DYNAMIC STABILITY OF A POWER SYSTEM AS AFFECTED BY ANGLE REGULATORS

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by

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CERTIFICATE

Certified that the dissertation entitled "DYNAMIC STABILITY OF A POWER SYSTEM AS AFFECTED BY ANGLE REGULATORS", which is being submitted by Shri S.K. Chaudhari in partial fulfilment for the award of the Degree of Master of Engineering in Electrical Engineering (POWER SYSTEMS ENGINEERING) of University of Roorkee, Roorkee is a record of student's own work carried out by him under my guidance and supervision. 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 about Eleven months for preparing this thesis for Master of Engineering at this University.

Dated: Nov. 30, 1968.

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(S.K. CHAUDHARI)

S Y N O P S I S

The dynamic stability a system consisting of hydro-electric generator connected to the infinite bus through a long transmission line is analysed in this thesis. The generator is equipped with excitation regulator responsive to the load angle δ and its first and second derivatives. The analysis is done in the following ways.

(i) Transfer function approach:

The feed-back control system block diagram is obtained by linearising the equation of the system about a chosen operating point. From this block diagram the characteristic equation of the system is obtained which is analysed by Routh Hurwitz criterion and modified Routh Hurwitz Criterion for various values of gain constants K_1, K_2 and K_3 of angle regulator and maximum initial operating angle and power limit in P.U. is obtained, at various values of gain constants.

(ii) State Space Approach:

Linearised equations of the system for incremental changes are written in the form a set of 1st order differential equations, as-

$$\dot{X} = A X$$

The methods of finding the eigen values of A, the sign of whose real part determines the stability, are given. The method of using the Liapunov's theorem is also given in the text.

For calculation work the digital computer I.B.M.1620 is used.

NOMENCLATURE

The following nomenclature defines the symbols used generally throughout this dissertation. In few instances the symbols used locally for a different quantity and is defined, where it has been used.

a_0, a_1, a_2, etc.	Constant coefficients of characteristic equation.
A^t	Transposed A
A	Coefficient matrix.
$A_1(p)$, $A_2(p)$	Functions of P.
E_0	Initial excitation voltage at no load in P.U. units.
e_0	Initial excitation voltage in p.u. refered to stator.
$e_{fd} = e_{fd}$	Field Excitation voltage.
$ed = e_d$, $e_q = eq$	Direct and quadrature axis voltage of the machine.
$e_t = et$	Terminal voltage
f(p)	Function of P.
I	Unit matrix
i	Current
$i_d = id$	direct-axis component of current
$i_q = iq$	Quadrature axis current.
i_{do}, i_{qo}	Initial values of current in d and q axis.
K_1, K_2 & K_3 etc.	Gain constants of angle regulator.
K_r	Gain constant of voltage regulator.
K_T	Turbine damping constant.
M	Inertia constant of the machine.
n	Speed.
$P = \frac{d}{dt}$	Laplace Operator
$p^2 = \frac{d^2}{dt^2}$	
r_{fd}	Field resistance
r	Line resistance

r_a	..	Armature resistance of the generator
r_{kd}	..	Damper winding resistance in d axis.
R	..	Total resistance of the system $(r+r_a)$
T'_{do},	..	Transient open circuit time constant
T''_{do}	..	Sub-transient open circuit time constant in d-axis.
T'_d	..	Direct axis transient short circuit time constant, in d axis.
T''_d	..	Direct axis sub-transient short circuit time constant.
T_1, T_2	..	Time constants of regúlator.
T''_{qo}	..	Quadrature axis sub-transient open circuit time constant.
T''_q	..	Quadrature axis sub-transient short circuit time constant.
T_{kd}	..	Direct axis damper leakage time constant.
T_i	..	Input torque to the turbine.
T_e	..	Electrical torque
T_m	..	Mechanical input torque to the generator.
U	..	Matrix-shown in Chapter 3.
V	..	Bus-bar voltage
$W=P\theta$	..	Speed of the machine.
X	..	Space Vector
$\dot{X}$	..	d/dt.X.
$x_d = x_d$	..	Direct-axis synchronous reactance.
$x_q = x_q$	..	Quadrature axis synchronous reactance.
X_d	..	Total of x_d and x_q.
x_{md}	..	Direct axis magnetising reactance.
x_{kd}	..	Direct axis damper leakage reactance.
$x_f=x_{fd}$	..	Field reactance.
x_{kq}	..	Q axis damper winding leakage reactance.
Y	...	is used as an vector

x .. line reactance (transmission).

$X_d = x_d + x$...

$X_q = x_q + x$

$X_d(p) = x_d(p) + x$

$X_q(p) = X_q(p) + x$

.. Phase difference between bus bar voltage and internal voltage of rotor (load angle).

.. Load angle at initial operating point.

.. Small deviation.

θ, θ_1, θ etc. are angles.

ϕ .. Power factor angle or impedance angle.

$\phi_d = \phi_d$ .. Direct axis flux

$\phi_q = \phi_q$ .. Quadrature axis flux

$\frac{d}{dt}$ .. First Derivative.

$\frac{d^2}{dt^2}$ .. Second derivative.

λ eign values.

C O N T E N T S.

CHAPTER I

GENERAL CONSIDERATIONS

1.1. INTRODUCTION:

The dissertation deals with the dynamic stability of a Power system consisting of a synchronous generator, which is connected to an infinite bus bar through a long transmission line. The generator is equipped with an angle regulator to regulate the excitation system. The effects of angle regulator on the system stability and voltage is considered.

1.1.1. Definition of Stability:

Power system stability may be broadly defined as the property of a power system which insures that it will remain in operating equilibrium through a normal and abnormal conditions. It is usually necessary for the purpose of analysis to classify the type of stability. Although stability could be defined as the ability to remain in synchronism of the system without undue sustained oscillations, the complete phenomenon is so difficult for rigorous analysis that it has become necessary to divide the problem up into three major classifications, namely (a) steady-state (b) transient and (c) hunting (sustained or cummulative oscillations.

Steady state stability is the stability of the system under conditions of gradual or relatively slow change in load. Transient stability on the otherhand means the stability of the system during sudden changes, such as short circuit or sudden changes in load. A study of phenomenon of sustained or cummulative oscillation has been directed in general towards the determination of the damping characteristics or dynamic stability of the system following a sudden infinitesimal load change. It should be kept in mind that stability is actually one characteristic and subdivided into different types for the purpose of analysis only.

1.1.2. Steady State and Dynamic Stability Limits

The steady state stability limit of a generator or a system is defined as the maximum power that can be transmitted for a slow change in load, the load change occuring slowly enough to allow for a similar change in excitation to bring the terminal voltage back to its normal value after each small load change. It is important to note that it is assumed that the control of excitation is such as to correct the voltage change after each small load change has occurred. Therefore, this is the stability limit for an infinitesimal change in load with constant field current. If the change in excitation is assumed to take place with or immediately following the load change, the stability limit under such condition is termed as dynamic stability limit. The dynamic stability limit in general be higher than the steady state stability limit.

1.1.3.0. Brief History

Initially in ninteenth century the problem of increasing the stability limit of interconnected power system was not actually felt in system of old design, for the following reasons: old power systems were designed to have good inherent voltage regulation. This requirement called for low reactances in all system elements. As a consequence of low reactances, the stability limit of a system, steady state as well as transient was well above the normal transmitted power.

Stability first became an important problem, in connection with long transmission lines which is associated with remote hydroelectric stations feeding power to metropolitan load centers. High investment in such long distance lines made it desirable to transmit as much power as possible over a given line. From about 1920 the problem of increasing the stability limit has been the object of thorough investigation.

1.1.4. Methods of increasing limit of Stability:

The use of Static compensators has for a long time been, and still is, an important method of increasing the stability limit of power systems; series capacitors and shunt reactors are used to alter the characteristics of the line as required. However, it has been found that it is not economical to compensate for more than 40-60 percent of the line reactance by series capacitor. Reduction of transmission line by the use of bundle conductors and by the use of parallel lines is also an important method of increasing the stability limit of the system.

The considerable amount of reactance in a transmission systems is contributed by the generator. The percentage of generator reactance decreases with increase in voltage, even at 400 KV generator reactance is in general about 20 percent of the total reactance. In India all the transmission lines are of 220KV or below and hence generator reactance will perhaps be more than 50 percent of the total reactance. By employing fast and continuously acting voltage regulators it is possible to cancel the effect of generator reactance on the system stability.

C.A. Nickle and F.L. Lawton,[1] most probably first of all tried an experimental artificial stabilisation of synchronous machine, using excitation regulation. In Literature[2,3,4,5] the various types of continuously acting excitation voltage regulators as described in section 1.2. Considered and found to increase the stability limit of the system. Lateron Concordia[6] considered the effect of an angle regulator on the steady state limit of the system in which the signal proportional load angle is used to regulate the excitation. Apart from these Venikov[7] have taken up the work using signal depending upon load angle and its first and second derivatives. He concluded that by using power angle, the current and derivatives of these quantities, zone of stability expands and permit operation at larger angles than the one corresponding to line limit. Thus a reserve in stability is obtained.

Hence by using fast and continuously acting excitation regulators, the machine can supply more power even at more than 90°, and the machine is said to be artificially stabilised. The investigation of stable operation of the machine at values of power angle greater than 90° is referred to the dynamic stability, and machine is said to be operating in dynamic stability region.

The various types of excitation regulators are described in section 1.2.

1.2. TYPES OF EXCITATION REGULATORS:

During the ten year period from 1935 to 1945 mainly two types of voltage regulators fullfilled all the needs of the electrical industry. These were the indirect acting rheostatic regulator and the direct acting rheostatic regulator. Later the excitation system underwent a period of change by reason of the progress in the development of regulating and excitation equipment. Efforts have been directed towards the development of more reliable, more accurate, more sensitive and quicker acting systems. Consequently, there are, now, many different excitation systems in use, each filling a specific need of the industry.

1.2.1. The Tirril Regulator:

In the past the commonest type of generator voltage regulator was the vibrating type or tirril regulator.[2,20] This regulator has contacts which open and close continuously several times per second. Under closed condition, they short circuit the regulating rheostat, and the armature field current and armature voltage build up and when the contacts are open the short circuited rheostat is reinserted in the field circuit causing the field current and armature voltage of the A.C. generator to decrease. Because of the time period of vibration is much shorter than the time constant of exciter field circuit, the percentage fluctuation in armature voltage is not great.

One type of vibrating regulator shown in Fig.(1) has a d.c. vibrating magnet. Two contacts are fitted on two pivoted arms, each of which is actuated by means of two electromagnets. One of the electromagnet is supplied from the direct voltage from the exciter armature and the other from the main generator by means of a potential transformer. A decrease of either the alternating or the direct voltage tends to close the main contacts and vice versa

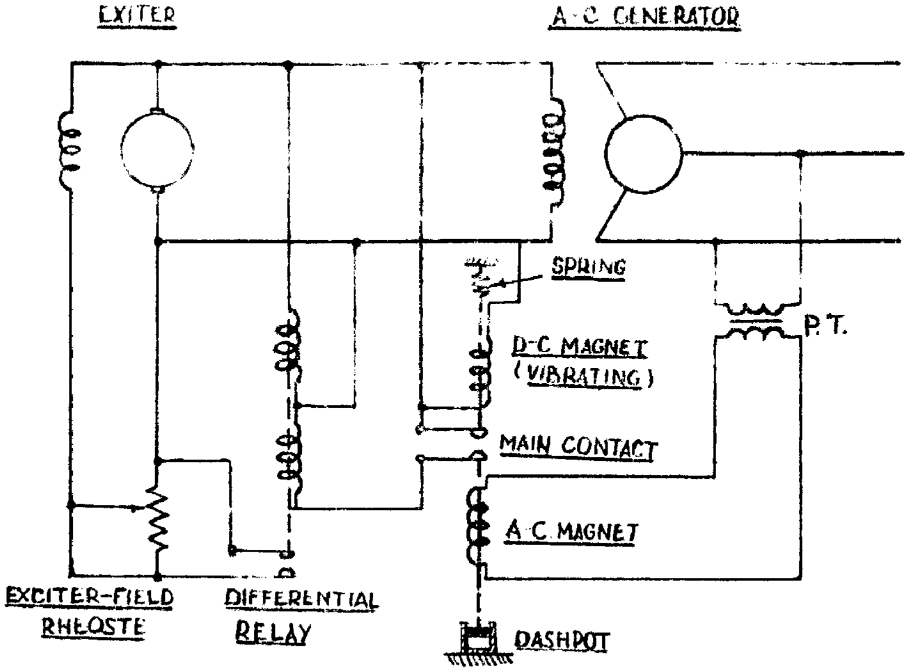


FIG:-1

TIRRILL VOLTAGE REGULATOR WITH D-C VIBRATING MAGNET

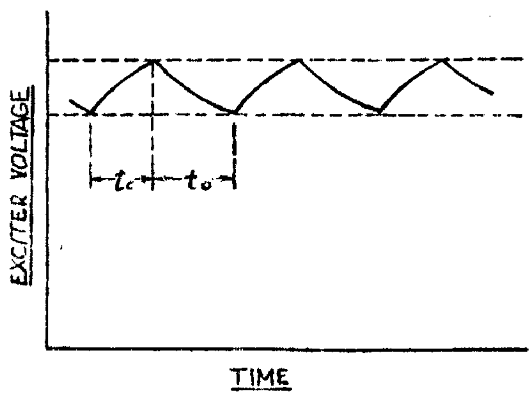


FIG:-2

EFFECT OF VIBRATING REGULATOR ON EXCITER VOLTAGE DURING STEADY CONDITIONS OF MAIN GENERATOR.

THE RATIO t_c / t_o IS CONSTANT

of either tends to open them.

When the alternating voltage is correct, the upward force of the a.c. magnet is in equilibrium with the unbalanced weight of the magnet core and counter weight. Furthermore, the force of this magnet is independent of the position within a certain range and therefore the magnetic core is in equilibrium during any position within this range provided the alternating voltage is remaining at its normal value. This magnet is provided with a heavily damping device of a dash pot. So that, if the alternating voltage of the main generator is not normal the magnet slowly moves the main contact controlled by it. On the otherhand the d.c. magnet force is opposed by the tension of a spring. This magnet and contact actuated by it are in continual vibration, caused by the following chain of events. When the exciter voltage is increased the upward pull on d.c. magnet system overcomes the force of the spring and opens the main contacts. Opening of the main contacts causes a differentially wound relay to open its contacts and thereby insert resistance in the exciter field circuit causing decrease in the exciter armature voltage and weakening d.c. magnet sufficiently so that under the force of spring main contacts closes again. Closing of main contacts closes the relay contacts, there by short circuiting the exciter field rheostat and causing the exciter voltage to build up. The process is repeated over and over again, with the result that exciter armature voltages constantly increases and decreases through a small range as shown in Fig.(2).

If the alternating voltage is too low, the a.c. magnet slowly raises the main contacts which it controls. The higher this contact is raised, the greater is the exciter voltage, and when the exciter has been increased enough to raise the alternating voltage to the correct value, the a.c. magnet comes to rest. Similarly, if the alternating voltage is too high, the a.c. magnet lowers its main contact and consequently lowers the exciter voltage and lowers the alternator voltage to its correct value. Although the Tirrill regulator gives good voltage regulation, it requires more maintenance than the modern types, it is noisy and there is possibility that a sticking contact may cause the voltage to go to high.

1.2.2. Rheostatic Regulators:

The Tirrill regulator was lateron superseded by regulators of the rheostatic type in which the regulating resistance is varied continuously or in steps instead of being first completely cut in, then completely cut out. Under steady conditions, all parts of the regulator are at rest, therefore wear is small. Rheostatic regulators are classified as direct acting and indirect acting type as mentioned in para one. In the direct acting type the voltage sensitive element of the regulator controls the rheostat through a direct mechanical connections, where as in the indirect acting rheostatic regulators, the voltage sensitive element operates contacts which in turn, control the motor to drive the rheostat.

1.2.3. The Impedance Type Regulator:

The Impedance type voltage regulator excitation system shown in Fig.(3) employs a main exciter rototrol to supply excitation to the alternator.[19] With the high degree of amplification obtainable with a rototrol, the energy requirements of control field are sufficiently small that they can be supplied by instrument transformer. The signal transmitted to the control field of the rototrol as a function of the generator terminal voltage is determined by the voltage regulator potential unit, voltage adjusting unit and automatic control unit. These voltage regulator devices consist entirely of impedance element and from this consideration

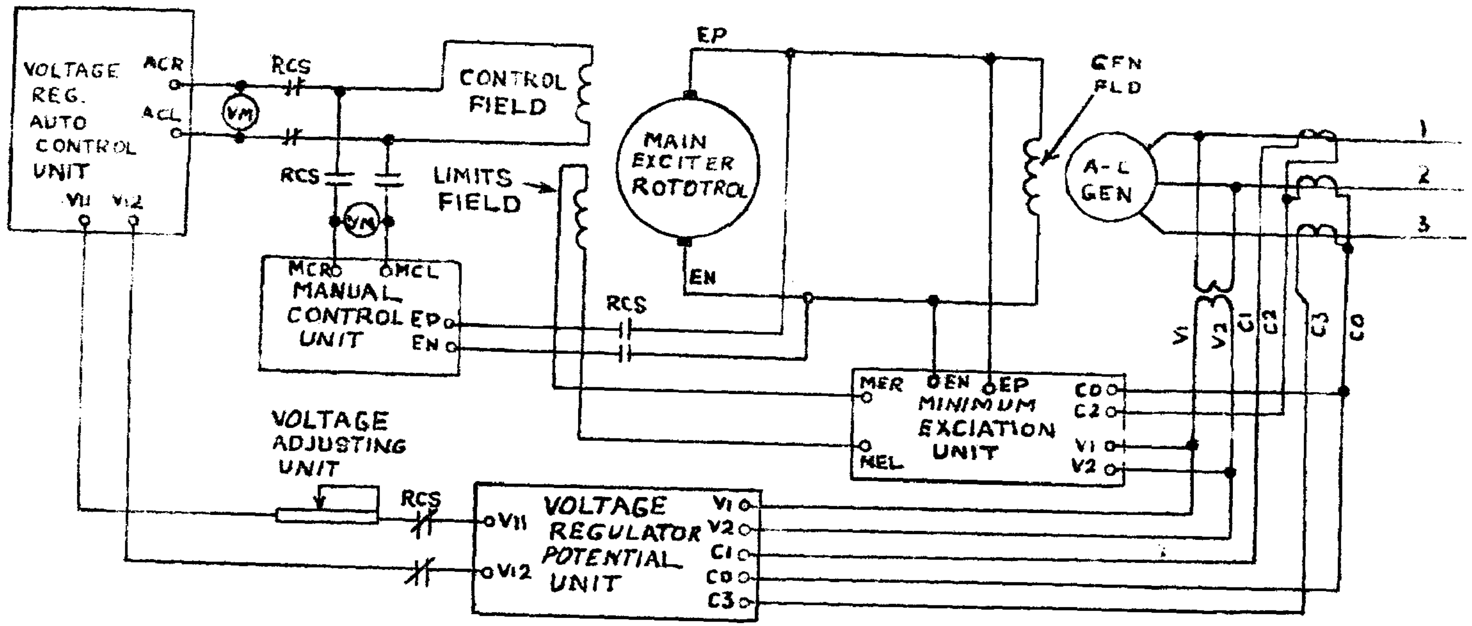


Fig. 3 BLOCK DIAGRAM OF THE IMPEDANCE-TYPE VOLTAGE REGULATOR AS USED IN A MAIN-EXCITER ROTOTROL EXCITATION SYSTEM.

the combinations of devices is said to be as an impedance type or static voltage regulator. The voltage regulator potential unit is energized by the generator line to line voltage and the currents of two phases. Its output is a single phase a.c. voltage, applied to the series connection of the voltage adjusting unit and automatic control unit. The automatic control unit is a voltage sensitive device which gives out a d.c. voltage output. The polarity and magnitude of this d.c. voltage are determined solely by the magnitude of the impressed a.c. voltage from the voltage adjusting unit. When the generator output is exactly at the rated value, the output voltage of the automatic control unit is zero. On the other hand if the generator voltage increases above the rated value is in the direction to decrease the excitation voltage whereas when the generator falls below the selected value the output of automatic control unit is in the direction to increase the a.c. generator excitation. When the voltage regulator is out of service, manual control of excitation system is by means of manual control unit. To ~~generate~~ guarantee synchronous machine steady state stability, that is, insure adequate excitation for all killowatt loads a minimum excitation unit is used.

When machines are working under conditions of dynamic stability they are continuously trying to fall out of step. But any change in rotor position is accompanied by a change in terminal voltage. Any delay of the regulator to these changes of voltages at this time has an adverse effect upon the performance of the system, because machine attains sufficient - velocity of separation very soon to make it very difficult to restore the machine to equilibrium. The controlled exciter should have a sufficiently fast response so that a call for increased or decreased exciter voltage by the regulator is promptly followed making a suitable

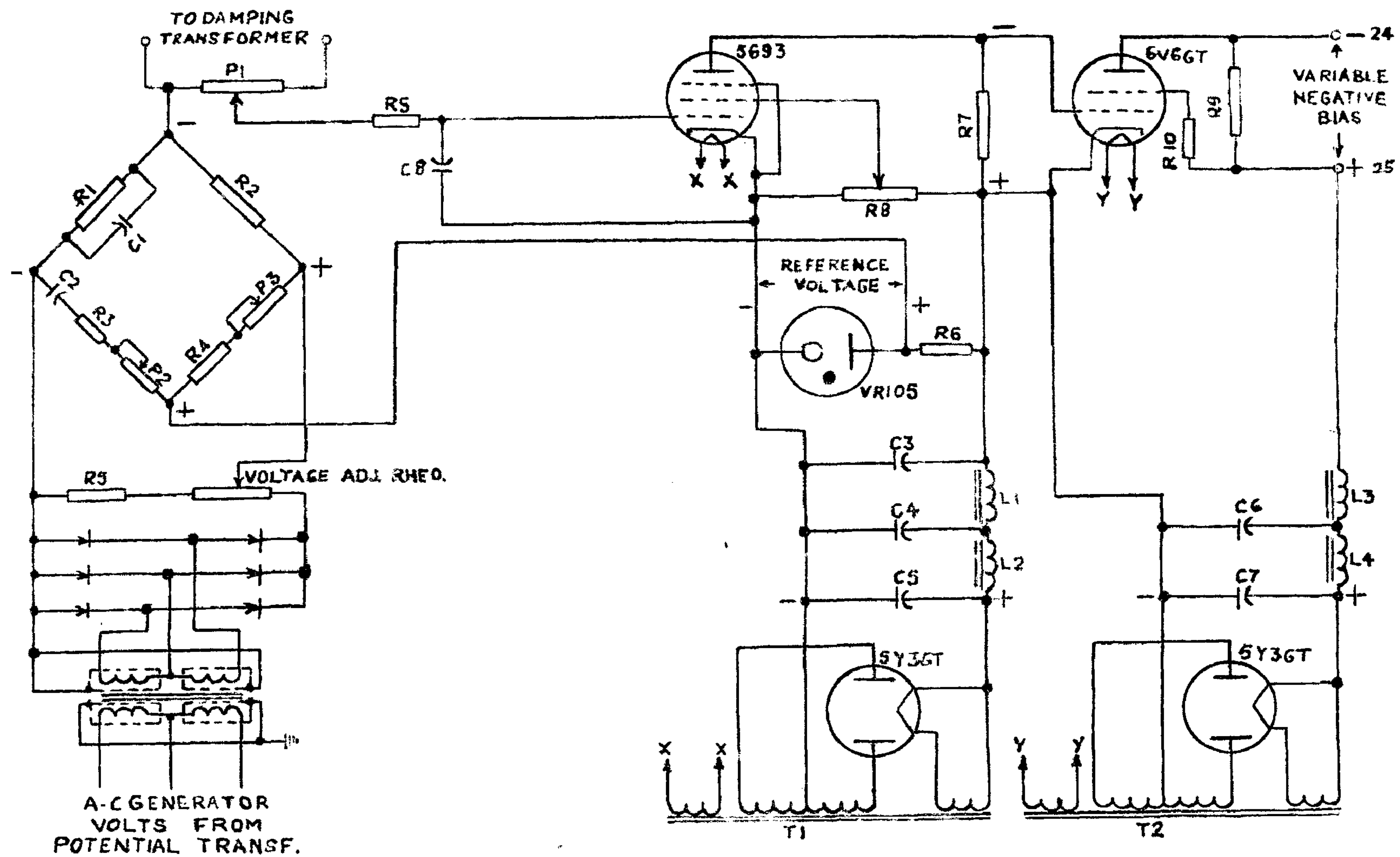


Fig-4 SCHEMATIC DIAGRAM OF THE ELECTRONIC GENERATOR VOLTAGE REGULATOR.

change in exciting current. Therefore, one of the most important requirement for a excitation regulator which attempts to enable a synchronous machine to operate in dynamic stability region is that it should have a faster response compared to the rate at which the machine tends to go out of step at the desired operating angle in the dynamic stability region. Electromechanical voltage regulators have dead bands i.e. excitation does not change for a small change in terminal voltage due to friction in moving parts and mechanical clearance between them.

The second important requirement for the excitation regulator is that it should have a very narrow dead band as is practically impossible to make a regulator having no dead band. Electronic voltage regulators have very narrow dead band equal to the noise voltage in the circuit.

1.2.4. Electronic Regulators:

Electronic type voltage regulators are available in many different forms, a typical one being shown in Fig.(4)[19] This particular regulator is used with the electronic main exciter but it can be modified for use with rototrol excitation systems which will be described later. A d.c. voltage proportional to average three phase alternator voltage is obtained from a three phase bridge type rectifier, the output of which is applied to a voltage - adjusting rheostat and a wein bridge type filter. Thus the output of the bridge circuit, which is the input to the regulator, is a smooth d.c. voltage. This type of filtering is of high degree without adding ~~underly~~ unduely long time constants to the regulator input circuit. The generator excitation regulator consists of two d.c. amplifiers and a reference voltage for comparing the regulation of the rectified generator terminal voltage. The first d.c. amplifier is high gain voltage amplifier using a 5693 tube having the characteristic same as a type 6SJ7 tube. The output of the voltage amplifier is fed into a power amplifier using a 6VGGT tube. The high gain voltage stage gives the regulator its high degree of sensitivity and the power amplifier supplies the variable negative bias voltage for controlling the thyratron firing tubes of electror main-exciter.

A full wave rectifier (5Y3GT tube) is used to supply the plate voltage of the 5693 tube through a filter giving a smooth (d.c. voltage with polarities as indicated and the d.c. reference voltage is obtained from the voltage drop across a type VR-105 voltage regulator tube connected in series with resistor R6 in series with resistor R6 accross the d.c. power supply. The reference voltage is also a d.c. voltage that remains constant for widevvariation of supply voltage. The rectified generator voltage is connected differentiately with the reference voltage and applied to the grid circuit of the 5693 tube. The amplified voltage from the 5693 tube appears accross the load resistor R7 with polarities as shown and this voltage drop is applied to the grid of the 6VGGT tube. The variable negative d.c. voltage output is obtained across the load resistor R9 of 6VGGT tube and applied to the grid circuit of the thyratron firing tubes of exciter.

Under normal conditions when alternator voltage is equal to regulated voltage, the grid of 5693 tube is established at particular bias voltage depending upon the magnitudes of rectified a.c. voltage and reference voltage. This grid bias establishes the current in the 5693 tube and drop across R7, whereby establishing the grid bias of the 6U6GT tube. Current in 6V6GT tube is thus fixed, causing corresponding drop across load resistance R9. The voltage remains constant as long the a.c. generated value is equal to the regulated value. As the a.c. generator voltage increases above normal value, the differential connection of the rectified generator voltage and reference voltage makes the grid bias of 5693 more negative than previously which reduces the current in R7 thereby reducing voltage drop across R7 and consequently reduces the negative bias voltage of the 6V6GT and causing an increase in current through tube and resistance R9. This increases the voltage drop across R9. This increase on the thyratron firing tube causes an increase in the angle of grid delay which reduces the main exciter voltage. In the case of lower a.c. voltage than normal all the operation mentioned are reversed and main exciter voltage is increased.

In the year 1945-46 there has been some discussion on the benefits (with respect to electric power system stability) to be obtained by the use of properly designed angle regulator. This was the most probably the first step taken towards the angle regulator and since then the classification of the excitation regulator is done to be on the basis of regulating signal i.e. whether the regulating signal is proportional to the change in terminal voltage or it is proportional to the change angle of rotor of the generator w.r.t. infinite bus. According to these regulating signals the excitation voltage regulators were classified as (i) voltage regulators and (ii) Angle regulator. Later on developments were done by various authors.

1.3. VOLTAGE REGULATORS

Voltage regulators are those excitation regulator in which the regulation of alternator excitation done by means of a regulating signal proportional to the terminal voltage variation from the normal rated voltage. They can be of electro-mechanical type or static voltage regulators. As now a days, stability of the power system is the main consideration for using voltage regulators and for this reason we require fast acting voltage regulators as mentioned earlier in introduction and preceding section; for this reason now-a-days static voltage regulators are prefered. In the preceding section few types of electromechanical and static regulators are already discussed. They are all voltage regulators.

Static voltage regulators can be made by using (i) magnetic amplifiers (ii) Transistors (iii) vacuum tubes.

Magnetic amplifiers can be said to have indefinitely long life although the associated selenium rectifiers may require replacement. They are robust in construction and require almost no maintenance. Time lag is half cycle for full wave connection, which is tolerable in most of the cases and can be further reduced by using high frequency power supply. Continuously acting commercial voltage regulators are mostly made using magnetic amplifiers However, a regulator using magnetic amplifiers does not lend itself easily to change in design constants (which is required for an investigation work.)

Transistors have the advantage of smaller size and absence of heaters over vacuum tube. As regards operation however they are not superior to vacuum tube. Also transistors which can operate at power level are not available.

Circuits using vacuum tubes are easier to design compared to circuits using magnetic amplifiers and transistors. Performance of magnetic amplifiers and transistors is no way superior to that of vacuum tubes.

1.3.1. <u>Block diagram circuit of Voltage Regulators:</u>

The first step which is common to all types of different designs regulators for alternator is to obtain a d.c. voltage proportional to the average of the r.m.s. values of three phase

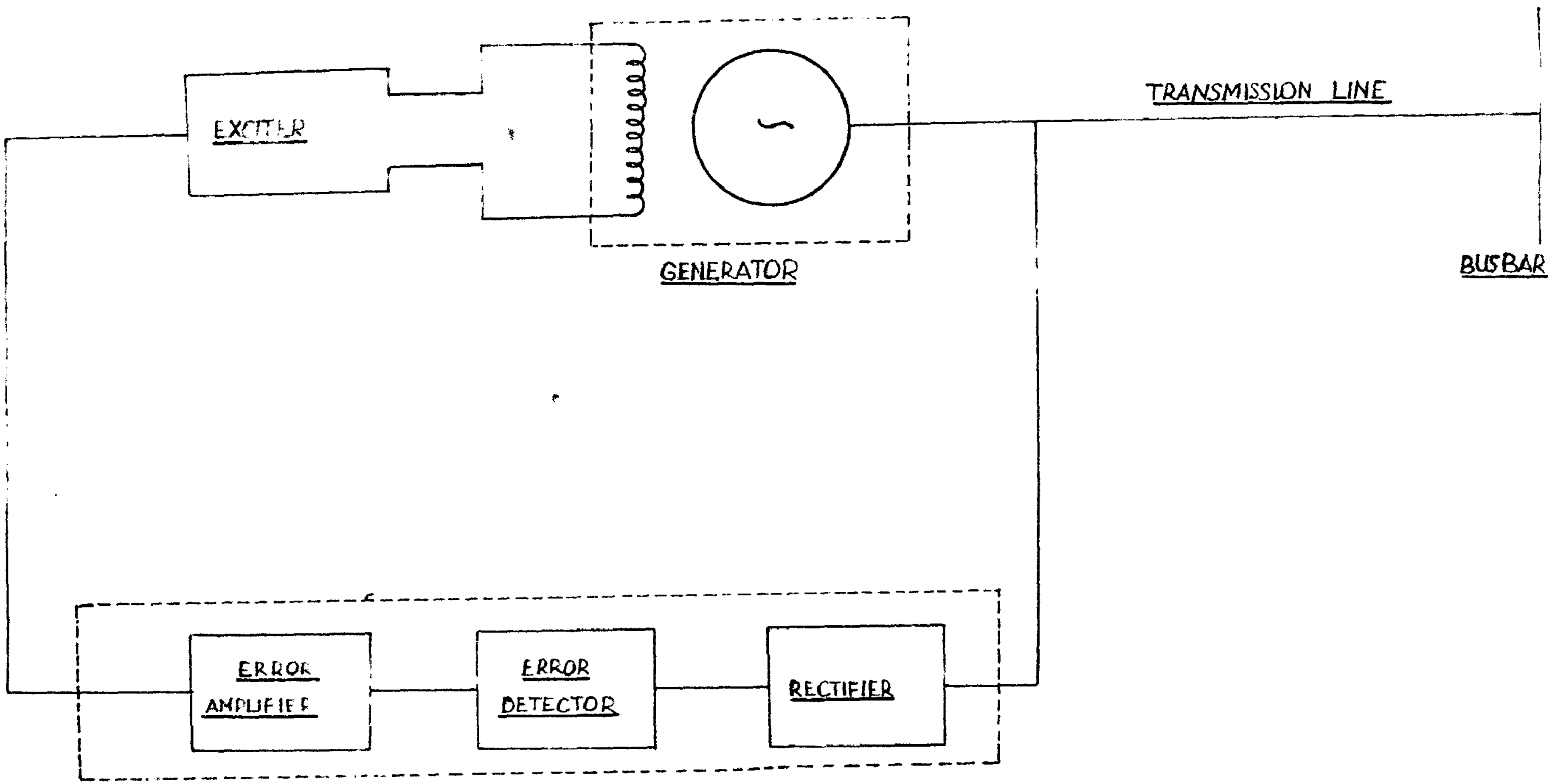


FIG:- 6 VOLTAGE REGULATOR

voltages. It is obtained by using a potential transformer and a rectifying unit. This d.c. voltage so obtained is compared with the reference d.c. voltage and error is amplified, by means of a d.c. amplifier. The amplified error (difference between reference d.c. voltage and d.c. voltage proportional to alternator voltage) is used to actuate the exciter. The block diagram is shown in Fig.(6).

The rectifying unit can be an electronic tube rectifier or bridge type rectifying unit, as described in preceeding section 1.2. in case of electronic voltage regulator or impedance type regulator.

In the error detector circuit batteries can be used for providing the reference voltage, since no current is drawn from the batteries and hence their life will be long. Also no current is drawn from the source whose error is to be detected. However, if the required reference voltage is large, the battery size become bulky. Cold cathode gas discharge tubes are also used for providing the reference voltage. A current is to be passed through the tubes for their operation which is also drawn from the same source whose error is to be detected.

The amplifier unit shown in the block diagram can be of the (i) electronic type as already described in the case of electronic voltage regulator in section 1.2 or (ii) It can be a magnetic amplifier which can amplify the error output of the error detector. In some cases the transistorised amplifier can also be used but as mentioned earlier in the section 1.3. that transistors which can operate at power level are not available commercially. Rotating amplifiers can also be used for amplification of error output. Rotating amplifiers will be described later on under the heading of excitation systems.

Magnetic Amplifier:

The circuits and arrangements of magnetic amplifiers are numerous, among them one type of magnetic amplifier is shown in Fig. (7a) where two iron cores are used, each having two windings, one carrying an alternating current and the other direct current. The d.c. windings must always be connected in series, but the alternating current may be connected in series or parallel. The characteristic of magnetic amplifier (Transductor) depend on whether the a.c. windings are in series or in parallel and also on whether an a.c. current is allowed to flow in the d.c. control circuit. If an a.c. current is allowed to flow to flow the effect is similar to connecting the a.c. current winding in parallel.

The series arrangement of thea.c. windings, together with the prevention of a.c. current flowing in the d.c. winding (by the use of inductor L) appears most common, shown in Fig.(7b). The method of operation will now be described briefly. In order to simplyfy the expalanation, following assumptions will be made.

(a) The magnetisation curve is an ideal curve, as shown in Fig.(7a), being composed of a portion OA (and OA') of infinite permeability and a portion AB (and A'B') of zero permeability.

(b) Resistance of the circuit is negligible.

(c) There are equal no. of turns on A.C. and d.c. windings.

Since the voltage induced in any winding is proportional to the rate of change of flux there can be no induced e.m.f. in the windings, when the core is in saturated condition, over the portion AB and A'B'. Considering the half cycle where the direction of current flow is as shown in Fig.(7-b) (i.e. from P to Q in Fig.7'b); since a.c. and d.c. in core 2 are in the same direction the core

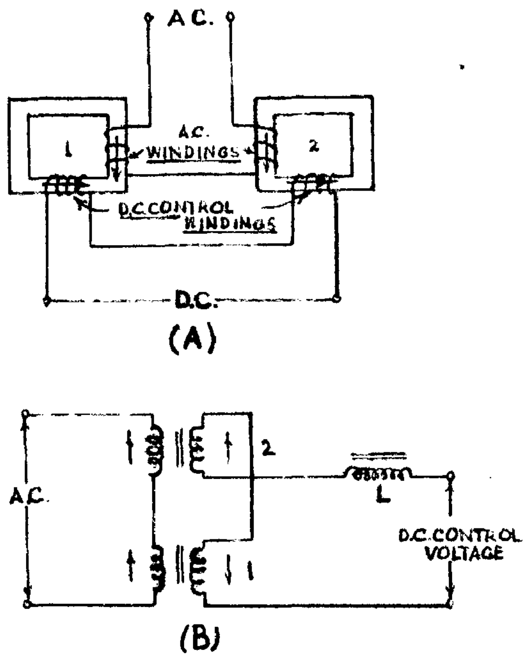


FIG:- 7

SIMPLE TRANSDUCTOR ARRANGEMENT

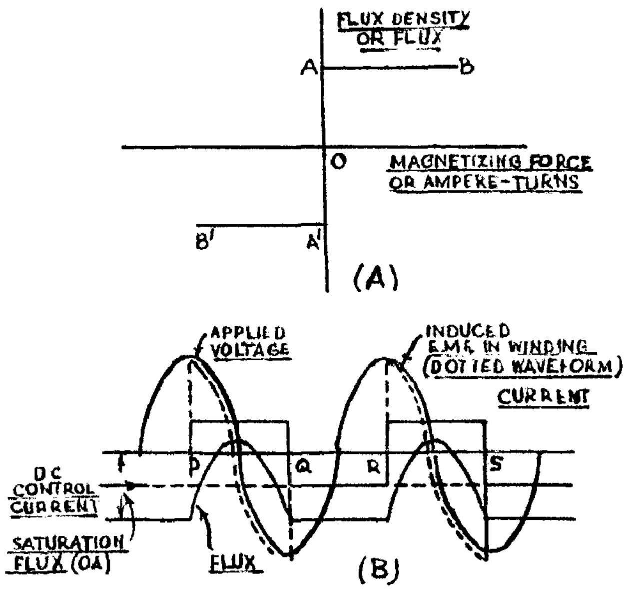


FIG:- 7.1

OPERATION OF SIMPLE TRANSDUCTOR ARRANGEMENT will be saturated and no e.m.f. can be induced in its windings. Since the applied voltage must be balanced by an equal and opposite e.m.f. induced in core 1 a change of flux must occur and hence the core must operate along the portion AA'. This means that the alternating current flowing must equal the direct current, so that ampere turns cancel, otherwise the core would be saturated and would not be operating along portion A'A. Thus, from P to Q a constant current flows in the a.c. winding, so that an e.m.f. equal to the supply voltage is induced in the winding. Exactly the same thing happens to core 2 during the other half cycle from Q to R. Hence the a.c. current through the transductor is of square wave shape and equal in magnitude to the direction current in the control windings. It may be considered that the apparatus behaves as d.c. transformer as a.c. and d.c. current must always be equal. The reactor L in Fig.(1-b) is used to prevent the flow of corresponding current which would upset the operation. The effect of series load in the a.c. winding is to modify the current slightly but principle is same.

1.3.2.0. Excitation Systems:

Since the output of final stage of amplifier in the block diagram Fig.(6) is given to regulate the field excitation system. And hence it is also essential to consider the proper selection of the excitation system for a particular type of regulator. The complete unit including excitation system is termed as excitation regulator. The excitation of the alternator is supplied by means of a generator known as the exciter. It was realised by the power engineers that the excitation systems are an important factor in the problem of determining the time variation of angle, voltage and other quantities during the transient disturbances.. The importance of excitation systems with high degree of responce for possible operation in dynamic stability region was also realised.

The main exciters for synchronous generators are in general d.c generators. But during literature survey it has also been found that V Easton[10] and TJ Chah[14] have given schemes for a.c. exciters with static rectifiers. Fairly recent development in designing of silicon rectifiers with current and peak inverse voltage, in excess of 100A and 2 KV made rectified a.c. power a practical source of excitation supply for large turbogenerators where d.c. exciters are found to be uneconomical. The a.c. exciter with static rectifier have found extensive application and it is already a standard practical in U.K. to use rotating a.c. excitation system with static rectifiers in all turbogenerator which are being recently manufactured. Long term durability and reliability is yet to be known and will however, be proved by years of service only.

The main d.c. exciters for synchronous machines are in general of three types.

1) Conventional d.c. generators
2) Rotating amplifiers
3) Electronic exciters.

1.3.2.1. The most common form of rotating main exciter is more or less conventional d.c. generator. The term 'Conventional' is used with the reservation since a d.c. generator built for the supplying excitation for a synchronous machine has incorporated in it many features to improve reliability and to reduce maintenance not found on d.c. generators used for other purposes. Aside from these special features theory of operation is same as d.c. generator. These conventional main exciters can be classified according to their method of excitation, being either self excited or separately excited. In the former the field winding or windings are connected across the terminals of the machine through variable resistors and in the later the field windings with their resistors are connected to a source of essentially constant voltage such as a small auxiliary flat compound generator, called a pilot exciter.

Another form of rotating exciter, those have got importance and are now in common use are rotating amplifiers; they are of several type d.c.generators. These are very different in their operation from the conventional d.c. generator. These have got importance because they have more power gain as compared to conventional d.c. generator. Due to properly of high power gain they are known as rotating amplifiers. Rotating amplifiers have the same construction as a conventional d.c. generator, except that the magnetic circuit of the former is so designed that it does not saturate in working range.

Mainly three commercial type rotating amplifiers are available.

1) Rototrol 2) Magnovolt exciter 3) Amplidyne.

1.3.2.2. The Rototrol generator or exciter (Fig 8) consists of a direct current armature with a series field. The machine is connected to the load (commonly the field of another generator) through the tunning resistance. Instead of using a series field a shunt field may be used with a suitable tunning resistor placed in series with it. In normal operation of d.c. machine the field resistance line is such as cutting the magnetisation curve well up the curve. The field resistance is so adjusted that the resistance line can lie in position along the straight portion of the magnetisation curve. The point of intersection with magnetisation curve, therefore, changes rapidly with slight change of field resistance or speed. This provides the high amplifying proportion of the Rototrol. By

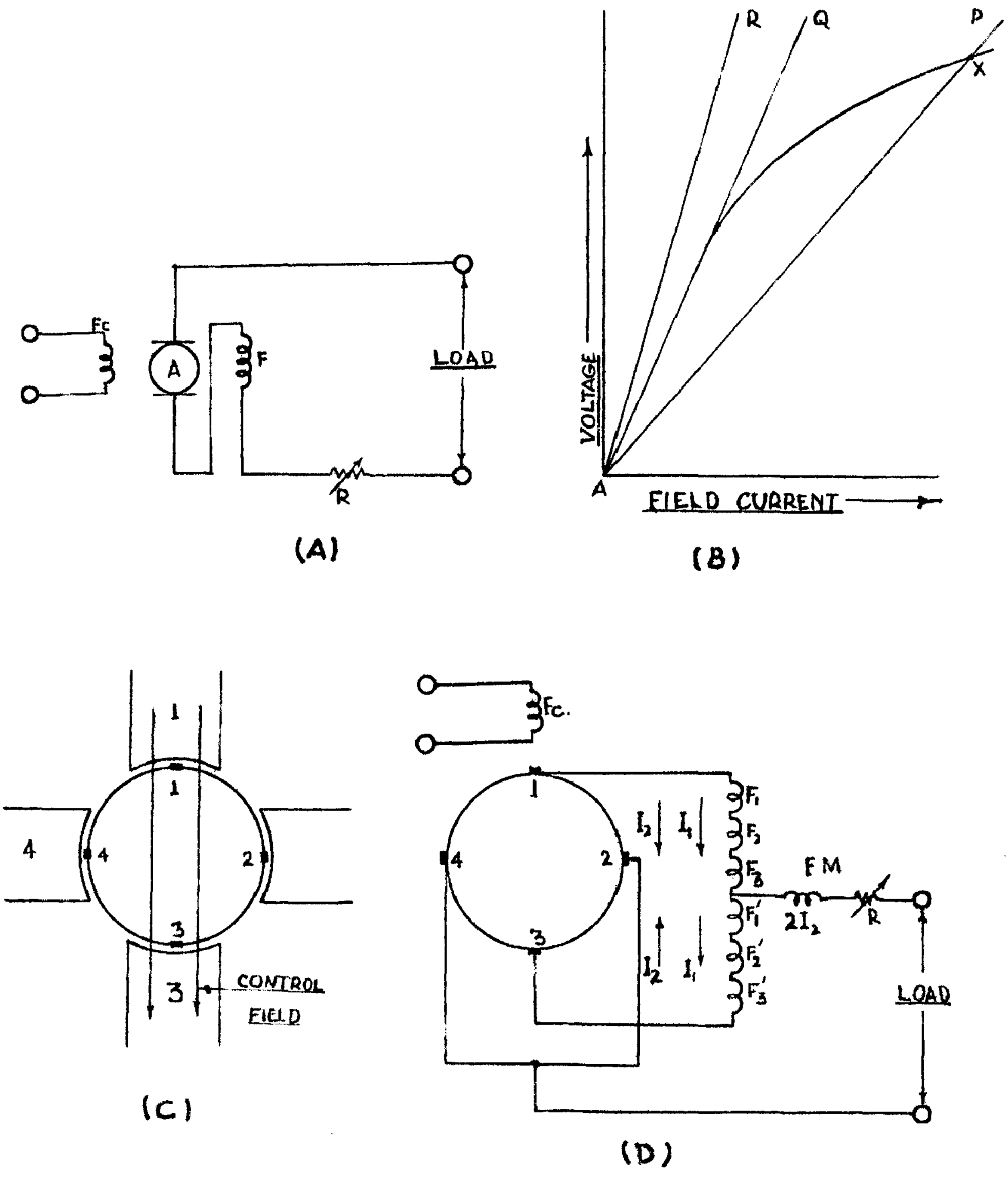


FIG 8

THE PRINCIPLE OF THE ROTOTROL EXCITER

(A) AND (B) SINGLE STAGE (C) AND (D) TWO STAGE small control field winding provided within the rototrol, the field resistance line may be moved to and fro by a small current in the control field winding. A slight movement of this line causes a rapid change of voltage and thus the output voltage is controlled by an extremely small power in the control circuit. Since the output voltage is critically dependent on the resistance of the field circuit and speed, the device is normally can be used in closed loop system, the actual control ampere turns being the difference between ampere turns of a reference field and a field winding carrying a current proportional to the voltage to be controlled. The device will always operate so as to make these ampere turns such that the controlled voltage remains the same. When the power requirement of a single stage rototrol is too great a two stage rototrol may be used. The second stage operates essentially as the single stage but receives its control ampere turns from the output of the first stage. The machine consists of four pole lap wound armature without equilisers, rotating in a four pole system. The control winding of the first stage is wound on two poles so as to produce a two pole field i.e. forming North and South poles. The flux produced by this will induce an e.m.f. and this voltage is used to excite all four poles to produce a four pole field system, which forms the second stage of the rototrol. The main field of the second stage is produced by a series winding on all four poles. To compensate armature reaction effects, it is necessary to use compensating winding on poles, otherwise large amplification are impossible. The two stage rototrol gives sufficient amplification but if more amplification is required three or more stag rototrol arrangements are possible.

1.3.2.3. Magnavolt Exciters

The single stage Magnavolt exciter is similar in principle

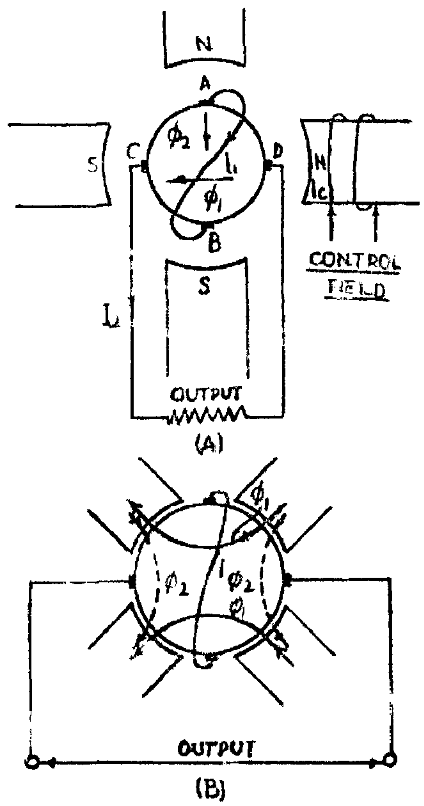
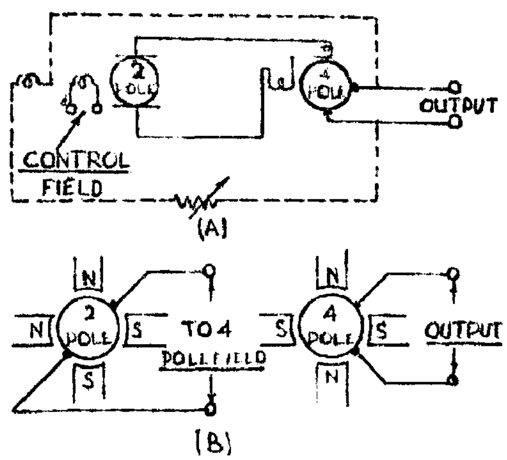


FIG- 9 THE METADYNE OR AMPLIDYNE
(A) ILLUSTRATINGI PRINCIPLE (B) ACTUAL ARRANGEMENT OF THE CIRCUIT



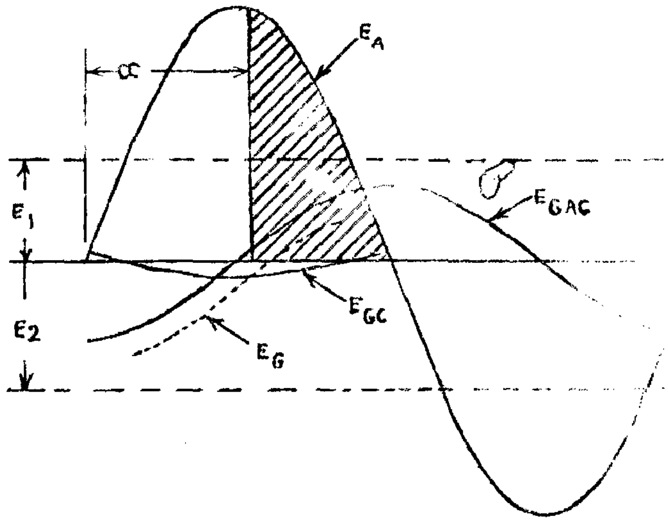
-10. THE PRINCIPLE OF THE TWO STAGE MAGNAVOLT to the single stage rototrol and may be provided with shunt or series self exciting windings. Due to the effect of mutual inductance between control field and self exciting field the speed response is limited and avoid it a two stage magnavolt exciter is required. The machine consists of a four physical pole field system in rotates an armature having two windings and two commutators. One of these windings is a two pole winding and the other four pole armature winding. The control winding is wound on the four poles so as to produce the polarity as shown in Fig. (10). This control winding induces an e.m.f. in the two pole armature winding but not in four pole winding. The voltage induced in the two pole winding feeds to the field coils, of the main four pole field (the coils being on the same polar projections as the control windings) and accordingly an e.m.f. is induced in the four pole armature winding, which is the output of the exciter. The four pole winding does not induce any e.m.f. in the two pole winding because each coil now spans two poles pitches. Since there is no mutual induction between two sets of field windings, as they are same way round one one pole and opposite way in the other, the speed of response is increased compared with the single-st type. The output voltage will change with speed and also its sensitivity but it is of little consequence. The size of control field can be reduced by providing positive feed back by means of additional field coil shown dotted but it reduces its stability.

1.3.2.4. Amplidyne:

The principle of this type of machine is shown in Fig.(9) The machine comprises a two pole direct current armature with a commutator rotating in a four pole field system. Suppose that a current is passed through the control field, then a flux ϕ_1 will be produced. As a result an e.m.f. will be generated across the brushes A and B and since these are short circuited, a current I_1 will flow, which will produce a flux ϕ_2 due to armature reaction effect and this flux will produce an e.m.f. across the brushes C and D and corresponding current in the load circuit. Since a small e.m.f. is required across brushes A and B to circulate the current through the short circuited armature, the flux ϕ_1 is only small and hence the ampere-turns produced by the control field need only be small. Due to load current I_2 flowing through the armature, an e.m.f. is produced by the armature reaction, opposing the flux ϕ_1. To reduce this effect a compensating winding is usually placed on the C-D axis, connected to the load circuit such that all the armature reaction effect is neutralised. An additional winding is, also placed on AB axis to supplement the armature-reaction ampere-turns due to I_1, known as the amplistor. Both of these additional windings reduce the ampere turns required for the control winding. In practice the, poles are not arranged as shown in Fig.(9)- (a) but are commonly arranged as shown in Fig.(9), (b) a number physical arrangements being possible. Instead of four pole field and two pole armature (known as one cycle metadyne) an eight pole field and four pole armature may be used (known as two cycle metadyne). By suitable construction the response time of a metadyne may be made very short, much less than that of conventional generator. The amplidyne is a two stage amplifier and gives power gain from 10000 to 250000. It has a short time constant of the order of 0.05 to 0.25 sec. Due to these reason it is more commonly used over other type of rotating amplifiers as main exciter.

1.3.2.5. <u>Electronic Exciter:</u>

Power rectifiers of ignitron type have been used for many years and have given reliable and efficient performance.



EA - FIRING [illegible] E ANODE VOLTAGE
EGC - CRITICAL GRID VOLTAGE OF FIRING TUB[illegible]
EGAC - PHACE SHIFTED A.C GRID BIAS VOLTAGE
E1 - FIXED POSITIVE GRID BIAS
E2 - VOLTAGE NEGATIVE GRID BIAS
EG - TOTAL GRID BIAS VOLTAGE
α - ANGLE OF GRID RE

Fig. ~~5a~~ 11 b CONTROL GRID VOLTAGES APPLIED TO THYRATRON FIRING TUBE.

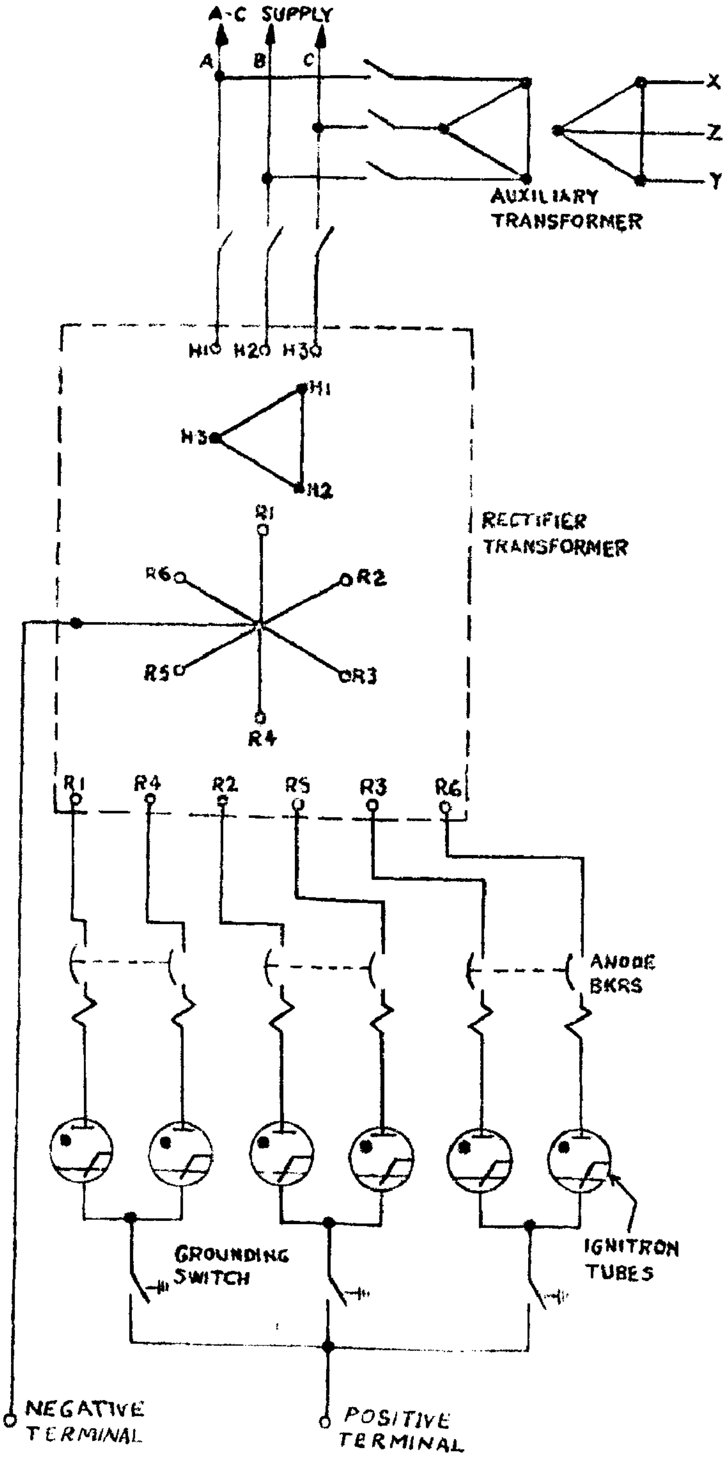


Fig ~~5b~~ 11 a. SIMPLIFIED CIRCUIT OF ELECTRONIC MAIN EXCITER SUPPLIED FROM THE A.C. GENERATOR TERMINALS THROUGH A RECTIFIER TRANSFORMER.

Their use as main exciter has been limited principally, they cost more. Although they have advantages over rotating type main exciter. Responce of the electronic excitation system is almost instantaneous. This feature is desirable because it improves the growth of exciting current after a sudden disturbance thus improving transient stability. Fast responce of excitation is also beneficial, when operation in dynamic stability region is desired.

The output of rectifier is only as reliable as the source of A.C. input. Thus this A.C. source must be considered as a part of the rectifier, and so far as an excitation source is concerned, it must be reliable. Three sources have been used in operating installations.

1) A.C. input for the rectifier is taken directly from the terminals of the A.C. generator being excited.

2) A.C. input is taken from a seperate A.C. supply that is independent of the A.C. generator being excited.

3) A.C. supply is taken from a seperate generator which gives power to the rectifier only and which is driven by the same drive as the main generator.

In the first case the exciter is said to be self excited where as in the later cases they called seperately excited.

A simplified circuit diagram of an electronic exciter with rectifier transformer is shown in Fig.(11a)[19] The delta connected primary of the transformer can be energized from the terminals of the main a.c. generator, from the plant auxiliary power supply or from some other independent source. The rectifier comprises of three groups of two ignitron tubes each, the two tubes of each group being connected to diametrically opposite phases of the six phase transformer secondary through a two pole, high speed circuit breaker. Thus if a breaker is opened, both tubes of a group are de-energized. Each pole of the anode breaker is equipped with a reverse current trip attachment and the breaker is automatically reclosed. If an ignitron arc back is occured, the breaker is automatically opened at high speed and reclosed, when arc-back has been cleared. If an arc back occurs second time within a short time, the anode breaker is again opens and locks in open position to permit inspection of the unit.

For firing ignitron tubes and d.c. voltage a thyratron tube is connected in parallel with the ignitron through its ignitor. The thyratron is made conductive when its anode voltage is positive w.r.t. to cathode and its grid voltage is released. Current then passes through the ignitron ignitor which initiates a cathode and fires the ignitron. If the ignitron should fail to conduct for any reason, the thyratron attempts to carry load current but is removed from the circuit by the thyratron breaker.

The magnitude of the output voltage of the electronic exciter is varied by controlling the point on its anode voltage wave at which the ignitron tube is made to conductive. This point is determined by releasing the control grid of the firing thyratron, which controlled by a sine wave grid transformer, a rectox supplying a fixed positive bias and a rectox supplying a variable negative bias for manual control and or an electronic regulator supplying variable negative bias for automatic control. The sine wave voltage E_{GAC} impressed on the grid of the thyratron is delayed almost 90° from the anode voltage and is connected in series with the positive and negative biases. These various voltages are shown in Fig.(11b). Rheostatic adjustment is done to give desired positive and negative grid-bias voltage. Manual control of the exciter voltage is obtained by means of rheostatic adjustment. The various bias voltages

E_1, E_2 and E_{GAC} add to give a total grid bias voltage, represented by E_G and varying the negative bias determines the point at which the total grid voltage becomes more positive than the critical grid voltage E_{GC} of the firing tube releasing the tube for conduction. The ignitron is then made conductive by the current in the igniter and remains conductive for the remainder of the half cycle of anode voltage the angle α in Fig.(11b) is defined as the angle of grid delay.

The use of positive and negative grid bias in this manner provides a wide range of control of the angle of the grid delay and consequently a wide range of exciter output voltage; when the exciter voltage is under the control of automatic electronic regulator, the manually controlled electronic bias E_2 is replaced by a variable negative bias voltage from the regulator.

The ignitron and thyratron tubes in electronic exciter are subject to deterioration and eventual failure and replacement and it is essential that consequent replacement be sustained without interfering with the excitation of a.c. generator. And hence electronic exciters are designed to supply full excitation requirements continuously with two of the six ignitron tubes out of service.

1.4. ANGLE REGULATOR:

An angle regulator is an excitation regulator of A.C. generator in which the excitation regulating signal is proportional to rotor angle of the A.C. generator with respect to the bus-bar voltage. Earlier C. Concordia (6) have defined the angle regulator as a regulator that varies the machine excitation voltage in response to the changes in the angle between the rotor interpolar axis and the effective system voltage so as to tend to restore the initially set angle. This regulator can also be used like voltage regulator for artificial stabilisation of synchronous machines. Lateron the angle regulator done by Venikov and Litkins; they compared regulating systems proportional to voltage, current and power angle and their derivatives and concluded that by using power angle, the current and derivatives of these quantities zone of stability expands and permits operation at larger than the one corresponding to line limit. Thus a reserve in stability is obtained in those cases above the line capacity by increasing voltage (about 10%) during abnormal operating conditions. This increase in voltage for small time has been found to be of no harm.

Lateron work on angle regulators have done by many authors and found encouraging results.

1.4.1. Measurement of Angles

As mentioned in the section 1.4 that in angle regulator we require a signal proportional to the rotor angle and we require the devices for measuring the rotor angle so that a signal proportional to rotor angle can be given to actuate the field of the main ~~regulate~~ exciter for stabilising the a.c. generator.

For a machine having constant excitation and connected directly to an infinite bus bar maximum power output is obtained for a value of power angle slightly less than 90°. Instability or loss of synchronism is indicated by the value of δ increasing continuously. The power angle is obtained by measuring the advancement of the rotor ahead of or falling behind its initial no load position with respect to a synchronously rotating axis. In order to do this a signal from the shaft has to be obtained whose phase shift w.r.t. a reference voltage can be measured. The signal from the shaft can be obtained by using any one of the instruments.

1) A magnetic pick up.

ii) An optical pick up

iii) Tachogenerator.

A magnetic pick up may be in the form of a coil, the reluctance of whose magnetic circuit is changed by the movement of a short iron force, once (in the case of two pole machine) in every revolution of the rotor. The shaft iron piece is mounted directly on the shaft and coil is located so that soft iron piece can move in and out of its magnetic circuit.

An optical pick up may be in the form of an arrangement in which the light falling on a photosensitive element is interrupted periodically by a disc mounted on the shaft of the machine, having opaque and transparent sectors. The current in the photo-sensitive element will contain an alternating component whose phase follows the rotor position w.r.t. to synchronously rotating reference axis.

A tachometer is most commonly used to generate a single phase alternating voltage whose phase follows the rotor position w.r.t. synchronously rotating axis.

By using these devices the work has been done by many authors for measurement of rotor angle. But the arrangement in most cases is not suitable for providing a signal for regulating the excitation of the a.c. generator.

A conventional method of measuring power angle can be used as follows. The Tachogenerator and busbar voltage waves are first converted into square waves by clipping circuits. The two square waves are then added in a cathode follower stage. The average voltage output of the cathode follower is proportional to the power angle. This signal can be utilized to actuate the field of the a.c. generator.

A method described in ref.(11) can be used for getting a signal to actuate the field of the a.c. generator. The method uses a phase comparison circuit which compares the phase of the bus bar voltage with that of the a.c. Tachogenerator voltage which is also at the bus bar frequency when the machines runs at synchronous speed. The average voltage output of the phase comparison circuit is directly proportional to the phase difference between the two a.c. voltages.

1.4.1.1. Description of the Basic Circuits

Refering to Fig.(12) and assuming ideal operation, each of the transistors T_1, T_2 and T_3 in effect functions as a switch, the collector to emitter circuit "Closing" when base is negative w.r.t. emitter and "opening" when base is positive with respect to emitter. Since T_1 and T_2 bases are driven in antiphase, for the half cycle of the bus signal that the T_1 'switch' is open, the T_2 switch is closed and vice-versa. During the half cycle of the tacho-generator signal that the T_3 switch is closed, the current flows from the battery (E) through T_3, the current path being completed through T_1 or T_2 which ever switched on. The battery current remains constant at E/R during this half cycle, so that for the time that the conduction is through T_2 say, point B is E volts positive w.r.t. point C, similarly, during the time T_1 is conducting point A is E volts positive w.r.t. C. The sum of the conduction periods of T_1 and T_2 is constant, (half period of Tachogenerator signal). The relative division of this time between T_1 and T_2 varying linearly with change in phase angle between the two signal inputs from bus bar and Tachogenerator.

If the voltage drop across the conducting transistor is ignored the average value of voltage between point A and B may vary from $+\frac{1}{2}E$ to $-\frac{1}{2}E$, these limits are corresponding to the conditions where tachogenerator voltage is in phase and antiphase respectively

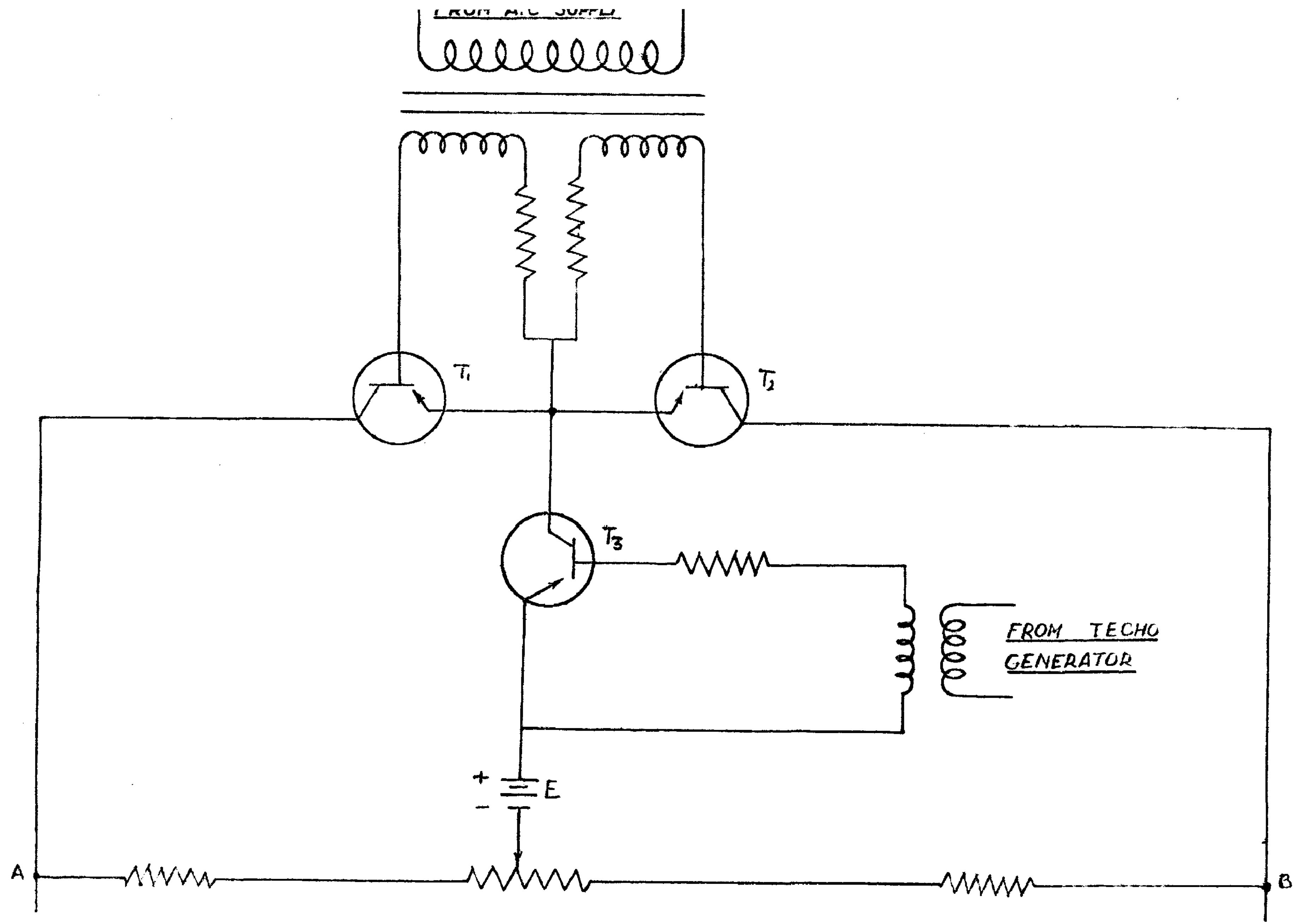


FIG:-12 **CIRCUIT FOR MEASURING ROTOR ANGLE** with bus bar voltage. The relative phase of the two signals is adjusted by some means, so that the average output voltage is zero when the δ =0 and maximum when δ =180, so that it can be used for angle proportional signal in angle regulator.

Practical arrangement of the circuit can be done as follows. For ideal circuit operation, the P.D. between point A and B (in Fig. 12)will in general be an unsymmetrical rectangular wave . The rotor angle is proportional to the average value of this voltage and so, for taking transient variation in a low pass filter is connected to points A and B.

It can be seen from the basic circuit that the average output voltage is zero when the two input signals are displaced in phase by 90°. To permit this setting of the zero position, some means of arbitrary varying the phase displacement between the two input signals must be available. The relative phase of tachogenerator signal can be varied, by rotation of synchronous machine stator, which is trunion mounted. In most cases the stator will not be trunion mounted and some external phase shifting device will be needed. This could be any of several different types and choice will probably be determined by what is available.

1.4.7. Circuit of Angle Regulator:

The circuit for angle Regulator firstly requires a device for providing a signal proportional to rotor angle. The circuit diagram is shown in Fig.(13) The rectified signal proportional to angle of the is then passed through differentiating circuits as shown in the diagram for producing first and second derivatives. signals. These signals proportional to angle δ and its first and second derivatives then amplified by means of voltage D.C. amplifiers. The output of these amplifiers is then added in a summation circuit known as power


SYSTEM
ANGLE
MEASURING
DEVICE

amplifier. This can be an electronic amplifier as discussed in the case of electronic voltage regulator in the section 1.2 or it can be an amplidyne where all the three signals are added to give an output proportional to these signal and in the amplified form. This amplidyne can also be used as main exciter for the a.c. generator. In the case of electronic power amplifier, the output of this amplifier controls the main exciter of the a.c. generator.

The d.c. voltage amplifier used in this case are also similar to that used in the case of voltage regulators. And a signal proportional to the angle is obtained as described under the heading of angle measurement. The summation circuit can be used amplidyne which also serves the purpose of main exciter. The amplidyne is already described in the voltage regulator. Here in this case there will be three control winding for the amplidyne one each for three signals proportional to angle, and its first and second derivatives. The output of the amplidyne is given to the field of the a.c. generat[illegible] As the output of the amplidyne is regulated by the signals mentioned above and hence out put of the a.c. generator is also regulated.

1.6. SYSTEM CONSIDERED AND THE STATEMENT OF THE PROBLEM

1.6.1. SYSTEM CONSIDERED:

It is well known that stability is mainly considered for a long transmission line system i.e. stability considerations are more important for a long transmission line system than a system which is associated with a short transmission line. Therefore the system considered is a hydrogenerator connected to an infinite busbar by means of a long transmission line. The hydrogenerator is fitted with an angle regulator whose actuating signal is proportional to rotor angle of the hydrogenerator with respect to bus bar voltage (δ) and its derivatives. The excitation system of the hydrogenerator is seperately excited and automatically regulated by means of the angle regulator.

The data for the system considered are as given below.

<u>Machine Constants:</u>

$x_{akd} = x_{fkd} = x_{afd} = x_{md} = 1.0$

$x_d = 1.2$

$x_q = 0.8$

$x_a = 0.01$

$r_{fd} = 0.0011$

$x_{ffd} = x_{kkd} = 1.1$

$r_{kd} = .02$

$M = 6$ sec.

<u>Time Constants of the hydrogenerator:</u>

$T'_{do} = 3.1528$ sec.

$T''_{do} = .00304$ sec.

$T'_d = .7720$ sec.

$T''_d = .00258$ sec.

$T_{kd} = .00159$

<u>Time constants of the Regulator:</u>

$T_1 = .08$

$T_2 = .005$ (gain constants are to be choosen for maximum stability limit)

<u>Transmission line Constants:</u>

$r = 0.05$

$x = 0.3$

<u>Turbine damping constant:</u>

$K_T = +3$

1.6.2. STATEMENT OF THE PROBLEM:

The problem to be considered in this dissertation is to find out the effects of the gain constants K_1, K_2 and K_3 of the angle regulator on the dynamic stability limit of the system considered above. For this to find out the effect of these constants on the coefficients of the characteristic equation i.e. how these coefficients affected by varying these gain constants. The effect of gain constant K_1 on the terminal voltage under steady-state operation is also to be obtained.

1.6.3. Author's approach to the Problem:

The machine equations are written in d and q axis as given by the park's taking one damper in d axis. Equations for the complete system are written in terms of d and q axis. The equation for the angle regulator (including excitation system) is considered as-

$$e = 1 + \frac{K_1\delta + K_2 p\delta + K_3 p^2\delta}{(1+T_1 p)(1+T_2 p)}$$

i.e. two time constants of the regulating system are considered. The system equations are linearised for small disturbance by considering equation differentials. From these linearised equation the characteristics equation of the system is formed by forming a block diagram of the system in one way of approach. Second way of approach is to form a set of 1st order differential equations from these linearised equations to form a 1st order vector differential equation (state space variable approach).

1.6.3.1. Block Diagram Approach:

After writing down the system equations in d and q axis and their derivatives for small disturbance, the authors approach is to formulate a block diagram as shown in the Fig.(1.6.2). In the block diagram various quantities are already shown. These quantiti are to be found out first. From this block diagram a characteristic equation of the complete system is determined by the formula.

$$1 + f(p)\ H(p) = 0$$

The characteristic equation obtained will be of the form mentioned below.

$$F(p) = a_0\ p^n + a_1\ p^{n-1} + a_2\ p^{n-2}\ \ldots\ldots + a_n = 0$$

For analysis of the system; the voltage variation of the terminal voltage with different values of K_1 is obtained for various values of load angles and also the power angle curves are drawn for various values of K_1.

The coefficients of the characteristic equations $a_0, a_1 \ldots\ldots a_n$ are obtained for load angles ranging from 60^o-120^o with various values of K_1, K_2 and K_3 (gain constants of the regulator) and the variation of these constants with K_1, K_2 and K_3 are plotted on the graph.

The stability of the system is tested for various values of load angles for different values of K_1, K_2 and K_3, i.e. the coefficients of the characteristic equation a_0, $a_1 \ldots\ldots a_n$ are found for different angles and with different values of K_1, K_2, K_3 and then stability is tested by Routh Hurwitz Criterion[22] and modified Routh Hurwitz Criterion.[18]

For calculation of terminal voltage and power at various values of load angle a digital computer programme is made, to calculate those values at various values of gain constant K_1.

For calculating coefficients of the characteristic equation also a digital computer programme is made by which the values of a_0, $a_1, \ldots\ldots a_n$ are calculated at various values of load angle ranging from 60° - 120° with various values of K_1 K_2 and K_3 and a subroutine is developed for Routh Hurwitz criterion to test the stability of the system at various values of angles with different values of K_1, K_2, and K_3 and to find out the stability limit.

1.6.2.2. State Space Approach:

The differential equations are linearised around the chosen operating point as in the transfer function approach. These equations are arranged in form of a set of first order differential equation as-

$$B\dot{X} = CX$$

where,

X is the state vector of the quantities such as ϕ_d, ϕ_q, i_d, i_q, Y_o, θ, η, e_{fd} etc. B and C are matrices of coefficients which depend upon the initial operating condition and the values of the system parameters. The above equation is written in the form-

$$\dot{X} = B^{-1}CX$$

or

$$\dot{X} = AX$$

where,

A is the characteristic matrix of the system. From this matrix the stability of the system can be tested. Theory of this will be described in the Chapter 3.

1.6.3. Assumptions made while writing the systems equations:

The following assumptions will made while writing the system equations.

1) The current in any winding produces m.m.f. wave which is sinusoidal distributed in air gap space i.e. the effect of slots are neglected.

2) Effect of eddy current and hysteresis is neglected.

3) Effect of saturation is also neglected.

4) The voltage induced in the armature by the rate of change of armature flux linkage, namely $p\phi_d$ and $p\phi_q$ are negligibl compared with the generated voltage by rotation of ϕ_d and ϕ_q at fundamental speed. i.e. $\phi_d p\theta$ and $\phi_q\ p\theta$ are large compared with $p\phi_d$ and $p\phi_q$ because $p\theta$ is large and ϕ_d and ϕ_q very slowly.

5) Salient pole type rotor is considered, and one damper is considered in d axis and no damper winding in the quad. rating axis is considered.

6) <u>Sign Conventions:</u>

(i) Voltage rise from neutral to phase terminal as positive.

(ii) Current in the direction of positive voltage is positive (This corresponds to generator action).

(iii) Flux producing positive voltage is positive (i.e. the field flux is positive, also field flux linkage).

(iv) Field current producing positive flux is positive.

(v) Field voltage producing positive field current is positive.

(The sign conventions are the same as that used by the Concordia).

7. Per unit system is used: It becomes easier to handle, however if p.u. quantities are used and if in addition, it is assumed that three p.u. mutual inductances on the d axis are all equal. This assumption is very nearly true for a normal synchronous machine, because leakage fluxes of the field coils and the damper bars are distinct and there is single main flux linking the and armature winding, co-

$L_{afd} = L_{akd} = L_{fkd} = X_{md}$

$X_{md} = X_d - X_1$

$p\theta = 1$ at normal speed.

P.U. current required to generate p.u. voltage on o.c. $= 1/X_{md}$.

The base field current $I_{fb} = X_{md}\, I_{fo}$ amps.

I_{fo} = field current in amps. to generate rated voltage on o.c.

The base field voltage $e_{fb} = \dfrac{X_{md}}{R_{fd}} \times e_{fo}$

e_{fo} = field voltage in volts required to generate the rated voltage on open circuit.

$r_{fd} = \frac{3}{2}\, r_{fd}$ (r_{fd} the actual field resistance).

(8) The machine is connected to an infinite bus bar through a transmission line having a resistance and inductance only, the effect of capacitance is neglected.

(9) Machine is equipped with an angle regulator which can be represented by two time constants same for all the signals i.e. for signals proportional to rotor angle and their derivatives but the gain constants are different for each to give maximum dynamic stability.

(10) The regulator is fast acting so the time constants considered in the above assumption are very small. The regulator is assumed to have ~~ordered~~ no dead band.

(11) Parameters of the control system remain unaltered throughout any transient change.

(12) The machine is subjected to small disturbances or in other words to small change of T_1 (the mech. input torque).

(13) Prime-mover speed governor does not respond to small change in speed, i.e. it has sufficiently wide dead band and once it is not considered.

CHAPTER - 2

ANALYSIS OF THE DYNAMIC STABILITY OF THE SYSTEM BY TRANSFER FUNCTION APPROACH:

2.1. FORMATION OF THE EQUATION OF THE SYSTEM:

The general equations for synchronous machine and transmission line system are writtenin d and q axis. And considering only small deviations of the variables from their steady-state values the system equations are linearised, since only infinitesimally small changes are of interest for finding out the dynamic stability of the system. Before writing the system equations the assumptions made are also considered.

Machine equations-

$$\phi_d = G(p)\ e_{fd} - x_d(p)\ i_d \quad \ldots \quad \ldots \qquad (1)$$

where,

$$G(p) = \frac{(1 + T_{kd}p)\ x_{md}}{r_{fd}(1+ T'_{do}p)(1+T''_{do}p)} \quad \ldots \qquad (1.01)$$

and

$$x_d(p) = \frac{(1+T'_d\ p)\ (1+ T''_d\ p)}{(1+T'_d\ p)\ (1+ T''_{do}p)} \quad \ldots \qquad (1.02)$$

$$\phi_q = -x_q i_q \quad \text{(neglecting damper in 'q' axis)} \qquad (2)$$

$$\phi_{do} = \frac{x_{md}}{r_{fd}}\ e_{fdo} - x_d\ i_{do} = e_o - x_d\ i_{do} \qquad (1.1)$$

$$\phi_{qo} = -x_q\ r_{qo} \quad \ldots \quad \ldots \qquad (2.1)$$

$$e_d = -\phi_q w - r_a\ i_d \quad \ldots \qquad (3)$$

$$e_q = +\phi_d w - r_a\ i_q \quad \ldots \qquad (4)$$

(3), (4): neglecting effect of $p\phi_d$ and $p\phi_q$ in comparison with $w\phi_d$ and $w\phi_q$.

$$e_{do} = -\phi_{qo} - r_a\ i_{do} \quad \ldots \qquad (3.1)$$

$$e_{qo} = \phi_{do} - r_a\ i_{qo} \quad \ldots \qquad (4.1)$$

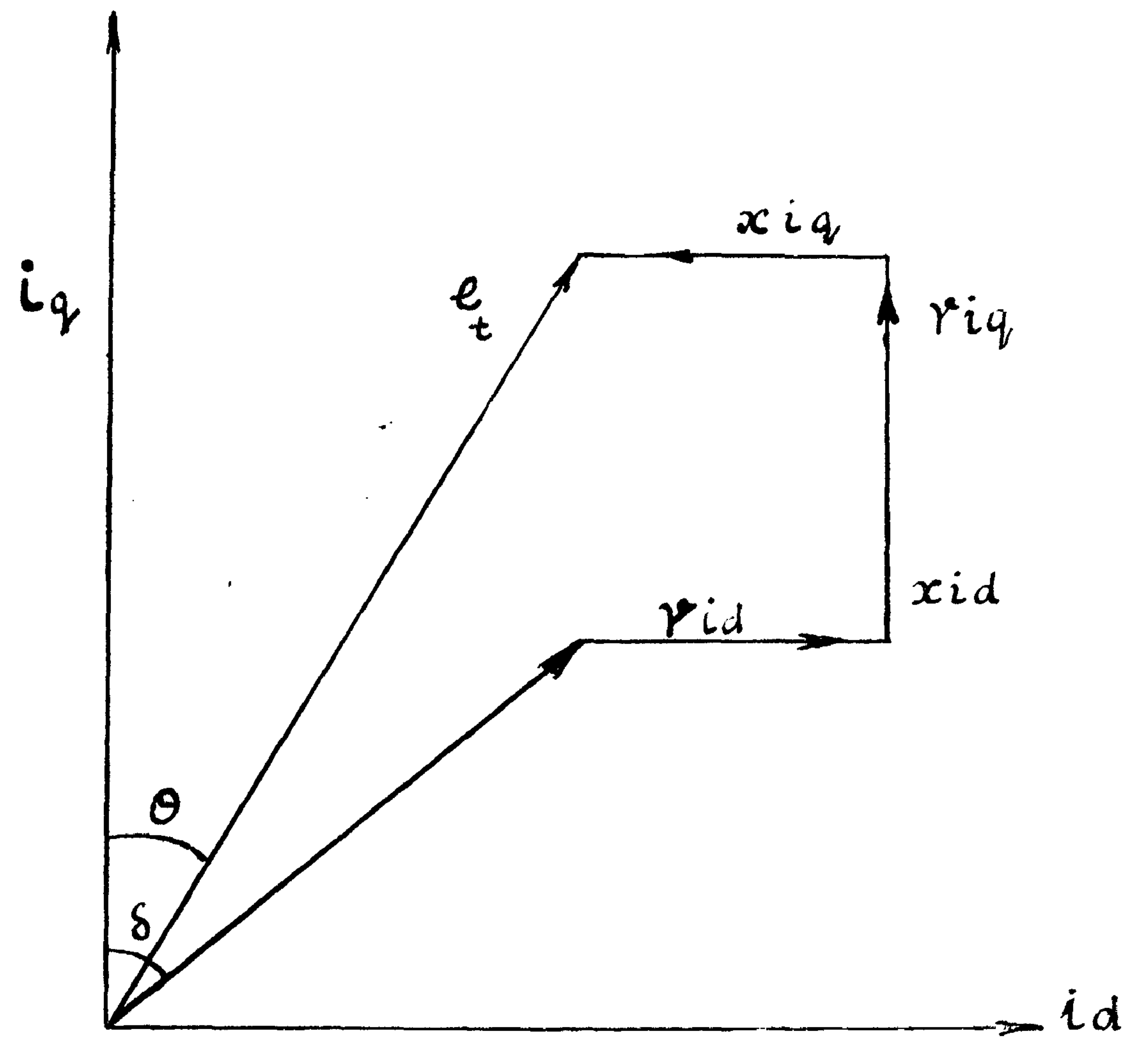
(3.1), (4.1): w_o =1 in p.u.

Equation ~~of~~ of transmission line:

$$e_d = V \sin\delta + r_{id} - x_{iq} \quad \ldots \qquad (5)$$

$$e_q = V \cos\delta + x_{id} + r_{iq} \quad \ldots \qquad (6)$$

(5), (6): From Vector diagram shown in Fig.



VECTOR DIAGRAM

FIG No. 14

$$e_{do} = V \sin \delta_o + r i_{do} - x i_{qo} \quad \ldots \quad (5.1)$$

$$e_{qo} = V \cos \delta_o + x i_{do} + r i_{qo} \quad \ldots \quad (6.1)$$

From equations 3.1, 4.1, 5.1 and 6.1-

$$(x_q + x) i_{qo} - (r_a + r)\, i_{do} = V \sin \delta_o$$

$$(x_d + x) i_{do} + (r_a + r)\, i_{qo} = e_o - V \cos \delta_o$$

$$\therefore i_{do} = \frac{\begin{vmatrix} V \sin \delta_o & (x_q + x) \\ e_o - V \cos \delta_o & (r_a + r) \end{vmatrix}}{\begin{vmatrix} -(r_a + r) & (x_q \pm x) \\ (x_d + x) & (r_a + r) \end{vmatrix}} = \frac{-RV \sin \delta_o + X_q (e_o - V \cos \delta_o)}{R^2 + X_d X_q} \quad \ldots (7)$$

$$i_{qo} = \frac{\begin{vmatrix} -(r_a + r) & V \sin \delta_o \\ (x_d + x) & e_o - V \cos \delta_o \end{vmatrix}}{\begin{vmatrix} -(r_a + r) & (x_q + x) \\ (x_d + x) & (r_a + r) \end{vmatrix}} = \frac{X_d V \sin \delta_o + R(e_o - V \cos \delta_o)}{R^2 + X_d X_q} \quad \ldots (8)$$

where,
$R = (r_a + r)$; $X_d = (x_d + x)$; $X_q = (x_q + x)$

equations 1.1 and 2.1 are modified as follows:

$$\phi_{do} = e_o - x_d \left[\frac{-RV \sin {}_o + X_q (e_o - V \cos {}_o)}{R^2 + X_d X_q} \right] \quad (1.2)$$

$$\phi_{qo} = x_q \left[\frac{X_d V \sin {}_o + R\, (E_o - V \cos {}_o)}{R^2 + X_d X_q} \right] \quad (2.2)$$

<u>Equation of the angle Regulator</u>: Choosing equation of regulator as-

$$e_R = \frac{(K_1 + K_2 p + K_3 p^2)\ \delta}{(1 + T_1 p)\ (1 + T_2 p)}$$

∴ equation of the complete field system including seperately excited winding-

$$e = \frac{r_{md}}{r_{fd}}\, e_{fd} = E_o + \frac{(K_1 + K_2 p + K3\, p^2)\ \delta}{(1 + T_1 p)\ (1 + T_2 p)} \quad (9)$$

$e_o = E_o + K_1 \delta_o$ (10)

where,

E_o is induced e.m.f. at no load $E_o = 1$ in p.u. (9b).

Equation of motion:

$$T_m - T_e = T_a = Mp^2 \delta \qquad - \; - \; - \; - \; - \; (11)$$

Equations (1) to (9) are linearised for small load disturbance at $\delta = \delta_o$ as follows:

From equation 1 and 2-

$$\Delta \phi_d = G(p) \; \Delta e_{fd} - X_d \, (p) \Delta i_d \qquad \ldots \qquad (12)$$

$$\Delta \phi_q = - x_q \, \Delta i_q \qquad \ldots \qquad \ldots \qquad (13)$$

From equations 3, 4, 5 and 6, following equations are obtained as mentioned in appendix 51 (eqn. A-7 and A-8).

$$\Delta i_d = \frac{-R(V \cos \delta_o + \phi_{qo} p) + X_q (V \sin \delta_o + \phi_{do} p)}{R^2 + X_d(p) \, X_q} \Delta \delta$$

$$+ \frac{X_q \, G(p) \, \Delta e_{fd}}{R^2 + X_d(p) \, X_q} \qquad \ldots \qquad (14)$$

$$\Delta i_q = \frac{R(V \sin \delta_o + \phi_{qo} p) + X_d(p)(V \cos \delta_o + \phi_{qo} p)}{R^2 + X_d(p) \, X_q} \cdot \Delta \delta$$

$$+ \frac{R \, G(p) \, \Delta e_{fd}}{R^2 + X_d(p) \, X_q} \qquad \ldots \qquad (15)$$

where,

$$X_d(p) = x_d(p) + x$$

From equation (9)-

$$e = \frac{X_{md}}{r_{fd}} \, e_{fd} = \frac{(K_1 + K_2 p + K_3 p^2)}{(1 + T_1 p) \, (1 + T_2 p)} \ldots \qquad (16)$$

Now torque equation for alternator is considered.

$$T_e = \;_d \, i_q - \;_q \, i_d$$

$$\Delta T_e = \Delta \phi_d i_{qo} + \phi_{do} \Delta i_q - \Delta \phi_q \, i_{do} - \phi_{qo} \Delta i_d \qquad (17)$$

By putting the values of $\Delta\phi_d$, $\Delta\phi_q$, Δi_q and Δi_d the following equations are obtained as complete expression is done in appendix.

$$\Delta T_e = A_1(p)\,\Delta e_{fd} + A_2(p)\,\Delta\delta \qquad \ldots \qquad (18)$$

where,

$$A_1(p) = \frac{i_{qo}[R^2 + X_d(p)X_q] + (\phi_{do} + x_q i_{do})R - (x_d(p)i_{qo} + \phi_{qo})X_q G(p)}{R^2 + X_d(p)\,X_q} \qquad \ldots \qquad (18.1)$$

$$A_2(p) = \frac{(\phi_{do} + x_q i_{do})[R(V \sin {}_o + \phi_{do}p) + X_d(p)(V_{\cos}\ {}_o + \phi_{qo}p)] + (X_d(p)i_{qo} + \phi_{qo})[R(V \cos {}_o + \phi_{qo}p) - X_q(V \sin {}_o + \phi_{do}p)]}{R^2 + X_d(p)\,X_q} \qquad \ldots \qquad (18.2)$$

as mentioned in equation A(10, A-11) of appendix 5-2.

<u>Equation of Excitation regulating system:</u> for small disturbance from equation (9)-

$$\Delta e = \frac{x_{md}}{r_{fd}}\Delta e_{fd} = \frac{(K_1 + K_2 p + K_3 p^2)}{(1+T_1 p)(1+T_2 p)}\Delta\delta \qquad (19)$$

equation of motion: for small disturbance-

$$\Delta T_m - \Delta T_e = \Delta T_a = Mp^2\Delta\delta \qquad \ldots \qquad (20)$$

Now for small disturbance the action of governor is not considered and so the equation for Turbine is taken as follows, since turbine input $\Delta T_i = 0$

$$\Delta T_m = -K_T \cdot p\,\Delta\delta \quad \ldots \qquad \ldots \qquad (21)$$

2.2. VOLTAGE OUTPUT OF THE MACHINE AND POWER ANGLE CURVES:

From steady-state equations (7), (8), (9b), 1.1., 2.1, 3.1 and 4.1 of section 2.1, the steady state variation of voltage for various values of K_1 is found out at various values of steady state angle δ_o. Also the power at various values of K_1 is also

VARIATION OF VL WITH ANGLE δ FOR VARIOUS VALUES OF K1

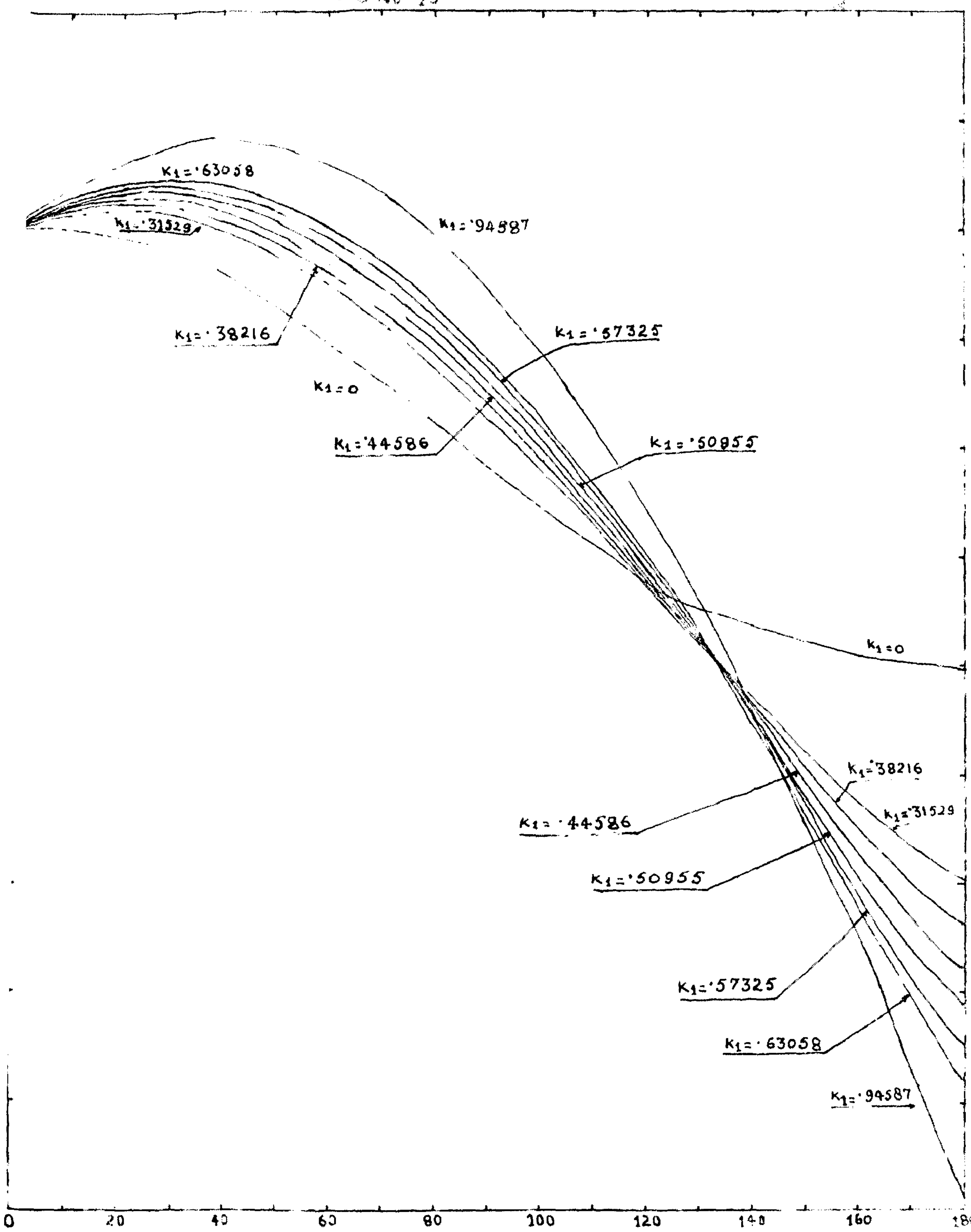


FIG NO 15

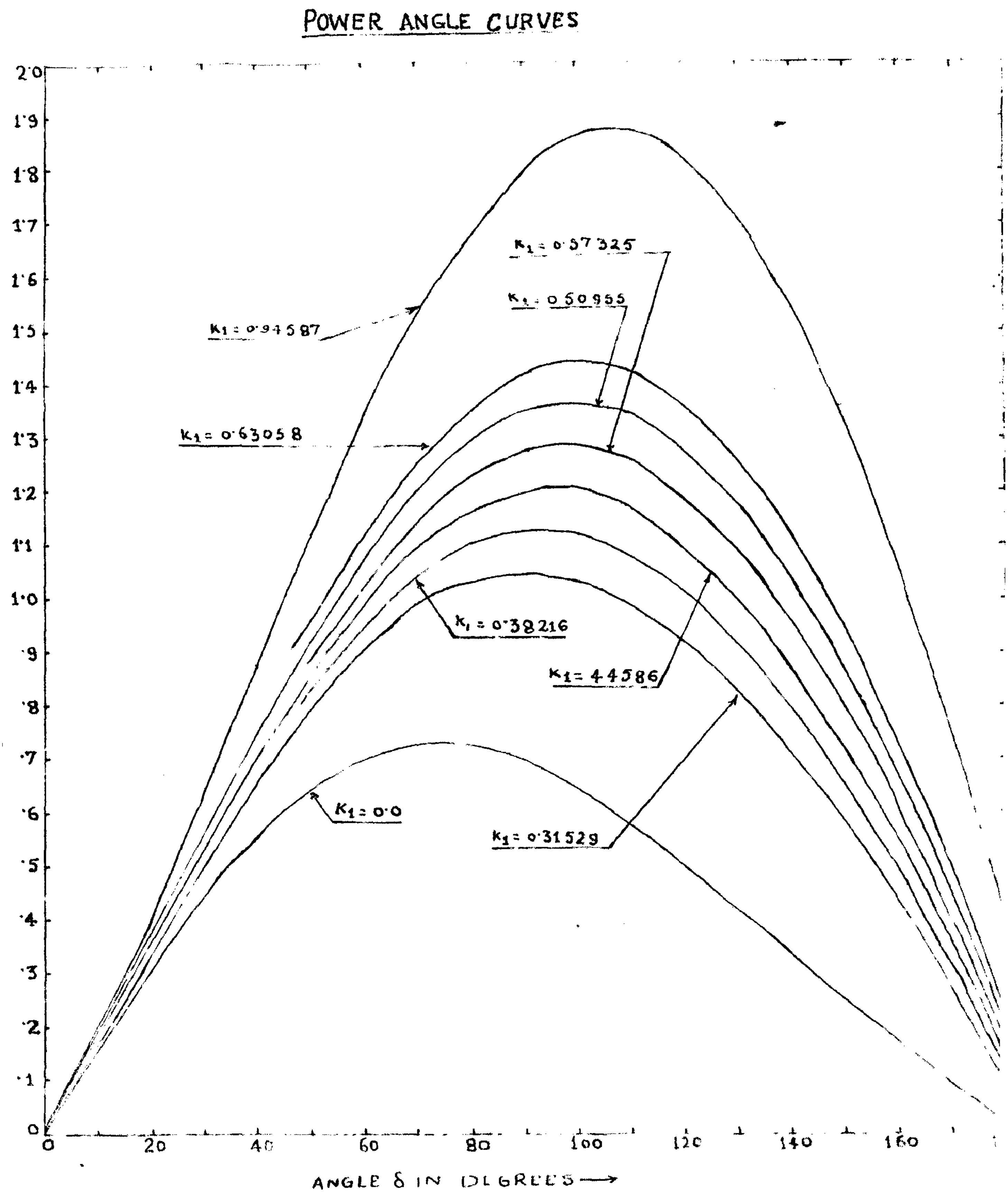

POWER ANGLE CURVES
2·0
1·9
1·8
1·7
1·6
1·5
1·4
1·3
1·2
1·1
1·0
·9
·8
·7
·6
·5
·4
·3
·2
·1
0
0
20
40
60
80
100
120
140
160
K1 = 0·94587
K1 = 0·57325
K1 = 0·50955
K1 = 0·63058
K1 = 0·38216
K1 = 4·4586
K1 = 0·0
K1 = 0·31529
ANGLE δ IN DEGREES →

FIG No 16

determined for various values of load angle. The voltage variation and power angle curves are shown on Fig.(15,16). For calculating voltage and power at a certain angle δ_o the calculating voltage and power at a certain angle δ_o the following systematic procedure is adopted and a programme is made for calculating power variation and voltage variation for different values of K_1 at various values of angle δ_o and plotted as shown in the diagram.

From equation 6, 7, 8, 3.1 and 4.1 of section 2.1-

$$e_o = 1 + K_1 \delta_o$$

$$\therefore i_{do} = \frac{-R\, V \sin\delta_o + X_q\,(e_o - V\cos\delta_o)}{R^2 + X_d X_q}$$

$$i_{qo} = \frac{X_d\, V \sin\delta_o + R\,(e_o - V\cos\delta_o)}{R^2 + X_d X_q}$$

Hence,

$$\psi_{do} = e_o - X_d\, i_{do}$$

$$\psi_{qo} = -X_q\, i_{qo}$$

$$e_{do} = -\psi_{qo} - r_a\, i_{do}$$

$$e_{qo} = \psi_{do} - r_a\, i_{qo}$$

$$\therefore e_t = \sqrt{(e_{do})^2 + (e_{qo})^2} \qquad \ldots \qquad (22)$$

$$\text{Power} = e_{do}\, i_{do} + e_{qo}\, i_{qo} \qquad \ldots \qquad (23)$$

So, from the equation (22) and (23) terminal voltage for various values of K_1 and power at various value of K_1 is determined at various values of steady-state angle δ_o and plotted as shown in Fig.(15,16).

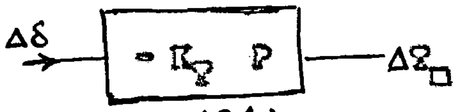
2.3. FORMATION OF BLOCK DIAGRAMS

Block diagram is formed from the equations obtained under the section 2.1 as follows.

From equation (2.1) i.e. $\Delta T_m = -K_2 P \Delta\delta$

Transfer fnc. $f_1(p) = \frac{\Delta T_m}{\Delta\delta} = -K_2 P$ ... (24)

This can be represented as follows in block diagram.



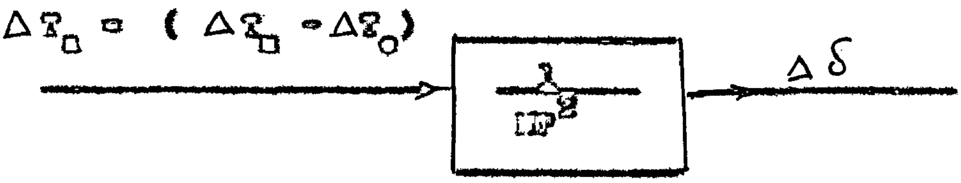
(2·1)

From equation (20),

Transfer function $f_2(p) = \frac{\Delta\delta}{\Delta T_m - \Delta T_e}$

$$f_2(p) = \frac{1}{Mp^2} \quad \ldots \quad (25)$$

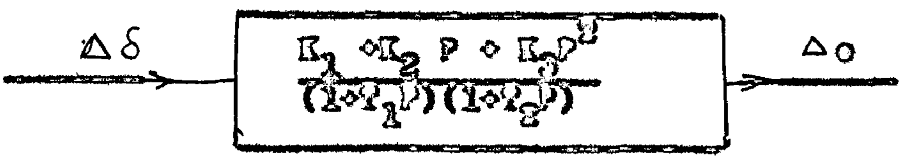
This can be represented in block diagram as mentioned below.



From equation (19) following transfer function is obtained-

$$f_3(p) = \frac{\Delta e}{\Delta\delta} = \frac{(K_1 + K_2 p + K_3 p^2)}{(1+T_1 p)(1+T_2 p)} \quad (26)$$

which is represented in block diagram as follows-



(2.3)

Now from equation (18), (18a) and (18b)-

$\Delta T_e = A_1(p)\,\Delta e_{gd} + A_2(p)\,\Delta\delta$

where,

$A_1(p)$ and $A_2(p)$ are defined in equation(18d) and (18e).

From these equations (18.1) and (18.2) the following equations are obtained as mentioned in appendix 2.

$$A_1(p) = A_1'(p).G(p)$$

where,

$$A_1'(p) = \frac{b_1 P^2 + b_2 P + b_3}{b_4 P^2 + b_5 P + b_6}$$

where ,

b_1, b_2, b_3, b_4, b_5 and b_6 are constant quantities depending on, a particular angle δ_o of the machine and machine and line constants etc. as defined by the equation 27.

$$b_1 = [i_{qo}(R^2 + xX_q) + (\phi_{do} + x_q i_{do}) R - \phi_{qo} X_q] T'_{do} T''_{do}$$

$$b_2 = [i_{qo}(R^2 + xX_q) + (\phi_{do} + x_q i_{do}) R - \phi_{qo} X_q](T'_{do} + T''_{do})$$

$$b_3 = [i_{qo} (R^2 + xX_q) + (\phi_{do} + x_q i_{do}) R - \phi_{qo} X_q]$$

$$b_4 = (R^2 + xX_q) T'_{do} T''_{do} + X_q x_d (T'_d T''_d)$$

$$b_5 = (R^2 + xX_q) (T'_{do} + T''_{do}) + X_d X_q (T'_d + T''_d)$$

$$b_6 = (R^2 + xX_q + x_d X_q) \qquad \ldots \qquad (27)$$

G(p) is already defined in earlier part of the Section (2.1)

And $A_2(p) = A_2'(p) + A_2''(p)$

where,

$$A_2'(p) = \frac{C_1 P^3 + C_2 P^2 + C_3 P + C_4}{b_4 P^2 + b_5 P + b_6}$$

Here C_1, C_2, C_3 are again constants, which are defined in equation (A-15) of Appendix 2, and b_4, b_5 and b_6 are same as mentioned earlier.

$A_2''(p)$ as obtained in equation (A-16) of Appendix 2.

$$A_2''(p) = \frac{C_5 P^3 + C_6 P^2 + C_7 P + C_8}{b_4 P^2 + b_5 P + b_6}$$

The C_5, C_6, C_7 and C_8 are defined in equations A-17. These are constant quantities for the particular angle δ_o.

$$\therefore A_2(p) = \frac{C_1p^3+C_2p^2+C_3p+C_4}{b_4p^2+b_5p+b_6} + \frac{C_5p^3+C_6p^2+C_7p+C_8}{b_4p^2+b_5p+b_6}$$

$$= \frac{b_7p^3+b_8p^2+b_9p+b_{10}}{b_4p^2+b_5p+b_6}$$

where, b_7, b_8, b_9, and b_{10} aare defined as follows:

$$b_7 = C_1+C_5=(R\phi_{do}+x\phi_{qo})T'_{do}T''_{do} + x_d\ \phi_{qo}T'_d\ T''_d +(R\phi_{qo}-X_q\phi_{do}).$$
$$(x_d i_{qo}T'_dT''_d + \phi_{qo}T'_{do}\ T''_{do}\ )$$

$$b_8 = C_2+C_6= [(R\phi_{do}+x\phi_{qo})(T'_{do}+T''_{do})+(RV\ \sin\delta_o+xV\cos\delta_o)T'_{do}T''_{do} +$$
$$x_d\phi_{qo}(T'_d+T''_d)+x_dV\text{Cos}\ _oT'_d\ T''_d)+[(R\phi_{qo}-X_q\phi_{do}).$$
$$[x_d i_{qo}(T'_d+T''_d)+\phi_{qo}(T'_{do}+T''_{do})]+(RV\ \text{Cos}\ _o-X_qV\ \sin\ _o).$$
$$(x_d i_{qo}T'_dT''_d+\phi_{qo}T'_{do}\ T''_{do})]$$

$$b_9 = C_3+C_7 =(R\phi_{do}+x\phi_{qo}+x_d\ \phi_{do})+(RV\ \sin\delta_o+xV\ \text{Cos}\delta_o).$$
$$(T'_{do}+T''_{do})+x_dV\ \text{Cos}\delta_o(T'_d+T''_d)+(x_d i_{qo}+\phi_{qo})(R\phi_{qo}-X_q\ \phi_{do})+$$
$$(RV\ \text{Cos}\delta_o-X_qV\ \sin\ )[X_d i_{qo}(T'_d+T''_d)+\phi_{qo}(T'_{do}+T''_{do})]$$

$$b_{10} = C_4+C_8 = RV\ \sin\ _o+xV\ \text{Cos}\ _o+ x_dV\ \text{Cos}\delta_o+(RV\text{Cos}\delta_o-X_qV\sin\delta_o).$$
$$(x_d i_{qo}+\phi_{qo}).$$

... (28)

$$\Delta T_e = A_1(p)\Delta e_{fd} + A_2(p)\Delta\delta$$
$$= A'_1(p).\ G(p)\ \ e_{fd} + [A'_2(p) + A''_2(p)\ ]$$
$$= \frac{b_1p^2+b_2p+b_3}{b_4p^2+b_5p+b_6}.\ G(p)\Delta e_{fd}+\frac{b_7p^3+b_8p^2+b_9p+b_{10}}{b_4p^2+b_5p+b_6}\Delta\delta$$

$$= \frac{b_1 p^2 + b_2 p + b_3}{b_4 p^2 + b_5 p + b_6} G(p) . \frac{r_{fd}}{X_{md}} . \Delta e + \frac{b_7 p^3 + b_8 p^2 + b_9 p + b_{10}}{b_4 p^2 + b_5 p + b_6} \Delta \delta$$

... (29)

or $\Delta T_e = \Delta T_{e1} + \Delta T_{e2}$

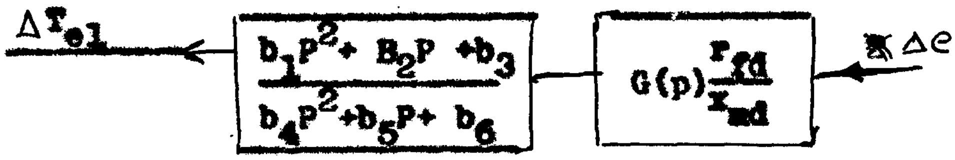
where,

$$T_{e1} = \frac{b_1 p^2 + b_2 p + b_3}{b_4 p^2 + b_5 p + b_6} . G(p) \frac{r_{fd}}{X_{md}} . \Delta e$$

.·. Transfer functions for ΔT_{e1} is-

$$f_4(p) = \frac{\Delta T_{e1}}{\Delta e} = \frac{b_1 p^2 + b_2 p + b_3}{b_4 p^2 + b_5 p + b_6} . G(p) \frac{r_{fd}}{X_{md}} \quad (30)$$

on block diagram it represented as follows-

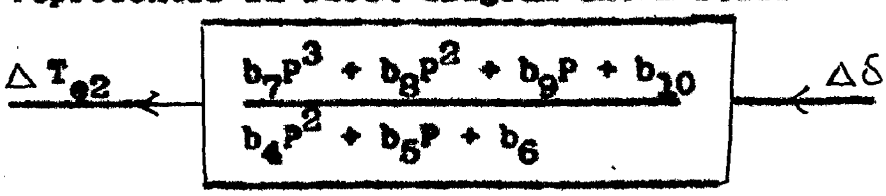


(2.4)

$$\Delta T_{e2} = \frac{b_7 p^3 + b_8 p^2 + b_9 + b_{10}}{b_4 p^2 + b_5 p + b_6} . \Delta \delta$$

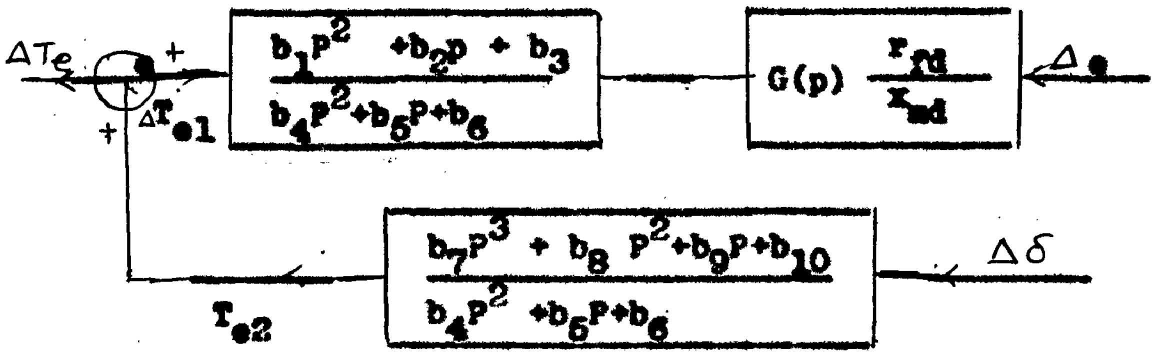
$$f_5(p) = \frac{\Delta T_{e2}}{\Delta \delta} = \frac{b_7 p^3 + b_8 p^2 + b_9 + b_{10}}{b_4 p^2 + b_5 p + b_6} \quad ... \quad (31)$$

It is represented in block diagram shown below-



(2.5)

Combining the two block diagram (2.4) and (2.5). The block diagram for obtaining ΔT_e is obtained as follows.



(2.6)

Now comparing the all the block diagrams i.e (2.1), (2.2) (2.3) and (2.6) complete block diagram is obtained as shown in Fig. 16.1

2.4. CHARACTERISTIC EQUATION:

Characteristic equation is obtained by reducing the block diagram and obtaining a single transfer function. This is now a form of control system.

Firstly reducing the three blocks in a row to a single one multiplying them.

$$f_4(p)=\frac{b_1p^2+b_2p+b_3}{b_4p^2+B_5p+b_6}\cdot\frac{1+T_{kd}\,p}{(T'_{do}p+1)(T''_{do}p+1)}\cdot\frac{x_{md}}{r_{fd}}\cdot\frac{r_{fd}}{x_{md}}$$

$$f_4(p)=\frac{b_1T_{kd}p^3+(b_1+b_2T_{kd})p^2+(b_2+b_3T_{kd})p+b_3}{(b_4p^2+b_5p+b_6)[T'_{do}T''_{do}p^2+(T'_{do}+T''_{do})p+1]} \qquad (32)$$

$$f_7(p)=\frac{\Delta T_{e1}}{\Delta\delta}=f_4(p).f_3(p)=\frac{(K_1+K_2p+K_3p^2)}{(1+T_1p)(1+T_2p)}\cdot$$

$$\frac{b_1T_{kd}p^3+(b_1+b_2T_{kd})p^2+(b_2+b_3T_{kd})p+b_3}{(b_4p^2+b_5p+b_6)[T'_{do}T''_{do}p^2+(T'_{do}+T''_{do})p+1]}$$

$$=\frac{(K_1+K_2p+K_3p^2)}{[1+(T_1+T_2)p+T_1T_2p^2]}\cdot\frac{b_1T_{kd}p^3+(b_1+b_2T_{kd})p^2+(b_2+b_3T_{kd})p+b_3}{[T'_{do}T''_{do}p^2+(T'_{do}+T''_{do})p+1](b_4p^2+b_5p+b_6)} \qquad \ldots (33)$$

Now total transfer function for ΔT_e -

$$f_8(p) = \frac{\Delta T_e}{\Delta \delta} = \frac{\Delta T_{e1}}{\Delta \delta} + \frac{\Delta T_{e2}}{\Delta \delta}$$

$$= f_7(p) + f_5(p)$$

$$f_8(p) = \frac{\dfrac{(K_1+K_2P+K_3P^2)(C_9P^3+C_{10}P^2+C_{11}P+C_{12})+(b_7P^3+b_8P^2+b_9P+b_{10})}{(1+C_{13}P+C_{14}P^2+C_{15}P^3+C_{16}P^4)(b_4P^2+b_5P+b_6)}}{(C_{16}P^4+C_{15}P^3+C_{14}P^2+C_{13}P+1)}$$

... (34)

where,

$C_9 = b_1T_{kd};$

$C_{10} = (b_1 + b_2 T_{kd}),$

$C_{11} = (b_2 + b_3 T_{kd})$

$C_{12} = b_3,$ (35)

$C_{13} = (T_1 + T_2 + T'_{do} + T''_{do}),$

$C_{14} = (T'_{do} + T''_{do})(T_1 + T_2) + T_1T_2 + T'_{do} T''_{do}$

$C_{15} = T_1T_2 (T'_{do} + T''_{do}) + T'_{do} T''_{do} (T_1 + T_2)$

$C_{16} = T_1T_2 T'_{do} T''_{do}$

Expanding equation (28) above by multiplying as obtained in appendix 4 (equation A-22).

$$f_8(p) = \frac{d_1P^7+d_2P^6+d_3P^5+d_4P^4+d_5P^3+d_6P^2+d_7P+d_8}{d_9P^6+d_{10}P^5+d_{11}P^4+d_{12}P^3+d_{13}P^2+d_{14}P+d_{15}}$$

... (36)

where, $d_1, d_2, d_3 \ldots\ldots d_{15}$ etc. are constants defined as below.

$d_1 = b_7C_{16};$

$d_2 = (b_8C_{16}+b_7C_{15}),$ (37)

$d_3 = (b_7C_{14} + b_8 C_{15} + K_3C_9)$

$$d_4 = (b_7C_{13} + b_8C_{14} + b_9C_{15} + K_3C_{10} + K_2C_9)$$

$$d_5 = (b_7 + b_8C_{13} + b_9C_{14} + b_{10}C_{15} + K_3C_{11} + K_2C_{10} + K_1C_9)$$

$$d_6 = (b_8 + b_9C_{13} + b_{10}C_{14} + K_3C_{12} + K_2C_{12} + K_2C_{11} + K_1C_{10})$$

$$d_7 = (b_9 + b_{10}C_{13} + K_2C_{12} + K_1C_{11}); \; d_8 = (K_1C_{12} + b_{10}) \qquad (37)$$

$$d_9 = C_{16}b_4;$$

$$d_{10} = (C_{16}b_5 + C_{15}b_4);$$

$$d_{11} = (C_{16}b_6 + C_{15}b_5 + C_{14}b_4)$$

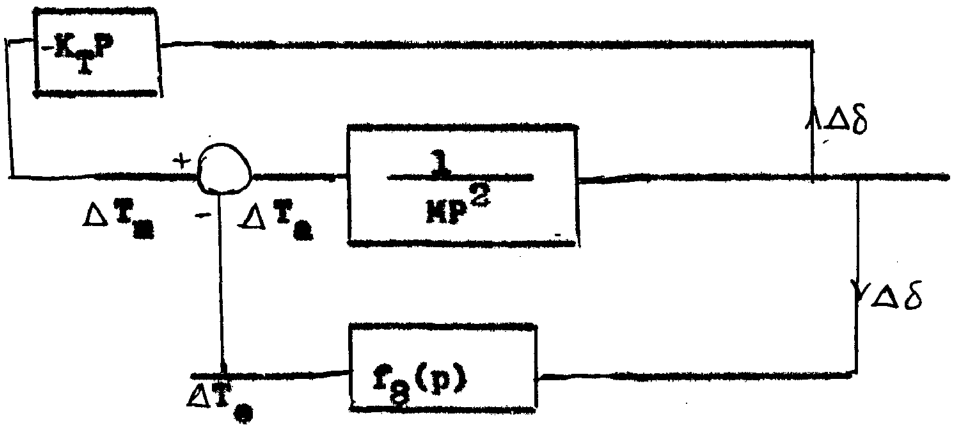
$$d_{12} = (C_{15}b_6 + C_{14}b_5 + C_{13}b_4);$$

$$d_{13} = (C_{14}b_6 + C_{13}b_5 + b_4);$$

$$d_{14} = (C_{13}b_6 + b_5)\ C$$

$$d_{15} = b_6$$

Hence the block diagram is reduced to as shown in Fig.(   )



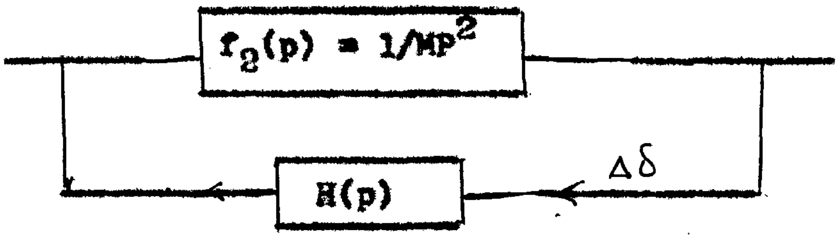
Now from block diagram (Fig.16.2) it is clear that the two feed back paths are there, one through $f_8(p)$ and another through turbine transfer function $f_1(p) = -K_TP$. Combining these two transfer functions, the total feedback transfer function is $H(p)$ is obtained-

$$-H(p) = f_8(p) - f_1(p)$$

$$= f_8(p) + K_TP.$$

$$H(p) = \frac{[(d_1+K_T d_9)P^7 + (d_2+K_T d_{10})P^6 + (d_3+K_T d_{11})P^5 + (d_4+K_T d_{12})P^4 + (d_5+K_T d_{13})P^3 + (d_6+K_T d_{14})P^2 + (d_7+K_T d_{15}) + d_8]}{d_9 P^6 + d_{10}P^5 + d_{11}P^4 + d_{12}P^3 + d_{13}P^2 + d_{14}P + d_{15}} \qquad \ldots \quad (38)$$

Therefore, now block diagram is reduced to the form of a feedback system as shown-



The characteristic equation is obtained as follows from the block diagram.

$$1 + f_2(p)\, H(p) = 0$$

$$\therefore 1 + \frac{1}{MP^2}\left[\frac{[(d_1+K_T d_9)P^7 + (d_2+K_T d_{10})P^6 + (d_3+K_T d_{11})P^5 + (d_4+K_T d_{12})P^4 + (d_5+K_T d_{13})P^3 + (d_6+K_T d_{14})P^2 + (d_7+K_T d_{15})P + d_8]}{d_9 P^6 + d_{10}P^5 + d_{11}P^4 + d_{12}P^3 + d_{13}P^2 + d_{14}P + d_{15}}\right] = 0 \qquad \ldots \quad (39)$$

Expanding above equation following equation is obtained as in appendix 4.

or $a_0 P^8 + a_1 P^7 + a_2 P^6 + a_3 P^5 + a_4 P^4 + a_5 P^3 + a_6 P^2 + a_7 P + a_8 = 0$

$$\ldots \quad (40)$$

where, constants $a_0, a_1 \ldots\ldots a_8$ are constant quantities as defined under.

$$a_0 = d_9 M \qquad (41)$$

$$a_1 = (d_{10}M + d_1 + K_T d_9);$$

$$a_2 = (d_{11}M + d_2 + K_T d_{10})$$

$a_3 = (d_{12}M + d_3 + K_T d_{11});$

$a_4 = (d_{13}M + K_T d_{12} + d_4);$

$a_5 = (d_{14}M + d_5 + K_T d_{13});$ (41)

$a_6 = (d_{15}M + K_T d_{14} + d_5);$

$a_7 = (d_7 + K_T d_{15});$

$a_8 = d_8$

... ~~(37)~~

where, d_1, d_2......d_{15} are defined in equation (37).

2.4. COEFFICIENTS OF CHARACTERISTIC EQUATION:

Coefficients of the characteristic equation are as given in equation (41) of section 2.3. From the equations (41), it is clear that a_8, is independent of turbine constant and inertia constant and a_o is independent of turbine constant. Whereas, a_7 is independent of inertia constant. As the problem is to see the effect of gain constants of the regulator the equations (36) are modified, as follows, so that from the equations itself the effect of angle regulator gain constants can be visualized. By putting the values of d_1, d_2, d_3, d_4, d_5 and d_7, d_8 in the equation (41) the following equations are obtained.

$a_o = d_{16},$

$a_1 = d_{17}$

$a_2 = d_{18};$

$a_3 = d_{19} + K_3C_9;$

$a_4 = d_{20} + K_3C_{10} + K_2C_9;$

$a_5 = d_{21} + K_3C_{11} + K_2C_{10} + K_1C_9;$

$a_6 = d_{22} + K_3C_{12} + K_2C_{11} + K_1C_{10}$

$a_7 = d_{23} + K_2C_{12} + K_1C_{11}$

$a_8 = K_1 C_{12} + b_{10}$ .... (42)

where,

$$d_{16} = d_9 M$$

$$d_{17} = (d_{10} M + d_1 + K_1 d_9)$$

$$d_{18} = (d_{11} M + K_1 d_{10} + d_2)$$

$$d_{19} = (d_{12} M + K_1 d_{11} + b_7 c_{14} + b_8 c_{15})$$

$$d_{20} = (d_{13} M + K_1 d_{12} + b_7 c_{13} + b_8 c_{14} + b_9 c_{15})$$

$$d_{21} = (d_{14} M + K_1 d_{13} + b_7 + b_8 c_{13} + b_9 c_{14} c_{14} + b_{10} c_{15})$$

$$d_{22} = d_{15} M + K_1 d_{14} + b_8 + b_9 c_{13} + b_{10} c_{14}$$

$$d_{23} = K_1 d_{15} + b_9 + b_{10} c_{13} + b_{11} c_{15}$$

... (43)

where,

$d_1, d_2, d_3 \ldots\ldots d_{15}$ are defined in equation (37)

$c_9, c_{10} \ldots\ldots c_{16}$ defined in equation (38)

$b_1, b_2 \ldots\ldots b_6; b_7, b_8, b_9, b_{10}$ are defined in equations (37) and (38).

From the equations (42) it is clear that the effect of K_1 is on coefficients $a_9, a_7, a_6,$ and a_5, K_2 is on a_7, a_6, a_5 and a_4; and that of K_3 is on a_6, a_5, a_4 and a_3 i.e. a_8 independent of K_2 and K_3. a_7 is independent of K_3. It means that by changing gain constants of the angle regulator the coefficients of the characteristic equation can be changed to improve the stability of the system. The coefficients a_0, a_1 and a_2 are independent of gain constants of the regulator.

The coefficients of the characteristic equation as shown in equation (43) are compared with the coefficients of the characteristics equation obtained by Venikov[8] for an electronic angle regulator, and it is found that the dependence of the coefficients on K_1, K_2, K_3 is similar to that. The coefficients obtained by

Venikov are affected as given below for a characteristic equation of the order of 7.

K_1 affects the coefficients a_7, a_6 and a_5.

K_2 affects the coefficients a_6 and a_5.

K_3 affects the coefficients a_5 and a_4.

The coefficients of the characteristic equation are calculated by the help of digital computer for various values of load angle (δ_o) ranging from 60 - 120° for the gain constants as shown below.

(i) $K_1 = 1.59$, $K_2 = K_3 = 0$

(ii) $K_1 = 1.59$ $K_2 = K_3 = 10$

(iii) $K_1 = 1.26116$ $K_2 = 0$, $K_3 = 0$

(iv) $K_1 = 1.26116$ $K_2 = 10$, $K_3 = 0$

(v) $K_1 = 1.26116$ $K_2 = 10$, $K_3 = 10$

and tabulated as shown in Tables 1-5.

Variation of various coefficients with angle δ_o is shown in graph plotted (Fig. 16.3) on a semilog paper for $K_1 = 1.59$ with $K_2 = 10$ and $K_3 = 10$. From the various tables and this graph it is seen that a_0, a_1, a_2 and a_4 having no appreciable change in its values for various angles. The most important coefficients seems to be a_3, a_7 and a_6 which are to be controlled not to become negative, other coefficients are nearly straight lines having a slope of about 120° with angle axis.

One graph is plotted for a_3, a_7, a_6 with various values of angle δo for two values of K_1 from table 1 and 3 shown in Fig. (17) showing the effect of K_1 on these coefficients. Another graph as

VALUES OF COEFFICIENTS FOR $K_1 = 1.59$, $K_2 = 0$, $K_3 = 0$

Angle in degree	A_0	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8
60	$.134190\times10^{-6}$	$.120497\times10^{-3}$	$.356934\times10^{-1}$	$.361434\times10$	$.447268\times10^{2}$	$.639332\times10^{2}$	$.35562\times10^{2}$	$.164523\times10^{2}$	$.323965\times10$
70	-do-	$.120493\times10^{-3}$	$.356897\times10^{-1}$	$.361298\times10$	$.445956\times10^{2}$	$.623062\times10^{2}$	$.330259\times10^{2}$	$.149085\times10^{2}$	$.295453\times10$
80	-do-	$.120487\times10^{-3}$	$.356836\times10^{-1}$	$.361149\times10$	$.444549\times10^{2}$	$.605362\times10^{2}$	$.299005\times10^{2}$	$.127139\times10^{2}$	$.251780\times10$
90	-do-	$.120482\times10^{-3}$	$.356783\times10^{-1}$	$.361000\times10$	$.443160\times10^{2}$	$.587513\times10^{2}$	$.262750\times10^{2}$	$.994384\times10$	$.194835\times10$
100	-do-	$.120477\times10^{-3}$	$.356734\times10^{-1}$	$.360863\times10$	$.441895\times10^{2}$	$.570756\times10^{2}$	$.222518\times10^{2}$	$.667393\times10$	$.126379\times10$
110	-do-	$.120473\times10^{-3}$	$.356694\times10^{-1}$	$.360750\times10$	$.440872\times10^{2}$	$.556465\times10^{2}$	$.179952\times10^{2}$	$.301396\times10$	$.486521$
115	-do-	$.120472\times10^{-3}$	$.356678\times10^{-1}$	$.360707\times10$	$.440484\times10^{2}$	$.550649\times10^{2}$	$.158397\times10^{2}$	$.107581\times10$	$.704510\times10^{-7}$
120	-do-	$.120470\times10^{-3}$	$.356666\times10^{-1}$	$.360675\times10$	$.440195\times10^{2}$	$.545922\times10^{2}$	$.137684\times10^{2}$	$-.909279$	$.35926.$

Angle in degree	A_0	I							
60	$.134190\times10^{-6}$	$.120497\times10^{-3}$	$.356934\times10^{-1}$	0.361434×10	$.448986\times10^{2}$	$.101193\times10^{3}$	$.843966\times10^{2}$	$.281986\times10^{2}$	$.323965\times10$
70	-do-	$.120493\times10^{-3}$	$.356887\times10^{-1}$	0.361298×10	$.447835\times10^{2}$	$.103059\times10^{3}$	$.864386\times10^{2}$	$.277560\times10^{2}$	$.295453\times10$
80	-do-	$.120487\times10^{-3}$	$.356836\times10^{-1}$	0.361149×10	$.446543\times10^{2}$	0.103798×10^{3}	$.866019\times10^{2}$	$.277560\times10^{2}$	$.295453\times10$
90	-do-	$.120482\times10^{-3}$	$.356783\times10^{-1}$	$.361000\times10$	$.445221\times10^{2}$	$.103476\times10^{3}$	$.848936\times10^{2}$	$.240435\times10^{2}$	$.194836\times10$
100	-do-	$.120477\times10^{-3}$	$.356734\times10^{-1}$	$.360863\times10$	$.443976\times10^{2}$	$.102205\times10^{3}$	$.814011\times10^{2}$	$.209013\times10^{2}$	$.126374\times10$
110	-do-	$.120473\times10^{-3}$	$.356694\times10^{-1}$	$.360750\times10$	0.442923×10^{2}	$.100132\times10^{3}$	$.763002\times10^{2}$	$.170382\times10^{2}$	$.486521$
115	-do-	$.120472\times10^{-3}$	$.356678\times10^{-1}$	$.360707\times10$	$.442503\times10^{2}$	$.988467\times10^{2}$	$.732223\times10^{2}$	$.148782\times10^{2}$	$.704510\times10$
120	-do-	$.120470\times10^{-3}$	$.356666\times10^{-1}$	$.360675\times10$	$.442169\times10^{2}$	$.974272\times10^{2}$	$.698471\times10^{2}$	$.125946\times10^{2}$	$.359260$

VALUES OF COEFFICIENTS FOR $K_1 = 1.26116$ $K_2 = 0.$ $K_3 = 0$

Angle θ	a_3	a_4	a_5	a_6	a_7	a_8
60°	.361475x10	.447797x10^2	64.54797	356159x10^2	.141637x10^2	.252037x10
70°	.361355x10	.446679x10^2	.631786x10^2	.336626x10^2	.127341x10^2	.222789x10
80°	.361233x10	.445471x10^2	.616812x10^2	.311769x10^2	.10822x10^2	.182509x10
90°	.361090x10	.444273x10^2	.601662x10^2	.282009x10^2	.849602x10	.133030x10
100°	.360967x10	.443178x10^2	.58742x10^2	.250799x10^2	.581653x10	.759132x10
110°	.360867x10	.442291x10^2	.575281x10^2	.216715x10^2	.28706x10	.129792x10
120°	.360799x10	.441703x10^2	.566363x10^2	.182258x10^2	.245703	-.539674x10

TABLE 4

VALUES OF COEFFICIENTS FOR $K_1 = 1.26116$, $K_2 = 10K_3 = 0$

Angle	a_3	a_4	a_5	a_6	a_7	a_8
60	.361475x10	.447798x10^2	.646646x10^2	.392839x10^2	.153032x10^2	.252037x10
70	.361355x10	.446679x10^2	.631968x10^2	.375898x10^2	.139779x10^2	.222789x10
80	.361233x10	.445471x10^2	.617005x10^2	.353354x10^2	.121396x10^2	.182609x10
90	.361090x10	.444273x10^2	.601662x10^2	.32576x10^2	.985334x10	.134303x10
100	.360967x10	.443178x10^2	.587619	.293874x10^2	.718076x10	.7599132
110	.360867x10	.442291x10^2	.575477x10^2	.258964x10^2	.420676x10	.129792
120	.360799x10	.441703x10^2	.566550x10^2	.222680x10^2	.103511x10	.539674

TABLE 5

VALUES OF COEFFICIENTS FOR K = 1.96116 K_2=10, K_3=10.

Angle	a_3	a_4	a_5	a_6	a_7	a_8
60°	.361475x10	$.449462 \times 10^2$	$.100544 \times 10^3$	$.506792 \times 10^2$	$.153032 \times 10^2$	.252037x10
70°	.361355x10	$.448496 \times 10^2$	$.102469 \times 10^3$	$.500278 \times 10^2$	$.139779 \times 10^2$	.222789x10
80°	.361233x10	$.447396 \times 10^2$	$.103285 \times 10^3$	$.485068 \times 10^2$	$.121396 \times 10^2$	.182609x10
90°	.361090x10	$.446256 \times 10^2$	$.103042 \times 10^3$	$.461497 \times 10^2$	.985334x10	.13303x10
100°	.369967x10	$.445178 \times 10^2$	$.101836 \times 10^3$	$.430297 \times 10^2$	.718076x10	.7509132
110°	.360867x10	$.444246 \times 10^2$	$.997966 \times 10^2$	$.392772 \times 10^2$	.420876x10	.129792
120°	.360799x10	$.443573 \times 10^2$	$.970762 \times 10^2$	$.350699 \times 10^2$	.420876x10	-.539674

shown in Fig.(18) is plotted, for the one value of K_1 with K_2=0 and 10 and K_3 = 0 showing the effect of variation of K_2 on the coefficients at various values of angles; a graph is also plotted showing the effect K_3 shown in Fig.(19) with one value of K_1 = 1.23116, K=10 and K_3 = 0, and 10.

From the above mentioned graphs the effects of K_1, K_2, K_3 on the coefficients is seen i.e. how they vary by varying these gain constants in the range of angles from 60° to 120°.

K_1 is having effects on a_8, a_7 and a_6 only and it has got no effect on other coefficients. By increasing the value of K_1, a_8 and a_7 are increasing whereas a_6 is reducing as shown in the graph Fig.(17).

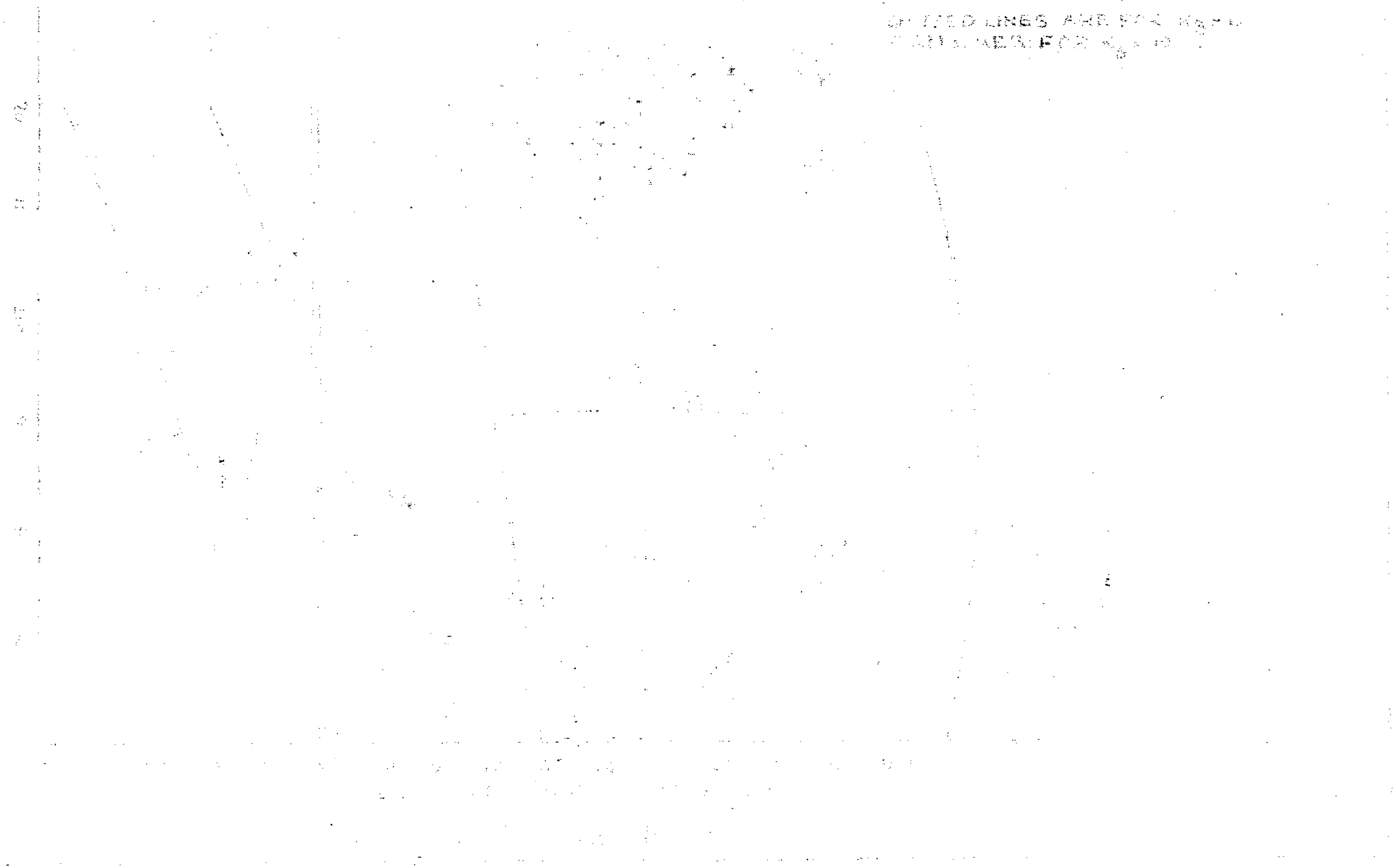
K_2 has effects on a_7, a_6 and a_5 only as shown in the Fig. 18. It has got very less effect on a_5. Mostly it improves a_7 and a_6 on other coefficients it has either negligible effect or not at all.

Effect of K_3 is shown on graph Fig.(19). It has got effect mainly on a_6 and a_5; a_4 is also affected very less; other coefficients are not affected by K_3.

2.5. STABILITY ANALYSIS

The stability analysis of the system is carried out by routh hurwitz criterion as mentioned in Chapter 1 for a particular angle δ_o; for this purpose constant a_0, a_1......a_8 are to be calculated for a particular angle δ_o and then routh hurwitz criteria is applied. A programme for digital computer has been made for the calculation of the coefficients and stability criteria. The stability limit under these conditions has been found for various values of K_1 (gain constant for the regulator with $K_2 = K_3 = 0$ and $K_2 = K_3 = 10$ but it was found that the limit achieved by

EFFECT OF GAIN CONSTANT K_3 ON COEFFICIENTS



K_1 is not increased by K_2 and K_3. It is due to the fact that machine and system constants are such that stability limit is only governed by the K_1 only.

From the graphs plotted for two values of K_1 coefficients a_9, a_7, a_8 shown in Fig.(17), it can be seen that a_9 becomes negative earlier to a_7 and a_8 so the improvement is not possible in stability limit by K_2 and K_3. Although the constants are improved for more stability limit by K_2 and K_3 but a_9 becomes negative so the system becomes unstable as a_9 is not affected by K_2 and K_3.

The stability limit of the system for various values K_1 is calculated in terms of angle δ_o and then from power angle curves obtained for various values of K_1; the stability limit, for various values of K_1 is found out, in terms p.u. power. It is tabulated as shown in Table 6 and the variation of stability limit is shown on the graph against the variation of K_1 Fig.(20).

TABLE 6

STABILITY LIMIT VARIATION WITH VARIATION OF K_1

S.No.	Values of K_1	Maximum value of δ_o	Power limit p.u.
1	0	70°	.720
2	.31529	80°	1.037
3	.63058	90°	1.42
4	.94587	100°	1.86
5	1.23	110°	2.30
6	1.89	115°	2.80

2.5.1. Application of the modified Routh Hurwitz Method[18]

For finding the value of K_2 and K_3 at 115^o load angle with $K_1 = 1.59$.

From equations (42) of section (2.4) it is seen that a_o, a_1, a_2 and a_8 are independent of K_2 and K_3. Other coefficients are depending upon the K_2 and K_3. By the help of digital computer the quantities associated with K_2 and K_3 such as C_9, C_{10}, C_{11}, C_{12} are calculated seperately and other constant quantities of the coefficients are calculated seperately, and the equation for the coefficients is given below in equation (44) for equation (39)

$$a_o = 0.134190 \times 10^6$$
$$a_1 = 0.120472 \times 10^{-3}$$
$$a_2 = 0.356676 \times 10^{-1}$$
$$a_3 = 0.367016 \times 10 + K_3(.205953 \times 10^{-4})$$
$$a_4 = 0.440431 \times 10^2 + K_3(.201010 \times 10^{-1}) + K_2(.20995 \times 10^{-4})$$
$$a_5 = 0.549815 \times 10^{+2} + K_3(.434453 \times 10) + K_2(.20101 \times 10^{-1})$$
$$a_6 = .154959 \times 10^2 + K_3(.137597 \times 10) + K_2(0.434453 \times 10)$$
$$a_7 = .760758 + K_2(.137597 \times 10)$$
$$a_8 = .250170 \times 10^{-2} \qquad \ldots \qquad (44)$$

Analysis is done as follows.

$$\mu_1(t) = a_8 - a_6 t + a_4 (t)^2 + a_2 t^3 + a_o t^4 = 0$$
$$\lambda_1(t) = a_7 - a_5 t + a_3 t^2 + a_1 t^3 = 0 \qquad \ldots \qquad (45)$$

The equations (45) must have all positive real distinct roots for stability of the system.

Therefore,

$$\lambda_1(-t) = a_7 + a_5 t + a_3 t^2 + a_1 t^3$$
$$\mu_1(-t) = a_8 + a_6 t + a_4 t^2 + a_2 t^3 + a_o t^4 \qquad \ldots \qquad (45.1)$$

must have no positive real roots.

Hence,

$$\lambda_{11}(t) = a_7 - a_3 t = 0$$

$$\lambda_{12}(t) = a_5 - a_1 t = 0 \qquad \ldots. \qquad (45.2)$$

$$\mu_{11}(t) = a_8 - a_4 t + a_0 t^2$$

$$\mu_{12}(t) = a_6 - a_2 t = 0 \qquad \ldots \qquad (45.3)$$

must have all positive real roots and the roots of $\lambda_1(+t)$ and $\mu_1(t)$ must be interlacing, so roots of $\lambda_{11}(t)$, $\lambda_{12}(t)$ and $\mu_{11}(t)$ $\mu_{12}(t)$ must also be interlacing.

From equation 45.2 for condition of positive real root and other condition; following conditions are seen by inspection.

a_7 and a_3 both should be greater than zero.

a_5 and a_1 both should be greater than zero.

as a_1 is constant quantity.

$\therefore$ a_5; a_3; a_7 (greater than) > 0 ... (46)

From equation (44) putting the values a_5; a_3; a_7 in (46) we see-

$$0.367016\text{x}10 + K_3(.209953\text{x}10^{-4}) > 0 \qquad \ldots \qquad (46.1)$$

$$0.549815\text{x}10^2 + K_3(.434453\text{x}10) + K_2(.20101\text{x}10^{-1}) > 0 \qquad (46.2)$$

$$0.760758 + K_2\ (.137597)\text{x}10 \text{ (greater than)} > 0 \qquad (46.3)$$

From equation 45.3 for positive real roots

$$+a_4 \pm \sqrt{a_4^2 - 4.a_0\ a_8} \text{ (greater than)} > 0 \qquad \ldots \qquad (47)$$

$$a_6;\ a_2 \text{ (greather than)} > 0 \ \ldots \qquad \ldots \qquad (48)$$

or by putting the values of co-efficients following equations are obtained.

$$.154959\text{x}10^2 + K_3(.137597) + K_2(.434453\text{x}10) \text{ greater than } 0$$

...(48.1)

and as a_0 and a_8 are constant quantities and are positive and

and the product of a_0 and a_3 lesser than a_4^2 as can be seen from eqn. (44). Therefore,

$$a_4 \pm \sqrt{a_4^2 - a_0\, a_8} \text{ (is greater than)} > 0$$ will have the condition.

a_4 (is greather) > 0

or $.400991 \times 10^2 + K_3(.20101 \times 10^{-1}) + K_2(.202953 \times 10^{-4}) > 0$

... (49)

By inspection from equations (46.1), (48.2), (46.3), (48.1) and (49) it can be seen that K_2 and K_3 are not affecting conditions mentioned above what-so-ever positive value of these constants chosen; even at $K_2 = K_3 = 0$, the above mentioned conditions are fulfilled. So the system stability here is not affected by the K_2 and K_3.

8.0. CONCLUSIONS:

1. The Co-efficients plotted on the graph sheet shows that the effect of gain constants K_1, K_2 and K_3 improves the coefficients for improving the stability.

2. As shown in the graphs K_1 affects the co-efficients a_3, a_7 and a_8; K_2 affects a_7, a_3 and a_5 but effect K_2 on a_5 is not appreciable. K_3 affects the a_3, a_8, and a_4 but here also a_4 is very less affected by K_3. Hence this result is identical to that obtained by Venikov.

3. The effect K_2 and K_3 is not there on the stability limit of the system considered as can be seen from the coefficients plotted that a_3 becomes negative earlier than a_7 and a_8 etc. so the system stability is governed by the K_1 only. The effect of K_2 and K_3 is also seen by Routh - Hurwitz Criterion and found that K_2 and K_3 has no effect on the system stability. The stability of the system is also analysed for $K_1 = 1.50$ at load angle $\delta = 116°$,

the effect of K_2 and K_3 is not found there also.

4. Stability limit increases as the gain constant K_1 of the regulator increases graph plotted in section 2.5 Fig.(20) shows the variation of the stability limit with K_1.

CHAPTER 3

STATE SPACE APPROACH FOR STABILITY ANALYSIS:

3.1. INTRODUCTION:

The techniques used generally for the analysis of synchronous machine operation in the dynamic stability region has followed traditionally the analysis of piece wise linear model. The methods used have been those used in servomechanics such as criteria of Routh or Nyquist or the pole zero method. However, a simple alternative is, with modern system analysis, to formulate the linearised problem, not in terms of a single high order differential equation, but in terms of sets of first order differential equations. It means that instead of writing high order differential equations for the system, additional variables are defined and the system is described by a set of first order-differential equations. In matrix form these set of differential equations are put and the investigations are done by using the matrix algebra. In matrix form, for a linear, time invariant system,

$$\dot{X} = A X + B U \qquad \ldots \qquad (30)$$
$$Y = C X$$

where,

X is a vector of state variables.

U is a vector of system inputs

Y is a vector of system outputs.

A, B and C are matrices.

3.2. In the case of the dynamic stability analysis of the power system considered, the turbine, the generator and its regulating equipment are considered to constitute an integral system. The stability of this system when disturbed from a stable operating point is to be analysed. Hence the state equation of the entire system can be written as-

$$\dot{X} = A X \quad \ldots \qquad \ldots \qquad (51)$$

It can be proved that the solution of (51) is stable if all the eigen values of A lie on the left hand side of the imaginary axis. Hence it is necessary only to find the eigen value of A to determine the stability. The methods of finding the eigen values of A are given in section 3.4.2. The use of Liapunov's second theorem is explained in section 3.4.1.

3.3. FORMATION OF CHARACTERISTIC MATRIX:

The first order differential equations are formed, the system equation as obtained in the appendix 3.5, which are summarised here to put them into matrix form or rather in vector differential form. Here the system considered for the same system as considered earlier except few changes that a generalised system is considered which has got a machine with one damper winding in each d and q axis and the excitation system considered consisting of both voltage proportional signal, and proportional signal to angle δ_o with its derivatives, so that when only voltage regulator is considered for analysis the gain constants of angle proportional signal can be kept constant and when angle regulator is considered only the gain constants of voltage regulator signal are kept to be zero. Leaving these minute differences other things are remaining the same and hence other assumptions made earlier are valid in this case also. The equations (A-32 to A-49) obtained in appendix as follows

$$p\Delta\phi_{d1} = -\frac{\Delta\phi_{d1}}{T'_{do}} + \frac{B_1\Delta e_{fd}}{T'_{do}} \quad \ldots \qquad \ldots \qquad (52)$$

$$p\Delta\phi_{d2} = -\frac{\Delta\phi_{d2}}{T'_{do}} + \frac{B_2\Delta e_{fd}}{T'_{do}} \quad \ldots \qquad \ldots \qquad (53)$$

$$p\ \phi_{d3} = -\frac{\Delta\phi_{d3}}{T'_{do}} + \frac{x_d\Delta i_d}{T'_{do}} \qquad \ldots \qquad (54)$$

$$P\Delta\phi_{d4} = \frac{T_{1d}\ x_d\ P\Delta i_d}{T'_{do}} = -\frac{\Delta\phi_{d4}}{T'_{do}} \qquad (55)$$

$$P\Delta\phi_{d5} = \frac{T_{2d}\ x_d\ P\Delta i_d}{T''_{do}} = -\frac{\Delta\phi_{d5}}{T''_{do}} \qquad (56)$$

where,

$$\Delta\phi_d = \Delta\phi_{d1} + \Delta\phi_{d2} - \Delta\phi_{d3} - \Delta\phi_{d4} - \Delta\phi_{d5}$$

and $T_{1d} = \dfrac{T'_d\ T''_d - (T'_d + T''_d)T'_{do} + T''_{do}T'_{do}}{(T''_{do} - T'_{do})}$, $B_1 = 1 + + \dfrac{1 - T_{kd}}{T'_{do} - T''_{do}}$

and $T_{2d} = \dfrac{T'_d T''_d - (T'_d + T''_d)T''_{do} + T''_{do} + T''^2_{do}}{(T''_{do} - T'_{do})}$; $B_2 = -\dfrac{1 - T_{kd}}{T'_{do} - T''_{do}}$

(56.1)

$$P\Delta\phi_q + \frac{T''_q\ x_q\ P\Delta i_q}{T''_{qo}} - p\Delta i_q = -\frac{\Delta\phi_q}{T''_{qo}} \frac{x_q}{T''_{qo}} \Delta i_q \qquad (57)$$

$$P\Delta i_d = \frac{1}{B_3}\Big[-\frac{\Delta\phi_{d1} + \Delta\phi_{d3} + \Delta\phi_{d4}}{T'_{do}} + \frac{-\Delta\phi_{d2} + \Delta\phi_{d5}}{T''_{do}} -$$

$$\left(\frac{x_d}{T'_{do}} + R\right)\Delta i_d - w_o\Delta\phi_q - \phi_{qo}\, n + x\,\Delta i_q - V\cos\delta_o +$$

$$\left(\frac{B_1}{T'_{do}} + \frac{B_2}{T''_{do}}\right)\Delta e_{fd}\Big] \quad \ldots \qquad (58)$$

where,

$B_3 = \left(\dfrac{T_{1d}}{T'_{do}} + \dfrac{T_{2d}}{T''_{do}}\right) x_d$ and B_1 and B_2 are defined earlier.

$$P\Delta i_q = \frac{1}{B_4}\Big[-\frac{\Delta\phi_q}{T''_{qo}} - \left(\frac{x_q}{T''_{qo}} + R\right)\Delta i_q + V\sin\delta_o + w_o\Delta\phi_d +$$

$$\phi_{do}\, n - x\,\Delta i_d\Big] \quad \ldots \quad \ldots \qquad (59)$$

where,

$$B_4 = \frac{T''_q}{T''_{qo}}\ x_q$$

Equations for regulating systems are as follows:

$$P\Delta\delta = n \quad \ldots \quad \ldots \qquad (60)$$

$$P\Delta e_{fd} = \Delta e'_{fd} \quad \ldots \quad \ldots \qquad (61)$$

$$p\Delta e'_{fd} - \frac{K_3}{T_1T_2}\, p\eta = K_1\Delta\delta + [K_2 + (\phi_{qo}\sin_{10} - \phi_{do}\cos_{10})K_r]\eta +$$

$$K_r v_o \sin\delta_{10}\Delta\phi_q - K_r v_o\cos\delta_{10}\Delta\phi_d +$$

$$K_r r_a \sin\delta_{10}\Delta i_d + K_r V_a\cos\delta_{10}\Delta i_q -$$

$$\Delta e_{fd} - (T_1+T_2)\Delta e'_{fd} \qquad (62)$$

where,

$$\sin\delta_{10} = \frac{e_{do}}{e_{to}} \quad \cos\delta_{10} = \frac{e_{qo}}{e_{to}} \qquad (62.1)$$

$$p\eta = +\frac{K_m\eta}{M} - \frac{i_q}{M}\Delta\phi_d - \frac{\phi_{do}}{M}\Delta i_q + \frac{i_{do}}{M}\Delta\phi_q + \frac{\phi_{qo}\Delta i_d}{M} \qquad (63)$$

when these twelve equations are put in matrix form we get a vector differential equation as shown below:

$$B\dot{X} = EX \quad \ldots \quad \ldots \qquad (64)$$

where,

B and E are 12 x 12 matrices and $\dot{X}$ and X are column vectors.

B has the diagonal elements $b_{11} = b_{22} = b_{33} = b_{44} = b_{55} \ldots b_{1212} = 1$ and $b_{48} = -\frac{T_{1d}X_d}{T'_{do}}$; $b_{57} = \frac{T_2X_d}{T''_{do}}$, $b_{68} = \frac{T''_qX_q}{T''_{qo}}$; $b_{10,12} = -\frac{K_3}{T_1T_2}$ and other elements are having zero value and X is column vector which can be represented as follows:~~and in fig.~~

$$X_t = (\Delta\phi_{d1}, \Delta\phi_{d2}; \Delta\phi_{d3}, \Delta\phi_{d4}, \Delta\phi_{d5}, \Delta\phi_q, \Delta i_d, \Delta i_q;$$
$$\Delta e_{fd}; \Delta e'_{fd}; \Delta\delta; \eta).$$

The elements of E matrix are shown as in Fig. (21).
Now from premultiplying by B^{-1} equation (13) we obtain-

$$(I)\dot{X} = B^{-1}E\,X \quad \ldots \qquad (65)$$

where,

B^{-1} is the inverse of B. This can be achieved by making transformation on both sides of equation (13) so that on left side B matrix changes to unit matrix and by making corresponding

ATRIX E (Fig 21)

	1	2	7	8	9	10	11	12
1.	$-\frac{1}{T'_{do}}$	-	-	-	$\frac{B_1}{T'_{do}}$	-	-	-
2.	0	$-\frac{1}{T''_{do}}$	-	-	B_2/T''_{do}	-	-	-
3.	-	-	io	-	-	-	-	-
4.	-	-	-	-	-	-	-	-
5.	-	-	-	-	-	-	-	-
6.	-	-	-	$-x_q/T''_{qo}$	-	-	-	-
7.	$-1/B_3T'_{do}$	$-1/B_3T''_{do}$	o)+R	x/B_3	$\frac{\frac{B_1}{T'_{do}}+\frac{B_2}{T''_{do}}}{B_3}$	-	$-V\cos{}_o/B_3$	$-\phi_{qo}/B_3$
8.	v_o/B_4	v_o/B_4	-	$-(\frac{x_q}{T''_{qo}}+R)/B_4$	-	-	$V\sin{}_o/B_4$	ϕ_{do}/B_4
9.	-	-	-	-	-	1	-	-
10.	$\frac{-K_r v_o \cos_{10}}{T_1T_2}$	$\frac{K_r v_o \cos}{T_1T_2}$	$\frac{\sin_{10}}{{}_1T_2}$	$\frac{K_r r_a \cos_{10}}{T_1T_2}$	$-1/T_1T_2$	$-\frac{T_1+T_2}{T_1T_2}$	$\frac{K_1}{T_1T_2}$	E10,12
11.	-	-	-	-	-	-	-	1
12.	$-i_{qo}/M$	$-i_{qo}/M$	o/M	ϕ_{do}/M	-	-	-	$-K_T/M$

where E_{10}

	$a_{10,2}$	7	$a_{10,8}$	$a_{10,9}$	$a_{10,10}$	$a_{10,11}$	$a_{10,12}$
	-		-	-	-	-	1
} $\dot{o}$	$-i_{qo}/M$	/M	ϕ_{do}/M	-	-	-	$-K_T/M$

change in E on right side B^{-1} E is obtained.

In equation (14) B^{-1} E is the characteristic matrix A and equation (14) can be written as-

$$\dot{X} = AX \qquad \ldots \qquad \ldots \qquad (66)$$

so that $A = B^{-1}E$

so that A matrix is as in Fig.(22)

where,

$$a_{41} = \frac{T_{1d}x_d}{B_3(T'_{do})^2};$$

$$a_{42} = -\frac{T_{1d}x_d}{B_3 T'_{do}T''_{do}};$$

$$a_{43} = \frac{T_{1d}x_d}{B_3(T'_{do})^2}$$

$$a_{44} = \left(\frac{T_{1d}\ x_d}{B_3(T'_{do})^2} - \frac{1}{T'_{do}}\right); \qquad (67)$$

$$a_{45} = \frac{T_{1d}x_d}{B_3 T'_{do}T''_{do}}$$

$$a_{46} = -\frac{v_o T_{1d}x_d}{B_3 T'_{do}},$$

$$a_{47} = -\left(\frac{x_d}{T'_{do}} + R\right)\frac{T_{1d}x_d}{B_3 T'_{do}};$$

$$a_{48} = \frac{x}{B_3}\cdot\frac{T_{1d}x_d}{T'_{do}}$$

$$a_{4,9} = \left(\frac{B_1}{T'_{do}} + \frac{B_2}{T''_{do}}\right)\frac{T_{1d}x_d}{T'_{do}\ B_3};$$

$$a_{4,11} = -\frac{V\ Cos\delta_o}{B_3}\cdot\frac{T_{1d}x_d}{T'_{do}}$$

$$a_{4,12} = -\phi_{qo}\cdot\frac{T_{1d}x_d}{B_3\ T'_{do}}$$

$$a_{51} = - \frac{T_{2d}x_d}{B_3 T'_{do} T''_{do}} ;$$

$$a_{52} = - \frac{T_{2d}x_d}{B_3 (T''_{do})^2}$$

$$a_{53} = a_{54} = \frac{T_{2d}x_d}{B_3 T'_{do} T''_{do}}$$

$$a_{55} = \left(\frac{T_{2d}x_d}{B_3 (T''_{do})^2} - \frac{1}{T''_{do}} \right) ;$$

$$a_{56} = - \left(\frac{v_o}{B_3} \quad \frac{T_{2d}x_d}{T''_{do}} \right) ;$$

$$a_{57} = - \left(\frac{x_d}{T'_{do}} + R \right) \frac{T_{2d}x_d}{B_3 T''_{do}}$$

$$a_{58} = \frac{x}{B_3} \cdot \frac{T_{2d}x_d}{T''_{do}}$$

$$a_{59} = \left(\frac{B_1}{T'_{do}} + \frac{B_2}{T''_{do}} \right) \frac{T_{2d}x_d}{T'_{do} B_3} ;$$

$$a_{5,11} = - \frac{V \cos\delta_o}{B_3} \cdot \frac{T_{2d}x_d}{T''_{do}}$$

$$a_{5,12} = - \frac{\beta_{qo}}{B_3} \cdot \frac{T_{2d}x_d}{T''_{do}}$$

$$a_{6,1} = - \frac{T''_q}{T''_{qo}} \cdot x_q \cdot \frac{v_o}{B_4} = a_{6,2} ;$$

$$a_{6,3} = a_{6,4} = a_{65} = \frac{T''_q}{T''_{qo}} x_q \cdot \frac{v_o}{B_4}$$

$$a_{66} = \frac{T''_q x_q}{(T''_{qo})^2 B_4} ;$$

$$a_{67} = \frac{x}{B_4} \cdot \frac{T''_q}{T''_{qo}} \cdot x_q ;$$

$$a_{68} = \left(\frac{x_q}{T''_{qo}} + R \right) \frac{T''_q}{T''_{qo}} \cdot \frac{x_q}{B_4} - \frac{x_q}{T''_{qo}}$$

$$a_{6,11} = - \frac{T''_q}{T''_{qo}} . x_q . \frac{V \sin\delta_o}{B_4}$$

$$a_{6,12} = - \frac{\psi_{do}}{B_4} . \frac{T''_q . x_q}{T''_{qo}}$$

$$a_{10,1} = -\left(\frac{K_r v_o \cos\delta_{10}}{T_1 T_2} + \frac{i_{qo}}{M} . \frac{K_3}{T_1 T_2}\right) = a_{10,2} = -a_{10,3} = -a_{10,4} = -a_{10,5}$$

$$a_{10,6} = \left(\frac{K_r v_o \sin\delta_{10}}{T_1 T_2} + \frac{i_{do}}{M} . \frac{K_3}{T_1 T_2}\right); \quad a_{10,7} = \left(\frac{K_r V_a \sin\delta_{10}}{T_1 T_2} + \frac{\psi_{qo}}{M} . \frac{K_3}{T_1 T_2}\right)$$

$$a_{10,8} = \left(\frac{K_r r_a \cos{}_{10}}{T_1 T_2} - \frac{\psi_{do}}{M} . \frac{K_3}{T_1 T_2}\right)$$

$$a_{10,9} = - \frac{1}{T_1 T_2};$$

$$a_{10,10} = - \frac{T_1 + T_2}{T_1 T_2}$$

$$a_{10,11} = \frac{K_1}{T_1 T_2}$$

$$a_{10,12} = \frac{\left[K_2 + (\psi_{qo} \sin\delta_{10} - \psi_{do} \cos\delta_{10}) K_r - \frac{K_T K_3}{M}\right]}{T_1 T_2}$$

blank spaces in the matrix shows that element is zero.

... (67)

3.4. METHODS OF ANALYSIS:

The analysis for the dynamical stability for small perturbation about an equilibrium operating point is described in equation 66,

i.e. $(\dot{X}) = A\ (x)$

can be done as follows;

i) Using the method of Liapunov.

ii) Finding the eign values of the coefficient matrix A.

3.4.1. Liapnov Method:

The basis of Liapnov method for transient response of a dynamical system represented by equation (66), is the solution of the equation.

$$(A^t)(G) + (G)(A) = -(C) \quad \ldots \qquad (68)$$

where,

(C) is a positive definite or positive semidefinite symetric matrix and G is a symmetric matrix[17]. It is known that-

1) when (C) is positive definite (~~16~~ 68) will yield a positive definite matrix G, if and only if, the system described by (66) is asymtotically stable.

2) If the system is asymptotically stable and the matrix (G) is positive definite or positive semidefinite, then following relationship is satisfied.

$$[(x^t)(G)(x)]_{x=0} = \int_{t=0}^{t} [(x^t)(C)(x)dt] \qquad (69)$$

Thus (~~16~~ 68) can be used with positive definite (C) matrix as a test for asymptotic stability; and (with any positive definite or semidefinite (C) matrix)as a means of evaluating the integral (69) given only the initial condition vector $(x)_{t=0}$.

A set of FORTRAN subroutines has been developed to produce the coefficients g_{ij} of the matrix (G) for any given matrix (A) and any no. of matrices (C). One of these subrotines test the matrix (G) to verify that it is positive definite and hence (provides a check on system stability at the expense of using atleast one positive definite matrix (C)).

3.4.2. Finding one eign values of Coefficient matrix A:

The dynamical stability can also be tested by finding the eign values of the coefficient matrix A. As mentioned in the section 3.2 the characteristic equation $|I-A| = 0$ is considered i.e. for stability roots of the characteristic equation should lie in the left half of the complex plain or in other words the eigen values of A should all have negative real parts for system to be stable which can be represented by equation (63) $\dot{X} = AX$.

For finding the eigen values the following method are adopted.

i) Q.R. Transformation method.

ii) Method of Fadeev's for simultaneous computation of coefficients of the characteristic polynomial and of the adjoint matrix.

3.4.2.1. Q.R. Transformation Method[12,13]:

The A matrix is transformed into Hessenberg form, before applying Q.R. Transformation. In this form all the elements below the first subdiagonal are zero. There are several well known methods for doing this. This can be done fairly easily by a series of elementry transformations of two different types.

Type 1. Interchange of rows P and Q or column P and Q.

$$\text{row } P \rightarrow \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} = I^{(PQ)}$$

Column Q.

Type 2. The purpose of this transform will be apparant in the example.

$$\text{row } P \longrightarrow \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ m_1 & m_2 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} = I^{(P)}$$

The computational procedure is explained below by means of an example to change it into hassanberg form.

Consider the matrix.

$$A = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix}$$

Select largest value and change columns to put it in 3rd column.

Assume largest value is $a_{42} = 4$. Post multiply A matrix by $I^{(32)}$

$$\begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{13} & a_{12} & a_{14} \\ a_{21} & a_{23} & a_{22} & a_{24} \\ a_{31} & a_{33} & a_{32} & a_{34} \\ a_{41} & a_{43} & a_{42} & a_{44} \end{bmatrix}$$

To preserve the stability transformation premultiplied by $(I^{(32)})^{-1}$. It turns out, that $(I^{(32)})^{-1} = I^{(32)}$

Hence,

$$(I^{(32)})^{-1} A(I^{32}) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} a_{11} & a_{13} & a_{12} & a_{14} \\ a_{21} & a_{23} & a_{22} & a_{24} \\ a_{31} & a_{33} & a_{32} & a_{34} \\ a_{41} & a_{43} & a_{42} & a_{44} \end{bmatrix}$$

$$= \begin{bmatrix} a_{11} & a_{13} & a_{12} & a_{14} \\ a_{31} & a_{33} & a_{32} & a_{34} \\ a_{21} & a_{23} & a_{22} & a_{24} \\ a_{41} & a_{43} & \alpha_4 & a_{44} \end{bmatrix}$$

Post multiply by $T^{(3)}$ $\quad m_1 = -\dfrac{a_{41}}{\alpha_4}$; $m_2 = -\dfrac{a_{43}}{\alpha_4}$

$$\begin{bmatrix} a_{11} & a_{13} & a_{12} & a_{14} \\ a_{31} & a_{33} & a_{32} & a_{34} \\ a_{21} & a_{23} & a_{22} & a_{24} \\ a_{41} & a_{43} & 4 & a_{44} \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ \frac{-a_{41}}{\alpha_4} & \frac{-a_{43}}{\alpha_4} & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} x & x & a_{12} & a_{14} \\ x & x & a_{32} & a_{34} \\ x & x & a_{22} & a_{24} \\ 0 & 0 & \alpha_4 & a_{44} \end{bmatrix}$$

To preserve similarity transformation premultiplied by $(T^{(3)})^{-1}$. Again the inverse of T(3* is determined by inspection.

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ \frac{a_{41}}{\alpha_4} & \frac{a_{43}}{\alpha_4} & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x & x & a_{12} & a_{14} \\ x & x & a_{32} & a_{34} \\ x & x & a_{22} & a_{24} \\ 0 & 0 & 4 & a_{44} \end{bmatrix} = \begin{bmatrix} a'_{11} & a'_{12} & a_{12} & a_{14} \\ a'_{21} & a'_{22} & a_{32} & a_{34} \\ a'_{31} & a'_{32} & a'_{33} & a'_{34} \\ 0 & 0 & \alpha_4 & a_{44} \end{bmatrix}$$

$$(T^{(3)})^{-1} (I^{(32)})^{-1} A (I^{(32)}) T^{(3)}$$

The process can be repeated now. Compare a'_{31} and a'_{32} to determine the largest absolute value, interchange columns if necessary. Post and Premultiply by $T^{(2)}$ and $(T^{(2)})^{-1}$

$$\begin{bmatrix} a'_{11} & a'_{12} & a_{12} & a_{14} \\ a'_{21} & a'_{22} & a_{32} & a_{34} \\ a'_{31} & \alpha_3 & a'_{33} & a'_{34} \\ 0 & 0 & \alpha_4 & a_{44} \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ \frac{-a'_{31}}{\alpha_3} & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} x & a'_{12} & a_{12} & a_{14} \\ x & a'_{22} & a_{32} & a_{34} \\ 0 & \alpha_3 & a'_{33} & a'_{34} \\ 0 & 0 & \alpha_4 & a_{44} \end{bmatrix}$$

The complete transformation which is-

$$(Y^{(2)})^{-1}\, I\, (Y^{(3)})^{-1}\, (I^{(32)})^{-1}\;\; A\, I^{(32)}\; Y^{(3)} I\;\; Y^{(2)}$$

converts A to almost triangular form.

This procedure can be applied systematically to non singular matrices of any size.

Reduction of an almost triangular matrix to one that is triangular, is based on the Q.R. transformation.

<u>Theorem 1:</u>

For any matrix A there exists a unitary matrix Q, such that A = QR where R is an upper triangular matrix which has real non negative diagonal elements. More-over a unique if A is non-singular.

A unitary matrix is one whose inverse is equal to its conjugate transpose, i.e.

$$(Q^{*})^{t} = Q^{-1}$$

A unitary matrix may be constructed as the product of a series of elementary unitary matrices.

An elementary unitary matrix differs from a unit matrix in one principal 2 x 2, submatrix. This matrix has one general form.

$$\begin{bmatrix} t_{ii} & t_{ij} \\ t_{ji} & t_{jj} \end{bmatrix} = \begin{pmatrix} e^{i\alpha}\cos\theta & -e^{-i\beta}\sin\theta \\ e^{i\gamma}\sin\theta & e^{i\delta}\cos\theta \end{pmatrix}$$

where,

α, β, γ, δ and θ are real and $\alpha - \beta - \gamma + \delta = 0$ or a multiple of 2 .

Q.R. transformation: is a iterative procedure defined as follows: $A^{(K)}$ is the transformed A matrix at the end of the (K-1) iteration.

$$A = A^{(1)}$$

The matrix $A^{(K)}$ is decomposed into the product of a unitary matrix $Q^{(K)}$ and upper triangular matrix $R^{(K)}$. The matrix $A^{(K+1)}$ is formed by premultiplying $Q^{(K)}$ and $R^{(K)}$ in the reverse order i.e. $A^{(K)} = Q^{(K)}R^{(K)}$; $A^{(K+1)} = R^{(K)}\ Q^{(K)}$.

It can be shown that Q.R. transformation is equivalent to a series of similarity transformation on A. This must be true in order to ensure that eigen values of A remains unchanged.

$A = A^{(1)} = Q^{(1)}\ R^{(1)}$

$\therefore (Q^{(1)})^{-1}\ A^{(1)} = R^{(1)}$

Now $A^{(2)} = R^{(1)}\ Q^{(1)} = (Q^{(1)})^{-1}\ A^{(1)}\ Q^{(1)}$

$A^{(2)}$ is therefore related to $A^{(1)}$ by means of a unitary similarity transformation.

Theorem 2:

If an non singular matrix A has eigen values of distinct modulus, then under the Q.R. transformation the elements below the principal diagonal tend to zero, modulii of those elements above the diagonal tend to fixed values and the elements on the principal - - diagonal tend to eigen values.

The forgoing results demonstrate that the Q.R. transformation is always possible and that repeated application will reduce A to an upper triangular matrix. To develop a computational procedure requires a convenient method for decomposing A into its respective Q.R. matrices. The following procedure is straight forward assuming that A has already been reduced to an almost triangular form.

The (n-1) subdiagonal elements $a_{i+1,i}$, which are assumed to be non zero and real are eliminated in turn by a series of unitary transformations starting with a_{21}. This procedure will be demonstrated by means of an example.

$$\begin{pmatrix} \mu & \nu & 0 & 0 \\ -\nu & \mu & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ 0 & a_{32} & a_{33} & a_{34} \\ 0 & 0 & a_{43} & a_{44} \end{pmatrix} = \begin{pmatrix} a'_{11} & a'_{12} & a'_{13} & a'_{14} \\ 0 & a'_{22} & a'_{23} & a'_{24} \\ 0 & a_{32} & a_{33} & a_{34} \\ 0 & 0 & a_{43} & a_{44} \end{pmatrix}$$

where,

$$M = \frac{a_{11}}{\sqrt{|a_{11}|^2 + a_{21}^2}} \qquad = \frac{a_{21}}{\sqrt{|a_{11}|^2 + a_{21}^2}}$$

The first matrix in the above equation is elementary unitary matrix according to earlier definition. μ and ν are less than 1, $\alpha = 1 = -\delta$, $r = B = 0$.

Repeat the process.

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \mu' & \nu' & 0 \\ 0 & -\nu' & \mu' & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} a'_{11} & a'_{12} & a'_{13} & a'_{14} \\ 0 & a'_{22} & a'_{23} & a'_{24} \\ 0 & a_{32} & a_{33} & a_{34} \\ 0 & 0 & a_{43} & a_{44} \end{pmatrix} = \begin{pmatrix} a'_{11} & a'_{12} & a'_{13} & a'_{14} \\ 0 & a''_{22} & a''_{23} & a''_{24} \\ 0 & 0 & a''_{33} & a''_{34} \\ 0 & 0 & a_{43} & a_{44} \end{pmatrix}$$

where, $$\mu' = \frac{a'_{22}}{\sqrt{|a'_{22}|^2 + a_{32}^2}} \qquad \nu = \frac{a_{32}}{\sqrt{|a_{22}|^2 + a_{32}^2}}$$

Eliminate a_{43} by similar operation. Combining the three steps here gives.

$$(Q^{(K)})^{-1} \quad A^{(K)} = R^{K}$$

where, $(Q^{(K)})^{-1}$ is the product of elementary unitary matrices used in the reduction. Also $(Q^{(K)})^{-1} = (Q^{(K)})^{t}$ so that inverting $(Q^{(K)})^{-1}$ is a simple operation. To compute $(A^{(K+1)})$ post multiply $R^{(K)}$ by the conjugate transposed of $(Q^{(K)})^{-1}$. This complete one iteration.

As with one iterative procedure the subdiagonal elements do not become identically zero. In order to reduce computing time elements below the diagonal are set equal to zero as soon as they become sufficiently small. This allows one of the eigen values to be removed and the order of the matrix may be reduced by dropping the appropriate rows and column. For example a Hessenberg matrix considered is reduced to the form below.

$$\begin{bmatrix} x & x & x & x & x \\ x & x & x & x & x \\ 0 & x & x & x & x \\ 0 & 0 & x & x & x \\ 0 & 0 & 0 & 0 & a \end{bmatrix}$$

Then it is known that the matrix has a real eigen value of 'a' and the last column and row can be dropped reducing the order of matrix by one. If the matrix is reduced into the form shown below.

$$\begin{bmatrix} x & x & x & x & x \\ x & x & x & x & x \\ 0 & x & x & x & x \\ 0 & 0 & 0 & x & x \\ 0 & 0 & 0 & x & x \end{bmatrix}$$

Then a pair of eigen values possibly complex can be found directly from the lower right 2x2 submatrix and the order of the original matrix is reduced by 2 by dropping last two rows and column. Actually, in the programme, if any element on the subdiagonal is reduced far enough to be considered a zero (with floating point computer operation, a true zero is practically never obtained) matrix is divided into two submatrices and these handled independently. It is this feature of breaking the large matrices into smaller pieces that make this method so powerful with the large systems.

3.4.3. METHOD OF FADEEV:

D.K. Fadeev[23] has suggested a method for the simultaneous determination of scalar coefficients $P_1, P_2 \ldots\ldots P_n$ of the characteristic polynomial-

$$\Delta(\lambda) = {}^{n} - P_1 {}^{n-1} - P_2 {}^{n-2} \ldots\ldots P_n = |A - \lambda I|$$

and of the matrix coefficients $C_1, C_2, C_3 \ldots\ldots C_{n-1}$ of the adjoint matrix $C(\lambda)$. He proposed to compute successively, instead of the traces the powers $A, A^2 \ldots\ldots A^n$, the traces of certain other matrices $A_1, A_2 \ldots\ldots, A_n$ and so to determine $P_1, P_2 \ldots\ldots P_n$ and $B_1\ B_2 \ldots\ldots B_n$ by the following formulas.

$$A_1 = A, \quad P_1 = \text{trace } A_1 \qquad B_1 = A_1 - P_1 I$$
$$A_2 = AB_1 \quad P_2 = \tfrac{1}{2} \text{ trace } A_2 \qquad B_2 = A_2 - P_2 I$$
$$- - - - - - - - - - - - - - - - - -$$
$$A_{n-1} = A\, B_{n-2} \quad P_{n-1} = \frac{1}{n-1} \text{ trace } A_{n-1} \quad B_{n-1} = A_{n-1} - P_{n-1} I$$
$$A_n = A\, B_{n-1} \quad P_n = \frac{1}{n} \text{ trace } A_n \qquad B_n = A_n - P_n I = 0$$

The last equation $B_n = A_n - P_n I = 0$ may be used to check the computation.

After obtaining the coefficients $P_1, P_2 \ldots\ldots P_n$ of the equation of $\Delta(\lambda)$. This equation is used to find out the characteristic values. A digital computer programme can be made to solve this equation, to get the eign values.

3.5. CONCLUSIONS:

1. The methods of matrix analysis can be used to advantage for the analysis of dynamic stability.

2. The Q-R transformation method is a very useful and widely used in finding the eigns values of the matrix A.

3. The method of Fadeev is another useful method which gives the characteristic equation of the matrix. This characteristic equation can be analysed by the Routh Hurtwitz criterion for stability.

CHAPTER 4

SUMMARY AND CONCLUSIONS

The dynamic stability limit of the system equipped with angle operated excitation regulator described in section 1.4 is analysed in this thesis.

Two basic approaches to the analysis are used namely.

(i) The transfer function approach and

(ii) The State space approach.

The Transfer function Approach:

The characteristic equation is obtained by linearising the differential equations of the system around the chosen operating point. The operating point is the initial power output or the load angle of the machine. The maximum initial power output for which the system retains stability after being disturbed incrementally is the dynamic stability limit of the system.

The characteristic equation obtained is analysed by the Routh Hurwitz Criterian. The coefficient of the characteristic equation which are the function of the system parameters and the initial operating conditions are determined for various values of the regulator gains and the load angle. These coefficients are plotted to show their variation with the load angle δ_0.

It is found that,

(i) The characteristic equation is of the eighth order.

(ii) The gain constant K_1 associated with the signal proportional to the load angle δ has predominent effect on the dynamic stability limit. Increase of this constant K_1 results in the increase of the stability limit. The choice of K_1 is then the determined by the limitation on the variation of the terminal voltage with load. Unlike the voltage regulators, the angle operated regulator does not keep the terminal voltage of the machine constant. The variation of terminal voltage is shown in Fig. (16) in Chapter 2. Another factor to limit the value of K_1 is the cieling voltage of the exciter. For the system considered with $K_1 = 1.59$, the voltage applied to the field winding of the alternator for a load angle of $\delta_o = 120^0$ is 4.2 p.u.

The constants K_2 and K_3 associated with the signals proportional to the first and second derivative of the load angle have only a minor effect on the dynamic stability limit. Nevertheless it is advisable to make the regulator respond to these signals as it will keep the stability under rapidly- changing conditions such as conditions- immediately after a fault etc.

2) <u>The State Space Approach:</u>

The equations of the system for incremental changes are written in the form of a set of first order differential equations, after linearising the system equations about a chosen operating point, as-

$$\dot{X} = A X$$

The methods of finding the eign values of matrix A, the sign of whose real part determines the stability, are given. The method of using the Liapunov's theorem is also given in the text. The methods of reducing matrix A to Hessenberg form before applying Q.R. transformation are also given in the text.

Q.R. transformation method seems to be the powerful tool for obtaining the eign values of a large matrix A.

CHAPTER 5

A_P_P_E_N_D_I_X

5.1. CALCULATION OF Δi_d & Δi_q:

From equations 3, 4, 5 and 6 generator and transmission line of Chapter 2 for small disturbance the following linearised equations are obtained.

Equation of machine:

$$\Delta e_d = - \phi_{qo} \ p \Delta\delta + x_q \Delta i_q - r_a \Delta i_d \quad \text{(A-1)}$$

$$\Delta e_q = \phi_{do} \ P \Delta\delta + G(p) \Delta e_{fd} - x_d(p) \Delta i_d - r_a \Delta i_q \quad \text{(A-2)}$$

Equation for Transmission line:

$$\Delta e_d = V \cos \delta_o + r \Delta i_d - x \Delta i_q \ \ldots \quad \text{(A-3)}$$

$$\Delta e_q = -V \sin \delta_o + x \Delta i_d + r \Delta i_q \ \ldots \quad \text{(A-4)}$$

From equation (A-1 and A-3) and (A-2 and A-4) the following equations are obtained.

From equation (1) and (3)

$$- \phi_{qo} \ p \Delta\delta + x_q \Delta i_q - r_a \Delta i_d = V \cos \delta_o + r \Delta i_d - x \Delta i_q$$

or

$$(x_q + x)\Delta i_q - (r_a + r) \Delta i_d = (V \cos \delta + \phi_{qo} p) \Delta\delta \quad \text{(A-5)}$$

From equation (A-2) and (A-4)

$$\phi_{do} p \Delta\delta + G(p) \Delta e_{fd} - x_d(p) \Delta i_d - r_a \Delta i_q = -V \sin \delta_o + x \Delta i_d + r \Delta i_q$$

or

$$[x_d(p) + x] \Delta i_d + (r_a + r) \Delta i_q = (V \sin\delta_o + \phi_{do} p) \Delta\delta + G(p) \Delta e_{fd} \ \ldots . \text{(A-6)}$$

Solving the equation (A-5) and (A-6) mentioned above for Δi_d and Δi_q by determinant.

$$i_d = \frac{\begin{vmatrix} (V \cos \delta_o + \phi_{qo} p) \Delta\delta & x_q + x \\ (V \sin \ \ _o + \phi_{do} p) \Delta\delta + G(p) \Delta e_{fd} & r_a + r \end{vmatrix}}{\begin{vmatrix} -(r_a + r) & x_q + x \\ x_d(p) + x & r_a + r \end{vmatrix}}$$

$$= \frac{-R(V\cos\delta_o + \phi_{qo}p) + x_q(V\sin\delta_o + \phi_{do}p)}{R^2 + X(d)\,X_q} \cdot \Delta\delta$$

$$+ \frac{X_q\,G(p)\,\Delta e_{fd}}{R^2 + X_d(p)\,X_q} \quad \ldots \qquad \text{(A-7)}$$

where,

$$R = r_a + r, \quad X_d(p) = x_d(p) + x$$

$$X_q = x + x_q$$

$$\Delta i_q = \frac{\begin{vmatrix} r_a + r & (V\cos\delta_o + \phi_{qo}p)\,\Delta\delta \\ x_d(p)+x & (V\sin\delta_o + \phi_{do}p) + G(p)\,\Delta e_{fd} \end{vmatrix}}{\begin{vmatrix} -(r_a+r) & x_q + x \\ x_d(p) + x & r_a + r \end{vmatrix}}$$

$$= \frac{R(V\sin\delta_o + \phi_{qo}p) + X_d(p)(V\cos\delta_o + \phi_{qo}p)}{R^2 + X_d(p)\,X_q} \cdot \Delta\delta$$

$$+ \frac{R\,G(p)\,\Delta e_{fd}}{R^2 + X_d(p)\,X_q} \quad \ldots \qquad \text{(A-8)}$$

<u>5.2.</u>

Torque equation of the generator in linearised form is equation 17 of Chapter 2.

$$\Delta T_e = \Delta\phi_d\, i_{qo} + \phi_{do}\Delta i_q - \Delta\phi_q\, i_{do} - \phi_{qo}\Delta i_d$$

Putting the value of $\Delta\phi_d$ and $\Delta\phi_q$ from equation (12) and (13) of Chapter 2.

$$\Delta T_e = [\,G(p)\,\Delta e_{fd} - x_d(p)\,\Delta i_d\,]\; i_{qo} + \phi_{do}\,\Delta i_q$$

$$- i_{do}\,(-x_q\,\Delta i_q) - \phi_{qo}\,\Delta i_d$$

or

$$\Delta T_e = G(p)\, i_{qo}\, \Delta e_{fd} + (\phi_{do} + x_q\, i_{do})\Delta i_q - (x_d(p)\, i_{qo} + \phi_{qo})\Delta i_d$$

By putting the values of Δi_q and Δi_d from equation (A-7) and (A-8) of appendix 5.1.

$$\Delta T_e = G(p) i_{qo} \Delta e_{fd} + (\phi_{do} + x_q i_{do}) \left[\frac{R(V\sin {}_o + \phi_{do}p) + X_d(p)(V\cos {}_o + \phi_{qo}p)}{R^2 + X_d(p) X_q} \right] \Delta\delta$$

$$- [x_d(p) i_{qo} + \phi_{qo}] \left[\frac{-R(V\cos {}_o + \phi_{qo}p) + X_q(V\sin {}_o + \phi_{do}p)}{R^2 + X_d(p)\, X_q} \right] \cdot \Delta\delta$$

$$+ \frac{(\phi_{do} + x_q i_{do})R - (x_d(p)\, i_{qo} + \phi_{qo})\, X_q}{R^2 + X_d(p)\, X_q} G(p)\, \Delta e_{fd}$$

$$\Delta T_e = \frac{i_{qo}(R^2 + xX_q + x_d(p)X_q) + (\phi_{do} + X_q i_{do})R - (x_d(p) i_{qo} + \phi_{qo}) \cdot X_q}{R^2 + X_d(p)\, X_q} \cdot$$

$$G(p)\Delta e_{fd} + (\phi_{do} + x_q i_{do}) \left[\frac{R(V\sin\delta_o + \phi_{do}p) + X_d(p)(V\cos\delta_o + \phi_{qo}p)}{R^2 + X_d(p)\, X_q} \right] \Delta\delta$$

$$-(x_d(p) i_{qo} + \phi_{qo}) \left[\frac{-R(V\cos\delta_o + \phi_{qo}p) + X_q(V\sin\delta_o + \phi_{do}p)}{R^2 + X_d(p)\, X_q} \right] \cdot \Delta\delta$$

$$= A_1(p)\, \Delta e_{fd} + A_2(p)\, \Delta\delta \quad \ldots \quad \text{(A-9)}$$

where,

$$A_2(p) = \frac{(\phi_{do} + X_q i_{do})[R(V\sin\delta_o + \phi_{do}p) + x_d(p)(V\cos\delta_o + \phi_{qo}p)] + }{R^2 + X_d(p)\, X_q}$$

$$\frac{(x_d(p) i_{qo} + \phi_{qo})[R(V\cos\delta_o + \phi_{qo}p) - X_q(V\sin\delta_o + \phi_{do}p)]}{}$$

(A-10)

$$\text{and } A_1(p) = i_{qo} \frac{[R^2 + xX_q + x_d(p)X_q] + (\phi_{do} + x_q i_{do})R - (x_d(p) i_{qo} + \phi_{qo})X_q}{R^2 + X_d(p)\, X_q} \cdot G(p)$$

(A-11)

Calculation of ΔT_e:

On expansion of these equations we get-

$$A_1(p) = A_1'(p).\ G(p)$$

where,

$$A_1'(p) = \frac{i_{qo}(R^2 + xX_q) + (\phi_{do} + x_q\, i_{do})R - \phi_{qo}\, X_q}{(R^2 + xX_q) + x_d(p)\, X_q}$$

$$= \frac{[i_{qo}(R^2+xX_q)+(\phi_{do}+x_q i_{do})R-\phi_{qo}X_q][T'_{do}T''_{do}P^2+(T'_{do}+T''_{do})P+1]}{(R^2+xX_q)[T'_{do}T''_{do}P^2+(T'_{do}+T''_{do})p+1]+X_q x_d[T'_dT''_dP^2 \ +(T'_d+T''_d)P+1]}$$

Let, $i_{qo}(R^2+xX_q)+(\phi_{do}+x_q i_{do})R-\phi_{qo}X_q = B$

$$\text{then } A_1'(p) = \frac{B[T'_{do}T''_{do}P^2 \ +(T'_{do}+T''_{do})P+1]}{(R^2+xX_q)[T'_{do}T''_{do}P^2+(T'_{do}+T''_{do})P+1]+X_q x_d[T'_dT''P^2+(T'_d+T''_d)p+1]}$$

$$= \frac{b_1P^2 + b_2P + b_3}{b_4\, P^2 + b_5P + b_6} \qquad \ldots \qquad \text{(A-12)}$$

where,

$b_1 = B\ XT'_{do}T''_{do}$

$b_2 = BX(T'_{do} + T''_{do})$

$b_3 = B$

$b_4 = (R^2 + xX_q)T'_{do}T''_{do}$

$b_5 = (R^2 + xX_q)(T'_{do} \ +T''_{do})+x_dX_q(T'_d \ +T''_d)$

$b_6 = (R^2 \ +xX_q + x_dX_q)$ $\qquad \ldots \qquad \ldots \qquad$ (A-13)

$$\text{and } G(p) = \frac{(1+ T_{kd}p)\ x_{md}}{[T'_{do}T''_{do}\ P^2 \ +(T'_{do}+T''_{do})P+1]r_{fd}} \qquad \text{(A-13.1)}$$

$A_2(p) = A'_2(p) \ +A''_2(p)$

$$A'_2(p) = (\phi_{do}+x_q i_{do}) \frac{[R(V\sin\delta_o + \phi_{do}p)+(x+x_d(p)(V\cos\delta_o+\phi_{qo}p)]}{(R^2+ xX_q)+ x_d(p)\ X_q}$$

$$=(\phi_{do}+x_q i_{do})\frac{[R(V\sin{}_o+\phi_{do}p)+x(V\cos{}_o+\phi_{qo}p)][T'_d T''_{do}p^2+(T'_{do}+T''_{do})P+1]}{(R^2+xX_q)[T'_{do}T''_{do}p^2+(T'_{do}+T''_{do})p+1]+X_q x_d[T'_d T''_d P^2+(T'_d+T''_d)P+1]}$$

$$+\frac{x_d(V\cos\delta_o+\phi_{qo}p)[T'_d T''_d\ P^2+(T'_d+T''_d)P+1]}{(R^2+xX_q)[T'_{do}T''_d\ P^2+(T'_{do}+T''_{do})P+1]+X_q x_d[T'_d T''_d P^2+(T'_d+T''_d)P+1]}$$

$$A'_2(p) = \frac{C_1P^3 + C_2P^2 + C_3P+C_4}{b_4P^2 + b_5P + b_6} \quad \ldots \quad \text{(A-14)}$$

where,

b_4, b_5 and b_6 are already defined.

and,

$$C_1 = (R\ \phi_{do}+x\phi_{qo})T'_{do}T''_{do}+x_d\ \phi_{qo}T'_d\ T''_d$$

$$C_2 = (R\phi_{do}+x\ \phi_{qo})(T'_{do}+T''_{do})+(RV\ \sin\delta_o+xV\ \cos\delta_o)T'_{do}T''_{do}+x_d\phi_{qo}\cdot (T'_d\ +T''_d)+x_dV\ \cos\delta_o\cdot T'_d\ T''_d$$

$$C_3 = (R\phi_{do}+x\phi_{qo}+x_d\phi_{do})+(RV\ \sin\delta_o+xV\ \cos\delta_o)(T'_{do}+T''_{do})+ x_dV\ \cos\delta_o(T'_d\ +T''_d)$$

$$C_4 = RV\ \sin\delta_o + xV\ \cos\delta_o + x_dV\ \cos\delta_o$$

$$A''_2(p) = \frac{[R(V\ \mathrm{Cos}\ {}_o+\phi_{qo}p)-X_q(V\ \sin\ {}_o+\phi_{do}p)][\dot{x}_d(p)i_{qo}+\phi_{qo}]}{R^2 + X_d(p)\ X_q} \quad \text{(A-15)}$$

$$=\frac{[R(V\cos\delta_o+\phi_{qo}p)-X_q(V\ \sin\delta_o+\phi_{do}p)][[x_d i_{qo}[T'_d T''_d P^2+(T'_d+T''_d)P+1]+\phi_{qo}[T'_{do}T''_{do}P^2+(T'_d+T''_d)P+1]]}{(R^2+xX_q)[T'_{do}T''_{do}P^2+(T'_{do}+T''_{do})P+1]+x_dX_q[T'_d T''_d P^2+(T'_d+T''_d)P+1]}$$

$$=\frac{C_5P^3+C_6P^2+C_7P\ +C_8}{b_4P^2 + b_5P + b_6} \quad \ldots \quad \text{(A-16)}$$

where,

where,

b_4, b_5 and b_6 are same defined earlier.

$$C_5 = (R\ \phi_{qo} - X_q\ \phi_{do})(x_d\ i_{qo}\ T'_d T''_d + \phi_{qo} T'_{do} T''_{do})$$

$$C_6 = (R\phi_{qo} - X_q\phi_{do})[x_d i_{qo}(T'_d + T''_d) + \phi_{qo}(T'_{do} + T''_{do})] + (RV\cos\delta_o -$$

$$X_q V \sin\delta_o)(x_d i_{qo} T'_d T''_d + \phi_{qo} T'_{do} T''_{do})$$

$$C_7 = (x_d i_{qo} + \phi_{qo})(R\phi_{qo} - X_q\phi_{do}) + (RV\cos\delta_o - X_q V \sin\delta_o).$$

$$[x_d i_{qo}(T'_d + T''_d) + \phi_{qo}\ (T'_{do} + T''_{do})]$$

$$C_8 = (RV\ \cos\delta_o - X_q\ V \sin\ \delta_o)(x_d\ i_{qo} + \phi_{qo})$$

(A-17)

$$\therefore A_2(p) = A'_2(p) + A''_2(p)$$

$$= \frac{b_7 p^3 + b_8 p^2 + b_9 p + b_{10}}{b_4 p^2 + b_5 p + b_6} \quad \ldots \qquad \text{(A-18)}$$

where,

$$b_7 = C_5 + C_1$$

$$b_8 = C_6 + C_2$$

$$b_9 = C_7 + C_3,$$

$$b_{10} = C_8 + C_4 \quad \ldots \quad \ldots \qquad \text{(A-18.1)}$$

$$\therefore \Delta T_e = A'_1 G(p)\ \Delta e_{fd} + A_2(p)\ \Delta\delta$$

$$= \frac{b_1 p^2 + b_2 p + b_3}{b_4 p^2 + b_5 p + b_6} . G(p)\Delta e_{fd} + \frac{b_7 p^3 + b_8 p^2 + b_9 p + b_{10}}{b_4 p^2 + b_5 p + b_6}\ \Delta\delta$$

... (A-19)

<u>5.3.</u>

For obtaining characteristic equation the block diagram is reduced.

Reducing the three blocks of a row to single one, the two blocks of $f_4(p)$ and one of $f_3(p)$, shown in fig.(161)Chapter 2 are reduced first.

$$f_4(p) = \frac{b_1P^2+b_2p+b_3}{b_4P^2+b_5p+b_6} \cdot \frac{(1+T_{kd}P)}{(T'_{do}P+1)(T''_{do}P+1)} \cdot \frac{x_{md}}{r_{fd}} \cdot \frac{r_{fd}}{x_{md}}$$

$$f_4(p) = \frac{b_1T_{kd}P^3+(b_1+b_2T_{kd})P^2+(b_2+b_3T_{kd})P+b_3}{(b_4P^2+b_5p+b_6)\{T'_{do}T''_{do}P^2+(T'_{do}+T''_{do})P+1)} \quad \ldots \quad (A-19)$$

Multiplying the $f_4(p)$ with third transfer function that of angle regulator i.e. $f_3(p)$, the complete transfer function for ΔT_{e1} is obtained follows.

$$f_7(p)=f_4(p).f_3(p)= \frac{(K_1+K_2P+K_3P^2)}{(1+T_1P)(1+T_2P)} \cdot \frac{\{b_1T_{kd}P^3+(b_1+b_2T_{kd})P^2+}{\{T'_{do}T''_{do}P^2+T'_{do}T''_{do}P+1)} \cdot \frac{(b_2+b_3T_{kd})P+b_3\}}{(b_4P^2+b_5P+b_6)}$$

Now total transfer function for ΔT_e combining both transfer functions ΔT_{e1} and ΔT_{e2} as shown in block diagram.

$$f_8(p) = \frac{\Delta T_e}{\Delta \delta} = \frac{\Delta T_{e1}}{\Delta \delta} + \frac{\Delta T_{e2}}{\Delta \delta}$$

$$= f_7(p) + f_5(p)$$

$$= \frac{(K_1+K_2P+K_3P^2)(C_9P^3+C_{10}P^2+C_{11}P+C_{12})}{(1+C_{13}P+C_{14}P^2+C_{15}P^3+C_{16}P^4)(b_4P^2+b_5P+b_6)} + \frac{b_7P^3+b_8P^2+b_9P+b_{10}}{b_4P^2+b_5P+b_6}$$

(A-20)

where,

$C_9 = b_1 T_{kd}$;

$C_{10} = (b_1 + b_2T_{kd})$;

$C_{11} = (b_2 + b_3 T_{kd})$

$C_{12} = b_3$,

$C_{13} = (T_1 + T_2 + T'_{do} + T''_{do})$;

$$C_{14} = (T'_{do} + T''_{do})\ (T_1 + T_2) + T_1 T_2 + T'_{do}\ T''_{do}$$

$$C_{15} = T_1 T_2 (T'_{do} + T''_{do}) + T'_{do}\ T''_{do}(T_1 + T_2)$$

$$C_{16} = T_1 T_2\ T'_{do}\ T''_{do} \qquad \ldots \qquad (A-21)$$

$$f_8(p) = \frac{(K_1 + K_2 P + K_3 P^2)(C_9 P^3 + C_{10} P^2 + C_{11} P + C_{12}) + (b_7 P^3 + b_8 P^2 + b_9 P + b_{10}) x}{(1 + C_{13} P + C_{14} P^2 + C_{15} P^3 + C_{16} P^4)(b_4 P^2 + b_5 P + b_6)}$$

$$\frac{C_{16} P^4 + C_{15} P^3 + C_{14} P^2 + C_{13} P + 1)}{}$$

$$= \frac{]b_7 C_{16} P^7 + (b_8 C_{16} + b_7 C_{15}) P^6 + (b_7 C_{14} + b_8 C_{15} + K_3 C_9) P^5 + (b_7 C_{13} + b_8 C_{14} +}{C_{16} b_4 P^6 + (C_{16} b_5 + C_{15} b_4) P^5 + (C_{16} b_6 + C_{15} b_5 + C_{14} b_4) P^4 + (C_{15} b_6 + C_{14} b}$$

$$\frac{b_9 C_{15} + K_3 C_{10} + K_2 C_9) P^4 + (b_7 + b_8 C_{13} + b_9 C_{14} + b_{10} C_{15} + K_3 C_{11} + K_2 C_{10} + K_1 C_9) P^3 +}{+ C_{13} b_4)^3 + (C_{14} b_6 + C_{13} b_5 + b_4) P^2 + (C_{13} b_6 + b_5) P + b_6}$$

$$\frac{(b_8 + b_9 C_{13} + b_{10} C_{14} + K_3 C_{12} + K_2 C_{11} + K_1 C_{10}) P^2 + (b_9 + b_{10} C_{13} + K_2 C_{12} + K_1 C_{11}) P +}{}$$

$$\frac{(K_1\ C_{12} + b_{10})\ ]}{}$$

$$f_8(p) = \frac{d_1 P^7 + d_2 P^6 + d_3 P^5 + d_4 P^4 + d_5 P^3 + d_6 P^2 + d_7 P + d_8}{d_9 P^6 + d_{10} P^5 + d_{11} P^4 + d_{12} P^3 + d_{13} P^2 + d_{14} P + d_{15}} \quad \ldots \quad (A-22)$$

where,

$$d_1 = b_7\ C_{16};$$

$$d_2 = (b_8\ C_{16} + b_7 C_{15});$$

$$d_3 = (b_7 C_{14} + b_8 C_{15} + K_3 C_9)$$

$$d_4 = (b_7 C_{13} + b_8 C_{14} + b_9 C_{15} + K_3 C_{10} + K_2 C_9)$$

$$d_5 = (b_7 + b_8 C_{13} + b_9 C_{14} + b_{10} C_{15} + K_3 C_{11} + K_2 C_{10} + K_1 C_9)$$

$d_6 = (b_8 + b_9 C_{13} + b_{10} C_{14} + K_3 C_{12} + K_2 C_{11} + K_1 C_{10})$

$d_7 = (b_9 + b_{10} C_{13} + K_2 C_{12} + K_1 C_{11})$

$d_8 = (K_1 C_{12} + b_{10})$

$d_9 = C_{16} b_4;$

$d_{10} = (C_{16} b_5 + C_{15} b_4);$

$d_{11} = (C_{16} b_6 + C_{15} b_5 + C_{14} b_4);$

$d_{12} = (C_{15} b_6 + C_{14} b_5 + C_{13} b_4);$

$d_{13} = (C_{14} b_6 + C_{13} b_5 + b_4)$

$d_{14} = (C_{13} b_6 + b_5)$

$d_{15} = b_6$

Now combining the transfer function for turbine also that feedback path in parallel with $f_8(p)$ we obtained H(p)-

$$H(p) = f_8(p) - f_1(p)$$

$$f_1(p) = -K_T P$$

$$\therefore H(p) = \frac{d_1 P^7 + d_2 P^6 + d_3 P^5 + d_4 P^4 + d_5 P^3 + d_6 P^2 + d_7 P + d_8}{d_9 P^6 + d_{10} P^5 + d_{11} P^4 + d_{12} P^3 + d_{13} P^2 + d_{14} P + d_{15}} + K_T P$$

$$= \frac{[(d_1 + K_T d_9) P^7 + (d_2 + K_T d_{10}) P^6 + (d_3 + K_T d_{11}) P^5 + (d_4 + K_T d_{12}) P^4 + (d_5 + K_T d_{13}) P^3 + (d_6 + K_T d_{14}) P^2 + (d_7 + K_T d_{15}) + d_8]}{d_9 P^6 + d_{10} P^5 + d_{11} P^4 + d_{12} P^3 + d_{13} P^2 + d_{14} P + d_{15}} \quad \ldots \quad (A-24)$$

Now characteristic equation is-

$$1 + H(p)\, f_2(p) = 0$$

or

$$1+\frac{1}{MP^2}\left[\frac{(d_1+K_Td_9)P^7+(d_2+K_Td_{10})P^6+(d_3+K_Td_{11})P^5+(d_4+K_Td_{12})P^4+(d_5+K_Td_{13})P^3+(d_6+K_Td_{14})P^2+(d_7+K_Td_{15})P+d_8}{d_9P^6+d_{10}P^5+d_{11}P^4+d_{12}P^3+d_{13}P^2+d_{14}P+d_{15}}\right]=0$$

or

$$\frac{\left[d_9MP^8+(d_{10}M+d_1+K_Td_9)P^7+(d_{11}M+d_2+K_Td_{10})P^6+(d_{12}M+d_3+K_Td_{11})P^5+(d_{13}M+K_Td_2+d_4)P^4+(d_{14}M+d_5+K_Td_{13})P^3+(d_{15}M+d_6+K_Td_{14})P^2+(d_7+K_Td_{15})+d_8\right]}{d_9P^8+d_{10}P^7+d_{11}P^6+d_2P^5+d_{13}P^4+d_{14}P^3+d_{15}P^2}=0$$

or $a_oP^8+a_1P^7+a_2P^6+a_3P^5+a_4P^4+a_5P^3+a_6P^2+a_7P+a_8=0$

where,

$a_o = d_9M;$

$a_1 = (d_{10}M + d_1 + K_Td_9);$

$a_2 = (d_{11}M + d_2 + K_Td_{10});$

$a_3 = (d_{12}M + d_3 + K_Td_{11});$

$a_4 = (d_{13}M + K_Td_{12} + d_4);$

$a_5 = (d_{14}M + d_5 + K_T d_{13});$

$a_6 = (d_{15}M + d_6 + K_T d_{14});$

$a_7 = (d_7 + K_Td_{15});$

$a6 = d_8$ ... (A-25)

5.4:

Putting the values of d_3.......d_6 and d_8 etc. in terms of K_1, K_2, and K_3 in equation (A-25) from equation (A-23).

$$a_0 = d_9M = C_{16}\ b_4$$

$$a_1 = (d_{10}M + K_Td_9 + d_1)$$

$$a_2 = (d_{11}M + K_Td_{10} + d_2)$$

$$a_3 = (d_{12}M + K_Td_{11} + b_7C_{14} + b_8C_{15} + K_3C_9)$$

$$a_4 = (d_{13}M + K_Td_{12} + b_7C_{13} + b_8C_{14} + b_9C_{15} + K_3C_{10} + K_2C_9)$$

$$a_5 = (d_{14}M + K_Td_{13} + b_7 + b_8C_{13} + b_9C_{14} + b_{10}C_{15} + K_3C_{11} + K_2C_{10} + K_1C_9)$$

$$a_6 = (d_{15}M + K_Td_{14} + b_8 + b_9C_{13} + b_{10}C_{14} + K_3C_{12} + K_2C_{11} + K_1C_{10})$$

$$a_7 = (K_Td_{15} + b_9 + b_{10}C_{13} + K_2C_{12} + K_1C_{11})$$

$$a_8 = d_8 = K_1C_{12} + b_{10}$$

Let, $d_9M = d_{16};$

$(d_{10}M + d_1 + K_Td_9) = d_{17}$

$d_{11}M + K_Td_{10} + d_2 = d_{18};$

$d_{12}M + K_Td_{11} + b_7C_{14} + b_8C_{15} = d_{19};$

$d_{13}M + K_Td_{12} + b_7C_{13} + b_8C_{14} + b_9C_{15} = d_{20}$

$d_{14}M + K_Td_{13} + b_7 + b_8C_{13} + b_9C_{14} + b_{10}C_{15} = d_{21}$

$d_{15}M + K_Td_{14} + b_8 + b_9C_{13} + b_{10}C_{14} + b_{11}C_{15} = d_{22}$

$KTd_{15} + b_9 + b_{10}C_{13} + b_{11}\ C_{15} = d_{23}$

... (A-26)

Therefore,

$a_0 = d_{16};$

$a_1 = d_{17};$

$a_2 = d_{18};$

$a_3 = d_{19} + K_3C_9;$

$a_4 = d_{20} + K_3C_{10} + K_2C_9$

$a_5 = d_{21} + K_3C_{11} + K_2C_{10} + K_1C_9$

$a_6 = d_{22} + K_3C_{12} + K_2C_{11} + K_1C_{10}$

$a_7 = d_{23} + K_2\ C_{12} + K_1C_{11}$ & $a_8 = K_1C_{12} + b_{10}$ ... (A-27)

5.5 State Space Approach

$$\Delta\phi_d = -\frac{x_d(1+T'_d P)(1+T''_d P)}{(1+T'_{do}P)(1+T''_{do}P)}\Delta i_d + \frac{1+T_{kd}P}{(1+T_{do}P)(1+T''_{do}P)}$$

$$\frac{x_{md}}{r_f}\Delta e_{fd}$$

$$= -x_d\left\{\frac{A_1}{1+T'_{do}P} + \frac{A_2}{1+T''_{do}P}\right\}\Delta i_d$$

$$+\left\{\frac{B_1}{1+T'_{do}P} + \frac{B_2}{1+T''_{do}P}\right\}\Delta e_{fd}$$

Calculation A_1 and A_2

$$A_1(1+T''_{do}P) + A_2(1+T'_{do}P) = 1+(T'_d+T''_d)P + T'_d T''_d P^2$$

Let $A_1 = (1+T_{1d}P)$

$A_2 = T_{2d}P$

Then

$$1+(T_{1d}+T''_{do})P + T''_{do}T_{1d}P^2 + T_{2d}P + T_{2d}T'_{do}P^2$$

$$= 1+(T'_d+T''_d)P + T'_d T''_d P^2$$

Comparing the coeffcients of P and P^2 etc.

$$T_1 + T''_{do} + T_{2d} = T'_d + T''_d$$

$$\therefore T_{1d} + T_{2d} = T'_d + T''_d - T''_{do} \quad \text{(A-28)}$$

$$T_{1d}T''_{do} + T_{2d}T'_{do} = T'_{d}T''_{d} \qquad \text{(A-29)}$$

From equations (A-28 + A-29) we calculate T_{1d} and T_{2d}

$$T_{1d} = \frac{T'_{d}T''_{d} - (T'_{d} + T''_{d})T'_{do} + T''_{do}\,T'_{do}}{(T''_{do} - T'_{do})}$$

$$T_{2d} = \frac{T'_{d}T''_{d} - (T'_{d} + T''_{d})T''_{do} + T''^{\,2}_{do}}{(T''_{do} - T'_{do})}$$

<u>Now calculate B_1 and B_2</u>

$$B_1\,(1 + T''_{do}P) + B_2\,(1 + T'_{do}P) = 1 + T_{kd}P$$

$$B_1 + B_2 = 1 \qquad \text{(A-30)}$$

$$B_1T''_{do} + B_2\,T'_{do} = T_{kd} \qquad \text{(A-31)}$$

From (A-30 and A-31) we have

$$B_1 = 1 + \frac{1 - T_{kd}}{T'_{do} - T''_{do}}$$

$$B_2 = -\frac{1 - T_{kd}}{T'_{do} - T''_{do}}$$

$$\Delta\phi d = -\,xd\left\{\frac{1 + T_1P}{1 + T'_{do}P} + \frac{T_2\,P}{1 + T''_{do}P}\right\}\Delta\, id$$

$$+\left\{\frac{B_1}{1 + T'_{do}P} + \frac{B_2}{1 + T''_{do}P}\right\}\Delta\ efd$$

$$= \frac{B_1\,\Delta efd}{1 + T'_{do}P} - \frac{xd\,\Delta id}{1 + T'_{do}P} - \frac{xd\ T_{1d}P\ \Delta id}{1 + T'_{do}P} +$$

$$+ \frac{B_2}{1+T''_{do}P} \Delta e_{fd} - \frac{x_d T_2 P \Delta i_d}{1+T''_{do}P}$$

$$\Delta\phi_d = \Delta\phi_{d_1} + \Delta\phi_{d_2} - \Delta\phi_{d_3} - \Delta\phi_{d_4} - \Delta\phi_{d_5}$$

$$\Delta\phi_{d_1} = \frac{B_1 \Delta e_{fd}}{1 + T'_{do}P} \qquad \therefore \Delta\phi_{d_1} + T'_{do}P \cdot \Delta\phi_{d1} = B_1 \cdot \Delta e_{fd}$$

$$\therefore P \cdot \Delta\phi_{d1} = - \frac{\Delta\phi_{d1}}{T'_{do}} + \frac{B_1 \Delta e_{fd}}{T'_{do}} \qquad (A-32)$$

$$P\Delta\phi_{d2} = - \frac{\Delta\phi_{d2}}{T'_{do}P} + \frac{B_1 \Delta e_{fd}}{T'_{do}} \quad - - - - - (A-33)$$

$$p\Delta\phi_{d_3} = - \frac{\Delta\phi_{d3}}{T_{do}'} + \frac{x_d \Delta i_d}{T_{do}'} \qquad (A-34)$$

$$\Delta\phi_{d_4} = \frac{T_{1d}P x_d}{1+T'_{do}P} \Delta i_d \qquad \therefore \Delta\phi_{d4} + T'_{do}P \cdot \Delta\phi_{d_4} =$$

$$= T_{1d} x_d P \cdot \Delta i_d$$

$$\therefore P\Delta\phi_{d4} - \frac{T_{1d} x_d}{T_{do}'} P\Delta i_d = - \frac{\Delta\phi_{d4}}{T_{do}'} \qquad (A-35)$$

$$\Delta\phi_{d_5} = \frac{x_d T_{2d}P \cdot \Delta i_d}{1+T''_{do}P} \quad \text{or } \Delta\phi_{d5} + T''_{do}P \Delta\phi_{d5}$$

$$= x_d T_{2d} P \cdot \Delta i_d$$

$$\text{or } P\Delta\phi_{d5} - \frac{x_d T_{2d} P \Delta i_d}{T''_{do}} = - \frac{\Delta\phi_{d5}}{T_{do}''} \qquad (A-36)$$

$$\Delta\phi_q = -x_q (p)\, i_q = - \frac{(1+T''_q P)}{(1+T''_{qo}P)} x_q \cdot i_q$$

$$\Delta\phi_q = - \frac{(1+T''_q P)}{(1+T''_{qo}P)} x_q \cdot \Delta i_q$$

$$\Delta\phi_q + T''_{qo} P \cdot \Delta\phi_q = - x_q \cdot \Delta i_q - T''_q x_q P\Delta i_q$$

or

$$P\Delta\phi_q + \frac{T''_q x_q P\Delta i_q}{T''_{qo}} = \frac{\Delta\phi_q}{T''_{qo}} - \frac{x_q}{T''_{q0}} \Delta i_q \quad \text{(A-37)}$$

$$e_d = P\phi_d - w\phi_q - r_a \cdot i_d \qquad \left\{\begin{array}{l} w = w_o + P\delta \\ \Delta w = P\Delta\delta \\ w_o = 1 \end{array}\right. \quad \text{(A-38)}$$

$$\therefore \Delta e_d = P\Delta\phi_d - w_o\Delta\phi_q - \phi_{qo}\Delta w - r_a \cdot \Delta i_d$$

$$= P\Delta\phi_d - w_o\Delta\phi_q - \phi_{qo} \cdot P\Delta\delta - r_a\Delta i_d$$

$$\Delta e_q = P\Delta\phi_q + w_o\Delta\phi_d + \phi_{do} P\Delta\delta - r_a \cdot \Delta i_q \quad \text{--- (A-38.1)}$$

$$\Delta e_t = \frac{e_{do}}{e_{to}}\Delta e_d + \frac{e_{qo}}{e_{to}}\Delta e_q$$

Let $\frac{e_{do}}{e_{to}} = \sin\delta_{10}$; $\frac{e_{qo}}{e_t} = \cos\delta_{10}$

$$\therefore \Delta e_t = \sin\delta_{10}\Delta e_d + \cos\delta_{10}\Delta e_q$$

Putting value of Δe_d and Δe_q from (A-38, A-38.1)

$$= \sin\delta_{10}(P\Delta\phi_d - w_o\Delta\phi_q - \phi_{qo}P\Delta\delta - r_a \cdot \Delta i_d)$$

$$+ \cos\delta_{10}(P\Delta\phi_q + w_o\Delta\phi_d + \phi_{do}P\Delta\delta - r_a \cdot \Delta i_q)$$

If we consider, $P\Delta\phi_d$ and $P\Delta\phi_q$ negligible. Then

$$e_t = \sin\delta_{10}(-w_o\Delta\phi_q - \phi_{qo}P\Delta\delta - r_a\Delta i_d)$$

$$+ \cos\delta_{10}(w_o\Delta\phi_d + \phi_{do}P\Delta\delta - r_a\Delta i_q)$$

$$= w_o\cos\delta_{10}\Delta\phi_d - w_o\sin\delta_{10}\Delta\phi_q + (\phi_{do}\cos\delta_{10} - \phi_{qo}$$

$$\sin\delta_{10})P\Delta\delta - r_a\sin\delta_{10}\Delta i_d - r_a\cos\delta_{10} \cdot \Delta i_q$$

Considering the linearised equation for voltage regulator about a chosen operating point as:-

$$\Delta e_{fd} = \frac{-k_r \Delta e_t + k_1 \Delta\delta + k_2 P\Delta\delta + k_3 P^2 \Delta\delta}{(1 + T_1 P)(1+T_2 P)}$$

$$= \frac{-k_r \Delta e_t + k_1 \Delta\delta + k_2 P\Delta\delta + k_3 P^2 \Delta\delta}{1+(T_1+T_2)P + T_1 T_2 P^2}$$

$$\therefore \Delta e_{fd} + (T_1+T_2)P\Delta e_{fd} + T_1 T_2 P^2 \Delta e_{fd} = -k_r \Delta e_t + k_1 \Delta\delta$$

$$+k_2 P\Delta\delta + k_3 P^2 \Delta\delta$$

or $\Delta e_{fd} + (T_1+T_2)P\Delta e_{fd} + T_1 T_2 P^2 \Delta e_{fd} = k_1 \Delta\delta + k_2 P\Delta\delta + k_3 P^2 \Delta\delta$ (A-39)

When only angle regulator is considered.

Let

$$P\Delta\delta = n \qquad \text{(A-40)}$$

$$P\Delta e_{fd} = \Delta e'_{fd} \qquad \text{(A-41)}$$

$$\therefore \Delta e_{fd} + (T_1+T_2)\Delta e'_{fd} + T_1 T_2 P \Delta e'_{fd} = k_1 \Delta\delta + k_2 n + K_3 P n$$

or $T_1 T_2 P \Delta e_{fd} - k_3 P n = k_1 \Delta\delta + k_2 n - \Delta e_{fd} - (T_1+T_2)\Delta e'_{fd}$ (A-42)

When only voltage regulator is considered , then

$$\Delta e_{fd} + (T_1+T_2)\Delta e'_{fd} + T_1 T_2 P\Delta e'_{fd} = -k_r \Delta e_t \qquad \text{(A-43)}$$

or $T_1 T_2 P \Delta e'_{fd} = -k_r \Delta e_t - \Delta e_{fd} - (T_1+T_2)\Delta e'_{fd}$

or $T_1T_2P\,\Delta e'_{fd} = -\Delta e_{fd} - (T_1+T_2)\,\Delta e'_{fd} + k_r w_o \sin\delta_{10}\cdot\Delta\phi_q$

$- k_r w_o \cos\delta_{10}\cdot\Delta\phi_d$

$+ (\phi_{qo}\sin\delta_{10} - \phi_{do}\cos\delta_{10})\,k_r n + k_r r_a \sin\delta_{10}\,\Delta i_d$

$+ k_r r_a \cos\delta_{10}\,\Delta i_q$

When both angle and voltage regulator are combined.

$$T_1T_2P\Delta e'_{fd} - k_3 P_n \eta = k_1\Delta\delta + (k_2 + (\phi_{qo}\sin\delta_{10} - \phi_{do}\cos\delta_{10})k_r)\cdot n$$

$$+ k_r w_o \sin\delta_{10}\,\Delta\phi_q - k_r w_o \cos\delta_{10}\cdot\Delta\phi_d$$

$$+ k_r r_a \sin\delta_{10}\,\Delta i_d + k_r r_a \cos\delta_{10}\cdot\Delta i_q$$

$$= \Delta e_{fd} - (T_1+T_2)\,\Delta e'_{fd} \qquad (A\text{-}44)$$

From equation of motion

$$MP_n\eta = -k_r n - i_{qo}\Delta\phi_d - \phi_{do}\Delta i_q + i_{do}\,\Delta\phi_q + \phi_{qo}\cdot\Delta i_d$$

$$P_n\eta = -\frac{k_{rn}\eta}{M} - \frac{i_{qo}\Delta\phi_d}{M} - \frac{\phi_{do}}{M}\Delta i_q + \frac{i_{do}}{M}\Delta\phi_q$$

$$+ \frac{\phi_{qo}}{M}\cdot\Delta i_d \qquad (A\text{-}45)$$

Now from transmission line equations we have.

$$\Delta e_d = V \cos \delta_0 \cdot \Delta \delta + r_e \cdot \Delta i_d - x \cdot \Delta i_q$$

$$\Delta e_q = - V \sin \delta_0 \cdot \Delta \delta + x \cdot \Delta i_d + r \cdot \Delta i_q$$

equating the value of Δe_d and Δe_q with the values obtained from machine equations (A-38 and A-38.1)

$$P \Delta \phi_d - v_o \Delta \phi_q - \phi_{qo} P \Delta \delta - r_a \Delta i_d = V \cos \delta_o$$

$$+ r_e \Delta i_d - x \Delta i_q$$

$$P \Delta \phi_q + v_o \Delta \phi_d + \phi d_o P \Delta \delta - r_a \Delta i_q = V \sin \delta_o + x \Delta i_d + r \Delta i_q$$

$$\therefore P \Delta \phi_d = v_o \Delta \phi_q + \phi_{qo} P \Delta \delta + R \cdot \Delta i_d - x \Delta i_q + V \cos \delta_o$$

$$L.H.S. = P(\Delta \phi d_1 + \Delta \phi d_2 - \Delta \phi d_3 - \Delta \phi d_4 - \Delta \phi d_5) \quad \text{Do}$$

$$L.H.S. = \frac{-\Delta \phi d_1}{T_{do'}} + \frac{B_1 \Delta e_{fd}}{T_{do'}} - \frac{\Delta \phi d_2}{T_{do''}} + \frac{B_2 \Delta e_{fd}}{T_{do''}}$$

$$+ \frac{\Delta \phi d_3}{T_{do'}} - \frac{x_d \Delta i_d}{T_{do'}} + \frac{\Delta \phi d_4}{T_{do'}}$$

$$- \frac{T_{1d} x_d}{T_{do'}} P \Delta i_d + \frac{\Delta \phi d_5}{T_{do''}} - \frac{T_{2d} x_d P \Delta i_d}{T_{do''}}$$

R.S. =

$$L.H.S. = \frac{\Delta\phi d_3 + \Delta\phi d_4 - \Delta\phi d_1}{T_{do'}} + \frac{\Delta\phi d_5 - \Delta\phi d_2}{T_{do''}}$$

$$- \frac{x_d \quad i_d}{T_d} + \left\{ \frac{B_1}{T_{do'}} + \frac{B_2}{T_{do''}} \right\} \Delta e_{fd}$$

$$- \left\{ \frac{T_{1d}}{T_{do'}} + \frac{T_{2d}}{T_{do''}} \right\} \cdot x_d P \Delta i_d$$

$$\therefore B_3 P \Delta i_d = \frac{-\Delta\phi d_1 + \Delta\phi d_3 + \Delta\phi d_4}{T_{do'}} + \frac{\Delta\phi d_2 + \Delta\phi d_5}{T_{do''}}$$

$$- \left(\frac{x_d}{T_{do'}} + R \right) \cdot \Delta i_d$$

$$- w_o \Delta\phi_q - \phi_{qo}{}^{n} + x \quad \Delta i_q - V \cos \delta_0$$

$$+ \left\{ \frac{B_1}{T_{do'}} + \frac{B_2}{T_{do}} \right\} \cdot \Delta e_{fd} \qquad \text{(A-46)}$$

Where $B_3 = \left(\frac{T_{1d}}{T_{do'}} + \frac{T_{2d}}{T_{do''}} \right) \cdot x_d$

$$P\Delta\phi_q = - \frac{\Delta\phi_q}{T_{qo''}} - \frac{x_q}{T_{qo''}} \Delta i_q - \frac{T_q}{T_{qo''}} x_q P\Delta i_q$$

$$B_4 P \Delta i_q = - \frac{\Delta\phi_q}{T_{qo''}} - \left(\frac{x_q}{T_{qo''}} + R \right) \Delta i_q + V \sin \delta_0$$

$$+ w_o \Delta\phi_d + \phi_{do}{}^{n} - x \Delta i_d. \qquad \text{(A-47)}$$

$$B_4 = \frac{T''_q}{T_{qo''}} x_q$$

$$\therefore\ p\Delta i_d = \frac{1}{B_3}\Bigg\{-\frac{\Delta\phi d_1 + \Delta\phi d_3 + \Delta\phi d_4}{T_{do'}} + \frac{-\Delta\phi d_2 + \Delta\phi d_5}{T_{do''}}$$

$$- \left(\frac{x_d}{T_{do'}} + R\right)\Delta i_d - w_o\,\Delta\phi_q - \phi_{qo}'' \qquad \text{(A-48)}$$

$$+ x\,\Delta i_q - V\cos\delta_o\,\Delta\delta + \left(\frac{B_1}{T_{do'}} + \frac{B_2}{T_{do''}}\right)\Bigg\}$$

$$p\Delta i_q = \frac{1}{B_4}\Bigg\{-\frac{\Delta\phi_q}{T_{qo''}} - \left(\frac{x_q}{T_{qo''}} + R\right)\Delta i_q$$

$$+ V\sin\delta_o\,\Delta\delta + w_o\,\Delta\phi_d + \phi_{do''}$$

$$-x_d\,\Delta i_d\Bigg\} \qquad \text{(A-49)}$$

—

5.6. Computer Programmes

(1) Programme for Voltage Variation and Power Angle Curves

```
C     STEADY STATE S.R.C.
    1 READ 10, AK, D
   10 FORMAT (2F 15.0)
      RA=0.01
      V=1
      R=0.05
      X= 0.3
      XD=1.2
      XQ= 0.8
      XQ1= XQ+X
      R1=R+RA
      XD1=XD+X
   20 E0= 1.+AK*D
      DIN= -R1*V*SINF(D)+XQ1*(E0-V*COSF(D))
      DID=R1**2. +XD1*XQ1
      DIO=DIN/DID
      QIN=XD1*V*SINF(D)+R1*(E0-V*COSF(D))
      QIO=QIN/DID
   30 DEO=V*SINF(D)+R*DIO-X*QIO
      QEO=V*COSF(D)+X*DIO+R*QIO
      TEO=(DEO*DEO+QEO*QEO)**0.5
      D1=ATANF(DEO/QEO)
      PO=DEO*DIO+QEO*QIO
      PUNCH 50,E0,TEO,D1,PO
   50 FORMAT(4F10.5)
      GOTO1
      END
```

(2) Programme to determine coefficients and stability by Routh hurwitz criterion

```
C   C   STABILITYTEST FOR TR1,TR2=0.0
        DIMENSION AK(3),AK2(4),AK3(4),D(8)
        READ10,XD,XQ,XM,RA
        READ10,X,R,AKI,V
        READ10,TD01,TD02,TD1,TD2,TKD
    10  FORMAT(5F12.0)
        READ25,(AK(I),I=1,3)
        READ25,(AK2(J),J=1,4)
        READ25,(AK3(K),K=1,4)
        READ25,(D(L),L=1,8)
    25  FORMAT(6F10.0)
    30  READ10,TR1,TR2
        XQ1=XQ+X
        R1=R+RA
        XD1=XD+X
        DID=(R1**2.)+XD1*XQ1
        CT1=(TD01*TD02)**2.
        CT2=TD01*TD02*TD1*TD2
        CT3=2.0*TD01*TD02*(TD01+TD02)
        CT4=TD01*TD02*(TD1+TD2)+TD1*TD2*(TD01+TD02)
        CT5=2.0*TD01*TD02+(TD01+TD02)**2.0
        CT6=TD01*TD02+TD1*TD2+(TD01+TD02)*(TD1+TD2)
        CT7=2.0*(TD01+TD02)
        CT8=TD01+TD02+TD1+TD2
        C=R1**2.0+M*XQ1
    40  DO20OL=1,8
        DO20OI=1,3
```

```
      EO=1.+AK(I)*D(L)
      DIN=-R1*V*SINF(D(L)+XЧ1*(EO-V*COSF(D(L))
      DIO=DIN/DID
      ЧIN=XD1*V*SINF(D(L)+R1*(EO-V*COSF(D(L)))
      ЧIO=ЧIN/DID
      DEO=V*SINF(D(L))+R*DIO-X*ЧIO
      ЧEO=V*COSF(D(L))+X*DIO+R*ЧIO
      TEO=(DEO*DEO+ЧEO*ЧEO)**0.5
      D1=ATANF(DEO/ЧEO)
      PO=DIO*DEO+ЧIO*ЧEO
      DPHIO=EO-XD*DIO
      ЧPHIO=-XQ*ЧIO
      A61=C*CT1+ XD*XЧ1*CT2
      A6= HM*A61
      C1=DPHIO+XЧ*DIO
      C2=R1*DPHIO+X*ЧPHIO
      C3=XЧ1*DPHIO-R1*ЧPHIO
      C4=DPHIO+XЧ*DIO
52    A52=C*CT3XD*XЧ1*CT4
      A53=(C1*C2-C3*ЧPHIO)*CT1
      A54=(C4*XD*ЧPHIO-C3*XD*ЧIO)*CT2
      A5=AKT*A61+HM*A52+A53+A54
      CD1=R1*V*SINF(D(L))+X*V*COSF(D(L))
      CD2=XЧ1*V*SINF(D(L))-R1*V*COSF(D(L))
      CD3=XD*V*COSF(D(L))
      A42=C*CT5+XD*XЧ1*CT6
      A43=C1*(CD1*CT1+CD3*CT2+C2*CT3+XD*ЧPHIO*CT4)
      A44=CD2*(ЧPHIO*CT1+XD*ЧIO*CT2)
```

```
      A45=C3*ЧPHI0*CT3+XD*ЧI0*CT4
54    A4+AK2*A52+HK*A42+A43-A44-A45
      A32=C*CT7+XD*XЧ1*CT8
      A33=C1*(CD1*CT3+CT3+CD3*CT4+C2*CT5+XD*ЧPHI0*CT6)
      A34=CD2*(ЧPHI0*CT3+XD*ЧI0*CT4)
      A35=C3*(ЧPHI0*CT5+XD*ЧI0*CT6)
      A3+AK2*A42+HK*A32+A33-A34-A35
      A22+C+XD*XЧ1
      A23=C1*(CD1*CT5+CD3*CT6+C2*CT7+XD*ЧPHI0*CT8)
      A24=CD2*(ЧPHI0*CT5+XD*ЧI0*CT6)
      A25=C3*(ЧPHI0*CT7+XD*ЧI0*CT8)
      A2=AK2*A32+HK*A22+A23-A24-A25
      A13=C1*(CD1*CT7+CD3*CT8+C2+XD*ЧPHI0)
      A14=CD2*(ЧPHI0*CT7+XD*ЧI0*CT8)
      A15=C3*(ЧPHI0+XD*ЧI0)
      A1=AK2*A22+A13-A14-A15
      A0=C1*(CD1+CD3)-CD2*(APHI0+XD*ЧI0)
      B0=ЧI0*C-ЧPHI0*XЧ1+R1*C1
      B1= B0*(TD01+TD02+TKD)
      B2=B0*(TD01*TD02+TKD*(TD01+TD02))
      B3=B0*TD01*TD02*TKD
      A08=A6*TR1*TR2
      A07=A6*(TR1*TR2)+A5*TR1*TR2
      A06=A6+A5*(TR1+TR2)+A4*TR1*TR2
100   DO200J=1,4
      DO200K=1,4
      A05=A5+A4*(TR1+TR2)+A3*TR1+TR2
      A04=A4+A3*(TR1+TR2)+A2*TR1*TR2+AK3(K)*B2+AK2(J)*B3
```

```
A03=A3+A2*(TR1+TR2)+A1*TR1*TR2+AK3(K)*B1+AK2(J)*B2+AK(I)*B3
A02=A2+A1*(TR1+TR2)+A0*TR1*TR2+AK3(K)*B0+AK2(J)*B1+AK(I)*B2
A01=A1+A0*(TR1+TR2)+AK(I)*B1+AK2(J)*B0
A00=A0+AK(I)*B0
   120   PUNCH 180,L,I,J,K,A08,A07,A06,A05
   125   PUNCH 190,A04,A03,A02,A01,A00
   150   B07=A06-A08*A05/A07
         B05= A04-A08*A03/A07
         B03= A02-A08*A01/A07
         B01=A00
         C07=A05-A07*B05/B07
         C05=A03-A07*B03/B07
         C03=A01-A07*B01/B07
         D07=B05-B07*B05/C07
         D05=B03-B07*C05/C07
         D03=B01
   160   E07=C05-C07*D05/D07
         E05=C03-C07*D03/D07
         F07=D05-D07*E05/E07
         E05=D03
         G07=E05-E07*F05/F07
         H07=F05
   170   PUNCH 180,L,I,J,K,A03,A07,B07,C07
   180   FORMAT(4I4,4E12.5)
         PUNCH 190,D07,E07,F07,G07,H07
         L,I,J,K,A03,A07,A06,A05
   190   FORMAT(4I4,4E12.
```

```
190   FORMAT(16X,5E11.5)
      A04,A03,A02,A01,A00
200   CONTINUE
      GOTO30
      END
```

Programme for determining constants(for determining the stability and calculating K_2 and K_3 for 1150 with K_1= 1.59)

```
C     C  CONSTANTSCHARACTERISTICS EQU.
      DIMENSIOND(4)
      READ10,XD,XQ,HM,RA
      READ10,X,R7ART,V
      READ10, TD01,TD02,TD1,TD2,TED
10    FORMAT(5F12.0)
      READ25,(D(L),L=1,4)
25    FORMAT(6F10.0)
30    READ10.TR1,TR2,AK
      XQ1=XQ+X
      R1=R+RA
      XD1=XD+X
      DID=(R1**2.)+XD1*XQ1
      CT1=(TD01*TD02)**2.
      CT2=TD01*TD02*TD1*TD2
      CT3=2.0*TD01*TD02* (TD02+TD02)
      CT4=TD01*TD02*(TD1+TD2)+TD1*TD2*(TD01+TD02)
      CT5=2.0*TD01*TD02+(TD01+TD02)**2.0
      CT6=TD01*TD02+TD1*TD2+(TD01+TD02)*(TD1+TD2)
      CT7=2.0*(TD01+TD02)
      CT8=TD01+TD02+TD1+TD2
      C=R1**2.0+X*XQ1
```

```
40      DO200L=1,4
        EO=1.+AK*D(L)
        DIN=-R1*V*SINF(D(L)+XЧ1*(EO-V*COSF(D(L)))
        DIO=DIN/ ID
        ЧIN=XD1*V*SINF(D(L))+R1*(EO-V*COSF(D(L)))
        ЧIO=ЧIN/DID
        DEO=V*SINF(D(L))+R*DIO-X*ЧIO
        ЧEO=V*COSF(D(L))+X*DIO+R*ЧIO
        TEO=(DEO*DEO+ЧEO*ЧEO)**0.5
        D1=ATANF(DEO/ЧEO)
        PO=DIO*DEO+ЧIO*ЧEO
        DPHIO=EO-XD*DIO
        ЧPHIO=-XЧ*ЧIO
        A61=C*CT1+XD*XЧ1*CT2
        A6=HM*A61
        C1=DPHIO+XЧ*DIO
        C2=R1*DPHIO+X*ЧPHIO
        C3=XЧ1*DPHIO-R1*ЧPHIO
        C4=DPHIO+XЧ*DIO
52      A52=C*CT3+XD*XЧ1XCT4
        A53= (C1*C2-C3*ЧPHIO)*CT1
        A54=(C4*XD*ЧPHIO-C3*XD*
        A5=AKM*A61+HM*A52+A53+A54
        CD1=R1*V*SINF(D(L))+X*V*COSF(D(L))
        CD2=XЧ1*V*SINF(D(L))-R1*V*COSF(D(L))
```

```
      CD3=XD*V*COMP(D(L))
      A42=C*CT5+XD*XW1*CT6
      A43=C1*(CD)*CT1+CD3*CT2+C2*CT3+XD*WPHIO*CT4)
      A44=CD2*(WPHIO*CT1+CT1+XD*WIO*CT2)
      A45=C3*WPHIO*CT3+XD*WIO*CT4
54    A4=AKT*A52+EM*A42+A43-A44-A45
      A32=C*CT7+XD*XW1*CT8
      A33=C1*(CD1*CT3*CT4+C2*CT5+XD*WPHIO*CT6)
      A34=CD2*(WPHIO*CT3+XD*WIO*CT4)
      A35=C3*(WPHIO*CT5+XD*WIO*CT6)
      A3=AKT*A42+EM*A32+A33-A34-A35
      A22=C+XD*XW1
      A23= C1*(CD1*CT5+CD3*CT6+C2*CT7+XD*WPHIO*CT8)
      A24=CD2*(WPHIO*CT5+XD*WIO*CT6)
      A25=C3*(WPHIO*CT7+XD*WIO*CT8)
55    A2=AKT*A32+EM*A22+A23-A24-A25
      A13=C1*(CD1*CT7+CD3*CT8+C2+XD*WPHIO)
      A14=CD2*(WPHIO*CT7+XD*WIO*CT8)
      A15=C3*(WPHIO+XD*W/IO)
      A1=AKT*A22+A13-A14-A15
      A0=C1*(CD1+CD3)-CD2*(WPHIO+XD*WIO)
      BC=WIO*C-WPHIO*XW1+R1*C1
      B1=BC*(TD01+TD02+TKD)
      B2=BC*(TD01*TD02+TKD*(TD01+TD02))
      B3=BC*TD01*TD02*TKD
```

```
      A08=A6*TR1*TR2
      A07=A6*(TR1+TR2)+A5*TR1*TR2
      A06=A6+A5*(TR1+TR2)+A4*TR1*TR2
      A05=A5+A4*(TR1+TR2)+A3*TR1*TR2
      A04=A4+A3*(TR1+TR2)+A2*TR1*TR2
      A03=A3+A2*(TR1+TR2}+A1*TR1*TR2+AK*B3
      A02=A2+A1*(TR1+TR2)+A0*TR1*TR2+AK*B2
      A01=A1+A0*(TR1+TR2)+AK*B1
      A00=A0+AK*B0
      PUNCH 180,L,B0,B1,B2,B3,A08,A07
180   FORMAT(I19,6E10.5)
      PUNCH190,A05,A04,A03,A02,A01,A00, A06
190   FORMAT(7E10.5)
200   CONTINUE
      GOTO30
      END
```

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