DYNAMIC SIMULATION OF H.V.D.C. SYSTEM ON COMPUTERS

by

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A Dissertation
submitted in partial fulfilment
of the requirements for the Degree
of
MASTER OF ENGINEERING
in
POWER SYSTEM ENGINEERING

1968

ELECTRICAL ENGINEERING DEPARTMENT
UNIVERSITY OF ROORKEE
ROORKEE
(INDIA)

C E R T I F I C A T E

Certified that the dissertation entitled "DYNAMIC SIMULATION OF H.V.D.C. SYSTEMS ON COMPUTERS" which is submitted by Sri Suresh Chandra Katiyar in partial fulfilment for the award of Degree of Master of Engineering in POWER SYSTEM ENGINEERING of University of Roorkee is a record of student's own work carried out by him under our supervision and guidance. The matter embodied in this dissertation has not been submitted for the award of any other Degree or Diploma.

This is further to certify that he has worked for a period of 8 months from January to August,1968 for preparing dissertation for Master of Engineering Degree at this University.

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A C K N O W L E D G E M E N T S

I am deeply grateful to my respected advisers Dr.T.S.M. Rao, Professor and Head, and Sri S.M. Peeran, Reader, both of Electrical Engineering Department, University of Roorkee, Roorkee, for their continuous assistance, guidance and encouragement in all phases of investigations.

I also express my sincere thanks to Prof. H.K. Kesavan Head, Computer Centre, I.I.T. Kanpur for providing various facilities in Computer Centre.

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ABSTRACT

The present work gives an introduction to HVDC systems and the method of simulation of HVDC system on digital and anolog computers in a dynamic manner. The introduction also includes a list of hvdc projects and their experiences, main testings laboratories and stations and the necessity of dynamic simulation. Due to repetitive nature of the digital technique, it has been given the name "Repetitive Process" by the author and is similar to the 'Central Process' developed by Hingorani, Hay and Crosbie. Since valve actions are similar and repetitive in nature, the repetition of one such process enables one to simulate the continuous operation of the convertor. 'Repetitive Process' can be adopted in four different manners. The four different ways depend upon analytical and numerical state variable approaches using circulating current or voltage drop calculations for defining the state of convertors at particular instant. State of convertor here means that whether the convertor is commutating or not. The technique is capable of giving voltage and current wave forms anywhere in the system under normal and abnormal conditions. For simplicity T-section of transmission line connecting two infinite a.c. sources, having a single bridge at each end has been considered. In addition to this convertor control systems, same as in central process representation have also been taken into account. The programs based upon the above techniques have been tested on digital computer IBM 7044, at I.I.T. Kanpur. Starting transients have also been studied on the above computer. An attempt has also been made towards dynamic simulation of HVDC system on Analog computer at the [illegible]. Summary and conclusions give the comparison of different methods of simulation and further studies possible.

List of Contents

NOMENCLATURE

1. Id_1, Id_2 = Instanteneous d.c. line currents.
2. i_1, i_2 = " circulating currents.
3. e_{1a}, e_{1b}, e_{1c} & e_{2a}, e_{2b} & e_{2c} " phase voltages.
4. i_{1a}, i_{1b}, i_{1c} & i_{2a}, i_{2b}, i_{2c} " phase currents.
5. Vd_1, V_{d2} = " terminal voltage at the end of convertors.
6. Vc = " mid point voltage of T-secti... of line.
7. l_1, l_2 = Transformer winding indunlances.
8. r_1, r_2 = Transformer " resistances.
9. L_{11}, L_{22} = Series impedance of T-section of line including the indudtance of smoothing inductors.
10. R_{11}, R_{22} = Series resistance of T-section of line including the indudtance of smoothing inductors.
11. C = Capacitance of whole line simulated at mid point of line.
12. α_1, α_2 = Angles of delay in firing.
13. $Id_1(o), Id_2(o)$, VC(o) = Values of Id_1, Id_2 & VC at t = 0.
14. W_1, W_2 = Frequencies of a.c.systems.
15. L_1, L_1 = Values of L_1 (defined in text) during commutation and noncommutation respectively.
16. R_1, R_1 = Values of R_1 " "
17. L_2, L_2 = Values of L_2 " "
18. R_2, R_2 = Values of R_2 " "

The subscript 1 represents quantities for convertor ... and subscript 2 represents quantities for converto...

1. INTRODUCTION

1.1. NECESSITY OF HVDC TRANSMISSION SYSTEM:

The modern EHV a.c.transmission suffers from the drawback of problem of stability, which is dependent on length of line and number of circuits used. In case of long a.c. lines suitable series and shunt compensation has to be provided for satisfactory operation of transmission line. Series capacitors reduce the reactance of line thereby increasing the capability of the line. Shunt reactors are necessary to keep the receiving end voltage or no load within limits(1). If synchronous condensers are used, the MVAR capacity required is almost comparable to the MWS transmitted. Inherently stable and economical alternate is HIGH VOLTAGE DIRECT CURRENT POWER TRANSMISSION which has been universally adopted at present for bulk power transmission. Economical bulk power transmission over long distance, non-synchronous operation, limited fault and low charging currents, interconnection of different frequency grids and earth and sea return are the encouraging factors for the adoption of hvdc power transmission.

An interesting characteristic of hvdc transmission is that d.c.transmission can itself determine the power transmitted, independently of power and frequency control of the power stations of the systems connected. The power transmission can be controlled by the transmission equipment itself, either by hand or automatically, whereas the a.c.power transmitted is entirely dependent upon measures taken in the interconnected power stations. It can not be said offhand that this is a disadvantage to the a.c. transmission, but in hvdc greater flexibility implies a new degree of freedom, which in some cases, would have operational superiority, if desired it would be certainly possible to give d.c. transmission such a program for its automatic regulation that it would behave like an a.c. transmission system(2).

The ground, in all practical cases, can be used as an effective return conductor, and its use as regular or as an emergent conductor, may imply considerable advantage. There is today no other limit to the voltage and power of an hvdc transmission than that set by the insulation of transformer and line.

1.2. HVDC TRANSMISSION SYSTEMS:

The main equipments of hvdc transmission systems are the convertors required at both ends and at any tapping of a d.c. transmission line. In addition to these smoothing reactors, several control and protection devices are also essential parts of hvdc transmission system. The control system is capable of meeting various voltage and power requirements. The grid controlled mercury arc tube with grading electrodes has proved to be a suitable valve in the convertors. Mercury arc valves are not available for very high voltage rating, maximum voltage does not exceed 200 kv at present. The usual connection of valves is 3 phase bridge connection, also known as Graetz Connection. This provides best utilization of transformer. Silicon controlled rectifiers are under development which may replace mercury arc rectifiers in future. HVDC terminal stations may contain more than one valve bridge. There is general tendency now-a-days that where d.c.terminal station is to contain more than one bridge, they will be connected in series, as against the universal practice of parallel connection in case of a.c. stations. This is because of the fact that series connections of valve bridges facilitates taking 'out' and 'in' of a bridge in case it develops a fault. A bypass valve is also connected across a.c. terminals of each bridge to help putting 'in' or 'out' of a particular bridge in the circuit[3]. The basic bridge configuration is shown in Fig.(1.1). The different types of HVDC transmission systems has been shown in the Fig.1.3). The obvious advantage of system shown Fig.(1.3d) is that where one terminal station develops a fault, the supply of the power can be continued through other terminal and earth.

The construction of electrode station is the main technical problem when earth or sea has to be used as

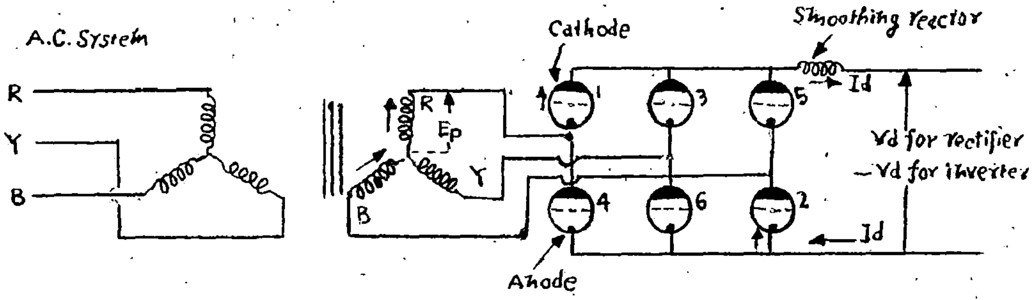
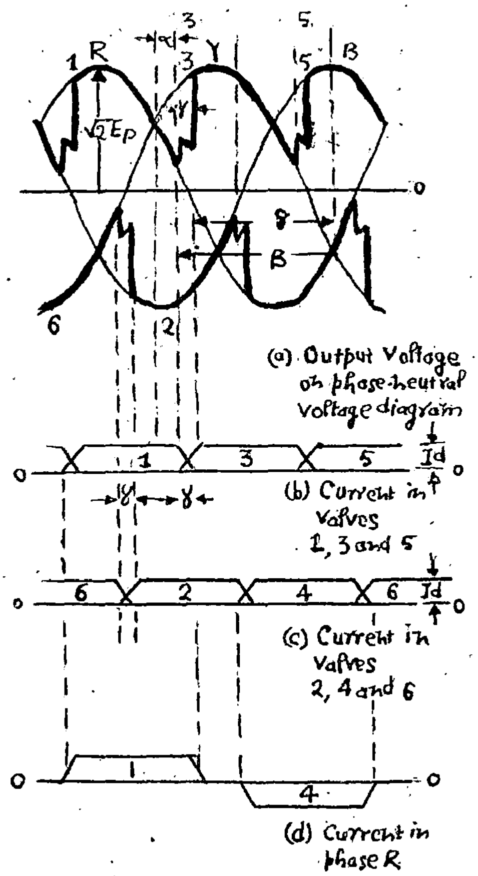


FIG (1·1) VALVE ARRANGEMENT



OPERATION AS RECTIFIER

FIGURE (1·12)

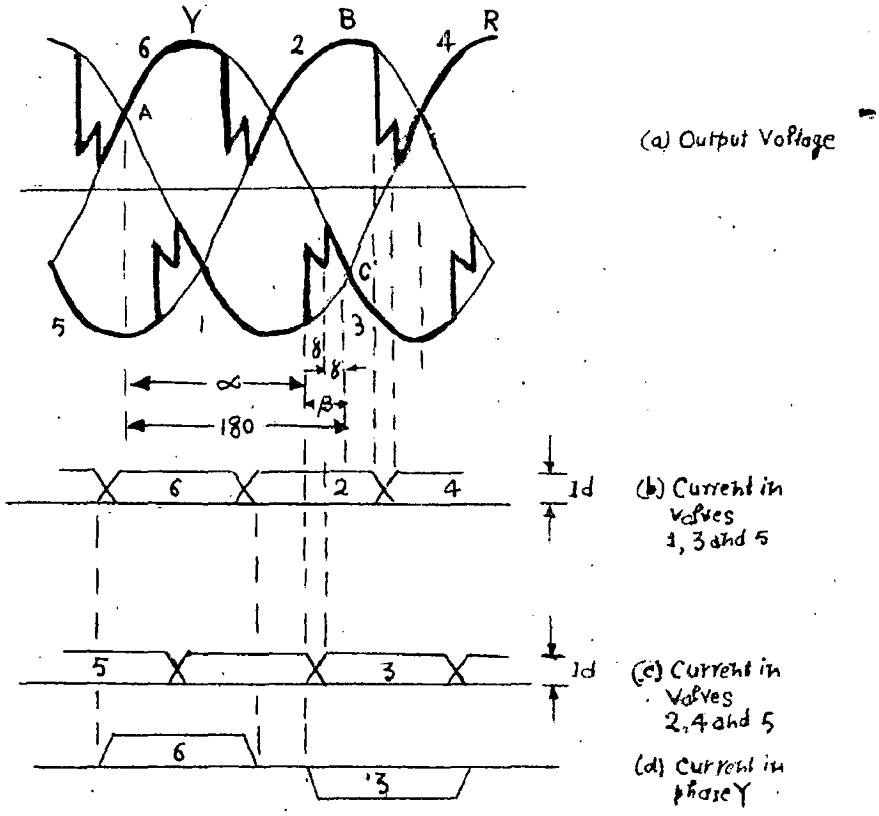


FIGURE (1.13)

OPERATION AS INVERTER

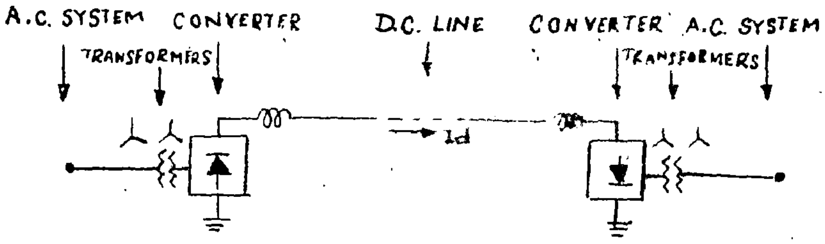


FIGURE 1·3 (a)

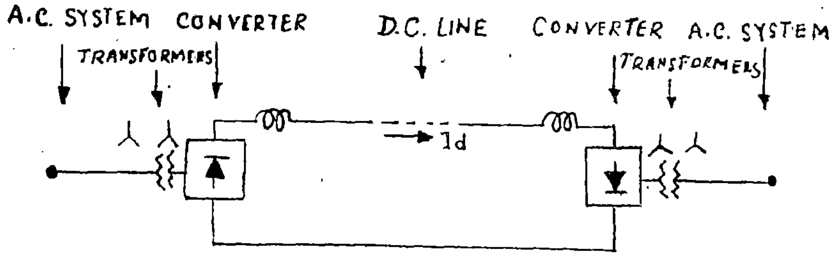


FIGURE 1·3 (b)

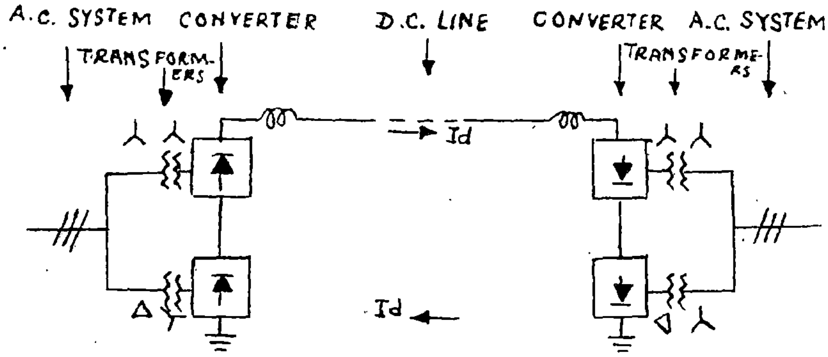


FIGURE 1·3 (c)

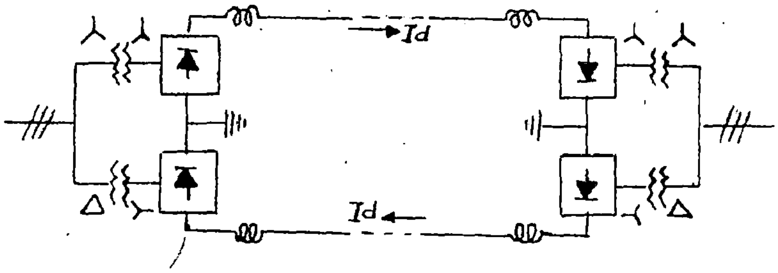


FIGURE 1·3 (d)

TYPES OF H.V.D.C. SYSTEMS

return. Conditions at two electrodes, the positive and the negative are, however, widely different. At the positive electrode, the anode, special provision must be made to avoid excessive loss of material by electrolytic corrosion. At the negative electrode, the cathode, on the other hand, no corrosion problem arises.

The two Figs.(1.12 and 1.13) show the operation of rectifier and invertor. The resulting current and voltage waves are also shown[4].

1.3. PARALLEL A.C.-D.C.SYSTEM[4]

In a parallel a.c. and d.c. system as shown in Fig.(1.15), power is transmitted jointly by a.c. and d.c. lines and total transmitting capacity is divided between the two. In existing A.C.systems, insertion of only one d.c.link will form this system. It does not involve as much cost as would be necessary to convert whole of the existing system into a d.c.one.

It is obvious that parallel (combined) a.c. - d.c. system will increase steady state power limit to a much higher level. This much increase in power level was not possible by a.c. single or double circuit system.

Under transient conditions, the effective control of d.c. power flow can be employed to raise stability limit. This is because of the fact that d.c. power can be changed more promptly simply by exercising the control of the firing angle. It is also noted that greater the initial d.c. power, greater is the improvement in stability observed.

In a.c. interconnected system, the fault current increases as the number of interconnections increase. But if a d.c. link is introduced in the neighbourhood, the contribution to the fault current through the d.c. link is limited, the total fault current is reduced.

1.4. REQUIRED REGULATION AND SYSTEM OPERATION:[5,6]

1.4.1. Required Regulation:-

Safety of operation and flexibility of are main requirement of control. It is important that the valves should be operated strictly within their current rating since there is substantial risk of damage if the current is increased beyond the rated value even for a short time. Constant current regulation is clearly desirable. If the reduction of invertor back voltage tends to increase the current to a large value, the rectifier grid control should rapidly increase the angle of firing thereby reducing the rectifier output voltage to such a value that the current is maintained constant or kept within the prescribed limit. In addition to constant current control, rectifier must be provided with automatic tap. Changing to keep α within the limit, say $10^0 < \alpha < 20^0$. This is done so as to achieve higher power factor at sending end.

On the other hand the invertor must be provided with a control such that its extinction angle δ_e , the angle between end commutation and following voltage zero of the commutating voltage is always minimum but somewhat in excess of deionization angle δ_o of a valve. It is assumed that deionization angle δ_o of a valve is constant, the extinction angle δ_e should be constant and slightly more than δ_o. Such a control is known as "Constant Extinction angle control" or 'CEA control'. It has also been considered preferable to provide in addition, a constant current regulator for invertor control, so that when current tends to decrease to its set value the angle of extinction is advanced further that what is needed for CEA control. This CEA control helps also in keeping reactive power requirement at receiving end minimum.

1.4.2. System operation:-

Let us consider a system of two convertors, one at each end (Fig.1.5). The convertors are provided with CEA and CC controls. If C.C. control setting of convertor A is in excess of the setting of convertor B, by a margin Idsm, the operating characteristics of the system is given by Fig.1.6. For the comparison, the characteristic of the convertor B has been turned upside down and the current in d.c. line is given by the point of intersection X_1 of the characteristics of two convertors. As seen A operates as a rectifier and B operates

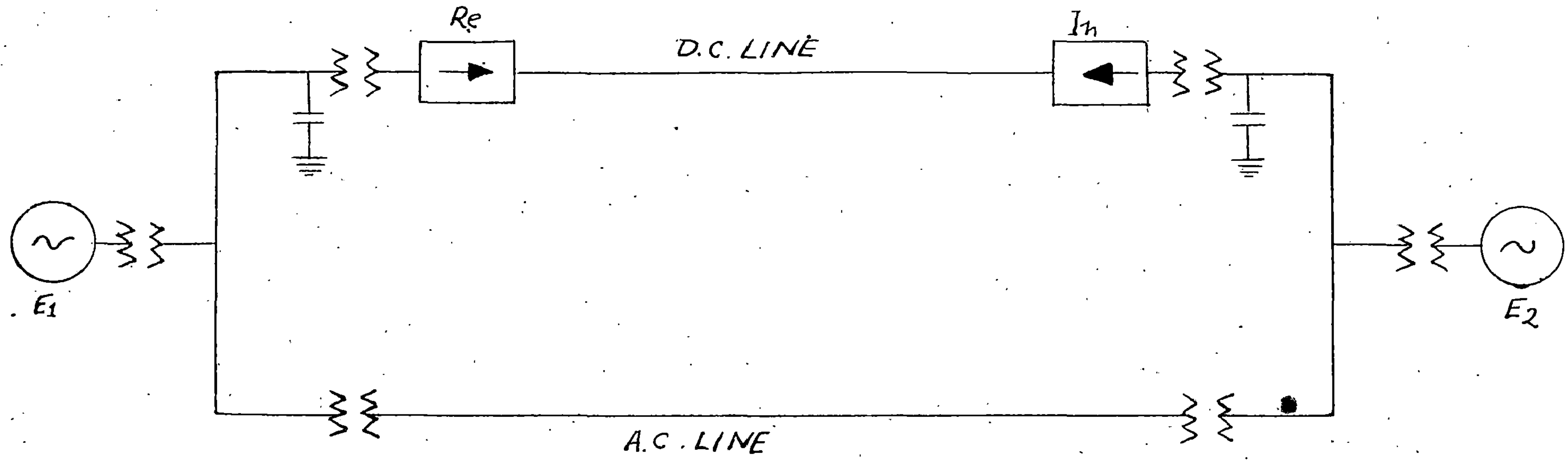


FIG (1·15) PARALLEL A.C. AND D.C. SYSTEM

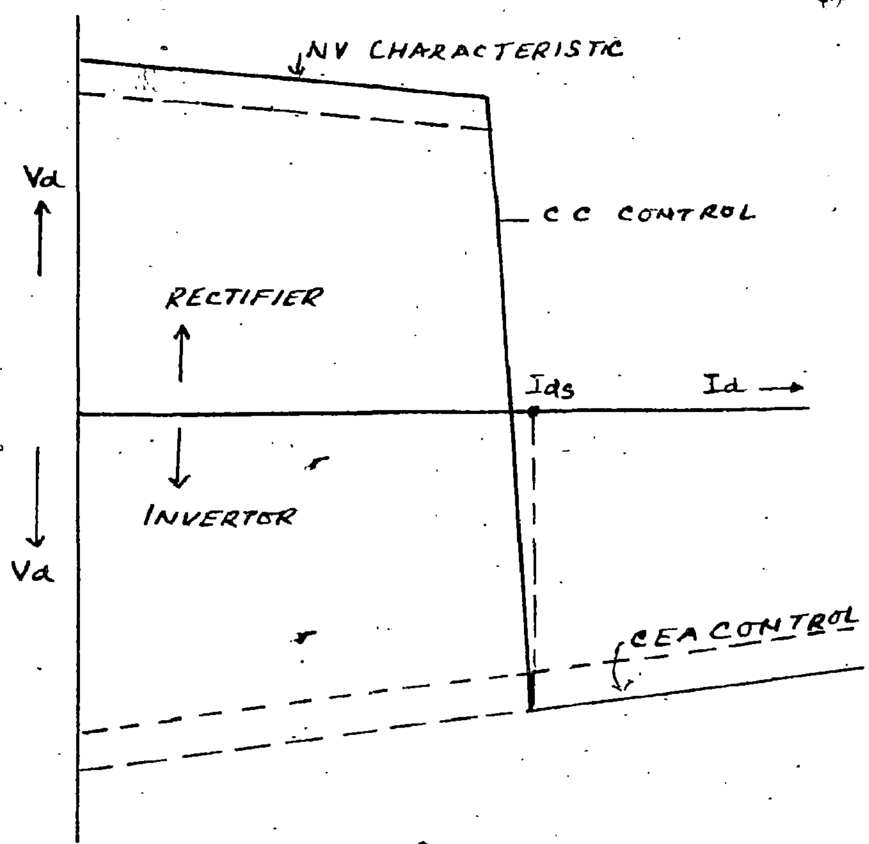
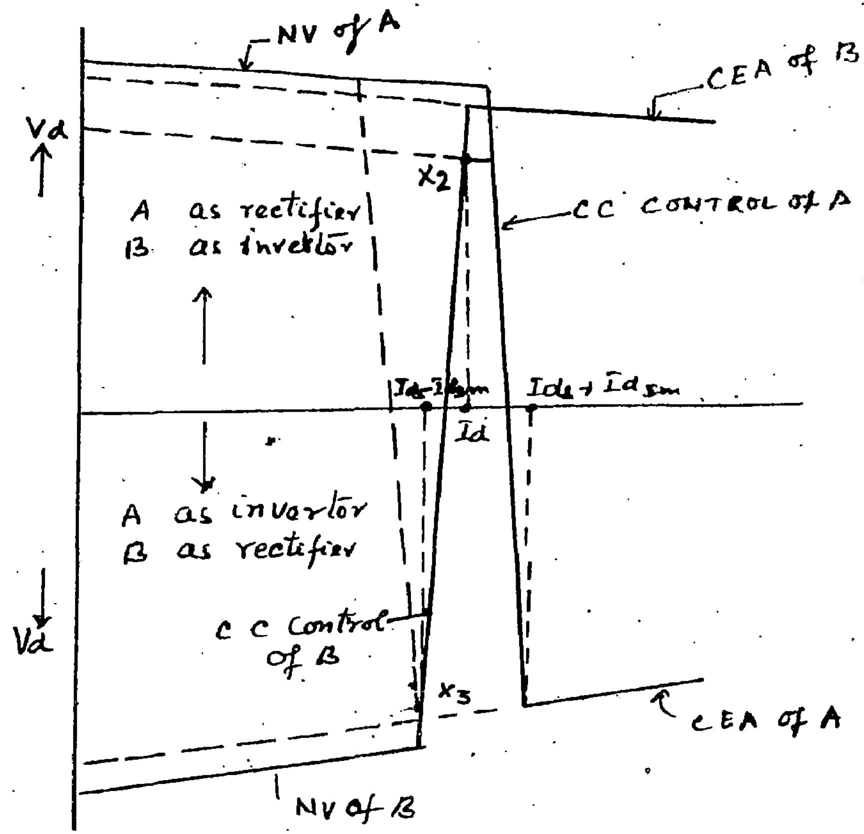
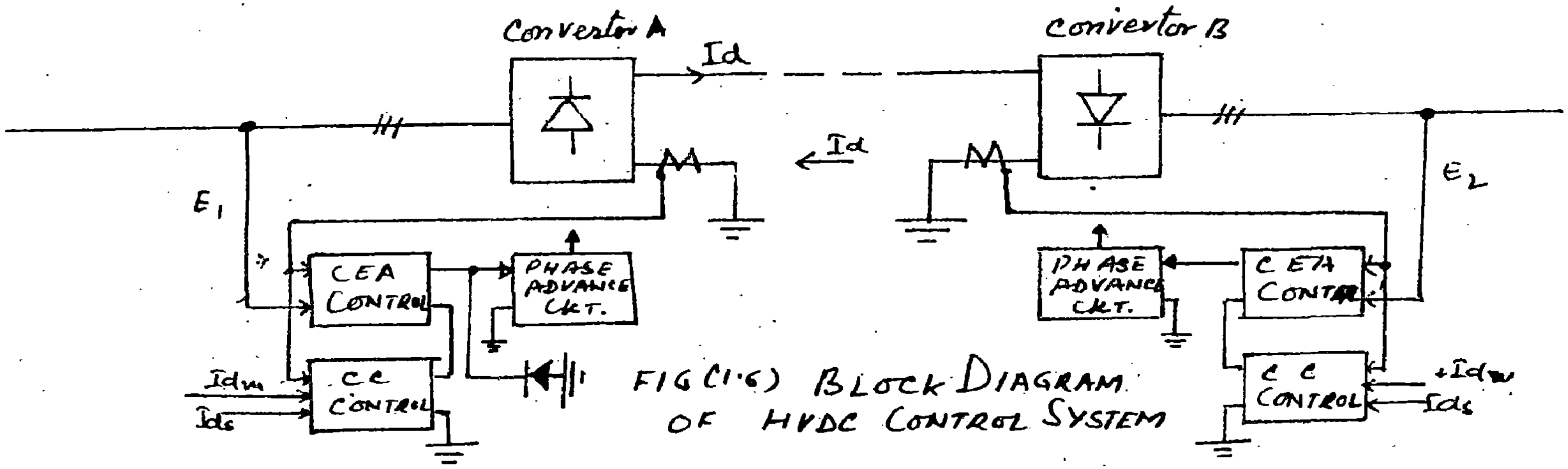


FIG FIG(1·5) COMPLETE CONTROL OF CONVERTOR FROM INVERSION TO RECTIFICATION



FIG(1·7) OPERATION OF HVdc System



FIG(1·6) BLOCK DIAGRAM OF HVDC CONTROL SYSTEM as an invertor. Also it is seen that when NV characteristic of A is higher than CEA characteristic of B, converter A operates on C.C. control and B on CEA control. This is because of the fact that the current is larger than the C.C. control setting of B. Whereas the current at A is sufficiently below the C.C. setting of A, so that it works on the CC characteristic on rectifier side of its operation.

However, due to fluctuations in a.c. voltage if NV characteristic falls below CEA characteristic of B, convertor A will operate on MV characteristic and B on CC control (point x2). Converter A will continue to operate as rectifier and converter B as invertor and steady state current under all circumstances will remain within the upper limit Ids + Idsm and lower limit Ids i.e. the system current will not change by more than Idsm.

By reversing the margin setting i.e. making the current setting of the converter B to exceed that of A, power flow can be automatically reversed. Converter B will now operate as rectifier and A as inverter; the reversal of power occurs as a result of the reversal of polarity (point x3 in Fig.1.7).

It is obvious that any mode of power control can be obtained by suitable controller to vary the current setting Ids of both convertors (involving a communication link). Margin setting will be set positive and negative according to the required direction of power flow.

1.5. HVDC POWER TRANSMISSION PROJECTS AND THEIR EXPERIENCES[7]

1.5.1. HVDC Power Projects in commission or under construction:

Year of inception	Country & Location	Voltage between poles bus	Length of Route miles			Power transmitted MW	Remarks
			Cable	OHL	Total		
(a) PROJECTS IN COMMISSION:							
1950	USSR (Moscow-Kashira) (Experimental only)	200	-	-	72	30	Mercury Arc Valves

1954	Sweden(Mainland-Gotland Link)	100	61	-	61	20	Two anode mercury valves, Earth return.
1961	England-France (Cross-Channel-Link)	200	34	-	34	160	Four anode mercury arch valves
1965	New Zealand (South-North Island)	500	25	300	385	600	Four anode mercury arch valves. Three cables, one laid-spare.
1965	Konti-Skan Scheme (Sweden-Denmark Across Island of Laeso)	250	46	56	102	250	Four anode arc valves, single cable earth return
1965	Japan(Sakama Frequency Changer)	250	-	-	-	300	Multianode mercury arc valves conversion from 50 c/s to 60 c/s and vice-versa.
1963	USSR(volgagrad Donbass)	800 (Final stage)	-	-	295	750 (Final stage)	Single anode mercury arc valves.

1.5.2. Projects Under construction:-

Year due							
1967	Sordinia Italy (Via Corsica)	200	95+64	31+ 100+ 54	2585	200	Four anode mercury arc valves single pole, earth return, but two conductors and two cables
1967 (1st stage) 1968 (2nd stage)	Canada Vancouver(Mainland of Canada)-Vancouver Island	130 (1st stage) 260 (2nd & 3rd stage)	17.5	25.5	43	78 (1st stage) 155 (2nd stage) 312 (3rd stage)	Multianode mercury arc valves, single pole earth return
1968	United States: 1st pacific coast intertic (Celilo, Oregen to Los Angles)	800	-	875	875	1440	Multianode mercury arc valves double pole
1971	United States 2nd Facific Coast Intertic(Celilo, Oregen to Mead)	800	-	875	875	1440	Multianode mercury arc valves, Double pole.
1971	England London Kingsnorth Project	532	51	-	51	640	Double pole, Three converter stations.

Long distance power transmission has been revolutionised by the ASEA hvdc equipment. The first line using this method was commissioned in 1954. Today 'ASEA' HVDC links combine all the power resources in western Europe to form one giant network, rationalise the power supply in Japan and give the North Island of Newzealand access to the invaluable power resources of the south Island. In the next few years 'ASEA' HVDC links will solve important power supply problems in Canada and the U.S.A. The total power transmitted by 'ASEA' and its licensees will then amount to about 5400 MW. 'ENGLISH ELECTRIC' is to supply the converter station electrical equipment to the Central Electricity Generating Board for the new 640 MW Kingsnorth-London DC Link.

1.5.3. Experience with existing D.C. links: (8,9)

It is perhaps appropriate here to preface some notes on the ensuing discussion by surveying experience gained on the existing d.c. links, as it was gathered at CIGRE.

The Gotland Link: connecting the island of Gotland with the mainland of Sweden (1954; 100 Km., 100 KV, 20 MW) continues to operate satisfactorily, after more than 12 years in service. The arc back frequency has fallen from 2.5 per valve group per operating month in 1964 to 0.7 in 1965. Valve maintenance seems to desirable although in no way necessary - after every five years operation. The anodic station at Vastevik has electrodes suspended in water from wooden frames. The walls of pools are here made of rather large boulders which gives plenty of water filled cavities. Water can then easily penetrate the pool and natural changes in sea level and the waves will give a washing out of the pool.

The England France Link: (1961; 56 Km, 200 KV, 160 MW), has not in recent years suffered a recurrence of the accidental faults on the submarine cables, nor the transformer faults that effected the French end of the link, during its early years of service. It now appears to be operating satisfactorily. The basic components - the valve themselves - are continuing to operate smoothly after more than four years' operation. There has never been a "permanent" fault in any high voltage valve.

There have, however, been a number of faults on miscellaneous auxiliary equipment. Interference on the control link coupling the two ends gave rise to trouble with the coding equipment concerned with load flow control, but this has been rectified.

The Volgagrad Donbass Link: (1963; 480 Km,800 KV, 750 MW) is now reported to operating at full power, but Russian engineers do not yet seem ready to provide details of commissioning and operating experience so far. They are, however, said to be considering a number of other d.c. schemes, for long distance transmission east and west across Russia, probably linking with high voltage a.c. connections running north and south.

The Sweden-Denmark (Konti-Skan) Scheme (1965, 165 Km, 250 KV 250 MW) is operating to the satisfaction of the two countries, and has in fact on more than one occasion been worked at a considerable overload. Some relatively minor problems have been experienced. Flashovers occurred at the Danish terminal end, probably due to salt pollution on the insulators. This was cured by increasing the insulation and by greasing the insulation with silicone grease. There had been some problems at the Swedish end with high inrush current in the convertor transformers. A first attempt to solve this problem, by fitting the appropriate circuit breaker with damping resistances, was successful. Further measures are being investigated. But this is not specially a d.c. problem, it has been found to apply to many other large modern transformers. At an early stage of planning, it was decided that the current in the sea cables should always flow from east to west i.e.from Sweden to Denmark. This means the magnetic field due to the current is always in the same direction of natural magnetism of the earth, thus causing least inconvenience to shipping. The reversal of power transmission will have to be affected by reversal of polarity rather than reversal of direction of current. With this arrangement the electrode on the Denish Side is always anode and that on Swedish side is always the cathode. The latter station could therefore be very simple and it consists, as on Gotland Link, of about 300 meters of noninsulated copper cable, laid on the sea bed.

Number of electrode wells is 25, which were considered adequate from a current carrying point of view. Due to the rather special conditions of the chosen site (wide areas of shallow water) natural washing out of a pool would have been quite inadequate, and it was therefore have been necessary to pump sea water to the pool. PVC (polyvinylchloride) piping has proved satisfactory for continuous circulation of water.

The Sakuma Frequency Changer, in Japan (1965; 250 KV, 300 MW) has been operating satisfactory, with interchange taking place in both directions.

The New Zealand North to South Island Project (1965; 620 Km, 500 KV, 600 MW) is in operation, although as the whole of filter banks were not in commission at the time of the CIGRE meeting it was working at half power. There had been some backfires on the valves, although they have not interferred with operation, and the valve manufactures are working intensively on development work to endeavour to effect a permanent remedy.

The operating experience gained from five of the six hvdc schemes so far in commission may be regarded as highly satisfactory: it is to be hoped that before long Russian engineers will be able to report on equally satisfactory experience with sixth scheme.

1.6. MAIN TESTING LABS' AND STATIONS:(10,11)

1.6.1. Major H.V.D.C. Testing Stations (employing high power and high voltage)

SWEDEN	Trollhattan and Ludvika (ASEA)
USSR	Direct current Institute, Leningard
Great Britain	Marchwood (C.E.G.B)
U.S.A.	Bonnevelle Power Administration, General Elecric Company, Schenectady

1.6.2. H.V.D.C.Laboratory Centres and experimental stations:

CANADA	Shawinigam Engineering Co.
GREAT BRITAIN	Manchester College of Science and Technology, Imperial College, London University

GERMANY	Rheinau
JAPAN	Central Research Institute of the Japanese Electric Power Industry The Electrotechnical Laboratory(E.T.L) of the Ministry of International Trade and Industry.
U.S.A.	The Edison Electric Institute Research Project (A.C/D.C. Parallel Operation)

1.7. NEED OF HVDC TRANSMISSION IN INDIA:[12]

The present transmission arrangements depend heavily on systems of radial feeders. Interconnection on a provincial basis, with a view to improve the present poor continuity of supply, saving standby plant and augmenting energy output by utilising diversity in rainfall and waterflow conditions. A national grid is also under consideration at present and it may be feasible after siting of base load stations. The CWPC is now carrying out an investigation to find the total water power potential in our country. This investigation is now being carried out for the whole of India from Cape Comorin to the Ganges Valley; the hydro potential of north has yet to be fully studied but the enormous potential of one of these rivers, the Brahmaputra, is well known. Even in south India, some of the hitherto unsuspected resources of water power have surprised the engineers responsible for the survey.

At present, many of the more readily accessible hydro sites are being exploited, some of which are low head stations on canals and coal fired stations are being built in the coal-fields. Some of latter are part of integrated hydro/thermal systems, such as the one in Damodar Valley in Bihar, and there are big projects such as Bhakra in the Punjab, and the Combined Hirakund Tikkapara-Naraj Scheme in Orissa. These schemes consume the efforts of India and her engineers at the present time. There is a certain amount of apprehension about the rate of growth. The questions of the possibility of harnessing and transmitting larger blocks of power, the possibility of obtaining marginal advantages from d.c. as against a.c. transmission under certain circumstances and the establishment of a national grid, are not yet considered. This does not mean that our engineers are not aware of advantages of greater d.c. system interconnection, or, for example, of making available the potential of Brahmaputra to the industries of north - eastern India by h.v.d.c. transmission. However, forward planning does not, at present, extend this far.

1.8. NECESSITY AND METHODS OF SIMULATION:

Realisation of speed and flexibility of h.v.d.c. control, switching operations, voltage and current transients, changing conditions, effect of different parameters on these and to obtain control parameters for stability under all conditions and many other aspects are leading to an increasing interest in the simulation of hvdc transmission system in a dynamic manner. For this the use of laboratory physical models of basic rectifier and invertor link is well established. Such models are particularly useful in examining filter over-voltages and valves' stresses (where exact transient analysis is difficult) and in the development of control circuits. However, the laboratory models have the inherent drawback, that the study of a wide range of system configurations, parameters, control and protection devices involves building and commissioning of great deal of control equipment, cost and time. A digital computer program, where parameters are represented numerically provides for many problems a flexible, accurate, economical and quick alternative to physical model.

The analogue representation given in fourth Chapter also forms a convenient flexible and experimental method of finding the dynamic response of H.V.D.C. system.

1.9. 'CENTRAL PROCESS' REPRESENTATION:[13]

One method of simulation, developed by Hingorani, Hay and Crossbie, is given below for the sake of comparison with the author's methods.

A central process can be mathematically represented on a digital computer by first order differential equations, for solution by step by step numerical methods. At any given time, a convertor and hence the central process, can be in only one of two possible conditions

(i) Commutating
(ii) Non-commutating

From loop aACc, when $i < Id$

$$eab + ebc = i2R + \frac{di}{dt}.\ 2L - IdR - \frac{dId}{dt} L \quad \ldots\ldots\ldots\ldots (1)$$

and from loop aABb

$$eab = iR + \frac{di}{dt} L + IdR + \frac{dId}{dt} L + Vd \quad \ldots\ldots\ldots\ldots (2)$$

When the commutating current i increases to become equal to Id, it indicates that the convertor changes to state (ii). The arm of the equivalent circuit valve is made inaffective by the equations.

$$Id = i \quad \& \quad \frac{dId}{dt} = \frac{di}{dt} \quad \ldots\ldots\ldots\ldots (3)$$

This equation replaces the equation (1), and then equation (2) and (3) represent the system.

The complete hvdc system under consideration and its equivalent circuit, are shown in Fig.(1.8). For simplicity, only one bridge at each end is considered, and the line is represented by a T-section. However, applying the same principle a system consisting of any number of bridges and several T-sections may be represented in a similar manner. By examination, it can be seen that seven first-order differential equations can represent the complete system. Each central process will require three equations, and one equation will be required to link the central processes. The first six of these equations are basically obtained from equation 1 , 2 and 3, the last equation being obtained from fig.(1.8).

The equations are

$$eab_1 + ebC_1 = i_1 2R_1 + \frac{di_1}{dt} 2L_1 - Id_1 - \frac{dId_1}{dt} L_1 \ldots\ldots \quad (4)$$

$$eab_1 = i_1 R_1 + \frac{di_1}{dt}.\ L_1 + Id_1 R_1 + \frac{dId_1}{dt} L_1 + Vd \ldots\ldots \quad (5a)$$

Substituting $Vd = Id_1\ Rd_1 + \frac{dId_1}{dt} + V_C$ in equation (5a)

$$eab_1 = i_1 R_1 + \frac{di_1}{dt} L_1 + Id_1(R_1 + Rd_1) + \frac{dId_1}{dt}(L_1 + Ld_1) + VC \ldots (5)$$

$$Id_1 = i_1 \quad \& \quad \frac{dId_1}{dt} = \frac{di_1}{dt} \quad \ldots\ldots\ldots\ldots (6)$$

Equations 4,5 & 6 are for the central process of convertor 1, but at any instant, only two are valid (i.e. depending on the state of the convertors)

$$1ab_2 + ebc2 = i_2\, 2R_2 + \frac{di_2}{dt} 2L_2 - Id_2R_2 - \frac{dId_2}{dt} L_2 \ldots\ldots\ldots (7)$$

$$1ab_2 = i_2R_2 + \frac{di_2}{dt} L_2 + Id_2(R_2-Rd_2) + \frac{dId_2}{dt} (L_2+Ld_2)-V_C \ldots (8)$$

$$Id_2 = i_2 \quad \& \quad \frac{dId_2}{dt} = \frac{di_2}{dt} \quad \ldots\ldots\ldots\ldots\ldots\ldots (9)$$

Similarly, equations 7,8 and 9 are for central process of convertor 2_1 with only two being valid at any instant, link equation being

$$\frac{Id_1 - Id_2}{C} = \frac{dv_c}{dt} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

If the line is represented by more than one T-section, the link equation will increases by two for each additional T-section.

Seven equations represent the system under consideration, but at any time only five of these are valid. The five equations selected depend upon the states of two convertors. There are four combinations of equations which may be valid and these arise from the following possibilities:

(i) Both convertors commutating (equations 5,8,10,4 & 7)

(ii)Convertor 1 commutating while convertor 2 is not (equations 5,8,10,4 & 9)

(iii)Convertor 2 commutating while convertor 1 is not (equations 5,8,10,6 & 7)

(iv) Neither convertor commutating 1 equations 5,8,10,6 & 9)

The selection of valid equations is made by determining which commutations are completed. During commutation, the current i, is less than the direct current, and it becomes equal to it only at the completion of commutation. Therefore, the following two equations are examined:

$$i_1 < Id_1 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (11)$$

$$i_2 < Id_2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (12)$$

Hence for case (i) $i_1 < Id_1$ & $i_2 < Id_2$

for case (ii) $i_1 < Id_1$ & $i_2 \nless Id_2$

for case(iii) $i_1 \nless Id_1$ & $i_2 \nless Id_2$

for case (iv) $i_1 \nless Id_1$ & $i_2 \nless Id_2$

It must be emphasized that the processes of convertor 1 & 2 are completing independent, and, at any given time, their process numbers may be different.

In order to use the central-process program repetitively, the following conditions must be observed. Each process commences with the commutating current being assigned the initial condition $i = 0$. The end of a process is determined by the firing of the next valve of the sequence, and it can be deduced (Fig.1.3) that next valve is fired $(60-\alpha_n+\alpha_{n+1})$ degrees after the n^{th} was fired. α_n is known, and α_{n+1} is determined and given to process program by the control system.

Representation of c.e.a. and c.c.control:

The equation for cea control ($B = 180-\alpha$) to

$$\sqrt{2}E \, Cos\alpha = 2 \, WL \, Id - \sqrt{2}E \, Cos \, \delta_c \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (11)$$

The action of c.c. control can be incorporated into equation (11) by the addition of x (Id), a function of Id:

$$\sqrt{2} \, E \, Cos\alpha = 2 \, WL \, Id - \sqrt{2} \, E \, Cos\delta_c + x \, (Id), \ldots\ldots (12)$$

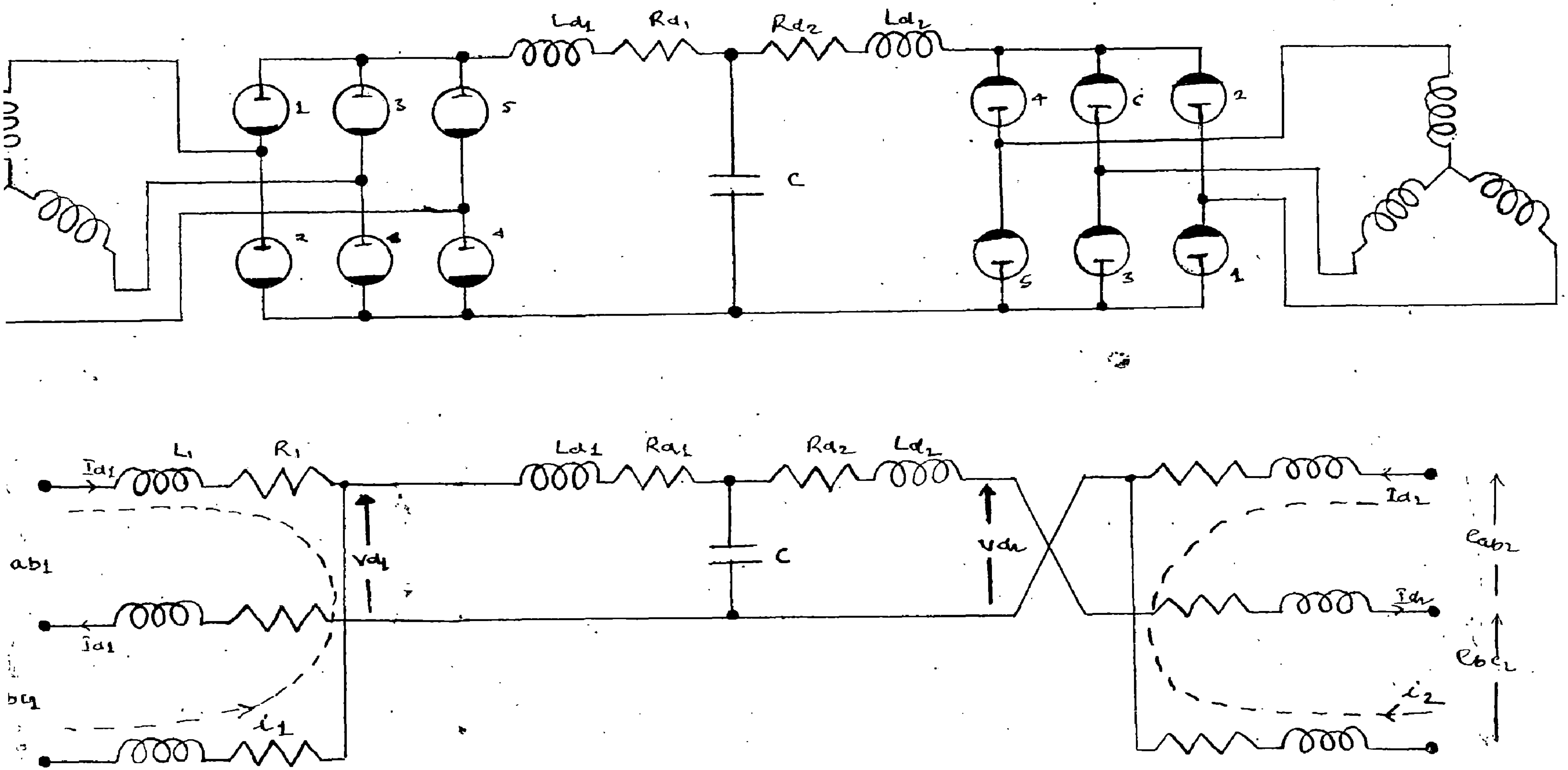
The value of x (Id) is such that if Id   Ids
x (Id) = 0

$$X \, (Id) = A \, (Id - Ids) \quad \ldots\ldots\ldots\ldots\ldots (13)$$

is constant which defines the slope of c.c. characteristic. It is negative and depends on the amplification factor of the C.C. system.

The complete control system can be represented by the following equations:

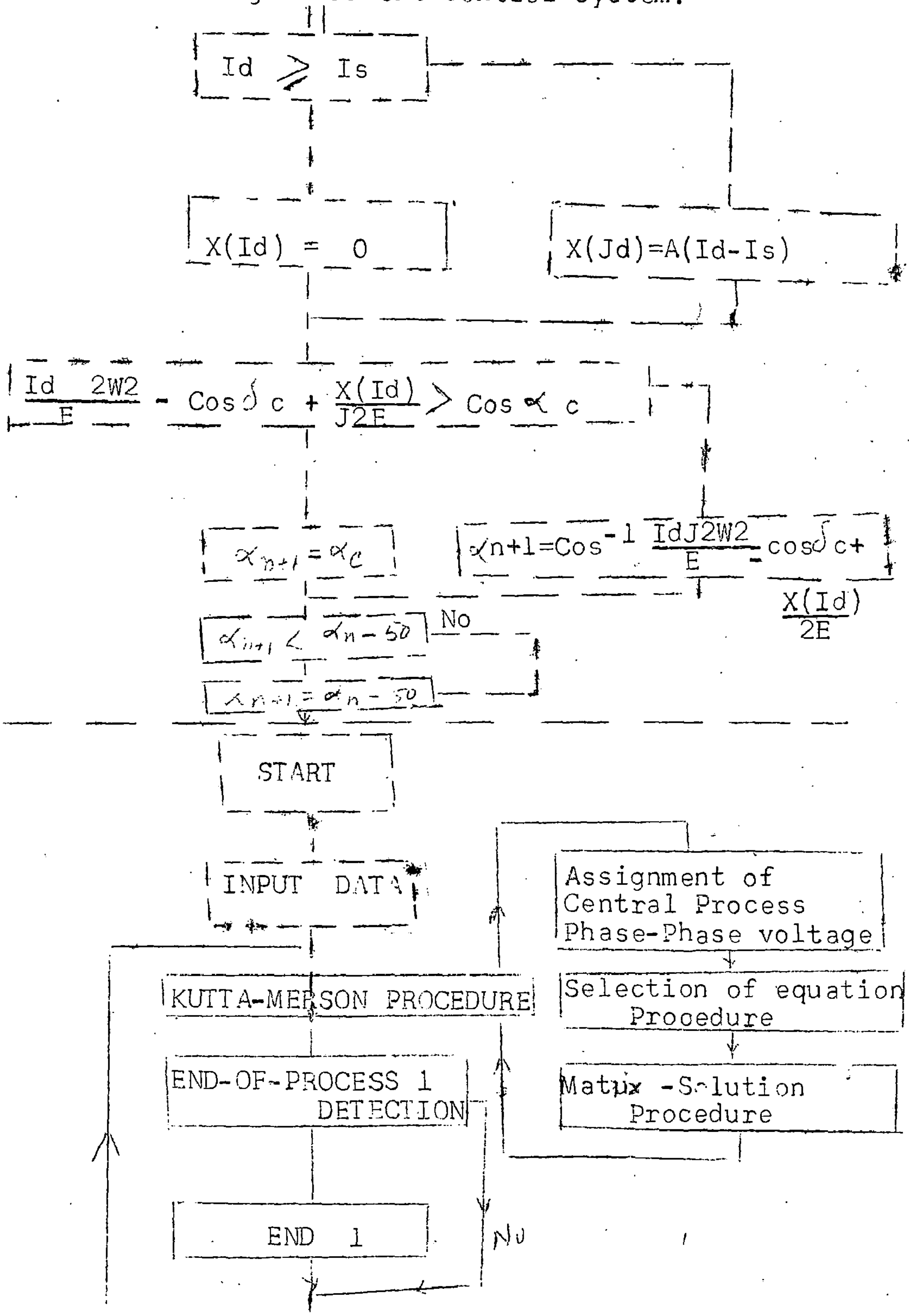
$$\left(\alpha = \alpha_c \quad \text{if} \quad \frac{Id \sqrt{2} \, WL}{E} - Cos\,\delta_c + \frac{x(Id)}{2E} > cos\,\alpha_r \right)$$

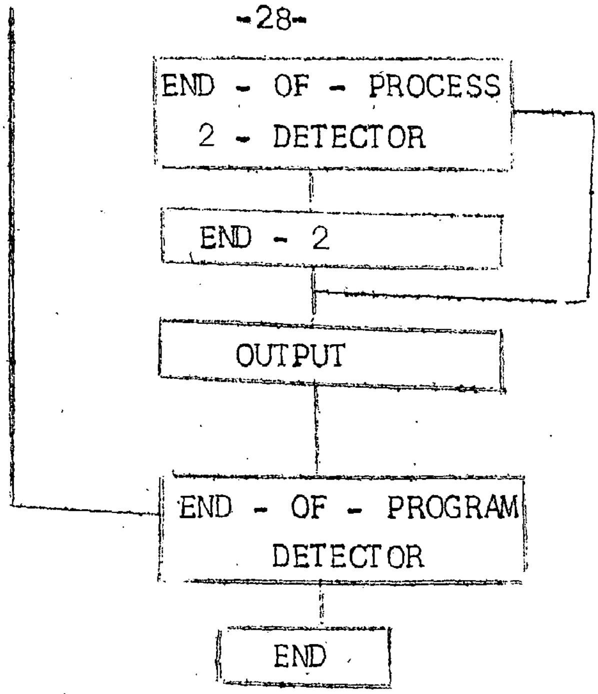


FIG(1·8) EQUIVALENT CIRCUIT FOR 'CENTRAL PROCESS'

Otherwise $\alpha_c = \cos^{-1} \frac{J2WL\ Id}{E} - \cos \delta_c + \frac{x(Id)}{J2E}$ .....(14)

The first part of equation(14) determines whether operation is on the nv characteristic, this is obtained by substitution of $\alpha = \alpha_c$, in equation (12) the value of x(Id) pertinent to the type of control is found from (13). Figure below shows flow diagram of the control system:





Complete Flow Diagram

1.10. AUTHOR'S APPROACH TO THE PROBLEM & ASSUMPTIONS MADE:

The author has modified the equations developed by A.M.Reider[14] for rectifier angle of delay α and invertor angle of advance β. With the help of 'circulating current' and 'voltage drop' detection the author proposes a method of dynamic simulation of hvdc systems on digital and on anolog computers. Due to the similarity of consecutive processes of the convertors, the differentiation among the different processes has not been made. Although the detection of process number can be made, one such process representation is repeated, and hence process is called 'Repetitive Process' by the author. Three equations only are necessary for representation and hence the three equations are written in a general form. The coefficients and angles have four values. The particular values of these depend upon the state of both convertors which is determined by circulating current and voltage drops at a particular instant. The generalised form of the equations have made possible an exact solution of equations.

Whenever there is change of coefficients and angle the initial values have to change and this is quite easy with digital computer. In state variable numerical approach initial values are changed automatically. Anolog simulation is also attempted by author. The effect of the time of operation of relays used in anolog simulation can be made negligible if proper time scaling is done and recording can be easily done. Assumptions made are:

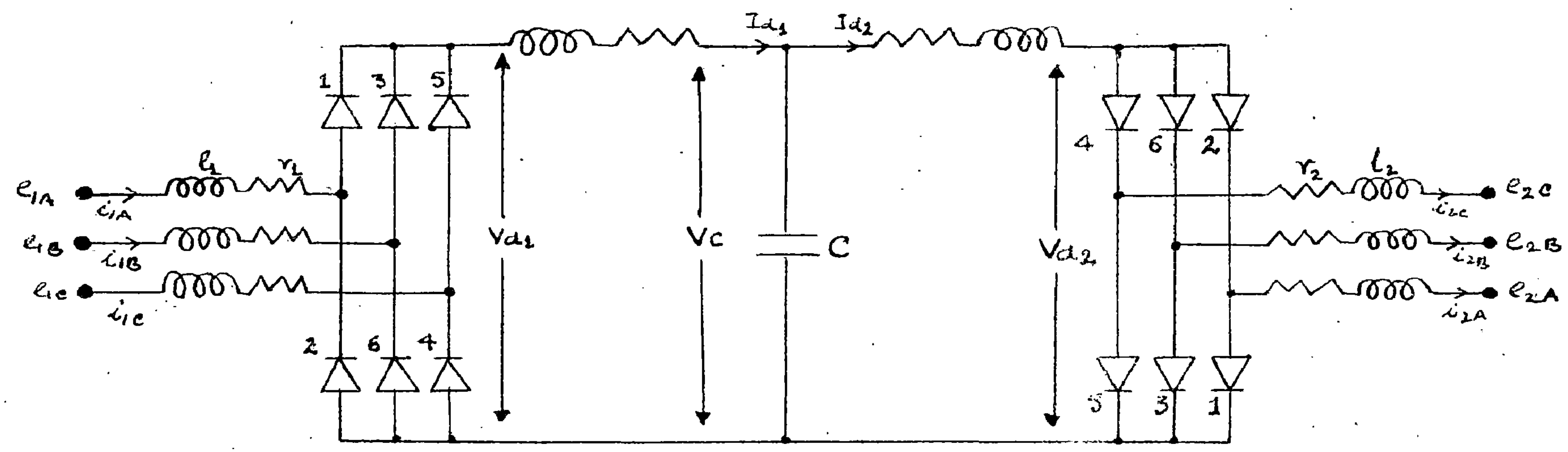
(1) Parameters are linear.

(2) Line is represented by nominal T-section.

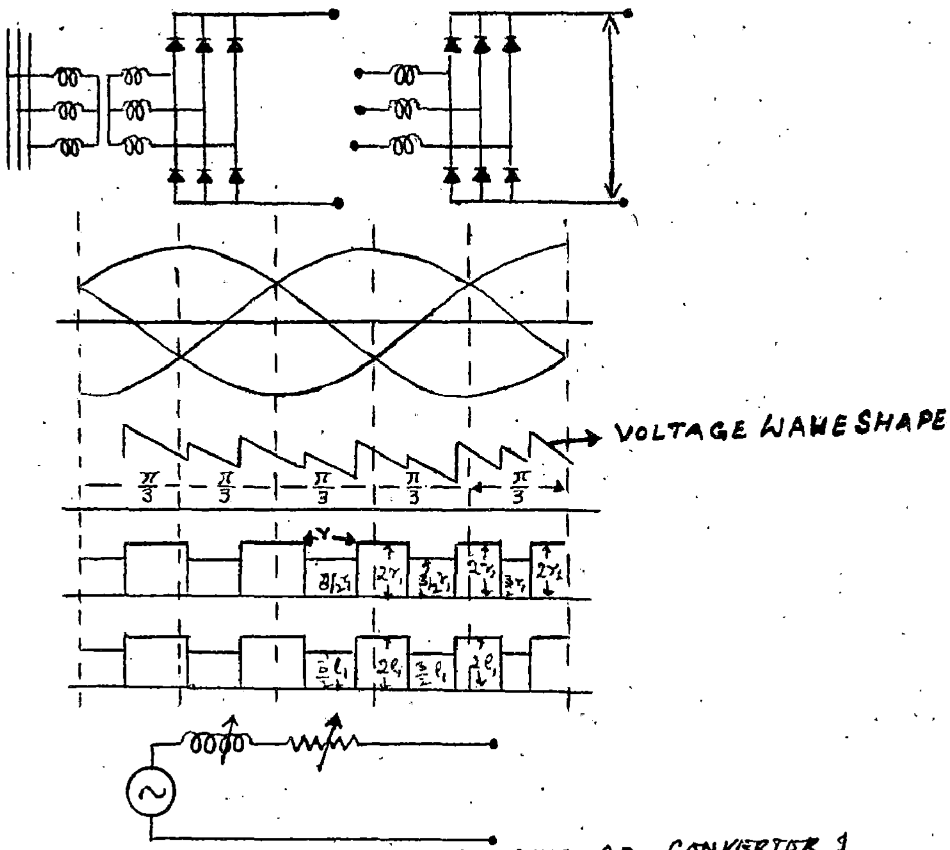
(3) Each convertor is provided with C.C. and C.E.A. control.

(4) Voltage drop across valves is neglected.

(5) Transformers at both ends are balanced.



FIG(2·1) EQUIVALENT CIRCUIT FOR 'REPETITIVE-PROCESS'



EQUIVALENT CIRCUIT OF CONVERTOR 1

FIG(2.2)

2. DIGITAL SIMULATION BY 'REPETITIVE PROCESS'

2.1. 'PROCESS':

Each process commences with firing of a valve which results in commutation (three valves are conducting, two out of them are in parallel) and is followed by non-commutation period (only two valves conduct in series). The end of the process is indicated by the firing of next valve in sequence.

2.2. DEVELOPMENT OF EQUIVALENT CIRCUIT:

During normal operation valves ignite in turns, in groups of three and two. If one such process, defined above, can be represented, the repetition of this, with insertion of correct initial conditions, will represent the continuous operation of the convertor. In Fig.(2.1), during commutation, when three valves are conducting i.e. valves 1,2 & 3 (the valve 3 is the new valve fired) the rectifier current is given by following equations:

$$\left.\begin{aligned} e_{1B} - e_{1C} &= l_1 \frac{di_{1A}}{dt} + r_1 i_{1A} - l_1 \frac{di_{1C}}{dt} - r_1 i_{1C} + Vd_1 \\ e_{1B} - e_{1C} &= l_1 \frac{di_{1B}}{dt} + r_1 i_{1B} - l_1 \frac{di_{1C}}{dt} - r_1 i_{1C} + Vd_1 \\ i_{1A} + i_{1B} &= Id_1 \\ - i_{1C} &= Id_1 \end{aligned}\right) \quad ..(2.1)$$

Taking the imitial phase emf's as

$$\left.\begin{aligned} e_{1A} &= E_1 \text{ Cos } (W_1 t + \pi/3) \\ e_{1B} &= E_1 \text{ Cos } (W_1 t - \pi/3) \\ e_{1C} &= E_1 \text{ Cos } (W_1 t - \pi) \end{aligned}\right) \quad ..(2.2)$$

We have from equations (2.1) and (2.2),

$$\frac{3}{2} E_1 \text{ Cos } W_1 t = 3/2\, l_1 \frac{dId_1}{dt} + \frac{3}{2} r_1 Id_1 + Vd_1 . \quad (2.3)$$

This equation by virtue of the symmetry of supply system e.m.f. will be valid during the operation of following sets of three valves 2,3,4 or 3,4,5, etc. also.

Similarly the current Id_1 during the conduction of two valves in series can be obtained as

$$\sqrt{3}E_1 \text{ Cos } (W_1t - \pi/6) = 2\ l_1 \frac{dId_1}{dt} + 2\ r_1\ Id_1 + Vd_1 \ldots (2.4)$$

When rectifier operates on a 'two-three' sequence the periods of two and three valve conduction alternate. The nature of this operation made AM Reider[14] to visualise the rectifier as a special d.c. generator with an e.m.f. equal to $\sqrt{3}\ E_1\ \text{Cos}(W_1t-\pi/6)$, when two valves are operating and to $\frac{3}{2}\ E_1\ \text{Cos}\ W_1t$ when three valves are operating. The internal active resistance and inductance of such a generator on the ignition and extinction of successive valves will change from $2r_1$ & $2l_1$ to $3/2\ r_1$ & $3/2\ l_1$ and back again. This is shown in Fig.(2.2) which shows saw tooth e.m.f. of generator combined with a stepwise change of active resistance and inductance.

Similarly the invertor current is governed by following equations:

For commutation period,

$$\frac{3}{2}\ E_2\ \text{Cos}(W_2t-\pi) = -\frac{3}{2}\ l_2 \frac{dId_2}{dt} - \frac{3}{2}\ r_2\ Id_2 + Vd_2 \ldots\ldots (2.5)$$

and for noncommutation period,

$$\sqrt{3}\ E_2\ \text{Cos}\ (W_2t-7\pi/6) = -2\ l_2 \frac{dId_2}{dt} - 2\ r_2\ Id_2 + Vd_2 \ldots\ldots (2.6)$$

Just as it was possible, on the basis of equations (2.3) and (2.4) to regard the rectifier as a special d.c. generator, the equations (2.5) and (2.6) enable us to regard invertor with receiving end system, as a special d.c. motor with a saw tooth back e.m.f. and step changing active internal resistance and inductance.

Using the above concept of special d.c. generator and motor, the author visualizes the whole of the hvdc transmission system as shown in Fig.(2.3). The special d.c.generator is driven by induction motor connected to a.c. bus at the sending end and takes power from the a.c.bus. The special d.c. motor drives the induction generator connected to the a.c. bus at the receiving end and deliver power to it. The induction motor takes lagging power from bus as the rectifier does. The induction generator takes excitation from a.c.bus(and hence the need of reactive power at receiving end) and supplies power to the a.c. bus at the same frequency as the invertor does. Now modifying the equations (2.3 - 2.6) for delay in firing.

$$\frac{3}{2}\ E_1 \ \text{Cos}\ (W_1 t+\alpha_1) = \frac{3}{2}\, l_1 \frac{dId_1}{dt} + \frac{3}{2}\, r_1\, Id_1 + Vd_1 \ldots\ldots\ldots (2.7)$$

$$3\ E_1 \ \text{Cos}\ (W_1 t+\alpha_1-\pi/6) = 2l_1 \frac{dId_1}{dt} + 2\, r_1\, Id_1 + Vd_1 \ldots\ldots (2.8)$$

$$\frac{3}{2}\ E_2 \ \text{Cos}(W_2 t + \alpha_2) = \frac{3}{2}\, l_2 \frac{dId_2}{dt} + \frac{3}{2}\, r_2 Id_2 - Vd_2 \ldots\ldots\ldots (2.9)$$

$$3\ E_2 \ \text{Cos}\ (W_2 t+\alpha_2-\pi/6) = 2\, l_2 \frac{dId_2}{dt} + 2\, r_2\, Id_2 - Vd_2 \ldots (2.10)$$

As shown in figure (2.3) only one T-section and one bridge at each end is considered for simplicity to illustrate the 'Repetitive Process'. More number of line sections and bridge will increase the number of equations but basically the approach will remain the same. From figure (2.3)

$$Vd_1 = V_c + L_{11} \frac{dId_1}{dt} + R_{11}\, Id_1 \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.11)$$

$$Vd_2 = V_c - L_{22} \frac{dId_2}{dt} - R_{22} Id_2 \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.12)$$

Substituting these in equations (2.7 - 2.8)

$$\frac{3}{2}\ E_1 \ \text{Cos}(W_1 t + \alpha_1) = (L_{11} + \frac{3}{2}\, l_1) \frac{dId_1}{dt} + (R_{11}+\frac{3}{2}\, r_1) Id_1 + V_c . (2.13)$$

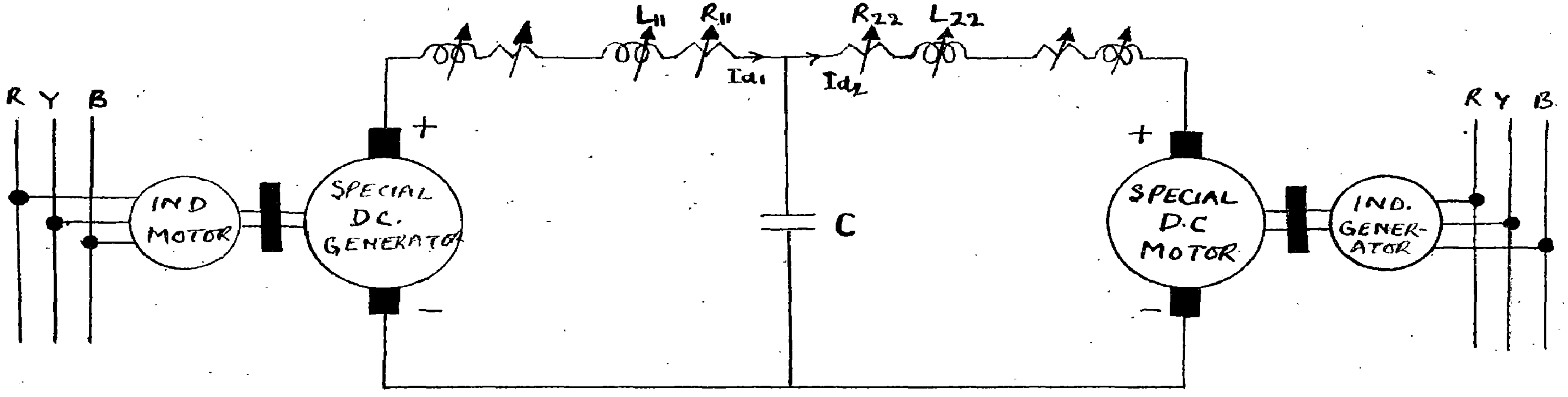
$$3\ E_1 \ \text{Cos}(W_1 t+\alpha_1-\pi/6) = (L_{11} + 2l_1) \frac{dId_1}{dt} + (R_{11}+2r_1)\ Id_1 + V_c . (2.14)$$

$$+ \frac{3}{2}\ E_2 \ \text{Cos}(W_2 t+\alpha_2) = (L_{22} + \frac{3}{2}\, l_2) \frac{dId_2}{dt} + (R_{22}+\frac{3}{2}\quad)\ Id_2 - V_c . (2.15)$$

$$+ 3\ E_2 \ \text{Cos}(W_2 t+\alpha_2-\pi/6) = (L_{22}+2l_2\ ) \frac{dId_2}{dt} + (R_{22}+2r_2)\ Id_2 - V_c . (2.16)$$

$$\frac{dv_c}{dt} = (Id_1 - Id_2) / C \ \ldots\ldots\ldots\ldots\ldots\ldots (2.17)$$

Three equations, one out of equations (2.13) and (2.14), one out of equations (2.15) and (2.16) and third equation (2.17) will represent the system in dynamic manner. The selection of equations depends upon the states of convertors. The state of convertor means whether convertor is commutating or not.



FIG(2·3) EQUIVALENT CIRCUIT OF HVDC TRANSMISSION SYSTEM

The author represents three equations required for simulation in general form and by changing the value of coefficients and angles on the change of any of convertor state, the equations will change automatically.

$$mE_1 \operatorname{Cos}(W_1 t + \theta) = L_1 \frac{dId_1}{dt} + R_1 Id_1 + V_c \quad \text{.................(2.18)}$$

$$nE_2 \operatorname{Cos}(W_2 t + \emptyset) = L_2 \frac{dId_2}{dt} + R_2 Id_2 - V_c \quad \text{.................(2.19)}$$

$$\frac{dvc}{dt} = (Id_1 - Id_2)/C \quad \text{.................(2.20)}$$

The changes in values of m, n, L_1, L_2, R_1, R_2 θ and $\emptyset$ are discussed in the next section.

2.3. COMMUTATION PHENOMENON IN CONVERTORS:

The valves of the bridge operate in sequence and the switching instant is controlled by the control system of the grid firing circuits. When the next valve is fixed, it finds that a valveis already conducting in parallel. But due to the alternating nature of the applied voltage through the transformer winding there is a decrease in voltage across the already conducting valve and increase in voltage across the valve fired. It results in decrease in the current through the already-conducting valve and increase in current through the new valve fired. This process goes on for a short period depending upon the values of the different parameters e.g.inductance and resistance of transformer winding and d.c. line current. A stage is reached when full line current is conducted by the new valve fired and the previous valve stops conducting. An expression for the circulating current has been derived in section (2.4.1) and in a particular case in section (4.2). The plot of above equation shows the nature of the two currents in different valves under commutation in Fig. This shows that current in the new valve fired flows in opposite direction to the line d.c. current in the beginning i.e. new valve derives an extra current from the old valve at the beginning and later on it relieves the old valve gradually.

2.4. SELECTION OF COEFFICIENTS AND ANGLES:

It has already been seen in the last section that three general equations will represent the entire hvdc transmission system. Now the problem is that of the detection of the different states of the convertors. One of the following four possibilities must exist at any particular instant:

Case	Convertor 1 (Rectifier)	Convertor 2 (Invertor)	R_1	L_1	R_2	L_2	Θ	ϕ	M	n
(1)	Commutating	Noncommutating	$R_{11}+\frac{3}{2}r_1$	$L_{11}+\frac{3}{2}l_1$	$R_{22}+2r_2$	$L_{22}+ sl_2$	α_1	$\alpha_2-\frac{\pi}{6}$	$\frac{3}{2}$	$\sqrt{3}$
(2)	Commutating	Commutating	$R_{11}+\frac{3}{2}r_1$	$L_{11}+\frac{3}{2}l_1$	$R_{22}+\frac{3}{2}r_2$	$L_{22}+\frac{3}{2}l_2$	α_1	α_2	$\frac{3}{2}$	$\frac{3}{2}$
(3)	Noncommutating	Commutating	$R_{11}+2r_1$	$L_{11}+2l_1$	$R_{22}+\frac{3}{2}r_2$	$L_{22}+\frac{3}{2}l_2$	$\alpha_1-\frac{\pi}{6}$	α_2	$\sqrt{3}$	$\frac{3}{2}$
(4)	Noncommutating	Noncommutating	$R_{11}+2r_1$	$L_{11}+2l_1$	$R_{22}+2r_2$	$L_{22}+2l_2$	$\alpha_1-\frac{\pi}{6}$	$\alpha_2-\frac{\pi}{6}$	$\sqrt{3}$	$\sqrt{3}$

From equation (2.1)

$$i_{1B}-i_{1A} = l_1 \frac{di_{1B}}{dt} - \frac{di_{1A}}{dt} + r_1 (i_{1B} - i_{1A})$$

$$\text{or, } i_{1B} = i_{1A} = l_1 (2 \frac{di_1}{dt} - \frac{dId_1}{dt} + r_1 (2i_1 - Id_1) \quad (i_{1B}=i_1)$$

$$\text{or } 2L_1 \frac{di_1}{dt} + R_1 i_1 = 3 E_1 \text{Sin}(W_1 t + \alpha_1) + R_1 \frac{dId_1}{dt} + r_1 Id_1 \quad (2.21)$$

As discussed in last section commutation is over when the circulating current reaches the value of direct line current. This means stopping of old valve under conduction and new valve conducting full direct current. Mathematically this condition will be reached when

$$i_1 = Id_1 \quad \text{and} \quad \frac{di_1}{dt} = \frac{dId_1}{dt}$$

Similarly for the invertor, the detection of the end of the commutation process is made when

$$i_2 = Id_2 \ \& \ \frac{di_2}{dt} = \frac{dId_2}{dt} \quad \ldots\ldots\ldots\ldots\ldots\ldots (22)$$

Above detection has given two methods of selection and will be discussed in the following sections.

2.4.1. By circulating currents:

In this method the circulating currents have to calculated at every instant and are then compared with direct line currents. With the help of Laplace transformation the exact analysis is done and the expressions for circulating currents have been found out (APPENDIX - I)

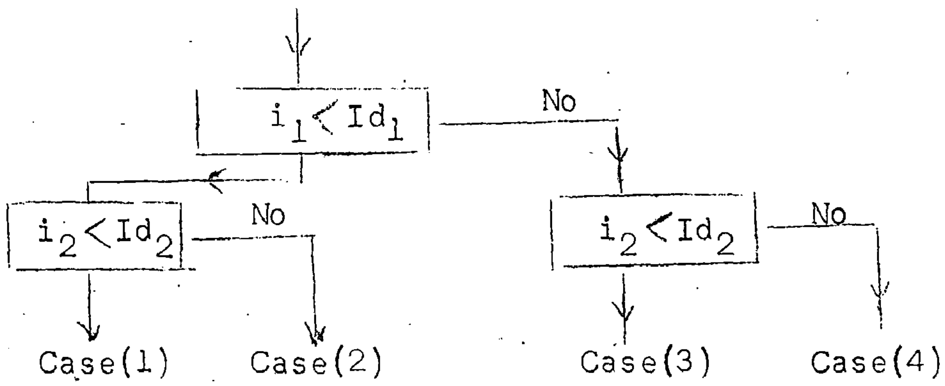
$$i_1 = \frac{Id_1}{2} + \frac{\sqrt{3}}{2}\,\frac{E_1}{(r_1^2 + W_1^2\,l_1^{\,2})^{1/2}}\,\text{Sin}\,(W_1 t + \theta - \theta c) - e^{-R_1/L_1 t}\left\{\frac{Id_1(o)}{2} + \frac{\sqrt{3}\,E_1}{2(r_1^2 + W_1^2 l_1^2)^{1/2}}\,\text{Sin}\,(\theta - \theta c)\right\} \qquad - (2.23)$$

$$i_2 = \frac{Id_2}{2} + \frac{\sqrt{3}}{2}\,\frac{E_2}{(r_2^2 + W_2^2\,l_2^2)^{1/2}}\,\text{Sin}(W_2 t + \phi - \phi o) - e^{-R_2 t/L_2}\left\{\frac{Id_2(o)}{2} + \frac{\sqrt{3}\,E_2}{2\,r_2^2 + W_2^2 L_2^2}\,\text{Sin}(\phi - \phi o)\right\} \qquad - (2.24)$$

For the different possible cases

Case (1)	$i_1 < Id_1$	$i_2 \nless Id_2$
Case (2)	$i_1 < Id_1$	$i_2 < Id_2$
Case (3)	$i_1 \nless Id_1$	$i_2 < Id_2$
Case (4)	$i_1 \nless Id_1$	$i_2 \nless Id_2$

A flow chart based upon above can be given as following



2.4.2. By voltage drops:

In this method the circulating currents need not be calculated only the d.c. line currents and their derivatives, which are otherwise also calculated, will decide the selection of coefficients. At the end of commutation, from equations (2.21) and (2.22), we have

$$l_1 \frac{dId_1}{dt} + r_1 Id_1 = 3 \quad E_1 \operatorname{Sin}(W_1 t + \Theta) - \qquad (2.25)$$

A little consideration over equations (2.21) and (2.25) give a new approach for the selection.

Now if

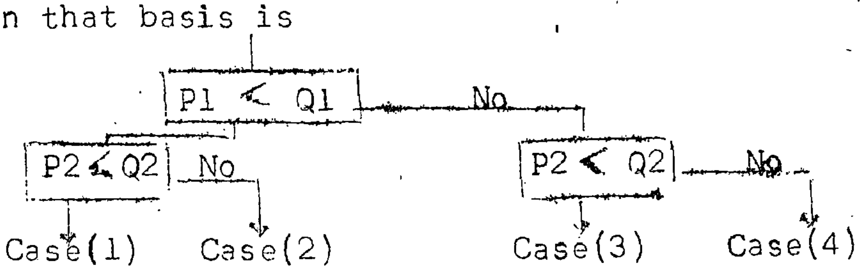
$$P_1 = 3 \quad E_1 \operatorname{Sin}(W_1 t + \Theta)$$

$$Q_1 = l_1 \frac{dId_1}{dt} + r_1 Id_1$$

$$P_2 = 3 \quad E_2 \operatorname{Sin}(W_2 t + \emptyset)$$

$$Q_2 = l_2 \frac{dId_2}{dt} + r_2 Id_2$$

A selection similar to last section can be made and a flow chart is given on that basis is



2.5. PROCESS NUMBER AND END DETECTION:

In normal operation there are six processes per cycle. Valves of each bridge are given numbers arbitrary. Program can also be made to specify the number of the process. To ensure that the number of processes does not exceed six, following relation can be used

$n = n + ((n-1) \div 6) \times 6$ where $\div$ is intiger division and n is the number of the process.

As mentioned earlier the end of each process is determined by the firing of the next valve in sequence. It becomes quite clear that next valve will be fired at $(60 - \alpha_n + \alpha_{n+1})$ degrees after the nth valve was fired, α_n is known and α_{n+1} is determined and given to process program by control system.

2.6. STATE VARIABLE NUMERICAL SOLUTION APPROACH:

It has already been seen that selection of coefficients and angles can be easily made. Now the solution of 3 general equations representing the system has to be found. Easiest is the numerical method using Ringa Kutta technique. Three equations (2.18, 2.19 and 2.20) can be arranged as following:

$$\frac{dId_1}{dt} = (mE_1 \cos (W_1 t + \theta) - R_1 Id_1 - Vc) / L_1$$

$$\frac{dId_2}{dt} = (nE_2 \cos (W_2 t + \emptyset) - R_2 Id_2 + Vc) / L_2$$

$$\frac{dvc}{dt} = (Id_1 - Id_2) / C$$

Let Y1, Y2 and Y3 represent Id_1, Id_2 and Vc

Defining functions with Y1, Y2 and Y3 as arguments ,Let

$$F1(Y1,Y3) = (mE_1 \text{ Cos } (W_1 t+\theta) - R_1\, Y1 - Y3) \;/\; L_1$$

$$F2(Y2,Y3) = (nE_2 \text{ Cos } (W_2 t+\emptyset) - R_2\, Y2 + Y3) \;/\; L_2$$

$$F3(Y1,Y2) = (Y1 - Y2) \;/\; C$$

Taking small increment Dt and using Runga Kutta technique

D(1) = Dt x F1 (Y(1), Y(3))

D(2) = Dt x F2 (Y(2), Y(3))

D(3) = Dt x F3 (Y(1), Y(2))

D(4) = Dt x F1 (Y(1) +.5 D(1), Y(3) +.5D(3))

D(5) = Dt x F2 (Y(2) +.5 D(2), Y(3) +.5D(3))

D(6) = Dt x F3 (Y(1) +.5 D(1), Y(2) +.5D(2))

D(7) = Dt x F1 (Y(1) +.5 D(4), Y(3) +.5D(6))

D(8) = Dt x F2 (Y(2) +.5 D(5), Y(3) +.5D(6))

D(9) = Dt x F3 (Y(1) +.5 D(4), Y(2) +.5D(5))

D(10)= Dt x F1 (Y(1) +.5 D(7), Y(3) +.5D(9))

$$D(11) = Dt \times F2\,(\,Y(2) + .5D(8),\ Y(3) + .5D(9)\,)$$
$$D(12) = Dt \times F3\,(\,Y(1) + .5D(7),\ Y(2) + .5D(8)\,)$$

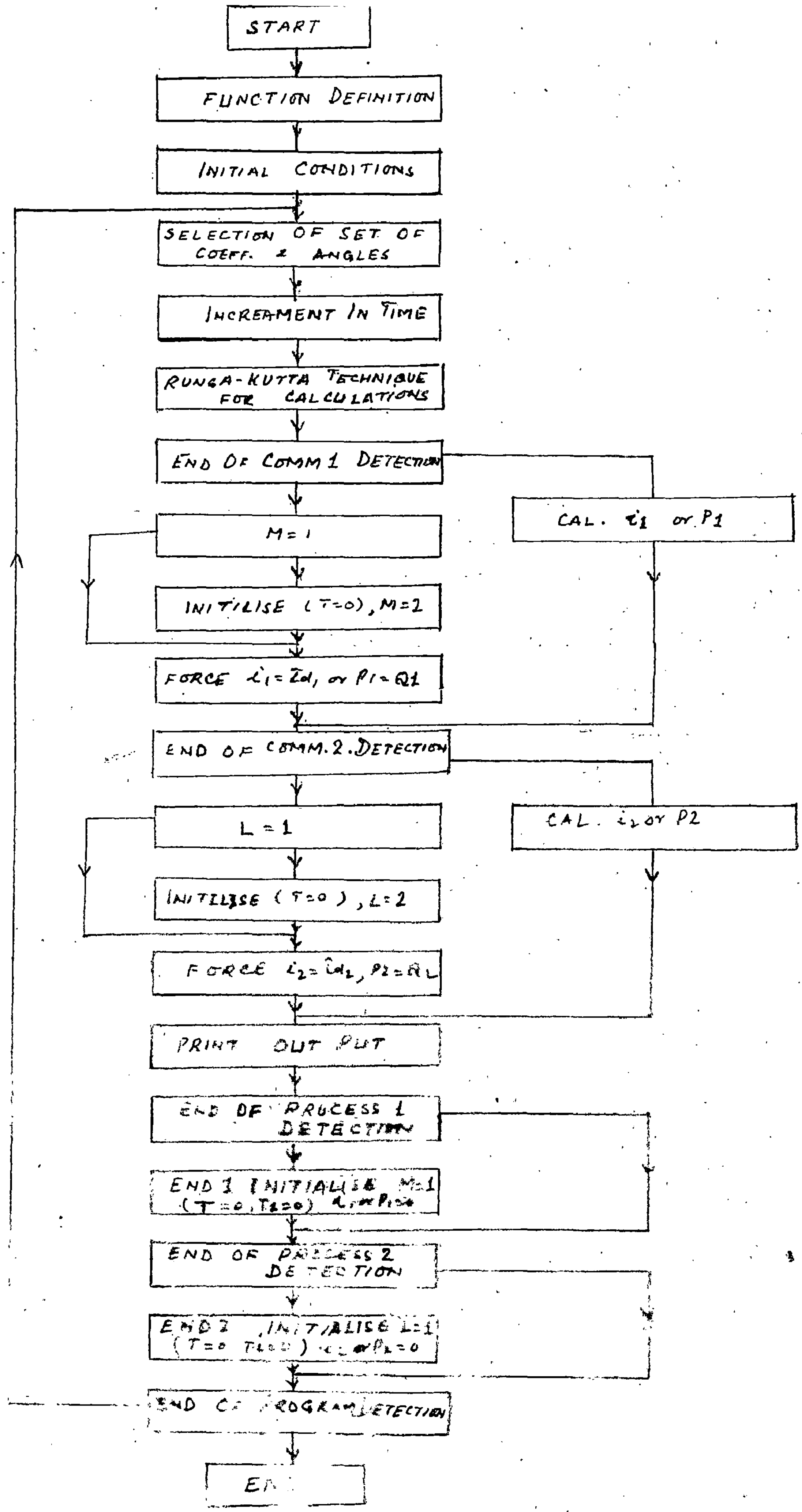
$$Y(1) = Y(1) + (D(1) + 2D(4) + 2D(7) + D(10)\,)\,/\,6$$
$$Y(2) = Y(2) + (D(2) + 2D(5) + 2D(8) + D(11)\,)\,/\,6$$
$$Y(3) = Y(3) + (D(3) + 2D(6) + 2D(9) + D(12)\,)\,/\,6$$

Thus at the next interval all the values of the variables are known. The output at the next interval can be following:

$$Id_1 = Y(1)$$
$$Id_2 = Y(2)$$
$$Vc = Y(3)$$
$$\frac{dId_1}{dt} = F1(Y(1),\ Y(3)\,)$$
$$\frac{dId_2}{dt} = F2(Y(2),\ Y(3)\,)$$
$$= F3(Y(1),\ Y(2)\,)$$

In addition to the current and the voltage, their derivatives are known. If initial values are not known the program is run with some assumed initial value for some time till steady state operation is reached.

Whenever a change in the state of the convertor is detected, the time variable is forced to zero and the coefficients and angles assume the appropriate values. To make the approach more clear the flow chart is given in the next page. The actual tested program is given in the Appendix II. To make the program self explanatory comment cards (A sort of dummy cards) have been introduced.



COMPLETE FLOW CHART FOR NUMERICAL STATE SPACE APPROACH

2.7. ANALYTICAL SOLUTION APPROACH:

The other exact solution is analytical. It will be of more general interest to see what the different frequency, time constants and terms contributing to the solution of differential equations are. Taking the Laplace Transform of three equations (2.18 - 2.20)

$$mE_1 \frac{p\cos\theta - W_1 \sin\theta}{p^2 + W_1^2} = (L_1 p + R_1)\, Id_1(p) + L_1 Id_1(o) + Vc - \qquad (2.26)$$

$$nE_2 \frac{p\cos\phi - W_2 \sin\phi}{p^2 + W_2^2} = (L_2 p + R_2)\, Id_2(p) + L_2 Id_2(o) - Vc - \qquad (2.27)$$

$$p\, Vc - Vc(o) = (Id_1(p) - Id_2(p))\,/\,C \qquad (2.28)$$

From equations (2.25 - 2.28)

$$L_1 L_2 c\, Id_1(p) = \frac{N(p)}{D(p)}\left[mE_1 \frac{(p\cos\theta - W_1 \sin\theta)}{p^2 + W_1^2} + L_1\, Id_1(o) - \frac{V_c(o)}{p}\right]$$

$$+ \frac{1}{D(p)}\left[nE_2 \frac{(p\cos\phi - W_2 \sin\phi)}{p^2 + W_2^2} + L_2 Id_2(o) + \frac{V_c(o)}{p}\right]$$

$$L_1 L_2 c\, Id_2(p) = \frac{1}{D(p)}\left[mE_1 \frac{(p\cos\theta - W_1 - \sin\theta)}{p^2 + W_1^2} + L_1 Id_1(o) + \frac{V_c(o)}{p}\right]$$

$$+ \frac{M(p)}{D(p)}\left[nE_2 \frac{(p\cos\phi - W_2 \sin\phi)}{p^2 + W_2^2} + L_1 Id_1(o) - \frac{V_c(o)}{p}\right]$$

Where D(p) is a third order polynomial while M(p) and N(p) are second order polynomials of p. D(p) may have any type of roots but in this particular case it must have one real and two complex roots. The expressions of Id_1 and Id_2 will be similar and solution can be written in a general form. (Appendix - I).

$$Id_j(t) = B_1 V_c(o) + B_2 mE_1 \sin(W_1 t + \theta + B_3) + B_4 nE_2 \sin(W_2 t + \phi + B_5)$$

$$+ e^{-At}\Big\{(B_6\, mE_1 \cos(\theta - B_7) - B_8 nE_2 \cos(\phi - B_9) - B_{10} Id_1(o) + B_{11} Id_2(o)$$

$$+ B_{12} V_c(o)\Big\}_j$$

$$+ e^{-Bt} (\sin Wt\ (mE_1\ B_{13}\sin(\Theta + B_{14}) - nE_2\ B_{15}\ \sin(\emptyset + B_{16})\ )$$

$$+ \cos Wt\ (B_{17} mE_1\ B_{13}\ \sin(\Theta + B_{18}) - nE_2\ B_{19}\ \cos(\emptyset - B_{20})\ )$$

$$+ e^{-Bt} (Id_2(o) B_{21}\ \sin(Wt - B_{22}) - B_{23}\ Id_1(o)\ \sin(Wt - B_{24})$$

$$- B_{25}\ V_c(o)\ \sin(Wt + B_{26})\ ) \quad \ldots\ldots\ldots\ldots\ldots\ldots(2.28)$$

From (2.28) the expression for $\frac{dId_j}{dt}$ can be obtained. Thus the Id_1, Id_2 and $\frac{dId_1}{dt}$ and $\frac{dId_2}{dt}$ can be easily calculated from the above expressions. In the digital program only one expression can perform the calculation for both currents and the other, for both derivatives. The coefficients and angles will change automatically in second round of calculations.

The voltage V_c can be manupulated very easily

$$V_c = (m\ E_1\ \cos(W_1 t + \Theta) - L_1\ \frac{dId_1}{dt} - R_1\ Id_1)$$

Whenever there is change in state of the convertor with a change in the coefficients and angles, the initial conditions also change and the time variable is forced to zero. A flow chart based on this is given in next page.

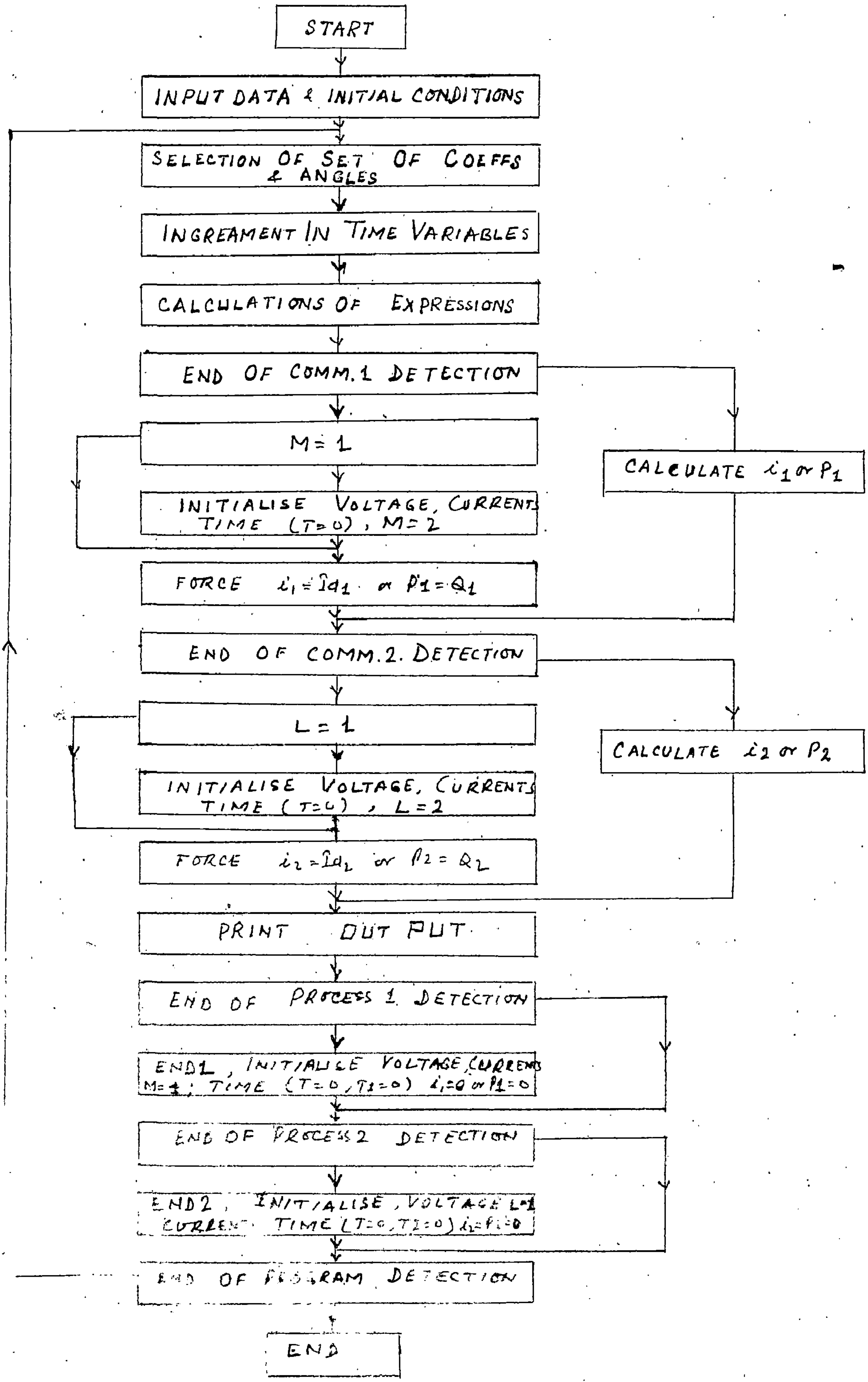
The digital program is in three parts for simplicity. First two programs are solely dependent upon the parameters of system. Once run for a particular system, it does not change with the operating conditions of the system. Programs tested based upon above are given in Appendix II and are self explanatory.

2.8. OUTPUT:

The actual output will depend upon the particular requirement of the program. Always some mathematical manipulations can be asked in programs. Line currents, valve currents and voltages at different points can be easily manipulated. For example the system end voltages are

$$Vd_1 = V_c + L_{11}\ \frac{dId_1}{dt} + R_{11}\ Id_1$$

$$Vd_2 = V_c - L_{22}\ \frac{dId_2}{dt} - R_{22}\ Id_2$$



COMPLETE FLOW CHART FOR ANALYTICAL SOLUTION APPROACH

2.9. TIME VARIABLES:

To facilitate the programming and understanding, three time variables have been introduced, T, T1 and T2. The time variable T is for the system equations and is forced to zero whenever there is change in states of any one of the convertors (i.e. commutation to non-commutation or non-commutation to commutation). Time variable T1 corresponds to the process of convertor 1 and is forced to zero at the end of the process of convertor 1 i.e. when commutation starts. Similarly T2 is the time variable corresponding to the process of convertor 2 and is forced to zero at the end of the process of convertor 2.

The phase difference of a.c. systems on two sides can be taken into account by giving suitable initial values to T1 and T2. The change in phase difference will shift the saw tooth voltage wave-shape of one convertor with respect to the other. Consequently the d.c. power transmission remains independent of phase difference of the a.c. systems. Hence h.v.d.c. is a nonsynchronous tie.

3. DYNAMIC TESTS MADE:

3.1. STARTING TRANSIENTS:

The starting transient can be studied in three parts: (1) The operation of rectifier as charging the line before the invertor starts conducting (2) When both start conducting and steady state is reached for a given value of the angle of firing (3) Constant current and constant extinction angle control act for the desired current setting. Here only first part has been studied i.e. when only rectifier is conducting. The equations (2.18 and 2.19) reduce to following for this case:

$$mE_1 \, Cos(W_1 t + \theta) = L_1 \frac{dId_1}{dt} + R_1 \, Id_1 + Vc \ldots\ldots (3.1)$$

$$\frac{dVc}{dt} = Id_1/C$$

Taking Laplace transform of above equations and solving for $Id_1(p)$ and $Vc(p)$

$$Id_1(p) = \frac{mE_1}{L_1} \frac{p}{p^2 + \frac{R_1}{L_1}p + \frac{1}{CL_1}} \frac{(p \, Cos \, \theta - W_1 Sin \, \theta)}{p^2 + W1^2} + \frac{p}{p^2 + \frac{R_1}{L_1}p + \frac{1}{CL_1}} X$$

$$Id_1(o) - \frac{Vc \, (o)}{L_1(p^2 + \frac{R_1}{L_1} p \, t \, \frac{1}{CL_1})}$$

$$Vc(p) = mE_1 \left\{ \frac{p \, Cos \, \Theta - W_1 Sin \, \Theta}{p^2 + W_1^2} \right\} \cdot \frac{1}{(L_1 \, Cp^2 + R_1 C_1 p + 1)} +$$

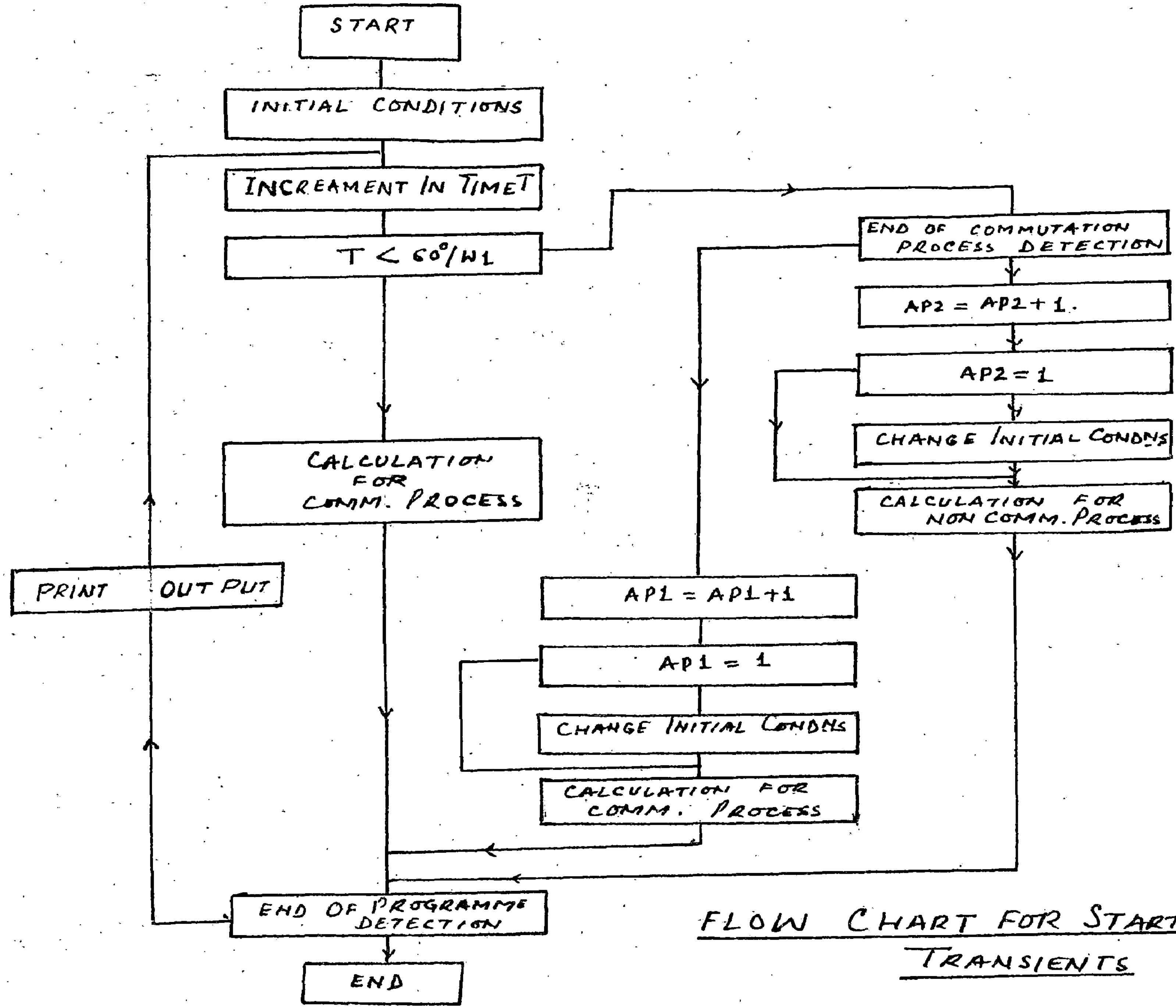
$$\frac{C(L_1 p + R_1)}{(L_1 Cp^2 + R_1 Cp + 1)} \, Vc(o) + L_1 \frac{Id_1(o)}{(L_1 C \, p^2 + R_1 Cp + 1)}$$

Taking the Laplace Inverse of above expressions (Appendix-I)

$$Id_1(t) = - mE_1 \left\{ C_{11} \, Sin(W_1 t + \theta + C_1 + B_{11}) - C_{22} Sin(W_1 t + \theta \, C_1 - B_{22}) \right\}$$

$$+ mE_1 \, e^{-Pt} \left\{ C_{11} \, Sin(Gt + C_1 t \, \theta + B_{11}) + C_{22} Sin(Gt + C_1 - \theta + B_{22}) \right\}$$

$$- U \, Id_1(o) \, e^{-Pt} \, Sin(Gt + C_1) - Vc(o) . V . e^{-Pt} Sin \, Gt \ldots . (3.3)$$



FLOW CHART FOR STARTING TRANSIENTS

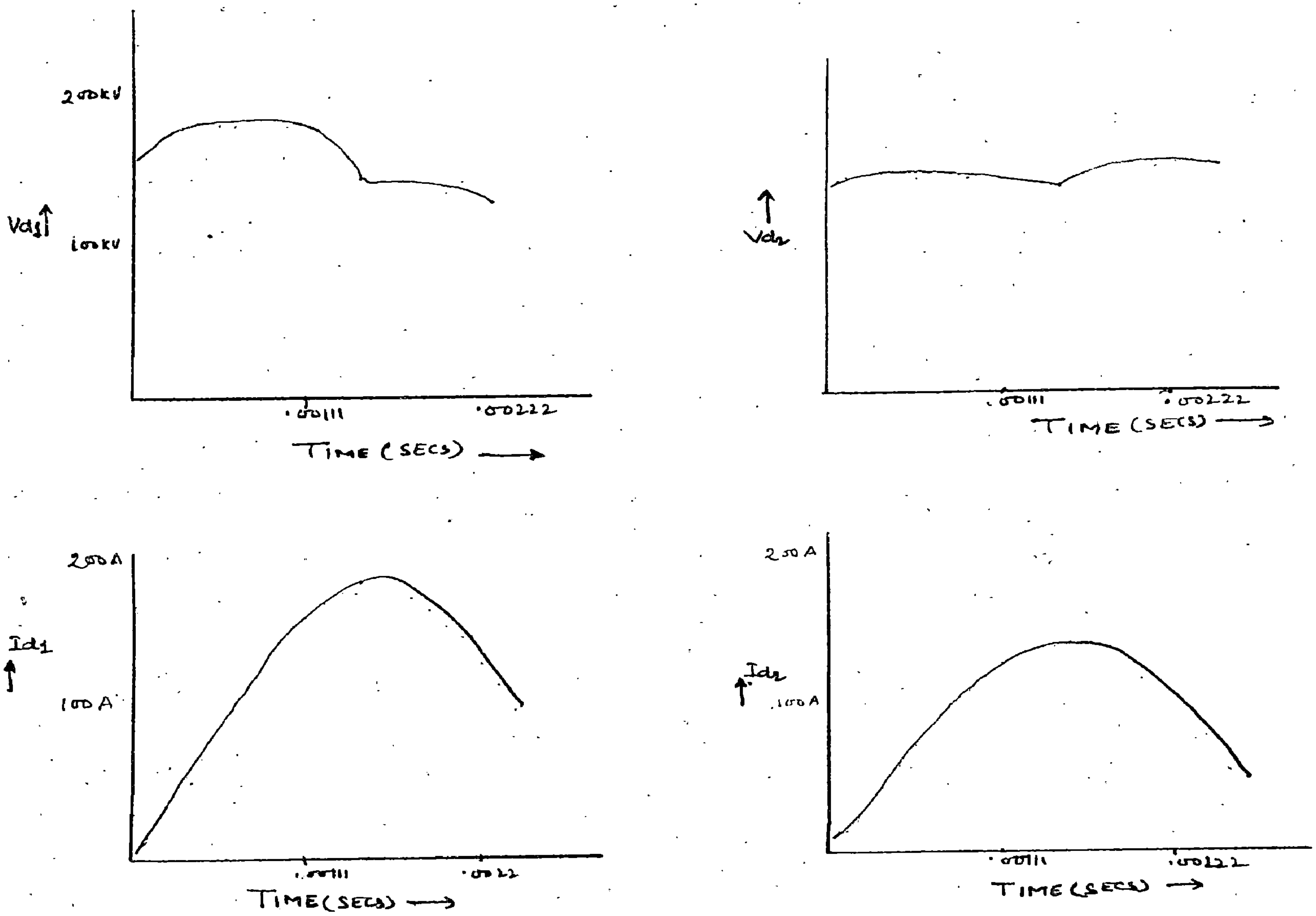
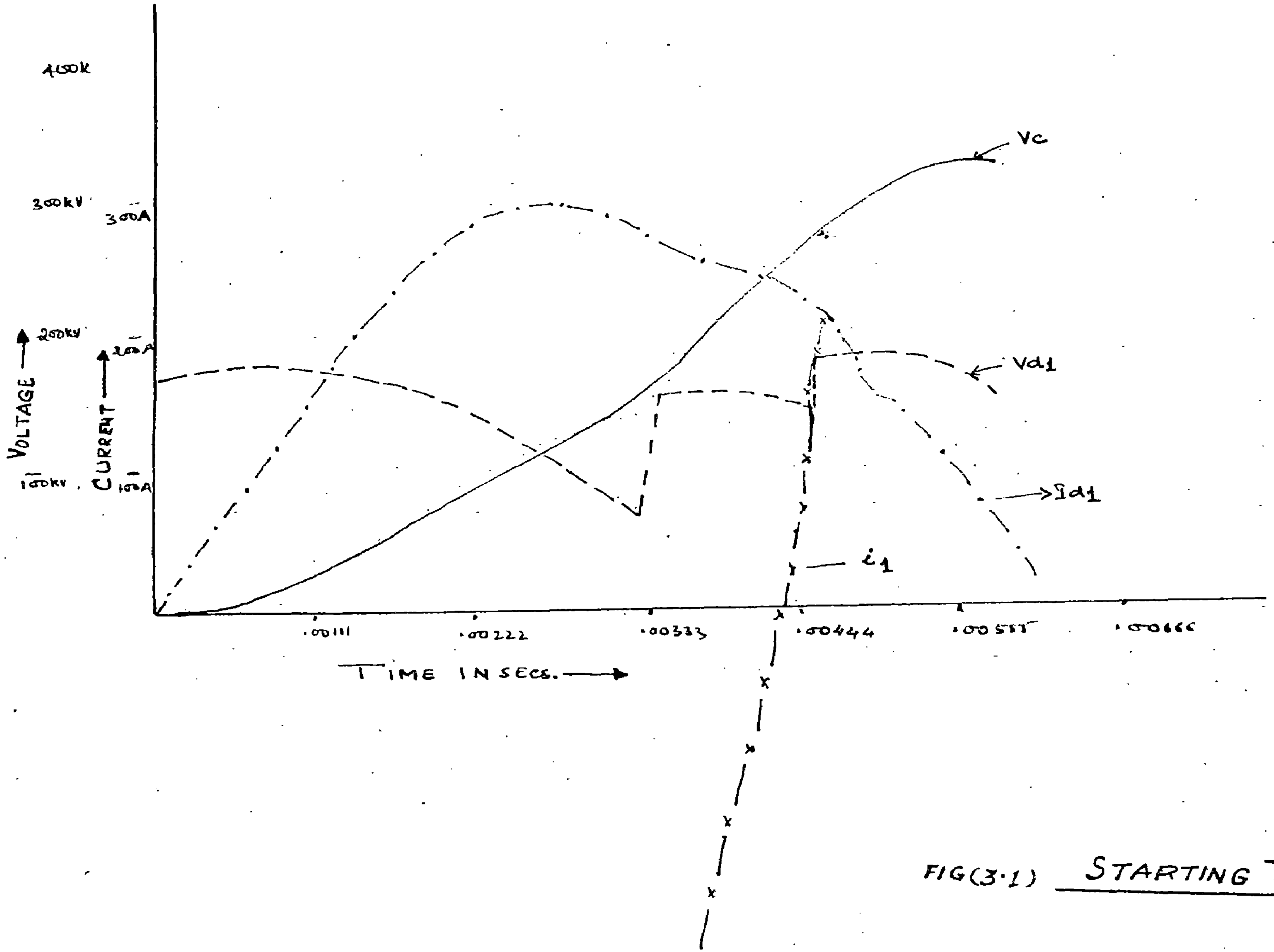


FIG (3.2) TEST RESULTS



FIG(3·1) STARTING TRANSIENTS

$$VC(t) = Y1 \sin(W_1 t+\theta+B_{11}) + Y2 \sin(Gt-\theta+B_{22})$$
$$- e^{-Pt}(Y1 \sin(Gt+\theta+B_{11}) + Y2 \sin(Gt-\theta+B_{22}))$$
$$+ V_C(o)\, e^{-Pt} \frac{R_1}{L_1 G} \sin Gt - \frac{1}{F} \sin(Gt-C_1) + \frac{Id_1(o)}{CW} e^{-Pt} \sin Gt \qquad \ldots\ldots\ldots\ldots(3,4)$$

The expression for $\frac{dId_1}{dt}$ can be obtained by differentiating equation (3.3).

A flow chart of the digital program is given in the next page. Actual program is given in Appendix-2. For simplicity the program was run in two parts.

The results obtained are plotted in Fig.(3.1). Due to capacitive nature of current the terminal voltage is less than the mid point voltage. The commutation state of rectifier is quite clear from the diagram.

3.2. STEADY STATE OPERATION:

The plotting of steady state currents and voltages shown in Fig.(3,2). The natural frequency observed in the analytical approach was approximately 3 times the power frequency. If complete plotting is done the whole pattern will repeat after each cycle. System studied has got same frequency of oscillation at the both ends. If frequencies are different these will exist periodicity between two frequencies i.e. after certain number of cycles the same thing will repeat.

4. ANALOG SIMULATION

4.1. GENERAL:

Analog simulation is physical realisation of the mathematical model. The mathematical model has already been developed in Part 2, while doing digital simulation. The five equations representing the system can be rewritten in following form:

$$\frac{3}{2} E_1 \operatorname{Cos} (W_1 t + \alpha_1) = L_1' \frac{dId_1}{dt} + R_1' Id_1 + V_c \quad \ldots\ldots\ldots\ldots (4.1)$$

$$3 E_1 \operatorname{Cos} (W_1 t + \alpha_1 - \pi/6) = L_1'' \frac{dId_1}{dt} + R_1'' Id_1 + V_c \quad \ldots\ldots\ldots (4.2)$$

$$\frac{3}{2} E_2 \operatorname{Cos} (W_2 t + \alpha_2) = L_2' \frac{dId_2}{dt} + R_2' Id_2 - V_c \quad \ldots\ldots\ldots\ldots (4.3)$$

$$3 E_2 \operatorname{Cos} (W_1 t + \alpha_2 - \pi/6) = L_2'' \frac{dId_2}{dt} + R_2'' Id_2 - V_c \quad \ldots\ldots\ldots (4.4)$$

$$\frac{dVc}{dt} = \frac{Id_1 - Id_2}{C} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.5)$$

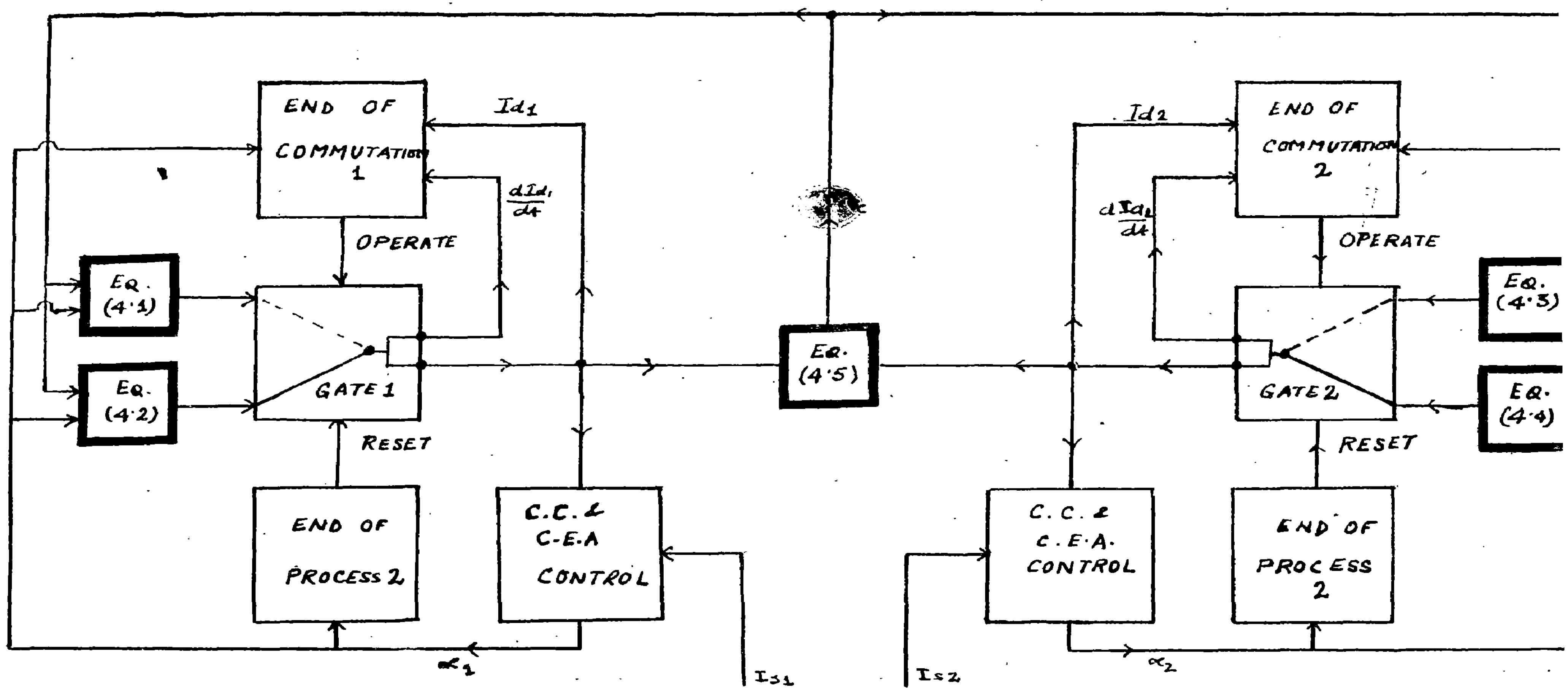
Three equations are valid at a time. Equation (4.5) remains valid at all times. Now it seems that each pair of equations (4.1 and 4.2) and (4.3 and 4.4) have to be connected to equation (4.5) through two separate gates. These gates will allow one equation to be connected at a time. The change over from one equation to other will be governed by commutation end and process end detections. Analog of constant current and constant extinction angle control can also be connected. Based upon these ideas, a block diagram is presented as in Fig.(4.1).

4.2. SYSTEM REPRESENTATION:

The two equations representing the operation of the convertor 1 (rectifier) can be rearranged as:

$$\frac{dId_1}{dt} = \frac{3}{2} \frac{E_1}{L_1'} \operatorname{Cos} (W_1 t + \alpha_1) - \frac{R_1'}{L_1'} Id_1 - \frac{1}{L_1'} Vc - \quad \text{(commutation)}$$

$$\frac{dId_2}{dt} = \sqrt{3} \frac{E_1}{L_1''} \operatorname{Cos} (W_1 t + \alpha_1 - \pi/6) - \frac{R_1''}{L_1''} Id_1 - \frac{1}{L_1''} Vc \quad \text{(non-commutation)}$$



FIG(4.1) BLOCK DIAGRAM FOR DYNAMIC ANALOG SIMULATION

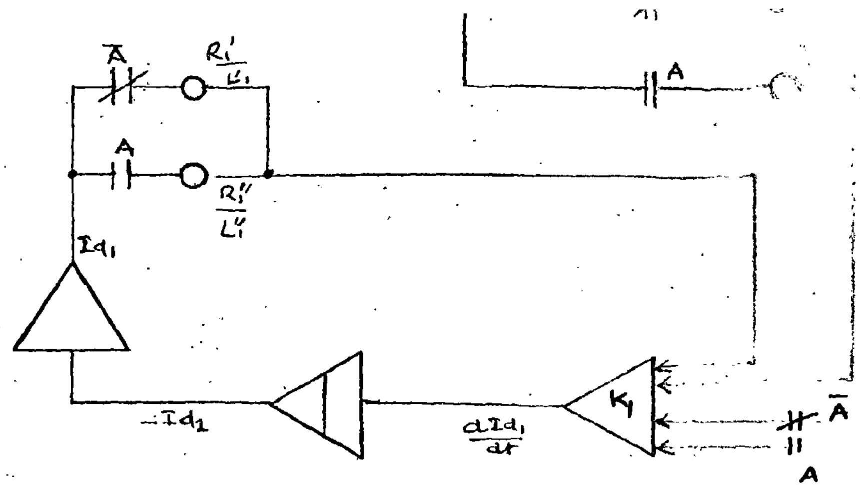
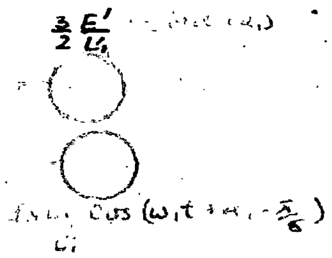
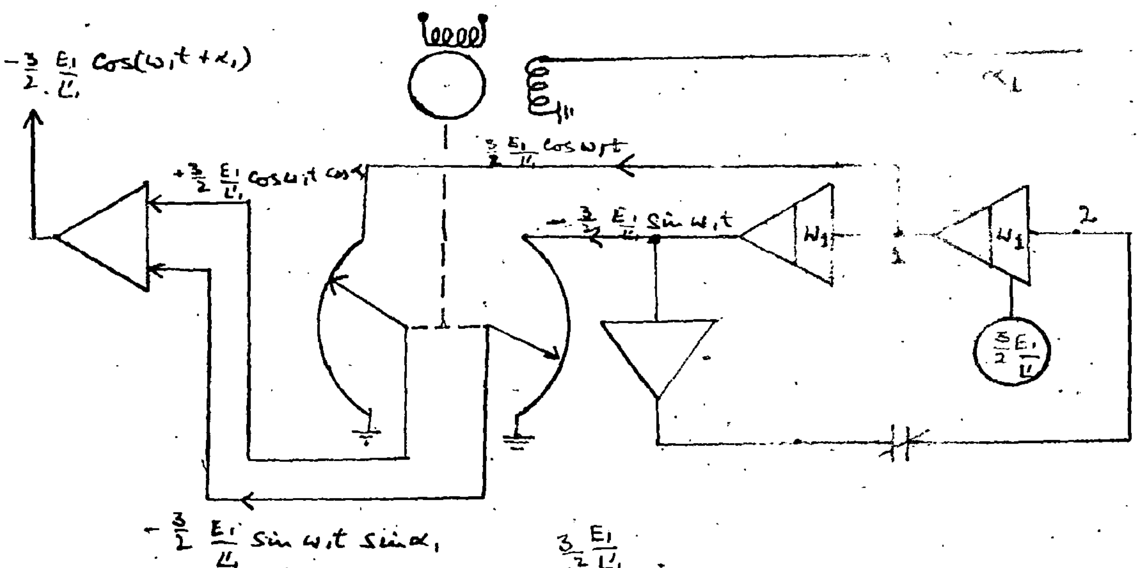


FIG (4·2a)





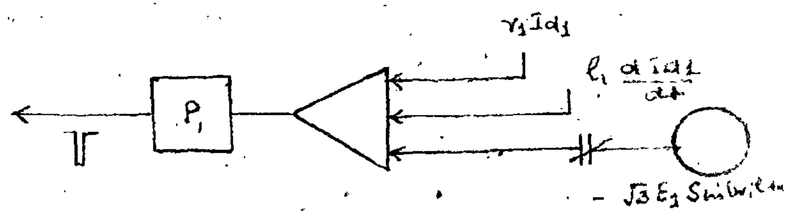


FIG (4·2c)

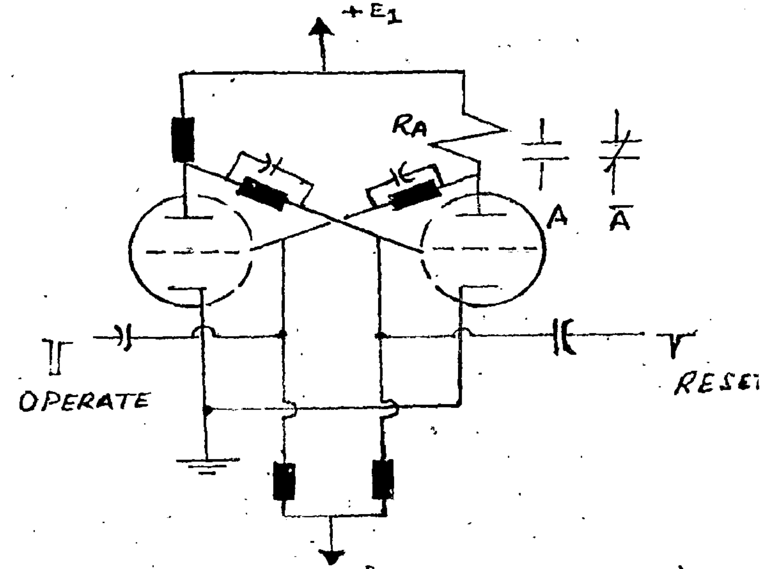


FIG (4·2d)

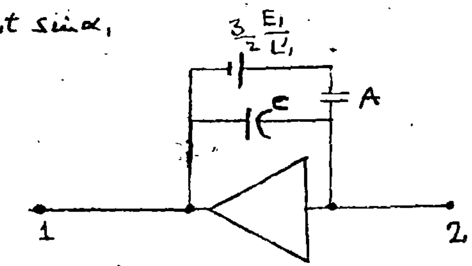


FIG (4·2b)

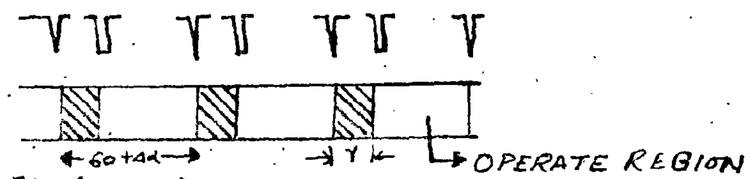


FIG (4·2e)

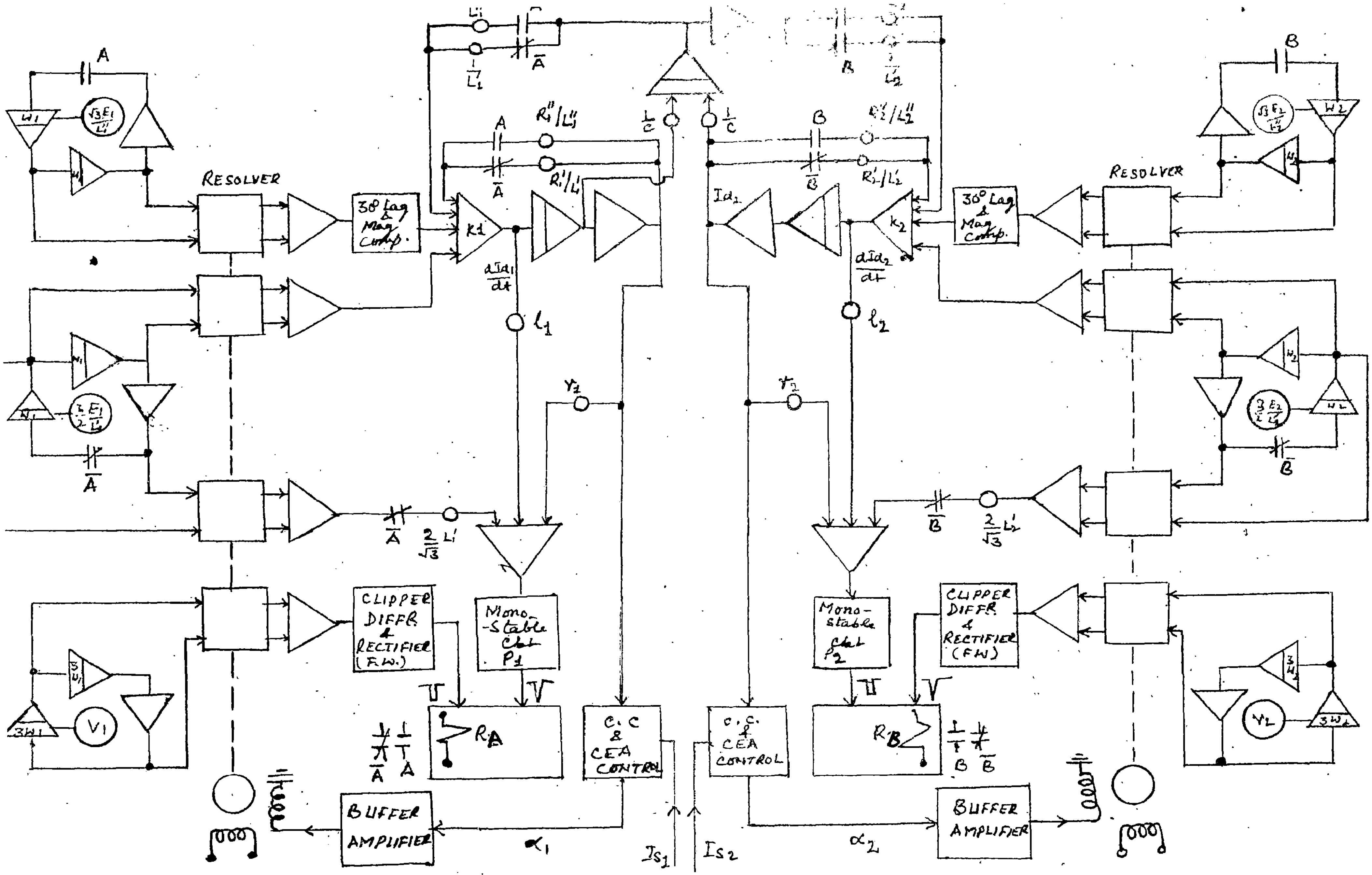


FIG (4.3) DYNAMIC ANALOG SETUP

The above two equations can be set up on anolog computer as shown in the Fig.(4.2a). Contacts A and $\overline{A}$, which are complementary in nature, are also shown. When contacts $\overline{A}$ are closed the set up represents the commutation process and when contacts A are closed the set up represents the non - commutation process. Due to complementary nature both cannot close or open simultaneously. The voltage sources connected to adder K_1 in Fig.(4.2a) are obtained from the sine and cosine function generators of frequency W_1. The delay of angle , which is not constant and depends upon the requirements of C.C. and C.E.A. control or of any other control simulated, is introduced in the cosine function as shown in Fig.(4.2b). The Sin α_1 and Cos α_1 are generated by sine and cosine resolver, the signal corresponding α_1 is obtained fromC.C and C.E.A. control circuit or any other control circuit simulated.

Here the 'Voltage drop' detection of end of commutation process has been proposed. As discussed in digital simulation the end of commutation is detected when $\sqrt{3}\ E_1$ Sin $(W_1 t + \alpha_1)$ becomes equal to $(l_1 \frac{dId_1}{dt} + r_1\, Id_1)$. The quantities Id_1 and $\frac{dId_1}{dt}$ are tapped from set up shown inFig.(4.2a). The generation of $\sqrt{3}\ E_1$ Sin $(W_1 t + \alpha_1)$ is similar to that of 3 E Cos $(W_1 t + \alpha_1)$. The set up for the end of commutation detection is shown in Fig.(4.2c). P_1 is a monostable multivibrator which gives a negative pulse output when the voltage input to it passes through zero. This negative pulse is sent to one of the grids of bistable circuit so as to operate the relay RA. The operation of relay closes contacts A and opens $\overline{A}$ contacts. Hence commutation-process set up is changed to noncommutation set up.

The relay RA is a special relay, electromagnetic in nature. It is placed in one of the plate circuits of bistable circuit shown in Fig.(4.2d). The relay operates when it receives a negative pulse at one of the grids negative pulse is sent to it at the end of commutation) and resets when it receives a negative pulse at other grid. The relay remains operated during the noncommutation period(contacts A remain closed)& remains unoperated(contacts $\overline{A}$ remain closed).Resetting of the relay causes back movement from noncommutation to commutation - period set up. Resetting is done by negative pulses at regular interval of (60 + $\triangle\alpha$) where $\triangle\alpha_1$ is the difference in firing angle of next valve to be fired, in sequence. The generation of negative pulses (six pulses per cycle) is done by clipping, differentiating and rectifying (full wave) the voltage produced by a function generator having three times the frequency of the system considered. The delay of angle α_1 is introduced in this voltage in a manner similar to one discussed above. The operation of the relay is shown in Fig.(4.2e).

A similar set up is made for convertor 2 (invertor) and both parts are connected by link equation $V_C = \int \frac{Id_1 - Id_2}{C} dt$ set-up. Id_1 and Id_2 are tapped from two set-ups and given to integrator to give V_C. The complete set-up is shown in Fig.(4.3). The C.C. and C.E.A. control anologue set-up can be taken as the same as given reference (15). Is_1 and Is_2 are the reference voltages representing the current settings for both sides. A buffer amplifier may be used in the output of C.C. and C.E.A. control anologue so that it is not loaded by servomotor of the Sine-cosine resolver. The other controls e.g. constant voltage and constant power can be simulated in similar manner only some modification is required. The external equipments required for anolog set up shown in Fig.(4.3) can be listed as (1) special relay with bistable circuit and complementary contacts (2) C.C. and C.E.A. control anolog (3) Monostable Vibrator for negative pulse at the end of commutation.

4.3. ADVANTAGES OF ANALOG SIMULATION:

1. More flexible and simple.
2. Recording can be done very easily.
3. Amplitude and time scaling is possible. Time scaling can be done in such a manner as to minimise the effect of the relay operating time.
4. Nonlinear parameters can be very easily represented.
5. Actual analog system of C.C. and C.E.A. control can be incorporated and different conditions can be changed.

5. SUMMARY AND CONCLUSION

The first Chapter of this thesis presents the necessity and importance of h.v.d.c. transmission for bulk power transfer over long distance. A brief review of the technical details and operating experiences of the various h.v.d.c. projects, commissioned and under construction, throughout the World, is given. The necessity of simulation in a dynamic manner is also given in this Chapter. A review of the 'Central Process' representation proposed by Messrs. Hingorani, Hay and Crosbie and the author's approach to the problem are given at the end of the Chapter.

With the help of the equations of the rectifier, invertor and the line, a simple equivalent circuit of the HVDC system is developed. The equations are written in the form proposed by A.M.Reider. The 'Repetitive Process' of dynamic simulation developed in the text is based upon these equations. This process is similar to the 'Central process' but is superior in some respects. Each convertor is represented by two equations, one for each mode of its operation i.e. commutating and non-commutating. The transmission line is represented by a single T-network. Hence, there are in all five equations - completely representing the h.v.d.c. system, three of them being valid at any time depending upon the state of the convertors. The equations are written in terms of the line currents at the two ends and the voltage of the line. Circulating currents between commutating valves are entirely eliminated. As the equations are similar for both states of the convertors (commutating and non-commutating) they are written in a generalised form. In this generalised form only the coefficients and the phase angles of the karmonic terms change. Two methods are proposed to detect the charge in the state of the convertors i.e. the circulating current method and the voltage 'drop' method.

The solution of the generalised equations is attempted as follows:

(i) The generalised equations are solved - analytically by the use of the conventional Laplace transforms. The plotting of the variables is then done by the computer which is programmed to select proper coefficients and angles. The voltage drop method or the circulating current method of the end of process detection is incorporated into this programme.

(ii) The Runga Kutta state-space technique is used to solve the equations on the computer. Here again the programme includes the end of process detection. A study of the starting transient has also been made. Further studies on the effect of increase, decrease and reversal of power-flow can be made using the proposed techniques. The effect of variation in the parameters of the system and the effect of constant voltage and constant power control can also be studied. Exact line and double bridge representation will need some modifications but the basic approach will be the same.

A method of simulating the HVDC system on an analogue computer is explained. Special circuits such as 'gates' are necessary to make the computer use only one of the two equations at a time. Non-linearities in the parameters of the system can be easily represented.

In all the above methods of simulation, the convertors are considered together with their control systems, such as the constant current control and constant extinction angle control system.

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APPENDIX – I

I.1 ANALYTICAL SOLUTION APPROACH

$$N(p) = L_2 C p^2 + R_2 C p + 1$$

$$M(p) = L_1 C p^2 + R_1 C p + 1$$

$$D(p) = p^3 + \frac{R_1}{L_1} + \frac{R_2}{L_2} p^2 (R_1 . R_2 . C + L_1 + L_2) p + \frac{R_1 + R_2}{L_1 \quad L_2 C}$$

$$Id_1(p) = \frac{1}{L_1 L_2 C} \frac{N(p)}{D(p)} \left[mE_1 \frac{p \cos \theta - W_1 \sin \theta}{p^2 + W_1^2} + L\, Id_1(o) - \frac{Vs(o)}{p} \right] + \frac{1}{L_1 L_2 C} \frac{1}{D(p)} \left[nE_2 \frac{p \cos \phi - W_2 \sin \phi}{p^2 + W_2^2} + L\, Id_2(o) + \frac{Vc(o)}{p} \right]$$

$$\frac{1}{L_1} C \frac{N(p)}{D(p)} = \frac{1}{L_1 L_2 C} \frac{L_2 C p^2 + R_2 C p + 1}{(p+A)(p^2+2Bp+D)} = \frac{1}{L_1} \frac{1}{p+A} \left[\frac{(\frac{R_2}{L_1} - 2B)p}{p^2+2Bp+D} - \frac{(D - 1/L_2 C)}{p^2+2Bp+D} + 1 \right] = \frac{1}{(p+A)} \left[\frac{1}{L_1} + \frac{Ep - F}{p^2+2Bp+D} \right]$$

$$\frac{Ep - F}{p^2+2Bp+D} = - \frac{E}{H} e^{-Bt} \sin(Wt - C_1) - \frac{F}{W} \sin Wt . e^{-Bt} = - e^{-Bt} \left(\frac{E}{H} \cos C_1 + \frac{F}{W} \right) \sin Wt . - \frac{E}{H} \sin C_1 \cos Wt = - e^{-Bt} . B_2 \sin (Wt - C_2)$$

$$\frac{p \cos \theta - W_1 \sin \theta}{(p+A)(p^2 + W_1^2)} = \int_0^t e^{-A(t-T)} \cos(W_1 T + \theta) . dT = e^{-At} \int_0^t e^{AT} . \cos (W_1 T + \theta) . dT = \frac{e^{-At}}{(W_1^2 + A^2)^{1/2}}$$

$$\left[e^{At} . \cos(W_1 t + \theta - C_3) - \cos(\theta - C_3) \right] = B_3 \cos(W_1 t + \theta - C_3) - e^{-At} \cos(\theta - C_3)$$

$$\frac{1}{} \left(\frac{1}{p+A} \right) . \frac{p \cos \theta - W_1 \sin \theta}{(p^2 + W_1^2)} = \frac{mE_1 B_3}{L_1} \left[\cos(W_1 t + \theta - C_3) - e^{-At} \cos (\theta - C_3) \right] = mE_1 B_{31} \left[\cos(W_1 t + \theta - C_3) - e^{-At} \cos (\theta - C_3) \right]$$

$$\mathcal{L}^{-1}\left[mE_1 \frac{p \cos\theta - W_1 \sin\theta}{(p+A)(p^2+W_1^2)} \cdot \frac{E\,p-F}{p^2+2Bp+D}\right] = -\,mE_1 B_2 B_3 \int_0^t \sin\left\{W(t-T)-C_2\right\} \cdot e^{-B(t-T)} \left[\cos(W_1 T+\theta - C_3) - e^{-At}\cos(\theta - C_3)\right] \cdot dT = G_2 + G_3$$

$$G_2 = mE_1 B_2 B_3 e^{-Bt} \int_0^t e^{BT} \cdot \sin(WT-Wt+C_2) \cdot \cos(W_1 T+\theta - C_3) \cdot dT = \frac{mE_1 B_2 \times B_3}{2} e^{-Bt} \int_0^t e^{BT} \left[\sin\left\{(W+W_1)T-Wt+C_2-C_3+\theta\right\} + \sin\left\{(W-W_1)T-Wt+C_2+C_3-\theta\right\}\right]$$

$$= \frac{mE_1 B_2 B_3}{2\left\{B^2+(W+W_1)^2\right\}^{1/2}} \left[\sin(W_1 t + C_2-C_3-C_4+\theta) + e^{-Bt}\sin(Wt-C_2+C_3+C_4-\theta)\right] - \frac{mE_1 \cdot B_2 \times B_3}{2\left\{B^2+(W-W_1)^2\right\}^{1/2}} \left[\sin(W_1 t-C_2-C_3+C_5+\theta) - e^{-Bt}\sin(Wt-C_2-C_3+C_5+\theta)\right]$$

$$= mE_1 B_{24} \sin(W_1 t+\theta+C_{24}) + e^{-Bt}\sin(Wt-C_{24}-\theta) - mE_1 B_{25} \sin(W_1 t + C_{25}+\theta) - e^{-Bt}\sin(Wt+C_{25}+\theta)$$

$$= mE_1 B_{24} \left[\sin(W_1 t+\theta+C_{24}) - B_{25}\sin(w_1 t+\theta+C_{25})\right] + mE_1 \left[B_{24}\sin(Wt-C_{24}-\theta) + B_{25} \cdot \sin(Wt+C_{25}+\theta)\right] \cdot e^{-Bt}$$

$$= mE_1 B_{45} \sin(W_1 t+\theta+C_{45}) + mE_1 e^{-Bt}\left[B_{24}\sin(Wt-C_{24}-\theta) + B_{25}\sin(Wt+C_{25}+\theta)\right]$$

$$G_3 = mE_1 B_2 \times B_3 e^{-Bt} \int_0^t \cos(\theta - C_3) \cdot e^{(B-A)T} \cdot \sin\left\{W(t-T)-C_2\right\} \cdot dT = mE_1 \left[B_{61} e^{-At} + e^{-Bt} B_6 \cdot \sin(Wt+C_{62})\right] \cdot \cos(\theta - C_3)$$

$$G_2+G_3 = mE_1 \cdot B_{45} \sin(W_1 t+\theta+C_{45}) + mE_1 \cdot B_{61} e^{-At} \cdot \cos(\theta - C_3)$$
$$+ mE_1 e^{-Bt}\left[B_{24} \cdot \sin(Wt-C_{24}-\theta) + B_{25} \cdot \sin(Wt+C_{25}+\theta) + B_6 \cdot \cos(\theta - C_3) \cdot \sin(Wt+C_{62})\right]$$
$$= mE_1 B_{45} \cdot \sin(W_1 t+\theta+C_{45}) + mE_1 B_{61} e^{-At} \cdot \cos(\theta - C_3)$$

$$+ mE_1 e^{-Bt}\Big\{\Big[\sin Wt \; B_{24}\cos(C_{24}+\theta) + B_{25}\cos(C_{25}+\theta) + B_6\cos(\theta - C_3).\cos(C_{62})\Big] + \Big[\cos Wt \Big(-B_{24}\cdot \sin(C_{24}+\theta) + B_{25}\cdot \sin(C_{25}+\theta) + B_6\cos(\theta-C_3).\sin(C_{62})\Big)\Big]\Big\}$$

$$= mE_1 \cdot B_{45}\sin(W_1 t + \theta + C_{45}) + mE_1 B_{61} e^{-At}.\cos(\theta - C_3)$$

$$+ mE_1 e^{-Bt}\sin Wt\Big\{\cos\theta\Big[B_{24}.\cos C_{24} + B_{25}\cos(C_{25}) + B_6\cos C_3\cdot\cos(C_{62})\Big] + \sin\theta\Big[-B_{24}\sin C_{24} - B_{25}\sin C_{25} + B_6\sin C_2\cos(C_{62})\Big]\Big\}$$

$$+ mE_1 e^{-Bt}\cos Wt\Big\{\sin\theta\Big[-B_{24}\cos C_{24} + B_{25}\cos(C_{25}) + B_6\sin C_3.\sin(C_{62})\Big] + \cos\theta\Big[-B_{24}\sin C_{24} + B_{25}\sin C_{25} + B_6\cos C_3\sin(C_{62})\Big]\Big\}$$

$$= mE_1 B_{45}\sin(W_1t+\theta+C_{45}) + mE_1 e^{-At}B_{61}\cos(\theta-C_3) + e^{-Bt}\Big[\sin Wt\cdot B_7\sin(\theta+C_7) + \cos Wt\cdot B_8\cos(\theta-C_8)\Big]$$

$$\frac{L_1}{L_1L_2C}\, Id_1(o)\cdot {}^{-1}\Big[\frac{N(p)}{D(p)}\Big] = + Id_1(o)\cdot L_1\Big[\frac{1}{L_1}e^{-At} - B_2\int_0^t e^{-BT}\sin(WT-C_2).\,e^{-A(t-T)}\,dT\Big]$$

$$= Id_1(o)\Big[e^{-At} - \frac{L\,B_2}{(A-B)^2+W^2}\Big[e^{-Bt}.\sin(Wt-C_2-C_8) + e^{-At}.\sin(C_2+C_6)\Big]\Big] = Id_1(o)\Big[-B_{51}e^{-At} - B_5\sin(Wt-C_{26})\Big]$$

$$-\frac{Vc(o)}{L_1L_2C}\,{}^{-1}\Big[\frac{1}{p}\frac{N(p)}{D(p)}\Big] = \frac{Vc(o)}{L_1}\int_0^t\Big[e^{-BT}B_5\sin(WT-C_{26}) + e^{-AT}B_{51}\Big].dT = \frac{Vc(o)}{L_1A}B_{51}(1-e^{-At})$$

$$- \frac{Vc(o).B_5}{L_1.(B^2+W^2)^{1/2}}\Big[e^{-Bt}.\sin(Wt-C_{26}+C_{10}) + \sin(C_{26}-C_{10})\Big]$$

$$= Vc(o).B_{52}(1-e^{-At}) - V_C(o)\Big[B_{53}\cdot e^{-Bt}.\sin(Wt+C_{16}) + B_{54}\Big]$$

$$\frac{nE_2}{L_1 L_2 C} \mathcal{L}^{-1}\left[\frac{p \cos \emptyset - W_2 \sin \emptyset}{p^2 + W_2^2} \cdot \frac{1}{D(p)} \right] =$$

$$= \frac{nE_2}{L_1 L_2 C} \cdot \frac{1}{W} \cdot \frac{1}{(A^2+W_2^2)^{1/2}} \int_0^t \left[\cos (W_2 T + \emptyset - F_1) - e^{-AT} \cos(\emptyset - F_1) \right] \cdot e^{-B(t-T)} \sin W(t-T) . dT$$

$$= \frac{-5 nE_2}{\sqrt{B^2+(W+W_2)^2}} \cdot D_1 \left[\sin(W_2 + \emptyset - F_1 + F_3) - e^{-Bt} . \sin(Wt + \emptyset - F_1 + F_3) \right] + \frac{5 nE_2 \cdot D_1}{\sqrt{B^2+(W-W_2)^2}} \left\{ \sin(W_2 t + \emptyset - F_1 + F_3) - e^{-Bt} . \sin (Wt + \emptyset - F_1 + F_3) \right\} - \frac{nE_2 \cdot D_1 \cdot \cos(\emptyset - F_1)}{\sqrt{(B-A)^2 + W^2}} \left[\sin F_4 \cdot e^{-At} + e^{-Bt} . \sin (Wt - F_4) \right]$$

$$= nE_2 \left[D_3 . \sin(W_2 t + \emptyset - F_1 + F_3) - D_2 \cdot \sin(W_2 t + \emptyset - F_1 - F_2) \right] - e^{-Bt} . nE_2 \left[D_3 . \sin(Wt + \emptyset - F_1 + F_3) + D_2 \cdot \sin (Wt - \emptyset + F_1 + F_2) \right] - nE_2 \left[D_4 \cdot \cos (\emptyset - F_1) . e^{-At} + D_5 e^{-Bt} + D_5 e^{-Bt} . \cos(\emptyset - F_1) \sin(Wt - F_4) \right]$$

$$= nE_2 . D_6 . \sin(W_2 t + \emptyset + F_6) - e^{-Bt} . nE_2 \left[D_3 \sin(Wt + \emptyset + F_{13}) + D_2 . \sin(Wt - \emptyset + F_{12}) \right] - nE_2 \left[D_4 \cos(\emptyset - F_1) e^{-At} + D_5 . e^{-Bt} . \cos(\emptyset - F_1) . \sin(Wt - F_4) \right]$$

$$= nE_2 . D_6 . \sin(W_2 t + \emptyset + F_6) - nE_2 . D_4 . \cos (\emptyset - F_1) . e^{-At} - e^{-Bt} nE_2 \left[D_3 \sin(Wt + \emptyset - F_{13}) + D_2 \sin (Wt - \emptyset + F_{12}) + D_5 . \cos(\emptyset - F_1) . \cos F_4 \right]$$

$$= nE_2 D_6 \sin(W_2 t + \emptyset + F_6) - e^{-At} . nE_2 . D_4 . \cos(\emptyset - F_1) - e^{-Bt} . nE_2 \sin Wt \cdot \left[D_3 . \cos(\emptyset - F_{13}) + D_2 \cos(\emptyset - F_{12}) + D_5 \cos(\emptyset - F_1) . \cos F_4 \right]$$

$$- nE_2 e^{-Bt} . (\cos Wt) \left[D_3 . \sin(\emptyset - F_{13}) - D_2 \sin (\emptyset - F_{12}) + D_5 \cos(\emptyset - F_1) . \sin F_4 \right]$$

$$\frac{nE_2}{L_1 L_2 C} \mathcal{L}^{-1}\left[\frac{p \cos \emptyset - W_2 \sin \emptyset}{p^2 + W_2^2} \cdot \frac{1}{D(p)} \right] =$$

$$= \frac{nE_2}{L_1 L_2 C} \cdot \frac{1}{W} \cdot \frac{1}{(A^2+W_2^2)^{1/2}} \int_0^t \left[\cos (W_2 T + \emptyset - F_1) - e^{-AT} \cos(\emptyset - F_1) \right] \cdot e^{-B(t-T)} \sin W(t-T) \cdot dT$$

$$= \frac{-5 nE_2}{\sqrt{B^2+(W+W_2)^2}} \cdot D_1 \left[\sin(W_2+\emptyset-F_1+F_3) - e^{-Bt} \cdot \sin(Wt+\emptyset-F_1+F_3) \right] + \frac{5 nE_2 \cdot D_1}{\sqrt{B^2+(W-W_2)^2}} \left\{ \sin(W_2 t+\emptyset-F_1+F_3) - e^{-Bt} \cdot \sin (Wt+\emptyset-F_1+F_3) \right\} - \frac{nE_2 \cdot D_1 \cdot \cos(\emptyset - F_1)}{\sqrt{(B-A)^2 + W^2}} \left[\sin F_4 \cdot e^{-At} + e^{-Bt} \cdot \sin (Wt - F_4) \right]$$

$$= nE_2 \left[D_3 \cdot \sin(W_2 t+\emptyset-F_1+F_3) - D_2 \cdot \sin(W_2 t+\emptyset-F_1-F_2) \right] - e^{-Bt} \cdot nE_2 \left[D_3 \cdot \sin(Wt+\emptyset-F_1+F_3) + D_2 \cdot \sin (Wt-\emptyset+F_1+F_2) \right] - nE_2 \left\{ D_4 \cdot \cos (\emptyset-F_1) \cdot e^{-At} + D_5 e^{-Bt} + D_5 e^{-Bt} \cdot \cos(\emptyset-F_1) \sin(Wt - F_4) \right]$$

$$= nE_2 \cdot D_6 \cdot \sin(W_2 t+\emptyset+F_6) - e^{-Bt} \cdot nE_2 \left[D_3 \sin(Wt+\emptyset+F_{13}) + D_2 \cdot \sin(Wt-\emptyset+F_{12}) \right] - nE_2 \left[D_4 \cos(\emptyset-F_1) e^{-At} + D_5 \cdot e^{-Bt} \cdot \cos(\emptyset-F_1) \cdot \sin(Wt-F_4) \right]$$

$$= nE_2 \cdot D_6 \cdot \sin(W_2 t + \emptyset + F_6) - nE_2 \cdot D_4 \cdot \cos (\emptyset-F_1) \cdot e^{-At} - e^{-Bt} nE_2 \left[D_3 \sin(Wt+\emptyset - F_{13}) + D_2 \sin (Wt-\emptyset+F_{12}) + D_5 \cdot \cos(\emptyset-F_1) \cdot \cos F_4 \right]$$

$$= nE_2 D_6 \sin(W_2 t+\emptyset+F_6) - e^{-At} \cdot nE_2 \cdot D_4 \cdot \cos(\emptyset-F_1) - e^{-Bt} \cdot nE_2 \sin Wt \cdot \left[D_3 \cdot \cos(\emptyset-F_{13}) + D_2 \cos(\emptyset-F_{12}) + D_5 \cos(\emptyset-F_1) \cdot \cos F_4 \right]$$

$$- nE_2 e^{-Bt} \cdot (\cos Wt) \left[D_3 \cdot \sin(\emptyset-F_{13}) - D_2 \sin (\emptyset-F_{12}) + D_5 \cos(\emptyset-F_1) \cdot \sin F_4 \right]$$

$$= nE_2 . D_6 . \mathrm{Sin}(W_2 t + \emptyset + F_6) - e^{-At} . nE_2 . D_4 . \mathrm{Cos}(\emptyset - F_1) - e^{-Bt}\, nE_2 \;\mathrm{Sin}\, Wt \left[\mathrm{Cos}\,\emptyset\, (D_3 \mathrm{Cos}\, F_{13} + D_2 \mathrm{Cos}\, F_{12} + D_5 \mathrm{Cos}\, F_4 . \mathrm{Cos}\, F_1) + \mathrm{Sin}\,\emptyset (D_3 \mathrm{Sin}\, F_{13} + D_2 \mathrm{Sin}\, F_{12} + D_5 \mathrm{Sin}\, F_1\, \mathrm{Cos}\, F_4) \right]$$

$$- nE_2\, e^{-Bt} \;\mathrm{Cos}\, Wt \left[\mathrm{Sin}\,\emptyset\, (D_3 \mathrm{Cos}\, F_{13} - D_2 \mathrm{Cos}\, F_{12} + D_5 \mathrm{Sin}\, F_4 . \mathrm{Sin}\, F_1) + \mathrm{Cos}\,\emptyset\, (-D_3 \mathrm{Sin}\, F_{13} + D_2 \mathrm{Sin}\, F_{12} + D_5 \mathrm{Sin}\, F_4\, \mathrm{Cos}\, F_1) \right]$$

$$= nE_2 . D_6\, \mathrm{Sin}(W_2 t + \emptyset + F_6) - e^{-At} .\, nE_2\, D_4\; \mathrm{Cos}(\emptyset - F_1) - nE_2 . e^{-Bt} \left[D_7\, \mathrm{Sin}\, Wt .\, \mathrm{Sin}(\emptyset + F_7) + D_8\, \mathrm{Cos}\, Wt .\, \mathrm{Cos}\, (\emptyset - F_8) \right]$$

$$\frac{L_2}{L_1 L_2 C}\; Id_2(o) \left[^{-1} \frac{1}{D(p)} \right. = \frac{Id_2(o)}{L_1 CW} . \int_0^t e^{-A(t-T)}\, \mathrm{Sin}\, (WT) .\; e^{-BT} .\, dT = \frac{Id_2(o)}{W\; L_1 C}\; e^{-At} \int_0^t e^{(A-B)} . \mathrm{Sin}\, WT .\, dT$$

$$= \frac{Id_2(o)}{WL_1 C \sqrt{(A-B)^2 + W^2}} \left[e^{-Bt} .\, \mathrm{Sin}\, (Wt - F_9) + \mathrm{Sin}\, F_9\, e^{-At} \right]$$

$$= Id_2(o) \left[D_9\, e^{-Bt} . \mathrm{Sin}\, (Wt - F_9) + D_{10}\, e^{-At} \right]$$

$$\frac{V_C(o)}{L_1 L_2 C} \left[^{-1} \frac{1}{p\, D(p)} \right. = \frac{V_C(o)}{L_2} \int_0^t \left[D_9\, e^{-Bt} .\, \mathrm{Sin}\, (Wt - F_9) + D_{10}\, e^{-At} \right] .\, dT - \frac{D_9}{L_2 \sqrt{B^2 + W^2}} \left[e^{-Bt} .\, \mathrm{Sin}(Wt - F_9 - C_{10}) + \mathrm{Sin}(F_9 + C_{10}) \right]$$

$$= V_C(o) \left[D_{12} (1 - e^{-At}) - D_{13}\; e^{-Bt}\, \mathrm{Sin}\, (Wt - F_{13}) - D_{14} \right]$$

Therefore

$$Id_1(t) = BO\,V_C(o) + mE_1 \cdot BO_1 \,\text{Sin}\,(W_1 t + \Theta + CO_1) + nE_2\, D_6 \,\text{Sin}\,(W_2 t + \emptyset + F_6)$$

$$+\, e^{-At}\Big[mE_1 \cdot BO_2 \cdot \text{Cos}(\Theta\; C_3) - nE_2\, D_4\,\text{Cos}\,(\emptyset - F_2) - B_5 1\, Id_1(o) + D_{10}\, Id_2(o)$$

$$+\, BO_3\, V_C\,(o)\Big] + e^{-Bt}\Big[\text{Sin Wt}\quad mE_1\, B_7\,\text{Sin}\,(\Theta + C_7) - nE_2\, D_7\,\text{Sin}\,(\emptyset + F_7)$$

$$+\, \text{Cos Wt}\quad mE_1 \cdot B_8\,\text{Cos}\,(\Theta - C_8) - D_8\, nE_2\,\text{Cos}\,(\emptyset - F_8)\Big]$$

$$+\, e^{-Bt}\Big[D_9\, Id_2(o) \cdot \text{Sin}\,(Wt - F_9) - B_5\, Id_1(o) \cdot \text{Sin}\,(Wt - C_{26}) - V_C(o) \cdot BO_4\,\text{Sin}\,(Wt + CO_4)\Big]$$

Constants used are:

$WN = \sqrt{D}$ $\qquad G = B / WN$ $\qquad H = \sqrt{1 - G \times G}$

$W = H \times WN$ $\qquad C_1 = \tan^{-1} (H/G)_2$ $\qquad E = (R_2 - 2.B.L_2)/(L_1.L_2)$

$F = (D.L_2.C - L) / (L_1.L_2.C)$ $\qquad S = (E/H)\ \text{Cos}\ C_1 + (F/W)$

$T = (E/H) \times \text{Sin}\ C_1$ $\qquad B_2 = \sqrt{S^2 + T^2}$

$C_2 = \tan^{-1} (T/S)$ $\qquad B_3 = 1./\sqrt{W_1^{\,2} + A^2}$

$C_3 = \tan^{-1} (W_1/A)$ $\qquad B_{31} = B_3/L_1$

$C_4 = \tan^{-1} (W + W_1) / B$ $\qquad C_5 = \tan^{-1} (W - W_1) / B$

$B_{24} = .5\, B_2\, B_3 / \sqrt{B^2 + (W + W_1)^2}$ $\qquad C_{24} = C_2 - C_3 - C_4$

$C_{25} = C_5 - C_2 - C_3$ $\qquad S_{11} = B_{24} \times \text{Cos}\ C_{24} - B_{25}\ \text{Cos}\ C_{25}$

$T_{11} = B_{24}\ \text{Sin}\ C_{24} - B_{25}\ \text{Sin}\ C_{25}$ $\qquad B_{45} = \sqrt{S_{11}^{\,2} + T_{11}^{\,2}}$

$C_{45} = \tan^{-1} \; (T_{11} / S_{11})$

$C_6 = \tan^{-1} \; (W/(A-B))$; $B_{61} = B_2 B_3 / \sqrt{(A-B)^2 + W^2}$

$B_{61} = B_6 \cdot \text{Sin} \; (C_6 + C_2)$

$C_{62} = C_6 + C_2$

$S_1 = - B_{24} \text{ Sin } C_{24} - B_{25} \text{ Sin } C_{25} + B_6 \cdot \text{Cos } C_{62} \cdot \text{Sin } C_3$

$T_1 = B_{24} \text{ Cos } C_{24} + B_{25} \text{ Cos } C_{25} + B_6 \cdot \text{Cos } C_{62} \cdot \text{Cos } C_3$

$B_7 = \sqrt{S_1^2 + T_1^2}$

$C_7 = \tan^{-1} \; (T_1 / S_1)$

$S_2 = - B_{24} \cdot \text{Sin } C_{24} + B_{25} \cdot \text{Sin } C_{25} + B_6 \cdot \text{Sin } C_{62} \cdot \text{Cos } C_3$

$T_2 = - B_{24} \cdot \text{Cos } C_{24} + B_{25} \cdot \text{Cos } C_{25} + B_6 \cdot \text{Sin } C_{62} \cdot \text{Sin } C_3$

$B_8 = \sqrt{S_2^2 + T_2^2}$

$C_8 = \tan^{-1} \; (T_2 / S_2)$

$C_{26} = C_2 + C_6$

$B_5 = B_2 \times L_1 / \sqrt{(A - B)^2 + W^2}$

$B_{51} = B_5 \cdot \text{Sin } C_{26} - 1$

$B_{52} = B_{51} / (L_1 . A)$

$B_{53} = B_5 / L_1 \cdot \sqrt{B^2 + W^2}$

$C_{10} = \tan^{-1} \; (W/B)$

$B_{54} = B_{53} \cdot \text{Sin } (C_{26} - C_{10})$

$C_{16} = - C_{26} + C_{10}$

$F_1 = \tan^{-1} \; (W_2 / A)$

$F_2 = \tan^{-1} \; (W + W_2) / B$

$F_3 = \tan^{-1} \; (W - W_2) / B$

$F_4 = \tan^{-1} \; (W/ (A-B))$

$D_1 = 1 / (L_1 \; L_2 . C . W \sqrt{A^2 + W_2^2}$

$D_2 = 5D_1 / \sqrt{B^2 + (W + W_2)^2}$

$D_3 = 5D_1 / \sqrt{B^2 + (W - W_2)^2}$

$D_4 = D_1 \cdot \text{Sin } F_4 / \sqrt{(A-B)^2 + W^2}$

$D_5 = D_1 / \sqrt{(A-B)^2 + W^2}$

$F_{12} = F_1 + F_2$

$T_3 = - D_3 \ \mathrm{Sin}\ (F_1 - F_3) + D_2\ \mathrm{Sin}\ (F_1 + F_2)$

$F_6 = \tan^{-1} (T_3 / S_3)$

$S_4 = - D_3 .\mathrm{Sin}\ F_{13} + D_2\ \mathrm{Sin}\ F_{12} + D_5\ \mathrm{Sin}\ F_1 .\ \mathrm{Cos}\ F_4$

$D_7 = \sqrt{S_4^2 + T_4^2}$

$S_5 = D_3 .\mathrm{Sin}\ (F_{13}) + D_2 .\ \mathrm{Sin}\ F_{12} - D_5 .\mathrm{Sin}\ F_4 - \mathrm{Cos}\ F_1$

$T_5 = D_3 .\mathrm{Cos}\ F_{13} - D_2\ \mathrm{Cos}\ F_{12} + D_5 .\mathrm{Sin}\ F_4 .\mathrm{Sin}\ F_1$

$F_8 = \tan^{-1} (T_5 / S_5)$

$D_{10} = D_9 .\mathrm{Sin}\ F_9$

$D_{13} = D_9 / (L_2 . \sqrt{B^2 + W^2})$

$D_{14} = D_{13} . \mathrm{Sin}\ (F_9 + C_{10})$

$T_6 = - B_{45} . \mathrm{Sin}\ C_{45} + B_{31} . \mathrm{Cos}\ C_3$

$BO_1 = \sqrt{S_6^2 + T_6^2}$

$BO_2 = B_{61} - B_{31}$

$S_7 = B_{53} . \mathrm{Cos}(C_{16}) + D_{13} . \mathrm{Cos}\ F_{13}$

$BO_4 = \sqrt{S_7^2 + T_7^2}$

$F_{13} = F_3 - F_1$

$S_3 = D_3\ \mathrm{Cos}\ (F_1 - F_3) - D_2\ \mathrm{Cos}(F_1 + F_2)$

$D_6 = \sqrt{S_3^2 + T_3^2}$

$T_4 = D_3 .\mathrm{Cos}\ F_{13} + D_2 \mathrm{Cos}\ F_{12} + D_5 \mathrm{Cos}\ F_1 . \mathrm{Cos}\ F_4$

$F_7 = \tan^{-1} (T_4 / S_4)$ $F_9 = F_4$

$D_8 = \sqrt{T_5^2 + S_5^2}$

$D_9 = 1 / (W . L_1 C . \sqrt{(A-B)^2 + W^2})$

$D_{12} = D_{10} / L_2$

$F_{13} = F_9 + C_{10}$

$BO = B_{52} - B_{54} + D_{12} - D_{14}$

$S_6 = - B_{45} . \mathrm{Cos}\ C_{45} + B_{31}\ \mathrm{Sin}\ C_3$

$CO_1 = \tan^{-1} (T_6 / S_6)$

$BO_3 = - D_{12} - B_{52}$

$T_7 = B_{53} . \mathrm{Sin}\ C_{16} - D_{13} . \mathrm{Sin}\ F_{13}$

$CO_4 = \tan^{-1} (T_7 / S_7)$.

$C_{45} = \tan^{-1} (T_{11} / S_{11})$ $\qquad$ $C_6 = \tan^{-1} (W/(A-B))$; $B_{61} = B_2 B_3 / \sqrt{(A-B)^2 + W^2}$

$B_{61} = B_6 \cdot \sin (C_6 + C_2)$ $\qquad$ $C_{62} = C_6 + C_2$

$S_1 = - B_{24} \sin C_{24} - B_{25} \sin C_{25} + B_6 \cdot \cos C_{62} \cdot \sin C_3$

$T_1 = B_{24} \cos C_{24} + B_{25} \cos C_{25} + B_6 \cdot \cos C_{62} \cdot \cos C_3$

$B_7 = \sqrt{S_1^2 + T_1^2}$ $\qquad$ $C_7 = \tan^{-1} (T_1 / S_1)$

$S_2 = - B_{24} \cdot \sin C_{24} + B_{25} \cdot \sin C_{25} + B_6 \cdot \sin C_{62} \cdot \cos C_3$

$T_2 = - B_{24} \cdot \cos C_{24} + B_{25} \cdot \cos C_{25} + B_6 \cdot \sin C_{62} \cdot \sin C_3$

$B_8 = \sqrt{S_2^2 + T_2^2}$ $\qquad$ $C_8 = \tan^{-1} (T_2 / S_2)$

$C_{26} = C_2 + C_6$ $\qquad$ $B_5 = B_2 \times L_1 / \sqrt{(A - B)^2 + W^2}$

$B_{51} = B_5 \cdot \sin C_{26} - 1$ $\qquad$ $B_{52} = B_{51} / (L_1 \cdot A)$

$B_{53} = B_5 / L_1 \cdot \sqrt{B^2 + W^2}$ $\qquad$ $C_{10} = \tan^{-1} (W/B)$

$B_{54} = B_{53} \cdot \sin (C_{26} - C_{10})$ $\qquad$ $C_{16} = - C_{26} + C_{10}$

$F_1 = \tan^{-1} (W_2 / A)$ $\qquad$ $F_2 = \tan^{-1} (W + W_2) / B$

$F_3 = \tan^{-1} (W - W_2) / B$ $\qquad$ $F_4 = \tan^{-1} (W/ (A-B))$

$D_1 = 1 / (L_1 L_2 \cdot C \cdot W \sqrt{A^2 + W_2^2}$ $\qquad$ $D_2 = 5D_1 / \sqrt{B^2 + (W + W_2)^2}$

$D_3 = 5D_1 / \sqrt{B^2 + (W-W_2)^2}$ $\qquad$ $D_4 = D_1 \cdot \sin F_4 / \sqrt{(A-B)^2 + W^2}$

Similarly

$$Id_2(t) = V_C(o)\ (-B_{52} + B_{54} - D_{12} + D_{14}) + mE_1 D_6 \cdot \text{Sin}\ (W_2t+\theta+F_6) + nE_2 B_{95}\ \text{Sin}(W_2t + \emptyset + C_{45})$$

$$+ nE_2\ B_{31} \cdot \text{Cos}\ (W_1t + \emptyset - C_3) + e^{-At}\Big[-mE_1 D_4 \text{Cos}(\theta - F_1) - nE_2 \cdot B_{31}\ \text{Cos}(\emptyset - C_3) + nE_2 B_{61}\ \text{Cos}/\emptyset - C$$

$$+ D_{10}\ Id_1(o) - B_{51}\ Id_2(o) + (B_{52} + D_{12})\ V_C(o)\Big] + e^{-Bt}\Big[\text{Sin Wt}\ \{-mE_1 D_7\ \text{Sin}\ (\theta + F_7)$$

$$+ nE_2 \cdot B_7\ \text{Sin}(\emptyset + C_7)\} + \text{Cos Wt}\ \{-mE_1 D_8\ \text{Cos}(\theta - F_8) + nE_2 \cdot B_8\ \text{Cos}\ (\emptyset - C_8)\}$$

$$+ e^{-Bt}\Big[-B_5\ Id_2\ \text{Sin}\ (Wt - C_{26}) + D_9\ Id_1\ \text{Sin}(Wt - F_9) + B_{53}\ V_C(o)\ \text{Sin}(Wt + C_{16})$$

$$+ D_{13} \cdot V_C(o) \cdot \text{Sin}\ (Wt - F_{13})\Big]$$

or

$$Id_2(t) = Bo\ V_C(o) - mE_1 D_6\ \text{Sin}\ (W_2t + \theta + F_6) - nE_2 \cdot BO1\ \text{Sin}\ (W_1t + \theta + CO_1)$$

$$+ e^{-At}\Big[mE_1 \cdot D_4\ \text{Cos}\ (\theta - F_2) - nE_2\ \text{Cos}\ (\emptyset - C_3) - D_{10}\ Id_1(o) - B_{51}\ Id_1(o) + BO_3\ V_C(o)\Big]$$

$$+ e^{-Bt}\Big[(\text{Sin Wt}) \cdot (mE_1 D_7\ \text{Sin}\ (\theta + F_7) - nE_2 B_7\ \text{Sin}\ (\emptyset + C_7)) + \text{Cos Wt}\ (mE_1 D_8\ \text{Cos}\ (\theta - F_8)$$

$$- nE_2 B_8\ \text{Cos}\ (\emptyset - C_8))\Big] + e^{-Bt}\Big[D_5\ Id_2(o)\ \text{Sin}\ (Wt - C_{26}) - D_9\ Id_1(o)\ \text{Sin}\ (Wt - F_9)$$

$$- V_C(o) \cdot Bo_4\ \text{Sin}\ (Wt + Co_4)\Big]$$

The constants for $Id_2(t)$ can be calculated by the same program of $Id_1(t)$ constant calculations only the value of R_1, L_1, R_2, L_2, W_1, & W_2 are to be replaced by R_2, L_2, R_1, L_1, W_2 & W_1 respectively.

In general $Id_1(t)$ and $Id_2(t)$ can be represented by same expression of $Idj(t)$

$$Idj(t) = B_1\ V_C(o) + B_2\ mE\ \text{Sin}\ (W_1t + \theta + B_3) + B_4\ nE_2\ \text{Sin}\ (W_2t + \emptyset + B_5) + e^{-At}$$

$$\Big[mE_1\ B_6\ \text{Cos}\ (\theta - B_7) - nE_2 B_8\ \text{Cos}(\emptyset - B_9) - B_{10}\ Id_1(o) + B_{11}\ Id_2(o) + B_{12}\ V_C(o)\Big] + e^{-Bt}$$

$$\Big[\text{Sin Wt}\ \{B_{13}\ mE_1\ \text{Sin}\ (\theta + B_{14}) - B_{15}\ nE_2\ \text{Sin}\ (\emptyset + B_{16})\} + \text{Cos Wt}\ (B_{17}\ mE_1\ \cos\ (\theta - B_{18})$$

$$- B_{19} \cos(\emptyset - B_{20}) + e^{-Bt}\left[B_{21}\, Id_2(o) \sin(Wt - B_{22}) - B_{23}\, Id_1(o) \sin(Wt - B_{24}) - B_{25}\, V_C(o) \sin(Wt + B_{26})\right]$$

I.2 STARTING TRANSIENTS

$$mE_1 \frac{p \cos\theta - W_1 \sin\theta}{p^2 + W_1^2} = (Lp+R)\, Id_1(p) + \frac{Id_1}{CP} + \frac{V_c(o)}{p} - LId_1(o) \quad \text{or} \quad pc.mE_1 \frac{(p \cos\theta - W_1 \sin\theta)}{p^2 + W_1^2}$$

$$= (CL\, p^2 + RCP + 1)\, Id_1 + C\, V_C(o) - CPL\, Id_1(o)$$

$$Id_1(p) = \frac{pc}{CLp^2 + RCp + 1} \cdot mE_1 \frac{p \cos\theta - W_1 \sin\theta}{(p^2 + W_1^2)} + \frac{Cp.\, L\, Id_1(o)}{CLp^2 + RCp + 1} = \frac{mE_1}{L} \frac{p}{(p^2 + \frac{R}{L}p + \frac{1}{CL})} \cdot \frac{p \cos\theta - W_1 \sin\theta}{p^2 + W_1^2}$$

$$+ \frac{p \quad Id_1(o)}{(p^2 + \frac{R}{L}p + \frac{1}{CL})} - \frac{V_C(o)}{L(p^2 + \frac{R}{L}p + \frac{1}{CL})}$$

$$Id_1(t) = -\frac{mE_1}{2L.F} \int^t e^{-PT}.2.\sin(GT + C_1).\cos(W_1 T - W_1 t - \theta).dT - \frac{Id_1(o)}{F}.e^{-Pt}.\sin(Gt + C_1) - \frac{VC(o)}{L.G} e^{-Pt}.\sin Gt$$

$$= -\frac{mE_1}{2L.F} \int^t e^{-PT} \quad \sin\left((G + W_1)\, T + C_1 - W_1 t - \theta\right) + \sin\ (G - W_1)\, T + C_1 + W_1 t + \theta) \quad dT - \frac{Id_1(o)}{F}.$$

$$e^{-Pt}.\sin(GT + C_1) - \frac{VC(o)}{L.G} \quad e^{-Pt}.\ \sin GT$$

$$= -\, mE_1 \quad C_{11} \sin(W_1 t + \theta + C_1 + B_{11}) - C_{22} \sin(W_1 t + \theta - C_1 - B_{22}) + mE_1\, e^{-Pt} \quad C_{11} \sin(Gt + C_1 + \theta + B$$

$$+ C_{22} \sin(Gt + C_1 - \theta + B_{22}) \quad - U\, Id_1(o)\, e^{-Pt}.\sin(Gt + C_1) - V_C(o).V.e^{-Pt} \sin$$

$$mE_1 \cos(W_1 t + \theta) = L \frac{dId_1}{dt} + R\, Id_1 + V_C(p) \text{ and } \frac{dV_C}{dt} = \frac{Id_1}{C} \qquad mE_1 \frac{p \cos\theta - W_1 \sin\theta}{p^2 + W_1^2} = (Lp+R)$$

$$Id_1 + V_C - L\, Id_1(o)\ ; \quad pVc(p) - V_C(o) = \frac{Id_1}{C}$$

$$\text{or, } mE_1 \frac{p \cos\theta - W_1 \sin\theta}{p^2 + W_1^2} = (Lp + R)\, C\, (p\, V_C(p) - V_C(o) + V_C - L\, Id_1(o) = (LCp^2 + RCp + 1)\, V_C(p) - C\,(Lp + R)\, V_C(o) - L\, Id_1(o)$$

$$\text{or, } Vc(p) = mE_1 \frac{p \cos\theta - W_1 \sin\theta}{p^2 + W_1^2} \cdot \frac{1}{(LCp^2 + RCP + 1)} + \frac{C\,(Lp + R)}{LCp^2 + RCP + 1} V_C(o) + \frac{L \quad Id_1(o)}{(LCp^2 + RCP + 1)}$$

$$V_C(t) = \frac{mE_1}{2\, G.L.C.} \int_o^t \left[e^{-PT} \left[\sin\left\{(G+W_1)\, T - W_1 t - \theta\right\} + \sin\left\{(G-W_1)\, T + W_1 t + \theta\right\}\right] dT + \frac{R}{L} \frac{V_C(o)}{G} e^{-Pt} . \sin Gt - \frac{V_C(o)}{F} e^{-Pt} \sin(GT-G) + \frac{Id_1(o)}{C.\, G} . \sin(GT)\right.$$

$$= - \frac{mE_1 F}{G.C} \left[(C_{11}) \left\{ \sin(Gt+\theta+B_{11}) \cdot e^{-Pt} - \sin(W_1 t + \theta + B_{11}) \right\} + C_{22} \left\{ \sin(Gt-\theta+B_{22})\, e^{-Pt} + \sin(W_1 t + \theta - B_{22}) \right\} \right] + \frac{V_C(o)}{} \cdot e^{-Pt} \left[\frac{R}{LG} \sin Gt - \frac{1}{F} \sin(GT - C_1) \right] + \frac{Id_1(o)}{C\, G} e^{-Pt} . \sin Gt$$

$$\text{Now} \quad Y = \frac{mE_1}{G\, C} F \qquad Y_1 = Y \quad C_{11} \qquad Y_2 = Y \quad C_{22}$$

$$= - e^{-Pt} \quad Y_1 \sin(Gt + \theta + B_{11}) + Y_2 \sin(Gt - \theta + B_{22}) + Y_1 . \sin(W_1 t + \theta + B_{11}) - Y_2 . \sin(W_1 t + \theta - B_{22}) + V_C(o)\, e^{-Pt} \quad \frac{R}{LG} \sin Gt - \frac{1}{F} \sin(Gt - C_1) + \frac{Id_1(o)}{C\, G} e^{-Pt} \sin Gt$$

Where constants used are:

$A = R / L$ $\quad B = 1/ L\,C.$, $D = B$, $E = .5A/D$ $\quad F = \sqrt{1 - E^2}$ $\quad G = F \cdot D$

$A_1 = .5H/L\,F \sqrt{P^2 + H^2}$ $\quad B_1 = .5P/L\,F \sqrt{P^2 + H^2}$ $\quad P = A/2$

$C_1 = \tan^{-1}(-F/E)$ $\quad H = G - W$ $\quad B_2 = .5P/ L\,F \sqrt{P^2 + Q^2}$ $\quad C_{11} = \sqrt{A_1^2 + B_1^2}$

$Q = G + W$ $\quad A_2 = .5Q / L\,F \sqrt{P^2 + Q^2}$

$$C_{22} = \sqrt{A_2^{\,2} + B_2^{\,2}} \qquad B_{11} = \tan^{-1} A1/B1 \qquad B_{22} = \tan^{-1} A_2/B2$$

$$S = C_{11}\,\mathrm{Cos}\,(C_1 + B_{11}) - C_{22}\,\mathrm{Cos}\,(C_1 + B_{22}) \qquad D_{11} = \sqrt{S^2 + T^2} \qquad E_{11} = \tan^{-1}(T/S)$$

$$T = C_{11}\,\mathrm{Sin}\,(C_1 + B_{11}) + C_{22}\,\mathrm{Cos}\,(C_1 + B_{22}) \qquad U = 1/F \qquad V = {}^{1}/F.D.L$$

1.3 Circulating Currents

$$e_B - e_A = \sqrt{3}E_1\,\mathrm{Sin}\,(W_1 t + \theta) = L_1\left(\frac{di_{1B}}{dt} - \frac{di_{1A}}{dt}\right) + R_1\,(i_{1B} - i_{1B}) \quad ; \left[-i_{1A} = -Id_1 + i_{1B}\right]$$

$$= L_1\left(\frac{2\,di_{1B}}{dt} - \frac{dId_1}{dt}\right) + R_1\,(2\,i_{1B} - Id_1)$$

Taking Laplace Transform of both sides:

$$\sqrt{3}.E_1 \frac{\mathrm{Sin}\,\theta.\,p + \mathrm{Cos}\,\theta\,.W_1}{W_1^{\,2} + p^2} = 2\,(L_1 p + R_1)\,i_1(p) + (L_1 p + R_1)\,Id_1(p) + L_1 Ido \qquad (i_{1B} = i_1)$$

$$i_1(p) = \frac{Id_1(p)}{2} - \frac{L_1\,Id_1(o)}{2(L_1 p + R_1)} + \frac{\sqrt{3}}{2}.E_1\frac{p\,\mathrm{Sin}\,\theta + W_1\,\mathrm{Cos}\,\theta}{W_1^{\,2} + p^2}\cdot\frac{1}{(L_1 p + R_1)}$$

$$i_1(t) = \frac{Id_1}{2} - \frac{Id_1(o)}{2}\,e^{-\frac{R1}{L1}t} + \frac{\sqrt{3}}{2\,L_1}E_1\int_0^t \mathrm{Sin}\,(W_1 T + \theta)\,.\,e^{-\frac{R1}{L1}(t-T)}.dT = \frac{Id_1}{2} - \frac{Id_1(o)}{2}\,e^{-\frac{R1}{L1}t} + \frac{\sqrt{3}E_1}{2L_1}\,e^{-\frac{R1}{L1}t}\int_0^t e^{\frac{R1}{L1}.T}.\mathrm{Sin}(W_1 T + \theta)\,dT$$

$$= \frac{Id_1}{2} - \frac{Id_1(o)}{2}.\,e^{-\frac{R1}{L1}t}. + \frac{\sqrt{3}}{2}.\frac{E1}{(R_1^{\,2} + L_1^{\,2}W_1^2)^{1/2}}\left[\mathrm{Sin}\,(W_1 t + \theta - \theta_C) - \mathrm{Sin}\,(\theta - \theta c).\,e^{-\frac{R1}{L1}t}\right]$$

$$\text{where } \theta_C = \tan^{-1}\frac{WL_1}{R_1}$$

APPENDIX II

```
C   C    STARTING TRANSIENTS PROGRAM PART I
C        STARTING CONSTANTS  KATIYAR  S C  EED  UOR
    10   READ20,R,Z,C,W
    20   FORMAT (4F15.6)
         A=R/Z
         B=1./(Z*C)
         D=B**.5
         E=.5*(A/D)
         F=(1.-E**2)**.5
         G=F*D
         C1=ATAN (-F/E)
         H=G-W
         P=A/2.
         A1=H/(2.*Z*F*(P**2+H**2))
         B1=P/(2.*Z*F*(P**2+Q**2))
         Q=G+W
         A2=Q/(2.*Z*F*(P**2+Q**2))
         B2=P/(2.*Z*F*(P**2+Q**2))
         C11=(A1**2+B1**2)**.5
         C22=(A2**2+B2**2)**.5
         B11=ATAN (A1/B1)
         B22=ATAN (A2/B2)
         S=C11*COS (C1+B11)-C22*COS (C1+B22)
         T=C11*SIN (C1+B11)+C22*SIN (C1+B22)
         D11=(S**2+T**2)**.5
         E11=ATAN (T/S)
         U=1./F
         V=1./(F*D*Z)
         PUNCH40,D11,E11,U,V,C11,B11
         PUNCH40,C1,C22,B22,P,G,F
    40   FORMAT(6F12.6)
         GO TO 10
         STOP
         END
C        R                  L            C          W1
         6.                 1.040        .000002    314.285
         5.75               1.030        .000002    314.285
```

OUTPUT OBTAINED

.000791	-.004747	1.000009	.001387	.001268	1.563187
-1.566636	.000477	1.567934	2.884615	693.368890	.999991
.000789	-.004537	1.000008	.001393	.001269	1.563498
-1.566790	.000480	1.568036	2.791262	696.727160	.999992

The value obtained above are substituted in expressions and starting transients program part 2 is as follows:

```
$JOB              OCRO92 NAME  S.C.KATIYAR
$IBJOB
$IBFTC
C                 STARTING TRANSIENT CALCULATIONS PROGRAM-2
C                 INPUT BY READ STATEMENT
                  READ30,AP1,AP2,T1,T
        30        FORMAT(4F10.6)
                  DT=.000111
                  X=1./696.727160
                  V=1./693.36889
                  Y=74100.*500000.*.9999
                  Y1=1.732*Y*.001268/693.36889
                  Y2=1.732*.000477/693.36889
                  Y3=1.5*Y*.001269/696.72716
                  Y4=1.5*Y*.00048/696.72716
C                 TIME INCREAMENT BY DT=.00011
       100        T1=T1+DT
                  T=T+DT
                  WT=314.285*T1
                  EX2=EXP(-2.884615*T1)
                  GT=693.36889*T1
C                 CHECK WHETHER T1< 60/W
                  IF(T-.003333)101,102
C                 CALCULATE VC ., VD1, Id1 OF NONCOMM.PROCESS
       101        A=61.5*SIN (WT+.347902)-163.732*SIN(WT+.345751)
                  B=EX2*(163.732*SIN (GT-.34575)+61.5*SIN (GT+.34790)
                  AD1=-A+B
                  V1=314.285*61.5*COS (WT+.347902)
                  V2=-314.285*163.732*COS (WT+.345751)
                  V3=-2.884615*B
                  V4=693.36889*EX2*(163.732*COS(GT-.34575)+61.5*
                                                COS (GT+.3479))
                  DAD1=-V1-V2+V3+V4
                  VC1=Y1*SIN (WT+1.912289)-Y2*SIN(WT-1.214087)
                  VC2=-EX2*(Y1*SIN (GT+1.912289)+Y2*SIN(GT+1.21087))
                  VC=VC1+VC2
                  VD1=VC+5.*AD1+DAD1
                  A1=AD1
                  GO TO 1001
       102        AP1=AP1+1.
                  IF(AP1-1.)204,103,204
C                 CHANGE THE INITIAL VALUE ONLY ONCE
       103        AD11=AD1
                  VC33=VC
                  T1=DT
                  A1=0.
                  WT=314.285*T1
C                 CHECK RECTIFIER COMMUTING OR NOT
       204        IF(A1-AD1)104,105,105
```

```
C     CALCULATION VC,VD1,Id,I1 FOR COMM.PROCESS
104   ET=696.72716*T1
      EX=EXP (-25.*T1)
      EX3=EXP (-2.791262*T1)
      A1=.5*(AD1-EX*AD11)+10177.*(.91*EX+SIN (WT-1.428))
      P=54.9959*SIN(WT+.352392)-141.049*SIN(WT+.345808)
      Q=EX3*(141.049*SIN (ET-.345808)+54.9959*SIN(ET+.
                                          352392))
      R=-EX3*(.001393*VC33*SIN(ET)+1.00008*AD11*SIN
                                       (ET-1.56679))
      AD1=-p+Q+R
      V1=314.285*54.9959*COS (WT+.352392)
      V2=-314.285*141.049*COS (WT+.345808)
      V4=-2.791262*(R+Q)
      V5=696.7271*EX3*(.001393*VC33*COS(ET)+AD11*COS
                                      (ET-1.566791))
      V3=696.7271*EX3*(141.049*COS (ET-.345808)+54.
                            9959*COS (ET+.35292))
      DAD1=-V1-V2+V3+V4-V5
      VC1=Y3*SIN (WT+1.912598)-Y4*SIN (WT-1.21398)
      VC2=-EX3*(Y3SIN (ET+1.912598)+Y4*SIN (ET+1.214398))
      VC3=VC33*EX3*(5.582524*X*SIN (ET)-SIN (ET-1.56679))
      VC4=AD11*EX3*500000.*X*SIN (ET)
      VC=VC1+VC2+VC3+VC4
      VD1=VC+5.*AD1+DAD1
      GO TO 1001
105   AP2=AP2+1.
      IF(AP2-1.)107,106,107
C     CHANGE THE INITIAL CONDITIONS ONCE AGAIN
106   T1=DT
      AD11=AD1
      VC33=VC
      GT=693.36889*T1
      WT=314.285*T1
      EX2=EXP (-2.884615*T1)
C     CALCULATIONS VC,KD1,Id1 FOR COMM.PROCESS
107   A=61.5*SIN (WT+.347902)-163.732*SIN(WT+.345751)
      B=EX2*(163.732*SIN (GT-.34575)+61.5*SIN(GT+.34790))
      C=-EX2*(1.000009*AD11*SIN (GT-1.566636)+.001393*
                                        VC33*SIN (GT))
      AD1=-A+B+C
      V1=314.285*61.5*COS (WT+.347902)
      V2=-314.285*163.732*COS (WT+.345751)
      V3=-2.88461*(B+C)
      V5=-693.3688*EX2*(AD11*COS (GT-1.5666)+.001393*
                                    VC33*COS (GT))
      V4=693.36889*EX2*(163.732*COS (GT-.34575)+61.5*
                                 COS (GT+.3479))
      DAD1=-V1-V2+V3+V4+V5
      VC1=Y1*SIN (WT+1.912289)-Y2*SIN (WT-1.214087)
      VC2=-EX2*(Y1*SIN (GT+1.912289)+Y2*SIN(GT+1.21087))
      VC3=VC33*EX2*(5.76923*V*SIN (GT)-SIN (GT-1.566636))
      VC4=AD11*EX2*500000.*V*SIN(GT)
      VC=VC1+VC2+VC3+VC4
      VD1=VC+5.*AD1+DAD1
      A1=AD1
```

```
C           END OF PROGRAM DETECTION
            IF(T-.00605) 1001,108,108
      1001  PRINT10,T,AD1,A1, VD1, VC
        10  FORMAT (5614.6)
            GO TO 100
       108  STOP
            END
            ENTRY
```

SYSTEM - SIMULATION PROGRAMS

```
C     C     ROOTS CALCULATIONS KATIYAR S C   EED  U O R
C           D(P) = (P+A)(P-P+2,BP+D)
      200   READ100, R1,R2,Z1,Z2,C
      100   FORMAT (5F12.8)
            AA=(R1/Z1)+(R2/Z2)
            BB=(R1*R2*C+Z1+Z2)/(Z1*Z2*C)
            T=(R1+R2)/(Z1*Z2*C)
            PP=BB-(AA**2)/3.
            Q=2.*((AA/3.)**3)-AA*BB/3.+T
            Q1=((PP/3.)**3)+(Q/2.)**2)
            W1=Q1**.5
            A1=(W1-Q/2.)**.33333
            B1=-(W1+Q/2.)**.33333
            X=A1+B1-AA/3.
            Y=-((A1+B1)/2.)-AA/3.
            V=.866*(A1-B1)
            Z=(Y**2)+(V**2)
            PUNCH103,X,Y,Z
      103   FORMAT(3F16.6)
            GO TO 200
            STOP
            END
C     R1          R2       L1        L2          C
      6.00        5.750    1.040     1.030       0.0000020
      6.0         6.0      1.040     1.040        .000002
      5.750       5.75     1.030     1.030        .000002
      5.75        6.0      1.030     1.040        .000002
```

OUTPUT OBTAINED

-5.676038	-2.837858	966026.670000
-5.768974	-2.884744	961360.060000
-5.582533	-2.791258	970694.160000
-5.676038	-2.837858	966026.670000

ANALYTICAL SOLUTION PROGRAMS

PROGRAM - I

```
C     C     OCR092 SC KATIYAR  ROORKEE UNIVERSITY
C           CONSTANTS FOR ID1 AND Id2 EXPRESSIONS
      10    READ100,Z1,Z2,R2,A,B,D
      100   FORMAT(6F12.6)
            W1=314.285
            W2=314.285
            C=.000002
            WN=SQRTF(D)
            G=B/WN
            H=SQRTF (1.-G*G)
            W=H*WN
            C1=ATANF(H/G)
            E=(R2-2.*B*Z2)/(Z1*Z2)
            F=(D*Z2*C-1.)/(Z1*Z2*C)
            S=(E/H)*COSF(C1)+(F/W)
            T=(E/H)*SINF(C1)
```

```
B2=SQRTF(S*S+T*T)
C2=ATANF(T/S)
B3=1./SQRTF(W1*W1+A*A)
C3=ATANF(W1/A)
B31=B3/Z1
C4=ATANF ((W+W1)/B)
C5=ATANF ((W-W1)/B)
B24=.5*B2*B3/SQRTF(B*B+(W+W1)*(W+W1))
B25=.5*B2*B3/SQRTF(B*B+(W-W1)*(W-W1))
C24=C2-C3-C4
C25=C5-C2-C3
S11=B24*COSF(C24)-B25*COSF(C25)
T11=B24*SINF(C24)-B25*SINF(C25)
B45=SORTF (S11*S11+T11*T11)
C45=ATANI (T11/S11)
C6=ATANF(W/(A-B))
B6=B2*B3/SQRTF ((A-B)*(A-B)+W*W)
B61=B6*SINF (C6+C2)
C62=C6+C2
S1=-B24*SINF(C24)-B25*SINF(C25)+B6*COSF(C62)*SINF
                                              (C3)
T1=B24*COSF (C24)+B25*COSF(C25)+B6*COSF(C62)*COSF
                                              (C3)
B7=SQRTF(S1*S1+T1*T1)
C7=ATANF(T1/S1)
S2=-B24*SINF(C24)+B25*SINF(C25)+B6*SINF(C62)*COSF
                                              (C3)
T2=-B24*COSF(C24)+B25*COSF(C25)+B6*SINF(C62)*SINF
                                              (C3)
B8=SQRTF(S2*S2+T2*T2)
C8=ATANF(T2/S2)
C26=C2+C6
B5=B2*Z1/SQRTF ((A-B)*(A-B)+W*W)
B51=B5*SINF(C26)-1.
B52=B51/(Z1*A)
B53=85/(Z1*SQRTF(B*B+W*W))
C10=ATANF(W/B)
B54=B53*SINF(C26-C10)
C16=-C26+C10
F1=ATANF(W2/A)
F2=ATANF(W+W2)/B)
F3=ATANF((W-W)/B)
F4=ATANF(W/(A-B))
D1=1./(Z1*Z2*C*W*SQRTF(A*A+W2*W2))
D2=D1/SQRTF(B*B+(W+W2)*(W+W2))* 2.
D3=D1/SQRTF(B*B+(W-W2)*(W-W2))* 2.
D4=D1*SINF(F4)/SQRTF((A-B)*(A-B)+W*W)
D5=D1/SQRTF((A-B)*(A-B)+W*W)
F13=F3-F1
F12=F1+F2
S3=D3*COSF(F1-F3)-D2*COSF.(F1+F2)
T3=-D3*SINF(F1-F3)+D2*SINF(F1+F2)
D6=SQRTF(S3*S3+T3*T3)
F6=ATANF(T3/S3)
T4=D3*COSF(F13)+D2*COSF(F12)+D5*COSF(F1)*COSF(F4)
```

```
      S4=-D3*SINF(F13)+D2*SINF(F12)+D5*SINF(F1)*COSF(F4)
      D7=SQRTF(S4*S4+T4*T4)
      F7=ATANF(T4/S4)
      F9=F4
      S5=-D3*SINF(F13)+D2*SINF(F12)-D5*SINF(F4)*COSF(F1)
      T5=D3*COSF(F13)-D2*COSF(F12)+D5*SINF(F4)*SINF(F1)
      D8=SQRTF(T5*T5+S5*S5)
      F8=ATANF(T5/S5)
      D9=1./(W*Z1*C*SQRTF((A-B)*(A-B)+W*W))
      D10=D9*SINF(F9)
      D12=D10/(Z2)
      D13=D9/(Z2*SQRTF(B*B+W*W))
      F13=F9+C10
      D14=D13*SINF(F9+C10)
      B0=B52-B54+D12-D14
      T6=-B45*SINF(C45)+B31*COSF(C3)
      S6=-B45*COSF(C45)+B31*SINF(C3)
      B01=SQRTF(S6*S6+T6*T6)
      C01=ATANF(T6/S6)
      B02=B61-B31
      B03=-D12-B52
      S7=B53*COSF(C16)+D13*COSF(F13)
      T7=B53*SINF(C16)-D13*SINF(F13)
      B04=SQRTF(S7*S7+T7*T7)
      C04=ATANF(T7/S7)
C     CONSTANTS FOR ID1
      PUNCH20,B01,C01,D6
      PUNCH20,F6,B02,C3,D4
      PUNCH20,F1,B51,D10,B03
      PUNCH20,B7,C7,D7,F7
      PUNCH20,B8,C8,D8,F8
      PUNCH20,D9,F9,B5,C26
      PUNCH18,B04,C04
C     CONSTANTS FOR ID2
      PUNCH20,B0,D6,F6,B01
      PUNCH20,C01,D4,F1,B02
      PUNCH10,C3,D10,B51,B03
      PUNCH20,D7,F7,B7,C7
      PUNCH20,D8,F8,B8,C8
      PUNCH20,B5,C26,D9,F9
      PUNCH18,B04,C04
18    FORMAT(2F18.8)
20    FORMAT(4F18.8)
      GOTO10
13    STOP
      END
C     L1        L2        R1     A            B           D
      1.04      1.03      5.75   5.7676038    2.837858    966026.67
      1.04      1.04      6.     5.768974     2.884744    961360.06
      1.03      1.04      6.     5.7676038    2.837858    966026.67
      1.03      1.03      5.75   5.582533     2.791258    970697.16
```

SAMPLE OUTPUT OF PROGRAM-I

C C OCR092 SC KATIYAR ROORKEE UNIVERSITY

.39940313	.00136383	.02083019	.00253995
-1.07607720	-.00153714	1.55244690	.00153714
1.55244690	-.50250960	.49767681	-.39940615
.00054213	1.56975350	.00254856	-.45627908
.00321690	1.55349870	.00355626	-.88082189
.49767902	1.56781550	.49749300	1.56762500
.0000056	.51084624		
.39940313	.00253995	-1.07607720	.00136383
.02083019	.00153714	1.55244690	-.00153714
1.55244690	.49767681	-.50250960	-.39940615
.00254856	-.45627908	.00054213	1.56975350
.00355626	-.88082189	.00321690	1.55349870
.49749300	1.56762500	.49767902	1.56781550
.00000562	.51084624		
.39750274	.00135466	.02099823	.00252967
-1.07676860	-.00152975	1.55244250	.00152975
1.55244250	-.50009300	.50009249	-.39750562
.00054638	1.56963720	.00253826	-.45557710
.00323347	1.55355040	.00354030	-.88015771
.50009467	1.56785470	.49990920	1.56785420
.00000289	1.51077530		
.39750274	.00252967	-1.07676860	.00135466
.02099823	.00152975	1.55244250	-.00152975
1.55244250	.50009249	-.50009300	-.39750562
.00253826	-.45557710	.00054638	1.56963720
.00354030	-.88015771	.00323347	1.55355040
.49990920	1.56785420	.50009467	1.56785470
.00000289	1.51077530		
.39940342	.00136045	.02103920	.00253995
-1.07607720	-.00153714	1.55244690	.00153714
1.55244690	-.49767660	.50250862	-.39940635
.00055271	1.56963200	.00254856	-.45627908
.00327968	1.55356270	.00355626	-.88082189
.50251085	1.56781550	.50232538	1.56800490
.00000540	-.55284997		
.39940342	.00253995	-1.07607720	.00136045
.02103920	.00153714	1.55244690	-.00153714
1.55244690	.50250862	-.49767660	-.39940635
.00254856	-.45627908	.00055271	1.56963200
.00355626	-.88082189	.00327968	1.55356270
.50232538	1.56800490	.50251085	1.56781550
.00000540	-.55284997		
.39855018	.00136971	.02028601	.00255037
-1.07597420	-.00154461	1.55303550	.00154461
1.55303550	-.50009110	.50009095	-.39855297
.00054843	1.56968780	.00255873	-.45761255
.00326301	1.55409560	.00357130	-.88129269
.50009297	1.56796320	.49991099	1.56796320
.00000280	1.50948070		
.39855018	.00255037	-1.07597420	.00136971
.02028601	.00154461	1.55303550	-.00154461
1.55303550	.50009095	-.50009110	-.39855297
.00255873	-.45761255	.00054843	1.56968780
.00357130	-.88129269	.003263	1.55409560
.49991099	1.56796320	.50009297	1.56796320
.00000280	1.50948070		

PROGRAM II

```
      JOB OCR092,TIME0005,PAGES0030,NAME  SCK
      $IBJOB
      $IBPTC
C     ANALYTICAL SOLUTION APPROACH WITH CIRCULATING
      CURRENT DETECTION
C     STORING COEFFICIENTS IN
      DIMENSIONB1(4,2),B2(4,2),B3(4,2),B4(4,2),B5(4,2),
                           B6(4,2)
      DIMENSIONB7(4,2),B8(4,2),B9(4,2),B10(4,2),B11
                           (4,2),B12(4,2)
      DIMENSIONB13(4,2),B14(4,2),B15(4,2),B16(4,2),B17
                           (4,2),B18(4,2)
      DIMENSIONB19(4,2),B20(4,2),B21(4,2),B22(4,2),B23
                           (4,2),B24(4,2)
      DIMENSIONB25(4,2),B26(4,2)
      DIMENSIONRA(4),RB(4),E1(4),E2(4),R(4),DZ(4),DR(4)
      DIMENSION AD(2),DAD(2),G1(2),G2(2),G3(2),G4(2),
                           G5(2),G6(2)
      DIMENSION G7(2),G8(2), G21(2),G22(2)
      READ 10,((B1(I,J),B2(I,J),B3(I,J),B4(I,J),I=1,4),
                                J=1,2)
      READ 10,((B5(I,J),B6(I,J),B7(I,J),B8(I,J),I=1,4),
                                J=1,2)
      READ 10,((B9(I,J),B10(I,J),B11(I,J),B12(I,J),
                            I=1,4),J=1,2)
      READ 10,((B13(I,J),B14(I,J),B15(I,J),B16(I,J),I=1,
                             4),J=1,2)
      READ 10,((B17(I,J),B18(I.J),B19(I,J),B20(I,J),
                           I=1,4),J=1,2)
      READ 10,((B21(I,J),B22(I,J),B23(I,J),B24(I,J),
                           I=1,4),J = 1,2)
      READ9, ((B25(I,J),B26 (I,J),I=1,4),J=1,2)
      READ 11,(RA(I),RB(I), R(I), E1(I), E2(I),I=1,4)
      READ9,(DZ(I),DR(I),I=1,4)
C     INITIAL CONDITIONS
      READ 18,AZ1,AZ2, AN1, AN2, AS1, AS2, DC
      READ 18,T,T1,T2,DT,DTT,TT,TTT
      READ 11,C1,C2, V1, V2, V3
      READ14,A1,A2,W1,W2,AC,A
    9 FORMAT(2F18.8)
   11 FORMAT (5F14.6)
   10 FORMAT (4F18.8)
   14 FORMAT (6F12.6)
   18 FORMAT (7F10.6)
      AD(1)=0.
      AD(2)=0.
      N1=3
      N2=2
      AF=(.866*V1)/(6.286*1.414)
      BF=(.866*V2)/(6.286*1.414)
      W11=1.414*.02*314.285/V1
      W22=1.414*.02*314.285/V2
      CF=COS (DC)
      CAC=COS (AC)
      M=2
      L=2
```

```
C          SELECTION OF COEFFICIENTS AND ANGLES BY
C          CIRCULATING CURRENTS
      100  IF(A1-AD(1))101,102,102
      101  IF(A2-AD(2))103,104,104
      102  IF(A-2AD(2))105,106,106
      103  I=1
C          BOTH NONCOMMUTATING
           Q=AN1-.52381
           P=AN2-.52381
           GO TO 200
      104  I=2
C          CONVERTOR ONE NONCOMMUTATING AND TWO COMMUTATING
           Q=AN1-.52381
           P=AN2
           GO TO 200
      105  I=3
C          CONVERTOR ONE COMMUTATING AND TWO NONCOMMUTATING
           Q=AN1
           P=AN2-.52381
           GO TO 200
      106  I=4
C          BOTH COMMUTATING
           O=AN1
           P=AN2
C          CALCULATION FOR NEW INCREAMENT OF DT
      200  T=T+DT
           TT=TT+DT
           T1=T1+DT
           T2=T2+DT
           WT1=W1*T
           WT2=W2*T
           GT=R(I)*T
           X1=EXP(-RA(I)*T)
           X2=EXP(-RB(I)*T)
           O=EXP(-25.*T1)
           S=EXP(-25.*T2)
           C31=AD(1)
           C32=AD(2)
           DO1 J=1,2
           AB1=E1(I)*B2(I,J)
           AB2=WT1+Q+B3(I,J)
           AB3=E2(I)*B4(I,J)
           AB4=WT2+P+B5(I,J)
           G1(J)=V3*B1(I,J)+AB1*SIN (AB2)+AB3*SIN(AB4)
           G21(J)=X1*E1(I)*B6(I,J)*COS(Q-B7(I,J))
           G22(J)=X1*E2(I)*B8(I,J)*COS(P-B9(I,J))
           G2(J)=G21(J)+G22(J)
           G3(J)=X1*(B12(I,J)*V3+B11(I,J)*C2-B10(I,J)*C1)
           AB5=E1(I)*B13(I,J)*SIN(Q+B14(I,J))
           AB6=E2(I)*B15(I,J)*SIN(P+B16(I,J))
           AB7=E1(I)*B17(I,J)*COS(Q-B18(I,J))
           AB8=E2(I)*B19(I,J)*COS(P-B20(I,J))
           G4(J)=X2*((AB5+AB6)*SIN (GT)+(AB7+AB8)*COS (GT))
           AB9=C2*B21(I,J)
           AB10=GT-B22(I,J)
           AB11=C1*B23(I,J)
           AB12=GT-B24(I,J)
```

```
      AB13=V3*B25(I,J)
      AB14=GT+B26(I,J)
      G5(J)=X2*(AB9*SIN(AB10)-AB11*SIN(AB12)-AB13*SIN
                                               (AB14)
      AD(J)=G1(J)+G2(J)+G3(J)+G4(J)+G5(J)
      G6(J)=W1*AB1*COS(AB2)+AB3*W2*COS(AB4)
      G7(J)=R(I)*X2*(COS (GT)*(AB5+AB6)-SIN(GT)*(AB7+AB8))
      G8(J)=X2*R(I)*(AB9*COS (AB10)-AB11*COS(AB12)-AB13*
                                            COS (AB14)
    1 DAD(J)=G6(J)-RA(I)*(G2(J)+G3(J))-RB(I)*(G4(J)+G5(J))
                                           +G7(J)+G8(J)
      AD(2)=-AD(2)
      VC=E1(I)*COS (WT1+Q)-DZ(I)*DAD(1)-DR(I)*AD(1)
      VD1=VC+5.*AD(1)+DAD(1)
      VD2=VC-5.*AD(2)-DAD(2)
      IF(A1-C31)301,402,402
C     CALCULATE CIR CURRENT ONE IF COMMUTATING
  301 A1=.5*AD(1)+AF*SIN(W1*T1+Q-1.492)-O*(.5*C1+AF*SIN
                                     (Q-1.492)
  402 IF(A2-C32)302,303,303
C     CALCULATE CIR CURRENT TWO IF COMMUTATING
  302 A2=.5*AD(2)+BF*SIN(W2*T2+P-1.492)-S*(.5*C2+BF*SIN
                                      (P-1.492))
  303 PRINT30,AD(1),AD(2),A1,A2
      PRINT31,VD1,VD2,VC,TT
   30 FORMAT(1HO*RECT CURRENT *E18.8,*INV CURRENT
                               *E18.8, *CIR ONE
     1 *E18.8,*CIR TWO *E18.8)
   31 FORMAT(1HO*RECT VOLTAGE *E18.8,*INV VOLTAGE
                               *E18.8,*MID VOLTAGE
     1 .*E18.8,*TIME SECS *E18.8)
      GOTO (3,110),M
C     END OF COMMUTATION ONE DETECTION
    3 IF(A1-AD(1))112,108,108
  108 M=2
C     CHANGE THE INITIAL CONDITION ONCE ONLY
      C1=AD(1)
      C2=AD(2)
      V3=VC
      T=0.
  110 A1=AD(1)
C     CC AND CEA CONTROL CALCULATION FOR CONVERTOR ONE
      IF(AS1-AD(1))1001,1001,1002
 1001 X10.
      GOTO1003
 1002 X=A*(AD(1)-AS1))
 1003 Y1=W11*AD(1)+(X/V1)-CF
      Y2=ABS(Y1)
      IF(Y2.GE.1.) GOTO 5001
      IF(CAC-Y1)1004,1005,1005
 1004 AN11=AC
      GOTO1006
 1005 AN11=ARCOS(Y1)
 1006 IF(AN11-AN1+.8727)1007,1008,1008
 1007 AN11=AN11-.8727
      GO TO1008
 5001 AN11=AN1
```

```
C           END OF PROCESS ONE DETECTION
     1008   IF(AN1-AN11+314.285*T1-1.04762)112,111,111
      111   N1=N1+1
C           CHANGE THE PROCESS ONE NUMBER AND INITIAL
            CONDITIONS ONCE ONLY
            N1=N1-((N1-1)/6)*6
            AN1=AN11
            A1=0.
            T1=0.
            T=0.
            C1=AD(1)
            C2=AD(2)
            V3=VC
            M=1
            BN1=N1
      112   GOTO(4,115),L
C           END OF COMMUTATION DETECTION CONV TWO
        4   IF(A2-VD(2))117,113,113
      113   L=2
C           CHANGE THE INITIAL CONDITIONS ONLY ONCE
            C1=AD(1)
            C2=AD(2)
            V3=VC
            T=0.
      115   A2=AD(2)
C           CC AND CEA CONTROL CALCULATION FOR CONVERTOR TWO
            IF(AS2-AD(2))2001,2001,2002
     2001   Z=0.
            GOTO2003
     2002   Z=A*(AD(2)-AS2)
     2003   U1=W22*AD(2)+(Z/V2)-CF
            U2=ABS(U1)
            IF(U2.GE.1.) GO TO 5002
            IF(CAC-U1)2004,2005,2005
     2004   AN22=AC
            GOTO2006
     2005   AN22=ARCOS(U1)
            GOTO2008
     5002   AN22=AN2
     2006   IF(AN22-AN2+.8727)2007,2008,2008
     2007   AN27=AN22-.8727
C           END OF PROCESS TWO DETECTIONS
     2008   IF(AN2-AN22+314.285*T2-1.04762)117,116,116
      116   N2=N2+1
C           CHANGE THE PROCESS TWO NUMBER AND INITIAL
            CONDITIONS ONCE ONLY
            N2=N2-((N2-1)/6)*6
            AN2=AN22
            A2=0.
            L=1
            C1=AD(1)
            C2=AD(2)
            V3=VC
            T=0.
            T2=0.
      117   BN1=N1
            BN2=N2
            PRINT32,AN1,AN2,BN1,BN2
```

```
32    FORMAT(1HO*ANGLE ONE *E18.8.*ANGLE TWO *E18.8,
                                        *PROCESS ONE*E18.8,
    1 ..*PROCESS TWO*E18.8)
C     END OF PROGRAM DETECTION
      IF(TT-TTT)100,120,120
120   STOP
      END
      ØENTRY
```

SAMPLE OF INPUT DATAS

C	B1	B2	B3	B4
	.39940313	.00136383	.02083019	.00253995
	.39750274	.00135466	.02099823	.00252967
	.39940342	.00136045	.02103920	.00253995
	.39855018	-.00136971	.02028601	-.00255037
	.39940313	-.00253995	-1.07607720	-.00136383
	.39750274	-.00252967	-1.07676860	-.00135466
	.39940342	-.00253995	-1.07607720	-.00136045
	.39855013	.00255037	-1.07597420	.00136971

C	B5	B6	B7	B8
	-1.07607720	-.00153714	1.55244690	.00153714
	-1.07676860	-.00152975	1.55244250	.00152975
	-1.07607720	-.00153714	1.55244690	.00153714
	-1.07597420	-.00154461	1.55303550	.00154461
	.02083019	.00153714	1.55244690	-.00153714
	.02099823	.00152975	1.55244250	-.00152975
	.02103920	.00153714	1.55244690	-.00153714
	.02028601	.00154461	1.55303550	-.00154461

C	B9	B10	B11	B12
	1.55244690	-.50250960	.49767681	-.39940615
	1.55244250	-.50009300	.50009249	-.39750562
	1.55244690	-.49767660	.50250862	-.39940635
	1.55303550	-.50009110	.50009095	-.39855297
	1.55244690	.49767681	-.50250960	-.39940615
	1.55244250	.50009249	-.50009300	-.39750562
	1.55244690	.50250862	-.49767660	-.39940635
	1.55303550	.50009095	-.50009110	-.39855297

C	B13	B14	B15	B16
	.00054213	1.56975350	.00254856	-.45627908
	.00054638	1.56963720	.00253826	-.45557710
	.00055271	1.56963200	.00254856	-.45627908
	.00054843	1.56968780	.00255873	-.45761255
	.00254856	-.45627908	.00054213	1.56975350
	.00253826	-.45557710	.00054638	1.56963720
	.00254856	-.45627908	.00055271	1.56963200
	.00255873	-.45761255	.00054843	1.56968780

C	B17	B18	B19	B20
	.00321690	1.55349870	.00355626	-.88082189
	.00323347	1.55355040	.00354030	-.88015771
	.00327968	1.55356270	.00355626	-.88082189
	.00326301	1.55409560	.00357130	-.88129269
	.00355626	-.88082189	.00321690	1.55349870
	.00354030	-.88015771	.00323347	1.55355040
	.00355626	-.88082189	.00327968	1.55356270
	.00357130	-.88129269	.00326301	1.55409560

C	B21	B22	B23	B24
	.49767902	1.56781550	.49749300	1.56762500
	.50009467	1.56785470	.49990920	1.56785420
	.50251085	1.56781550	.50232538	1.56800490
	.50009297	1.56796320	.49991099	1.56796320
	.49749300	1.56762500	.49767902	1.56781550
	.49990920	1.56785420	.50009467	1.56785470
	.50232533	1.56800490	.50251085	1.56781550
	.49991099	1.56796320	.50009297	1.56796320

C	B25	B26
	.00000562	.51084624
	.00000289	1.51077530
	.00000540	-.55284997
	.00000280	1.50948070
	.00000562	.51084624
	.00000289	1.51077530
	.00000540	-.55284997
	.00000280	1.50948070

C	A	B	W	mE1	nE2
	5.768974	2.884744	980.4	128341.2	115524.4
	5.7676038	2.837858	982.8	128341.2	100050.
	5.7676038	2.837858	982.8	111150.	115524.4
	5.582533	2.791258	989.0	111150.	100050.

C	R	L
	1.04	6.
	1.04	6.
	1.03	5.75
	1.03	5.75

C	AZ1	AZ2	ALPHA1,	ALPHA2,	IS1,	IS2.	DELTAG
	0.	0.	.349	2.92	300.	200.	.1745

C	T1.	T2.	TJ,	DT,	DTT,	TT,	TTT
	0.	.0032778	0.	.00011	0.	0.	.08

C	ID1(o),	ID2(o),	V1,	V2,	VC(o)
	0.	0.	128341.2	115524.4	0.

C	I1	I2	W1	W2	ALPHAC,	A
	0.	0.	314.285	314.285	0.	2170.

NUMERICAL SOLUTION APPROACH PROGRAMS

PROGRAM - III

```
      $JOB OCR092, TIME0014, PAGES0100,NAME SC KATIYAR
      $IBJOB
      $IBFTC
C     NUMERICAL STATE VARIABLE APPROACH WITH VOLTAGE
      DROP DETECTION
      DIMENSION DR1(4),DR2(4), D(12), Y(3)
      DIMENSION AD(2),DAD(2),G1(4),G2(4),RA(4),RB(4),RD(4),
                                    DZ1(4), DZ2(4)
C     FUNCTION DEFINITION
      F1(Y1,Y3)=(E1*COS(WT1+Q)-R1*Y1-Y3)/X1
      F2(y2,Y3)=(E2*COS(WT2+P)-R2*Y2+Y3)/X2
      F3(Y1,Y2)=(Y1-Y2)/C
C     INPUT DATAS
      READ10,(DZ1(I),DZ2(I),DR1(I),DR2(I),I=1,4)
      READ12,(G1(I),G2(I),I=1,4)
      READ11,C1,C2,V1,V2,V3
      READ11,AN1,AN2,AS1,AS2,DC
      READ14,P1,P2,W1,W2,AC,A
      READ14, T,T1,T2,DT, TT,TTT
   10 FORMAT(4F18.8)
   11 FORMAT(5F14.5)
   12 FORMAT(2F12.4)
   14 FORMAT(6F12.6)
C     INITIAL CONDITION
      Y(1)=0
      Y(2)=0
      Y(3)=0
      C=.000002
      Q1=P1
      Q2=P2
      N1=3
      N2=2
      AF=(.866*V1)/(6.286*1.414)
      BF=(.866*V2)/(6.286*1.414)
      W11=1.414*.02*314.285/V1
      W22=1.414*.02*314.285/V2
      CAC=COS (AC)
      CF=COS(DC)
      M=2
      L=2
C     SELECTION BY'VOLTAGE DROP'DETECTION
  100 IF(P1-Q1  ) 101,102,102
  101 IF(P2-Q2  ) 103,104,104
  102 IF(P2-Q2  ) 105,106,106
  103 I=1
C     BOTH NONCOMMUTATING
      Q=AN1-.52381
      P=AN2-.52381
      GO TO 200
  104 I=2
```

```
C           CALCULATE P1 IF CONVERTOR ONE COMM.
      301   P1=1.732*V1*SIN(WT1+Q)
      402   IF(P2-C32)302,303,303
C           CALCULATE P2 IF CONVERTOR TWO COMM.
      302   P2=1.732*V2*SIN(WT2+P)
      303   PRINT30,AD(1),AD(2),P1,P2
            PRINT31,VD1,VD2,VC,TT
       30   FORMAT (1HO*RECT CURRENT *E18.8,* INV CURRENT
                                   *E18.8, *DROP ONE
          1.*E18.8,*DROP TWO *E18.8)
       31   FORMAT(1HO*RECT VOLTAGE*E18.8,* VOLTAGE*18.8,
                                  *MID VOLTAGE
          1  *E18.8,*TIME SECS *E18.8)
       32   FORMAT (1HO* ANGLE ONE *E18.8,*ANGLE TWO
                            *E18.8,*PROCESS ONE*E18.8,
          1  *PROCESS, TWO*E18.8)
            GOTO(3,110),M
C           END OF COMMUTATION ONE DETECTION
        3   IF(P1-Q1) 112,108,108
      108   M=2
C           INITIALISE THE TIME VARIABLE ONCE ONLY
      110   P1=Q1
C           CC AND CEA CONTROL CALCULATIONS OF CONVERTOR ONE
            IF(AS1-AD(1))1001,1001,1002
     1001   X=0.
            GOTOT003
     1002   X=A*(AD(1)-AS1)
     1003   H1=W11*AD(1)+(X/V1)-CF
            H2=ABS(H1)
            IF(H2.GE.1.)  GOTO 5001
            IF(CAC-H1)1004,1005,1005
     1004   AN11=AC
            GOTO1006
     1005   AN11=ARCOS(H1)
     1006   IF(AN11-AN1+.8727)1007,1008,1008
     1007   AN11=AN11-.8727
            GO TO1008
     5001   AN11=AN1
C           END OF PROCESS ONE DETECTION
     1008   IF(AN1-AN11+314.285*T1-1.04762)112,111,111
      111   N1=N1+1
C           CHANGE PROCESS ONE NUMBER AND INITIALISE THE.
                                 TIME ONCE ONLY
            N1=N1-((N1-1)/6)*6
            AN1=AN11
            P1=0.
            T1=0.
            T=0.
            M=1
      112   GOTO(4,115),L
C           END OF COMMUTATION ONE DETECTION
        4   IF(P2-Q2)117,113,113
      113   L=2
C           INITIALISE THE TIME ONLY ONCE
            T=0.
      115   P2=Q2
```

```
C          CC AND CEA CONTROL CALCULATIONS FOR CONVERTOR TWO
           IF(AS2-AD(2))2001,2001,2002
     2001  Z=C.
           GOTO2003
     2002  Z=A*(AD(2)-AS2)
     2003  U1=W22*AD(2)+(Z/V2)-CF
           U2=ABS(U1)
           IF(U2.GE.1.) GO TO 5002
           IF(CAC-U1)2004,2005,2005
     2004  AN22=AC
           GOTO2006
     2005  AN22=ARCOS(U1)
     2006  IF(AN22-AN2+.8727)2007,2008,2008
     2007  AN22=AN22-.8727
           GOTO2008
     5002  AN22=AN2
C          END OF PROCESS TWO DETECTION
     2008  IF(AN2-AN22+314.285*T2-1.04762)117,116,116
      116  N2=N2+1
C          CHANGE THE PROCESS TWO NUMBER AND INITIALISE
                               THE TIME ONCE ONLY
           N2=N2-((N2-1)/6)*6
           AN2=AN22
           P2=0.
           L=1
           T=0.
           T2=0.
      117  BN1=N1
           BN2=N2
           PRINT32,AN1,AN2,BN1,BN2
C          END OF PROGRAM DETECTION
           IF(TT-TTT)100,120,120
      120  STOP
           END
           $ENTRY
C          SAMPLE OF INPUT DATAS
C      L1         L2         R1         R2
       1.04       1.04       6.         6.
       1.04       1.03       6.         5.75
       1.03       1.04       5.75       6.
       1.03       1.03       5.75       5.765
C      mE1                   mE2
       128341.2              115524.4
       128341.2              100050.
       111150.               115524.4
       111150.               100050.
C            SAME OF PROGRAM II
       0.         0.         128341.2    115524.4    0.
       .349       2.92       300.        200.        .175
       0.         0.         314.285     314.285     0.2170
       0.         .0033      0.          .00011      0.008
```

PROGRAM - IV

```
          $JOB  OCR092, TIME0005, PAGES0030;NAME SC KATIYAR
          $IBJOB
          $IBFTC
C         NUMERICAL STATE VARIABLE SOLUTION WITH CIRCULATING
          CURRENT DETECTION
          DIMENSION AD(2),DAD(2),G1(4),G2(4),RA(4),RB(4),
          RD(4), DZ1(4), DZ2(4)
          DIMENSION DR1(4), DR2(4), D(12), Y(3)
C         FUNCTION DEFINITION
          F1(Y1,Y3)=(E1*COS(WT1+Q)-R1*Y1-Y3)/X1
          F2(Y2,Y3)=( E2*COS(WT2+P)-R2*Y2+Y3)/X2
          F3(Y1,Y2)=(Y1-Y2)/C
C         INPUT DATAS
          READ10,(DZ1(I),DZ2(I),DR1(I),DR2(I),I=1,4)
          READ12,(G1(I),G2(I),I=1,4)
          READ11,C1,C2,V1,V2,V3
          RFAD11,AN1,AN2,AS1,AS2,DC
          READ14,A1,A2,W1,W2,AC,A
          READ14, T,T1,T2,DT,TT,TTT
     10   FORMAT(4F18.8)
     11   FORMAT(5F14.5)
     12   FORMAT(2F12.4)
     14   FORMAT(6F12.6)
C         INITIAL CONDITIONS
          Y(1)=0
          Y(2)=0
          Y(3)=0
          C=.000002
          AD(1)=0
          AD(2)=0
          N1=3
          N2=2
          AF=(.866*V1)/(6.286*1.414)
          BF=(.866*V2)/(6.286*1.414)
          W11=1.414*.02*314.285/V1
          V22=1.414*.02*314.285/V2
          CAC=COS(AC)
          CF=COS(DC)
          M=2
          L=2
C         SELECTION BY CIRCULATING CURRENTS
    100   IF(A1-AD(1))101,102,102
    101   IF(A2-AD(2))103,104,104
    102   IF(A2-AD(2))105,106,106
    103   I=1
C         BOTH NONCOMMUTATING
          Q=AN1-.52381
          P=AN2-.52381
          GO TO 200
    104   I=2
C         CONVR ONE NONCOMMUTATING AND TWO COMMUTATING
          Q=AN1-.52381
          P=AN2
          GO TO 200
    105   I=3
```

PROGRAM - IV

```
            $JOB   OCR092, TIME0005, PAGES0030,NAME SC KATIYAR
            $IBJOB
            $IBFTC
C           NUMERICAL STATE VARIABLE SOLUTION WITH CIRCULATING
            CURRENT DETECTION
            DIMENSION AD(2),DAD(2),G1(4),G2(4),RA(4),RB(4),
            RD(4), DZ1(4), DZ2(4)
            DIMENSION DR1(4), DR2(4), D(12), Y(3)
C           FUNCTION DEFINITION
            F1(Y1,Y3)=(E1*COS(WT1+Q)-R1*Y1-Y3)/X1
            F2(Y2,Y3)=( E2*COS(WT2+P)-R2*Y2+Y3)/X2
            F3(Y1,Y2)=(Y1-Y2)/C
C           INPUT DATAS
            READ10,(DZ1(I),DZ2(I),DR1(I),DR2(I),I=1,4)
            READ12,(G1(I),G2(I),I=1,4)
            READ11,C1,C2,V1,V2,V3
            RFAD11,AN1,AN2,AS1,AS2,DC
            READ14,A1,A2,W1,W2,AC,A
            READ14, T,T1,T2,DT,TT,TTT
      10    FORMAT(4F18.8)
      11    FORMAT(5F14.5)
      12    FORMAT(2F12.4)
      14    FORMAT(6F12.6)
C           INITIAL CONDITIONS
            Y(1)=0
            Y(2)=0
            Y(3)=0
            C=.000002
            AD(1)=0
            AD(2)=0
            N1=3
            N2=2
            AF=(.866*V1)/(6.286*1.414)
            BF=(.866*V2)/(6.286*1.414)
            W11=1.414*.02*314.285/V1
            V22=1.414*.02*314.285/V2
            CAC=COS(AC)
            CF=COS(DC)
            M=2
            L=2
C           SELECTION BY CIRCULATING CURRENTS
     100    IF(A1-AD(1))101,102,102
     101    IF(A2-AD(2))103,104,104
     102    IF(A2-AD(2))105,106,106
     103    I=1
C           BOTH NONCOMMUTATING
            Q=AN1-.52381
            P=AN2-.52381
            GO TO 200
     104    I=2
C           CONVR ONE NONCOMMUTATING AND TWO COMMUTATING
            Q=AN1-.52381
            P=AN2
            GO TO 200
     105    I=3
```

```
C         CONVR ONE COMMUTATING AND TWO NONCOMMUTATING
          O=AN1
          P=AN2-.52381
          GO TO 200
      106 I=4
C         BOTH COMMUTATING
          Q=AN1
          P=AN2
      200 T=T+DT
C         TIME INCREAMENT BY DT
          TT=TT+DT
          T1=T1+DT
          T2=T2+DT
          WT1=W1*T
          WT2=W2*T
          O=EXP(-25.*T1)
          S=EXP(-25.*T2)
          C31=AD(1)
          C32=AD(2)
          E1=G1(I)*1.412
          E2=G2(I)*1.412
          X1=DZ1(I)
          X2=DZ2(I)
          R1=DR1(I)
          R2=DR2(I)
C         RUNGA-KUTTA TECHNIQUE
          D(1)=DT*F1(Y(1),Y(3))
          D(2)=DT*F2(Y(2),Y(3))
          D(3)=DT*F3(Y(1),Y(2))
          D(4)=DT*F1(Y(1)+.5*D(1),Y(3)+.5*D(3))
          D(5)=DT*F2(Y(2)+.5*D(2),Y(3)+.5*D(3))
          D(6)=DT*F3(Y(1)+.5*D(1),Y(2)+.5*D(2))
          D(7)=DT*F1(Y(1)+.5*D(4),Y(3)+.5*D(6))
          D(8)=DT*F2(Y(2)+.5*D(5),Y(3)+.5*D(6))
          D(9)=DT*F3(Y(1)+.5*D(4),Y(2)+.5*D(5))
          D(10)=DT*F1(Y(1)+.5*D(7),Y(3)+.5*D(9))
          D(11)=DT*F2(Y(2)+.5*D(8),Y(3)+.5*D(9))
          D(12)=DT*F3(Y(1)+.5*D(7),Y(2)+.5*D(8))
          Y(1)=Y(1)+(D(1)+2.*D(4)+2.*D(7)+D(10))/6.
          Y(2)=Y(2)+(D(2)+2.*D(5)+2.*D(8)+D(11))/6.
          Y(3)=Y(3)+(D(3)+2.*D(6)+2.*D(9)+D(12))/6.
          AD(1)=Y(1)
          AD(2)= Y(2)
          VC=Y(3)
          DAD(1)=F1(Y(1),Y(3))
          DAD(2)=F2(Y(2),Y(3))
          VD1=VC+5.*AD(1)+DAD(1)
          VD2=VC-5.*AD(2)-DAD(2)
          IF(A1-C31)301,402,402
C         CALCULATE I1 IF ONE COMMUTATING
      301 A1-.5*AD(1)+AF*SIN(W1*T1+Q-1.492)-O*(.5*C1+AF*SIN
                                               (Q-1.492))
      402 IF(A2-C32)302,303,303
C         CALCULATE I2 IF TWO COMMUTATING
      302 A2=.5*AD(2)+BF*SIN(W2T2+P-1.492)-S*(.5C2+BF*SIN
                                           (P-1.492))
      303 PRINT30,AD(1),AD(2),A1,A2
          PRINT31,VD1,VD2,VC,TT
       30 FORMAT(1HO*RECT CURRENT *E18.8,*INV CURRENT
                                  *E18.8, * CIR ONE
         1 *E18.8, *CIR TWO *E18.8)
```

```
 31     FORMAT(1HO*RECT VOLTAGE*E18.8,*INV VOLTAGE*E18.8,
                                              *MID VOLTAGE
      1  *E18.8, *TIME SECS *E18.8)
        GOTO(3,110),M
C       END OF COMMUTATION ONE DETECTION
  3     IF(A1-AD(1))112,108,108
 108    M=2
C       CHANGE THE INITIAL CONDITIONS ONCE ONLY
        C1=AD(1)
        C2=AD(2)
        V3=VC
        T=0
 110    A1=AD(1)
C       CC AND CEA CONTROL CALCULATIONS FOR CONVERTOR ONE
        IF(AS1-AD(1))1001,1001,1002
1001    X=0.
        GOTO1003
1002    X=A*(AD(1)-AS1)
1003    H1=W11*AD(1)+(x/V1)-CF
        H2=APS(H1)
        IF(H2.GE.1.) GOTO 5001
        IF(CAC-H1)1004,1005,1005
1004    AN11=AC
        GOTO1006
1005    AN11=ARCOS(H1)
1006    IF(AN11-AN1+.8727)1007,1008,1008
1007    AN11=AN11-.8727
        GO TO1008
5001    AN11=AN1
C       END OF PROCESS ONE DETECTION
1008    IF(AN1-AN11+314.285*T1-1.04762)112,111,111
 111    A1=N1+1
C       CHANGE THE PROCESS ONE NUMBER AND INITIAL
        VALUES ONCE
        N1=N1-((N1-1)/6)*6
        AN1=AN11
        A1=0
        T1=0
        T=0
        C1=AD(1)
        C2=AD(2)
        V3=VC
        M=1
 112    GOTO(4,115),L
C       END OF COMMUTATION ONE DETECTION
  4     IF(A2-AD(2))117,113,113
 113    L=2
C       CHANGE THE VALUES ONCE ONLY
        C1=AD(1)
        C2=AD(2)
        V3=VC
        T=0
 115    A2=AD(2)
C       CC AND CEA CONTROL CALCULATIONS FOR CONVERTOR TWO
        IF(AS2-AD(2))2001,2001,2002
2001    Z=0.
        GOTO2003
```

```
      2002  Z=A*(AD(2)-AS2)
      2003  U1=W22*AD(2)+(Z/V2)-CF
            U2=ABS(U1)
            IF(U2.GE.1.) GO TO 5002
            IF(CAC-U1)2004,2005,2005
      2004  AN22=AC
            GOTO2006
      2005  AN22=ARCOS(U1)
      2006  IF(AN22-AN2+.8727)2007,2008,2008
      2007  AN22=AN22-.8727
            GOTO2008
      5002  AN22=AN2
C           END OF PROCESS TWO DETECTION
      2008  IF(AN2-AN22+314.285*T2-1.04762)117,116,116
       116  N2=N2+1
C           CHANGE THE PROCESS TWO NUMBER AND INITIAL
            VALUES ONCE ONLY
            N2=N2-((N2-1)/6)*6
            AN2=AN22
            A2=0.
            L=1
            C1=AD(1)
            C2=AD(2)
            V3=VC
            T=0.
            T2=0.
       117  BN1=N1
            BN2=N2
            PRINT32,AN1,AN2,BN1,BN2
        32  FORMAT(1HO*ANGLE ONE *E18.8,*ANGLE TWO *E18.8,
                                  *PROCESS ONE*E18.8,
          1  *PROCESS TWO*E18.8)
C           END OF PROGRAM DETECTION
            IF(TT-TTT)100,120,120
       120  STOP
            END
            ØENTRY
```

INPUT DATA SAMPE SAME AS OF PROGRAM III

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