PARAMETER CO-ORDINATION OF A DOUBLY EXCITED SYNCHRONOUS GENERATOR

A DISSERTATION
submitted in partial fulfilment of
the requirements for the award of the Degree
of
MASTER OF ENGINEERING
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by
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C E R T I F I C A T E

Certified that the dissertation entitled " Parameter coordination of a Doubly-Excited Synchronous Generator" is being submitted by Shri T.S. Baghel in partial fulfilment for the award of the degree of Master of Engineering in Electrical (Power Apparatus and Electric Drives) of University of Roorkee, Roorkee is a record of student's own work carried out by him under my supervision and guidance. The matter embodied in this dissertation has not been submitted for the award of any other degree or diploma.

This is to further certify that he has worked for a period of 6 months from January 1977 to June 1977, for preparing this dissertation at this University.

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ABSTRACT

The problem of absolute stability and transient response of a Doubly-Excited Synchronous Generator, connected to an infinite bus-bar through lumped R.L.C. parameters has been investigated in this dissertation. The d- and q- axis machine fields are assumed to be regulated by AVRS responding to deviations in the machine terminal voltage, current and load angle and their first two time derivatives. The prime mover governor is of a 3 term type, sensing the variations in the machine load angle, speed and accelaration.

The effects of certain parameters namely reactive power, load angle, transmission line capacitive reactance, AVR time constants, product of governor time constant and proportionate gain constant of current regulator on the stability region in the parameter plane have been studied.

The d-decomposition technique is used to obtain the stability regions in the following planes :

(i) $K_{1I} - K_{2I}$; (ii) $K_{1V} - K_{2V}$; (iii) $K_{1\delta} - K_{2\delta}$

i.e. first and second derivative gain constants of current, voltage and angle regulator.

This will to a great extent overcome the often encountered difficulty of setting the regulator gains at Commissioning stage to ensure the system stability with a prescribed quality of the system transient response.

A number of simplifying assumptions have been made so that this problem can be conveniently solved making use of the departmental computer TDC 312 only.

LIST OF SYMBOLS

V_B = Infinite Busbar Voltage.

V_t = Terminal Voltage.

e_d = Direct-axis Component of Terminal Voltage.

e_q = Quadrature-axis Component of Terminal Voltage.

V_{fd} = Direct-axis Field Voltage (reffered to stator).

V_{fq} = Quadrature-axis Field Voltage (reffered to stator).

E = Voltage Behind Steady-State Reactance.

E_d = Voltage Proportional to q-axis Field Current.

E_q = Voltage Proportional to d-axis Field Current.

ψ_d = Flux Linkage of d-axis Stator Circuit.

ψ_q = Flux Linkage of q-axis Stator Circuit.

I = Load Current.

I_d = Direct-axis Component of Load Current.

I_q = Quadrature-axis Component of Load Current.

I_{fd} = Direct-axis Field Current.

I_{fq} = Quadrature-axis Field Current.

X_{md} = Direct-axis Magnetising Reactance.

X_{mq} = Quadrature-axis Magnetising Reactance.

X_d = Direct-axis Synchronous Reactance.

X_q = Quadrature-axis Synchronous Reactance.

X_{fd} = Total Reactance of d-axis Field Winding.

X_{fq} = Total Reactance of q-axis Field Winding.

T'_{do} = Direct-axis Transient Open-Circuit Time Constant.

T'_{qo} = Quadrature axis Transient Open-Circuit Time Constant.

T_d = Direct-axis Transient Short-Circuit Time Constant.

T_q = Quadrature-axis transient short-circuit time constant.

X_L = Tie-line inductive reactance.

X_c = Tie-line capacitive reactance.

r_L = Tie-line resistance.

r = Machine resistance.

t = time, S.

p = d/dt operator.

M = Inertia constant.

δ = Load angle

P_d = Damping coefficient.

P_e = Electrical power developed

P_m = Mechanical power input.

<u>The Governing Scheme</u>

K_{go} = Rotor-displacement gain constant.

K_{g1} = Speed gain constant.

K_{g2} = Acceleration gain constant.

T_{g1}, T_{g2} = Time constants.

<u>The Voltage Regulator</u>

K_{ov} = Gain constant for voltage deviation.

K_{1v} = Gain constant for first time derivative of voltage.

K_{2v} = Gain constant for second time derivative of voltage.

K_{OI}, K_{1I}, K_{2I}, $K_{1\delta}$, $K_{2\delta}$ are respective gain constants for current and load angle.

T_{E1}, T_{E2} = Time constants of d and q axis V.R. circuits respectively.

C O N T E N T S

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CHAPTER -1

Introduction

REVIEW

In future, higher voltage transmission and distribution and the increasing use of h.v cables will cause a rapid rise of surplus reactive power which can not be economically fully-compensated for by parallel reactors. The most economic turbogenerator designs must uses the highest practicable steam temperatures and pressures for maximum efficiency and minimum size of the turbine, making the problems of the absorption of surplus reactive power more difficult to solve. The most economic generators are designed with the lowest short circuit ratios.

These economic advantages carry with them reactive and transient performance penalties because of the reduced reactive absorbing capabilities of the generator and the lower inertia of the set. J.A. Soper and A.R. Fagg[1], experimenting with a 5 K.VA machine, showed the feasibility of a new form of turbogenerator using a rotor winding of two sections in "X" formation. Controlling the torque and reactive requirement, separately.

The main feature of the d.w.r. control is that the torque winding has a closed-loop rotor angle control, so that the reactive winding generates no torque ideally. This is an essential part of the scheme and all the other features depend on it. The reactive-winding axis is thus in line with the generator flux and can operate continuously with negative excitation, without causing a pole slip.

They used successfully the same mathematical model in modified form to represent the divided-winding-rotor turbogenerator which had produced accurate results, when compared with actual system tests on a conventional 30 M.W. turbogenerator involving 3-phase faults on the h.v. busbar for their simulation.

The d.w.r. generator range of reactive absorption at full load was found, in their simulation to extend beyond -2.3 p.u. (leading) without instability, whereas the conventionally wound rotor turbogenerator simulation showed the C.W.r to be unstable at -0.9 p.u.

The 3 phase fault duration that the d.w.r. was shown to withstand when absorbing any amount of reactive power at full load, up to the maximum absorption simulated (-2.3) was shown to be not less than 0.4 s. for maximum plant-load-conditions or 0.32 for minimum plant-load-conditions comparable c.w.r.

performance at the practicable stability limit was shown to be - 0-225 reactive absorption, which withstood a fault duration of 0.32 s with maximum plant conditions, or 0.25 s with minimum plant conditions.

The simulation showed that the recovery rate of generator terminal voltage to step falls in infinite bus-bar voltage for the d.w.r. was approximately twice that of the c.w.r.

To deal with a divided winding rotor (d.w.r.) synchronous machine in which the two field windings are not located on the rotor axes and may not have equal numbers of turns, an equivalent machine is introduced with field windings on the direct and quadrature axes by R.G. Harley and B. Adkins[2]. They have shown that the use of a torque-field winding controlled by a load angle feedback is an effective way of extending the range of stable operation of a synchronous generator. Their results indicate that the angle feed-back stabilises the voltage feedback and permits the use of extremely high values of a.v.r. gain that would cause instability if the angle regulator feedback were removed. They used nyquist criterion to determine the stability limits of a multi feedback system.

As opposed to the very detailed simulation results presented by Soper and Fagg[1], the brief paper by R.B. Robinson[3] shows that the machine is nonsalient for transient changes and may be represented by a constant voltage behind a transient reactance. This gives a simple understanding of its performance compared with a conventional machine which shows a large degree of transient saliency. Thus, whatever the initial conditions of loading d.w.r. will give greater transient power transfer than a conventional turboalternator, and should exhibit better transient-stability performance. The difference will be most marked under initial leading power-factor loading, where the voltage behind transient reactances (X_d' , X_q) of the conventional turboalternator issmall owing to its transient saliency.

M. Ramamurthi and B.W. Hogg's[4] analysis shows how the positional change of the resultant m.m.f. due to the induced currents, gives an inherent advantage to the doubly-excited machine over a conventional synchronous machine, for the improvement of transient stability. When excitation controls are employed, there is further improvement in the transient stability limit, with a greater contribution coming from the voltage regulator. This advantage is greatest when the machine is absorbing leading reactive power, or is under heavy loads.

Stability studies of d.w.r. synchronous machine, equipped with common types of voltage and angle regulators and speed governor are made employing the Routh-Hurwitz criterion by P. Subramanium and O.P. Malik[5]. The speed governor is found to increase the stability limits. Employing feedback stabilisation in the voltage and angle regulators is found to improve the stability limits, and also it permits the use of compartively large values of angle regulator gain for a given negative reactive power absorption. Further, using the D- partition method, they have determined the stability boundaries in the plane of two parameters of the angle regulator, and the dependence of these boundaries on other system parameters is investigated in detail.

The roots of the characteristic equation of a divided winding rotor synchronous machine equipped with regulators for controlling voltage, torque angle and speed are evaluated by P. Subramanium and O.P. Malik[6]. Under different operating conditions, sensitivity of the critical root of the system for small variations in various control parameters are determined. From these results, the effect of the parameters on the root locations, and hence on system performance, can be ascertained. Using this approach, it is shown how the parameters of the control circuits of the d.w.r. synchronous machine may be chosen for better steady-state and transient performance. The critical root of the characteristic equation describing the system is highly sensitive to the variations in the regulator and stabiliser gains, and the exciter time constant of the angle regulator. By properly choosing these parameters, a system with better performance under a given set of conditions can be designed.

Analogue and digital-computer studies of a synchronous machine with various 2-axis excitation control system have been made by M. Ramamurthi, D. Williams and B.W. Hogg[7]. The steady-state and transient performances of the same machine are analysed, assuming different control schemes, such as rotor-angle control and asynchronised operation, and are compared with a conventional machine. The effects of damper windings, regulator time constants and stabilising circuits on the steady-state performance are shown by regulation curves. It is confirmed that the voltage-regulator loop gain has virtually no effect on steady-state stability, provided the winding with a.v.r. control is aligned with the flux axis by an angle regulator. The improved transient-stability limits obtained with high gains are shown. The fundamentally different transient behaviour of unregulated doubly-excited and conventional synchronous machines is explained, and confirmed using accurate mathematical models of the machines. The method of small oscillations is applied to determine the speed stability of an asynchronised synchronous machine, and the transient performances of three different control schemes are compared in terms of swing curve and switching time curves.

The theoretical treatment by S.C. Kapoor, S.S. Kalsi and B. Adkins[8] consists of two parts. First, some general results are deduced from simplified equations, particularly relating to the limitations of a direct axis regulator and the benefit of using an angle signal with the quadrature regulator. More complete computations are then made to obtain stability limit curves for many alternative schemes. Their work is concerned with the steady state stability of a 1-machine system, in which a generator is connected to an infinite bus through a reactance. The alternative studies included simple proportionate regulators and more elaborate schemes using first and second derivative elements, and the angle signal was taken alternatively from the infinite bus and generator terminals.

An investigation into the behaviour of a divided winding-rotor synchronous generator, equipped with regulators for controlling the terminal voltage, torque angle and speed, when subjected to unbalanced short circuits at its terminal is made by P. Subramanium, and O.P. Malik[9]. The performance of the machine has been compared with that of conventional would rotor arrangement. It has been observed that the d.w.r. arrangement exhibits exceptionally superior transient performance characteristics compared with the c.w.r. machine, even under unbalanced-fault conditions, which the machine has to encounter more often in practice than balanced faults. The angle and voltage regulators are affective in enabling the d.w.r. machine to withstand larger fault durations, providing the versatility of the new machine.

Some transient-stability studies have been made by P. Subramanium and O.P. Malik[10] of a divided-winding-rotor synchronous generator equipped with regulators for controlling the voltage, torque angle and speed. It has been observed that the machine is quite capable of withstanding severe forms of load shedding, and that the angle regulator is quite effective in checking the magnitudes of rotor-angle swing. Other abnormalities, such as opening of excitation circuits, with and without external faults, have also been studied. The reversal of reactive field current, following a three-phase short circuit, has been found to be not absolutely essential for maintaining the stability of the machine. The torque field excitation has been observed to be a major stabilising factor specially under leading power factor conditions.

The comparison made by D.P. Sen Gupta, B.W. Hogg and M.Yau[12] of the total synchronising and damping torque in conventional and doubly-excited synchronous machines has shown that, within the normal operating limits of the machine, the synchronising torque is increased by the inclusion of an additional field winding, whereas the damping torque is reduced, thus making the machine more prone to hunting. Although the doubly excited machine is inherently less damped than a conventional machine, the presence of an additional control system on the second field winding can more than compensate for this deficiency.

A state space model of a turbogenerator with direct and quadrature axis excitation system is formulated by

S. Raman and S.C. Kapoor[13] for the study of the stability of, and the interaction between, various regulators. The direct and quadrature excitations are controlled by the signals taken from the terminal voltage and the rotor angle, respectively. It is shown that this model can be extended to the case where the excitation windings are not at right angles. The stability limit plots and transient responses of the system are determined with the help of a digital computer. The effects of damper windings, the time delay in regulator and the initial position of the quadrature axis with respect to the infinite busbar on the stability-limit plot and on the transient response for small perturbations. The quadrature-axis regulator increases the reactive absorption and is almost independent of the active power level. An increase in the regulator time delay decreases the maximum value of the negative power upto which the system is stable, while the regulator gain-range is increased. The effects of damper windings and the interaction between regulators are marginal. A change in the equilibrium position of the quadrature axis with respect to the infinite bus bar voltage increases the interaction between the direct and quadrature axis regulators. The speed governor increases the integral square error of the transient response due to small perturbations in any of the states. For the system with direct and quadrature-axis excitations direct-axis regulator decreases the integral square error.

The method of D-decomposition technique is used by J. Nanda[15] for the analysis of steady-state stability of a two machine system with the machine provided with a fast acting electronic-excitation voltage regulator using proportional signals of voltage and current, and the first and second derivatives of current signals. Voltage regulator gains for maximum alternator stability are determined. This would, to a great extent, overcome the often encountered difficulty of setting the regulator gains at commission stage by trial and error, until a good step response under open-circuit condition is achieved. The effect of several parameters also the electro-mechanical transient process of the receiving and system represented by an equivalent machine offinite capacity on steady state stability of the system is investigated for properly designing the parameters of the voltage regulator.

The method of D-decomposition technique, for optimizing the derivative gain settings of the excitation voltage regulators for best steady-state stability condition, i.e. for maximum alternator stability and best transient response for small perturbations, is also considered by J. Nanda[16].

The transient-stability problem of the doubly excited machine has been attacked through Liapunov's direct method by T.K. Mukherjee, B. Bhattacharya and A.K. Choudhury[17]. They have considered a second-order mathematical model of this machine connected to an infinite busbar, without any regulator, and generated a Liapunov function. The region of asymptotic stability in the state space is compared for the doubly and singly excited synchronous machines and it is verified that there is an improvement in this region for the doubly-excited case.

V.K. Verma[18] has included regulators also for the transient-stability study through Liapunov's direct method. He has drawn following deductions -

(i) The critical fault-clearing time is higher for the u.p.f. conditions compared to the leading p.f. conditions for the same power transfer and parameters.

(ii) Critical clearing time T_c improves very slowly with increase in K_{ov} and δ sensitive gains (ratio $K_{o\delta} : K_{1\delta}$ fixed).

(iii) Increase of K_{1v}, other parameters fixed, improves T_c for lower range of K_{1v}. At higher values of K_{1v}, T_c is almost constant.

(iv) Higher values of T_c are achieved with doubly-excited machine compared to a singly-excited machine. This improvement is remarkable for the leading p.f. conditions.

Author's Contribution

The present work is concerned with a study of the effects of various parameters of the control loop using forced regulators on the steady-state stability of a power system. The system considered is a doubly-excited alternator connected to an infinite bus through tie line. The tie line is represented by lumped resistance, inductive and capacitive reactances.

The D-decompositon technique has been used to investigate the effects of various parameters on the regions of absolute stability, and a given degree of stability in the plane of first and second derivative gains of voltage, current and angle-regulators.

The objective of this study is to obtain coordinated values of the regulator parameters to result in a stable system with the given quality settling time property of the system transient response.

CHAPTER - 2

Formulation of the problem

The scheme studied is a doubly excited single machine system with automatic voltage and current regulators (sensing terminal voltage and line current deviations, and their first two time derivatives) on the direct axis field, and an angle regulator (sensing load-angle deviation and its first two derivatives) on the quadrature axis field and a 3 term governing scheme with two time lags. Fig.2.1 gives a schematic layouts of the system with regulators.

2.1 Machine Equations

For a machine which has field coil on each axis. The stator d- and q- axis flux linkages are

$$d = - X_d i_d + X_{md} I_{fd} \qquad 2.1$$

and

$$q = - X_q i_q + X_{md} I_{fd} \qquad 2.2$$

It should be noted that the damper circuits have been ignored here and they have been taken care of later by a damping coefficient P_d .

The d- axis field voltage

$$V_{fd} = R_{fd} I_{fd} + p\,(- i_d X_{md} + X_{fd} I_{fd})$$

From which

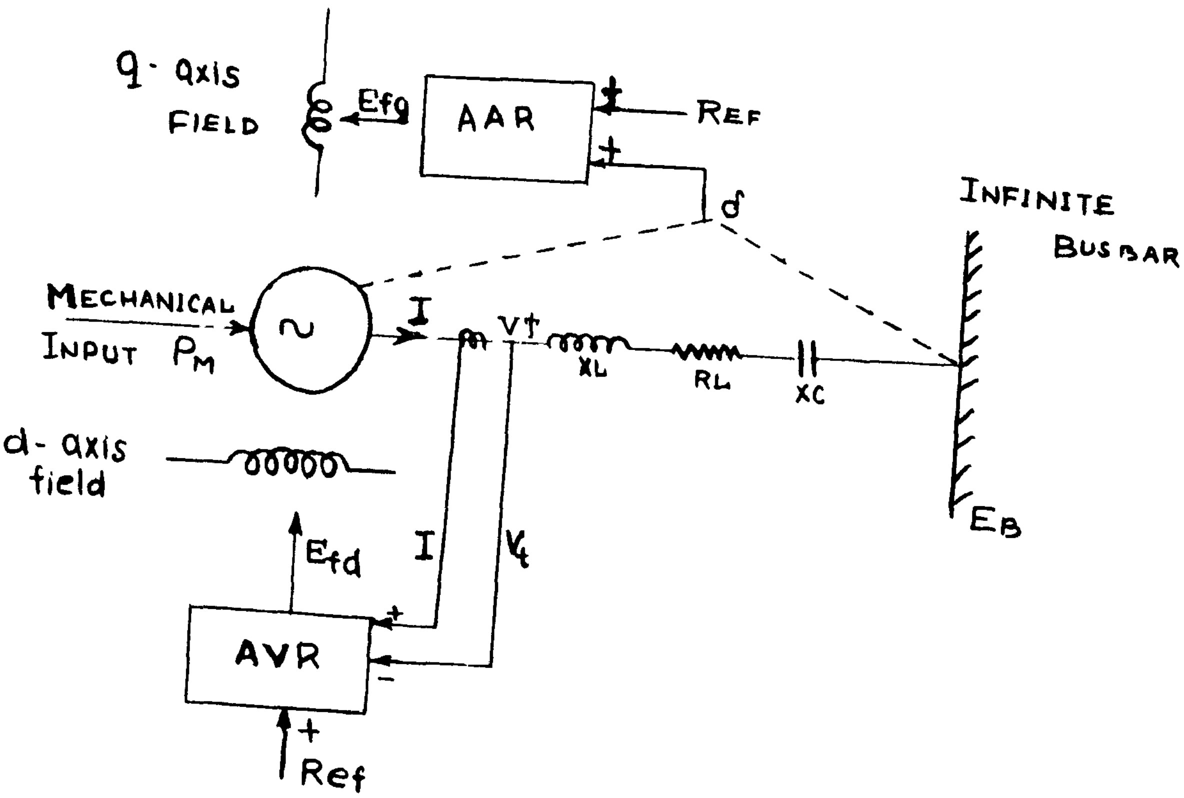


FIG 2.1 SYSTEM MODEL OF A DOUBLY EXCITED SYNCHRONOUS MACHINE

$$I_{fd} = \frac{V_{fd} + X_{md}\, p i_d}{R_{fd} + X_{fd} p}$$

Substituting this in (2.1)

$$\psi_d = - X_d i_d + X_{md} \left(\frac{V_{fd} + X_{md} p i_d}{R_{fd} + X_{fd} p} \right)$$

$$= - \left(X_d - \frac{X^2_{md}\, p}{R_{fd} + X_{fd} p} \right) i_d + \frac{X_{md}\, V_{fd}}{R_{fd} + X_{fd}\, p}$$

$$= - X_d \left| \frac{\dfrac{1 + \left(X_{fd} - \dfrac{X^2_{md}}{X_d} \right) p}{R_{fd}}}{1 + \dfrac{X_{fd}}{R_{fd}}\, p} \right| i_d + \frac{X_{md}}{R_{fd}} \frac{V_{fd}}{1 + \dfrac{X_{fd}}{R_{fd}}\, p}$$

$$= - X_d \left| \frac{1 + T'_d p}{1 + T'_{do} p} \right| i_d + \frac{V_{fd}}{1 + T'_{do} p}$$

which can be written in the form

$$\psi_d = - X_d(p) i_d + G_d(p)\, V_{fd} \qquad 2.3$$

Similarly $\psi_q = - X_q(p)\, i_q + G_q(p) V_{fd}$ 2.4

where $X_d(p) = \dfrac{X_d(1 + T_d'p)}{(1 + T_{do}'p)}$, $G_d(p) = \dfrac{1}{(1 + T_{do}'\,p)}$

$$V_{fd} = \frac{X_{md}}{R_{fd}} V_{fd} \quad , \qquad V_{fq} = \frac{X_{mq}}{R_{fq}} V_{fq}$$

$$G_q(p) = \frac{1}{(1 + T'_{qo}p)} \quad , \qquad X_q(p) = X_q\frac{(1 + T_q'p)}{(1 + T'_{qo}p)}$$

The d- and q- axis components of machine terminal voltages are given by

$$e_d = -\psi_q p\theta - \gamma i_d \qquad 2.5$$

$$e_q = \psi_d p\theta - \gamma i_q \qquad 2.6$$

After neglecting the transformer voltage terms, which are very small compared to the speed voltages.

Linearization of 2.5 and 2.6 around initial operating condition then gives

$$\Delta e_d = -\psi_{qo} p \Delta\delta - \Delta\psi_q - \gamma\Delta i_d \qquad 2.7$$

and $\Delta e_q = \psi_{do} p \Delta\delta + \Delta\psi_d - \gamma\Delta i_q$ 2.8

It may be noted that $(p\theta)_o$ is unity in p.u. system.

Substituting 2.3 and 2.4 in 2.7 and 2.8 gives

$$\Delta e_d = -\psi_{qo} p\Delta\delta - \gamma\Delta i_d + X_q(p)\Delta i_q - G_q(p)\Delta V_{fq}$$

$$\Delta e_q = \psi_{do} p\Delta\delta - \gamma\Delta i_q - X_d(p)\Delta i_d + G_d(p)\Delta V_{fd}$$

Now $\Delta V_{fq} = G_{\delta}(p)\Delta\delta$

and $\Delta V_{fd} = - G_v(p)\Delta V_t + G_i(p)\Delta I$

where
$$G_{\delta}(p) = \frac{K_{o\delta} + K_{1\delta}p + K_{2\delta}p^2}{1 + T_{e2}p}$$

$$G_v(p) = \frac{K_{ov} + K_{1v}p + K_{2v}p^2}{1 + T_{e1}\,p}$$ and

$$G_i(p) = \frac{K_{oi} + K_{1i}p + K_{2i}p^2}{1 + T_{e1}p}$$

also since $V_t^2 = e_d^{\,2} + e_q^{\,2}$ and

$$I^2 = i_d^2 + i_q^2$$

hence
$$\Delta V_t = \frac{e_{do}}{V_{to}}\Delta e_d + \frac{e_{qo}}{V_{to}}\Delta e_q$$

$$= S_d\,\Delta e_d + S_q\,\Delta e_q$$

and
$$\Delta I = \frac{i_{do}}{I_o}\Delta i_d + \frac{i_{qo}}{I_o}\Delta i_{qo}$$

$$= C_d\,\Delta i_d + C_q\,\Delta i_{qo}$$

Thus ΔV_{fd} can be expressed as

$$\Delta V_{fd} = - G_v(p)\,|S_d\Delta e_d + S_q\Delta e_q| + G_I(p)\,|\,C_d\Delta i_d + C_q\Delta i_q\,|$$

Substituting the expressions for ΔV_{fd} and ΔV_{fq} in the expressions of Δe_d and Δe_q gives the following expressions for Δe_d and Δe_q

$$\Delta e_d = -\psi_{qo} p \Delta \delta + X_q(p) \Delta i_q - \gamma \Delta i_d - G_q(p) \quad G_\delta(p) \quad \delta \qquad 2.9$$

$$\Delta e_q = \psi_{do} p \Delta \delta - X_d(p) \Delta i_d - \gamma \Delta i_d + \left| -G_v(p) \left\{ S_d \Delta e_d + S_q \Delta e_q \right\} + \right.$$

$$\left. + G_I(p) \left\{ C_d \Delta i_d + C_q \Delta i_q \right\} \right| \qquad 2.10$$

Expressions, for e_d and e_q can also be derived from the tie-line equations as follows. For phase a (The system is under balanced operation)

$$V_t = V_b + (\gamma_L + X_L p) i_a + X_c \int i_a dt$$

$$= V_b + (\gamma_L + X_L p + \frac{X_c}{p}) i_a$$

In terms of Park's components of voltages and current it can be written as

$$e_d \cos\theta - e_q \sin\theta = V_d \cos\theta - V_q \sin\theta + (\gamma_L + X_L p + \frac{X_c}{p}) \cdot$$

$$\cdot (i_d \cos\theta - i_q \sin\theta)$$

$$= V_d \cos\theta - V_q \sin\theta + \gamma_L (i_d \cos\theta - i_q \sin\theta)$$

$$+ X_L(-i_d \sin\theta p\theta + \cos\theta p i_d - i_q \cos\theta p\theta - \sin\theta p i_q)$$

$$+ \frac{X_c}{p} (i_d \cos\theta - i_q \sin\theta)$$

Multiplying throughout by p

$$p(e_d \cos\theta - e_q \sin\theta) = p(U_d \cos\theta - U_q \sin\theta) + \gamma_L p(i_d \cos\theta - i_q \sin\theta)$$

$$+ X_L p \left\{ -(i_d \sin\theta + i_q \cos\theta)p\theta + \cos\theta p i_d - \sin\theta p i_q \right\}$$

$$+ X_c (i_d \cos\theta - i_q \sin\theta)$$

Performing the indicated operations

$$\left\{ (-e_d \sin\theta - e_q \cos\theta)p\theta + \cos\theta p e_d - \sin\theta p e_q \right\}$$

$$= (-U_d \sin\theta p\theta - U_q \cos\theta p\theta + \cos\theta p U_d - \sin\theta p U_q)$$

$$+ \gamma_L \left| (i_d \sin\theta + i_q \cos\theta)p\theta + \cos\theta p i_d - \sin\theta p i_q \right|$$

$$+ X_L \left| -(i_d \sin\theta + i_q \cos\theta)p^2\theta - p\theta(i_d \cos\theta p\theta - i_q \sin\theta p\theta + \right.$$

$$+ \sin\theta p i_d + \cos\theta p i_q)$$

$$\left. + p i_d(-\sin\theta)p\theta - p i_q(\cos\theta p\theta) + \cos\theta p^2 i_d - \sin\theta p^2 i_q \right|$$

$$+ X_c \quad i_d \cos\theta - i_q \sin\theta$$

Equating separately coefficients of terms involving Cos θ and Sin θ.

$$p e_d - e_q p\theta = U_q p\theta + p U_d + \gamma_L(-i_q p\theta + p i_d)$$

$$+ X_L \left| -i_q p^2\theta - p\theta(i_d p\theta + p i_q) - p i_q p\theta + p^2 i_d \right| + X_c i_d$$

and
$$-e_d p\theta - p e_q = -U_d p\theta - p U_q + \gamma_L(-i_d p\theta - p i_q)$$

$$+ X_L \left| -i_d p^2\theta - p\theta(-i_q p\theta + p i_d) - p i_d p\theta - p^2 i_q \right| - X_c i_q$$

As Park's components of voltages and currents are more or less constant or if at all they change the rate is small. Taking this into consideration the term having derivatives of Park's voltages and currents can be netlected. This simplifies the above expressions as

$$-e_q p\theta = U_q p\theta - \gamma_L i_q p\theta - X_L i_q p^2\theta - X_L i_d (p\theta)^2 + X_c i_d$$

$$-e_d p\theta = -U_d p\theta - \gamma_L i_d p\theta - X_L i_d p^2\theta + X_L i_q (p\theta)^2 - X_c i_q$$

Linearizing these equations

$$-e_{qo} p\Delta\delta - \Delta e_q = -\Delta V_q - U_{qo} p\Delta\delta - \gamma_L(\Delta i_q + i_{qo} p\Delta\delta) - X_L i_{qo} p^2 \Delta\delta$$
$$- X_L(2i_{do} p\Delta\delta + \Delta i_d) + X_c \Delta i_d$$

$$\therefore -\Delta e_q = | VSin\delta_o - VCos\delta_o p - \gamma_L i_{qo} p - X_L i_{qo} p^2 - 2X_L i_{do} p + e_{qo} p | \Delta \delta$$
$$+ | X_c - X_L | \Delta i_d + (-\gamma_L) \Delta i_q \qquad 2.11$$

and

$$-e_{do} p\Delta\delta - \Delta e_d = -VSin\delta_o p\Delta\delta - \Delta U_d - \gamma_L(i_{do} p\Delta\delta + \Delta i_d)$$
$$-X_L \left\{ i_{do} p^2 \Delta\delta \right\} + X_L \left\{ 2i_{qo} p\Delta\delta + \Delta i_q \right\} - X_c \Delta i_q$$

$$\therefore -\Delta e_d = | -VSin\,\delta_o p + CVCos\delta_o - \gamma_L i_{do} p - X_L i_{do} p^2 + 2X_L i_{qo} p + e_{do} p | \Delta\delta$$
$$+ | -\gamma_L | \Delta i_d + | X_L - X_c | \Delta i_q \qquad 2.12$$

From 2.9 and 2.12

$$\left| -\psi_{qo} - G_q(p)G_\delta(p) \right| \Delta\delta - \gamma\Delta i_d + X_q(p)\Delta i_q$$

$$= \left| \gamma_L i_{do}p + X_L i_{do}p^2 - 2X_L i_{qo}p + VSin\delta_o p + VCos\delta_o - e_{do}p \right| \Delta\delta$$

$$+ \gamma_L \Delta i_d - (X_L - X_e)\Delta i_q$$

$$\therefore \left| X_L i_{do}p^2 + (\gamma_L i_{do} - 2X_L i_{qo} + VSin\delta_o - e_{do} + \psi_{qo})p + VCos\delta_o \right.$$

$$\left. + G_q(p)\,G_\delta(p) \right| \Delta\delta + (\gamma + \gamma_L)\Delta i_d - \left| X_q(p) + (X_L - X_e) \right| \Delta i_q$$

$$= 0 \qquad 2.13$$

Equation 2.10 after substituting the expression for e_d and e_q from 2.11 and 2.12 and rearranging gives

$$\left| \psi_{do}p\Delta\delta \right| + \left| -X_d(p) + C_d G_d(p)G_I(p) \right| \Delta i_d + \left| -\gamma + C_q G_d(p)G_I(p) \right| \Delta i_q +$$

$$+ \left| -S_d G_d(p)G_v(p) \right| \times \left| \left\{ VSin\delta_o p + VCos\delta_o - e_{do}p + \gamma_L i_{do}p + X_L i_{do}p^2 - \right. \right.$$

$$\left. \left. -2X_L i_{qo}p \right\} \Delta\delta + \gamma_L \ i_d - (X_L - X_e)\Delta i_q \right|$$

$$+ \left| -S_q G_d(p)G_v(p) - 1 \right| \left| \left\{ -VSin\delta_o + VCos\delta_o p + \gamma_L i_{qo}p + X_L i_{qo}p^2 \right. \right.$$

$$\left. \left. + 2i_{do}X_L p - e_{qo}p \right\} \Delta\delta + (X_L - X_e)\Delta i_d + \gamma_L \Delta i_q \right| = 0$$

$$\therefore \left| \psi_{do}p - S_d G_d(p)G_v(p)\, f_1(p) + f_2(p)\left\{ -S_q G_d(p)G_v(p) - 1 \right\} \right| \Delta\delta$$

$$+ \left| -X_d(p) + C_d G_d(p)G_I(p) + \gamma_L \left\{ -S_d G_d(p)G_v(p) \right\} + (X_L - X_e)\,. \right.$$

$$\left. \left\{ -S_q G_d(p)G_v(p) - 1 \right\} \right| \Delta i_d$$

$$+ \left| -\gamma + C_q G_d(p) G_I(p) + (X_L - X_e)\, S_d G_d(p) G_v(p) + \gamma_L \left\{ -S_q G_d(p) G_v(p) - 1 \right\} \right| \Delta i_q = 0 \qquad 2.14$$

where

$$f_1(b) = V \sin\delta_o p + V\cos\delta - e_{do} p + X_L i_{do} p^2 - 2X_L i_{qo} p + \gamma_L i_{do} p$$

and

$$f_2(p) = -V\sin\delta_o + V\cos\delta_o p + \gamma_L i_{qo} p + X_L i_{qo} p^2 + 2X_L i_{do} p - e_{qo} p$$

Linearisation of machine swing equation gives

$$Mp^2 \Delta\delta + P_d p \Delta\delta + \Delta P_e = \Delta P_m$$

or $(Mp^2 + P_d p)\Delta\delta + \Delta P_e = -G_g(p)\Delta\delta$

where

$$G_q(p) = \frac{K_{go} + K_{g1} p + K_{g2} p^2}{(1+T_{g1} p)(1+T_{g2} p)}$$

$$\Delta P_e = \Delta(T_e p\theta) = T_{eo} p \Delta\delta + \Delta T_e$$

$$= T_{eo} p \Delta\delta + \Delta\{\psi_d i_q - \psi_q i_d\}$$

$$\Delta P_e = T_{eo} p \Delta\delta + i_{qo} \Delta\psi_d - i_{do} \Delta\psi_q + \psi_{do} \Delta i_q - \psi_{qo} \Delta i_d$$

$$\Delta P_e = T_{eo} p \Delta\delta + \psi_{do} \Delta i_q - \psi_{qo} \Delta i_d + i_{qo} \{\Delta e_q - \psi_{do} p \Delta\delta + \gamma\Delta i_q$$

$$- i_{do} \left\{ -\Delta e_d - \psi_{qo} p \Delta\delta - \gamma\Delta i_d \right\}$$

$$\Delta P_e = | T_{eo}p-(\psi_{do}i_{qo}-\psi_{qo}i_{do})p| \Delta\delta + |-\psi_{qo}+\gamma i_{do}|\Delta i_d$$

$$+|\psi_{do}+\gamma i_{qo}|\Delta i_q + i_{qo}\Delta e_d + i_{do}\Delta e_d$$

$$\Delta P_e = (-\psi_{qo}+\gamma i_{do})\Delta i_d + (\psi_{do}+\gamma i_{qo})\Delta i_q$$

$$+ i_{qo}\left\{f_2(p)\Delta\delta + (X_L-X_c)\Delta i_d + \gamma_L \Delta i_q\right\}$$

$$+ i_{do}\left\{f_1(p)\Delta\delta + \gamma_L\ i_d - (X_L-X_c)\Delta i_q\right\}$$

$$\therefore\ |Mp^2 + P_d p + G_g(p) + i_{qo}f_2(p) + i_{do}f_1(p)|\Delta\delta$$

$$+ |(-\psi_{qo}+\gamma i_{do}) + i_{qo}(X_L-X_c) + i_{do}X_L|\Delta i_d$$

$$+ |(\psi_{do}+\gamma i_{qo}) + i_{qo}\gamma_L - i_{do}(X_L-X_c)|\Delta i_g = 0 \qquad 2.15$$

Let $f_4(p) = Mp^2 + P_d p + G_g(p) + i_{qo}f_2(p) + i_{do}f_1(p)$

and $f_3(p) = f_1(p) + \psi_{qo}p$

Thus three homogeneous equations 2.13 to 2.15 involving three unknowns δ, Δi_d and Δi_q have been derived.

For nontrivial solution the determinant of the coefficient matrix must be zero

$$\therefore \quad \begin{vmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{vmatrix} = 0 \qquad 2.16$$

where $A_{11} = f_3(p) + G_g(p)G_\delta(p)$

$A_{12} = \gamma_L + \gamma$

$A_{13} = -|X_q(p) + (X_L - X_c)|$

$A_{21} = \psi_{do}p - f_2(p) - G_d(p)G_v(p)\{S_d f_1(p) + S_q f_2(p)\}$

$A_{22} = -X_d(p) - (X_L - X_c) - G_d(p)G_v(p)\{\gamma_L S_d + (X_L - X_c)S_q\}$

$+ C_d G_d(p)G_I(p)$

$A_{23} = -(\gamma + \gamma_L) + G_d(p)G_v(p)\{(X_L - X_c)S_d - \gamma_L S_q\}$

$A_{31} = f_4(p)$

$A_{32} = -\psi_{qo} + (\gamma + \gamma_L)i_{do} + i_{qo}(X_L - X_c)$

$A_{33} = \psi_{do} + (\gamma + \gamma_L)i_{qo} - i_{do}(X_L - X_c)$

Equation 2.16 gives

$$A_{11}\{A_{22}A_{33} - A_{23}A_{32}\} - A_{12}\{A_{21}A_{33} - A_{23}A_{31}\}$$

$$+ A_{13}\{A_{21}A_{32} - A_{22}A_{31}\} = 0$$

For D-decomposition in the plane of K1δ - K2δ.

The above expression can be written in the form

$$|f_3(p) + G_q(p)G_\delta(p)|K_1(p) + K_2(p) = 0$$

where $K_1(p) = A_{22}A_{33} - A_{23}A_{32}$

and $K_2(p) = A_{13} \quad A_{21}A_{32} - A_{22}A_{31} \quad - A_{12} \quad A_{21}A_{33} - A_{23}A_{31}$

$$\text{or } K_1(p)G_q(p) \left| \frac{K_{0\delta} + K_{1\delta}p + K_{2\delta}p^2}{(1 + T_{E2}p)} \right| + K_2(p) + f_3(p)K_1(p) = 0$$

$$\frac{K_1(p)G_q(p)}{(1 + T_{E2}p)} \left| K_{1\delta}p + K_{2\delta}p^2 \right| + \frac{K_1(p)G_q(p)K_{0\delta}}{(1 + T_{E2}p)} + K_2(p) +$$

$$+ f_3(p)K_1(p) = 0 \qquad 2.17$$

Similarly for D-composition in the planes of $K_{1v} - K_{2v}$ and $K_{1I} - K_{2I}$ rearrange the determinant - 2.16 in the convenient form

$$\begin{vmatrix} A_{21} & A_{22} & A_{23} \\ A_{11} & A_{12} & A_{13} \\ A_{31} & A_{32} & A_{33} \end{vmatrix} = 0$$

$$\text{or } A_{21}S_1 - A_{22}S_2 + A_{23}S_3 = 0 \qquad 2.18$$

where $S_1 = A_{12}A_{33} - A_{13}A_{32}$

$S_2 = A_{11}A_{33} - A_{13}A_{31}$

and $S_3 = A_{11}A_{32} - A_{12}A_{31}$

Equation 2.18 can be written as

$$\left| \psi_{do}p - f_2(p) - G_d(p)G_v(p)F_1(p) \right| S_1$$

$$-\left| -X_d(p) - (X_L - X_c) - G_d(p)G_v(p)P_1 + C_d G_d(p)G_I(p) \right| S_2$$

$$+ \left| -(\gamma + \gamma_L) + G_d(p)G_v(p)P_2 + C_q G_d(p)G_I(p) \right| S_3 \quad = 0$$

where $F_1(p) = S_d f_1(p) + S_q f_2(p)$

$$P_1 = \gamma_L S_d + (X_L - X_c)\, S_q$$

$$P_2 = (X_L - X_c)\, S_d - \gamma_L S_q$$

or $G_d(p)\, G_v(p) \left| -S_1 F_1(p) + P_1 S_2 + P_2 S_3 \right|$

$$+ G_d(p)\, G_I(p) \left| - C_d S_2 + C_q S_3 \right|$$

$$+ \left| \psi_{do}p - f_2(p) \right| S_1 + \left| X_d(p) + (X_L - X_c) \right| S_2$$

$$- (\gamma + \gamma_L)\, S_3 = 0$$

or $K_1(p)G_d(p)G_v(p) + K_2(p)G_d(p)G_I(p) + K_3(p) = 0$

or $$\frac{K_1(p)G_d(p)}{(1 + T_{E1}p)} \left\{ K_{1v}p + K_{2v}p^2 \right\} + \frac{K_2(p)G_d(p)}{(1 + T_{E1}p)} \left\{ K_{1I}p + K_{2I}p^2 \right\}$$

$$+ \frac{K_1(p)G_d(p)}{(1 + T_{E1}p)} K_{vo} + \frac{K_2(p)G_d(p)}{(1 + T_{E1}p)} K_{oI} + K_3(p) = 0$$

where $K_1(p) = - S_1 F_1 + P_1 S_2 + P_2 S_3$

$$K_2(p) = - C_d S_2 + C_q S_3$$

$$K_3(p) = | \psi_{do} p - f_2(p) | + | X_d(p) + (X_L - X_c) | S_2$$

$$- (\gamma + \gamma_L) S_3$$

CHAPTER -3

The D-decomposition Technique and Mikhailav's Stability Criterion

The method of D-decomposition is used for the present study. This technique also known as the Domain separation, or D-partitioning technique first presented by Neimark in 1948, is an extremely powerful method for the study of asymptotic stability in linearised multiparameter - autonomous systems. The method is particularly valuable for determining the controlling parameters required to meet a given performance requirement. This method has been used in the present work to determine the appropriate values of stabilising gains if the fast acting voltage current and angle regulators to ensure steady state stability with a desired quality of the transient response.

The importance and application of the D-decomposition technique is widely reflected in Russian literature as, for example, in the translated texts of Meerov[22] and Aizerman[23]. The D-decomposition technique is faster than root- locus technique and comparisions with Routh - Hurwitz method shows the technique to be greately superior.

D-Decomposition Technique[22,23]

The technique lies in determining the characteristic equation of a linearized system in the form

$$a_o p^n + a_1 p^{n-1} + \ldots\ldots + a_{n-1} p + a_n = 0 \qquad 3.1$$

where $p = d/dt$ and regrouping it in such a way that the whole of the parameter space can be decomposed into domains. The domains, corresponding to stable conditions, are subsequently identified. It it is now required to analyse steady-state stability of an alternator and to determine suitable value of the gains for the first and second derivative feed-back signals of the associated regulation, then the technique searches for contours in the gain plane which determines the domains of stability.

In equation 3.1 some of the coefficients $a_o, a_1, \ldots, a_n$ will be independent of the first and second derivative gains K_1 and K_2. The rest of the coefficients are assumed to be linear functions of K_1 and K_2. Let the equation (3.1) be now regrouped in the form

$$K_2 Q(p) + K_1 N(p) + R(p) = 0 \qquad 3.2$$

where $Q(p)$, $N(p)$, $R(p)$ are polynomials in p.

For the absolute stability studies substituting $p = jw$ in the above equation and separating the real and imaginary parts one gets

$$K_2 Q_1(w) + K_1 N_1(w) + R_1(w) = 0 \qquad 3.3$$

$$K_2 Q_2(w) + K_1 N_2(w) + R_2(w) = 0 \qquad 3.4$$

where $Q_1(w)$, $N_1(w)$ and $R_1(w)$ are the real parts and $Q_2(w)$, $N_2(w)$, $R_2(w)$ are the imaginary parts of the polynomials.

Solving equations 3.3 and 3.4

$$K_1 = \frac{\begin{vmatrix} Q_1(w) & -R_1(w) \\ Q_2(w) & -R_2(w) \end{vmatrix}}{\begin{vmatrix} Q_1(w) & N_1(w) \\ Q_2(w) & N_2(w) \end{vmatrix}} \quad 3.5$$

$$K_2 = \frac{\begin{vmatrix} -R_1(w) & N_1(w) \\ -R_2(w) & N_2(w) \end{vmatrix}}{\begin{vmatrix} Q_1(w) & N_1(w) \\ Q_2(w) & N_2(w) \end{vmatrix}} \quad 3.6$$

By assigning suitable values to w from 0 to ∞ in equations (3.5) and (3.6) it is possible to transform the $p = jw$ axis of the p plane onto the $K_2 - K_1$ parameter plane. The contour in the parameter plane divided the parameter plane in to a no. of regions (domains). Hatching rules are available to identify which of the domains in the gain plane corresponds to a stable operating condition.

The existance of a region of stability indicates that it is possible to obtain stability in a given system by appropriate choice of the derivative gains. A large region of stability requires less efforts in setting the regulator parameters places less stringent demand on the stability of the regulator characteristic and is accompanied by more reliable operation. Each stability region gives a conclusive answer to the problem for only one operating point in the power system. Therefore, in this approach it is necessary to plot regions for all typical operating points and for all possible changes in system quantities that may arise. If an area in the region is common to all points of credible operation, system stability can be secured by a single regulator setting for all changes in the operating conditions and power system quantities.

<u>Hatching rule of the D-partioning boundary</u>

If the denominator of equation (3.6) is called Δ then hatching rules are as follows.

i) If $\Delta > 0$ then shade twide the boundary on the left as w increases.

ii) If $\Delta < 0$ then shade twice the right as w increases.

iii) A straight line D-partion boundary may occure at a particular value of w($w = w_c$) if the equations (3.3) and (3.4) become linearly dependent for this w_c . A matching shading is done for this special line. Noting the shading on the contour obtained for values of w just greater and smaller than w_c, the special line is shaded once only.

Crossing of D partition boundary from twice shaded to unshaded side results in loss of two roots to the right hand side in p -plane.

Crossing of the singular line in the parameter plane from shaded to unshaded side results in loss of one root to the right hand side is the p-plane.

Once the region of maximum number of roots in the left hand side of p-plane is marked, then question of ascertaining whether the region marked is realy a stable region arises. To answer this question one of the point in this region is selected and after putting the values of the parameters in the original characteristic equation it is tested whether all the roots lie in the negative half or not. If the answer is positive then it is confirmed that all the points in the region will correspond to stable system.

To check this the author has made use of Mikhailov's stability criterion.

Mikhailov's Stability Criterion[23] :

The essence of the Mikhailov criterion lies in the following proposition.

A system is stable, provided its characteristic equation

$$f(p) = a_0 p^n + a_1 p^{n-1} + \dots + a_{n-1} p + a_n = 0$$

satisfies the following conditions.

1. $f(jw) \neq 0$ at $w = 0$, i.e. $a_n \neq 0$
2. The locus of the end points of the vector $f(jw)$, when w varies from 0 to ∞, traverses in succession (without gaps)

by n quadrants in anticlockwise manner a_n equations of n^{th} order (with $a_n > 0$). This condition can be replaced by the following three conditions,

(a) If in $f(jw)$, the real and imaginary parts are so separated that $f(jw) = g(w) + jh(w)$ then $g(w) = 0$ and $h(w) = 0$ must have real roots.

(b) The value of $g(w)$ and the rate of change of $h(w)$ at the point $w = 0$, in the other words, the value of $g(o)$ and $jw(o)$ must be of equal similar sign.

(c) The points, where $g(w)$ and $h(w)$ traverse zero, must alternate so that when w increases starting from zero the points at which $g(w)$ and $h(w)$ pass through zero, alternate in turn.

Let $f(p) = (p-Z_1)\,(p-Z_2)\,........\,(p-Z_n)$

If jw is substituted for p we obtain

$f(jw) = (jw - Z_1)\,(jw - Z_2)\,........(jw - Z_n)$

$F(jw)$ constitutes a vector whose modulus is equal to the product of the moduli of all the vectorial factors and whose argument is equal to the sum of the arguments of all the vectorial factors. At $w = 0$ the vector $f(jw)$ has a purely real value $f(o)$ whose argument is equal to zero because in an equation with real coefficients the roots can be either real or occure in conjugate pair. The argument of real root is zero and sum of the arguments of conjugate roots pairs is also zero. The reference line from which the argument is measured is the negative real half axis when w varies from 0 to

– the angle for each real root changes by $\pi/2$ and for each pair of conjugate roots by π. Consequently for an n^{th} order equation, if all roots lie on one side of imaginary axis, the total angle $f(jw)$ changes by the magnitude $\pi/2\ n$.

It is apparant from this that for a stable system, the vector $f(jw)$ must traverse n quadrant in a definite sequence.

Thus to determine whether the system is stable, it is necessary to adapt the following procedure -

1. Find the characteristic equation $f(p)$
2. Substitute jw for p in this equation.
3. Separate the real part of $f(jw)$ from the imaginary.
4. Construct $f(jw)$, with w varying from 0 to ∞.

If the number of successive quadrants through which the vector $f(jw)$ passes is equal to the order of the characteristic equation, then the analysed system is stable.

CHAPTER - 4

The Problem of Absolute Stability

For determining the regions of absolute stability in the planes of first and second derivative gain constants of current, voltage and angle regulators the equations (2.17) and (2.19) have been used. Theexpression for first and second derivative constants as functions of angular frequency (w) will be found.

First in all terms expressed as function of p earlier in Chapter -2, p = jw will be substituted and then these will be split, into real and imaginary terms.

4.1 D-Partitioning in the plane of $K1\delta$ - $K2\delta$

$$Gd(jw) = GdR + jwGdI = \frac{1}{1 + jTdo'w} = \frac{1-jTdo'w}{1 + Tdo'^2w^2} \qquad 4.1$$

$$Gq(jw) = GqR + jwGqI = \frac{1}{(1 + jTqo'w)} = \frac{1-jTqo'w}{1 + Tqo'^2w^2} \qquad 4.2$$

$$GV(jw) = GVR + jwGVI = \frac{KOV + jK1Vw - K2Vw^2}{1 + jwT_{e1}}$$

$$= \frac{|KOV - w^2(K2V - Te1K1V)| + jw|K1V - Te1(KOV - w^2K2V)|}{1 + w^2 T_{e1}^2} \quad \ldots \quad 4.3$$

$$GI(jw) = GIR + jwGII$$

$$= \frac{|KOI - w^2(K2I - Te1K1I)| + jw|K1I - Te1(KOI - w^2K2I)|}{1 + Te1^2 w^2} \quad \ldots \quad 4.4$$

$$f_1(jw) = f_1R + jwfII$$

$$= (VCos\delta o - w^2 ido X_L) + jw(V\ Sin\delta o - edo + \gamma_L ido - 2X_L iqo) \quad \ldots \quad 4.5$$

$$f_2(jw) = f_2R + jwf_2I$$

$$= (-VSin\delta o - iqo\ X_L w^2) + jw(V\ Cos\delta o - eqo + \gamma_L iqo + 2ido X_L) \quad \ldots \quad 4.6$$

$$f_3(jw) = f_3R + jwf_3I$$

$$= (f_1R + jwf1I) + jw\psi_{qo} \quad 4.7$$

$$Gg(jw) = GgR + jwGgI$$

$$= \frac{|(Kgo + Kg2w^2)(1 - Tg1Tg2w^2) + w^2Kg1(Tg1 + Tg2)| + jw|Kg1(1 - Tg1Tg2w^2) - (Tg1 + Tg2)(Kgo - Kg2w^2)|}{|(1 - Tg1\ Tg2\ w^2)^2 + (Tg1 + Tg2)^2 w^2|} \quad \ldots \quad 4.8$$

$$A31(jw) = A\ 31R + jwA31I = f4(jw)$$

$$= (GgR + iqof2R + idof1R - w^2M) +$$

$$jw(Pd + GgI + iqof2I + idof1I) \qquad 4.9$$

$$Xd(jw) = XdR + jwXdI = \frac{Xd \mid 1 + jwTd' \mid}{1 + jwTdo'}$$

$$= \frac{Xd \mid (1+w^2Tdo'Td') - jw(Tdo' - Td') \mid}{1 + w^2Tdo'^2} \qquad 4.10$$

$$Xj(jw) = XqR + jwXqI$$

$$= \frac{Xq \mid (1+w^2T'qo) - jw(Tqo' - Tq) \mid}{(1 + w^2Tqo'^2)} \qquad 4.11$$

$$Gd(jw)\ GV(jw) = GdVR + jwGdVI$$

$$= (GdR\ GVR - w^2GdI\ GVI) + jw(GdRGVI + GdIGVR)$$

$$\ldots \qquad 4.12$$

$$Gd(jw)GI(jw) = GdIR + jwGdII$$

$$= (GdRGIR - w^2GdI\ GII) + dw(GdRGII + GdIGIR)$$

$$\ldots \qquad 4.13$$

$$Gd(jw)GV(jw)f_1(jw) = AR + jwAI$$

$$= GdVIR + jw\ GdV1I$$

$$= (GdVRf1R - w^2GdVI\ f1I) +$$

$$+ jw(GdVRf1I + GdVIf1R) \qquad 4.14$$

$$Gd(p)\ GV(p)f2(p) = GdV2R + jwGdV2I = BR + jwBI$$

$$= (\ GdVRf2R - w^2GdVIf2I\ ) +$$

$$+jw(GdVRf2I + GdVIf2R) \qquad 4.15$$

$$A21(jw) = A21R + jwA21I$$

$$= - |SdAR + SqBR + f2R| + jw|\Psi do - SdAI - SqBI - f2I| \quad \ldots \quad 4.16$$

$$A22(jw) = A22R + jwA22I$$

$$= |- XdR + CdGdIR - \left\{\Upsilon_L sd + (X_L - X_c)\ Sq\right\}\ GdVR - (X_L - X_c)|$$

$$+jw|\ -XdI + CdGdII - \left\{\Upsilon_L sd + (X_L - X_c)Sq\right\}\ GdVI\ | \qquad 4.17$$

$$A23(jw) = A23R + jwA23I$$

$$= |\ -(\Upsilon + \Upsilon_L) + CqGdIR + \left\{Sd(X_L - X_c) - \Upsilon_L sq\right\}\ GdVR\ |$$

$$+ jw|\ CqGdII + \left\{Sd(X_L - X_c) - \Upsilon_L Sq\right\}\ GdVI\ | \qquad 4.18$$

$$K1(jw) = AK1R + jwAK1I = A22A33 - A23A32$$

$$= (A33A22R - A32A23R) + jw(A33A22I - A32A23I) \qquad 4.19$$

$$A13(jw) = A13R + jwA13I$$

$$= - |\ XqR + (X_L - X_c)| - jwXqI \qquad 4.20$$

$$AA + jwBB = (A12A23 - A13A22)$$

$$= (A12A23R - A13RA22R + w^2\,A13I\,A22I) +$$

$$+jw(A12A23I - A13IA22R - A13RA22I) \qquad 4.21$$

$$K2(jw) = AK2R + jwAk2I$$

$$= |(AA.A31R - w^2 BB.A31I) - A12.A33\,A21R$$

$$+ A32(A13RA21R - w^2 A13.A21I)| +$$

$$+jw|(AA.A31I + BB.A31R) - A12A33.A21I +$$

$$+ A32(A13R\,A21I + A13I\,A21R)| \qquad 4.22$$

$$\frac{K1(jw)\;Gq(jw)}{(1+jwT_{e2})} = X + jwY \qquad 4.23$$

$$= \frac{|(AK1RGqR - w^2 AK1IGqI) + jw(AK1RGqI + AK1IGqR)| \times (1-jwT_{e2})}{1 + w^2\,T_{e2}^{\;2}}$$

$$X + jwY = \frac{|(AK1RGqR - w^2 AK1IGqI) + w^2 T_{e2}(AK1RGqI + AK1IGqR)| + +jw|(AK1RGqI + AK1IGqR) - T_{e2}(AK1RGqR - w^2 AK1IGqI)|}{1 + w^2 T_{e2}^{\;2}}$$

$$f3(jw)\;K1(jw) = fKR + jwfKI$$

$$= (f3RAK1R - w^2 f3IAK1I) + jw(f3RAK1I + f3IAK1R)$$

$$\ldots \qquad 4.24$$

$$\therefore \frac{K1(p)Gq(p)}{(1+T_{e2}(p)} \left| K1\delta p + K2\delta p^2 \right| + \frac{K1(p)Gq(p)K0\delta}{(1+T_{e2}p)} +$$

$$+ K2(p) + f3(p)K1(p) = 0$$

may be written in the form.

$$(X + jwY)(jwK1\delta - w^2K2\delta) + (X + jwY)\ K0\delta + AK2R + jwAK2I +$$

$$+ fKR + jwfKI = 0$$

or

$$-w^2YK1\delta - Xw^2K2\delta + XK0\delta + AK2R + fKR = 0$$

$$XK1\delta - w^3YK2\delta + wYK0\delta + wAK2I + wfKI = 0$$

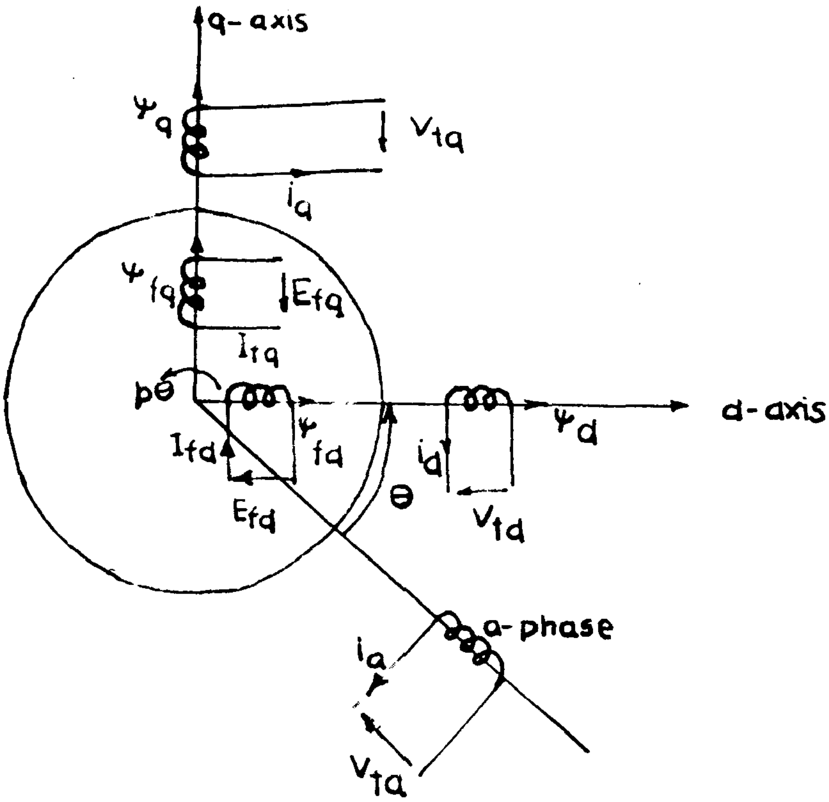
$$DEN = w^2(X^2 + w^2Y^2)$$

$$K1\delta = \frac{Y(K0\delta X + AK2R + fKR) - X(YK0\delta + AK2I + fKI)}{X^2 + w^2Y^2}$$

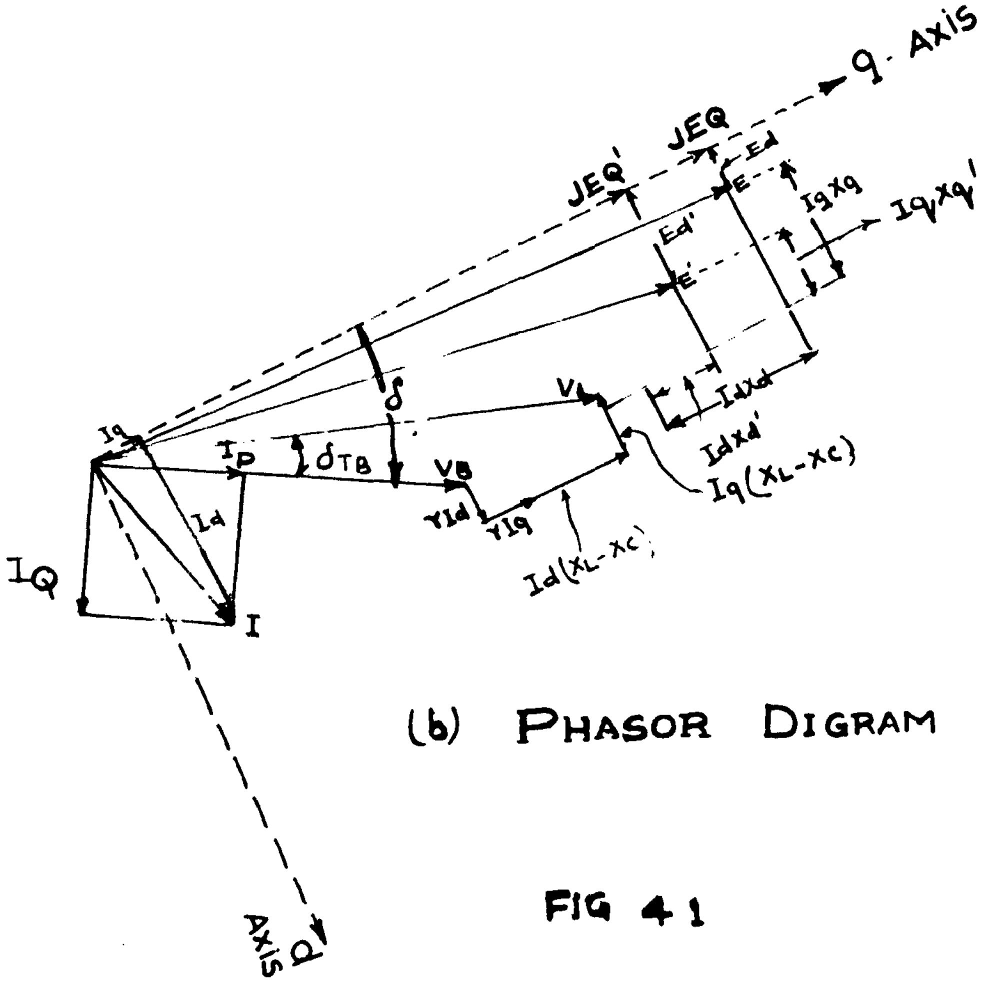
And

$$= \frac{Y(YK0\delta + AK2I + fKI) + (X\ (XK0\delta + AK2R + fKR)/w^2 \,|}{X^2 + w^2Y^2}$$

Now by varying the values of w from 0 to ∞ different values of K1δ and K2δ are obtained and graphs are plotted to see the effects of different parameters. The computer programme for carrying out this calculation is given in the Appendix 1.1 The phasor diagram for obtaining initial values is given in the fig. 4.1.



(a) A DOUBLY EXCITED SYNCHRONOUS MACHINE



(b) PHASOR DIGRAM

FIG 4 1

4.2 D-partitioning in the plane of K1V - K2V

The expressions not defined in this section are the same as per section 4.1

$$F1(jw) = AFRI + jwAFI1$$

$$= (Sdf1R + Sqf2R) + jw(Sdf1I + Sqf2I) \quad 4.25$$

$$S1(jw) = S1R + jwS1I$$

$$= A12A33 - A13A32$$

$$= A12A33 - A32A13R - jwA32A13I$$

$$= |(\Upsilon+\Upsilon_L)A33 - A32A13R)| + jw(-A32A13I) \quad 4.26$$

$$S2(jw) = S2R + jwS2I$$

$$= A33(A11R + jwA11I) - (A13R\ A31R - w^2 A13IA31I)$$

$$+jw(A13RA31I + A13IA31R) \quad 4.27$$

$$S3(jw) = S3R + jwS3I$$

$$= A32\ \ A11R + jwA11I\ \ - (\Upsilon + \Upsilon_L)\ (A31R + jwA31I)$$

$$= A32A11R - (\Upsilon+\Upsilon_L)(A31R) + jw(A32A11I - (\Upsilon+\Upsilon_L)A31I$$

$$\ldots \quad 4.28$$

$$K1(jw) = AK1R + jwAK1I$$

$$= |-(F1RS1R-w^2F1IS1I) + F1S2R + F2S3R| +$$

$$+jw|-F1Rs1I - F1IS1R + F1S2I + F2S3I| \quad 4.29$$

$$K2(jw) = AK2R + jwAK2I$$

$$= \left| -CdS2R + CqS3R \right| + jw(-CdS2I + CqS3I) \qquad 4.30$$

$$K3(jw) = AK3R + jwAK3I$$

$$= \left| f2RS1R - w^2\left\{ \psi do - f2I \right\} S1I + \left\{ XdR + (X_L - X_c) \right\} S_2R - \right.$$

$$\left. - w^2 S2IXdI - (\gamma + \gamma_L) S3R \right|$$

$$+ jw\left| S1R\left\{ \psi do - f2I \right\} + S1I \left\{ -f2R \right\} + S2RXdI + S2I. \right.$$

$$\left. \cdot \left\{ Xd_R + (X_L - X_c) \right\} - (\gamma + \gamma_L) S3I \right.$$

$$\ldots \qquad 4.31$$

$$\frac{Gd(w)}{1+jT_{e1}(w)} = \frac{(GdR + jwGdI)(1-jwT_{e1})}{1 + w^2 T_{e1}^2}$$

$$= GdER + jwGdEI$$

$$= \frac{(GdR - w^2 T_{e1} GdI) + jw(GdI - T_{e1} GdR)}{1+w^2 T_{e1}^2}$$

$$\frac{K1(jw)Gd(w)}{(1+jT_{e1}w)} = GKR1 + jwGKI \qquad 4.32$$

$$= (AK1R + jwAK1I)(GdER + jwGdEI)$$

$$= (AK1RGdER - w^2 AK1IGdEI) +$$

$$+ jw(AK1RGdEI + AK1IGdER)$$

$$\frac{K2(jw)Gd(jw)}{(1+jT_{e1}w)} = GKR2 + jwGKI2 \qquad 4.33$$

$$= (AK2RGdER - w^{2}AK2IGdEI) + jw(AK2RGdEI + AK2IGdER)$$

$$\frac{K2(jw)\ Gd(jw)}{1+jwT_{e}} (KOI - w^{2}K2I + jwK1I) + \frac{K1(jw)\ Gd(jw)}{1+jwT_{e1}} KOV + K3(p)$$

$$= BKR + jwBKI \qquad 4.34$$

$$= \left| GKR2(KOI - w^{2}K2I) - w^{2}(GKI2.K1I) + KOVGKRI + AK3R \right|$$

$$+ jw(GKR2.K1I + GKI2(KOI - w^{2}K2I) + KOVGKI1 + AK{<}I \,|$$

$$(GKR1 + jwGKI1)(jwKIV - w^{2}K2V) + BKR + jwBKI = 0 \qquad 4.35$$

$$\therefore -w^{2}(GKI1)\ K1V - w^{2}(GKR1)\ K2V + BKR = 0$$

$$w(GKR1)\ KIV - w^{3}(GKI1)\ K2V + wBKI = 0$$

$$K2V = \frac{\begin{vmatrix} -w^{2}GKI1 & -BKR \\ wGKR1 & -wBKI \end{vmatrix}}{\quad}$$

$$= \frac{(BKI)(GKI1) + \dfrac{(BKR)(GKR1)}{w^{2}}}{DEN}$$

$$K1V = \frac{\begin{vmatrix} -BKR & -w^2 GKR1 \\ -wBKI & -w^3 GKI1 \end{vmatrix}}{}$$

$$= \frac{(BKR)(GKI1) - (GKR1)(BKI)}{DEN = (GKR1)^2 + w^2 (GKI1)^2}$$

Computer programme for calculating K1V - K2V for different value of w is given in Appendix 1.7

4.3 D-Partitioning in the plane of K1I - K2I

Up to equation (4.33) the derivation is same for K1I - K2I also

$$\frac{K1(jw)\ Gd(jw)}{1+jwT_{e1}} (KOV + jwKIV - w^2 K2V) + \frac{K2(jw)\ Gd(jw)}{1+jwT_{e1}}\ KOI$$

$$+ K3\ (jw) = BKR + jw\ BKI$$

$$= |\ GKR1(KOV - w^2 K2V) - w^2 (GKI1)(K1V) + KOIGKR2 + K3R\ |$$

$$+ jw|\ (GKR1)(K1V) + (GKI1)(KOV - w^2 K2V) + KOIGKI2 + K3I\ |$$

$$\therefore (GKR2 + jwGKI2)\ (jwK1I - w^2 K2I) + BKR + jwBKI = 0$$

$$DEN = GKR^2 2 + w^2 \times GKI_2{}^2$$

$$K1I = \frac{(BKR)\ (GKI2) - (BKI)(GKR2)}{DEN}$$

AND

$$K2I = \frac{(BKI)\ (GKI2) + \dfrac{(BKR)(GKR2)}{w^2}}{DEN}$$

The programme for calculating K1I - K2I for different values of w is given in Appendix 1.3

4.4 Check by Mikhailav's Stability Criterion

Use is made of the equation (2.19) for this check. It will be noted that the characteristic equation (2.19) contains terms which are ratios of two expressions in p. In order to develop a form, suitable for this check, the equation (2.19) is first multiplied by a term D(p) containing all thettime constants. D(p) is given by

$$D(p) = (1 + Tdo'p)\ (1 + T_{e1}p)\ (1 + Tqo'p)\ (1 + T_{e2}p)\ (1 + Tg1p)\ (1 + Tg2p)$$

Equations (4.35) can be written in expanded form as follow

$$(GKR1 + jwGKI1)\ (jwK1V - w^2K2V) + BKR + jwBKI$$

$$= -w^2(K2VGKR1 + K1VGKI1) + BKR + jw\left\{BKI + K1VGKR1 - w^2K2VGKI1\right\}$$

$$= U + jV$$

$$D(jw) = | (1 - w^2 Tdo'Tgo') + jw (Tdo' + Tgo') | x$$

$$| (1 - T_{e1} T_{e2} w^2) + jw (Te1 + T_{e2}) | x$$

$$| (1 - Tg1\ Tg2\ w^2) + jw (Tg1 + Tg2) |$$

$$= (C_1 + jwD1) (C_2\ jD2) (C_3 + jw D_3)$$

$$= | (C_1C_2 - w^2 D_1D2) + jw (C_1D2 + D_1C_2) | (C_3 + jwD_3)$$

$$= | (C_1C_2 - w^2 D1D2) C_3 - w^2 D_3(C_1D2 + D1C_2) |$$

$$+ jw | C_3(C_1D_2 + D_1C_2) + D_3(C_1C_2 - w^2 D1D_2) |$$

$$= DR + jw DI$$

$$ARR + jwAII = (U + jwV) (DR + jwDI)$$

$$= (UDR - w^2 VDI) + jw(UDI + VDR) \qquad 4.3$$

By varying w from 0 to ∞ the locus of characteristic vector ARR + jwAII is studied. The system characteristic equation is of eighth order. For any point selected from within the region (containing maximum number of roots to the left of jw axis in the p plane) obtained by D-partitioning if the ch. vector ~~proves~~ passes through eight quadrants in succession the point selected will belong to the stable zone.

The computer programming for getting ARR-AII for different values of w is given in Appendix 1.4.

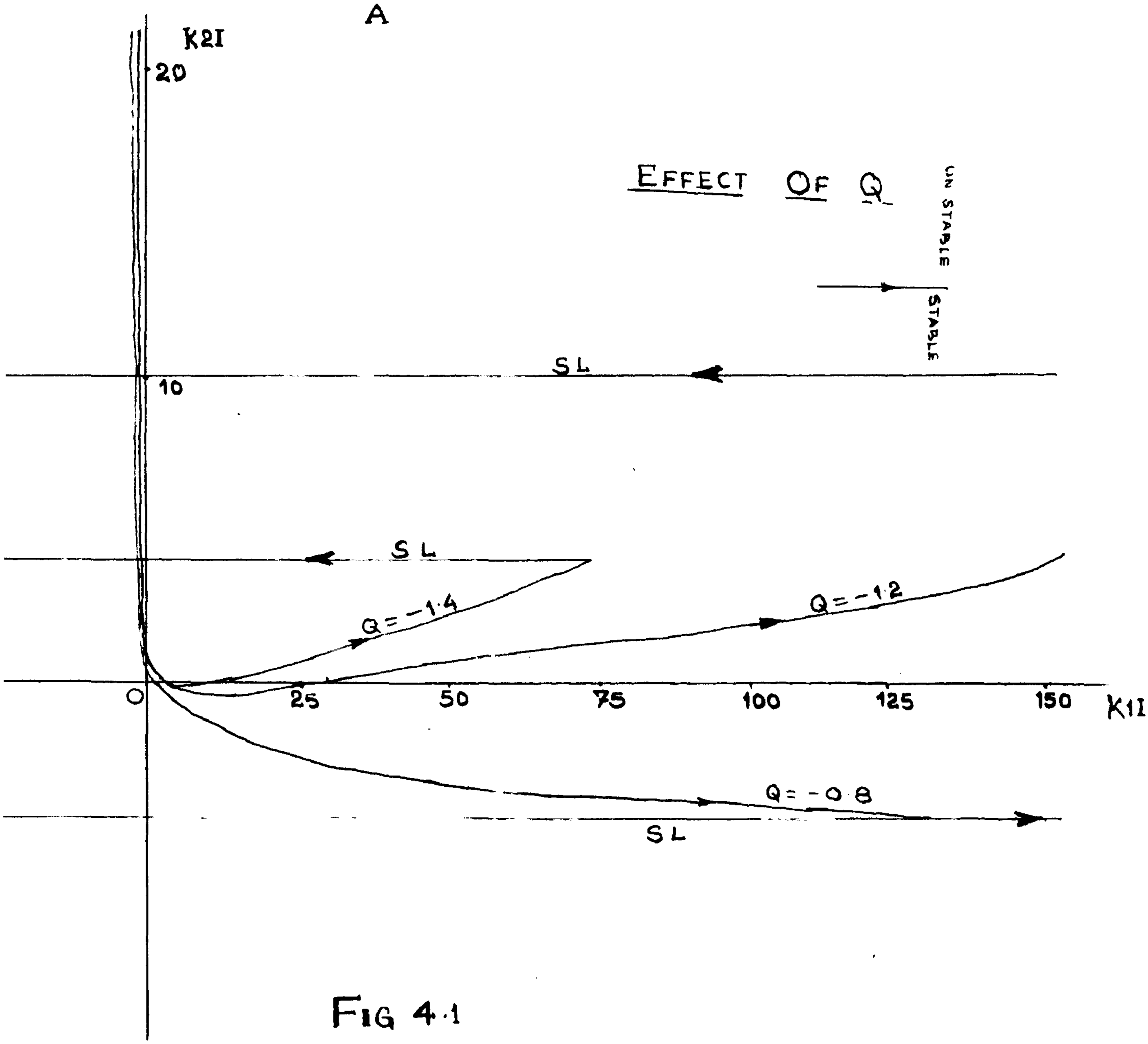
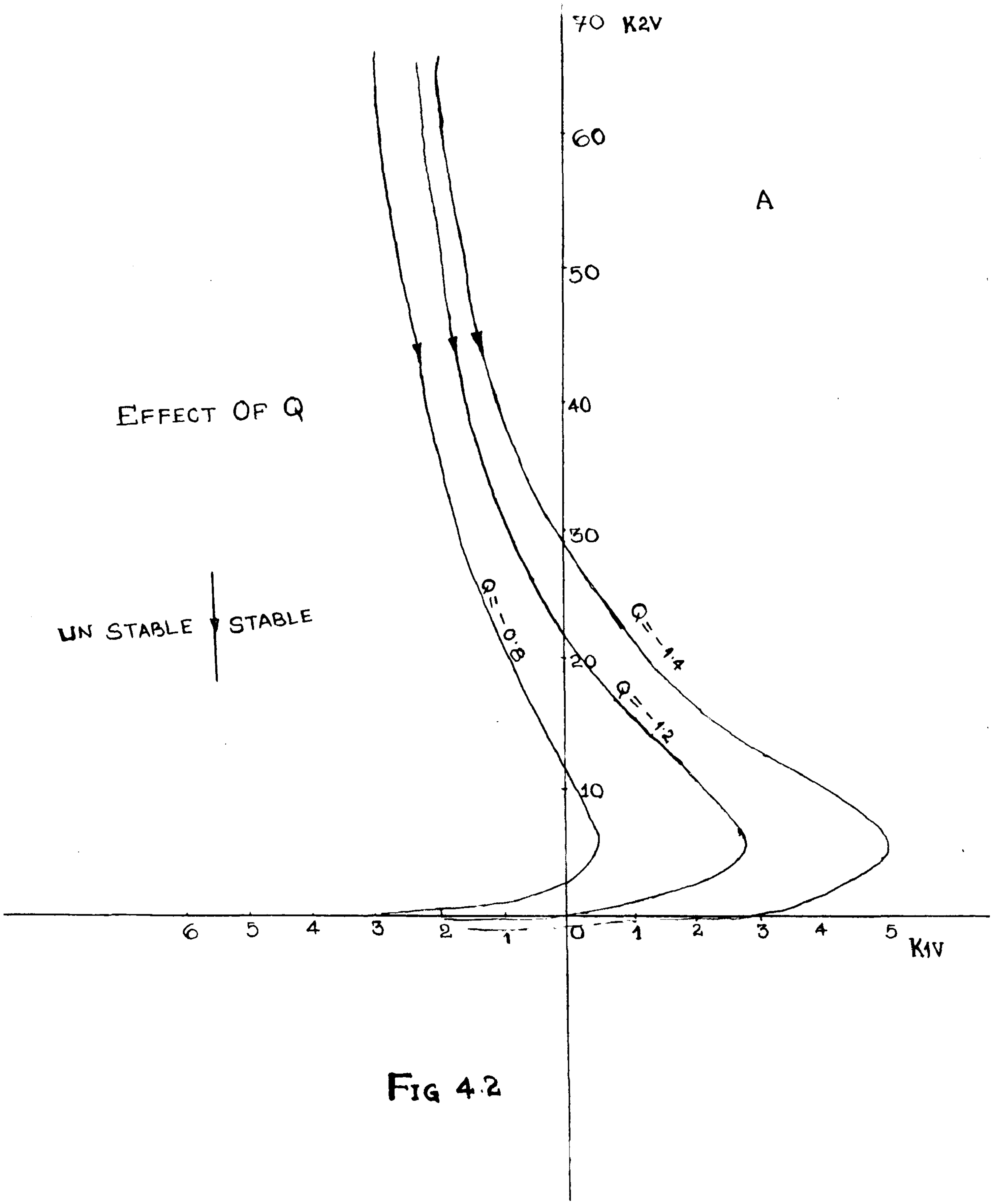

A
K2I
20
EFFECT OF Q
UN STABLE
STABLE
SL
10
SL
Q=-1·4
Q=-1·2
O
25
50
75
100
125
150
K1I
Q=-0·8
SL

FIG 4·1



70 K2V
60
50
40
30
20
10
A
EFFECT OF Q
UN STABLE
STABLE
Q = -0.8
Q = -1.2
Q = -1.4
6 5 4 3 2 1 0 1 2 3 4 5
K1V

FIG 4.2

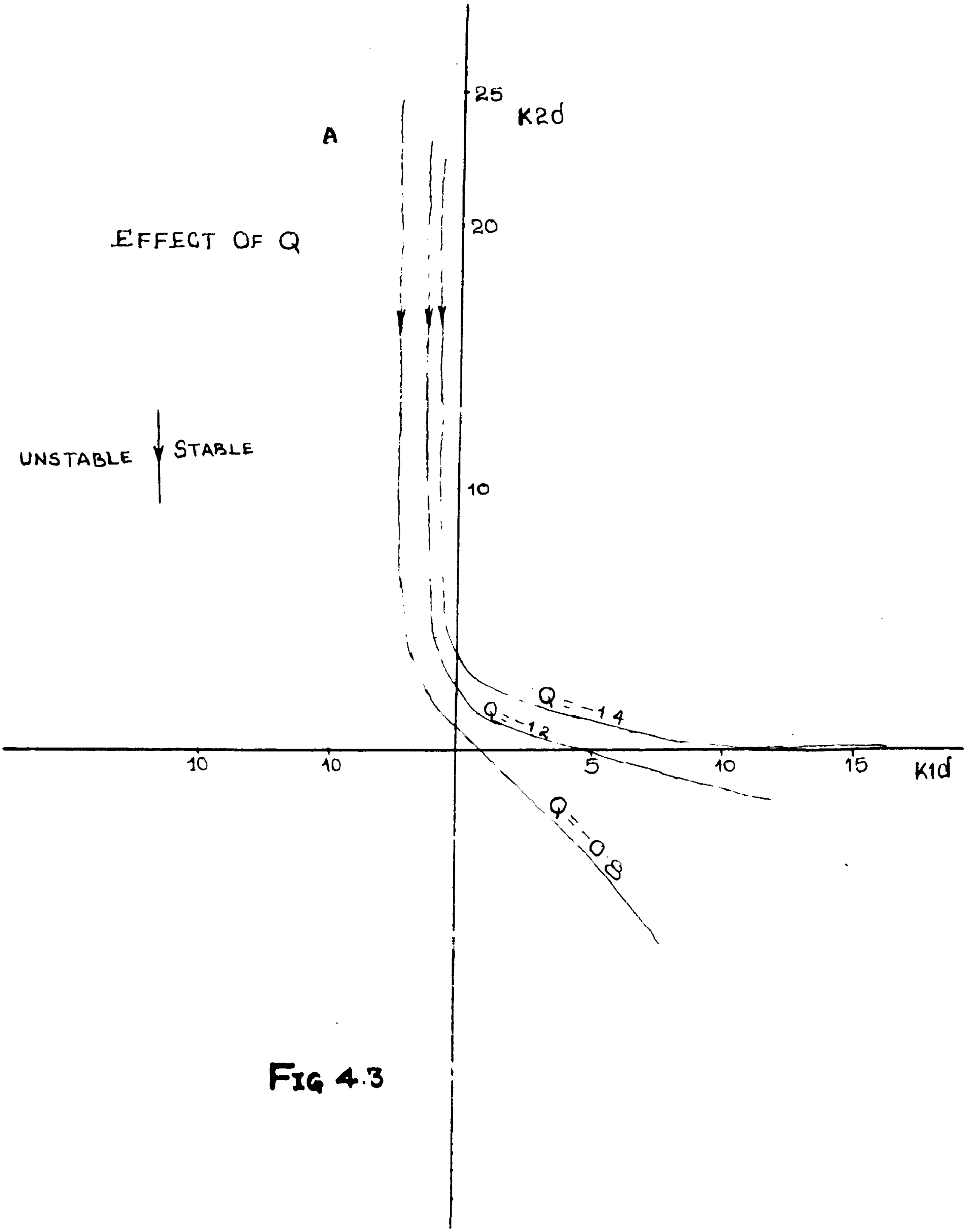

25
K2d
A
20
EFFECT OF Q
UNSTABLE
STABLE
10
Q = -1.4
Q = -1.2
10
10
5
10
15
K1d
Q = -0.8

FIG 4.3

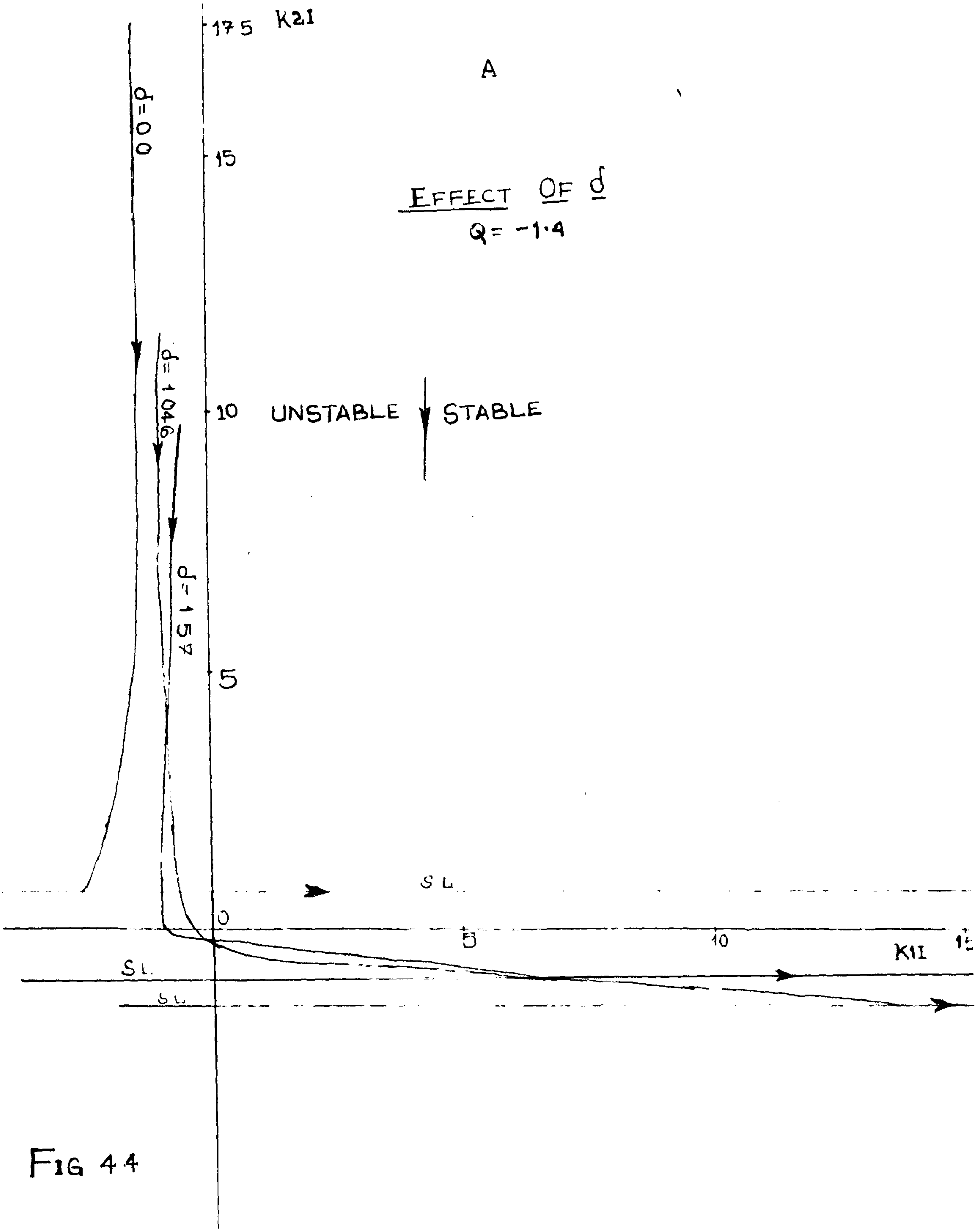

K21
17.5
15
10
5
0
5
10
15
K11
A
EFFECT OF d
Q= -1·4
UNSTABLE
STABLE
d=0.0
d=1.046
d=1.57
SL
SL
SL

FIG 4.4

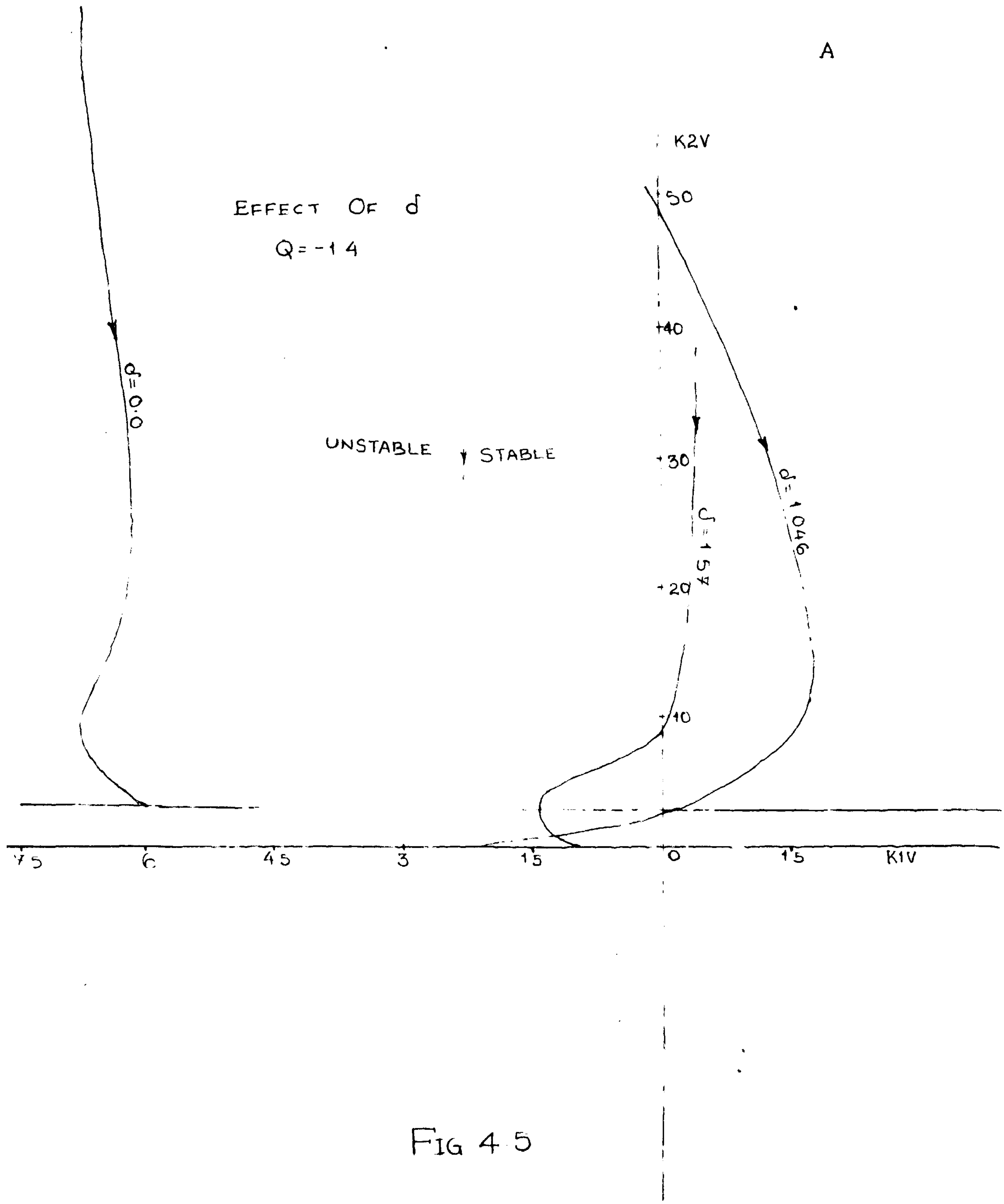

A
K2V
EFFECT OF δ
Q = -1 4
δ=0.0
UNSTABLE
STABLE
50
40
30
20
10
δ=1.046
δ=1.57
7.5
6
4.5
3
1.5
0
1.5
K1V

FIG 4.5

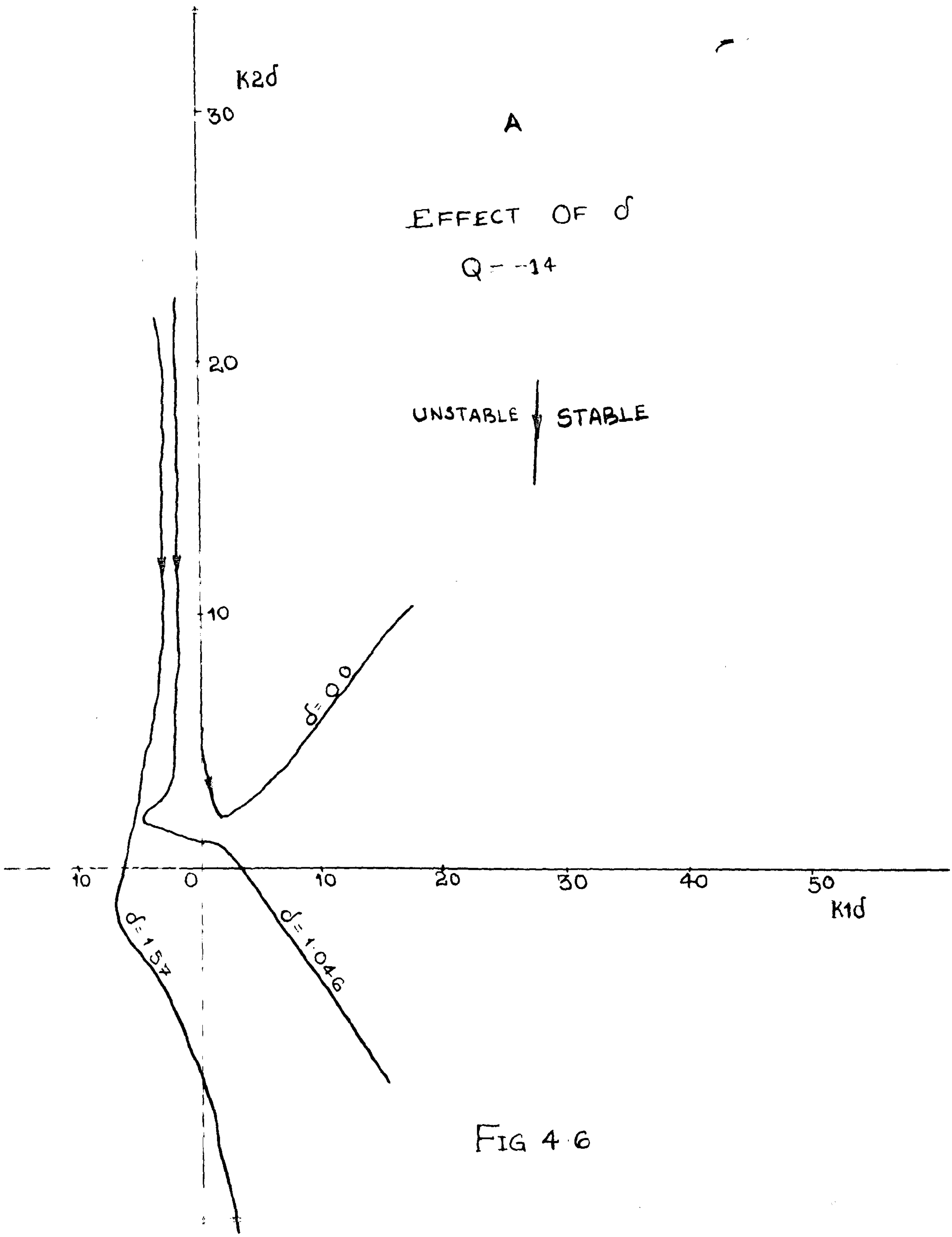

K2δ
30
20
10
A
EFFECT OF δ
Q = -14
UNSTABLE
STABLE
δ = 0.0
δ = 1.57
δ = 1.046
10
0
10
20
30
40
50
K1δ

FIG 4.6

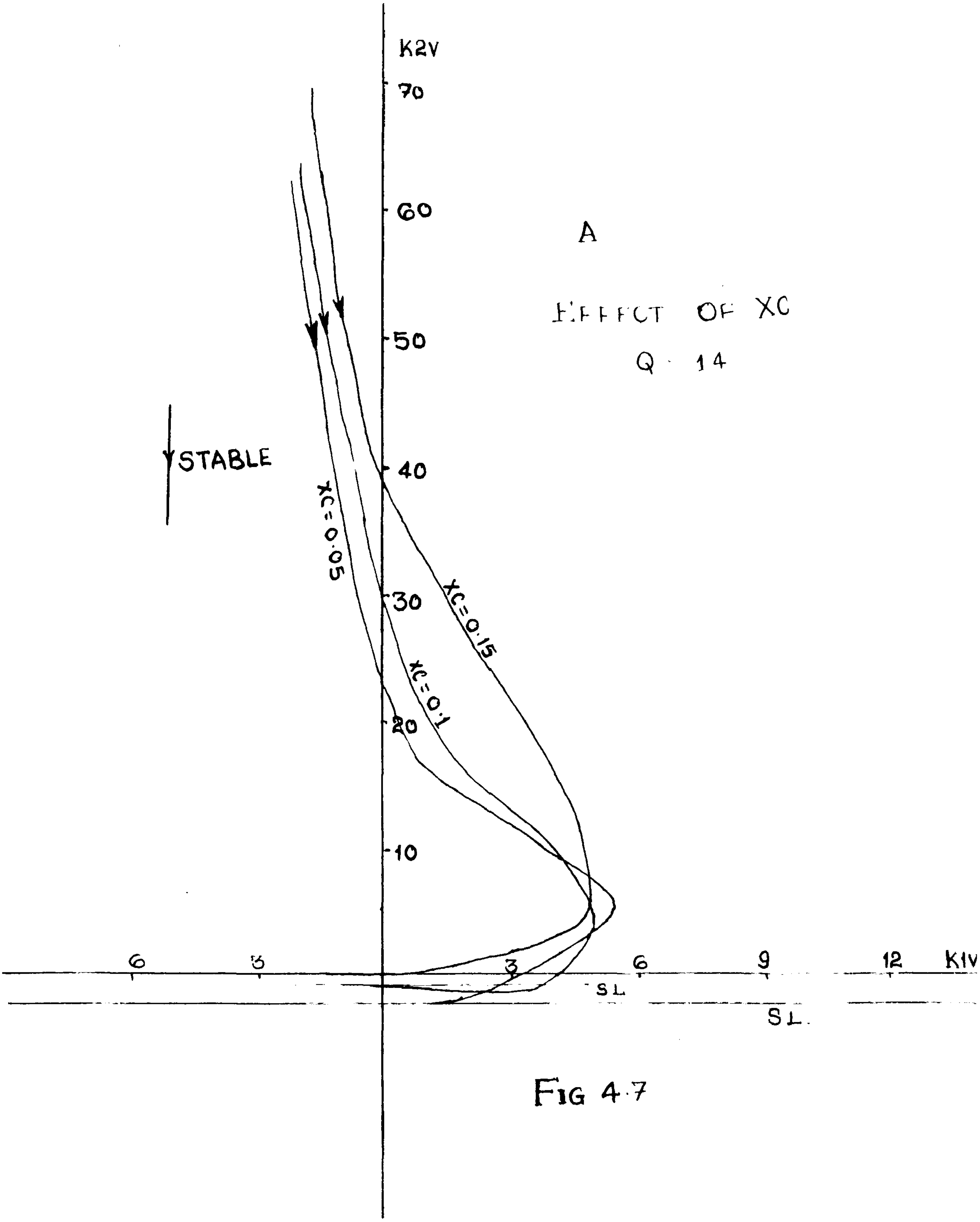
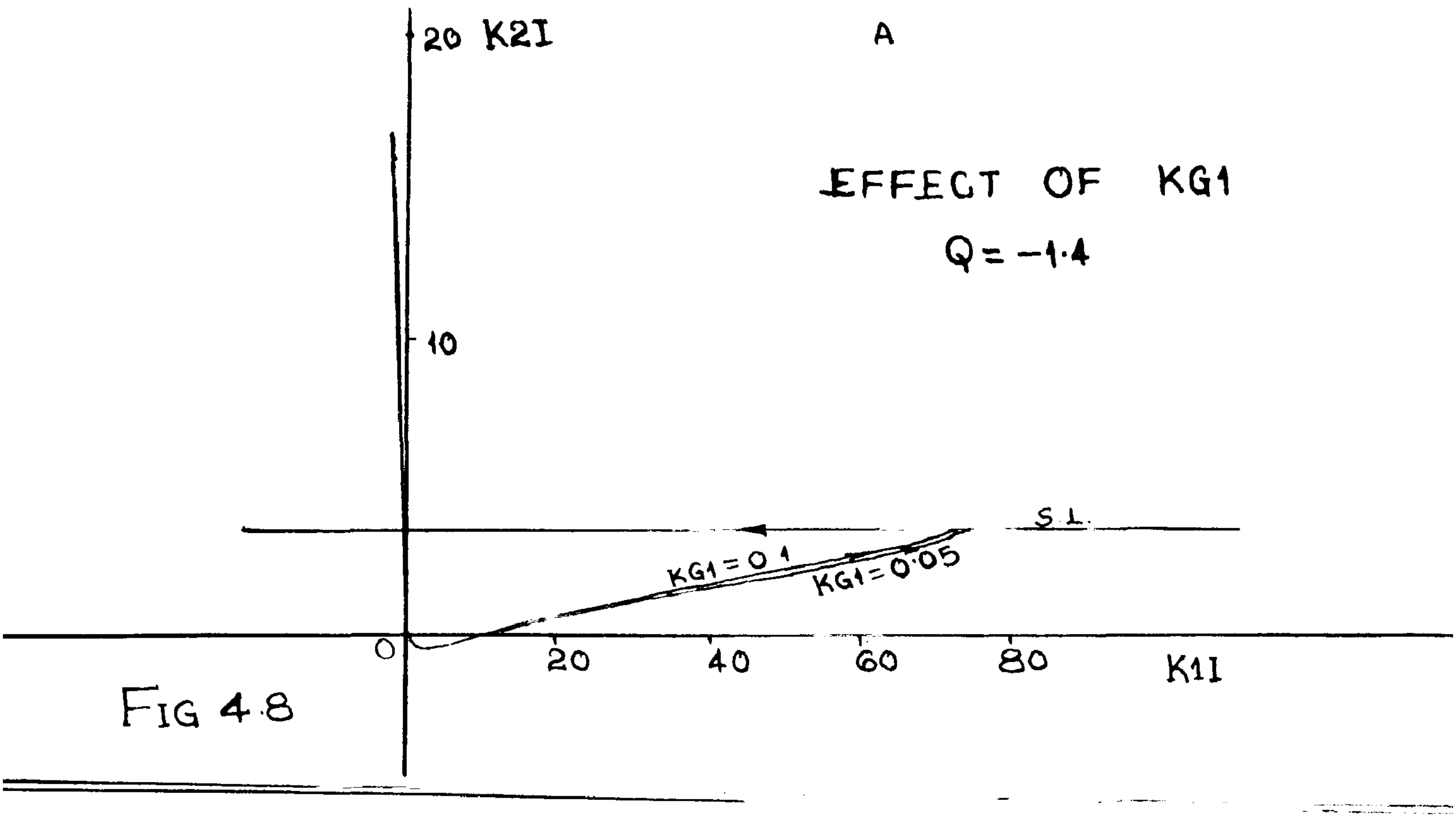
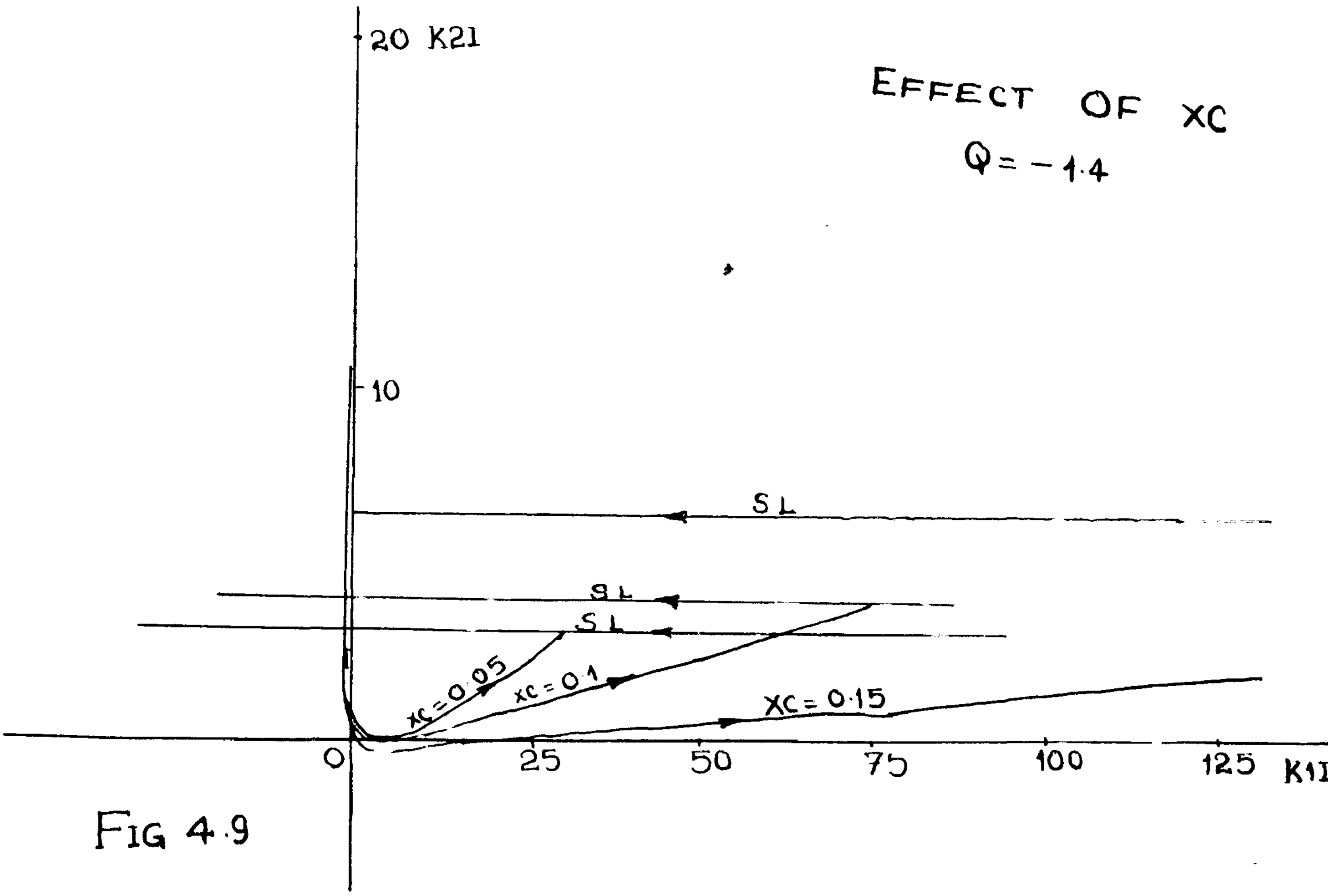

K2V
70
60
50
40
30
20
10
A
EFFECT OF XC
Q · 14
STABLE
XC=0.05
XC=0.1
XC=0.15
6
3
3
6
9
12
K1V
SL
SL

FIG 4·7



20 K2I
A
EFFECT OF KG1
Q = -1.4
10
S L
KG1 = 0.1
KG1 = 0.05
0
20
40
60
80
K1I

FIG 4.8



20 K21
EFFECT OF XC
Q = -1.4
10
S L
S L
S L
XC = 0.05
XC = 0.1
XC = 0.15
0
25
50
75
100
125
K1I

FIG 4.9

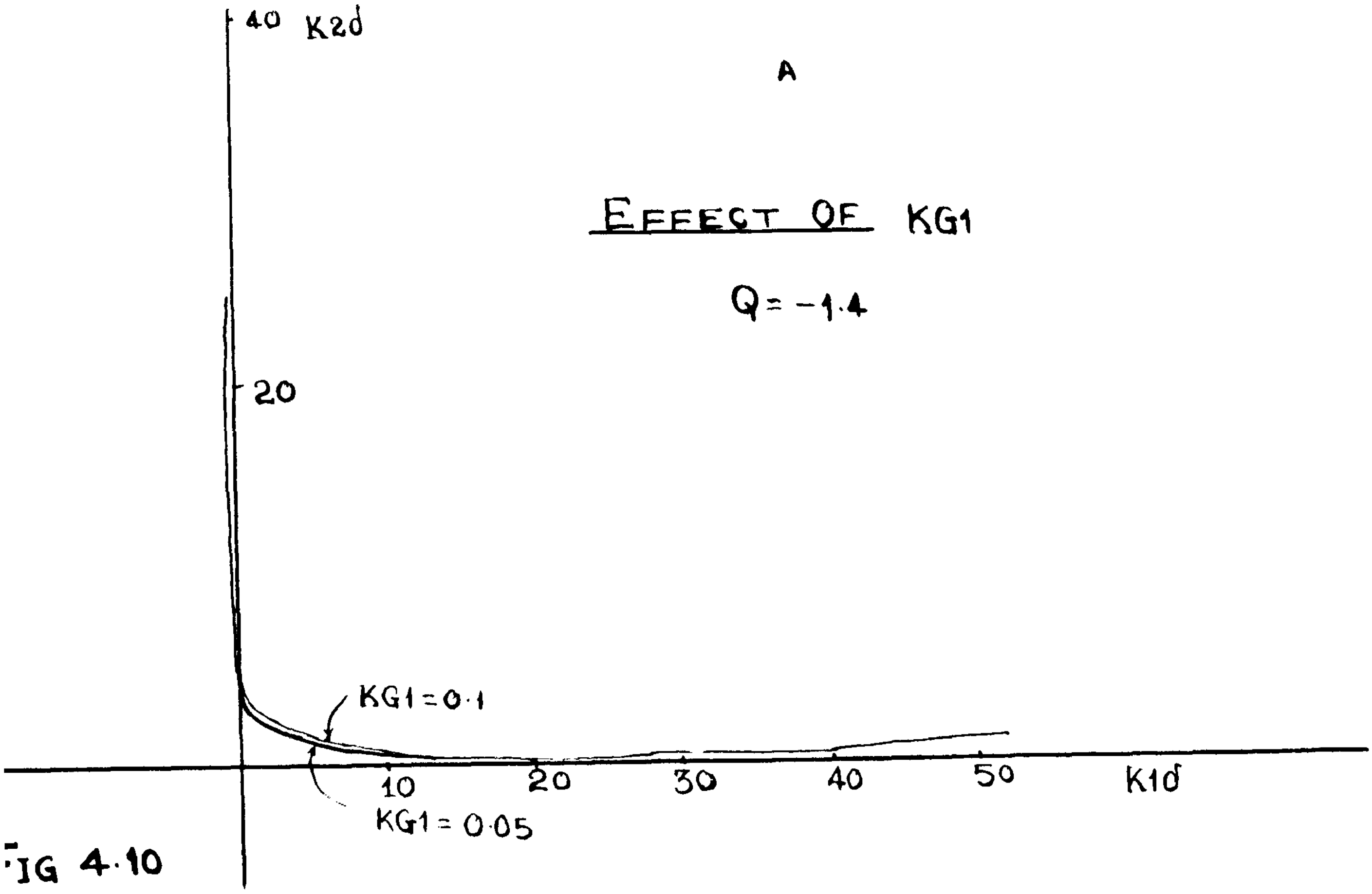


FIG 4.10

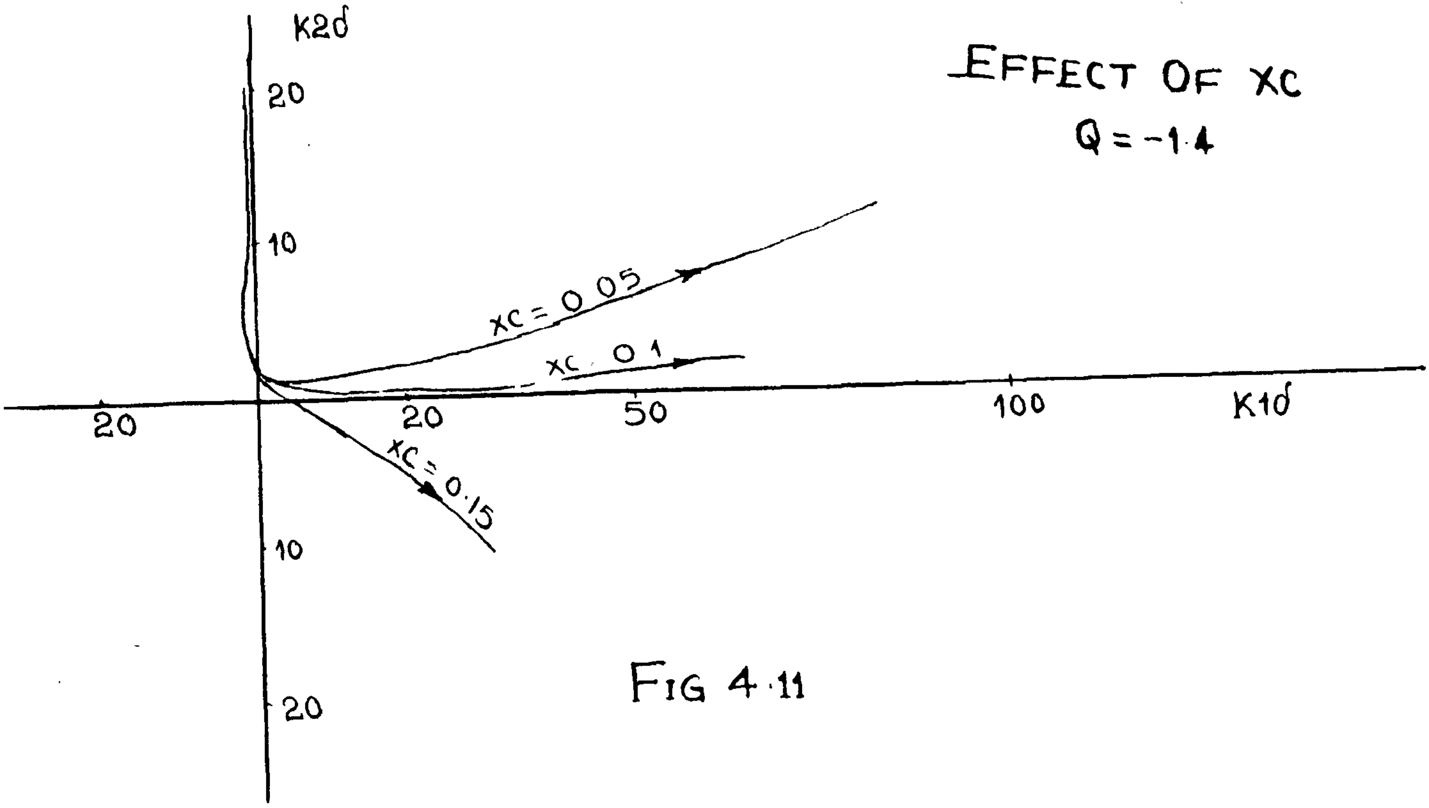


FIG 4.11

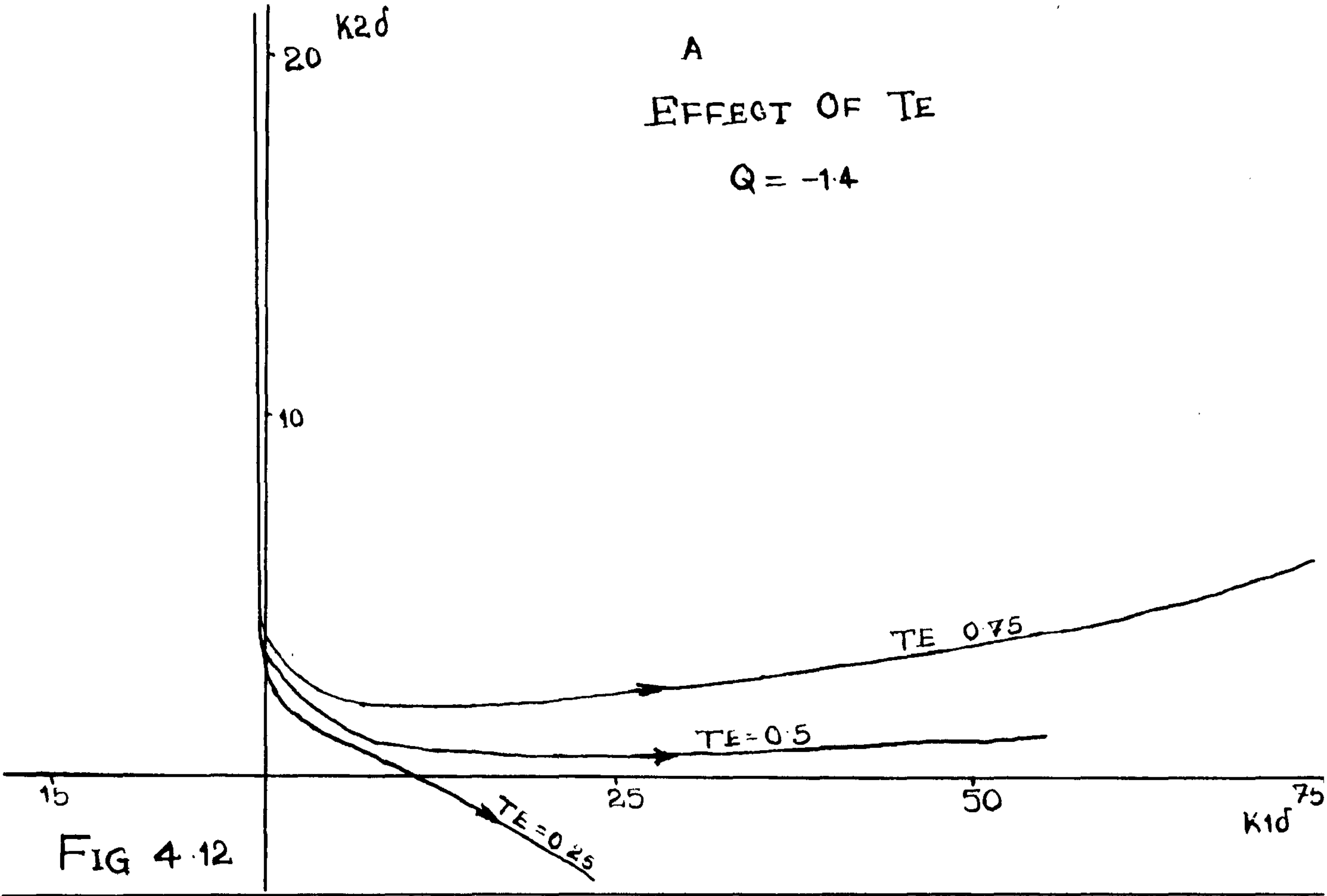


FIG 4.12

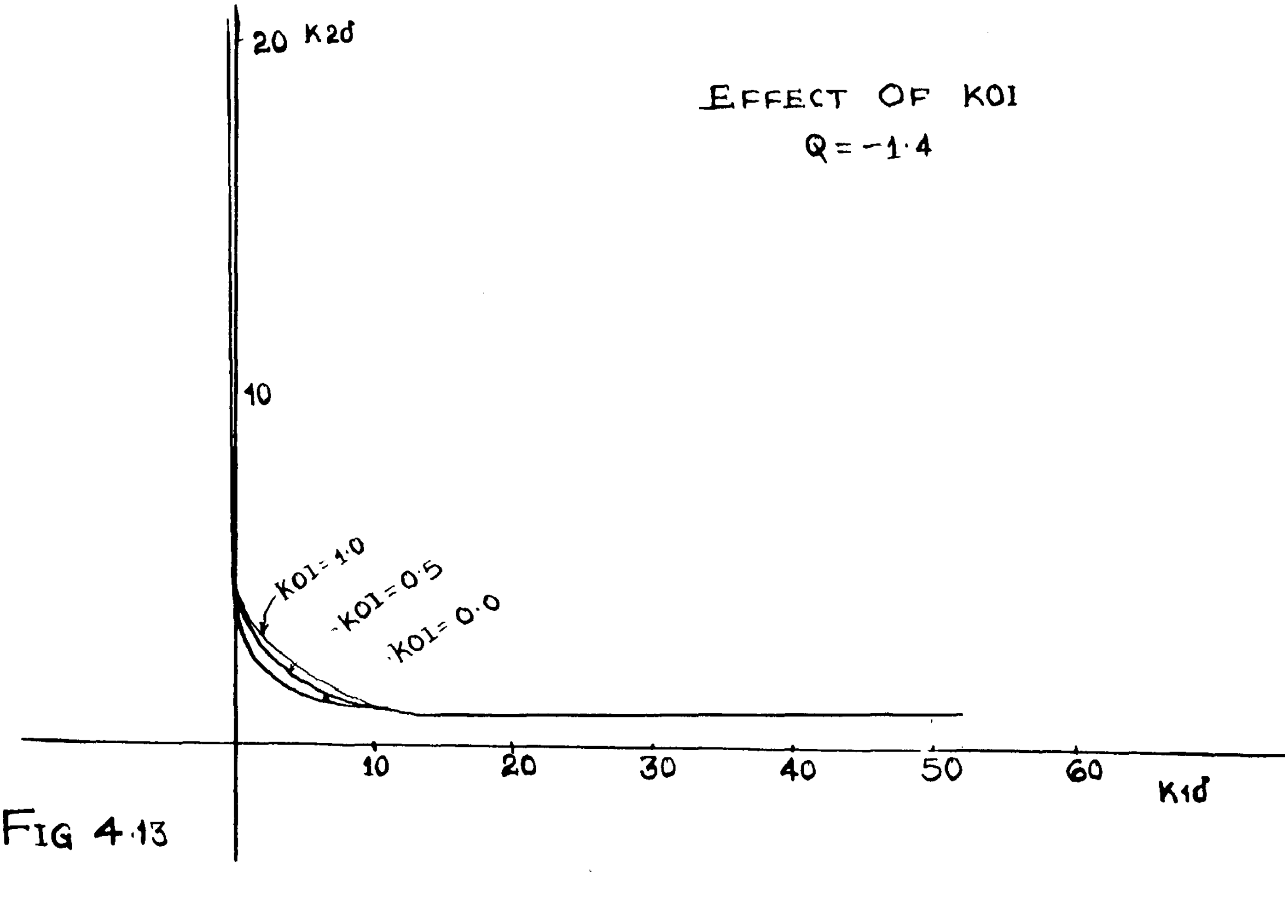


FIG 4.13

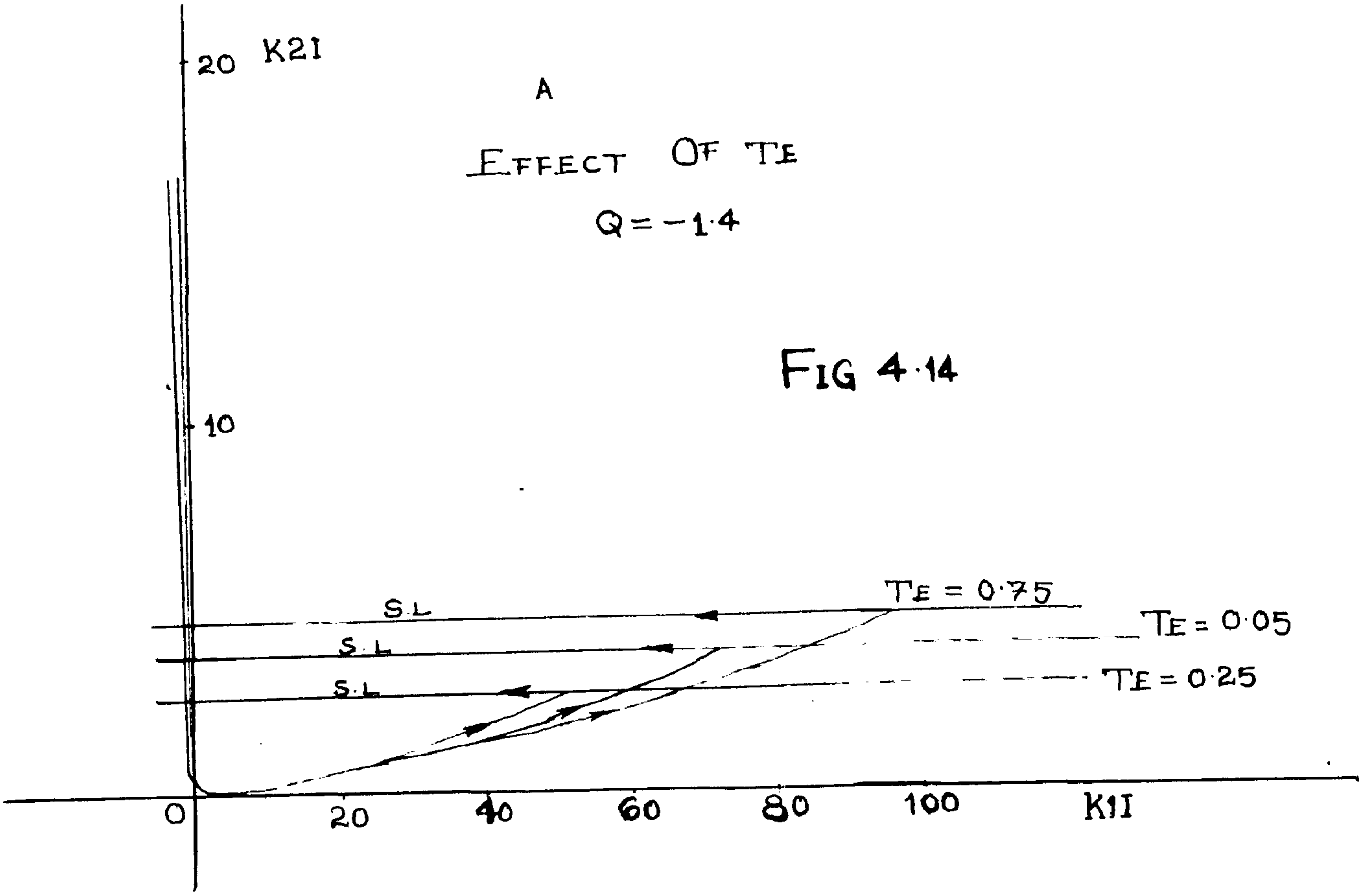


FIG 4·14

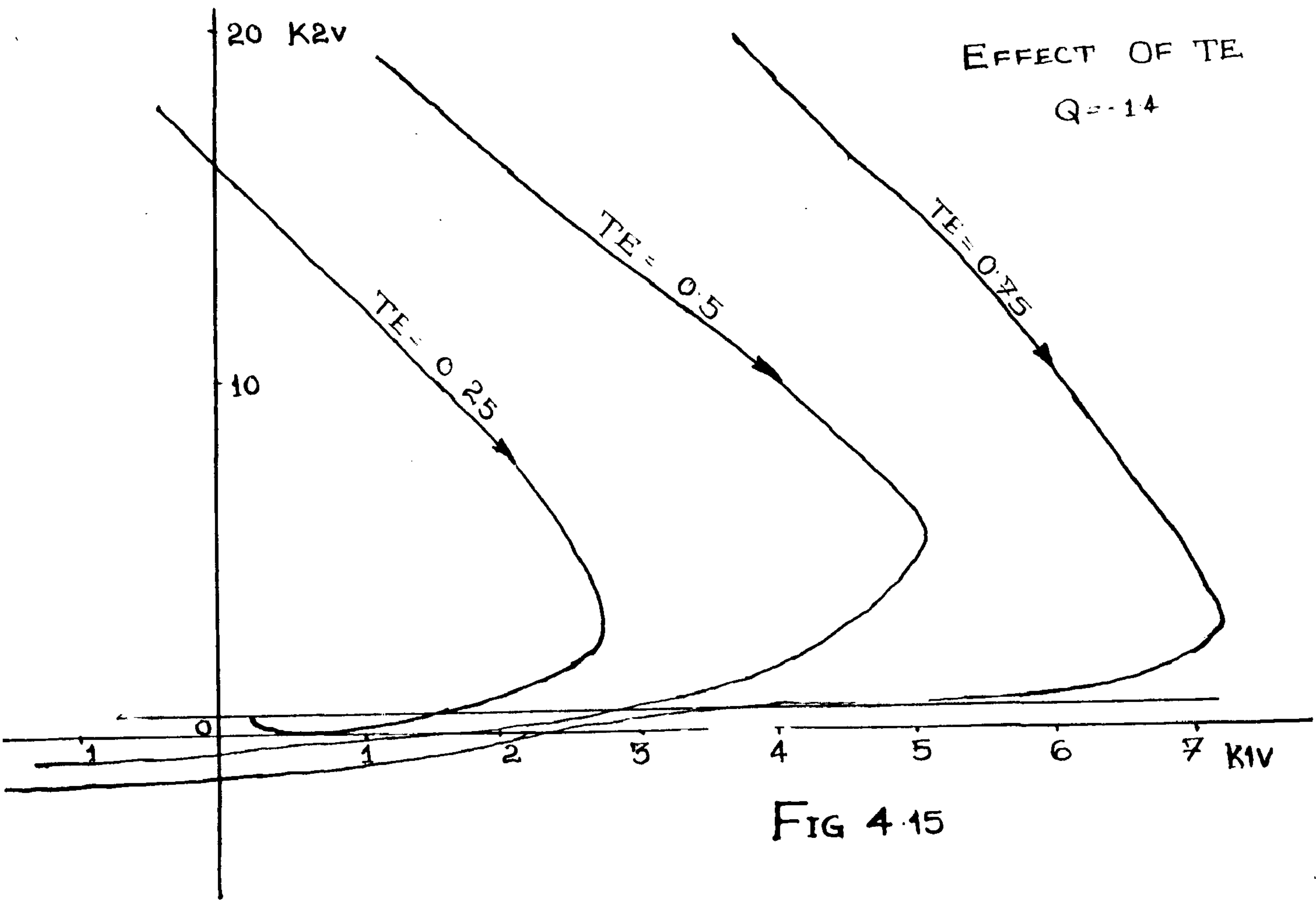


FIG 4·15

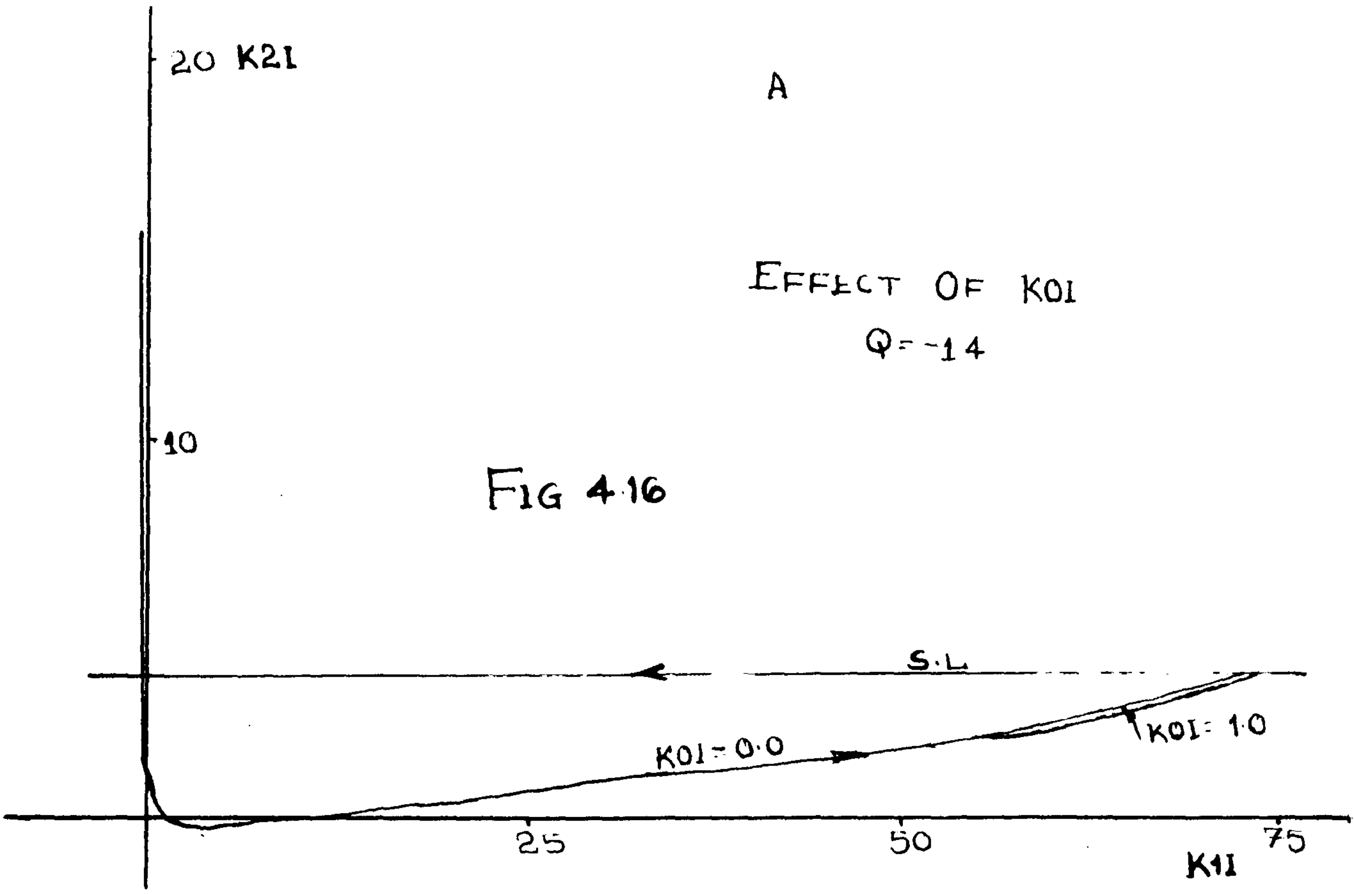


FIG 4.16

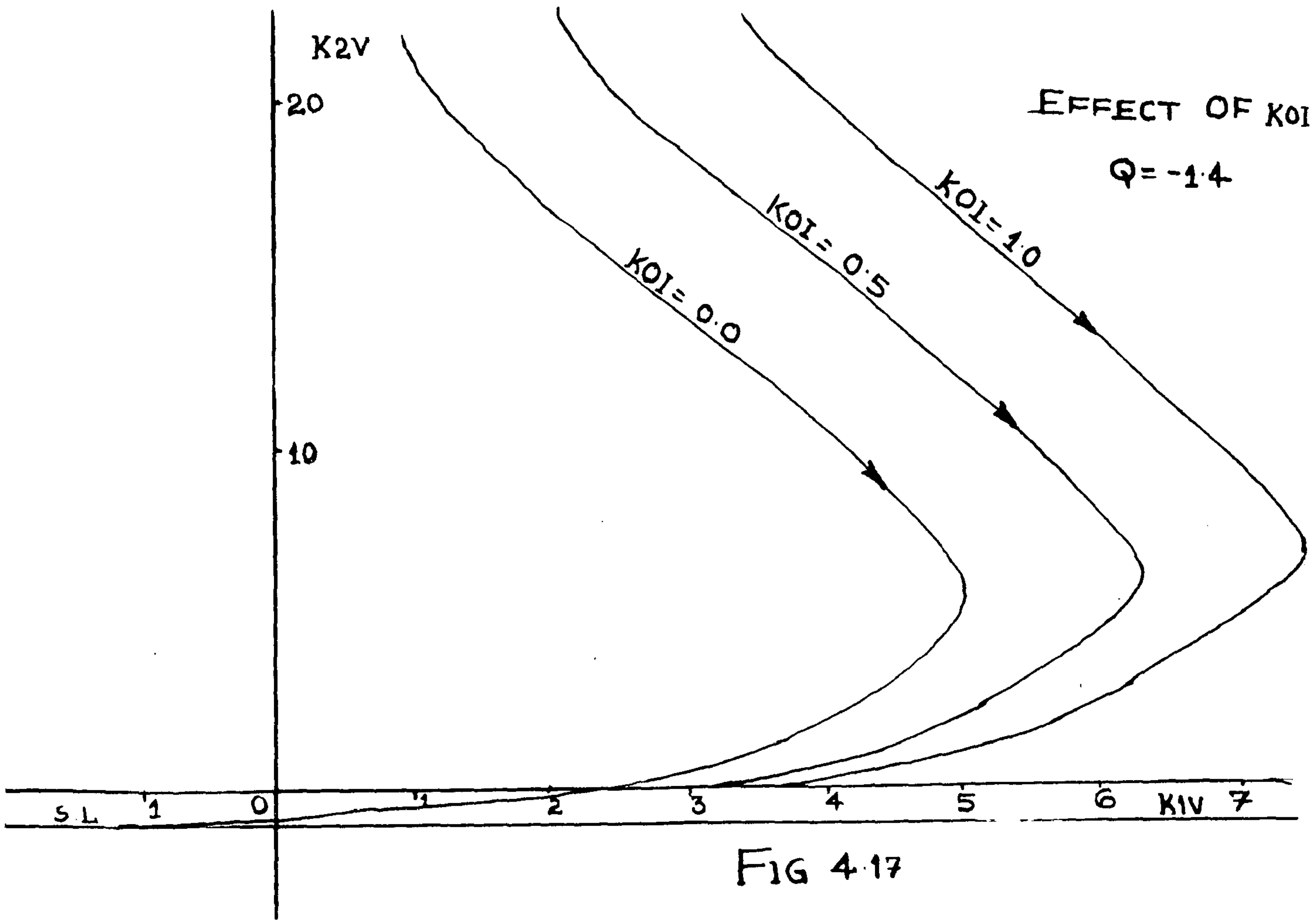


FIG 4.17

Calculations and Results

All the computational work is carried on the departmental computer TDC-312. The effect of variation in Q, X_e, δ, TE, KOI, KGI parameters on the stable region in the parameter plane is studied. Graphs of the computer results are given in Fig. 4.1, 4.2, 4.3 ... etc.

Discussion

Study has been made for selection of six gain constants namely K1I, K2I, K1V - K2V, and K1δ - K2δ for absolute stability by using D-Partitioning technique. The effects of varying Q, δ, X_e , TE, Tg1, KOI are being particularly studied.

Discussions for Absolute Stability

i) Effect of Q (leading reactive power at infinite bus)

Increase in Q is found to reduce the stability region obtained in the planes of K1V -K2V, K1I -K2I and K1δ -K2δ. The rate of reduction being fastest in the plane of K1I -K2I and least in the plane of K1δ - K2δ.

Above inference has been drawn from the figures 4.1 to 4.3.

ii) Effect of δ (Initial steady state load angle)

Fig. 4.4 and 4.5 show the effect of varying δ on the stability region in the planes of K1I - K2I and K1V - K2V. It is noted that there exists a critical angle δ which gives least area of stability and the angles above and below this angle give greater stable zone. Apperantly $\delta = 0$ case gives largest area but the second derivatives gain constants has to be greater than a certain minimum value. Fig. 4.6 shows that increase in δ gives larger stability area in the plane of $K1\delta - K2\delta$.

iii) Effect of X_c (Series capacitance in the tie line)

The increase of X_c increases the stability zone in the planes of $K1I - K2I$ and $K1\delta - K2\delta$ but this increase is remarkable in the $K1\delta - K2\delta$ plane (Fig. 4.9 and 4.11).

Fig. 4.9 shows that the increase in X_c reduces the stability area in the plane of $K1V - K2V$.

iv) Effect of T_E (V.R. Circuit time constants) $T_{E1} = T_{E2} = T_E$

The increase in T_E gives reduction in the stability areas in the planes of $K1V - K2V$ and $K1\delta - K2\delta$ while it increases the stability area in the plane of $K1I - K2I$ plane. But it may be noted that the stability area in $K1I - K2I$ plane is very small compared to other two planes (fig. 4.12, 4.14, 4.15).

v) Effect of KOI (Propertionate gain constant of current regulator).

Fig. 4.13 shows that increase of KOI causes insignificant decrease in the stability region obtained. Almost whole of the first quadrant happens to be stable zone. Fig 4.16 shows that increase of KOI does not change the stability regions obtained in the plane of K1I - K2I plane. The stability region is very much limited compared to other two cases.

Fig. 4.17 shows a gradual reduction in the stability zone in the plane of K1V - K2V.

vi) Effect of KG1 (speed gain constant of the Governor)

Increase in KG1 reduces the stability area obtained in the plane of K1I - K2I at a very slow rate, the overall area is very small in size (fig.4.8).

Increase of KG1 produces insignificant decrease in the stability area obtained in the plane of K1δ - K2δ. Almost complete first quadrant is a stable region (Fig.4.10).

CHAPTER -5

Relative Stability Study

In an earlier chapter the problem of parameter co-ordination to ensure system stability has been discussed. The aim of study in this chapter is to ensure a desired relative stability (degree of stability of the system i.e. to ensure a certain settling time for the transient response of the system. The settling time of the system is related to the location of poles of the system characteristic equation on the left hand side of jw axis in the p-plane. For stable system all the roots of characteristic equation be real negative numbers or complex number with negative real parts. The rate of decay of each component in the transient response is determined by the absolute value of the real part of the corresponding root. The larger the absolute value of the real part of the root the more fapid is the process of decay of the transient response. Evidently it is the component of the transient process with the smallest value of the real part of the root (only the absolute value is relevant) which will decay more slowly than other components. If the duration of dying out of the component with the smallest damping exponent (i.e. largest time constant) is equal to or smaller than the period of settling down consistant with the technical requirement, than the actual duration of transient process will certainly not be larger. It can be assumed that the transient process is completed after 3 to 4 time constants. This time constant is the reciprocal of the real part of the smallest root. Thus to ensure prescribed value of settling time of transient process of the system a line parallel to jw axis in the p-plane but shifted towards the left hand side by an amount (reciprocal of the desired maximum settling time) will be transformed on to the desired coordinating parameter planes. Such a process is effected making use of d partioning technique which has been described in the earlier chapter.

5.1 D-Partioning in the plane of K1δ - K2δ

$$Gd(p) = \frac{1}{(1 + Tdo'P)}$$

replacing p by σ + jw.

$$Gd(\sigma + jw) = GdR + jwGdI = \frac{1}{1 + Tdo'(\sigma + jw)}$$

$$= \frac{1}{(1 + Tdo'\sigma) + jwTdo'}$$

$$\therefore \; GdR + jwGdI = \frac{(1 + Tdo'\sigma) - jwTdo'}{(1 + Tdo'\sigma)^2 + Tdo'^2 w^2}$$

$$= \frac{1 + Tdo'\sigma}{A_1} - \frac{jwTdo'}{A_1}$$

where $A_1 = (1 + Tdo'\sigma)^2 + Tdo'^2 w^2$

Similarly $Gq(p) = GqR + jw\, GqI$

$$= \frac{1 + Tqo'\sigma}{A_2} - \frac{jwTqo'}{A_2}$$

where $A_2 = (1 + Tqo'\sigma)^2 + Tqo'^2 w^2$

$$Gv(p) = \frac{KOV + K1Vp + K2Vp^2}{1 + T_{e1}P}$$

$$GV(\sigma + jw) = GVR + jwGVI = \frac{KOV + K1V(\sigma + jw) + K2V(\sigma + jw)^2}{1 + T_{e1}(\sigma + jw)}$$

$$= \frac{(KOV + \sigma K1V + \sigma^2 K2V - K2Vw^2) + jw(K1V + 2\ \ K2V)}{(1 + T_{e1}\sigma) + jwT_{e1}}$$

$A = KOV + \sigma K1V + \sigma^2 K2V - K2Vw^2$

$B = K1V + 2\sigma\ K2V$

$$\therefore\ GVR + jwGVI = \frac{(A + jwB)\ \ (1 + T_{e1}\sigma) - jwT_{e1}}{(1 + T_{e1}\sigma)^2 + T_{e1}^2\ w^2}$$

$$= \frac{A(1 + T_{e1}\sigma) + w^2 BT_e}{A_3} + \frac{jw\ \ B(1+T_{e1}\sigma) - T_{e1}A}{A_3}$$

where $A_3 = (1 + T_{e1}\sigma)^2 + T_{e1}^2 w^2$

Similarly $GI(p) = \dfrac{KOI + K1IP + K2Ip^2}{(1 + T_{e1}p)}$

$$A = KOI + \sigma K1I + \sigma^2 K2I - K2Iw^2$$

$$B = K1I + 2\sigma K2I$$

$$GIR + jwGII = GI(\sigma + jw) = \left| \frac{A(1 + \sigma T_{e1}) + w^2 T_{e1}B}{A_3} \right| + jw \left| \frac{B(1 + \sigma T_{e1}) - T_{e1}}{A_3} \right|$$

$$f1(p) = VCos\delta o + p(\gamma_L ido - edo + VSin\delta o - 2X_L iqo) + X_L idop^2$$

$$f1(\sigma + jw) = VCos\delta o + (\sigma + jw)(\gamma_L ido - edo + VSin\delta o - 2X_L iqo) + (\sigma + jw)^2 X_L ido$$

$$A = \gamma_L ido - edo + VSin\delta o - 2X_L iqo$$

$$B = X_L ido$$

$$f1R + jwf1I = VCos\delta o + \sigma A + (\sigma^2 - w^2)B + jw(A + 2\sigma B)$$

$$f2(p) = -VSin\delta o + p(VCos\delta o + \gamma_L iqo + 2idoX_L - eqo + X_L iqop^2$$

$$A = VCos\delta o + \gamma_L iqo + 2idoX_L - eqo$$

$$B = X_L iqo$$

$$f2(\sigma + jw) = f2R + jwF2I = \left\{ -VSin\delta o + \sigma A + (\sigma^2 - w^2) B \right\} + jw(A + 2\sigma B)$$

$$f3(\sigma + jw) = f3R + jwf3I = f1(\sigma + jw) + \psi qo(\sigma + jw)$$

$$= (f1R + \sigma \psi qo) + jw(f1I + \psi qo)$$

$$Gg(p) = \frac{Kgo + Kg1p + Kg2p^2}{(1 + Tg1p)(1+Tg2p)} = \frac{Kgo + Kg1p + Kg2p^2}{1+(Tg1 + Tg2)p+Tg1Tg2p^2}$$

$$TGO = Tg1 + Tg2 , \qquad TGT = Tg1\ Tg2$$

$$Gg(\sigma + jw) = \frac{Kgo + \sigma Kg1 + (\sigma^2 - w^2)Kg2 + jw(Kg1 + 2\sigma Kg2)}{1+\sigma Tgo + (\sigma^2 - w^2)TGT + jw(TGO + 2\sigma TGT)}$$

$$A = Kgo + \sigma Kg1 + (\sigma^2 - w^2)\ Kg2$$

$$B = Kg1 + 2\sigma Kg2$$

$$C = 1 + \sigma Tgo + (\sigma^2 - w^2)\ TGT$$

$$D = TGO + 2\sigma TGT$$

$$GgR + jwGgI = \frac{A + jw}{C + jwD} \qquad \frac{(A + jwB)\ (C - jwD)}{C^2 + D^2}$$

$$= \frac{AC + w^2BD}{C^2 + D^2} + \frac{jw(BC - DA)}{C^2 + D^2}$$

$$A31(p) = f4(p) = Mp^2 + Pdp + Gg(p) + iqof2(p) + idof1(p)$$

$$A31(\sigma + jw) = (\sigma + jw)^2M + Pd(\sigma + jw) + GgR + jwGgI +$$

$$+ iqo(f2R + jwf2I) + ido(f1R + jwf1I)$$

$$A31R + jw31I = M(\sigma^2 - w^2) + Pd + GgR + iqof2R + idof1R$$

$$+ jw(2\sigma M + Pd + GgI + iqof2I + idof1I\ )$$

$$Xd(p) = \frac{Xd(\ 1 + Td'p)}{1 + Tdo'p}$$

$$Xd(\sigma + jw) = \frac{Xd\left\{ 1 + (\sigma + jw)\, Td' \right\}}{1 + (\sigma + jw)\, Tdo'}$$

$$= \frac{Xd\left\{ (1 + \sigma Td') + jwTd' \right\}}{(1 + \sigma Tdo') + jwTdo'}$$

$$= \frac{Xd\left\{ (1 + \sigma Td')(1 + \sigma Tdo') + w^2 Td'Tdo' \right.}{(1 + \sigma Tdo')^2 + w^2\, Tdo'^2}$$

$$+ \frac{jwXd\left\{ Td'(1 + \sigma Tdo') - Tdo'(1 + \sigma Td') \right)}{(1 + \sigma Tdo')^2 + w^2\, Tdo'^2}$$

$$Xq(\sigma + jw) = XqR + jwXqI$$

$$\frac{Xq\left\{ (1 + \sigma Tq')\,(1 + \sigma Tqo') + w^2 T'q\; Tqo' \right.}{(1 + \sigma Tqo')^2 + w^2\, T'qo^2}$$

$$\frac{jwXq\left\{ T'q\,(1 + \sigma Tqo') - Tqo'(1 + \sigma Tqo') \right)}{(1 + \sigma Tqo')^2 + w^2\, Tqo'^2}$$

$$Gd(\sigma + jw)\; GV\,(\sigma + jw) = GdVR + jwGdVI$$

$$= (GdRGVR - w^2 GdI\; GVI) + jw(GdRGVI + GdIGVR)$$

$$Gd(\sigma + jw)\; GI(\sigma + jw) = GdIR + jwGdII$$

$$= (GdRGIR - w^2 GdI\; GII) + jw(GdRGII + GdIGIR)$$

$$Gd(\sigma + jw)\; GV(\sigma + jw) f1(\sigma + jw) = AR + jwAI$$

$$= (GdVRf1R - w^2 GdVIf1I) +$$

$$jw(GdVRf1I + GdVIf1R)$$

$$Gd(\sigma + jw)\ GV(\sigma + jw)\ f2(\sigma + jw) = BR + jwBI$$

$$= (GdVRf2R - w^2 GdVIf2I) + jw(GdVRf2I + GdVIf2R)$$

$$A21(p) = \psi dop - f2(p) - Gd(p)GV(p)\left\{Sdf1(p) + Sqf2(p)\right\}$$

$$A21(\sigma + jw) = A21R + jw\ A21I$$

$$= \left\{\sigma\psi do - f2R - SdAR - SqBR\right\} + jw\left\{\psi do - f2I - SdAI - SqBI\right\}$$

$$A22(p) = -Xd(p) - (X_L - X_c) - Gd(p)\ GV(p)\left\{\gamma_L Sd + (X_L - X_c)\ Sq\right\}$$

$$+ CdGd(p)\ GI(p)$$

$$P_1 = \gamma_L Sd + (X_L - X_c)\ Sq$$

$$A22(\sigma + jw) = A22R + jwA22I$$

$$= -XdR - jwXdI - (X_L - X_c) - P_1 GdVR - jwP_1 GdVI$$

$$+ CdGdIR + jw\ CdGd_I I$$

$$= |\ - XdR + CdGdIR - P_1 GdVR - X_L + X_c |$$

$$+ jw|\ -XdI + CdGd_I I - P_1 GdVI\ |$$

$$A23(p) = -(\gamma + \gamma_L) + Gd(p)\ Gv(p)\left\{(X_L - X_c)\ Sd - \gamma_L Sq\right\} +$$

$$+ CqGd(p)GI(p)$$

$$P_2 = (X_L - X_c)\ Sd - {}_L Sq$$

$$A23\ (\sigma + jw) = A23R + jw\ A23I$$

$$= |\ -(\gamma + \gamma_L) + GdVRP_2 + CqGdIR\ | +$$

$$+ jw|\ CqGd_I I + P_2 GdVI\ |$$

$$K1(p) = A22A33 - A23A32$$

$$K1(\sigma + jw) = AK1R + jwAL1I$$

$$= (A33A22R - A32A23R) + jw(A33A22I - A32A23I)$$

$$A13(p) = - | Xq(p) + (X_L - X_e) |$$

$$A13(\sigma + jw) = A13R + jwA13I$$

$$= - | XqR + (X_L - X_e) | - jwXqI$$

$$AA + jwBB = (A12A23 - A13A22)$$

$$= | A12A23R - A13RA22R + w^2 A13IA22I |$$

$$+ jw | A12A23I - A13IA22R - A13RA22I |$$

$$K2(\sigma + jw) = AK2R + jwAK2I$$

$$= | (AA.A31R - w^2 BB.A31I) - A12\ A33\ A21R +$$

$$+ A32(A13RA21R - w^2 A13IA21I) |$$

$$+ jw | (AAA31I + BBA31R) - A12A33A21I + A32(A13RA21I$$

$$+ A13I\ A21A) |$$

$$\frac{K1(\sigma + jw)\ Gq(\sigma + jw)}{1 + T_{e2}(\sigma + jw)} = X + jwY$$

$$= \frac{| (AK1RGqR - w^2 AK1IGqI)(1 + \sigma T_{e2}) + w^2 (AK1RGqI + AK1IGqR) T_{e2} | + jw | (AK1RGqI + AK1IGqR)(1 + \sigma T_{e2}) - T_{e2}(AK1RGqR - w^2 AK1IGqI) |}{(1 + \sigma T_{e2})^2 + w^2\ Te2^2}$$

$$f3(\sigma+jw)\ K1(\sigma+jw) = fKR + jwfKI$$

$$= (f3RAK1R - w^2 f3I\ AK1I) + jw(f3RAK1I + f3IAK1R)$$

$$\therefore \frac{K1(p)Gq(p)}{(1+T_{e2}p)} \left| K1\delta p + K2\delta p^2 \right| + \frac{K1(p)Gq(p)Ko\delta}{(1+T_{e2}p)} +$$

$+K2(p) + f3(p)\ K1(p) = 0$ May be written as

$$(X + jwY) \left| (\sigma+jw)K1\delta + (\sigma+jw)^2\ K2\delta \right| + (X + jwY)\ Ko\delta +$$

$$+ AK2R + jwAK2I + fKR + jwfKI = 0$$

or $(X + jwY) \left| \sigma K1\delta + jwK1\delta + (\sigma^2 - w^2)\ K2\delta + j2w\sigma K2\delta \right|$

$$+ (X + jwY)\ KO\delta + AK2R + jwAK2I + fKR + jwfKI = 0$$

$$\sigma XK1\delta + jwK1\delta X + (\sigma^2 - w^2)\ K2\delta X + j2w\sigma K2\delta\ x + jwY\sigma K1\delta - w^2 YK1\delta$$

$$+ jwY(\sigma^2 - w^2)\ K2\delta - 2w^2 Y\sigma K2\delta + (X + jYw)\ Ko\delta = 0$$

or $(\sigma X - w^2 Y)\ K1\delta + \ (\sigma^2 - w^2)X - 2w^2 Y\sigma \}\ K2\delta + XKo\delta + AK2R$

$$+ fKR = 0$$

$$(wX + wY\sigma)K1\delta + \left\{ 2w\sigma X + wX(\sigma^2 - w^2) \right\}\ K2\delta + wYko\delta +$$

$$wAK2I + wfKI = 0$$

$$DEN = \left| (\sigma X - w^2 Y)\ \left\{ (2w\sigma X + wY\ (\sigma^2 - w^2) \right\} \right|$$

$$- \left| (wX + wY\sigma) \left\{ (\sigma^2 - w^2)x - 2w^2 Y\sigma \right\} \right|$$

$$A = r_L ido - 2X_L iqo + VSin\delta o - edo + \psi qo$$

$$B = X_L ido$$

$$A11(\sigma + jw) = AR11 + jwAI11$$

$$= |VCos\delta o + (\sigma^2 - w^2)B + \sigma A + GqDR) + jw(2\sigma B + A + GqdI)$$

$$F1(p) = Sdf1(p) + Sqf2(p)$$

$$F1(\sigma + jw) = SdF1R + Sqf2R + jw(Sdf1I + Sqf2I)$$

$$S1(p) = A12A33 - A13A32$$

$$S1(\sigma + jw) = S1R + jwS1I$$

$$= (A12A33 - A32A13R) - jwA32A13I$$

$$= |(r + r_L)A33 - A32A13R)| + jw(-A32A13I)$$

$$S2(p) = A11A33 - A13A32$$

$$S2(\sigma + jw) = S2R + jwS2I$$

$$= A33A11R - (A13RA31R - w^2 A31IA13I) +$$

$$+ jw(A33A11I - A13RA31I + A13IA31R)$$

$$S3(\sigma + jw) = S3R + jwS3I$$

$$= A32A11R - (r + r_L)A31R + jw \; A32A11I - (r + r_L)A31I$$

$$K1(p) = - S1F1 + P1S2 + P2S3$$

$$K1(\sigma + jw) = |-(AFR1S1R - w^2 AFI1S1I) + P1S2R + P2S3R| +$$

$$+ jw|-AFR1S1I - AFI1S1R + P1S2I + P2S3I|$$

$$k1\delta = \frac{-\left\{(\sigma^2-w^2)\,Yw + 2W\sigma X\right\}\left\{XKo\delta + AK2R + fKR\right. + \left.\right. + \left\{(\sigma^2-w^2)\,X\;2w^2Y\sigma\right\}\left\{wYKo\delta + wAK2I + wfKI\right\}}{DEN}$$

$$K2\delta = \frac{-(\sigma X - w^2Y)(wYKo\delta + wAK2I + wfKI) + (wX + wY\sigma)(XKo\delta + AK2R + fKR)}{DEN}$$

5.8 D-Partitioning in the plane of K1V - K2V

$$G\delta(b) = \frac{Ko\delta + K1\delta p + K2\delta p^2}{1 + T_{e2}P}$$

$$A = Ko\delta + \sigma K1\delta + \sigma^2 K2\delta - K2\delta w^2$$

$$B = K1\delta + 2\sigma K2\delta$$

$$G\delta(\sigma + jw) = DGR + jwDGI$$

$$= \frac{A(1+\sigma T_{e1}) + w^2T_{e1}B}{A_3} + \frac{+jw\;\;B(1+\sigma T_{e1}) - T_{e1}A}{A_3}$$

where $A_3 = (1 + Te1\,\sigma)^2 + Te1^2w^2$, $Te1 = Te2 = T_e$

$$Gq(\sigma+jw)\,G\delta(\sigma+jw) = GQDR + jwGQDI$$

$$= (GqRDGR - w^2GqIDGI) + jw(GqRDGI + GqIDGR)$$

$$A11(p) = VCos\delta o + p^2X_Lido + p(\gamma_Lido - 2X_Liqo + VSin\,\delta o - edo + qo) + Gq(p)\,G\delta(p)$$

$$K2(\sigma+jw) = AK2R + jwAK2I$$

$$= |-CdS2R + CqS3R| + jw|-CdS2I + CqS3I|$$

$$K3(\sigma+jw) = Ak3R + jwAK3I$$

$$= |\Psi do(S1R\sigma - w^2 S1I) - \{F2RS1R - w^2 f2I\ S1I\} +$$

$$XdR\ S2R - w^2 XdIS2I + (X_L - X_o)S2R| - (\gamma + \gamma_L)S3R|$$

$$+jw|\Psi do(S1R + \sigma S1I) - (F2RS1I + f2IS1R) +$$

$$+ XdRS2I + XdIS2R + (X_L - X_o)S2I - (\gamma + \gamma_L)S3I|$$

$$Gd(\sigma+jw) = GDER + jwGdEI$$

$$= \frac{GdR(1+\sigma T_e) + w^2 GdIT_e}{A_3} + jw\frac{(1+\sigma T_e)GdI - T_e GdR}{A_3}$$

$$\frac{K1(\sigma+jw)\ Gd(\sigma+jw)}{(1 + T_e(\sigma+jw)\}} = GKR1 + jwGKI1$$

$$= (AK1RGDER - w^2 AK1IGdEI) +$$

$$+jw(AK1RGdEI + AK1IGdER)$$

$$\frac{K2(\sigma+jw)\ Gd(\sigma+jw)}{(1 + T_e(\sigma+jw)\}} = GKR2 + jwGKI2$$

$$= (AK2RGdER - w^2 AK2IGDEI) +$$

$$+ jw(AK2RGdEI + AK2IGdER)$$

$$\frac{K2(p)Gd(p)}{(1 + T_e p)} (KOI + K1Ip + K2Ip^2) + \frac{K1(p)Gd(p)}{(1+T_e p)} KOV + K3(p)$$

$$= BKR + jwBKI$$

$$A = KOI + \sigma K1I + (\sigma^2 - w^2) K2I$$

$$B = K1I + 2\sigma K2I$$

$$BKR + jwBKI = (GKR2 + jwGKI2)(A + jwB) + (GKR1 + jwGKI1)KOV + K3(p)$$

$$= | GKR2A - w^2GKI2B + GKR1KOV + AK3R |$$

$$= + jw | AGKI2 + GKR2B + GKI1 \; KOV + AK3I |$$

$$\therefore (GKR1 + jwGKI1)(K1Vp + K2Vp^2) + BKR + jwBKI = 0$$

or $$(GKR1 + jwGKI1)\{(\sigma + jw)K1V + (\sigma + jw)^2 K2V\} + BKR + jwBKI = 0$$

$$(GKR1 \sigma K1V - w^2 GKI1K1V + (\sigma^2 - w^2)GKR1K2V - w^2 GKI1 \, 2\sigma K2V + BKR = 0$$

or $$(\sigma GKR1 - w^2 GKI_1)K1V + \{(\sigma^2 - w^2)GKR1 - w^2 GKI_1 2\sigma\} K2V + BKR = 0$$

and $$(wGKI_1 \sigma + wGKR1) K1V + \{(\sigma^2 - w^2)w \, GKI_1 + 2\sigma wGKR_1\} K2V + w \, BKI = 0$$

$$A = (\sigma^2 - w^2) wGKI_1 + 2\sigma wGKR_1$$

$$B = \sigma GKR1 - w^2 GKI1$$

$$C = (\sigma^2 - w^2)\, GKR1 - w^2 GKI_1 \sigma 2$$

$$D = wGKI_1 \sigma + w\, GKR_1$$

$$K1V = \frac{-A \times BKR + w\, BKI \times C}{AB - CD} \quad ; \quad K2V = \frac{-B \times wBKI + BKR \times D}{AB - CD}$$

5.3 D-Partitioning in the plane of K1I - K2I

$$\frac{K1(p)Gd(p)}{1 + T_e p}(KOV + K1Vp + K2Vp^2) + \frac{K2(p)Gd(p)}{1 + T_e p} KOI + K3(p)$$

$$= BKR + jwBKI$$

$$A = |\, KOV + \sigma K1V + (\sigma^2 - w^2)\, K2V \,|$$

$$B = |\, K1V + 2\sigma K2V \,|$$

$$BKR + jwBKI = |GKR1.A - w^2 GKI_1 B + GKR_2 KOI + AK3R\,|$$

$$+ jw|\, A.GKI_1 + GKR_1 B + GKI_2 KOI + AK3I \,|$$

$$\therefore (GKR2 + jwGKI_2)(K_1 IP + K2Ip^2) + BKR + jwBKI = 0$$

$$A = (\sigma^2 - w^2)\, wGKI_2 + 2\sigma wGKR2$$

$$B = \sigma GKR2 - w^2 GKI_2$$

$$C = (\sigma^2 - w^2) GKR2 - w^2 GKI_2\, 2\sigma$$

$$D = \sigma\, wGKI_2 + wGKR_2$$

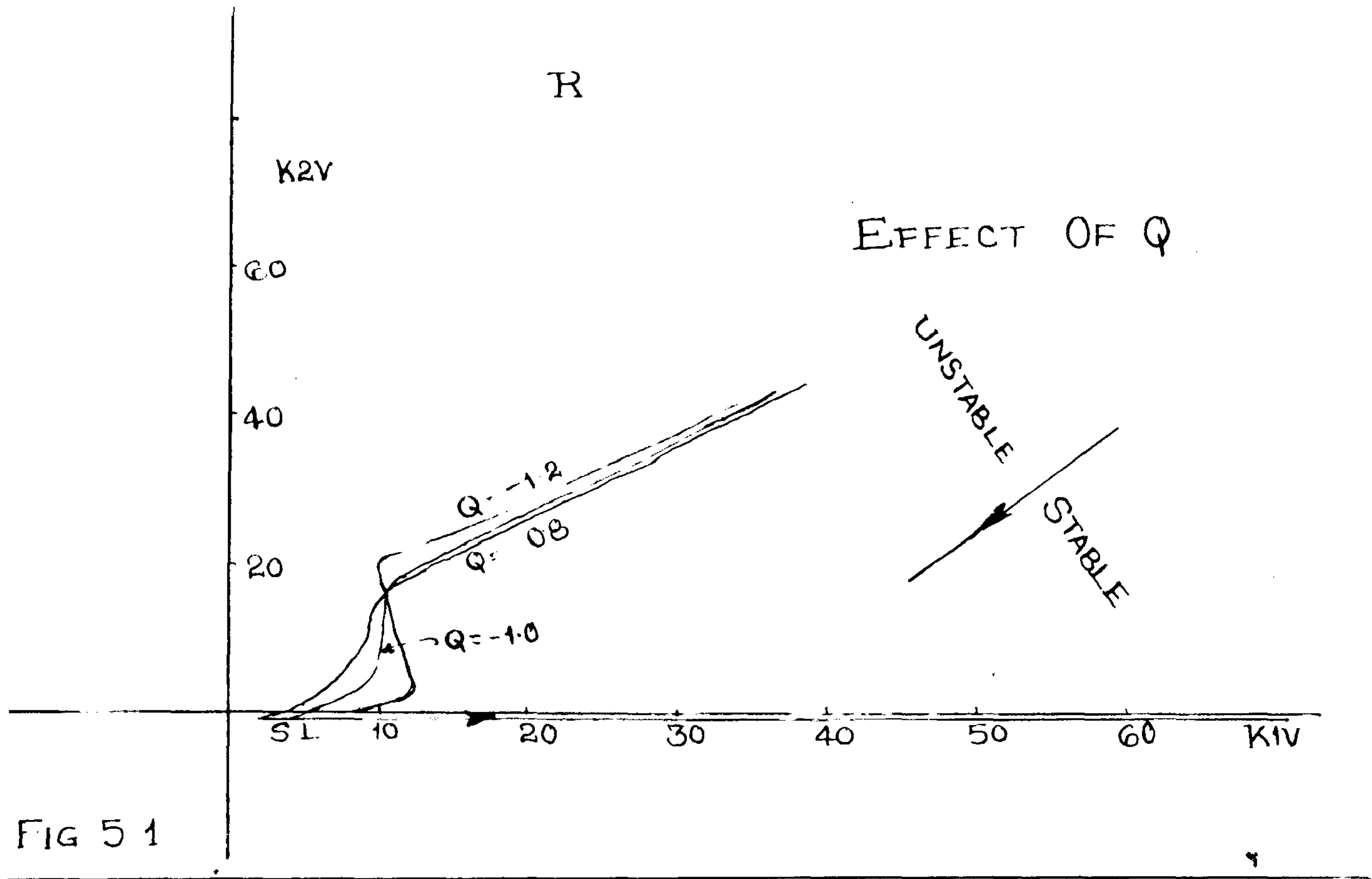

R
K2V
60
40
20
EFFECT OF Q
UNSTABLE
STABLE
Q= -1.2
Q= 08
Q= -1.0
S L.
10
20
30
40
50
60
K1V

FIG 5 1

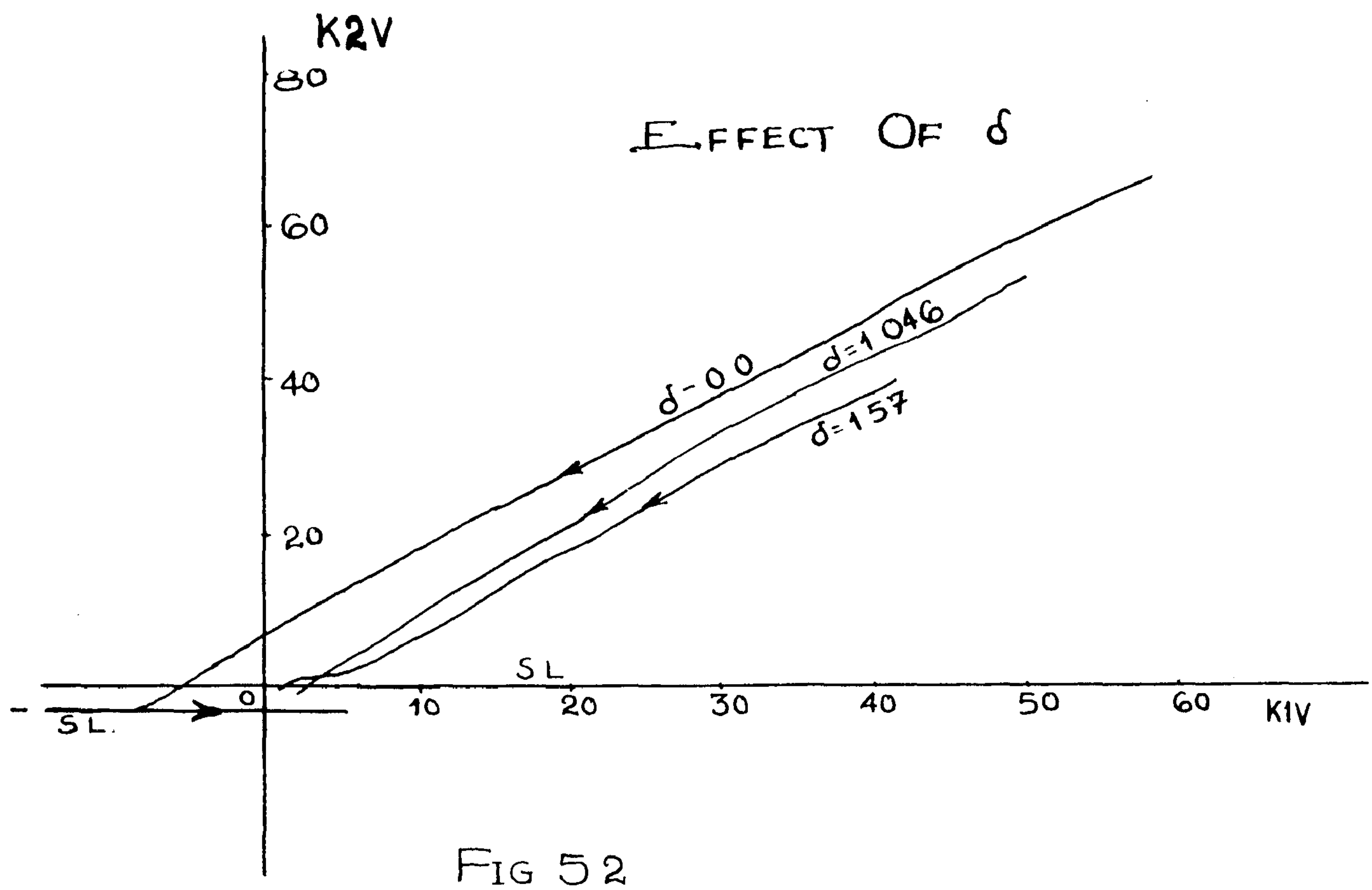
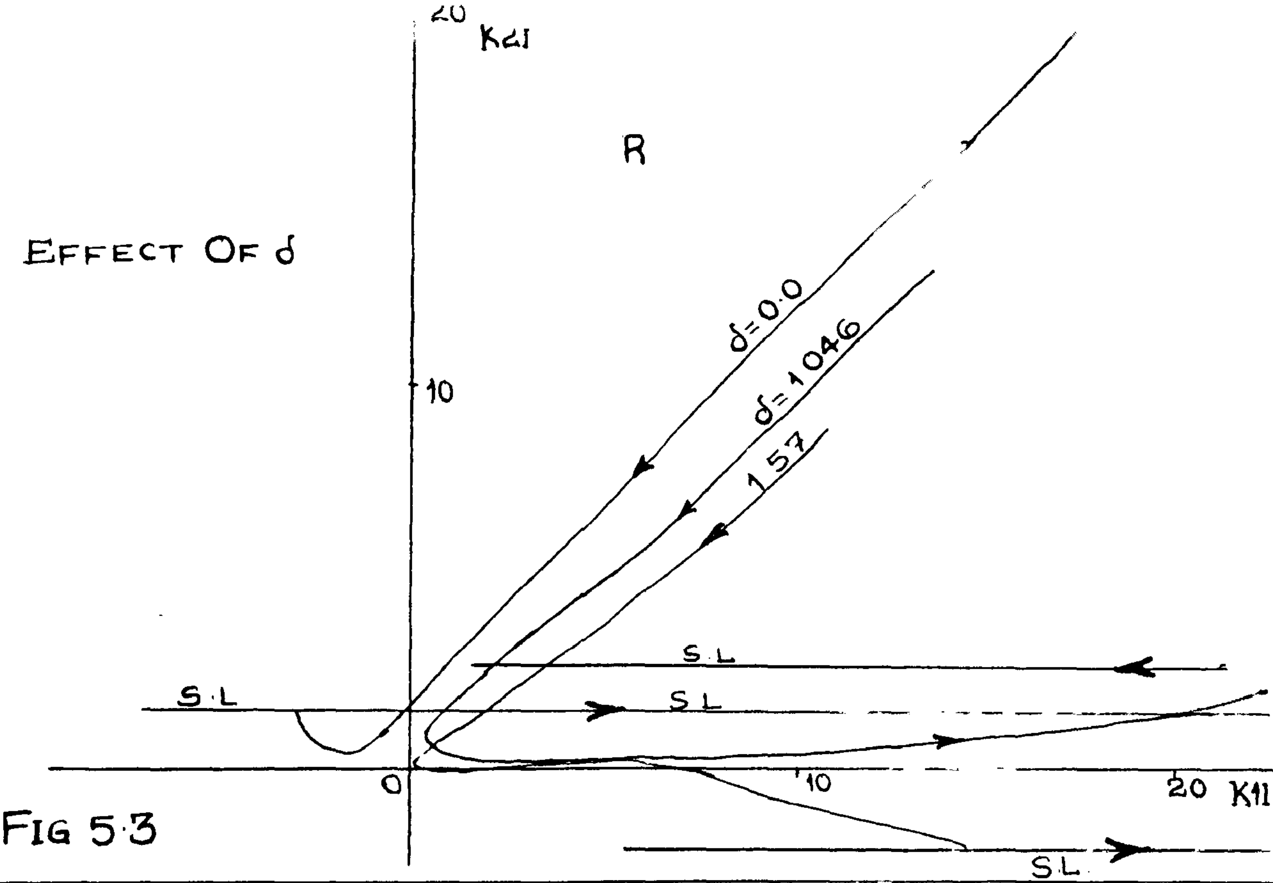
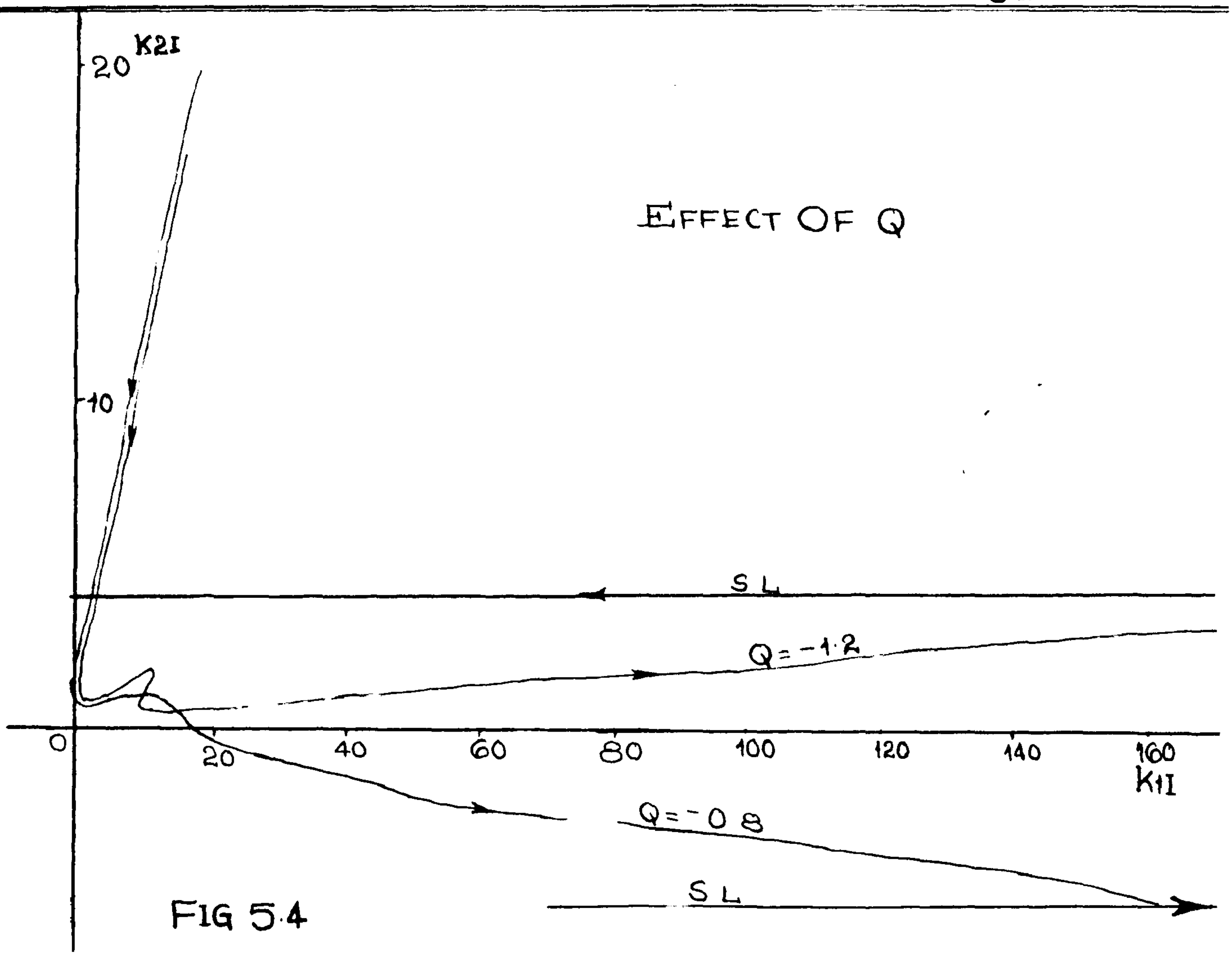

K2V
80
60
40
20
EFFECT OF δ
δ=0.0
δ=1.046
δ=1.57
S L
S L.
0
10
20
30
40
50
60
K1V

FIG 5 2



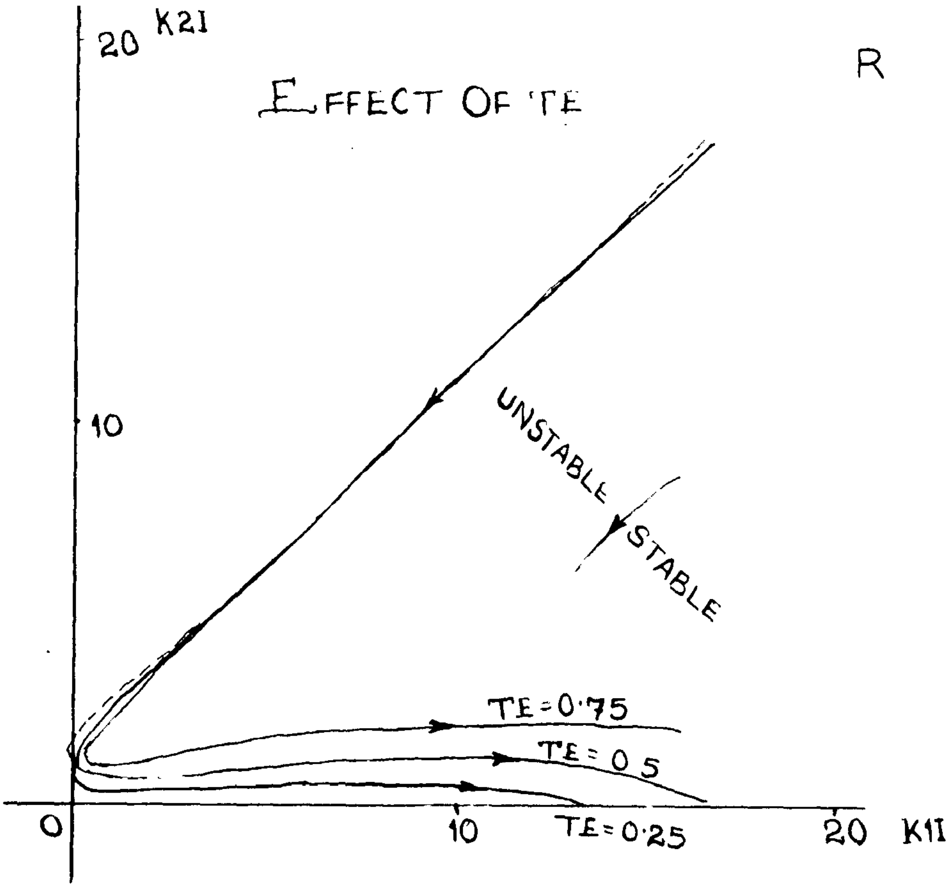
20
K21
R
EFFECT OF δ
δ=0.0
δ=1.046
10
1.57
S.L
S.L
S.L
0
10
20
K11
S.L

FIG 5.3



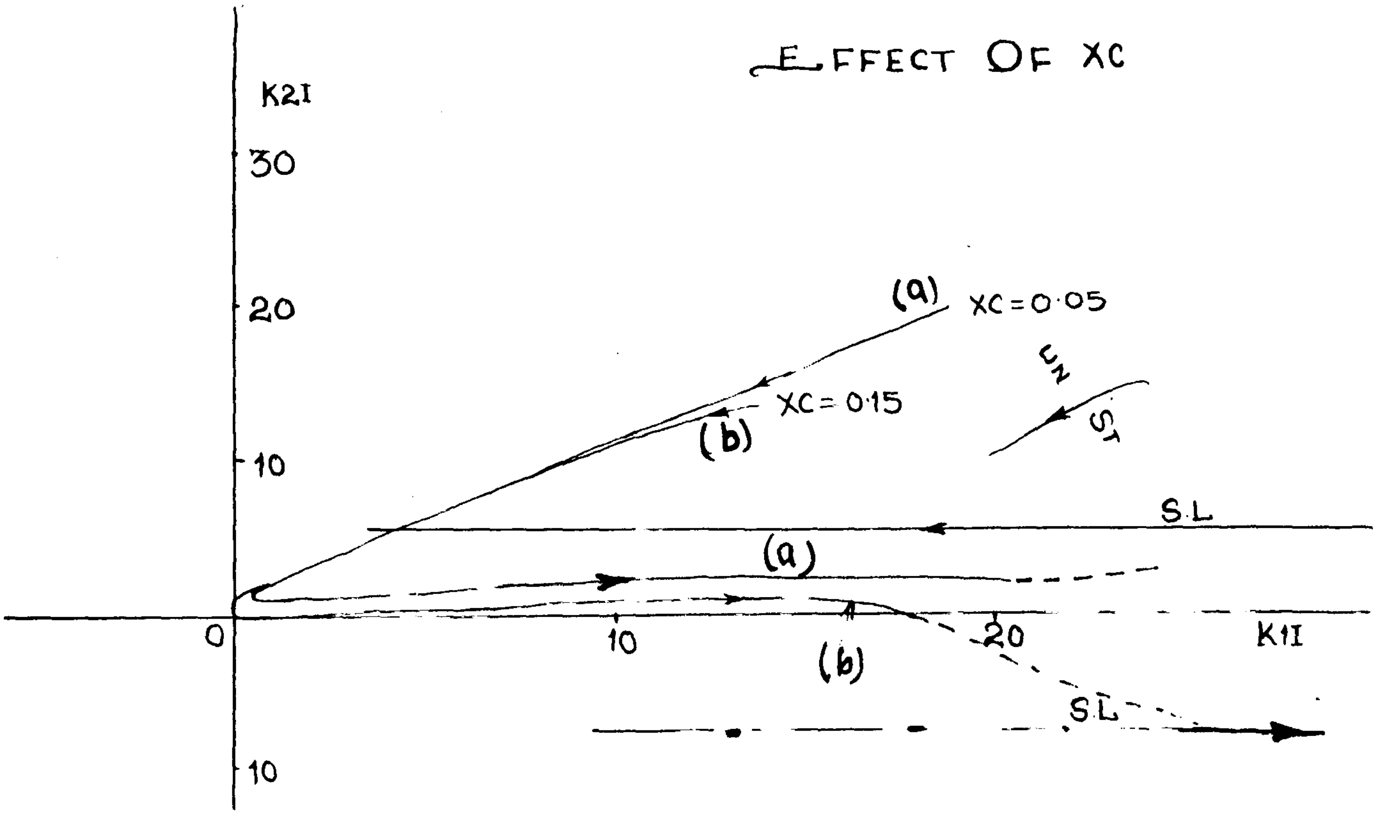
20
K21
EFFECT OF Q
10
S L
Q=-1.2
0
20
40
60
80
100
120
140
160
K11
Q=-0.8
S L

FIG 5.4



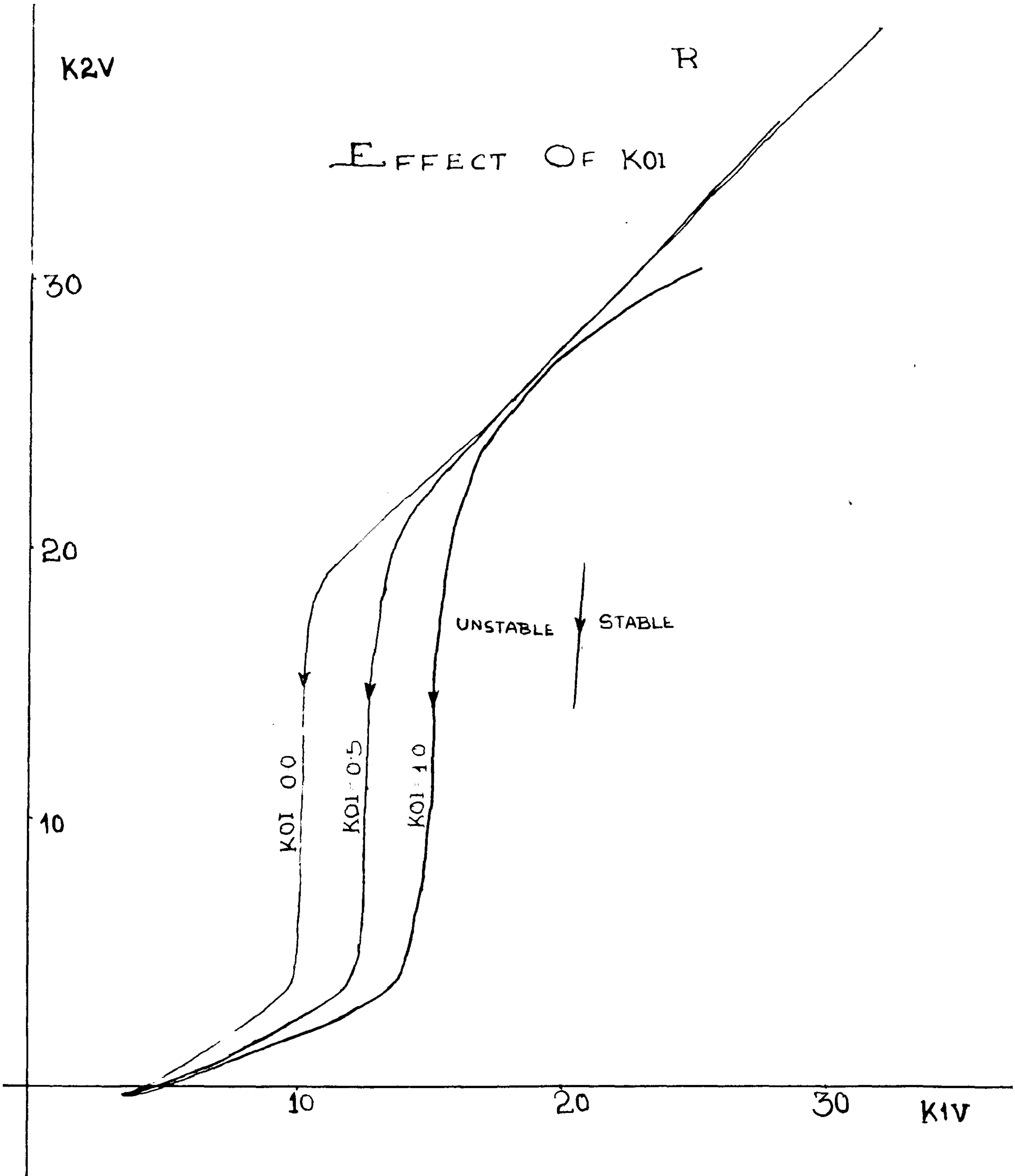
20
K2I
R
EFFECT OF TE
10
UNSTABLE
STABLE
TE=0·75
TE=0 5
0
10
TE=0·25
20
K1I

FIG 5·5



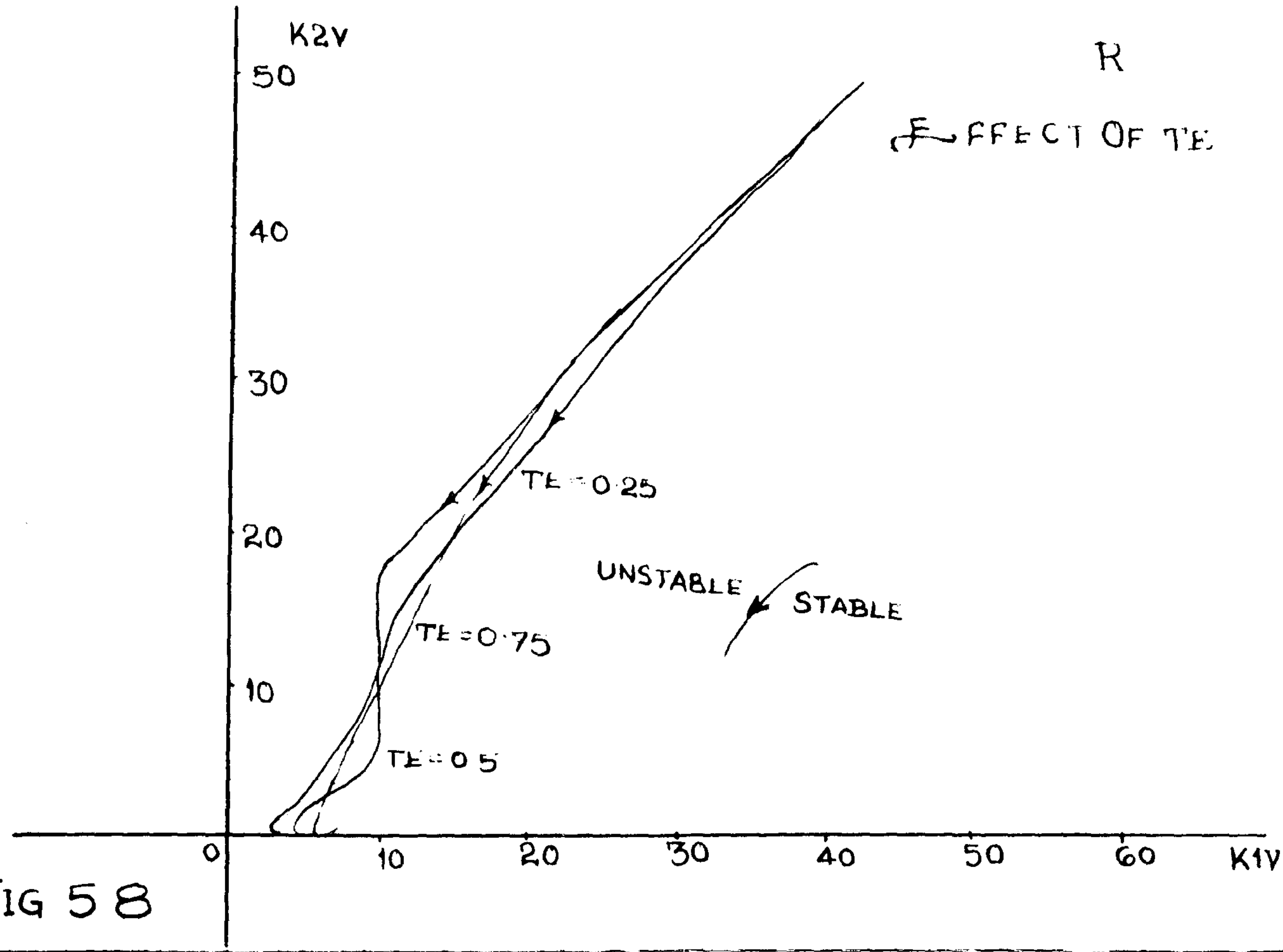
EFFECT OF XC
K2I
30
20
(a)
XC=0·05
UN
ST
XC=0·15
(b)
10
S.L
(a)
0
10
20
K1I
(b)
S.L
10

FIG 5 6



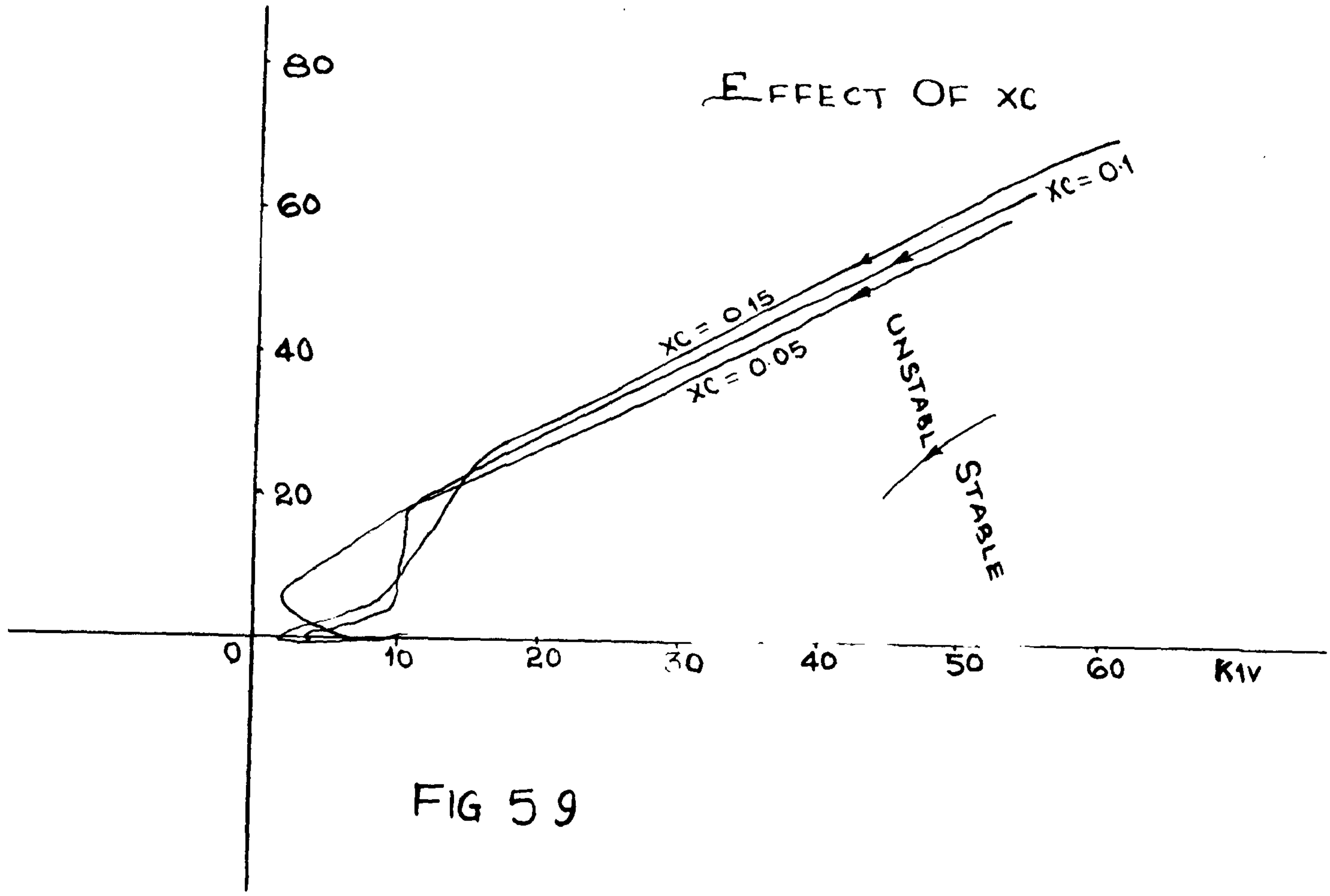
K2V
R
EFFECT OF K01
30
20
10
10
20
30
K1V
UNSTABLE
STABLE
K01 0.0
K01 0.5
K01 1.0

FIG 5 7



K2V
50
40
30
20
10
0
10
20
30
40
50
60
K1V
R
EFFECT OF TE
TE = 0·25
TE = 0·75
TE = 0 5
UNSTABLE
STABLE

FIG 58



80
60
40
20
0
10
20
30
40
50
60
K1V
EFFECT OF XC
XC = 0·1
XC = 0·15
XC = 0·05
UNSTABL
STABLE

FIG 59

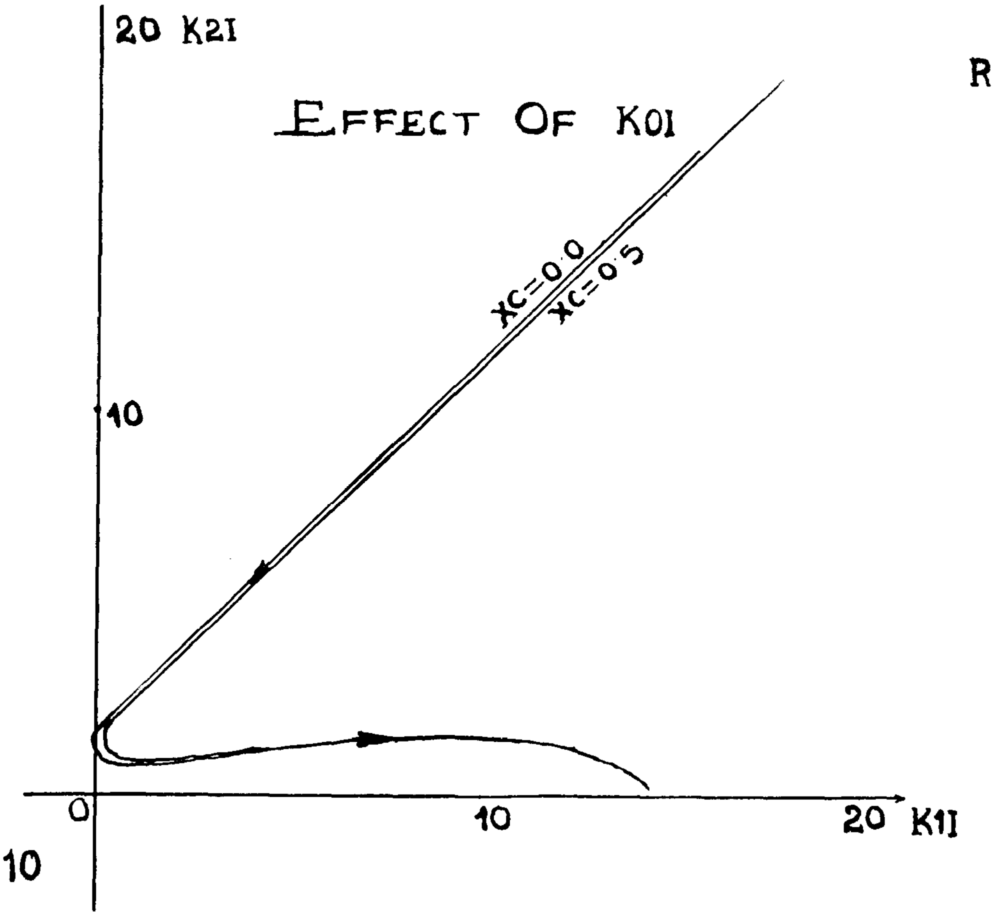


FIG 5·10

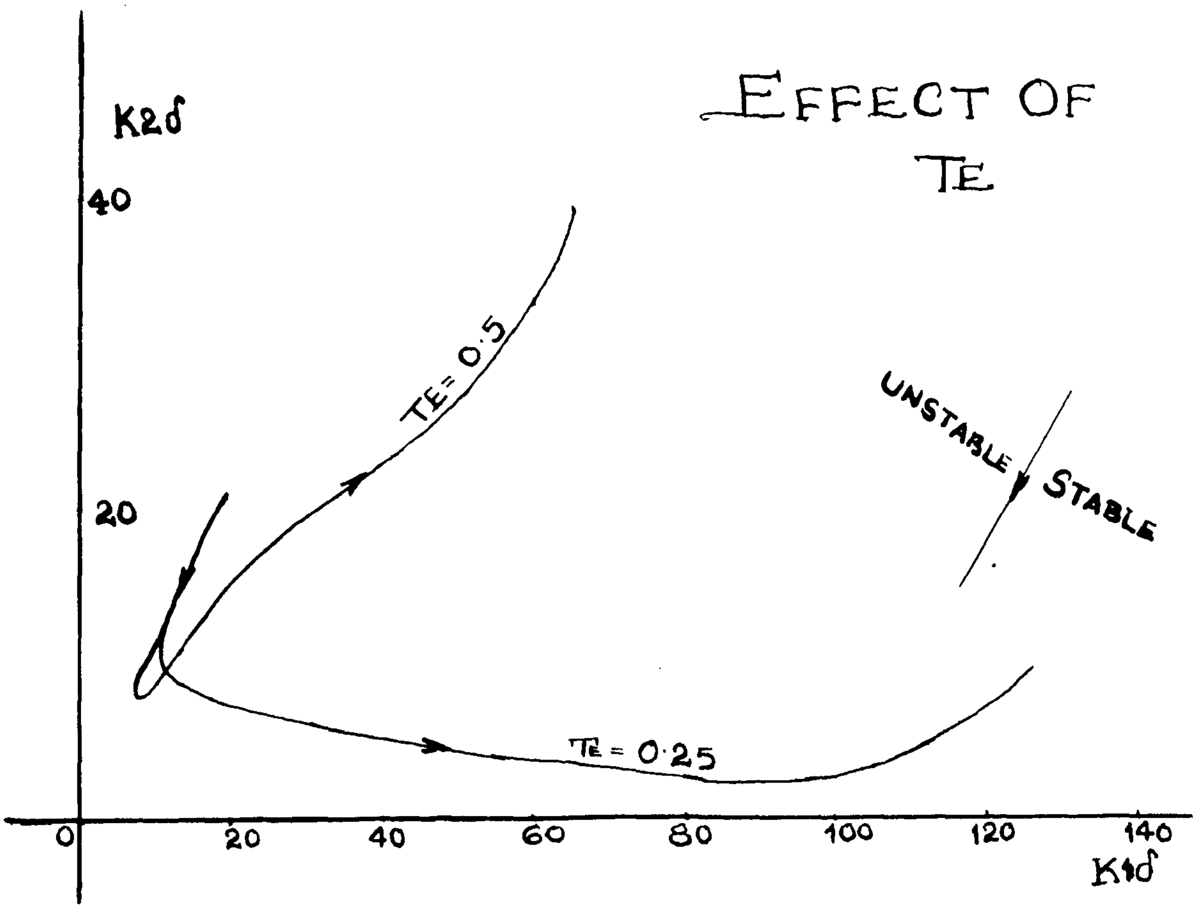


FIG 5·11

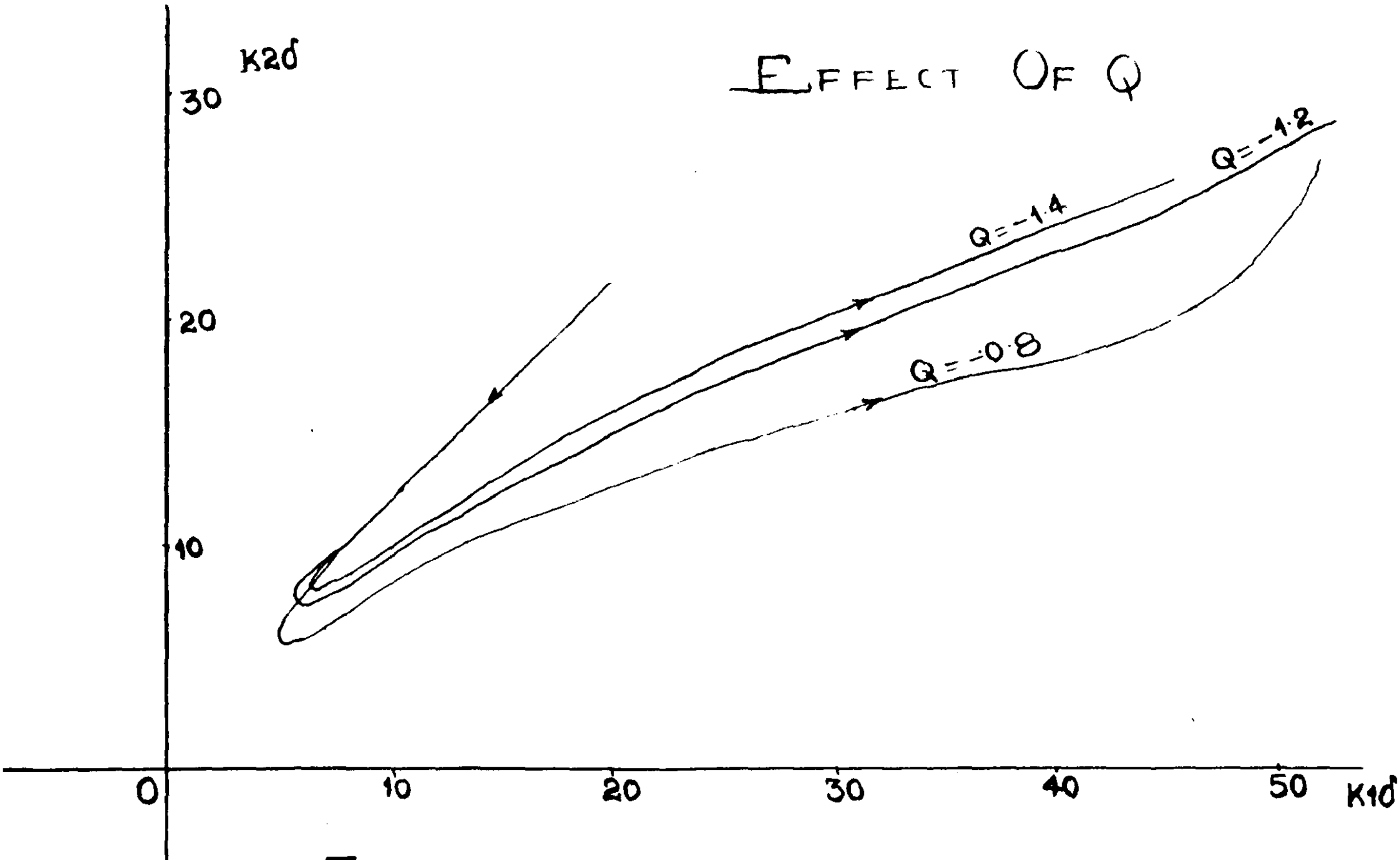


FIG 5.12

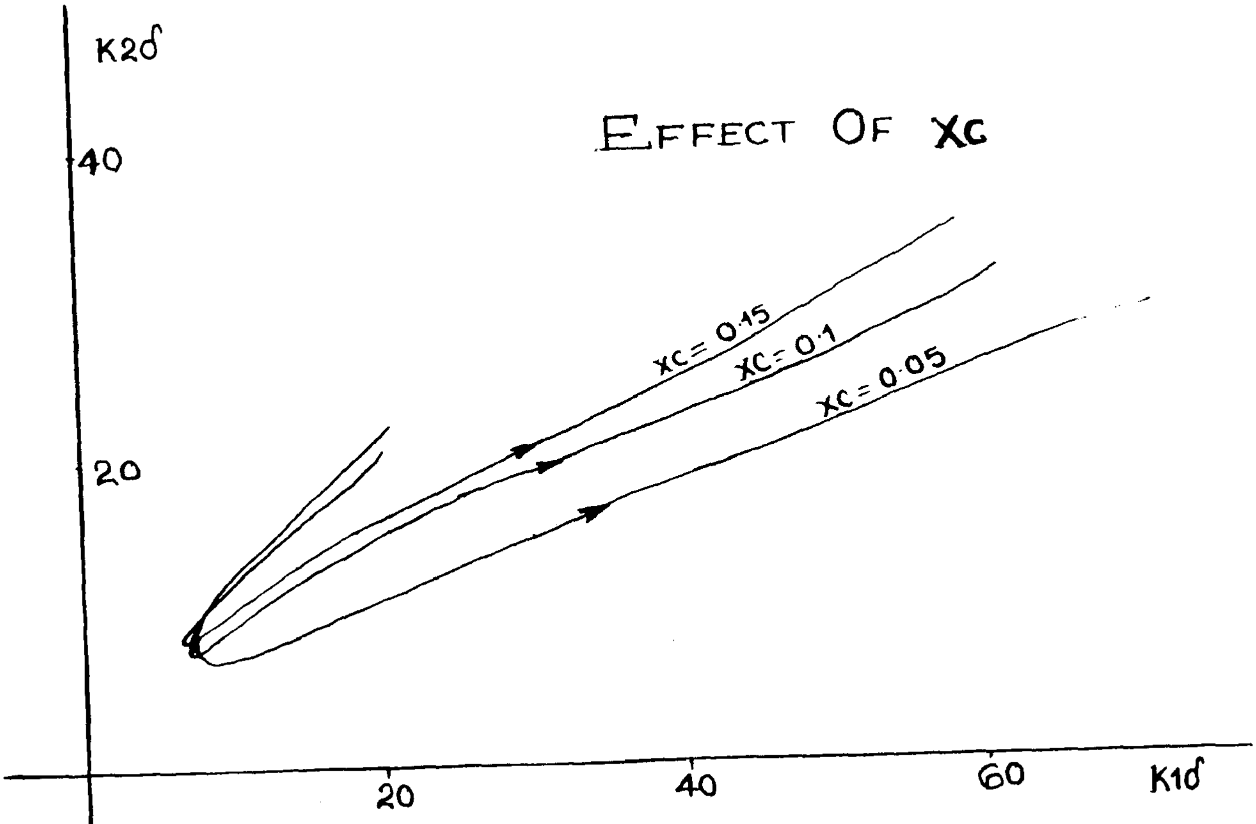


FIG 5 13

$$\therefore \quad K1I = \frac{-A.BKR + wBKR + w\ BKI \times C}{AB - CD}$$

$$K2I = \frac{-B \times wBKI + BKR \times D}{AB - CD}$$

Thus the expressions of first and second derivatives gain constants are found in term of σ and w. Now making σ constant and varying w from 0 to ∞ different values of derivatives gain constant are obtained. By varying the parameters (Q, X_e, δ, T_E and KOI) whose effect are sought to be studied in the plane of first and second derivative gain constant, different graphs have been plotted.

Calculation and Results

Calculation are carried out in the computer (TDC -312) and the results are plotted in fig. 5.1, 2.. etc. The computer programmes are given in the Appendix 2.

Discussion

1) Effect of Q

In general the effect of increase of Q is found to reduce the relative stability area obtained in the planes of K1I - K2I, K1V - K2V and K1δ - K2δ, meaning thereby that the quality of the transient response deteriorates with increase in Q (Fig.5.1, 5.3, 5.12).

ii) Effect of δ

Fig. 5.2 shows that increase in initial load angle δ continuously reduces the relative stability area in the plane of K1V - K2V Fig. F.3 shows that increase in δ to a certain critical value reduces the stability area to a minimum in the plane of K1I - K2I. Thus better transient performance can be obtained by setting the initial load gangle a small value (0° order) in general.

iii) Effect of X_c

Fig.5.6 and Fig.5.9 indicate an increase in the relative stability area with increase in X_c in the planes of K1I - K2I, and K1V - K2V. The region being smaller in the plane of K1I - K2I. This indicates improvement in the system transient performance with increase in X_c. In other wards there is greater flexibility in selection of K1I - K2I and K1V- K2V in case larger value of X_c is used.

Fig. 5.13 shows a reverse trend with increase in X_c in the plane of K1δ - K2δ. Thus adjustment K1δ - K2δ parameters within a limited area . For higher X_c selection of K1δ - K2δ parameters will pose a tedious problem to ensure a satisfactory transient response.

iv) Effect of T_E

Increase in T_E reduces the relative stability area obtained in the planes of K1I - K2I and K1δ - K2δ (Fig.5.5 and 5.11). The reduction being faster in the latter parameters plane. Effect of variation in T_E produces negligible change in the relative stability region obtained in the plane of K1V - K2V (Fig. 5.8). Thus if K1δ - K2δ are selected as flexible parameter then greater difficulty will be faced in their selection with increase in T_E so as to ensure a desired transient performance.

V) Effect of KOI

Fig. 5.7 shows that there is reduction in the relative stability region in the plane of K1V - K2V with increase in KOI whereas Fig.5.10 show in significant effect of variation of KOI in the region in the plane of K1I - K2I. Thus greater flexibility in parameter selection to ensure a prescribed transient response is possible in the case of K1I - K2I parameters.

CHAPTER - 6

CONCLUSIONS

The problem os parameter coordination of a " doubly excited synchronous machine" is studied by using D-decomposition technique. The study is made in the following planes

I K1I - K2I

II K1V - K2V

III K1δ - K2δ

The first and second derivative gain constants of voltage current and angle regulators are the parameters of interest.

The system studied is a doubly excited synchronous machine connected to infinite bus bar through transmission line. The lumped parameter R_L, X_L and X_c represent the distributed resistance, inductive reactance and capacitive reactance of the transmission line. The machine is fitted with VR on the d axis sensing the deviation in terminal voltage line current and their first and second time derivatives. The q axis rotor field is fed by an a.a.r. which senses the rotor angle δ and its first two time derivatives. Only one time lag each in the regulator circuits on the d- , and q- axis field circuits is incorporated. The Governor is of the 3-term type with two effective time lags.

Two separate studies have been done

I. Study for absolute steady-state stability

II. Study for relative stability to ensure a desired quantity (settling time) of the transient response.

The Graphs have been plotted for these two cases separately.

Following conclusions can be drawn from the study of the graphs.

In order to stabily operate the system at highed leading KVAR, with a certain specified settling time of the transient response larger flexibility in parameter co-ordination can be obained by adjusting the first two derivative angle regulator gain constants i.e. K1δ - K2δ. The least flexible parameters appear to be K1I - K2I.

A smaller initial load angle δ, (nearly equal to zero degree) may be selected to ensure stable operation with a desired transient response.

In order to operate the system with larger series capacitance X_c better performance can be obtained by, coordination of K1I - K2I parameters of the AVR.

For satisfactory operation with higher values of voltage regulator time constants greater flexibility appear to exist in selecting K1V - K2V as coordinating parameters. Sofar the stability point of view is concerned proportionate gain constant of current regulator (KOI) and speed gain constant of the governor do not play any significant role.

Scope of further study

1. In the present study the angle between the two field windings has been taken as 90° whereas it can be taken any general angle α and then this angle can be maximised.

2. The relative effectiveness of the regulators can be studied by comparing the integral-type performance index to ensure better transient response.

3. More rigorous analysis can be done without making certain simplifying assumptions such as, neglect of transformer voltage terms, damper circuit dynamics and considering distributed transmission line parameters instead of lumped parameters.

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Symbols used in Computer Programme

δ = DL, xd = XD, xq = XQ, xd' = XDD, xq' = XQD,
Td' = TDD, Tdo' = TDO, Tq' = TQD, Tqo' = TQO, KOV = VZ,
K1V = VO, K2V = VT, Te = TE, KOI = CZ, K1I = CO,
K2I = CT, KOδ = DZ, K1δ = DO, K2δ = DT, Kgo = GZ,
Kg1 = GO, Kg2 = GT, Tg1 + Tg2 = TGO, Tg1 + Tg2 + TGT,
I = EI, do = SHD, qo = SHQ, M = AM.

Numerical values of the constants of the system

Rl = 0.05, XL = 0.3, XC = 0.1, DL = 0.523, R = 0.01,
xd = 1.2, xq = 0.8, xd' = 0.29, xq' = 0.47, Td' = 0.77,
Tdo' = 3.2, Tq' = 1.9, Tqo' = 3.2, KOV = 10.0, K1V = 1.0,
K2V = 0.5, Te1 = Te2 = 0.5, KOI = 0.0, K1I = 0.0, K2I = 0.0,
KOδ = 5.0, K1δ = 0.5, K2δ = 0.05, Kgo = 0.0, Kg1 = 0.05,
Kg2 = 0.05, Tg1 = 0.5, Tg2 = 0.1, M = 0.0192, Pd = 0.0032,
P = 1.0.

APPENDIX 1

```
  D-PARTITIONING IN PLANE OF K1V-L2V
DL=0.523$RL=0.05$XL=0.3$Q=-1.4$R=0.01$XD=1.2$XQ=0.8$XDD=0.29$XQD=0.47$TD=0.77
TDO=3.2$TQ=1.9$TQO=3.2$VZ=10.0$VO=0.0$VT=0.0$XC=0.1$CZ=0.0$DZ=5.0$DO=0.5
DT=0.05$CO=0.0$CT=0.0
GZ=0.0$GO=0.05$GT=0.05$TGO=0.6$TGT=0.05$AM=0.0192$PD=0.0032$P=1.0
READ  TE
WRITE 5,TD,TDO,TQ,TQO,VZ,TE,CZ,CO,CT,DZ,DO,DT,GZ,GO,GT,TGO,TGT,AM,PD,P
5@FORMAT(/,E,E,E,E,E) $ A=SINF(DL) $ B=COSF(DL) $ EID=P*A+Q*B $ EIQ=P*B-Q*A
EI=SQTF(EID*EID+EIQ*EIQ) $ VTI=1.+(EID*RL-EIQ*(XL-XC))*A+(EIQ*RL+EID*(XL-XC))*B
VTO=(EIQ*(XL-XC)-EID*RL)*B+(EIQ*RL+EID*(XL-XC))*A $ VT=SQTF(VTI*VTI+VTO*VTO)
DLTB=ATNF(VTO/VTI) $ VTD=VT*SINF(DL-DLTB) $ VTQ=VT*COSF(DL-DLTB) $ SID=VTQ+R*EIQ
SIQ=-VTD-R*EID $ SD=VTD/VT $ SQ=VTQ/VT $ CD=EID/EI $ CQ=EIQ/EI
P1=RL*SD+(XL-XC)*SQ $ P2=(XL-XC)*SD-RL*SQ
A32=EIQ*(XL-XC)-SIQ+EID*(R+RL) $ A33=SID+(R+RL)*EIQ-EID*(XL-XC) $ 2@READ W
WS=W*W $ A1=1.+WS*TDO*TDO $ A2=1.+WS*TQO*TQO $ A3=1.+WS*TE*TE $ A4=1.-WS*TGT
A5=WS*TGO*TGO $ A5=A4*A4+A5 $ A6=GZ-GT*WS $ GDR=1.0/A1 $ GDI=-GDR*TDO
GQR=1.0/A2$ GQI=-GQR*TQO $ DGR=(DZ-WS*(DT-TE*DO))/A3 $ DGI=(DO-TE*(DZ-WS*DT))/A3
GQDR=GQR*DGR-WS*GQI*DGI $ GQDI=GQR*DGI+GQI*DGR $ AR11=B-WS*XL*EID+GQDR
XDR=XD*(1.+WS*TD*TDO)/A1 $ XDI=-XD*(TDO-TD)/A1
XQR=XQ*(1.+WS*TQ*TQO)/A2 $ XQI=-XQ*(TQO-TQ)/A2
AI11=RL*EID-2.*XL*EIQ+A-VTD+SIQ+GQDI $ AR13=-XQR-XL+XC $ AI13=-XQI
FR2=-A-EIQ*XL*WS $ FI2=B-VTQ+RL*EIQ+2.*EID*XL $ FR1=B-EID*XL*WS
FI1=A-VTD+RL*EID-2.*XL*EIQ $ AFR1=SD*FR1+SQ*FR2 $ AFI1=SD*FI1+SQ*FI2
GGR=(A4*A6+WS*GO*TGO)/A5 $ GGI=(GO*A4-TGO*A6)/A5$ AR31=GGR+EIQ*FR2+EID*FR1-AM*WS
AI31=PD+GGI+EIQ*FI2+EID*FI1 $ SR1=(R+RL)*A33-A32*AR13 $ SI1=-A32*AI13
SR2=A33*AR11-(AR13*AR31-WS*AI13*AI31) $ SI2=A33*AI11-AR13*AI31-AI13*AR31
SR3=A32*AR11-(R+RL)*AR31 $ SI3=A32*AI11-(R+RL)*AI31
AKR1=-AFR1*SR1+WS*AFI1*SI1+P1*SR2+P2*SR3
AKI1=-AFR1*SI1-AFI1*SR1+P1*SI2+P2*SI3  $ AKR2=-CD*SR2+CQ*SR3
AKI2=-CD*SI2+CQ*SI3 $ AKR3=-FR2*SR1-WS*SI1*(SID-FI2)+(XDR+XL-XC)*SR2
AKR3=AKR3+(-WS*SI2*XDI)-(R+RL)*SR3 $ AKI3=SR1*(SID-FI2)-SI1*FR2+SR2*XDI
AKI3=AKI3+SI2*(XDR+XL-XC)-(R+RL)*SI3 $ GDER=(GDR-WS*TE*GDI)/A3
GDEI=(GDI-TE*GDR)/A3 $ GKR1=AKR1*GDER-WS*AKI1*GDEI $ GKI1=AKR1*GDEI+AKI1*GDER
GKR2=AKR2*GDER-WS*AKI2*GDEI $ GKI2=AKR2*GDEI+AKI2*GDER
BKR=GKR2*(CZ-WS*CT)-WS*GKI2*CO+VZ*GKR1+AKR3 $ BKI=GKR2*CO+GKI2*(CZ-WS*CT)
BKI=BKI+VZ*GKI1+AKI3 $ DEN=GKR1*GKR1+WS*GKI1*GKI1 $ IF(DEN)1,2,1
1@VO=(BKR*GKI1-BKI*GKR1)/DEN $ VT=(BKI*GKI1+(BKR*GKR1)/WS)/DEN
WRITE 3,W,DEN,VO,VT $ 3@FORMAT(/,E,E,E,E) $ GO TO 2 $ STOP $ END
```

D-PARTITIONING IN PLANE OF K1I-K2I

```
DL=0.523$RL=0.05$XL=0.3$Q=-1.4$R=0.01$XD=1.2$XQ=0.8$XDD=0.29$XQD=0.47$TD=0.77
CZ=0.0
TDO=3.2$TQ=1.9$TQO=3.2$VZ=10.0$VO=0.0$VT=0.0$XC=0.1$TE=0.5$DZ=5.0$DO=0.5
DT=0.05$GZ=0.0$GO=0.05$GT=0.05$TGO=0.6$TGT=0.05$AM=0.0192$PD=0.0032$P=1.0
WRITE5,DL,RL,XL,XC,R,XD,XQ,XDD,XQD,TD,TDO,TQ,TQO,VZ,VO,VT,TE,CZ
WRITE5,DZ,DO,DT,GZ,GO,GT,TGO,TGT,AM,PD,P,Q   $ 5@FORMAT(/,E,E,E,E,E)
                          A=SINF(DL) $ B=COSF(DL) $ EID=P*A+Q*B $ EIQ=P*B-Q*A
EI=SQTF(EID*EID+EIQ*EIQ) $ VTI=1.+(EID*RL-EIQ*(XL-XC))*A+(EIQ*RL+EID*(XL-XC))*B
VTO=(EIQ*(XL-XC)-EID*RL)*B+(EIQ*RL+EID*(XL-XC))*A $ VT=SQTF(VTI*VTI+VTO*VTO)
DLTB=ATNF(VTO/VTI) $ VTD=VT*SINF(DL-DLTB) $ VTQ=VT*COSF(DL-DLTB) $ SID=VTQ+R*EIQ
SIQ=-VTD-R*EID $ SD=VTD/VT $ SQ=VTQ/VT $ CD=EID/EI $ CQ=EIQ/EI
P1=RL*SD+(XL-XC)*SQ $ P2=(XL-XC)*SD-RL*SQ
A32=EIQ*(XL-XC)-SIQ+EID*(R+RL) $ A33=SID+(R+RL)*EIQ-EID*(XL-XC) $ 2@READ W
WS=W*W $ A1=1.+WS*TDO*TDO $ A2=1.+WS*TQO*TQO $ A3=1.+WS*TE*TE $ A4=1.-WS*TGT
A5=WS*TGO*TGO $ A5=A4*A4+A5 $ A6=GZ-GT*WS $ GDR=1.0/A1 $ GDI=-GDR*TDO
GQR=1.0/A2$ GQI=-GQR*TQO $ DGR=(DZ-WS*(DT-TE*DO))/A3 $ DGI=(DO-TE*(DZ-WS*DT))/A3
GQDR=GQR*DGR-WS*GQI*DGI $ GQDI=GQR*DGI+GQI*DGR $ AR11=B-WS*XL*EID+GQDR
XDR=XD*(1.+WS*TD*TDO)/A1 $ XDI=-XD*(TDO-TD)/A1
XQR=XQ*(1.+WS*TQ*TQO)/A2 $ XQI=-XQ*(TQO-TQ)/A2
AI11=RL*EID-2.*XL*EIQ+A-VTD+SIQ+GQDI $ AR13=-XQR-XL+XC $ AI13=-XQI
FR2=-A-EIQ+XL*WS $ FI2=B-VTQ+RL*EIQ+2.*EID*XL $ FR1=B-EID*XL*WS
FI1=A-VTD+RL*EID-2.*XL*EIQ $ AFR1=SD*FR1+SQ*FR2 $ AFI1=SD*FI1+SQ*FI2
GGR=(A4*A6+WS*GO*TGO)/A5 $ GGI=(GO*A4-TGO*A6)/A5$ AR31=GGR+EIQ*FR2+EID*FR1-AM*WS
AI31=PD+GGI+EIQ*FI2+EID*FI1 $ SR1=(R+RL)*A33-A32*AR13 $ SI1=-A32*AI13
SR2=A33*AR11-(AR13*AR31-WS*AI13*AI31) $ SI2=A33*AI11-AR13*AI31-AI13*AR31
SR3=A32*AR11-(R+RL)*AR31 $ SI3=A32*AI11-(R+RL)*AI31
AKR1=-AFR1*SR1+WS*AFI1*SI1+P1*SR2+P2*SR3
AKI1=-AFR1*SI1-AFI1*SR1+P1*SI2+P2*SI3  $ AKR2=-CD*SR2+CQ*SR3
AKI2=-CD*SI2+CQ*SI3 $ AKR3=-FR2*SR1-WS*SI1*(SID-FI2)+(XDR+XL-XC)*SR2
AKR3=AKR3+(-WS*SI2*XDI)-(R+RL)*SR3 $ AKI3=SR1*(SID-FI2)-SI1*FR2+SR2*XDI
AKI3=AKI3+SI2*(XDR+XL-XC)-(R+RL)*SI3 $ GDER=(GDR-WS*TE*GDI)/A3
GDEI=(GDI-TE*GDR)/A3 $ GKR1=AKR1*GDER-WS*AKI1*GDEI $ GKI1=AKR1*GDEI+AKI1*GDER
GKR2=AKR2*GDER-WS*AKI2*GDEI $ GKI2=AKR2*GDEI+AKI2*GDER
BKR=GKR1*(VZ-WS*VT)-WS*GKI1*VO+CZ*GKR2+AKR3 $ BKI=GKR1*VO+GKI1*(VZ-WS*VT)
BKI=BKI+CZ*GKI2+AKI3 $ DEN=GKR2*GKR2+WS*GKI2*GKI2 $ IF(DEN)1,2,1
1@CO=(BKR*GKI2-BKI*GKR2)/DEN $ CT=(BKI*GKI2+(BKR*GKR2/WS))/DEN
WRITE 3,W,DEN,CO,CT $ 3@FORMAT(/,E,E,E,E) $ GO TO 2 $ STOP $ END
```

```
D-PARTITIONG IN PLANE OF K1D-K2D
DL=0.523$RL=0.05$XL=0.3$Q=-1.4$R=0.01$XD=1.2$XQ=0.8$XDD=0.29$XQD=0.47$TD=0.77
TDO=3.2$TQ=1.9$TQO=3.2$VZ=10.0$XC=0.1
VO=1.0$VT=0.5$        CO=0.0$CT=0.0
DZ=5.0$GZ=0.0$GO=0.05$GT=0.05$TGO=0.6$TGT=0.05$AM=0.0192$PD=0.0032$P=1.0
READ  TE
A=SINF(DL) $ B=COSF(DL) $ EID=P*A+Q*B $ EIQ=P*B-Q*A $ EI=SQTF(EID*EID+EIQ*EIQ
VTI=1.+(EID*RL-EIQ*(XL-XC))*A+(EIG*RL+EID*(XL-XC))*B
VTO=(EIQ*(XL-XC)-EID*RL)*B+(EIQ*RL+EID*(XL-XC))*A $ VT=SQTF(VTI*VTI+VTO*VTO)
SIQ=-R*EID-VTD $ SD=VTD/VT $ SQ=VTQ/VT $ CD=EID/EI $ CQ=EIQ/EI
A32=EIQ*(XL-XC)-SIQ+EID*(R+RL) $ A33=SID+(R+RL)*EIQ-EID*(XL-XC) $ 1 READ W
DLTB=ATNF(VTO/VTI) $ VTD=VT*SINF(DL-DLTB) $ VTQ=VT*COSF(DL-DLTB) $ SID=VTQ+R*(
WS=W*W $ A1=1.+WS*TDO*TDO $ A2=1.+WS*TQO*TQO $ A3=1.+WS*TE*TE$A4=1.-WS*TGT
A5=WS*TGO*TGO $ A5=A4*A4+A5 $ GDR=1.0/A1 $ GDI=-GDR*TDO $ GQR=1.0/A2
GQI=-GQR*TQO $ GVR=(VZ-WS*(VT-TE*VO))/A3 $ GVI=(VO-TE*(VZ-WS*VT))/A3
GIR=(CZ-WS*(CT-TE*CO))/A3 $ GII=(CO-TE*(CZ-WS*CT))/A3 $ F1R=B-XL*EID*WS
F1I=A-VTD+RL*EID-2.*XL*EIQ $ F3R=F1R $ F3I=F1I+SIQ $ F2R=-A-EIQ*XL*WS
 F2I=B-VTQ+RL*EIQ+2.*XL*EID $ A6=GZ-GT*WS $ GGR=(A6*A4+WS*GO*TGO)/A5
GGI=(GO*A4-TGO*A6)/A5 $ A31R=GGR+F2R*EIQ+F1R*EID-AM*WS
A31I=PD+GGI+EIQ*F2I+EID*F1I $ XDR=XD*(1.+WS*TD*TDO)/A1 $ XDI=-XD*(TDO-TD)/A1
XQR=XQ*(1.+WS*TQ*TQO)/A2 $ XQI=-XQ*(TQO-TQ)/A2 $ GDVR=GDR*GVR-WS*GDI*GVI
GDVI=GDR*GVI+GDI*GVR $ GDIR=GDR*GIR-WS*GDI*GII $ GDII=GDR*GII+GDI*GIR
AR=GDVR*F1R-WS*GDVI*F1I $ AI=GDVR*F1I+GDVI*F1R $ BR=GDVR*F2R-WS*GDVI*F2I
BI=GDVR*F2I+GDVI*F2R $ A21R=-(SD*AR+SQ*BR+F2R) $ A21I=SID-SD*AI-SQ*BI-F2I
P1=RL*SD+SQ*(XL-XC) $ P2=SD*(XL-XC)-RL*SQ $ A22I=-XDI+CD*GDII-P1*GDVI
A22R=-XDR+CD*GDIR-P1*GDVR-(XL-XC) $ A23R=CQ*GDIR-R-RL+P2*GDVR
A23I=CQ*GDII+P2*GDVI $ AK1R=A33*A22R-A32*A23R $ AK1I=A33*A22I-A32*A23I
A13R=-XQR-XL+XC $ A13I=-XQI $ AA=(R+RL)*A23R-A13R*A22R+WS*A13I*A22I
BB=(R+RL)*A23I-A13I*A22R-A13R*A22I $ AK2R=AA*A31R-WS*BB*A31I-(R+RL)*A33*A21R
AK2R=AK2R+A32*(A13R*A21R-WS*A13I*A21I) $ AK2I=AA*A31I+BB*A31R-(R+RL)*A33*A21I
AK2I=AK2I+A32*(A13R*A21I+A13I*A21R) $ X=AK1R*GQR-WS*AK1I*GQI
X=(X+WS*TE*(AK1R*GQI+AK1I*GQR))/A3 $ Y=AK1R*GQI+AK1I*GQR-TE*(AK1R*GQR)
Y=(Y+TE*WS*AK1I*GQI)/A3 $ FKR=F3R*AK1R-WS*F3I*AK1I
FKI=F3R*AK1I+F3I*AK1R $ DEN=X*X+Y*Y*WS $ IF(DEN)2,1,2 $ 2 ADO=DZ*X+AK2R+FKR
ADT=Y*DZ+AK2I+FKI $ DO=(Y*ADO-X*ADT)/DEN $ DT=(Y*ADT+(X*ADO)/WS)/DEN
WRITE 3,W,DEN,DO,DT   $ 3 FORMAT(/,E,E,E,E) $ GO TO 1 $ STOP $ END
```

```
STABILITY CHECK ...MIKHAILOV CRITERION
DL=0.523$RL=0.05$XL=0.3$XC=0.1$R=0.01$XD=1.2$XQ=0.8$XDD=0.29$XQD=0.47$TD=0.77
TDO=3.2$TQ=1.9$TQO=3.2$TE=0.5$GZ=0.0$GO=0.05$GT=0.05$TGO=0.6$TGT=0.05$AM=0.0192
PD=0.0032$P=1.0
READ  VZ,VO,VT,CZ,CO,CT,DZ,DO,DT,G
WRITE5,DL,RL,XL,XC,R,XD,XQ,XDD,XQD,TD,TDO,TQ,TQO,VZ,VO,VT,TE
WRITE5,CZ,CO,CT,DZ,DO,DT,GZ,GO,GT,TGO,TGT,AM,PD,P,Q $ 5@FORMAT(/,E,E,E,E,E)
                              A=SINF(DL) $ B=COSF(DL) $ EID=P*A+Q*B $ EIQ=P*B-Q*A
EI=SQTF(EID*EID+EIQ*EIQ) $ VTI=1.+(EID*RL-EIQ*(XL-XC))*A+(EIQ*RL+EID*(XL-XC))*B
VTO=(EIQ*(XL-XC)-EID*RL)*B+(EIQ*RL+EID*(XL-XC))*A $ VT=SQTF(VTI*VTI+VTO*VTO)
DLTB=ATNF(VTO/VTI) $ VTD=VT*SINF(DL-DLTB) $ VTQ=VT*COSF(DL-DLTB) $ SID=VTQ+R*EI
SIQ=-VTD-R*EID $ SD=VTD/VT $ SQ=VTQ/VT $ CD=EID/EI $ CQ=EIQ/EI
P1=RL*SD+(XL-XC)*SQ $ P2=(XL-XC)*SD-RL*SQ
A32=EIQ*(XL-XC)-SIQ+EID*(R+RL) $ A33=SID+(R+RL)*EIQ-EID*(XL-XC) $ 2@READ W
WS=W*W $ A1=1.+WS*TDO*TDO $ A2=1.+WS*TQO*TQO $ A3=1.+WS*TE*TE $ A4=1.-WS*TGT
A5=WS*TGO*TGO $ A5=A4*A4+A5 $ A6=GZ-GT*WS $ GDR=1.0/A1 $ GDI=-GDR*TDO
GQR=1.0/A2$ GQI=-GQR*TQO $ DGR=(DZ-WS*(DT-TE*DO))/A3 $ DGI=(DO-TE*(DZ-WS*DT))/A
GQDR=GQR*DGR-WS*GQI*DGI $ GQDI=GQR*DGI+GQI*DGR $ AR11=B-WS*XL*EID+GQDR
XDR=XD*(1.+WS*TD*TDO)/A1 $ XDI=-XD*(TDO-TD)/A1
XQR=XQ*(1.+WS*TQ*TQO)/A2 $ XQI=-XQ*(TQO-TQ)/A2
AI11=RL*EID-2.*XL*EIQ+A-VTD+SIQ+GQDI $ AR13=-XQR-XL+XC $ AI13=-XQI
FR2=-A-EIQ*XL*WS $ FI2=B-VTQ+RL*EIQ+2.*EID*XL $ FR1=B-EID*XL*WS
FI1=A-VTD+RL*EID-2.*XL*EIQ $ AFR1=SD*FR1+SQ*FR2 $ AFI1=SD*FI1+SQ*FI2
GGR=(A4*A6+WS*GO*TGO)/A5 $ GGI=(GO*A4-TGO*A6)/A5$ AR31=GGR+EIQ*FR2+EID*FR1-AM*W
AI31=PD+GGI+EIQ*FI2+EID*FI1 $ SR1=(R+RL)*A33-A32*AR13 $ SI1=-A32*AI13
SR2=A33*AR11-(AR13*AR31-WS*AI13*AI31) $ SI2=A33*AI11-AR13*AI31-AI13*AR31
SR3=A32*AR11-(R+RL)*AR31 $ SI3=A32*AI11-(R+RL)*AI31
AKR1=-AFR1*SR1+WS*AFI1*SI1+P1*SR2+P2*SR3
AKI1=-AFR1*SI1-AFI1*SR1+P1*SI2+P2*SI3  $ AKR2=-CD*SR2+CQ*SR3
AKI2=-CD*SI2+CQ*SI3 $ AKR3=-FR2*SR1-WS*SI1*(SID-FI2)+(XDR+XL-XC)*SR2
AKR3=AKR3+(-WS*SI2*XDI)-(R+RL)*SR3 $ AKI3=SR1*(SID-FI2)-SI1*FR2+SR2*XDI
AKI3=AKI3+SI2*(XDR+XL-XC)-(R+RL)*SI3 $ GDER=(GDR-WS*TE*GDI)/A3
GDEI=(GDI-TE*GDR)/A3 $ GKR1=AKR1*GDER-WS*AKI1*GDEI $ GKI1=AKR1*GDEI+AKI1*GDER
GKR2=AKR2*GDER-WS*AKI2*GDEI $ GKI2=AKR2*GDEI+AKI2*GDER
BKR=GKR2*(CZ-WS*CT)-WS*GKI2*CO+VZ*GKR1+AKR3
BKI=GKR2*CO+GKI2*(CZ-WS*CT)+VZ*GKI1+AKI3
U=BKR-WS*(VT*GKR1+VO*GKI1) $ V=BKI+VO*GKR1-WS*VT*GKI1 $ C1=1.-WS*TDO*TQO
C2=1.-WS*TE*TE $ D1=TDO+TQO $ D2=2.*TE $ D3=TGO $ AC1=C1*C2-WS*D1*D2
AC2=C1*D2+D1*C2 $ DR=AC1*A4-WS*D3*AC2 $ DI=A4*AC2+D3*AC1$ ARR=U*DR-WS*V*DI
         AII=W*(U*DI+V*DR) $  WRITE 5,W,ARR,AII      $ GO TO 2 $ STOP $ END
```

APPENDIX 2.

```
  D-PARTITIONING IN PLANE OF K1V-K2V
DL=0.523$RL=0.05$XL=0.3$S=-.5 $R=0.01$XD=1.2$XQ=0.8$XDD=0.29$XQD=0.47$TD=0.77
TDO=3.2$TQ=1.9$TQO=3.2$VZ=10.0$CO=0.0$CT=0.0$XC=0.1$CZ=0.0$DZ=5.0$DO=0.5
DT=0.05$GZ=0.0$GO=0.05$GT=0.05$TGO=0.6$TGT=0.05$AM=0.0192$PD=0.0032$P=1.0$Q=-1.0
READ TE$SS=S*S
                        A=SINF(DL) $ B=COSF(DL) $ EID=P*A+Q*B $ EIQ=P*B-Q*A
EI=SQTF(EID*EID+EIQ*EIQ) $ VTI=1.+(EID*RL-EIQ*(XL-XC))*A+(EIQ*RL+EID*(XL-XC))*B
VTO=(EIQ*(XL-XC)-EID*RL)*B+(EIQ*RL+EID*(XL-XC))*A $ VT=SQTF(VTI*VTI+VTO*VTO)
DLTB=ATNF(VTO/VTI) $ VTD=VT*SINF(DL-DLTB) $ VTQ=VT*COSF(DL-DLTB) $ SID=VTQ+R*EIQ
SIQ=-VTD-R*EID $ SD=VTD/VT $ SQ=VTQ/VT $ CD=EID/EI $ CQ=EIQ/EI
P1=RL*SD+(XL-XC)*SQ $ P2=(XL-XC)*SD-RL*SQ
A32=EIQ*(XL-XC)-SIQ+EID*(R+RL) $ A33=SID+(R+RL)*EIQ-EID*(XL-XC) $ 2@READ W
WS=W*W$A1=(1.+TDO*S)$A1=A1*A1+WS*TDO*TDO$A2=1.+TQO*S
GQI=-TQO/A2$A3=1.+TE*S$A3=A3*A3+WS*TE*TE
A2=A2*A2+WS*TQO*TQO$GDR=(1.+TDO*S)/A1$GDI=-TDO/A1$GQR=(1.+TQO*S)/A2
C=DZ+S*DO+SS*DT-WS*DT$D=DO+2.*S*DT
DGR=(C*(1.+S*TE)+WS*TE*D)/A3$DGI=(D*(1.+S*TE)-TE*C)/A3
GQDR=GQR*DGR-WS*GQI*DGI$GQDI=GQR*DGI+GQI*DGR
C=RL*EID-2.*XL*EIQ+A-VTD+SIQ$D=XL*EID
AR31=AM*(SS-WS)+PD*S+GGR+EIQ*FR2+EID*FR1$AI31=2.*S*AM+PD+GGI+EIQ*FI2+EID*FI1
AR11=B+(SS-WS)*D+S*C+GQDR$XDR=XD*((1.+S*TD)*(1.+S*TDO)+WS*TD*TDO)/A1
XDI=XD*(TD*(1.+S*TDO)-TDO*(1.+S*TD))/A1
XQR=XQ*((1.+S*TQ)*(1.+S*TQO)+WS*TQ*TQO)/A2
XQI=XQ*(TQ*(1.+S*TQO)-TQO*(1.+S*TQ))/A2$AI11=2.*S*D+C+GQDI
AR13=-XQR-XL+XC$AI13=-XQI
C=B+RL*EIQ+2.*EID*XL-VTQ$D=XL*EIQ
FR2=-A+S*C+(SS-WS)*D$FI2=C+2.*S*D
C=RL*EID-VTD+A-2.*XL*EIQ$D=XL*EID$FR1=B+S*C+(SS-WS)*D$FI1=C+2.*S*D
AFR1=SD*FR1+SQ*FR2$AFI1=SD*FI1+SQ*FI2
AG=GZ+S*GO+(SS-WS)*GT$BG=GO+2.*S*GT$C=1.+S*TGO+(SS-WS)*TGT$D=TGO+2.*S*TGT
GGR=(AG*C+W*BG*D)/(C*C+D*D)$GGI=(BG*C-D*AG)/(C*C+D*D)
SR1=(R+RL)*A33-A32*AR13$SI1=-A32*AI13
SR2=A33*AR11-(AR13*AR31-WS*AI13*AI31)$SI2=A33*AI11-AR13*AI31*AI13*AR31
SR3=A32*AR11-(R+RL)*AR31$SI3=A32*AI11-(R+RL)*AI31
AKR1=-AFR1*SR1+WS*AFI1*SI1+P1*SR2+P2*SR3$AKI1=-AFR1*SI1-AFI1*SR1+P1*SI2+P2*SI3
AKR2=-CD*SR2+CQ*SR3$AKI2=-CD*SI2+CQ*SI3
AKR3=SID*(SR1*S-WS*SI1)-(FR2*SR1-WS*FI2*SI1)
AKR3=AKR3+(XDR*SR2-WSJXDI*SI2+(XL-XC)*SR2)-(R+RL)*SR3
AKI3=SID*(SR1+S*SI1)-(FR2*SI1+FI2*SR1)
AKI3=AKI3+(XDR*SI2+XDI*SR2+(XL-XC)*SI2)-(R+RL)*SI3
GDER=(GDR*(1.+S*TE)+WS*GDI*TE)/A3$GDEI=((1.+S*TE)*GDI-TE*GDR)/A3
GKR1=AKR1*GDER-WS*AKI1*GDEI$GKI1=AKR1*GDEI+AKI1*GDER
GKR2=AKR2*GDER-WS*AKI2*GDEI$GKI2=AKR2*GDEI+AKI2*GDER
AG=CZ+S*CO+(SS-WS)*CT$BG=CO+2.*S*CT
BKR=GKR2*AG-WS*GKI2*BG+GKR1*VZ+AKR3$BKI=AG*GKI2+GKR2*BG+GKI1*VZ+AKI3
AG=(SS-WS)*W*GKI1+2.*S*W*GKR1$BG=S*GKR1-WS*GKI1
C=(SS-WS)*GKR1-WS*GKI1*2.*S$D=S*W*GKI1+W*GKR1$DEN=AG*BG-C*D
IF(DEN)1,2,1$ 1@VO=(-AG*BKR+W*BKI*C)/DEN$VT=(-BG*W*BKI+BKR*D)/DEN
WRITE3,W,DEN,VO,VT$ 3@FORMAT(/,E,E,E,E)$GO TO2$STOP$END
```

```
  D-PARTITIONING IN PLANE OF K1I-K2I
DL=0.523$RL=0.05$XL=0.3$S=-.5 $R=0.01$XD=1.2$XQ=0.8$XDD=0.29$XQD=0.47$TD=0.77
TDO=3.2$TQ=1.9$TQO=3.2$VZ=10.0$VO=0.0$VT=0.0$XC=0.1$CZ=0.0$DZ=5.0$DO=0.5
DT=0.05$GZ=0.0$GO=0.05$GT=0.05$TGO=0.6$TGT=0.05$AM=0.0192$PD=0.0032$P=1.0$Q=-1.0
READ TE$SS=S*S
                              A=SINF(DL) $ B=COSF(DL) $ EID=P*A+Q*B $ EIQ=P*B-Q*A
EI=SQTF(EID*EID+EIQ*EIQ) $ VTI=1.+(EID*RL-EIQ*(XL-XC))*A+(EIQ*RL+EID*(XL-XC))*B
VTO=(EIQ*(XL-XC)-EID*RL)*B+(EIQ*RL+EID*(XL-XC))*A $ VT=SQTF(VTI*VTI+VTO*VTO)
DLTB=ATNF(VTO/VTI) $ VTD=VT*SINF(DL-DLTB) $ VTQ=VT*COSF(DL-DLTB) $ SID=VTQ+R*EIQ
SIQ=-VTD-R*EID $ SD=VTD/VT $ SQ=VTQ/VT $ CD=EID/EI $ CQ=EIQ/EI
P1=RL*SD+(XL-XC)*SQ $ P2=(XL-XC)*SD-RL*SQ
A32=EIQ*(XL-XC)-SIQ+EID*(R+RL) $ A33=SID+(R+RL)*EIQ-EID*(XL-XC) $ 2@READ W
WS=W*W$A1=(1.+TDO*S)$A1=A1*A1+WS*TDO*TDO$A2=1.+TQO*S
A2=A2*A2+WS*TQO*TQO$GDR=(1.+TDO*S)/A1$GDI=-TDO/A1$GQR=(1.+TQO*S)/A2
GQI=-TQO/A2$A3=1.+TE*S$A3=A3*A3+WS*TE*TE
C=DZ+S*DO+SS*DT-WS*DT$D=DO+2.*S*DT
DGR=(C*(1.+S*TE)+WS*TE*D)/A3$DGI=(D*(1.+S*TE)-TE*C)/A3
GQDR=GQR*DGR-WS*GQI*DGI$GQDI=GQR*DGI+GQI*DGR
C=RL*EID-2.*XL*EIQ+A-VTD+SIQ$D=XL*EID
AR11=B+(SS-WS)*D+S*C+GQDR$XDR=XD*((1.+S*TD)*(1.+S*TDO)+WS*TD*TDO)/A1
XDI=XD*(TD*(1.+S*TDO)-TDO*(1.+S*TD))/A1
XQR=XQ*((1.+S*TQ)*(1.+S*TQO)+WS*TQ*TQO)/A2
XQI=XQ*(TQ*(1.+S*TQO)-TQO*(1.+S*TQ))/A2$AI11=2.*S*D+C+GQDI
AR13=-XQR-XL+XC$AI13=-XQI
C=B+RL*EIQ+2.*EID*XL-VTQ$D=XL*EIQ
FR2=-A+S*C+(SS-WS)*D$FI2=C+2.*S*D
C=RL*EID-VTD+A-2.*XL*EIQ$D=XL*EID$FR1=B+S*C+(SS-WS)*D$FI1=C+2.*S*D
AFR1=SD*FR1+SQ*FR2$AFI1=SD*FI1+SQ*FI2
AG=GZ+S*GO+(SS-WS)*GT$BG=GO+2.*S*GT$C=1.+S*TGO+(SS-WS)*TGT$D=TGO+2.*S*TGT
GGR=(AG*C+W*BG*D)/(C*C+D*D)$GGI=(BG*C-D*AG)/(C*C+D*D)
AR31=AM*(SS-WS)+PD*S+GGR+EIQ*FR2+EID*FR1$AI31=2.*S*AM+PD+GGI+EIQ*FI2+EID*FI1
SR1=(R+RL)*A33-A32*AR13$SI1=-A32*AI13
SR2=A33*AR11-(AR13*AR31-WS*AI13*AI31)$SI2=A33*AI11-AR13*AI31-AI13*AR31
SR3=A32*AR11-(R+RL)*AR31$SI3=A32*AI11-(R+RL)*AI31
AKR1=-AFR1*SR1+WS*AFI1*SI1+P1*SR2+P2*SR3$AKI1=-AFR1*SI1-AFI1*SR1+P1*SI2+P2*SI3
AKR2=-CD*SR2+CQ*SR3$AKI2=-CD*SI2+CQ*SI3
AKR3=SID*(SR1*S-WS*SI1)-(FR2*SR1-WS*FI2*SI1)
AKR3=AKR3+(XDR*SR2-WS*XDI*SI2+(XL-XC)*SR2)-(R+RL)*SR3
AKI3=SID*(SR1+S*SI1)-(FR2*SI1+FI2*SR1)
AKI3=AKI3+(XDR*SI2+XDI*SR2+(XL-XC)*SI2)-(R+RL)*SI3
GDER=(GDR*(1.+S*TE)+WS*GDI*TE)/A3$GDEI=((1.+S*TE)*GDI-TE*GDR)/A3
GKR1=AKR1*GDER-WS*AKI1*GDEI$GKI1=AKR1*GDEI+AKI1*GDER
GKR2=AKR2*GDER-WS*AKI2*GDEI$GKI2=AKR2*GDEI+AKI2*GDER
AG=VZ+S*VO+(SS-WS)*VT$BG=VO+2.*S*VT
BKR=GKR1*AG-WS*GKI1*BG+GKR2*CZ+AKR3$BKI=AG*GKI1+GKR1*BG+GKI2*CZ+AKI3
AG=(SS-WS)*W*GKI2+2.*S*W*GKR2$BG=S*GKR2-WS*GKI2
C=(SS-WS)*GKR2-WS*GKI2*2.*S$D=S*W*GKI2+W*GKR2$DEN=AG*BG-C*D
 IF(DEN)1,2,1$  1@CO=(-AG*BKR+W*BKI*C)/DEN$CT=(-BG*W*BKI+BKR*D)/DEN
WRITE3,W,DEN,CO,CT$3@FORMAT(/,E,E,E,E)$GOTO2$STOP$END
```

```
D-PARTITIONG IN PLANE OF K1D-K2D
Q=-1.0$  RL=0.05$XL=0.3$       R=0.01$XD=1.2$XQ=0.8$XDD=0.29$XQD=0.47$TD=0.77
TDO=3.2$TQ=1.9$TQO=3.2$VZ=10.0$XC=0.1
DZ=5.0$GZ=0.0$GO=0.05$GT=0.05$TGO=0.6$TGT=0.05$AM=0.0192$PD=0.0032$P=1.0
VO=1.0$VT=0.5$  S=-0.5      $TE=0.5
READ  DL $  SS=S*S
A=SINF(DL) $ B=COSF(DL) $ EID=P*A+Q*B $ EIQ=P*B-Q*A $ EI=SQTF(EID*EID+EIQ*EIQ)
VTI=1.+(EID*RL-EIQ*(XL-XC))*A+(EIQ*RL+EID*(XL-XC))*B
VTO=(EIQ*(XL-XC)-EID*RL)*B+(EIQ*RL+EID*(XL-XC))*A $ VT=SQTF(VTI*VTI+VTO*VTO)
SIQ=-R*EID-VTD $ SD=VTD/VT $ SQ=VTQ/VT $ CD=EID/EI $ CQ=EIQ/EI
P1=RL*SD+(XL-XC)*SQ $ P2=(XL-XC)*SD-RL*SQ
A32=EIQ*(XL-XC)-SIQ+EID*(R+RL) $ A33=SID+(R+RL)*EIQ-EID*(XL-XC) $ 1@READ W
DLTB=ATNF(VTO/VTI) $ VTD=VT*SINF(DL-DLTB) $ VTQ=VT*COSF(DL-DLTB) $ SID=VTQ+R*EIQ
WS=W*W$A1=(1.+TDO*S)$A1=A1*A1+WS*TDO*TDO$A2=1.+TQO*S
A2=A2*A2+WS*TQO*TQO$GDR=(1.+TDO*S)/A1$GDI=-TDO/A1$GQR=(1.+TQO*S)/A2
GQI=-TQO/A2$A3=1.+TE*S$A3=A3*A3+WS*TE*TE
C=VZ+S*VO+SS*VT-WS*VT$D=VO+2.*S*VT
GVR=(C*(1.+TE*S)+WS*D*TE)/A3$GVI=(D*(1.+TE*S)-TE*C)/A3
C=RL*EID-VTD+A-2.*XL*EIQ$ D=XL-EID
FR1=B+S*C+(SS-WS)*D$ FI1=C+2.*S*D
FR3=FR1+S*SIQ$FI3=FI1+SIQ
C=B+RL*EIQ+2.*EID*XL-VTQ$D=XL*EIQ
FR2=-A+S*C+(SS-WS)*D$FI2=C+2.*S*D
AG=GZ+S*GO+(SS-WS)*GT$BG=GO+2.*S*GT$C=1.+S*TGO+(SS-WS)*TGT$D=TGO+2.*S*TGT
GGR=(AG*C+W*BG*D)/(C*C+D*D)$GGI=(BG*C-D*AG)/(C*C+D*D)
AR31=AM*(SS-WS)+PD*S+GGR+EIQ*FR2+EID*FR1$AI31=2.*S*AM+PD+GGI+EIQ*FI2+EID*FI1
                              XDR=XD*((1.+S*TD)*(1.+S*TDO)+WS*TD*TDO)/A1
XDI=XD*(TD*(1.+S*TDO)-TDO*(1.+S*TD))/A1
XQR=XQ*((1.+S*TQ)*(1.+S*TQO)+WS*TQ*TQO)/A2
XQI=XQ*(TQ*(1.+S*TQO)-TQO*(1.+S*TQ))/A2
GDVR=GDR*GVR-WS*GDI*GVI$GDVI=GDR*GVI+GDI*GVR
AR=GDVR*FR1-WS*GDVI*FI1$AI=GDVR*FI1+GDVI*FR1
BR=GDVR*FR2-WS*GDVI*FI2$BI=GDVR*FI2+GDVI*FR2
AR12=(S*SID-FR2-SD*AR-SQ*BR)$AI12=SID-SD*AI-FI2-SQ*BI
AR22=-XDR          -P1*GDVR-XL+XC$AI22=-XDI          -P1*GDVI
AR23=        -R-RL+P2*GDVR$AI23=        +P2*GDVI
AKR1=A33*AR22-A32*AR23$AKI1=A33*AI22-A32*AI23
AR13=-XQR-XL+XC$AI13=-XQI
AA=(R+RL)*AR23-AR13*AR22+WS*AI13*AI22
BB=(R+RL)*AI23-AI13*AR22-AR13*AI22
AKR2=AA*AR31-WS*BB*AI31-(R+RL)*A33*AR21
AKR2=AKR2+A32*(AR13*AR21-WS*AI13*AI21)
AKI2=AA*AI31+BB*AR31-(R+RL)*A33*AI21
AKI2=AKI2+A32*(AR13*AI21+AI13*AR21)
X=(AKR1*GQR-WS*AKI1*GQI)*(1.+S*TE)
X=(X+WS*TE*(AKR1*GQI+AKI1*GQR))/A3
Y=(AKR1*GQI+AKI1*GQR)*(1.+S*TE)
Y=(Y-TE*(AKR1*GQR-WS*AKI1*GQI))/A3
FKR=FR3*AKR1-WS*FI3*AKI1$FKI=FR3*AKI1+FI3*AKR1
AG=S*X-WS*Y$BG=((SS-WS)*X-2.*WS*Y*S)$C=W*X+W*Y*S$D=2.*W*S*X+W*Y*(SS-WS)
DEN=AG*D-C*BG$   IF(DEN)2,1,2
  2@ ADO=DZ*X+AKR2+FKR$ADT=(Y*DZ+AKI2+FKI)*W
DO=(BG*ADT-ADO*D)/DEN$DT=(C*ADO-AG*ADT)/DEN
 WRITE3,W,DEN,DO,DT$   3@ FORMAT(/,E,E,E,E)$GOTO1$STOP$END
```