetrical faults. A simple and efficient relay circuit has been made for creating and clearing the fault for different values of fault clearing time.

In Chapter 8 a procedure is explained for representing the multimachine system on the analogue computer.

Various methods of simulating the power system are discussed critically in Chapter 1 and it has been proved by physical reasoning that analogue computer forms one of the most convenient methods for power system studies.

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