INFLUENCE OF D.C.TRANSMISSION SYSTEM ON TRANSIENT STABILITY OF AN ASSOCIATED POWER SYSTEM

A DISSERTATION
Submitted in partial fulfilment
of the requirements for the award of the Degree
of
MASTER OF ENGINEERING
in
ELECTRICAL ENGINEERING
(POWER SYSTEM ENGINEERING)

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JUNE, 1979

CERTIFICATE

Certified that the dissertation entitled 'Influence of a D.C. Transmission System on the Transient Stability of an Associated Power System' which is being submitted by Sri Vinod Kumar Agarwal in partial fulfilment for the award of Degree of Master of Engineering in 'Power System Engineering' of University of Roorkee, Roorkee is a record of Student's own work carried out by him under our guidance and supervision. The matter embodied in this dissertation has not been submitted for the award of any other degree or diploma.

This is further to certify that he has worked for a period of 5 months from 1/1/1979 to 6/6/1979 for preparing this dissertation for Master of Engineering Degree at this University.

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ACKNOWLEDGEMENT

I wish to express my profound gratitude to my guides and supervisers Sri M.L. Dewal and Sri Subodh Agarwal, Lecturers in Electrical Engineering Department, University of Roorkee for their expert guidance, constructive criticism and constant encouragement throughout the dissertation work.

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CONTENTS

SYNOPSIS

The analysis carried out here evaluated the influence of D.C. line on the system's transient stability when it is operated in parallel with an A.C. line connecting two synchronous systems. The effect of sudden increase even for the short time interval in the d.c. power level on power system stability, after the clearing of an a.c. fault, has been investigated.

The swing curves of the system are calculated and plotted with the help of point by point method, when three phase faults are considered to occur at rectifier bus and middle of the a.c. transmission line. The post fault voltage dips are taken into account in swing curve calculations.

Two control schemes for boosting the power in the d.c. link after the fault occurred have been developed.

CHAPTER I

INTRODUCTION

When we talk about d.c. transmission today, we mean however, something that is basically different. One is in fact convinced that alternating current holds a unique position both as far as the generation of electrical energy is concerned and also for the distribution of this energy to the ultimate consumers. This situation, favouring alternating current, may be attributed to its commutator-free generators and above all to the ease with which the voltage at the generation side can be transformed up to the desired transmission voltage, just as it similarly can be readily reduced again at the consumer side to the various voltage values required. The position, at which the application of direct current appears today to be favourable within the overall process of electrical energy transport from producer to consumer, is thus limited to the high voltage transmission area.

Fundamentally d.c. is the simplest way of transmitting electric power. In a d.c. line current and voltage remains fairly constant as there are no inductive or capacitive effects of the kind that arise in an a.c. line as a result of the periodical changes in current direction and reversals in voltage polarity. These effects produce inductive voltage drops over the line and capacitive leakage currents across the insulation, thus increasing the cost of transmission.

In the course of the great strides made in a.c. transmission over the last two decades, means have been evolved for making lines electrically shorter by reducing their inductive reactance. The tendency of an inductor to resist current flow can be partly compensated by inserting capacitors in series with the conductor. Under optimum conditions this technique can double the load carrying capability, but it involves additional cost.

D.C. transmission, on the other hand, has no stability limitation of this kind because it is inherently asynchronous. Like a fluid coupling between two mechanical systems it allows power to be transmitted between systems operating at different frequencies.

Power flow over the d.c. link can be controlled by means of timing signals applied to the convertor grids. Since there is a limit to the current that the convertor can withstand the control circuit can be designed; so this limit can not be exceeded. Thus if a fault should occur in one of the systems - a generator failing for example - the d.c. line will not trip out, but will 'do its best' and transmit all the power within its ability where an an a.c. link would have to be disconnected.

In the early part of this decade the electrical power industry in the U.S.A. was stirred by the proposals to interconnect the hydro-generation complex of the pacific northwest with the load region in southern California, by means of high voltage d.c. transmission lines. Most engineers immediately recognised the important distinction that such a d.c. line would have in operating in parallel with high voltage A.C. line whereas, the then existing d.c. lines (and others underway or projected) were all isolated links between otherwise separate a.c. systems. As interest in d.c. transmission grew, some power engineers also recognised that HVDC transmission technology could be a potentially useful tool in the ever accelerating expansion of power systems. Even though no other applications could be foreseen in the immediate future, there were strong arguments in favour of immediate study and research on the possibilities or limitations of the integration of d.c. lines into the already integrated a.c. systems.

When considering the integration of a d.c. line into an a.c. network, interactions between the two systems during transient disturbances become of paramount importance. Disturbances within the a.c. system will be evidenced at the convertor buses as a change in the magnitude of the voltage, a change in its phase angle or even a change in its system frequency, depending on the nature and magnitude of the disturbance. While the convertor controls are designed to compensate for such disturbances, their ability to do so depends on the severity of the disturbance.

CHAPTER II

STABILISATION OF ALTERNATING CURRENT NETWORKS

The power[1] exchanged between the a.c. network is determined by the relative angular position of the various pole wheels, and when the equilibrium is disturbed these wheel positions must give rise to corrective power flow leading finally to a new state of equilibrium.

The corrective power must have a synchronizing effect on the rotation speeds, that is, angles that are too small for the future condition of equilibrium must be increased and angles that are too large must be reduced. However, this necessary characteristic is insufficient to establish the new equilibrium. Since the machines would have their highest and lowest angular velocities exactly when the equilibrium angle was reached, they would hunt around the equilibrium point and, because of non-linearities of the process, would lead to increasing swings until finally they would fall out of step. Such a process may extend over several seconds and a further task of the corrective power is to damp these oscillations.

A network is termed stable if, after a disturbance, it returns to a final condition of equilibrium. On the other hand, if the angle between the sets increases steadily, the network is transiently unstable, whilst hunting around the equilibrium point until finally the network sections fall out of step is termed dynamic instability. Any sudden change in the network conditions (load changes, failure of turbine sets, line faults, change of network configuration etc.) imposes different demands on the energy stored in the rotating masses of the individual machines, and therefore, gives rise to phenomena of the kind described above. On the other hand, there are factors which counteract instabilities, for instance, voltage and frequency dependence of the load. However, in large and particularly in extensive networks, such factors are often insufficient and have to be reinforced by artificial means. These means can be divided into two groups, depending on the energy store from which they draw the corrective power for stabilisation.

(a) The corrective powers originate from the energies already stored in the rotating masses of the network. Examples of means of reinforcing such a power exchange are the series capacitor, which reduces the electrical distance between the two points in a network compared with the geographical distance, field control of generators with or without a frequency control signal and in special cases the temporary switching in of additional resistors. D.C. transmission links also belong to this group. They enable corrective power to be transported between two points in a network, regardless of the relative phase relationship of the voltage at these points, and our task is to find control signals which have a stabilising effect on the a.c.network.

Of course, d.c. transmission always behave as asynchronous links. If despite this, we call the said d.c. links synchronous, this is not to cast doubt on these properties but to express the fact that the end points of the d.c. links are connected to a common network. Thus, in the case of synchronous transmission links there are always in addition to the d.c. transmission link itself, one or several a.c. connections between the end points of the link.

(b) The correction power originates from energy stores outside the electrical system with its rotating masses, for instance, from the water or steam reserves of the turbine. The time constant of the water flow, and the fact that its effect at the beginning of a control process acts in a wrong direction mean that the control of water turbines cannot be included among the means of improving stability. Steam power stations react more quickly, but the permitted rate of power increase is limited. There are d.c. links in this group as well, namely those that draw the power from other, asynchronous networks with the same or different nominal frequency. In this context we shall refer to them as asynchronous transmission links. They enable the spinning reserve of both networks to be used jointly, despite the asynchronism, but also enable the rotating energy of one network to be made available to the other network for purposes of stabilisation and to do so without a merger of the short circuit capacities in both networks. Here, too, limitations may mean that this stabilisation assistance can only be used upto to the point beyond which it would lead to the propagation of a fault into the other network.

CHAPTER III

COMPARISON OF SYSTEM OSCILLATIONS BY JOINT USAGE OF D.C AND A.C. SYSTEMS CONNECTED IN PARALLEL USING THE ENERGY OR SPEED VARIATION IN [illegible] NETWORKS AS CONTROLLING SIGNALS

The d.c. transmission link must be supervised by a control device, since it obtains no information from the a.c. network as to the appropriate power exchange and its fluctuations.

In this method orders of frequency difference derived from interconnected networks are superimposed on normal convertor control. It is found that it leads to considerable improvement in transient stability of transmission. In this case the d.c. line has to take the load from the a.c. line during a short time, which means that apparatus belonging to the D.C. system must tolerate this overload. The short circuit capacities of both networks should be high enough to make a fast change of generator power from A.C. to D.C. lines possible.

During transient processes, the definition of the frequency as the reciprocal of the periodic time measured between zero passages, for example of the voltage at any point on the network, does not provide us with the quantity that we wish to influence by control intervention. The zero passages can be shifted by temporary d.c. components or by load changes, without necessarily changing the actual network frequency. In view of the fast reactions of which a d.c. transmission link is capable, it is therefore not permissible to use currents or voltages of the electrical system in order to determine the frequency.

The quantity of interest in connection with frequency control is the angular velocity of the machines in the network. Frequency is a convenient means of expressing this velocity without regard for the number of poles of the individual machine. Therefore for our purpose frequency is only a measure of machine rotation speed and has little to do with the time between zero passages of voltages or currents in the associated networks. It is tied to rotating mass, has an instantaneous value and can be differentiated. It is measured by a tachometer generator or by means of the machine voltage behind the transient reactance, and is entirely free of the fluctuations of the external electrical system around it.

<u>Alternating Current Transmission</u>[2]

The a.c. power exchange between two machine is

$$P = \frac{E_1 \cdot E_2}{X} \sin\delta \qquad \ldots (1)$$

Where E_1 and E_2 are the two machine voltages behind their transient reactance, δ the phase angle and X the total reactance between them. By using series capacitor, X can be adjusted, meaning thereby that this factor can be adjusted for a certain transmission, but it can not be changed continuously. The angle δ however, is determined by frequency regulators in both networks and also by inertia associated with generators and partly with the loads. Thus the actual transmitted power is governed by the inter-connected networks and there is no arrangement in the link itself for the necessary control of the exchanged power.

Development of Transfer Function of A.C.-D.C. parallel operating system

For the system shown in Fig.1 certain assumptions are made to make representation simpler. These are:

(1) A.C. and D.C. lines do not have any loss.

(2) Interconnected networks at two ends of the transmission lines are free of frequency dependent loads, consequently no damping torques are present. This means that a.c. system will oscillate by itself and can only be damped by parallel d.c. system.

(3) During transient state, it is assumed that frequency regulators are not acting.

Now if rated power of the networks are P_1 and P_2 and inertia constants are H_1 and H_2 respectively then a magnitude

2.

of equivalent rotating energy common to both network can be defined by the network W given by

$$W = \frac{(P_1H_1)(P_2H_2)}{(P_1H_1+P_2H_2)} \qquad \dots (2)$$

suppose that in the network 1(?) of Fig.1 power is increased by ΔP, the increase in frequency is given by Δf_1 which is

$$\Delta f_1 = \frac{f_0}{p(P_1H_1)} \Delta P \qquad \dots (3)$$

Similarly Δf_2 change in frequency of network 2 is given by

$$\Delta f_2 = \frac{f_0}{p(P_2H_2)} \Delta P \qquad \dots (4)$$

from equation (3) and equation (4)

~~from equation (3) and equation (4).~~

$$\frac{\Delta f_1}{\Delta P} = \frac{f_0}{p(P_1H_1)} = \text{transfer function of network 1}$$

$$\frac{\Delta f_2}{\Delta P} = \frac{f_0}{p(P_2H_2)} = \text{transfer function network 2}$$

The transmitted power on the A.C. line is given by equation (1). Let now this power be increased by $\Delta P_{A.C.}$ and due to it phase angle increased from δ to $\delta+\Delta\delta$. Hence,

$$P_{A.C.} + \Delta P_{A.C.} = \frac{E_1E_2 \sin(\delta+\Delta\delta)}{X}$$

$$= \frac{E_1E_2}{X}\sin\delta \cos\Delta\delta + \frac{E_1E_2}{X}\cos\delta \sin\Delta\delta$$

Now if change in the angle is not large roughly $\cos \Delta\delta \cong 1$

and $\sin\Delta\delta \cong \Delta\delta$

$$\therefore P_{A.C.} + \Delta P_{A.C.} = \frac{E_1E_2}{X}\sin\delta + \frac{E_1E_2}{X}\cos\delta\ \Delta\delta$$

and $\frac{E_1E_2}{X}\sin\delta = P_{A.C.}$ — according to equation (1)

Hence,

$$\Delta P_{A.C} = \frac{E_1E_2}{X}\cos\delta.\Delta\delta$$

as $\Delta\delta = \frac{(\Delta f_1 - \Delta f_2)\ 2\pi}{p}$

because $\frac{d}{dt}(\Delta\delta) = 2\pi\Delta f$, where $\Delta f = \Delta f_1 - \Delta f_2$.

If $\frac{2\pi\ E_1E_2}{X} = D$

then

$$\Delta P_{A.C} = \frac{D\cos\delta\ \Delta f}{p}$$

or $\frac{\Delta P_{A.C.}}{\Delta f} = \frac{D\cos\delta}{p}$ = Transfer function for A.C. link ... (6)

The d.c. link is governed by its control device which for steady state conditions may work according to any programme, but steady state programme is superimposed by a transient programme supplied by frequency difference Δf between the two networks. The transfer function for the transient programme is called L(p) and the power change of the d.c. link is

$$\Delta P_{d.c.} = F(p)\Delta f$$

Now suitable terms have to be found for F(p) in order to increase the stability of the total transmission and to limit the phase angle $\Delta\delta$, when the a.c. link is broken. The limitation of $\Delta\delta$ leads to improvement of transient stability.

Figure 2 shows the interconnection of all these transfer functions. In both the sides of the transmission, and the distribution of the power when the power flow between the networks is changed by a disturbance ΔP.

The a.c. transmission and the network are connected as shown in the Fig. 2. For d.c. link we will provide the magnitude Δf as a supply for its regulators.

From the close loops in Fig. 2, we find that

$$\Delta f_1 = \left[\Delta P - \left(F(p) + \frac{D\cos\delta}{p}\right)\Delta f\right] \frac{f_0}{p(P_1 H_1)} \qquad \text{... (7A)}$$

$$\Delta f_2 = \left[\Delta P - \left(F(p) + \frac{D\cos\delta}{p}\right)\Delta f\right] \frac{f_0}{p(P_2 H_2)} \qquad \text{... (7B)}$$

Introducing the equations (2) to (6) we get a general solution for all magnitudes of interest as follows:

$$\frac{\Delta f}{f_0} = \frac{\Delta P}{T} \frac{p}{p^2 + \frac{f_0}{T} pF(p) + \frac{f_0}{T} D \cos\delta} \qquad \ldots (8)$$

$$\Delta\delta = 2\pi \frac{f_0 \Delta P}{T} \frac{1}{p^2 + \frac{f_0}{T} pF(p) + \frac{f_0}{T} D \cos\delta} \qquad \ldots (9)$$

$$\frac{\Delta P_1}{\Delta P} = \frac{\frac{f_0}{T} D \cos\delta}{p^2 + \frac{f_0}{T} pF(p) + \frac{f_0}{T} D \cos\delta} \qquad \ldots (10)$$

$$\frac{\Delta P_2}{\Delta P} = \frac{\frac{f_0}{T} pF(p)}{p^2 + \frac{f_0}{T} pF(p) + \frac{f_0}{T} D \cos\delta} \qquad \ldots (11)$$

$$\frac{\Delta P_1 + \Delta P_2}{\Delta P} = 1 - \frac{p^2}{p^2 + \frac{f_0}{T} pF(p) + \frac{f_0}{T} D\delta} \qquad \ldots (12)$$

In the denominators of all these equations the transfer function of the d.c. system appears in the form pF(p). Therefore a constant term in this function, the frequency difference itself, will give us a damping effect for the system.

The d.c. transmission itself does not produce such a term and therefore it oscillates. But in a real network such a term is produced mostly by some frequency depending loads. This means that it is not the transmission itself but certain circumstances in the interconnected network that makes the a.c. transmission stable.

It is an advantage that the degree of oscillation damping can now be determined by a proper choice of the constant term in the transfer function of the regulator in a parallel d.c. transmission.

The behaviour of the transmission as a whole can be further improved by adding more terms to the transfer function, especially terms of integral type. These terms will limit the phase angle difference between the networks when the a.c. transmission is broken due to a passing line fault.

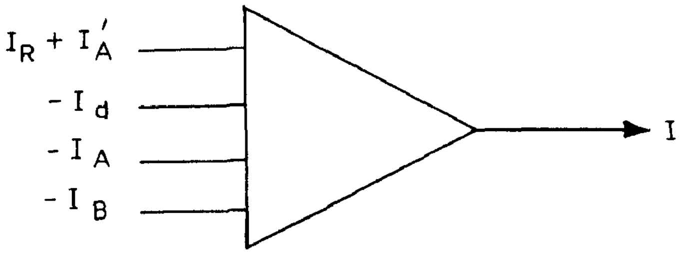
(b) Power Boost Control

Two control systems for boosting the power in the d.c. line after the fault occurred were studied. These systems do not require a data link for transmitting information from one end of the link to the other end as in the case of frequency control.

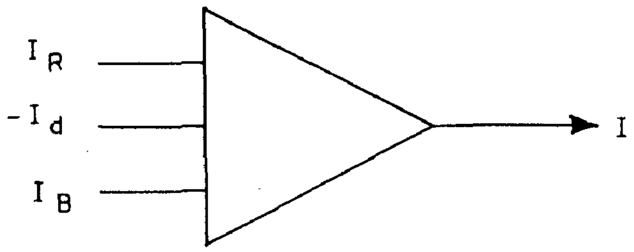
(1) Power boost proportional to the power flowing in the more heavily loaded parallel a.c. line (fig.3a)

With this control scheme the power transfer in the more heavily loaded parallel a.c. line is measured by a [illegible]-transducer. Its associated operational amplifier output is fed into the summing junction of the converter panel of the rectifier end. This additional signal, which is

(a) Power boost proportional to power flowing in the more heavily loaded parallel a.c. line.



(b) Constant power boost



I_R	=	Current order signal
I_d	=	Current response signal
I_A	=	Signal proportional to the power in the more heavily loaded a.c. line.
I'_A	=	Constant signal equal to I_A
I_B	=	Constant signal from the battery.

of opposite polarity to the current order signal initially set at twice the desired value, maintains the d.c. current in the given operating condition.

When the fault was initiated, the power flowing in this line dropped to zero which resulted in an additional power boost in the d.c. line. To avoid overloading the line, a battery through a relay, with a signal proportional to this boost signal was also connected to the summing junction in order to bring the d.c. power transfer back to its normal condition 10 cycles after the faulted line had been isolated.

(2) Constant power boost after the fault (fig.3b)

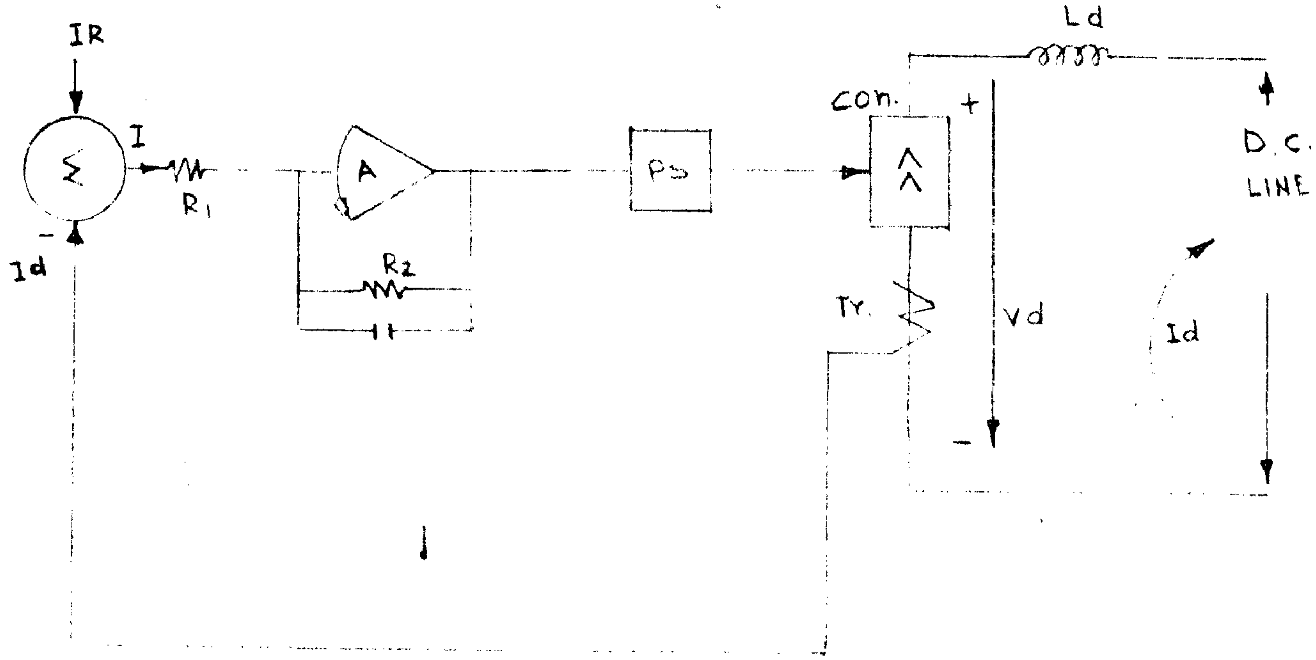
Due to the big dips in voltages at both buses during the fault, the power transfer remains at zero even when the current in the d.c. line has been doubled. Actually this power boost does not come into effect until the fault has been isolated. Thus a battery operated signal, connected through the back contact of the line breaker of the parallel a.c. line to the summing junction of the converter, was used to provide the power boost signal. When the breaker tripped, this signal doubled the d.c. power transfer for a period of 10 cycles. As in previous scheme, improvement in transient stability limit was obtained.

Scheme for Constant Current-Regulator with Power Boost

Figure 4 shows the scheme. Constant current control involves the following:-

1. Measurement of direct current I_d (called current response signal)
2. Comparison of I_d with the set value I_R, the current order signal.
3. Amplification of the difference $I_R - I_d$ called the error.
4. Application of the output signal of the amplifier to a phase shift circuit that alters the ignition angle α of the valves in the proper direction for reducing the error.

If the measured current in a rectifier is less than the set value of current, α must be decreased in order to increase $\cos \alpha$ and thus raise the internal voltage of the rectifier. The difference between the internal voltages of the rectifier and the invertor is thereby increased, and the direct current is increased proportionally. If the measured current exceeds the set current, α must be increased instead of decreased, and all the quantities mentioned above are changed in the opposite direction.



PS — PHASE SHIFT CIRCUIT

Ir — CURRENT ORDER SIGNAL

Id — CURRENT RESPONSE SIGNAL

R1 — INPUT RESISTOR

R2 — FEEDBACK RESISTOR

C — FEEDBACK CAPACITOR

A — HIGH GAIN AMPLIFIER

CON — CONVERTER

Ld — D.C. REACTOR

Tr — D.C. CURRENT TRANSFORMER

I — ERROR SIGNAL

FIG. 4 . . .

In the inverter, if the measured current is too low, the internal voltage must be decreased instead of being increased as in the rectifier in order to increase the difference of internal voltages. This refers, however, to absolute value of the inverter voltage. If we consider the inverter voltage to be negative which is usual if the same converter sometimes rectifies and at other times inverts, the algebraic value of inverter voltage must be increased as in a rectifier, and to accomplish this, a must be decreased as in a rectifier.

The current regulator is a simple kind of feedback amplifier characterized by a gain and a time constant.

In the case of power boost where the summing junction in fig. 4 is supplied with following zero signals.

1- Case: Power boost proportional to the power flowing in the more heavily loaded parallel a-c line

I_A = signal proportional to the power in the more heavily loaded a.c. line.

I_A' = constant signal equal to I_A

I_B = constant signal from the battery

The conditions at the summing junction (Σ) will be as explained below:

Operating mode $I = I_d - I_d + I'_A - I_A - I_D$

Before the fault $I'_A = I_A$ $I_D = 0$

During the fault $I_A = 0.$ $I_D = 0$

10 cycles after the fault $I_A = 0.$ $I_D = I'_A$

2- CASE : Constant power boost after the fault in the case the conditions at the coming junction will be

Operating mode, $I = I_d - I_d + I_D$

Before the fault $I_D = 0$

During the fault $I_D = 0$

after the fault $I_D =$ constant

10 cycles after the fault $I_D = 0.$

Fault Condition

When a three phase fault occurs in one of the a.c. lines near the generator end, the voltage collapses, and in the absence of power exchange the generator accelerates and motor decelerates. The dynamic performance of a d.c. link following disturbance shows that while the current builds up very quickly (from the blocked condition) the voltages takes some 3 to 9 cycles to reach, a reasonably value. The effect introduces some delay in pickingup up power by the d.c. link. The stability limit will depend on this delay.

The recovery of the d.c.(6) voltage after the fault is cleared, becomes almost instantaneous when the power boost is present. The fast recovery rate with the boost present can be explained as follows.

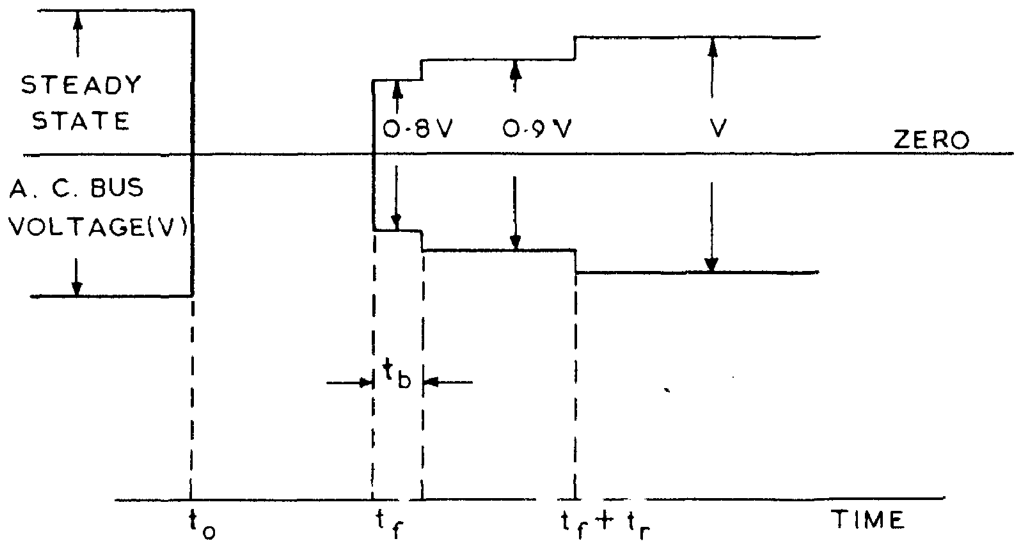
With the rectifier terminals regulated by a constant current control, the response of the d.c. voltage can be characterized by a first order differential equation as

$$V + T\frac{dV}{dt} = KE \quad \text{or} \quad V(t) = KE\left(1 - e^{-\left(\frac{1}{T}\right)t}\right)$$

where

- $V(t)$ is the d.c. voltage
- T is the time constant of the regulator
- K is the gain of the amplifier and the phase shift circuit
- E is the error signal which results from the difference of the monitored direct current and the setting of the current order.

At the instant when the fault was cleared the d.c.current changes almost instantaneously from zero to the set value. As a result, the d.c. voltage recovers exponentially at a rate corresponding to the time constant of the regulator and at a magnitude corresponding to the gain and the error signal. With the boost in current at this instant, the error signal will double and the recovery time will be cut in half.



t_f - FAULT DURATION

t_b - TIME DURATION OF BOOST

t_r - REGULATOR RECOVERY

FIG.6.

CURRENT CONTROL OF THE DIRECT CURRENT TRANSMISSION LINK

The mode[3] of operation of the current controller is closely linked with the method by which the firing impulses are produced, which may be individual phase control or equidistant firing control. However, a common aspect of both systems is that the firing instants are determined for all valves together at ground potential and then transferred to the potential of the individual valves. This is done either by means of transformers or by light signals. In the latter case the required impulse power must be made available at the potential of the individual valves.

Another aspect independent of the firing control method is concerned with the impulse duration. At any instant it must be possible for one of the valves in a commutation group to take over conduction of the current, in other words, the deblocked time of the next valve in the commutation group begins. This is necessary in order to create, on starting, a current path through all commutation groups in spite of displaced beginnings of their deblocked times. In addition, when working with small currents or in connection with transients, harmonics in the valve current may temporarily extinguish the current. The current must then at any time be able to find a way through all commutation groups so that it can re-establish itself. This requirement can be met in various ways.

(a) an impulse is ended by the signal that releases the next impulse in the commutation group. This makes the impulse duration in steady-state operation 120° (long impulse) and slightly shorter or longer during control processes.

(b) During the deblocked time of a valve sufficiently frequently repeated short impulses are given. They must be applied simultaneously to the deblocked x valves of all commutation groups.

(c) Single short impulse at firing instant with repetition of the impulse as soon asthe valve voltage becomes positive during the deblocked time.

Method (a) is easiest to put into practice but with the light transmission the time for which the light source is alight should be minimised in order to increase its life, and methods with short impulses are therefore preferred.

In determination of the instant at which the deblocked time begins, it is assumed both for individual phase control and for equidistant firing control, that an impulse is given as soon as a voltage that changes with time (called the control function) coming from smaller valves reaches the valve of a reference direct voltage. The magnitude of the said direct voltage, and therefore the beginning of the deblocked time, is determined in both firing control methods by the controller. The difference lies in different conditions for the generation of the control function.

A further aspect independent of the firing control procedure is concerned with the principle by which the firing instant is determined in inverter operation, in order to obtain the desired extinction angle. Essentially two different methods have been used for this.

(A) Measurement of the result(γ) and steps to improve it in the next cycle.

(B) Continuous pre-calculation of the expected result on the basis of facts already known before the firing instant, and initiation of the firing impulse at the moment for which the prediction indicates the desired result.

<u>Telecommunication Link</u>

Some control tasks require the transmission of such a small quantity of information that the information channel can also be made available for information not belonging to the control tasks. In other cases the entire channel is required for control purposes or the information must be transmitted in analogue form. Analogue transmission imposes considerable demands on the fidelity of reproduction and calls for regular inspection and adjustment, and this form of transmission is generally avoided nowadays.

A microwave link offers a large number of transmission channels. There must be line of sight between the aerials, and this requires tall masts and short distances between the relay stations. It is not always possible to find a suitable site with available auxiliary power for the relay stations, for instance, in case of D.C. transmission links across the sea. Longer distances can be bridged with radio links in the 100 MHz region. They are occasionally subject to fading so that it is advisable to provide two different carrier frequencies. The probability that this phenomenon would occur simultaneously on both frequencies, and that such a condition would last for any length of time, has proved to be very slight.

For economic reasons, it is not possible to erect a telephone line solely for the d.c. transmission link. However, public telephone lines can be rented if special guarantees against crosstalk can be obtained.

CHAPTER IV

FAULT CONDITION

(a) Problem considered for analysis has been shown in the fig. 5. The system considered comprises of three parallel a.c. link, which connects two synchronous system. The two synchronous system composed of one machine each at end A and B, of same capacity. Each machine is of 100 MVA capacity. The direct axis transient reactance of the machine is 0.7 p.u. The transmission circuits have negligible resistance and each line has a reactance of 0.7 p.u. on 100 MVA base. The voltage at bus A is 1.05 p.u. and at bus B is 1.00 p.u. A three phase fault occurs at (i) bus A and (ii) at the middle of one transmission line and is clear after 7 cycles in case (i) and after 8 cycles in case (ii) by simultaneous opening of circuit breaker at both ends of the faulty line.

The power is considered to flow from machine at end A to end B.

(b) One of the a.c. line is replaced by a d.c. line equipped with rectifier and inverter at the sending end and receiving end respectively. A three phase fault as in case A occurs at (i) the rectifier bus A and (ii) at middle of one a.c. transmission line.

Analysis and Results of A.C. system

A.C. system at is shown in fig.5.

Case A: (i) When there is no d.c. line, and 3-Ø fault is at the rectifier bus.

Equivalent transmission line reactance before occurrence of the fault is

$$X_{eq} = \frac{.7}{3} = 0.233 = X_1$$

Equivalent line reactance while the fault is on

$$X_{eq} = \infty = X_2$$

When the fault is cleared by disconnecting the faulty line, the equivalent reactance is

$$X_{eq} = \frac{.7}{2} = .35 = X_3$$

The power angle equation, giving the output P_{uA} of generator A as a function of the angle δ between voltages V_A and V_B is

$$P_{uA} = \frac{V_A V_B}{X} \sin\delta = c \sin\delta$$

where c has the following values.

Before fault.

$$C_1 = \frac{V_A \quad V_B}{X_1} = \frac{1.08 \times 1}{.233} = 4.62$$

During fault (for 7 cycles)

$$C_2 = \frac{1.08 \times 1}{\infty} = 0$$

After fault clearing:

The fault is cleared by isolating the faulted A.C. line after 7 cycles from the occurrence of the fault

$$C_3 = \frac{1.09 \times 1}{0.53} = 2.04$$

<u>Initial condition</u>

The power output of the station A before the fault

$$P_{eA} = 1.0 \text{ p.u.}, \quad P_{eB} = 0$$

The initial angular position of A with respect to B is found by the prefault power angle equation

$$P_{eA} = 4.42 \sin \delta = 1.0$$

$$\therefore \sin \delta = \frac{1.0}{4.42} = 0.226$$

$$\therefore \quad \delta = 13.2^{\circ}$$

<u>Inertia Constant</u>

The equivalent inertia constant of machine A and B is

$$H = \frac{H_A \, H_B}{H_A + H_B}$$

$H_A = 2.76 \times 10^{-6}$ p.u.
$H_B = 2.76 \times 10^{-6}$ p.u.

$$\therefore H = \frac{2.76 \times 10^{-6} \times 2.76 \times 10^{-6}}{2.76 \times 10^{-6} + 2.76 \times 10^{-6}}$$

$$= 1.38 \times 10^{-6}$$

Point by Point Calculation of Swing Curve

Taking the time interval as $\Delta t = 0.02$ sec.
The steps of calculation for each point are as follows:

$$P_a(n-1) = P_I - P_m(n-1) = 1.0 - P_m(n-1)$$

$$\frac{(\Delta t)^2}{M} P_a(n-1) = \frac{(0.02)^2}{1.[illegible]} P_a(n-1)$$

$$= 2.9\, P_a(n-1)$$

$$\Delta\delta_n = \Delta\delta_{n-1} + 2.9\, P_a(n-1)$$
$$\delta_n = \delta_{n-1} + \Delta\delta_n$$
$$P_{m} = C \sin \delta_n.$$

The dynamic performance shows that after the disturbance, while the current builds up very quickly the voltage takes some 5 to 9 cycles to reach a reasonably steady value. This effect introduces some delay in picking up power by the link load after the disturbance.

(i) Considering the .9 times the bus voltages for 5 cycles after the fault is cleared as in this case

$$C_5 = \frac{1.03 \times 1.[illegible]\ .66}{0.93}$$

$$= 1.88$$

(ii) Considering the bus voltages 0.9 times for further 2 cycles and then at a total 9 cycles the bus voltages are ~~1.0 p.u.~~ steady.

$$C_3 = \frac{1.03 \times 1 \times .01}{0.7}$$

$$= 2.38$$

The point by point of swing curve calculations are carried out in Table 1.

Case A: (ii) When there is no d.c. line and a three phase to ground fault at middle of the a.c. line

$$P_{uA} = 1.0, \quad P_{d.c} = 0$$

Before fault

$$X_1 = 0.2 + 0.233 + 0.2 = 0.633$$

$$E_A = 1.03 \text{ p.u.}$$

$$E_B = 1.00 \text{ p.u.}$$

$$C_1 = \frac{E_A E_B}{X} = \frac{1.03 \times 1}{.633} = 1.625$$

$$P_{uA} = 1.0 = 1.625 \sin\delta$$

$$\therefore \sin\delta = \frac{1.0}{1.625} = 0.615$$

$$\therefore \delta = 38^{\circ}$$

During the fault (for 8 cycles)

$$X_2 = 1.49$$

$$C_2 = \frac{1.03 \times 1.00}{1.49}$$

$$= 0.69$$

After the fault

The fault is cleared by isolating the faulted A.C. line after 8 cycles from the commencement of the fault.

$$X_3 = 0.2 + .39 + .2 = 0.79$$

$$C_3 = \frac{1.08 \times 1.0}{.79} = 1.37$$

The point by point of swing curve calculations are carried out in Table -4.

Analysis and results of equivalent A.C./ D.C. System

The swing equation of a parallel A.C./D.C. net work.

Whether or not a system can maintain stability after the fault can be determined by a system of non-linear differential equations, the swing equations. For a simple two machine problem as shown in fig. the equivalent swing equation of the two machine with respect to an infinite bus can be written as

$$\frac{M_1 M_2}{M_1 + M_2} \frac{d^2\delta}{dt^2} = \frac{M_1 M_2}{M_1 + M_2} \left[\frac{P_{a1}}{M_1} - \frac{P_{a2}}{M_2} \right]$$

$$= \frac{M_2 P_{i1} - M_1 P_{i2}}{M_1 + M_2} - \frac{M_2 P_{u1} - M_1 P_{u2}}{M_1 + M_2}$$

or

$$M \frac{d^2\delta}{dt^2} = P_{ieq} - P_{ueq}$$

where M_1 and M_2 are the inertia constants of the machines.

P_{a1} and P_{a2} are the accelerating powers,

P_{i1} and P_{i2} are the shaft power inputs

P_{u1} and P_{u2} are the electrical power outputs of the machines.

M is the equivalent inertia constant

P_{ieq} is the equivalent shaft power input

P_{ueq} is the equivalent electrical power output.

With the insertion of the d.c. transmission tie, assumptions are made.

1. The d.c. transmission tie is operated in a constant current mode such that the d.c. power transfer can be assumed constant except during the fault.

2. The boost in power occurs instantaneously to the set value when the faulted network has been isolated.

3. The generators connecting to the d.c. terminals have relatively high short circuit capabilities so as to compensate the excessive withdrawal of reactive power which may result in depressing the alternating and direct voltage during the boost.

It is, however, widely acknowledged that some of the assumed constants cannot be maintained exactly even with present day automatic voltage regulators. A swing equation in which the magnitudes of the two voltages may vary with is recommended, so that the post fault voltage dips can be taken into account in solving for the swing curves.

The electrical power output can be written as

$$P_{u1} = Re\left[E_1 I_1^*\right]$$
$$= Re\left[(V_1 + jI_1 x'd_1) I_1\right]^*$$
$$= Re\left[V_1 I_1^*\right]$$
$$= P_{V1}$$

Similarly $P_{u2} = P_{V2}$

where P_{V1} and P_{V2} are the active power inputs into the transmission network. These inputs derived from the fig.

$$P_{V1} = P_{d.c.} + \frac{|V_1||V_2|}{X_{eq}} \sin\delta$$

If the d.c. transmission tie is made such that a boost in power occurs after the faulted line has been isolated the d.c. power can be written as

$$P_{D.C.} = P_{d.c.} + \Delta P_{d.c}$$

where, $P_{d.c.}$ is the steady state d.c. power and

$$\Delta P_{d.c.} = \begin{cases} 0 \text{ for prefault and fault condition and when the boost is discontinued.} \\ \text{Defined value for a limited amount of time in the post-fault condition.} \end{cases}$$

<u>Case B(4)</u> When one A.C. line is replaced by a d.c. line and the fault is at the rectifier bus

<u>Before fault</u>

$$X_1 = \frac{.7}{2} = 0.35$$

$$C_1 = \frac{1.0 \times 1}{.35} = \text{[illegible]}$$

$$P_{m1} = 0.6 \text{ p.u.}$$

$$P_{d.c.} = 0.4 \text{ p.u.}$$

$$\therefore \quad P_{m1} = C_1 \sin\delta = 0.6$$

$$\text{or} \quad \text{[illegible]} \sin\delta = 0.6$$

$$\sin\delta = \frac{0.6}{\text{[illegible]}}$$

$$= \text{[illegible]}$$

$$\delta = \text{[illegible]}^{\circ}$$

<u>During fault</u> (for 7 cycles)

$$X_2 = \infty$$

$$C_2 = 0$$

<u>After fault clearing:</u> The fault is cleared by isolating the faulted A.C. line after 7 cycles from the occurrence of the fault.

$$X_3 = 0.7$$

$$C_3 = \frac{1.0 \times 1}{0.7} = \text{[illegible]}$$

<u>Without the d.c. Power Boost</u>

$$\Delta P_{d.c.} = 0$$

Without the power boost the recovery of the d.c. voltage after the fault was cleared is rather slow.

(i) On considering 0.8 times the bus voltages for 3 cycles after the fault was cleared.

$$C_3 = \frac{1.03 \times 1 \times 0.64}{0.7}$$

$$= 0.942$$

and $P_{d.c.} = 0.4 \times 0.8$

$$= 0.32 \text{ p.u.}$$

(ii) On considering 0.9 times the bus voltages for further 2 cycles and then after total 5 cycles the bus voltages are ~~1.0 p.u.~~ steady.

$$C_3 = \frac{1.03 \times 1 \times 0.81}{0.7}$$

$$= 1.19$$

and $P_{d.c.} = .4 \times .9 = .36$

The point-by-point swing curve calculations are carried out in Table 2.

<u>With the d.c. power boost</u>

When the power boost is present after the fault clearing the recovery of the d.c. voltage is almost instentaneous.

With the d.c. power boost

When the power boost is present after the fault clearing, the recovery of the d.c. voltage is almost instantaneous.

The power boost after the fault clearing

$$\Delta P_{do} = 0.6 \text{ p.u.}$$

The duration of power boost is 10 cycles.

The point-by-point of swing curve calculations are carried out in Table 9.

Case D:(ii)

On replacing one A.C. line with the d.c. line and three phase to ground fault at middle of the A.C. line.

$$P_{mA} = P_{Ac1} + P_{Ac2} = 0.7$$

$$P_{d.c.} = 0.3 \text{ p.u.}$$

Before the fault

$$X_1 = 0.2+0.33+0.2 = 0.73$$

$$C_1 = \frac{1.0\times1}{0.73} = 1.37$$

$$P_{mA} = 1.37 \sin\delta = 0.7$$

$$\therefore \sin\delta = \frac{0.7}{1.37} = 0.51$$

$$\therefore \delta = 30.6^\circ$$

<u>During the fault</u> (for 8 cycles)

$$X_2 = 2.5$$

$$C_2 = \frac{1.0971}{2.5}$$

$$= .44$$

<u>After the fault</u>

The fault is cleared by isolating the faulted A.C. line after 8 cycles from the occurrence of the fault

$$X_3 = .2+.7+.2 = 1.1$$

$$C_3 = \frac{1.0971}{1.1}$$

$$= 0.997$$

<u>Without the power boost</u>

$$\Delta P_{dc} = 0$$

The calculations are carried out in Table 9.

<u>With the power boost</u>

$$\Delta P_{dc} = 0.3 \text{ p.u.}$$

Duration of power boost = 6 cycles

The point-by point of swing curve calculations are ~~are~~ carried out in table 10.

Table 1

t(sec)	C (p.u.)	sin δ	P_u (p.u.)	P_a (p.u.)	2.9 P_a (elect.deg)	Δδ (elec.deg)	δ (elec.deg)
1	2	3	4	5	6	7	8
0−	4.42	.226	1	0			13.1°
0+	0	0.226	0	1			
0_{avg}				0.5	1.45		
						1.45	
0.02	0	0.25	0	1	2.9		14.55
						4.35	
0.04	0	0.324	0	1	2.9		18.90
						7.25	
0.06	0	0.44	0	1	2.9		26.15
						10.15	
0.08	0	0.592	0	1	2.9		36.30
						13.05	
0.10	0	0.757	0	1	2.9		49.3
						15.95	
0.12	0	0.91	0	1	2.9	19.8	65.30
0.14−	0	0.995	0	1			85.1
0.14+	1.78	0.995	1.87	−.87			85.1
0.14 avg				+0.06	.17		

Table 1 continued

1	2	3	4	5	6	7	8
0.16	1.00	0.965	1.01	-0.81	-2.35	17.62	105.07
0.18	1.00	0.04	1.53	-0.53	-1.68	16.00	122.69
0.20	1.00	0.66	1.24	-0.24	-0.695	15.30	138.6
0.22	2.30	0.44	1.05	-0.05	-0.145	15.15	153.9
0.24	2.30	0.182	0.433	+0.567	+1.64		169.0

<u>Table 2</u>

t (sec)	C (p.u.)	sinδ	P_u (p.u.)	P_a (p.u.)	2.9 P_a (elect.deg)	Δδ (elect.deg)	δ (elect. deg)
1	2	3	4	5	6	7	8
0-	2.94	0.204	1	0	-	-	11.8°
0+	0	0.204	0	1			11.8°
0 avg				0.5	1.45		
						1.45	
0.02	0	0.230	0	1	2.9		13.25
						4.35	
0.04	0	0.302	0	1	2.9		17.60
						7.25	
0.06	0	0.42	0	1	2.9		
						10.15	
0.08	0	0.574	0	1	2.9		
						13.05	
0.10	0	0.744	0	1	2.9		48.05
						15.95	
0.12	0	0.9	0	1	2.9		64.00
						18.85	

Table 2 continued

1	2	3	4	5	6	7	8
0.14–	0	0.99	0	1	2.9	–	82.85
0.14+	0.942	0.99	1.25	–0.25		–	82.85
0.14 avg				0.375	1.03	– 19.93	–
0.16	0.942	0.975	1.23 (.91+.32)	–.23	–.617	– 19.31	102.78
0.18	0.942	0.85	1.12 (.8+0.32)	–.12	–.348	– 18.96	122.0
0.20	0.942	0.63	0.91	+.09	.26	– 19.22	140.96
0.22	1.19	0.342	0.768	.232	.67	19.89	160.1
0.24	1.19	0	0.36	0.63	1.84	–	17?.9

Table-3

t (sec.) 1	C (p.u.) 2	Sinδ 3	P_u (p.u.) 4	P_a (p.u.) 5	$2.9P_a$ (elec.deg) 6	Δδ (elect.deg) 7	δ (elect.deg) 8
							11.8°
0-	2.94	.204	1	0			11.8°
0+	0	.204	0	1			
avg				0.5	1.45	1.45	13.25
0.02	0	0.230	0	1	2.9	4.35	17.60
0.04	0	0.302	0	1	2.9	7.25	24.85
0.06	0	0.42	0	1	2.9	10.15	35.00
0.08	0	0.574	0	1	2.9	13.05	48.05
0.10	0	0.744	0	1	2.9	15.95	64.00
0.12	0	0.9	0	1	2.9	18.85	

Table contd.

Table 3 continued

1	2	3	4	5	6	7	8
0.14-	0	0.99	0	1	2.9	-	82.85
0.14+	1.47	0.99	2.25	-1.25			82.85
0.14 avg				-1.25	-.362	18.48	
0.16	1.47	0.90	2.24	-1.24	-3.5	14.90	101.33
0.18	1.67	0.9	2.12	-1.12	-3.25	11.73	116.31
0.20	1.47	0.79	1.96	-0.96	-2.70	8.95	120.04
0.22	1.47	0.682	1.8	-0.8	-2.32	6.63	136.99
0.24	1.47	0.593	1.69	-0.67	-1.94	4.69	143.62
0.26	1.47	0.53	1.50	-0.53		3.0	143.31
0.28	1.47	0.40	1.5	0.5	-1.45	1.55	151.3
0.30	1.47	0.457	1.47	-0.47	-1.36	0.19	152.85
0.32	1.47	0.455	1.47	-0.47	-1.36	-	153.04

Table contd.

Table 3 continued

1	2	3	4	5	6	7	8
						-1.17	
0.34	1.47	0.473	1.495 (.8+.695)	-.495	-1.43	–	151.07
						-2.60	
0.36	1.47	0.51	1.15 (0.4+.75)	-.15	-.435		149.27
						-3.035	
0.38	1.47	0.555	1.217 (0.4+.817)	-.217	-.63		146.23
						-3.66	
0.40	1.47	0.61	1.295	-.295	-.355		142.57
						-4.51	
							139.0

TABLE -4

t (sec)	C (p.u.)	sinδ	P_u (p.u.)	P_a (p.u.)	11.6 P_a (deg.elec.)	Δδ (elec.deg)	δ (elec.deg)
1	2	3	4	5	6	7	8
0-	1.625	0.615	1.0	0			38^{o}
0+	0.69	0.615	0.425	0.575			38^{o}
0 avg				0.287	3.33	3.33	
0.04	0.69	0.66	0.455	0.545	6.32	9.65	41.33
0.08	0.69	0.775	0.535	0.465	5.4	15.05	50.98
0.12	0.69	0.914	0.63	0.37	4.3	19.35	66.0

Table continued

Table 4 continued

1	2	3	4	5	6	7	8
0.16-	0.69	0.995	1.687	0.313			85.35
0.16+	1.37	0.995	1.36	-0.36			85.35
0.16 avg				-0.02	-0.232		
						19.12	
0.20	1.37	0.969	1.32	-0.32	-3.56		144.47
						15.56	
0.24	1.37	0.865	1.195	-0.183	-2.14		[illegible]
						13.42	
0.28	1.37	0.725	0.995	+0.005	+0.05		133.49
						13.47	
0.32	1.37	0.545	0.75	0.25	+2.9		140.92

TABLE 5

t (sec)	C (p.u.)	Sinδ	P_u (p.u.)	P_a (p.u.)	11.6 P_a (elect.deg)	Δδ (elect.deg)	δ (elect.deg)
0−	1.37	0.51	1	0			3[illegible].6
0+	0.44	0.51	0.524	0.476			
0 avg				0.238	2.76	2.76	
0.04	0.44	0.55	0.542	0.458	5.3	8.0	3[illegible].26
0.08	0.44	0.66	0.59	0.41	4.75	12.75	[illegible]1.36
0.12	0.44	0.81	0.656	0.346	4.0	16.75	54.[illegible]

Table cont.

Table 5 continued

1	2	3	4	5	6	7	8
0.16-	0.44	0.944	0.715	0.285			
0.16+	0.937	0.944	1.104	-0.184			7[illegible].73
0.16avg				0.05	-0.58		[illegible].73
0.20	0.937	0.996	1.255	-0.255	-2.72	16.17	
0.24	0.937	0.986	1.22	-0.22	-2.55	13.45	[illegible].58
0.28	0.937	0.93	1.172	-0.172	-2.0	10.9	3[illegible].37
0.32	0.937	0.865	1.11	-0.11	-1.28	8.9	[illegible].7
0.36	0.937	0.79	1.04	-0.04	-0.46	7.62	12[illegible].27
0.40	0.837	0.71	0.96	+0.04	+0.46	7.16	[illegible]7.79
							134.95

TABLE-6

t (sec)	C (p.u.)	sinδ	P_u (p.u.)	P_a (p.u.)	11.6 P_a (elect.deg)	Δδ (elec.deg.)	δ (elec.deg)
1	2	3	4	5	6	7	8
0−	1.97	0.51	1	0			[illegible]
0+	0.44	0.51	0.524	0.476			
0avg				0.[illegible]	2.76	2.76	
0.05	0.44	0.55	0.542	0.4[illegible]	5.3	8.0	[illegible]
0.10	0.44	0.66	0.59	0.42	4.75	12.75	[illegible]
0.15	0.44	0.01	0.656	[illegible]	4.0	16.75	[illegible]

Table continued

Table 6 continued

1	2	3	4	5	6	7	8
0.36–	0.45	0.946	0.725	0.5[illegible]			7.[illegible]
0.265	0.937	0.946	0 1.4[illegible] (.[illegible])	-0.4[illegible]			7.[illegible]
0.26avg							
				-.1	-1.16	13.99	
0.[illegible]	0.937	0.997	1.5[illegible]	-2.3[illegible]	-6.2	9.59	[illegible]
0.[illegible]	0.937	0.995	(1.992	-0.392	-6.10	3.21	[illegible].79
0.[illegible]	0.37	0.99	1.[illegible]	-0.[illegible]	-6.1	-2.89	[illegible]
0.32	0.937	0.992	1.29	-2.19	-2.67	-3.96	[illegible]
0.15	0.937	1	1.257	-0.257	-2.75	-8.11	[illegible]
0.40	0.937	0.99	1.227	-0.127	-2.64		[illegible]

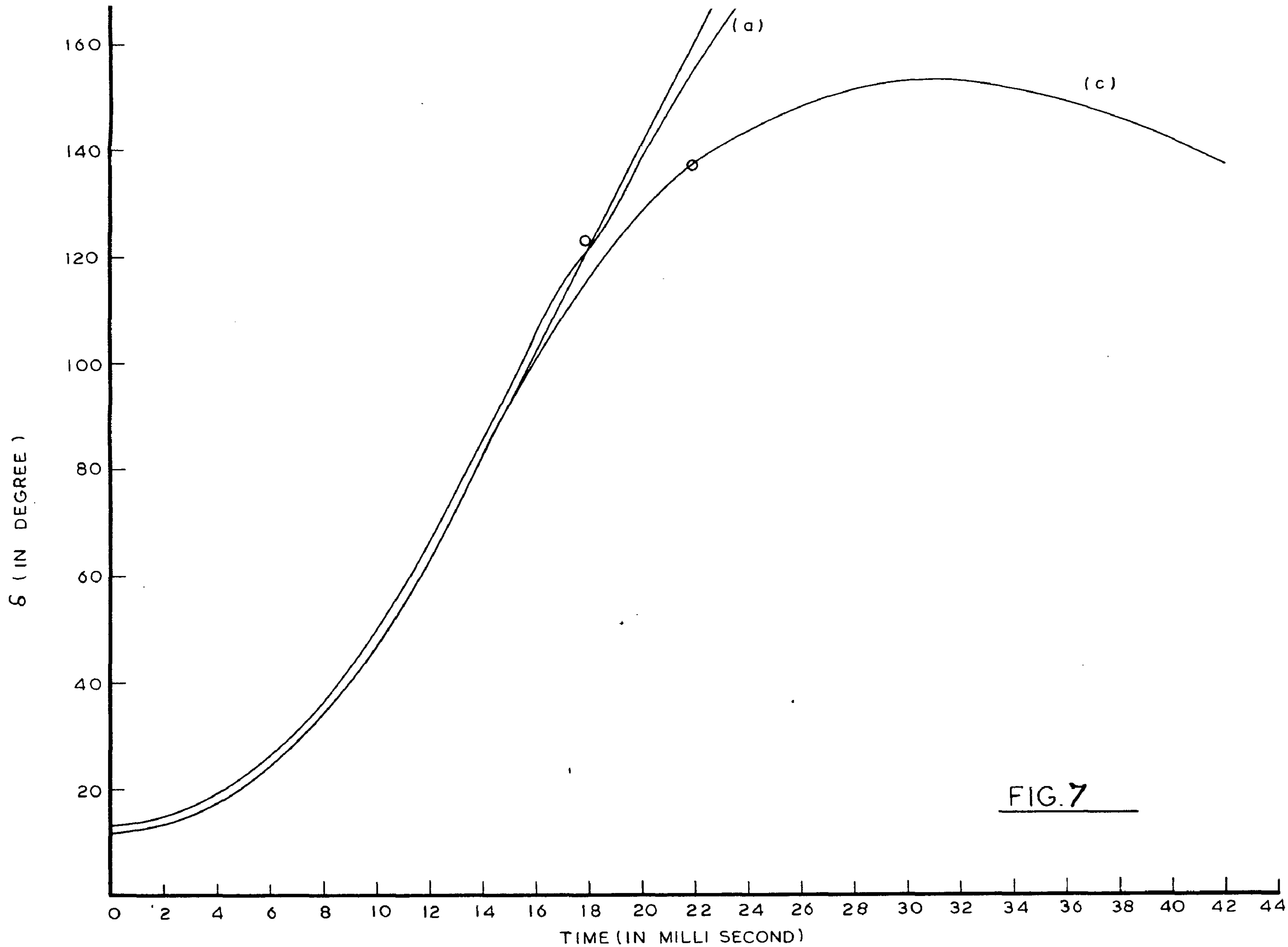

160
140
120
100
80
60
40
20
δ (IN DEGREE)
(a)
(c)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
42
44
TIME (IN MILLI SECOND)

FIG. 7

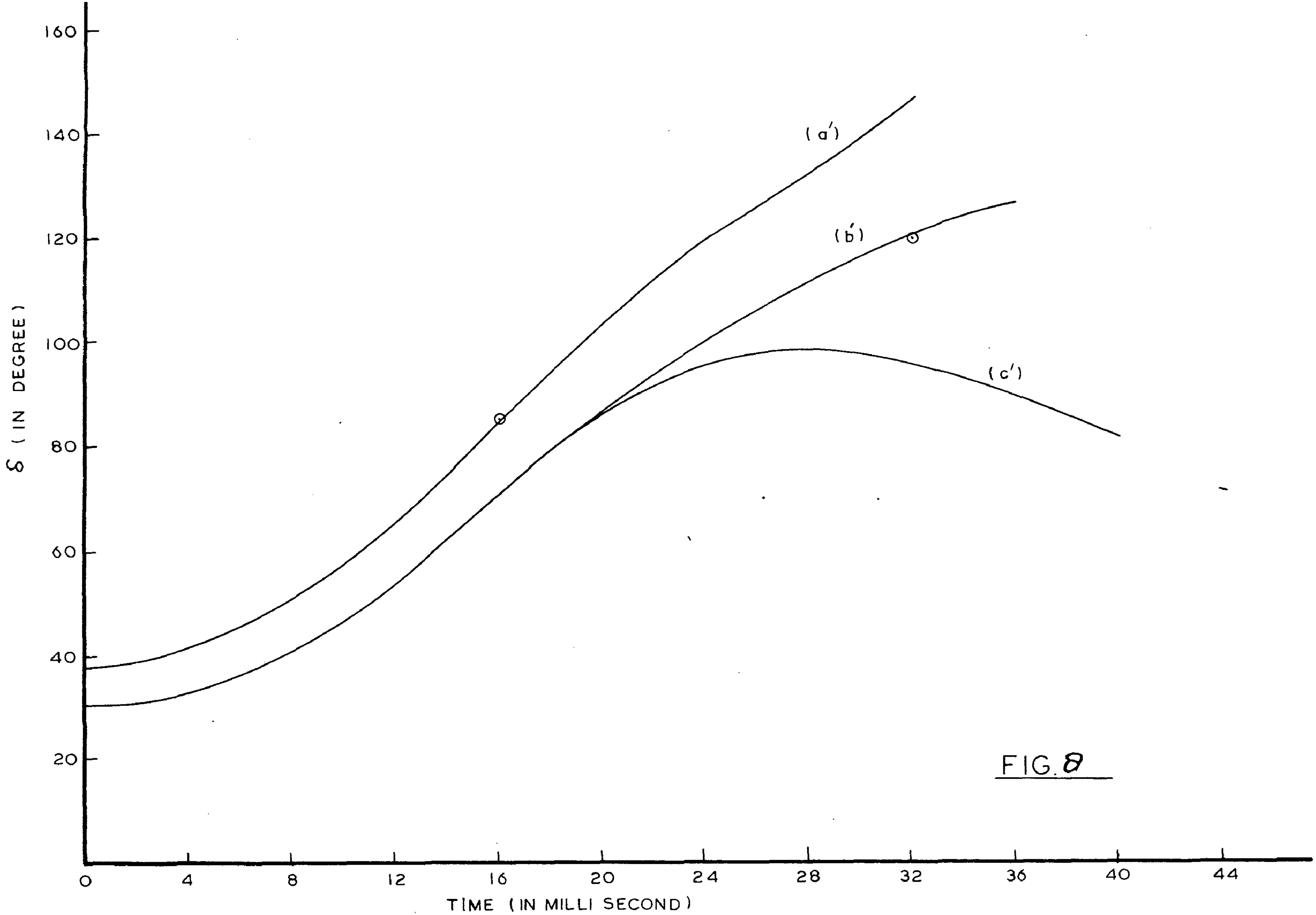

δ (IN DEGREE)
160
140
120
100
80
60
40
20
0
4
8
12
16
20
24
28
32
36
40
44
TIME (IN MILLI SECOND)
(a′)
(b′)
(c′)

FIG. 8

RESULTS

1. In the case of a fault at rectifier bus the curve a,b, c in fig. 7 are drawn for the swing curves tabulated in Tables 1,2, and 3 respectively.

Curve a - with no transmission tie

Curve b - with d.c. transmission tie

curve c - with d.c. transmission tie equipped with a power boost for 0.2 sec after the isolation of the 7 cycles fault on the a.c. line.

The curves a and b shows that in this case the system is unstable.

The curve c, indicates that the system is stable. Thus when the d.c. tie line is connected in parallel with the A.C. line and there is a power boost in the d.c. line even for a short interval after the fault isolation, the system is stable.

2. In the case of a fault at middle of the a.c. transmission line the curves a', b', and c' in the fig. 8 are drawn for the swing curves tabulated in table 4,5 and 6.

Curve a' - with no transmission tie.

Curve b' - with D.C. transmission tie.

Curve c' - with d.c. transmission tie equipped with a power boost for 0.2 second after the isolation of 8 cycles fault on the a.c. line.

The curves a' and b' indicate that the systemis unstable.

Thus the system which is unstable without d.c. line is unstable too with the D.C. line without power boost.

The curve C' indicates that the system is stable. Thus when the d.c. tie line is connected in parallel with the A.C. line and there is a power boost in d.c. line even for a short interval after the fault isolation, the system is stable.

CHAPTER V

CONCLUSION

In this study stability improvement is ascertained by utilizing the fast controllability of the d.c. power transfer in compensating for the inherently slow response of the a.c. system subjected to a major disturbance. It is, however, unlikely that the d.c. transmission tie will be built and operated well below its full capacity while the remaining capacity is reserved for cases of occurrence of severe disturbances within the network. From the swing curves calculated, it is clear that this additional power transfer after the fault, even if for a small time interval, can provide sufficient effect to speed up the system response in reaching a new state of equilibrium and to make the assumption of constant voltage more valid. This is also of important due to the fact that most d.c. tie can withstand as much as double rated load current for a small interval.

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