DESIGN ASPECTS OF EHV SUBSTATIONS

A DISSERTATION

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By

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C E R T I F I C A T E

Certified that the dissertation entitled DESIGN ASPECTS OF E H V SUBSTATIONS which is being submitted by M.G. GHAMSARY in partial fulfilment for the award of the degree of Master of Engineering in Electrical Engineering (Power System Engineering) of the University of Roorkee, Roorkee, U.P., INDIA is a record of student's own work carried out by him under my supervision and guidance. The matter embodied in this dissertation has not been published elsewhere nor submitted for the award of any other degree or diploma.

This is to further certify that he has worked for a period of nine months from August 1984 to April 1985 for preparing this dissertation at this university.

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SYNOPSIS

EHV substations are a vital link in present power grid systems of India. Their proper design involves a knowledge of all components, equipment, their arrangements, layout as well as their costs and reliability. In order to be able to design substation with high reliability and minimum cost, three main criterias namely, technical, cost and reliability have been considered.

Technically the substation should have proper layout of equipments, operational flexibility, protection arrangement, simplicity and minimum maintenance requirements.

In the present work, cost and reliability criteria of substation design have been discussed in detail. The various possible bus-bar arrangements for a 400 KV substation have been studied from the cost and reliability point of view. A comparison of the cost criteria for various bus-bar arrangements has been made and discussed in light of such study in other countries.

The substation reliability has been computed by tie-set and cut-set method. A computer programme has also been developed for this study. The substation reliability values for different bus bar arrangements have been compared.

The dependence of system reliability on different component failure rates has been discussed. Reliability comparison of two bus bar arrangements on different component failure rates has also been discussed.

The comparison of cost and reliability values of ring bus, duplicate bus, sectionalised bus and single bus arrangement has been made.

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CHAPTER-1

INTRODUCTION

The substation is one of the keylinks between the source of power generation and consumer and exercise a vital influence on the reliability of power supply. Basically it provides a point for controlling the flow of power along different routes by means of various equipments such as transformers, circuit breakers, and isolators etc., which are jointed together to a common bus. In order to cope with massive power generation to meet the increased demands, India has increased the transmission voltage from 220 K.V. to 400 K.V. and started construction of regional grids which will be interconnected to form a national grid. Design of EHV substation has therefore assumed great importance. Some of the important design criteria for E.H.V. substation for taking proper techno-economic decisions are as follows:

(i) Choice of bus-bar scheme

(ii) Study of overvoltages and selection of insulation levels.

(iii) Selection of equipments and components

(iv) Reliability level.

These points are briefly described here:

(i) <u>Choice of bus-bar scheme</u> - Generally the selection of bus-bar system presents a complex problems as it has to be considered in relation to requirements of the system as a whole. The selection varies with the voltage of substation, type of substation and reliability desired.

The total investment on a substation is directly related with the type of the bus scheme as it affects the requirement of equipment, space requirement, height, type of structure etc. As in most other engineering disciplines, greater flexibility can be achieved by choosing more elaborate scheme and investing more money. However, as the investment is increased beyond a certain limit the incremental benefit due to additional investment in terms of resulting improvement in performance starts declining:

(ii) Study of over voltages and selection of insulation levels

Over voltages in power system occure due to:-

(a) Atmospheric over voltages due to lightening strokes
(b) Temporary overvoltages due to load rejection, and
(c) Switching overvoltages.

Atmospheric overvoltages which are caused due to lightening strokes are not of much importance at E.H.V. level. Temporary overvoltages are caused due to load rejection, single line to ground fault, and resonance phenomena related to inrush current when transformer and reactors are energised. Temporary overvoltage is important for selection of lightening arrestors which has a direct bearing on the insulation levels adopted for design of equipment.

Switching overvoltages are caused due to de-energisation, energisation and re-energisation of lines, switching of faulted lines, switching off unloaded transformers, out of phase switching and ferro-resonance phenomena. In the design of equipment, efforts are made to limit the value of switching overvoltages to less than 2.5 p.u. They may be controlled by putting opening and closing resistors in the circuit breakers. To evaluate the overvoltages, it is necessary that TNA/Digital computer studies of the power systems are carried out. This would be helpful in determination of insulation level more accurately.

The choice of insulation level has a considerable influence on the cost and reliability of the substation. Insulation level for E.H.V. system is determined not only on the basis of lightening overvoltages but on the bases of switching and power frequency overvoltages also. The switching and power frequency overvoltages have, therefore to be evaluated more carefully. Larger saving in the cost of equipment can be effected by adopting reduced insulation level. This is possible due to improvement in the design of protective devices.

(iii) <u>Selection of equipments and components</u>

In E.H.V. substations, various electrical equipment constitutes about 70 percent of the total cost of the substation. Therefore substation design is influenced to a great extend by the type of various equipments and that are selected by the type of auxilliary equipment within the substation. For the proper slection of the type of equipments and compoents, there are many factors which are to be considered. These factors are voltage level, load capacity, environmental considerations, site space limitations and transmission line right-of-way requirements. The choice of insulation level and coordination practices are to be considered very carefully as they affect the cost considerably. The decision on the type of equipments for substation has ultimately to be taken on the basis of minimum cost for an acceptable reliability level.

(iv) Reliability level-with the increase in the bulk of power transmission over long distances, the importance of reliability of H.V. equipments for example, circuit breakers is appreciated by the manufacturers and users both. The objective of an electric utility is to ensure an uninterruption and quality power supply to its consumers. Any interruption in power supply can result in loss of production in industries and inconvenience to other users. The substations are the main links between generating station and load centers. Hence to ensure continuity of supply, it is necessary to have high reliability levels at the substation. A substation with low reliability level will lead to frequent supply breakdown and will indirectly affect the economy a conglomeration.

A substation is consisted of large number of components like circuit breaker, isolator, etc. The performance of the substation is dependent on the performance of the various components. Larger failure rate of the components will result in poor performance of the substation. In other words, the reliability of substation is directly dependent on the reliability of the components. If the failure rate of the components is known, the reliability of the substation can be evaluated using any standard reliability evaluation techniques e.g. block diagram reduction method, path set and cut set method etc. Several surveys have been conducted by various electricity supply authorities in several countries to determine the present statistics of failure and how to reduce its rate. A recent survey conducted by a French electricity authority, showed that the failure rate of circuit breakers in a particular system worked out to be approximately 8 percent, i.e., breakers per hundred circuit breaker years. The number of circuit breakers covered under the survey was about 8000 Nos. of different makes(2).

1.1 Arrangement of the thesis

This thesis is divided in six sections which is arranged in the order in which the work was done.

Chapter 1 gives the introduction which explains some of the important design criteria for E.H.V. substation for taking proper techno-economic decisions.

Chapter 2 gives the detailed study about switching schemes. Firstly the importance to this field is given with some of the technical points related to the economic selection of bus-bar arrangement. Then the different types of bus-bar arrangement. Then the different types of bus schemes with the advantages and disadvantages have been described. The percentages of application of these arrangements in respect of E.H.V. substation throughout the World have also been discussed.

Chapter 3 gives the details of substation equipments and components and the factors influencing the proper selection of the type of equipments and their arrangements. Next part of this section gives the different types of relaying schemes, then grounding and design of earth mat in substation.

Chapter 4 gives the design criteria related to E.H.V. substation. Detailed consideration of economy and reliability and the techniques for evaluating the reliability of sub-station have been discussed. The improvement of substation reliability evaluation has also been discussed.

Chapter 5 gives the result and discussion and Chapter 6 gives the conclusions.

The numbering of the equations, the figures and the tables correspond to the number of the section/sub-section where it appears.

CHAPTER-2

SWITCHING SCHEMES (BUS-BAR ARRANGEMENTS)

Substation buses are the most important part of the station structure since they carry high amounts of energy in a confined space. They must be carefully designed in order that the construction may provide adequately and economically for the utilization of the electric energy generated and at the same time have sufficient structual strength to withstand the maximum stresses that may be imposed on the conductors, and in turn on the structure, by heavy current under short-circuit conditions.

Generally the selection of a switching scheme presents a complex problem as it has to be considered in relation to requirements of the system as a whole. The selection varies with the voltage of substation, type of substation and the reliability desired . The total investment on a substation is directly related with the type of the bus schemes as it affect the requirement of equipment, space requirement,height, type of structures etc. while making economic selection some of the technical points which deserve consideration are as follows:

(i) Simple and symmetrical appearance for operational convenience and safety of personnel.

(ii) Minimum height and space required satisfying electrical clearances.

(iii) Bus rating should be adequate considering load current, fault current-corana discharge, etc.

(iv) Bus-bar arrangement should be adaptable to future extension(2,3).

The various types of bus-bar arrangements are discussed in the following sections.

2.1 GENERAL BUS ARRANGEMENTS(2,3,4,5,6)

In a large generating plant, an elaborate arrangement of bus bars is necessary in order that duplicate supply of is always available in case of a fault, which may otherwise dislocate a large area. These arrangements are described in details so that one may get a good idea of basic pattern of substations generally met in practice. Each of the arrangement described has its own advantages and disadvantages. The choice of a particular arrangement depends upon the relative importance placed on such items as safety, reliability, simplicity of relaying, flexibility of operation, ease of maintenance, location of connecting lines, provision for expansion and good appearance. The basic arrangement are the following types:

I. Single bus
II. Sectionalised single bus
III. Double bus double breaker
IV. Main and transfer bus
V. Double main and transfer bus
VI. Double bus single breaker
VII. Ring bus
VIII. Breaker and-a-half.

Some of these arrangements may be modified by the addition of bus tie breakers, bus sectionalising devices, breaker by pass facilities and extra transfer buses.

(I) Single bus-bar Fig (2.1)

In this scheme of bus bar connections, a single set of bus bars is used for the complete substation. All the incoming and outgoing lines are connected to this bus-bar through isolator switches and circuit breakers. The glaring disadvantage of this type of connection is that it can cause a serious outage in the event of breaker or bus failure. Morover, when maintenance is to be carried out on any one of the feeder-sections or on a part of bus-bar, the whole of the supply is to be disconnected. The following are the advantages and disadvantages of single bus bar system:

Advantages:

1. It is the cheapest arrangement.
2. The relaying on this system is simple.

Disadvantages:

1. The bigest disadvantage of this system is complete shut down of substation in case of failure of bus or any circuit breaker.
2. It is very difficult to do any maintenance.
3. Bus cannot be extended without completely de-energising substation.
4. It can be used only where loads can be interrupted or have other supply.

This type of bus bar is not normally used for major substation

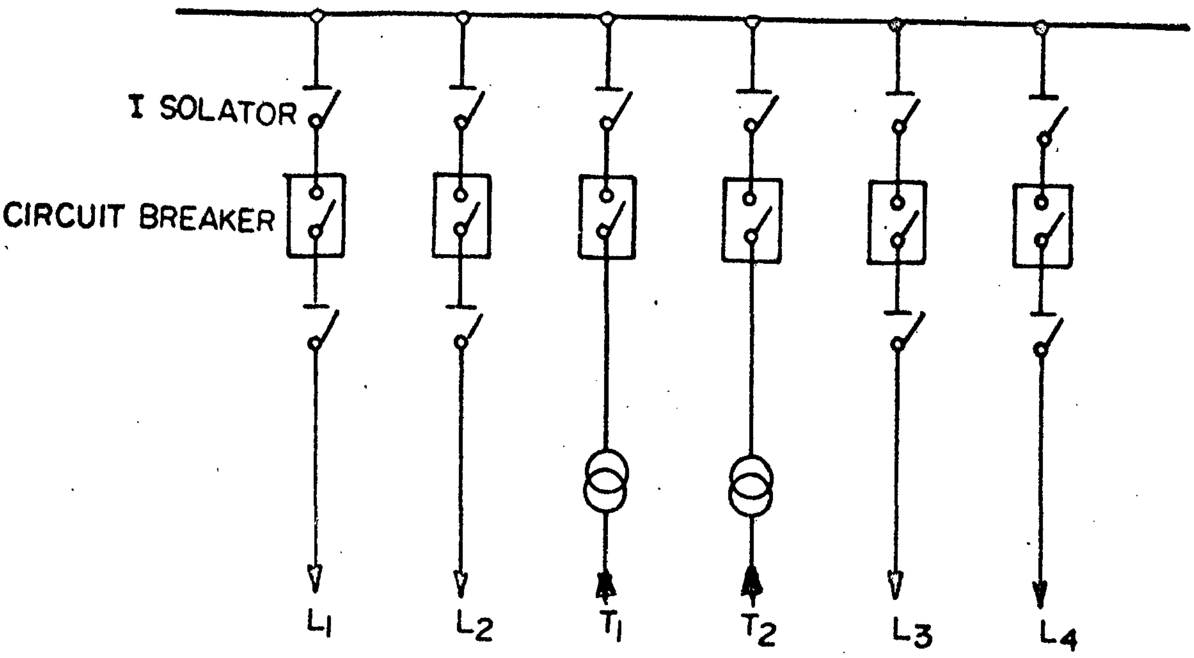


FIGURE.(2·1)- SINGLE BUS.

L_1, L_2, L_3, L_4 = OUT GOING LINES
T_1 & T_2 = TRANSFORMERS (IN COMING LINES)

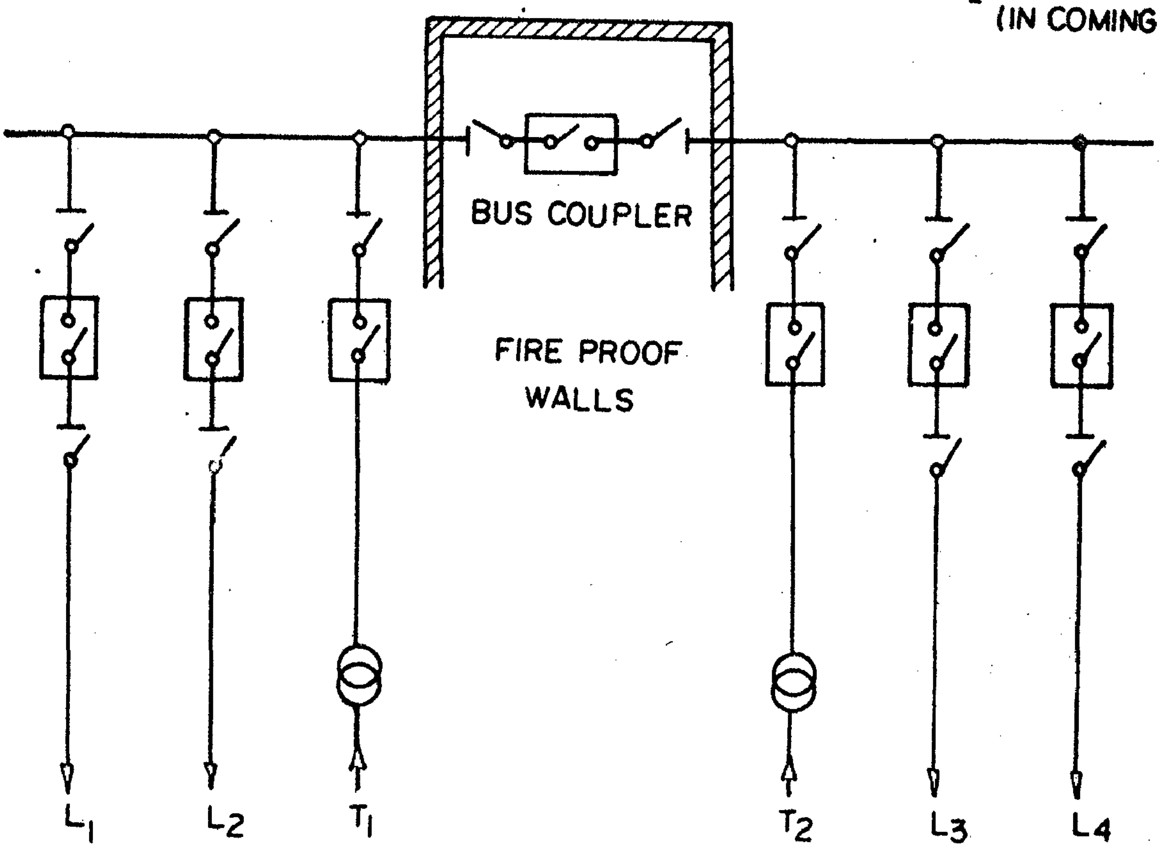


FIGURE.(2·2)-SECTIONALISED SINGLE BUS

II. Sectionalised single bus Fig(2.2)

The sectionalisation of the busbars ensures continuity of supply on other feeders, at the time of maintenance or repair of certain portion of the busbars. The whole of the supply will not have to be shut down. Normally the number of sections of a bus bar are 2 to 3 in a substation, but actually it is limited by the short circuit current to be handled. Another advantage of sectionalisation is that the circuit breakers of low rupturing capacity can be used on the sections as compared to the circuit breakers having high rupturing capacity in the previous case. In case of duplicate feeders, they are connected to different sections of the busbars so that in the event of a fault on one the bus-bar sections, the feeders connected to it are immediately transferred to the healthy bus-bar section and the faulty section is isolated.

The bus-bar sections are coupled or connected to each other through a bus coupler which is nothing but a circuit breaker. The utility of providing a coupler is that sometimes it has to break or isolate a section while it is carrying current.

At times air-break isolators are used in place of circuit breakers as bus couplers due to economy, but it must be remembered that any isolation affected by them must take place under off load conditions otherwise it may cause spark.

A double isolation is however necessary when the circuit breaker is used as bus coupler. Sectionalisation of the bus-bars also provides protection against fire of one section from another, by suitably placing the bus coupler within the fire proof walls as shown in the Fig (2.2). Important point to note is that the sections should be synchronised before the bus coupler is closed for sharing the load. The following are the advantages and disadvantages of the system.

Advantages

1. In the sectionalised single bus bar system with two sections only one additional breaker will be needed, thus its cost in comparison to single bus-bar system will not be much.

2. The operation of this system is as simple as that of the single bus-bar.

3. The maintenance cost of this system is comparable with the single bus bar system.

4. For maintenance or repairs of the bus-bar only one half of the bus-bar is required to be de-energised and possibility of complete shut down is thereby avoided.

5. It is possible to utilise the bus-bar potential for line relays.

Disadvantages

1. In case of a fault on the bus-bar, one half of the section will be switched off.

2. For regular maintenance also, one of the bus-bar is to be de-energised.

3. For maintaining or repairing a circuit breaker, circuit is required to be isolated from the bus-bar.

4. When circuit breaker of any circuit of this system fails, there will be shutdown of supply of one-half of the bus-bar. The bus-bar can again be energised by isolating the faulty circuit breaker.

5. If at any stage, a circuit is required to be added to the existing system, half of the bus-bar is to be de-energised during the period the work is carried on.

III. Double bus, double breaker Fig (2.3)

In double bus double breaker scheme, each feeder-circuit is having two circuit breakers as shown in Fig (2.3). In such schemes however no bus-coupler is needed. Normally each circuit is connected to both buses but in some cases, half of the circuits could operate on each bus. With the result, there will be loss of half of the circuits in case of bus or breaker failure.

The location of the main buses must be such as to prevent faults spreading to both buses. Although such a scheme is very costly, yet it represent a high order of reliability when all circuits are connected to operate on both buses.

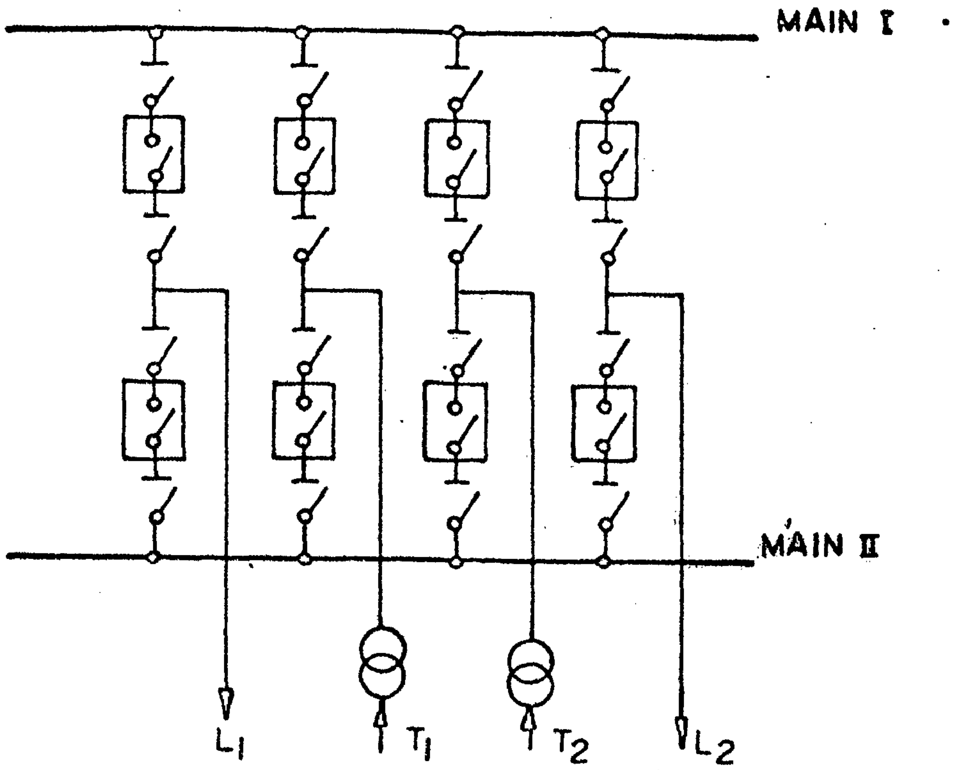


FIGURE.(2·3)-DOUBLE BUS DOUBLE BREAKER.

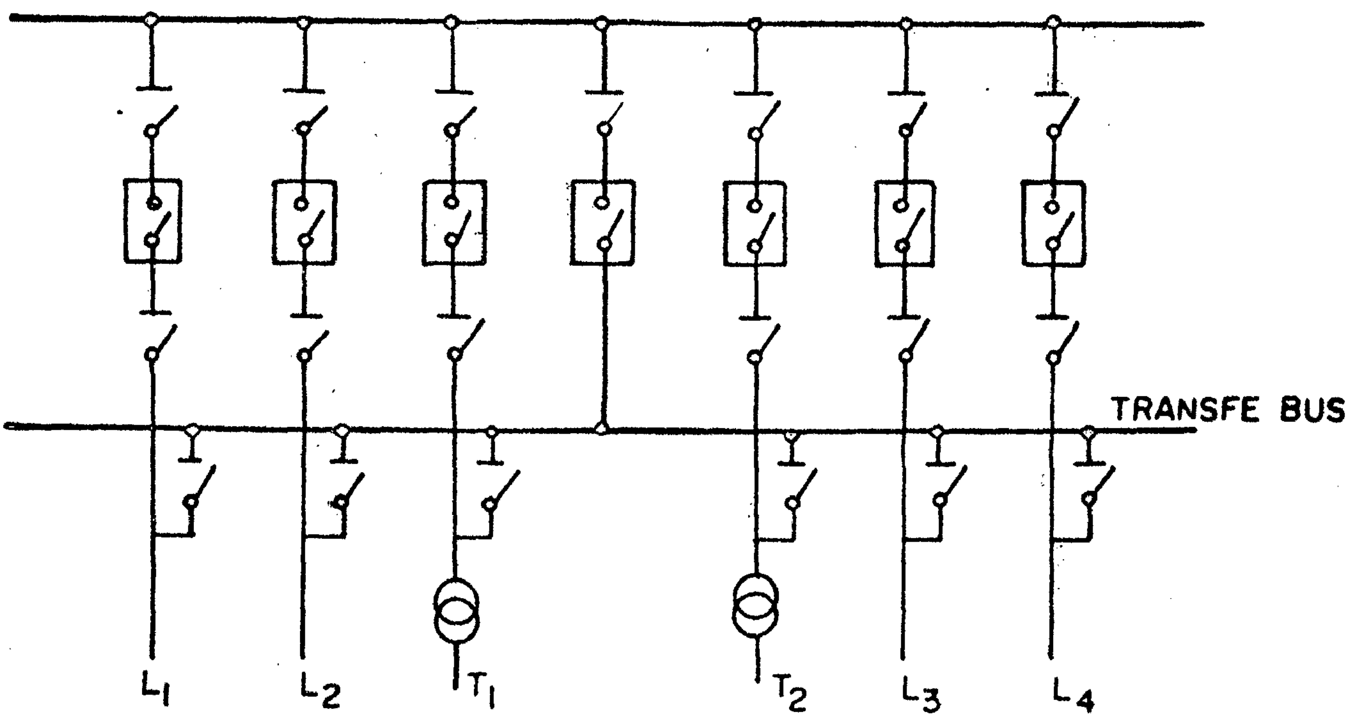


FIGURE.(2·4)-MAIN AND TRANSFER BUS.

Advantages

1. It has maximum flexibility and reliability since faults and maintenance intrrupt the service to minimum.
2. Each circuit has two dedicated breakers.
3. Each feeder circuit may be connected to either bus.

Disadvantages

1. It is the costliest bus arrangement.
2. Maintenance costs are high.
3. In case of breaker failure half of the circuits will be lost if circuits are not connected to both buses.

IV. Main and transfer bus Fig (2.4)

Almost all the modern generating stations, use two bus-bars, one main bus and the other transfer bus as auxiliary. This scheme adds a transfer bus to the single bus scheme. An extra bus-tie circuit breaker is provided to tie the main and transfer buses together. The main advantage consists in fact that whole of the load is transferred to the auxiliary bus-bar when maintenance or repairs are being done on the main bus-bar. When a circuit breaker is removed far, maintenance. The bus-tie circuit breaker is used to keep that circuit energised unless the protective relays are also transferred. The bus-tie relaying must be capable of protecting transmission lines or generator. Since the relaying selectivity is poor. This is considered rather unsatisfactory.

There is an arrangement of connecting current-transformer to the line and bus relaying. In this case, when a circuit breaker is taken out of service for maintenance, the line and bus relaying need not be transferred.

No circuit breakers remains to protect any of the feeder circuit if the main bus is ever taken out of service for maintenance. Failure of the main bus or any circuit breaker would cause the shut down of entire substation

The advantages and disadvantages of the system are:

Advantages

1. It ensures supply in case of any fault in one of the bus, the circuit can be transferred to the transfer bus.
2. The circuit breaker can be maintained with uninterrupted supply.
3. Potential devices may be used on the main bus for relaying.
4. Low initial and ultimate cost.

Disadvantages:

1. It requires one extra circuit breaker for the bus tie.
2. When maintaining a circuit breaker, switching becames complicated.
3. With failure of bus or any circuit breaker, the entire substation will be shutdown.

V. Double main and transfer bus Fig (2.5)

This is a combination of the double main and transfer bus scheme. This arrangement is also called as main, reserve and transfer bus scheme in which the reserved bus functions as a second main bus to which any or all of the feeders and incoming power sources may be connected. The following are the advantages and disadvantages of double main and transfer bus system:

Advantages:

1. Most flexible operation
2. Highest reliability
3. It provides taking any circuit breaker out of service for maintenance without affecting the supply to any of the feeders line.
4. Requires only one breaker per circuit
5. Any bus can be taken out of service at any time for maintenance.
6. Bus failure does not remove any feeder circuits from service.
7. Circuit can be transferred from one bus to other by use of bus tie breaker and bus selector disconnect switches.
8. Lower interrupting capacity feeder breakers may be used with this scheme since the short circuit capability of only one transformer bank need to be considered for normal operation.

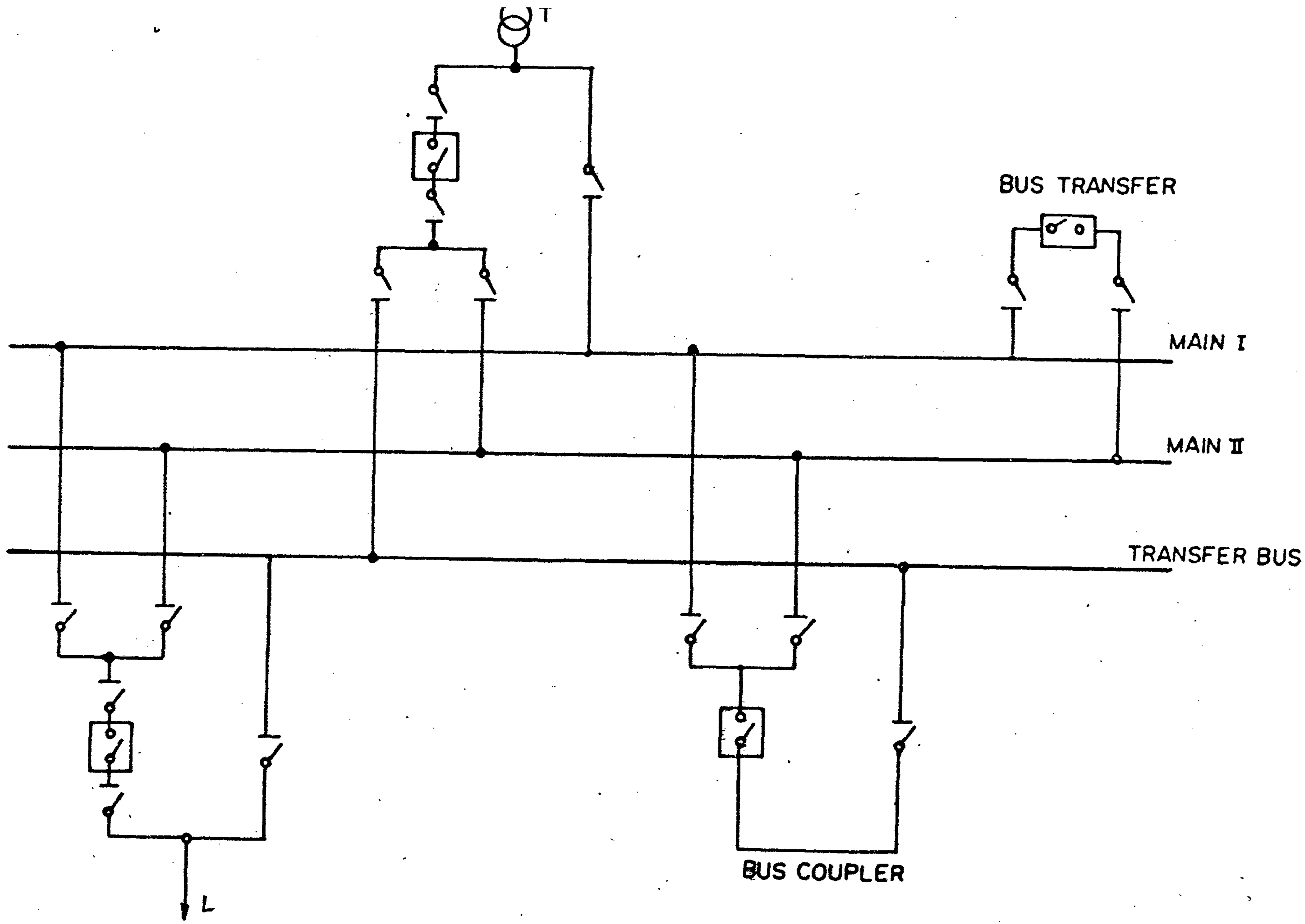


FIGURE (2·5)- DOUBLE MAIN AND TRANSFER BUS

Disadvantages:

1. It requires two extra breakers for the bus tie and bus transfer bay.
2. Five disconnector switches are required per circuit.
3. It introduces slight complication.
4. It occupies more area.

VI. Double bus single breaker Fig (2.6)

This scheme envisages use of two identical bus bars. Each circuit includes two bus selector disconnect switches. In such a scheme a bus coupler breaker is provided as it enables on load change-over from one bus bar to another without deenergizing the load circuit. The circuit may all operate from No.1 main bus Fig(2.6). or half of the circuit may be operated off either bus. In case of bus or breaker failure in the first case, the entire station will be out of service and half of the circuit would be lost for bus or breaker failure in the second case. Avery selective bus protective relaying scheme is required when circuits operate from both No.1 and No.2 bus.

Advantages

1. By using bus tie breaker and bus selector disconnect switches, the circuit can be transferred from one bus to another.
2. Either bus bar may be taken out for maintenance and cleaning of insulators.
3. Permits some flexibility with two operating buses.

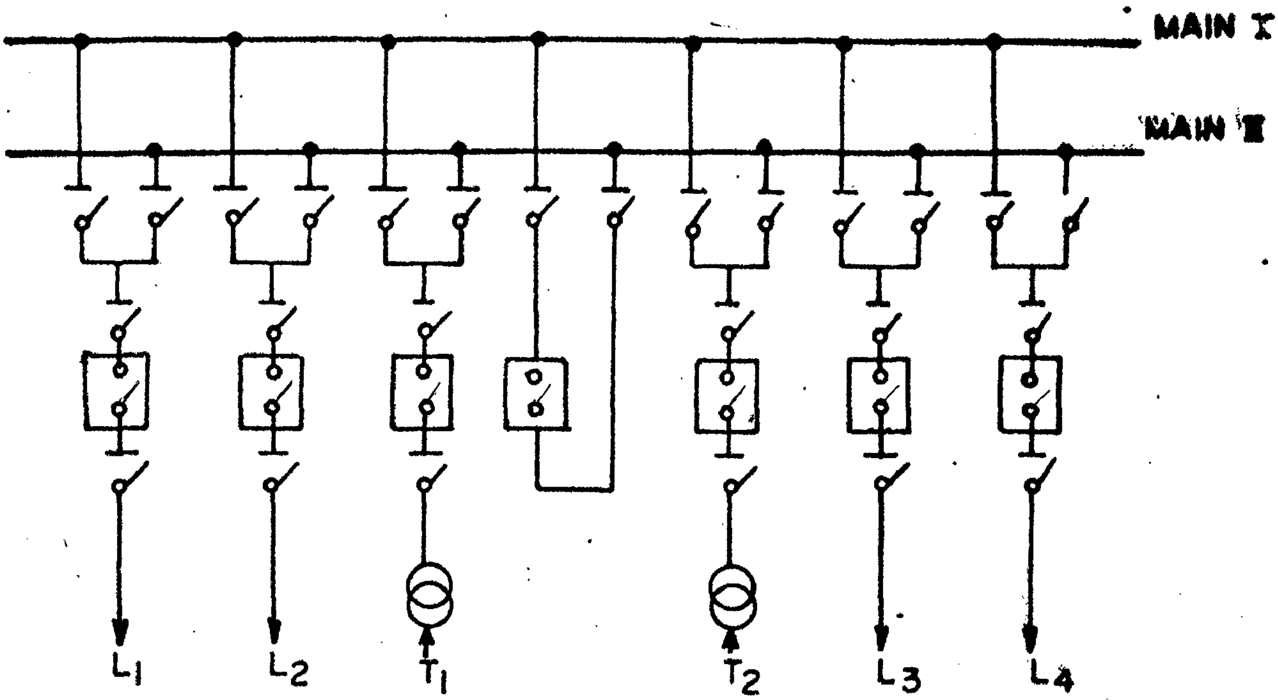


FIGURE. (2·6)-DOUBLE BUS SINGLE BREAKER

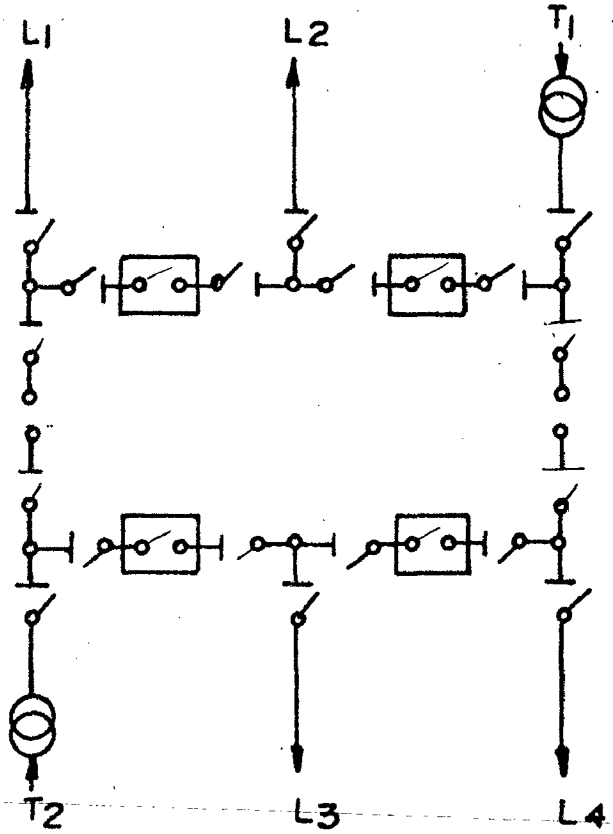


FIGURE. (2·7)- RING BUS.

Disadvantages

1. With failure of line breaker, all the circuits connected to that bus will be out of service.
2. Failure of bus tie breaker results in entire shut down of substation.
3. Bus protection scheme may cause loss of substation when it operates if all circuits are connected to that bus.
4. One extra breaker is required for bus tie.

VII. Ring bus Fig(2.7)

In this scheme, the idea is an extension of sectionalised scheme where the ends of the bus bars are returned upon themselves to form a ring as shown in Fig (2.7) There are the same number of circuits as there are breakers. All breakers are closed during normal operation, when fault occurs on a circuit, two breakers are tripped and incase one of the breakers fails to clear the fault an additional circuit will be tripped by operation of breaker-failure back up relays.

For an extended circuit outage, the line disconnect switch may be opened and the ring can be closed because the circuit connected to the ring are arranged so that sources are alternated with the load.

Advantages

1. Circuit breakers can be maintained without interrupting the supply.

2. At the time of failure of the circuit breaker of bus section only the effective circuit goes out of service while the healthy circuits are not affected.
3. The arrangement is quite economical.
4. It provides double feed to all the feeders at minimum eost.
5. It does not use the main bus.
6. All switching is done with breakers.
7. It requires only one breaker per circuit.

Disadvantages

1. It is necessary to supply potential to relays separately to each of the circuit.
2. If a single set of relays are used, the circuit must be taken out of service to maintain the relays.
3. It is difficult to add any new circuit to the ring.
4. Breaker failure during a fault on one of the circuits causes loss of one additional circuit-owing to operation of breaker-failure relaying.
5. If a fault occures during a breaker maintenance period, the ring can be separated into two sections.

VIII. Breaker and a Haulf Fig (2.8)

In this system three circuit breakers are used for two feeders between the main buses. The system has been illustrated in Fig (8) which shows that six circuit breakers have been used for four feeders. This comes to $1^1/2$ circuit breaker for each feeder.

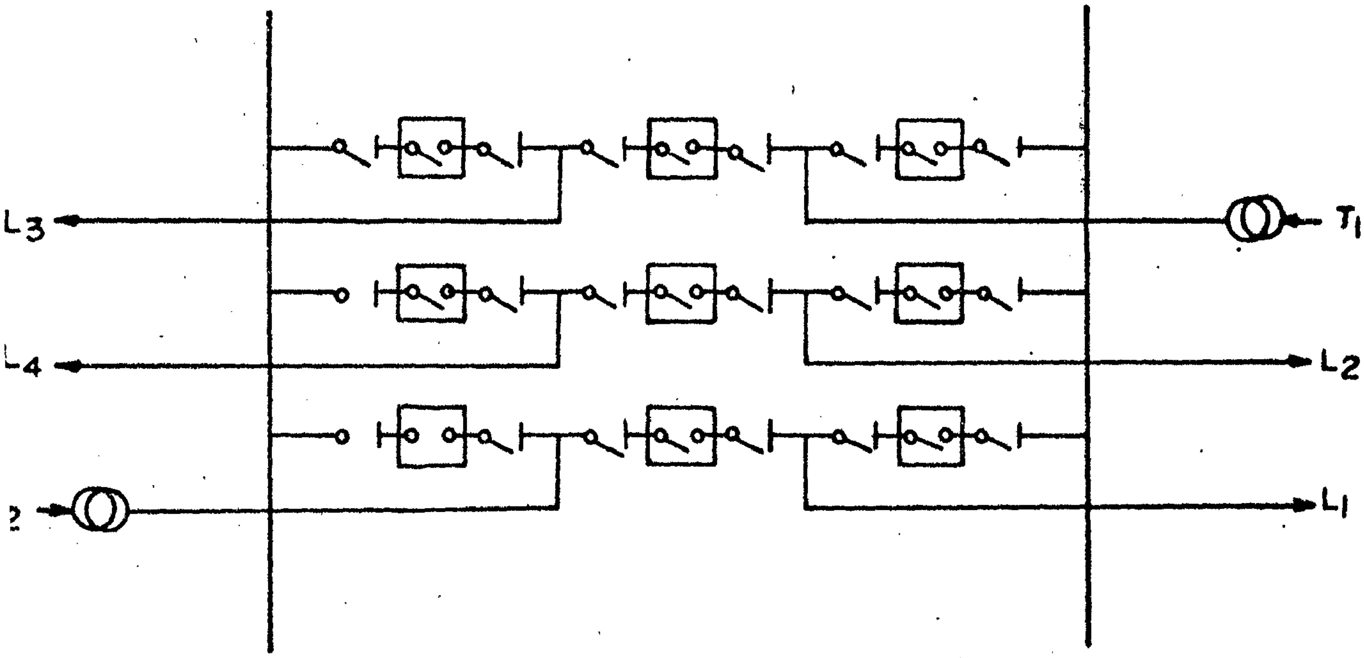


FIGURE. (2·8)-BREAKER AND-A-HALF

All breakers are closed under normal operating conditions. Tripping of a circuit is done by opening of two associated circuit breakers.

No additional circuit is lost if a line trip involves failure of a bus breaker while a additional circuit will be tripped under failure of tie breaker.

With sources connected opposite loads, it is possible to operate with both buses out of service.

Advantages

1. The system is economical as compared to double bus double breaker arrangement.
2. A fault on a breaker or in a bus will not interrupt the supply.
3. Breaker failure of bus side breakers removes only one circuit from service.
4. No disconnect switching required for normal operation.
5. It is having the most flexible operation

Disadvantages

1. The relaying becomes more complicated because at the time of fault two breakers are to be opened.
2. The maintenance cost is higher.
3. $1^1/2$ breakers per circuit.

Open bus arrangement and inverted bus arrangement:

A typical conventional open bus substation arrangement using breaker-and-a-half scheme is shown in Fig (2.9). In this scheme, the buses are arranged to run the length of the station and are located toward the outside of the station. Use of such type of arrangement requires three distinct levels of bus to make the necessary cross overs and connections to each substation bay. For example at 230 KV, these levels are 16 ft for the first level above ground, 30 ft high for the main bus location, and 57 ft for the highest level of bus, Fig (2.9).

This scheme has the advantages of requiring a minimum of land area per bay and relative ease of maintenance, and is ideally suited to a transmission line through connection where a substation must be cut into a line right-of-way.

Another arrangement is the inverted-bus, breaker-and-a-half scheme for EHV substations as shown in Fig(2.10). with this arrangement all outgoing circuit take-off towers are located on the outer perimeter of the station, eliminating the cross-over of line or exit facilities. Main buses are located in the middle of substation, with all disconnecting switches, circuit breakers, and all bay equipment located outboard of the main buses. In this scheme, the overall height of the highest bus in 230 KV station is reduced from 57 ft as indicated in previous scheme to 30 ft above the ground. The end result of the inverted bus arrangement

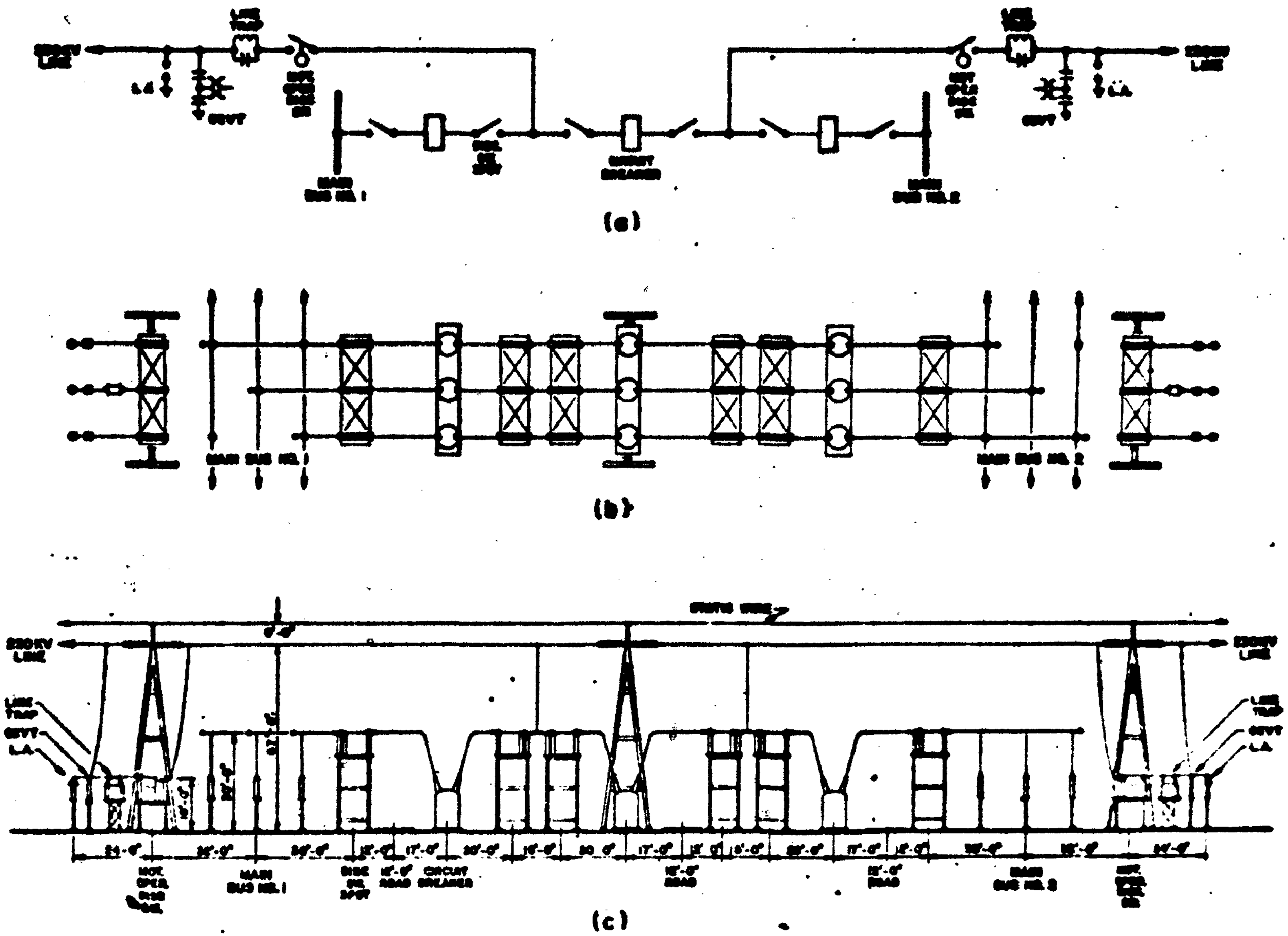
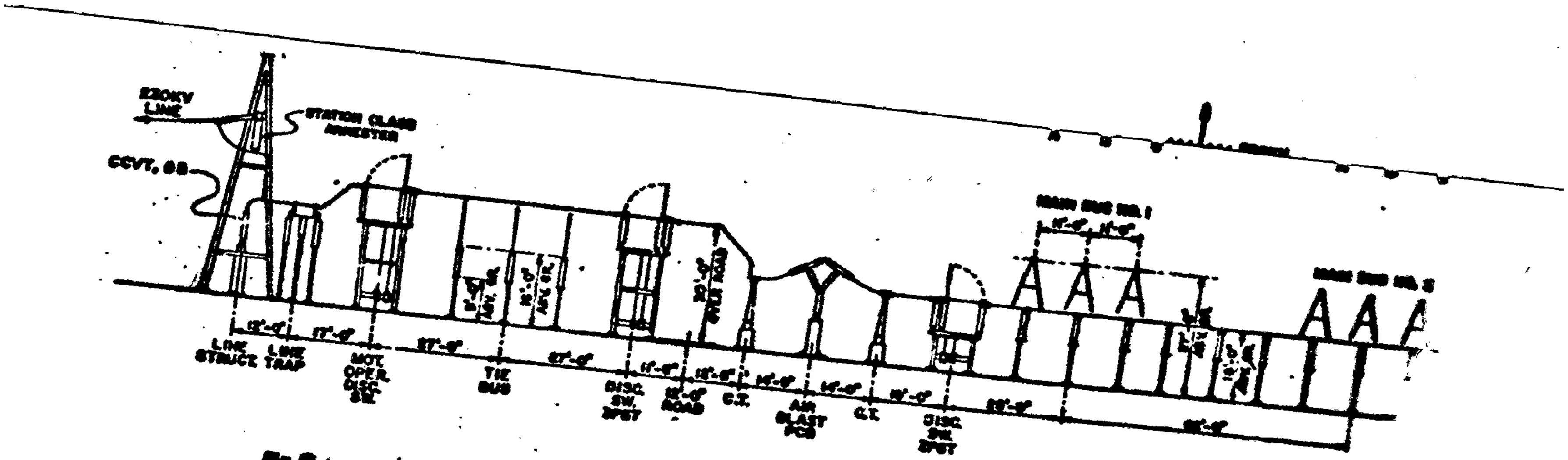


Fig 2.9 Typical conventional substation layout, breaker-and-a-half scheme. (*a*) Main one-line diagram; (*b*) plan; (*c*) elevation.



(c)

Fig 2.1(c) Typical 230-kV inverted-bus substation. (a) One-line diagram; (b) plan; (c) elevation.

presents a very low-profile station with many advantages in areas where beauty and aesthetic qualities are a necessity for good publications(3).

With consideration of switching scheme, following are the percentages of application of various types of bus-bar arrangement in respect of EHV substation throughout the world.

Duplicate bus-bar	33 percent
Main and transfer bus-bar	33 percent
Different schemes	34 percent

(Duplicate bus-bar system with by pass, etc.)

On a close scruting of the switching arrangements adopted in various countries one finds that following schemes have been used:

Country	Switching scheme
France	Double bus single breaker
Sweden	Main and transfer
United Kingdom	Double bus single breaker with by pass arrangement
U.S.A.	Ring main, Double bus double breaker Breaker and-a-half.
U.S.S.R.	Double bus double breaker

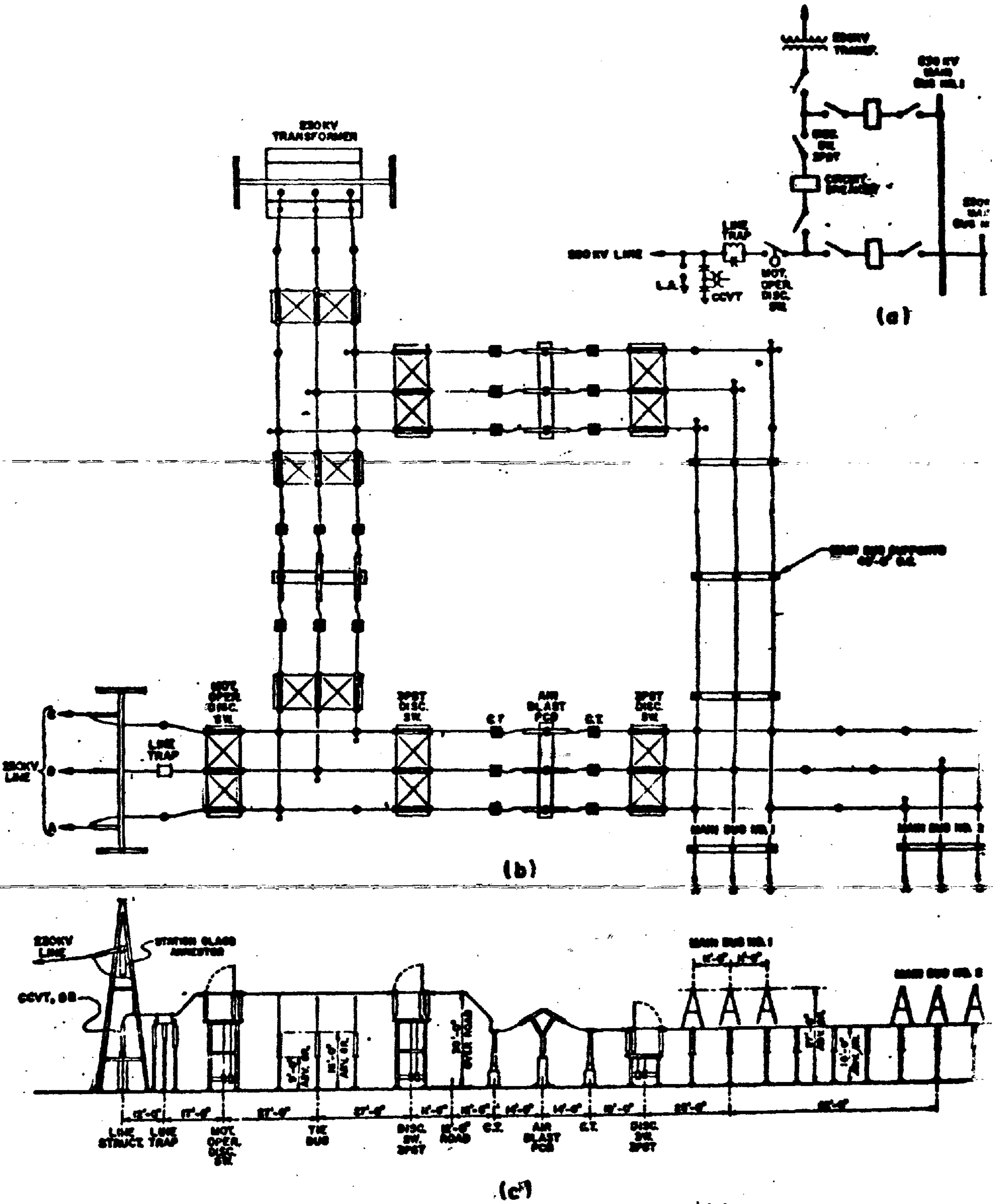


Fig. 2.1a Typical 230-kV inverted-bus substation. (a) One-line diagram; (b) plan; (c) elevation.

In India, U.P. and Maharashtra states have adopted double bus and transfer scheme, be as construction board have adopted breaker-and-a half scheme(2,3).

CHAPTER-3

SUBSTATION EQUIPMENTS AND COMPONENTS

The substation design is influenced to a great extend by the type of the various equipments, their accessories and their arrangements. There are many factors which influence the proper selection of the type of equipments and their arrangement for a given application. The most appropriate type of station depends on such factors as voltage level, load capacity, environmental considerations, site space limitations, and transmission line right-of-way requirements. In addition design criteria can vary between systems. One of the primary requirements of a good substation design is that it should be as economical as possible and at the same time it should have high reliability. With continuing general increase in the cost of materials and labour and the comparatively large programme for expansion of transmission and distribution facilities, every effort must be made to select criteria that represent the best compromise to satisfy the system requirements at minimum cost. One of the important factors which has a considerable influence on the cost and reliability of the system, especially at EHV is the choice of insulation levels and coordination practices. Larger saving in the cost of equipment can be effected by a drop of one level in BIL. Since the major substation costs are reflected in the power transformers, circuit breakers, and disconnecting switches, the bus layout and switching arrangement selected will determine the number of switches and circuit breakers required, a careful analysis of alternative switching sc scheme is essential, especially at EHV levels, and can also result in considerable savings by choosing the minimum equipment to satisfy system requirements(1,2,4,7).

In the following sections, the details of substation equipments and components are discussed.

3.1 Bus arrangements for E.H.V. substation

One of the important aspects in the design of E.H.V. substation is the choice of switching scheme which is given by a particular bus arrangement. The main considerations are the cost, flexibility of operation and reliability of the system. The simplest single bus-bar arrangement is lowest in cost but affords no flexibility of operation. The main and transfer bus arrangement provides facility for maintenance of circuit breakers without interruption of supply. The double bus-bar arrangement provides maintenance of bus-bars and other equipment connected to it. Breaker-and-a half scheme which has got three circuit breakers for controlling two circuits provides maintenance of any bus or circuit breaker without interruption of supply. Another scheme which has been found to be most reliable bus-bar is double bus-bar with a transfer bus. This scheme provides taking out or any circuit breaker out of service for maintenance without affecting the supply to any of the feeder lines(1,2).

The different types of bus bar arrangements have already been explained in article 2.

3.1.1 Physical layout

Generally three level switch yards at 400 KV are designed:

(i) lower most level used for connections from bus-bars to bus isolators,

(ii) intermediate level used for bus-bars (strain buses)and

(iii) top level for overhead connections and taking off the line conductors.

This may have minor variations depending on the requirements(2,4,7).

3.1.2 Types of bus-bars

The open bus substation arrangement consists essentially open bus construction using either rigid or strain bus design or combination of rigid and strain bus. In the rigid type, pipes are used for bus-bar and also for making connections among the various equipments whenever required. The bus-bars and connections are supported on pedestal insulators. This leads to a low type of switchyard wherein equipment as well as the bus-bars are spread out thus requiring a large space. Since the bus-bars are rigid, the clearances remain constant. Besides, as the bus-bars and connections are not very high from the ground, the maintenance is easy. Due to large diameter of the pipes, the corana loss is also substantially less.

It is also claimed that this system is more reliable than the strain bus. However, besides requiring large area, this type of bus-bar has the disadvantage of comparatively high cost.

The strain type bus-bars are an overhead system of wires strung between two supporting structures and supported by strain type insulators. The stringing tension may be limited to 500-900 kg depending upon the size of the conductor used. This arrangement is more economical than the rigid bus arrangement. Besides, in view of the general shortage of aluminium pipes in the India only strain type bus-bars are recommended for the present(1,3).

3.1.3 Current carrying capacity of bus-bar(3,8)

The heating effects produced by the current, limit the current-carrying capacity of a bus-bar. Generally the bus-bars are rated on the basis of the temperature rise which can be permitted without danger of overheating equipment terminals, joints, and bus connections. For plain copper and aluminum buses, the permissible temperature rise is usually limited to $30^{o}C$ above an ambient temperature of $40^{o}C$. This is an average temperature rise, and a maximum or hot spot temperature rise of $35^{o}C$ is permissible. There are

TABLE 3.1 Current Ratings for Bare Copper Tubular Bus, Outdoors'

(40°C Ambient Temperature, 98%, Conductivity Copper, Frequency 60 Hz. Wind Velocity 2 fts/s at 90° angle)

Nominal size	Outside diameter in.	Inside diameter in.	Current ratings, A		
			30°C rise	40°C rise	50°C rise
			Standard Pipe Sizes		
1/2	0.840	0.625	545	615	675
3/4	1.050	0.822	675	765	850
1	1.315	1.062	850	975	1080
1 1/4	1.660	1.368	1120	1275	1415
1 1/2	1.900	1.600	1270	1445	1600
2	2.375	2.062	1570	1780	1980
2 1/2	2.875	2.500	1990	2275	2525
3	3.500	3.062	2540	2870	3225
3 1/2	4.000	3.500	3020	3465	3860
4	4.500	4.000	3365	3810	4305
			Extra heavy pipe sizes		
1/2	0.840	0.542	615	705	775
3/4	1.050	0.736	760	875	970
1	1.315	0.951	1000	1140	1255
1 1/4	1.660	1.272	1255	1445	1600
1 1/2	1.900	1.494	1445	1650	1830
2	2.375	1.933	1830	2080	2325
2 1/2	2.875	2.315	2365	2720	3020
3	3.500	2.892	2970	3365	3710
3 1/2	4.000	3.358	3380	3860	4255
4	4.500	3.818	3840	4350	4850

TABLE 3.2 Current Ratings for Bare Aluminium Tubular Bus, Outdoors'

(Rating Based on 30°C over 40°C Ambient, Frequency 60 Hz, Wind Velocity 2 ft/s Cross wind).

Nominal size	Outside diameter, in.	Inside diameter, in.	Current ratings, A [1]	Current ratings, A [2]
		ASA Schedule 40 (Standard Pipe Size		
1/2	0.840	0.622	405	355
3/4	1.050	0.824	495	440
1	1.315	1.049	650	575
$1^1/4$	1.660	1.380	810	720
$1^1/2$	1.900	1.610	925	820
2	2.375	2.067	1150	1020
$2^1/2$	2.875	2.469	1550	1370
3	3.500	3.068	1890	1670
$3^1/2$	4.000	3.548	2170	1920
4	4.500	4.026	2460	2180
5	5.563	5.047	3080	2730
		ASA Schedule 80 (Extra heavy Pipe size)		
1/2	0.840	0.546	455	400
3/4	1.050	0.742	565	500
1	1.315	0.957	740	655
$1^1/4$	1.660	1.278	930	825
$1^1/2$	1.900	1.500	1070	945
2	2.375	1.939	1350	1200
$2^1/2$	2.875	2.323	1780	1580
3	3.500	2.900	2190	1940
$3^1/2$	4.000	3.364	2530	2240
4	4.500	3.826	2880	2560
5	5.563	4.813	3640	3230

[1] 6063 -T6- 53 % LACS typical

[2] 6061 -T6- 40 % LACS typical

many factors which cause the heating of a bus-bar, such as the type of material used, the size and shape of the conductor, the surface area, ventilation, and inductive heating caused by the proximity of magnetic materials. Current-carrying capacities of copper and aluminum tublar buses of different dimensions are shown in Tables (3.1) and (3.2).

3.1.4 Bus-bar material(1,6)

In the case of rigid bus arrangement aluminum pipes are commonly used. The sizes of pipes commonly used for various voltages are given below:

33 KV	40 mm	220 KV	90 mm
66 KV	65 mm	400 KV	100 mm
132 KV	80 mm		

Since aluminum oxides rapidly great care is necessary in making connections. In case of long spans expansion joints should be provided to avoid strain on the supporting insulators due to thermal expansion or contraction of the pipe.

Materials in common use for bus-bars and connections of the strain type are ACSR and all aluminum conductors. Bundle conductors are used where high ratings for bus-bars are required. The following sizes are commonly used

66 KV	37/2.79 mm	ACSR
132 KV	37/4.27 mm	ACSR
220 KV	61/3.99 mm	ACSR
400 KV	61/4.27 mm	ACSR in duplex

3.1.5 Skin effect

The resistance of a conductor is affected by the frequency of the current carried by it. An alternating current passing through a conductor tends to distribute itself non uniformly throughout the cross-section, those portion of the conductor situated at or near the surface carry a major portion of the total current. The effect increases the effective resistance of the line conductor and decreases the effective internal reactance. Skin effect is very important in heavy-current buses where a number of conductors are used in parallel, because it affects not only each conductor but each group of conductors as a unit. Tubes have less skin effect resistance than flat conductors of the same cross section, and tubes with thin walls are affected the least by skin effect. Because of greater resistance of aluminium, skin effect is lesser as compare to copper. Conductor of similar cross section (3,9).

3.1.6 Proximity Effect

The skin effect has been considered with can assumption that there is no other current carrying conductor near, but when a current carrying conductor is near by, its flux will link with the conductor considered and its effect to the nearer half of the conductor will be more with the further half. So like skin effect, it effects the current distribution and results in an increase in the effective resistance of the conductor and decrease of effective internal reactance. The proximity effect must be taken into account for buses carrying alternative current; the effect on 3-phase buses is less than on single-phase buses. Tublar conductor used on alternating current have a better Current distribution than any other shape of conductor of similar cross-sectional area, but they also have a relatively small surface for dissipating heat losses. While designing a tublar bus, these two factors must be properly balanced(3,5,6).

3.1.7 Thermal expansion

One of the important factors in the design of a bus-bar is consideration of thermal expansion and contraction, particularly where heavy-current buses or buses of long lengths are involved. An aluminum bus will expand 0.0105 in/ft of length for a temperature rise of $38^{o}C(100^{o}F)$. In order to protect insulator supports, disconnecting switches, and equipment terminals from the stresses set up by the thermal expansion of the conductors, provision should be made for expansion by means of expansion joints and damps permitting tubing to slide. By insertion of a piece of cable inside the tublar bus, vibration of long tublar-bus spans which has been experienced to some extent can be eliminated(3,10).

3.1.8 Electrical clearances(2,4,7)

Smaller air clearances reduce substation costs but increase flashover risks. For substations connected to overhead lines above 300 KV , non flashover air clearances are generally determined by switching impulse withstand voltages and by the electrode configurations. Switching and lightening impulse levels to ground are fixed after detailed study of maximum switching impulse overvoltages likely to appear at the particular substation and careful choice of measures to limit these over voltages by selection of switable system parameters, surge arresters, and circuit interrupting devices. Thus two values of air clearances corresponding to switching and lightening impulse withstand voltages to ground are determined. Where from the higher one is the needed minimum phase to ground air clearance. Depending upon the over voltage controls employed, switching impulse withstand voltages to ground can be correlated with switching impulse withstand voltages between phases for fixing minimum air clearances between phases. The clearances governing the substation design are earth clearance, phase clearance and safety clearance. While deciding the clearances for EHV and UHV systems, lightening surges are not critical. These clearances are selected from the consideration of switching surges.

(a) Phase to ground clearance

Following: are the various types of phase-to-ground clearances encountered in a substation:

(i) Distance between conductor and structures

(ii) Distance between live parts of the equipment and structures.

(iii) Distance between live conductor and ground.

These are governed by the electrode configuration and the value of the minimum phase-to-ground clearance varies from 3 to 4 metres.

(b) Phase-to-phase clearance

Phase-to-phase clearance is very important due to the fact that the consequences of phase faults are very severe for the system. There are three types of phase-to-phase clearances in a substation:

(i) Distance between live conductors, viz., phases of incoming and outgoing lines and bus-bars.
(ii) Distance between live conductor and apparatus.
(iii) Distance between live terminals of the apparatus such as breaker poles, disconnecting switches.

The distance between two bays are not only determined by the phase clearances but also by the necessity of carrying out the maintenance work. The clearances at(ii) and (iii) above depend upon electrode configuration and are difficult to define. The minimum values of phase-to-phase clearance vary from 4.0 to 4.75 meters.

(c) <u>Safety clearance</u>

Safety clearances comprise

(i) Ground clearance and
(ii) Section clearance.

The ground clearance is defined as the minimum clearance from any point where a person may be required to stand to the nearest part not at earth potential of an insulator supporting the live conductor. The section clearance is defined as the minimum clearance from any point where a person may be required to stand to the nearest unscreened live conductor. The basis for fixing the section clearance is to take height of a man with stretched hands plus the phase-to-ground clearance..

The values of ground and section clearance generally adopted for 400 KV substation design are as follows:

Ground clearance	2.60 m
Section clearance	6.00 m

The substation design finalised after taking into consideration various clearances required to be maintained for safe operation as well as the safety of personnel and space required for movement of equipment under energised connections of the various circuit in the switchyard.

3.1.9 Mechanical and Electrical forces

The modern electrical grid substations in EHU systems are designed for high short circuit current in view of future expansion. This emphasises the consideration of the effect of short circuit current on mechanical design of columns and beams for the substation. The forces on the conductors, hardware, beam and columns due to 3-phase short circuits on a strung bus using bundled conductors are caused by magnetic attraction between the bundled-conductors and by phase to phase repulsion of adjacent phases. The electromagnetic force exerted between two current carrying conductor is a function of the current, its decrement rate, the shape and arrangement of conductors, and the natural frequencies of the complete assembly, including mounting structure, insulators, and conductors. Obviously it is not feasible to cover each and every case with one simple equation, even if some approximations are made, because of large number of variables involved, including the wind range of constants for support structures. In the following equation, the force produced by the maximum peak current is calculated. Due to intertia and flexibility of the system, in most cases, the calculated force is higher than that which actually occurs. This fact tends to compensate for the neglect of resonant forces. For usual practical conditions, the equation, therefore, is sufficiently accurate.

$$F = M \frac{8.0352 \times I^2}{S \times 10^7} \text{ kg/m of conductor}$$

where,

M = multiplying factor

I = short-circuit current, A (defined in Table 3.3)

S = spacing between centre lines of conductors, in.

Select the corresponding M factor from Table 3.3 after determining the value of I.

TABLE 3.3 Multiplying Factor(M) for Calculation of Electromagnetic Forces

Circuit	Amperes(I) expressed as	Multiplying factor(M)
dc	Max. peak	1.0
ac,3-phase	Max. peak	0.866
ac,3-phase	rms asymmetrical	$(0.866 \times 1.63^2) = 2.3$
ac,3-phase	rms symmetrical	$(0.866 \times 2.82^2) = 6.9$
1 phase of 3 phase or 1 phase	Max. peak	1.0
1 phase of 3 phase or 1 phase	rms asymmetrical	$(1.63^2) = 2.66$
1 phase of 3 phase or 1 phase	rms symmetrical	$(2.82^2) = 8.0$

The above procedure cannot be used for calculating stresses in the case of structures with long spans held in tension by strain insulators, but approximate estimates can be made by following the procedure generally used for calculating mechanical stresses in transmission line conductors.
The resultant of stresses due to the short-circuit load together with the dead, ice and wind loads, is the total stress in an outdoor bus(2,3,11,15).

3.1.10 Site selection

Civil-engineering work associated with the substation should be initiated as early as possible in order to ensure that the best available site is selected. The ideal site for a substation is naturally the centre of gravity of the electrical load but in practice the cost and availability of land, access for heavy vehicles, considerations of plant installation and handling future expansion of the substation etc. are equally, if not more important where land is cheap the need for economy in area is not always appreciated. It is not only the cost of land but also that of its treatment which must be taken into account. Levelling, surfacing and enclosing land are usually expensive., so too are roads, trenches and cables, length of which is a function of sub-station dimensions. Very large overal economics can be made by reducing the ground area occupied by a sub-station(6,3,12).

3.1.11 Structures

To support the bus-bar and different equipment in a sub-station two types of structures are generally used:

(1) Steel structure

(2) R.C.C. structures

In case of high type or low type of substation layout, steel structures are made from different sizes of steel members in a latticed form.

For supporting the main bus-bars, use of R.C.C. structures are not very much common in India for high voltage substations. In low voltage sub-stations, the use of R.C.C. structures is generally restricted for supporting the different types of equipment including bus-bars. At times in high voltage substation, the foundations of equipment are made of concrete(12).

3.2 Circuit breakers

The increase of fault level in EHV system has influenced the requirement of circuit breakers in many respects. The need for faster protection considered from system operation point of view has necessiated faster opening type for circuit breakers(2). Circuit breakers consist, essentially, of current carrying contacts called electrodes. These are normally engaged but, under predetermined conditions, separate to interrupt the circuit.

When the contacts are separated an are is struck between them. This arc plays an important part in the interruption process as it provides for the gradual transition from the current carrying to the voltage withstanding states of the contacts, but it is dangerous on account of the energy generated in it in the form of heat which may result in explosive forces. The main problem in a circuit breaker is, therefore, to extinguish the arc shortly after it has started and before the energy generated by it has reached a dangerous value(6).

Circuit Breakers' function

The two functions of switchgear in any power system are:

(a) To permit plant and distributors (transmission lines) to be conveniently put into and taken out of service.

(b) To enable the same plant and lines- when these become faulty - to be rapidly and safely isolated automatically from the unfaulted system.

The first of these could be served by relatively simple switches; the second, however, requires circuit-breakers which are much more robust and capable of breaking the large values of fault power (MVA) that result from faults an major power systems. Since all plants and lines are liable to develop faults as a result of mechanical damage, electrical breakdown, errors in operations etc., the simple switch is ruled out in favour of automatic circuit breakers, even for the switching function(2,6).

3.2.1 Classification of circuit breakers

All high circuit breakers may be classified under two main headings:

(i) Oil circuit breakers

(ii) Oilless circuit breakers.

Oil circuit breakers can be sub-divided into:

(i) bulk oil circuit breakers using a large quantity of oil, and

(ii) low oil circuit breakers which operate with a minimum amount of oil (low oil circuit-breakers are also called minimum oil breakers or small oil circuit breakers).

In the bulk oil breakers the transformer oil, with which they are filled, is used to extinguish the arc during opening of the contacts and to insulate the current conducting parts from one another and from the earthed tank. In the low oil circuit-breakers the oil serves only for arc extenction; their current conducting parts are insulated by air and procelain, or organic insulating materials.

The main type of oilless circuit breaker are:

(i) Hard gas circuit breakers in which the arc is extinguished by gases generated when the wall surfaces of the arc - extinguishing chambers, lined with insulating materials capable of producing large amount of gases, are decomposed by the arc (such materials are fibre organic glass etc.).

(ii) Air blast circuit breakers in which compressed air extinguishes the arc.

(iii) Sulphur Hexa Fluoride Circuit-breakers in which SF_6 under pressure is used as an arc extinguisher(6).

Three types of circuit-breakers are available for EHV levels, i.e., air blast, minimum oil and Sulphur hexa-Flouride(SF_6) type. The choice depends on economics, size, maintenance and reliability. Circuit-breaker should be suitable for breaking small inductive currents without causing excessive over voltages and line charging current without restrikes, handling evolving faults presently, 2 cycle circuit breaker are available and are in use on EHV system and 1-cycle breaker may be the choice of UHV system. EHV circuit breakers are provided with pre-insertion resistors for controlling switching surges(2,13).

3.2.2 Factors governing the selection of circuit breakers

The selection of the type of circuit breakers is governed mainly by the following important factors:

(a) Use of pre-insertion resistors to control the switching surge over voltage;

(b) Requirement of inherent restrike-free operation under all conditions;

(c) Consistent characteristics;

(d) Simple and reliable mechanism;

(e) Operating speed;

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(f) Ease in maintenance;

(g) Reliability and life of plant in view of future developments(2).

3.3 Disconnect switches (Isolators)

Disconnect switches are used for transfer of load from one bus to another and also to isolate equipment for maintenance. Although there are a large variety of disconnect switches available, the factor which has the maximum influence on the station layout is whether the disconnect switch is of the vertical break type or horizontal break type. The followings are the types of 400 KV isolators.

1. Single pole vertical reach isolators without earthing switch, complete with its fixed contacts, to be attached to strung bus bars having 4 Moose , conductor, 0.5 sq.in. Cu. Eq. ACSR bundle.

2. Single pole vertical reach isolators as above but with one earthing switch.

3.(a) Three phase isolators (centre break type) with two earthing switches one on each side having independent operating mechanism.

(b) Three phase isolators (Centre break type) with one earthing switch only having independent operating mechanism.

(c) Three phase isolators (centre break type) without any earthing switch suitable for tandem arrangement.

3.3.1 Factor Governing the selection of Isolators(2,14)

As the 400 KV system is being developed for the first time in India, due care and precautions have been taken for providing sufficient security and reliability in operation under all normal and abnormal system conditions. In absence of past experience in India, the available experience of various utilities abroad who had long years of operating experience have been utilised. Accordingly the layout of the 400 KV substation utilised double main and transfer bus system with strung main, transfer and jack buses, pipe connectors have been adopted only for connections between isolatros, circuit breakers and other equipments such as instrument transformers, lightening arrestors, power transformers, etc.

The pantograph type vertical break isolators have following advantages:

1. Better open gap coordination:

The only purpose for purchasing and installing an isolator is to provide a visible open gap in the circuit. On this open gap the men's lives may depend. To achieve this it is fitting and proper that the isolator should be selected in such a way that any surge, either a lightening or switching will be directed to ground rather than flash across the open gap.

2. Cost of structures:

Due to large open gap requirements in double break isolators over single break isolators the size of the double break isolators is much larger causing increased cost of structures, whereas in case of pantograph type isolators only one insulator has to be supported causing still reduction in cost.

3. <u>Phase to phase clearance requirements:</u>

Due to larger open gap requirements the phase spacing of the double break isolators at 400 KV must be at least 1525 mm (.5 ft) greater than that of the vertical break isolators for the same phase to phase switching surge withstand values.

4. <u>Requirement of Fourth Insulator:</u>

For full blade control the double break isolators require four insulators per pole instead of three. This increases the isolator weight, installation and maintenance cost by $33^{1}/3$ percent.

5. <u>Reduced cost of insulators of pantograph type isolators:</u>

In case of horizontal single break isolator the cost of insulator is more due to fact that long blade movement requires larger cantilever strength. Where as in pentograph type vertical break isolator the requirement of cantilever strength is negligible causing less cost involvement towards insulators hence reduction in over all cost of the isolator.

6. Clarity and lower bay size requirements

For clarify and providing adequate clearances pantograph type bus isolators have been preferred over the horizontal break and horizontal travel isolators to avoid direct taps from the bus bars to isolator which are unavoidable for the later version. The wind may give rise to large swings of the tap connection hence larger bay widths may be required for the horizontal break isolators. Hence the pentograph type bus isolators are most suited.

3.4 Reactors

The use of shunt reactors for controlling the power frequency over voltages under no load or light load conditions are needed for EHV long lines. These may be connected directly to the line depending upon the requirements or to the tertiary windings of power transformers which are in circuit with the system to be compensated. Shunt reactors may be either fixed impedance type or variable impedance type. Fixed impedance type reactors are either core type or coreless type. The choice between two types depends on the equipment available, the MUAR rating and the space available at site. Difficulty in producing a reasonably quiet reactor of core type for larger rating has led to the manufacture of coreless type, impedance, thermal rating, power factor and noise level are the important parameters of shunt reactors. The location and capacity of shunt reactors are decided on the basis of the studies carried out on TNA/Digital - computer(2).

3.5 Power transformers

Transformer usually forms the costliest piece of equipment in a substation and is, therefore, very important from the point of view of station design. Transformers employed for interconnecting 400 KV system with 220 KV or 132 KV network are generally auto-transformers. These transformers are provided with delta connected tertiary winding for connection to shunt reactors or synchronous condensers. At generating stations step-up transformers are installed. With the increase in the unit size and quantum of power to be handled, the transport limitation is an important factor to be considered in deciding the capacity, and whether single phase or three-phase units should be adopted. In this regard some new means of transportation have to be explored for coping with the large size power transformers to be installed at major grid substations and power stations. The practice of assembly of large transformers at site has been in vogue in other countries and in India also transport limitations may warrant consideration of the same. Other parameters of importance are the BIL of the winding, reactance, tap range, noise level and method of cooling as these have direct bearing on the cost of a transformer(1,2,16).

3.6 Instrument Transformers

There are two types of current transformers e.g. bushing type and wound type. Bushing types are accommodated within the transformer and breaker bushings. Wound types are invariably separately mounted and thus require much more space than bushing type. (Air blast circuit breakes and minimum oil circuit-breakers are not provided with bushing types CTS) and hence separate CTS are to provided in such case. Bushing type CTS are usually used in the case of bulk oil circuit breakers. For ground fault relaying the CTS may be provided either in the bushing of the tertiary winding of the 3 winding transformer or in the transformer nutral or a combination of both depending upon the magnitude of the fault current. The voltage transformers are either electromagnetic type or capacitor type. The electromagnetic types are more accurate, but costly and hence are preferred for metering purposes. Capacitance voltage transformer is often used in power system for voltage measurements. In contrast to simple capacitance divider which requires a high impedance meter like a V.T.V.M. or an electrostatic voltmeters a CVT can be connected to a low impedance device like a Watt-meter pressure coil or a relay coil. CVT can supply a load of a few VA. A matching transformer is connected between the load or meter M and C_2 as shown in Fig (3.1).

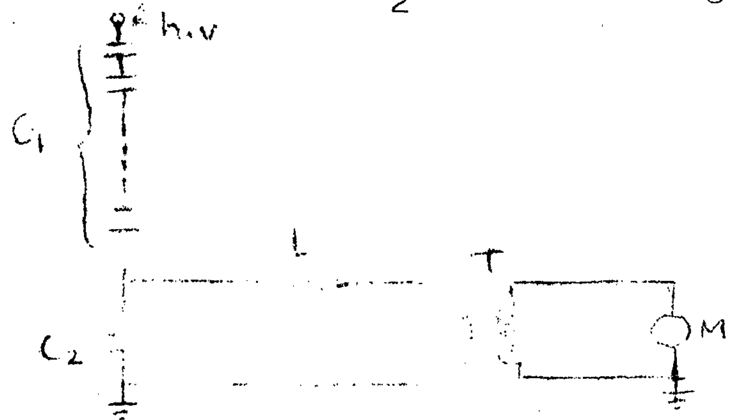


Fig (3.1)

The advantages of a CUT are:

(i) Simple design and easy installation,

(ii) It can be used both as a voltage measuring device for meter and relaying purposes and also as a coupling condenser for power line carrier communication and relaying.

(iii) provides isolation between the high voltage terminal and low voltage metering.

3.7 <u>Lighting Arresters</u>

The substation equipment has to be provided against travelling waves due to lightening strokes on the line entering the substation. The apparatus most commonly used for this purpose is the lightening arrester. Further, lightening arresters are provided as near as possible to the transformer terminals as it happens to be the costliest single piece of equipment.

The lightening arresters provided for protecting the transformers against travelling voltage surges also afford protection to other equipment on the bus side which lie within a safe distance from the lightening arrester location. In large substations it may not be possible for a single lightening arrester to protect all equipment. In such case lightening arresters are to be provided on all lines entering into the substation and if required also on bus. For determining the required number of lightening arresters and their fault condition is not removed or isolated rapidly, there may be danger to personnel and possibly further system disturbances such as over loading, instability or even damage to healthy equipment. It is therefore very necessary that system faults are detected speedily and remedial action initiated. Protective relaying is charged with this responsibility.

Many E.H.V. and U.H.V. systems use two sets of protective relays for lines, buses, and transformers. Many utilities use one set of electromechanical relays for transmission-line protection, with a completely separate, redundant set of solid-state relays to provide a second protective relaying package. Use of two separate sets of relays operating from separate potential and current transformers and from seperate station batteries allows testing of relays without the necessity of removing the protected line or bus from service. For more difficult relaying applications, such as E.H.V. lines using series capacitors in the line, some companies use two sets of solid-state relays to provide the protection systems. Transmission-line relay terminals are located at the substation and comprise many different types of relaying schemes as follows:

(1) Direct underreaching
(2) Permissive underreaching
(3) Directional comparison
(4) Phase comparison
(5) Pilot wire.

location, each case has to be studied considering the isokeraunic level of the site as well (1,2,12,16).

3.8 Insulators

One of the primary and important factor which effect the reliability of supply and safety of personnel in a substation is provision of adequate insulation. The station design should be so evolved that the quantity of insulators is a minimum commensurate with the security of supply. An important consideration in determining the insulation in a substation is the problem of insulator polution, particularly those which are near either the sea or a thermal station or an industrial plant. As a first step to combat this problem, special insulators with higher leakage distance should be used. In case this does not suffice, washing the insulators by using live line equipment has to be restored to and this aspect has to be kept in mind while deciding the layout of the substation. Another method which has been used successfully is the use of suitable type of greases or compounds applied on the surface of insulators. This, however, also requires cleaning of insulators, the frequency depending upon the degree and to the type of pollution(1).

3.9 Protective Relaying

A large 400 KV interconnected network requires enormous capital investment. Damage to plant may be caused by the vast quantities of energy released in the event of a short circuit fault or a human error fault. Further if the

(1) Direct underreaching Fault Relays

Fault relays sense fault power flow into the line at each terminal of the protected line. Their zones of operation must overlap but not overeach any remote terminals, Fig (3.1). At any terminal, the operation of relays initiates both the opening of the local breaker and the transmission of continuous remote tripping signal to instantaneous operation of all remote breakers. Considering Fig (3.1), for a line fault near bus A, the fault relays at A trip breaker A directly and send a transfer trip singal to B. The reception of this trip signal at B trips breaker B.

(2) Permissive under Reaching Relays

This system is almost the same as that of direct underreaching system, with the addition of fault detector units at each terminal. The fault detectors must overreach all remote terminals. They are used to provide added security by supervising remote tripping. Considering Fig (3.1), when there is fault near A, the fault relays at A trip breaker. A directly and send a transfer trip signal to B. Breaker B will be tripped by reception of the trip signal plus the operation of the fault detector relays at B, Fig (3.2).

(3) Permissive Overreaching Relays

At each terminal of the protected line, these relays sense the fault power flow into the line, with their zones of operation overreaching all remote terminals. Both the operation of the local fault relays and a transfer trip

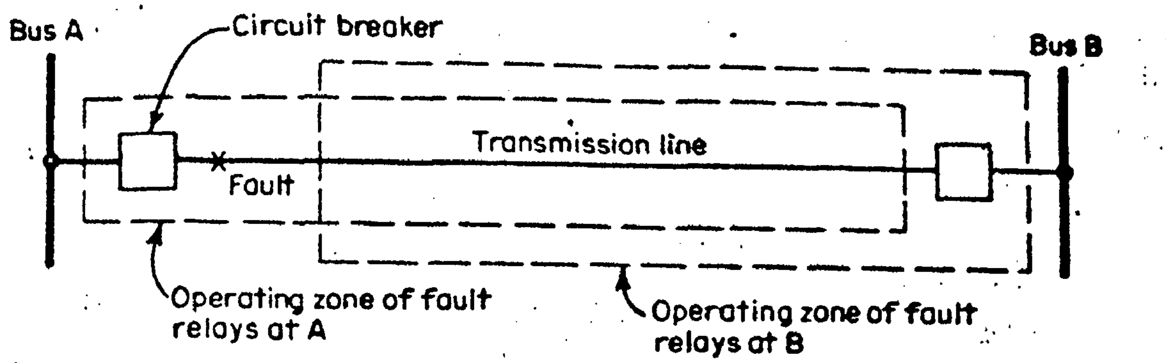


Fig. 3.1 Fault relay operating zones for the underreaching transfer trip transmission-line pilot relaying system.

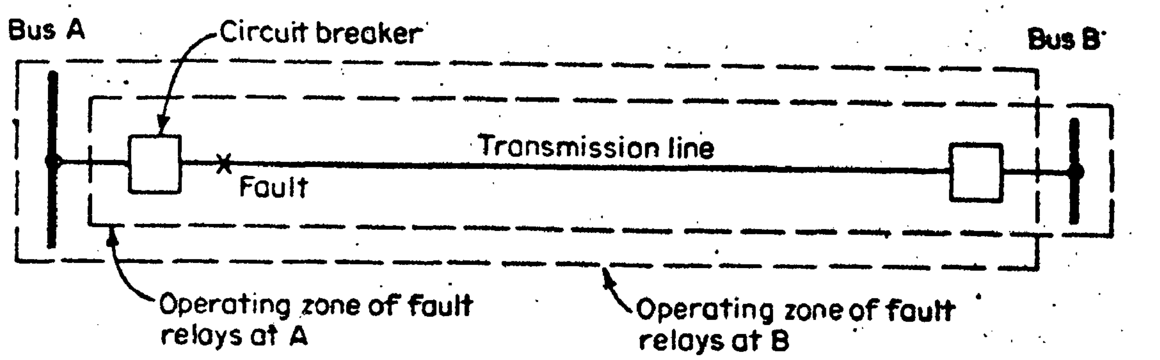


Fig. 3.2 Fault relay operating zones for the overreaching transmission-line pilot relaying system.

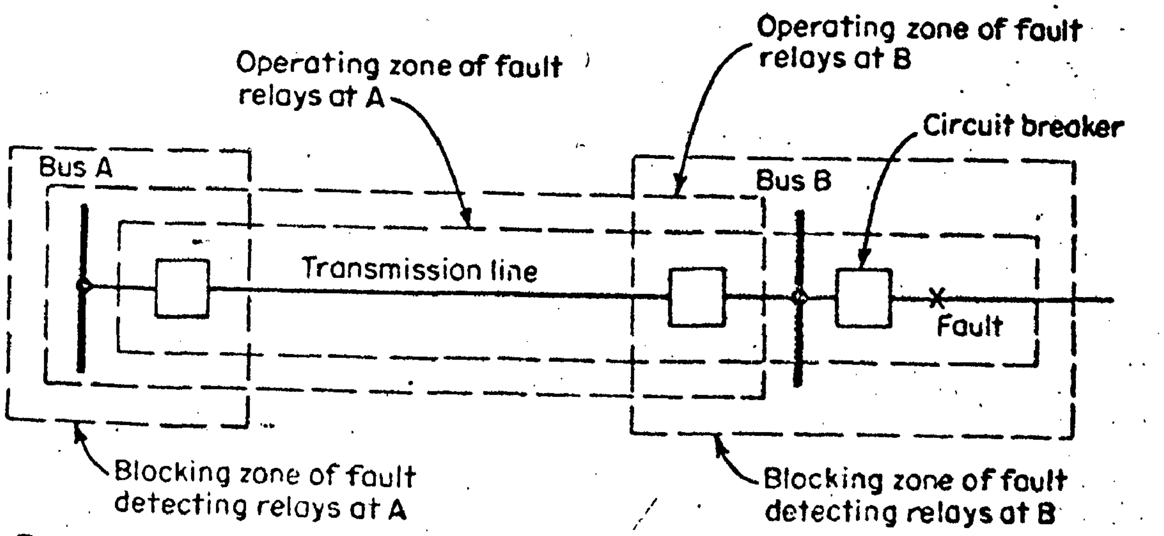


Fig. 3.3 Fault and blocking relay operating zones for the directional-comparison transmission-line pilot relay system.

signal from all of the remote terminals are required to trip any breaker. For example, considering fig (3.2), when there is a line fault near A, fault relays at A operate and transmit a trip signal to B. Similarly the relays at B operate and transmit a trip signal to A. Operation of the fault relay A plus the remote trip signal from B trip breaker A. Likewise, operation of fault relay B plus the remote trip signal from B trip breaker B.

<u>Directional-comparison Relays</u>

Fault relays at each terminal of the protected line section sense fault power flow into the line. The channel signal in these systems(3.3) is used to block tripping in contrast to its use to initiate tripping in the previous three system. Their zones of operation must over-reach all remote terminals. At each terminal, additional fault detecting units are required to initiate the channel blocking signal. Further their operating zones must extend or be set more sensitively than the fault relays at the far terminals. For example, the blocking zone at B must extend further behind breaker B (to the right) than the operating zone of the fault relays at A,Fig(3.3). Similarly, the blocking zone at A must extend further out into the system (to the left) than the operating zone of the fault relays at B, with consideration of line AB, when there is an internal fault on it, no channel signal is transmitted from any terminal or if transmitted, it is cut off by the fault relays.

In this absence of any channel signal, fault relays at A instantly trip breaker A, and fault relays at B instantly trip breaker B. For the external fault to the right of B as shown in fig (3.2), the blocking zone relays at B transmit a blocking channel signal to prevent the fault relays at A from tripping breaker A. As B operating zone does not see this fault, breaker B will not be tripped.

(5) Phase-Comparison Relays

At each end of the protected line, the three line currents are converted into a proportional single phase voltage. The phase angles of the voltages are compared by permitting the positive half cycle of the voltage to transmit a half wave signal block over the pilot channel. These blocks are out of phase for external fault so that alternately the local and then the remote signal provides essentially a continuous signal to block or prevent tripping. In the case of internal faults the local and remote signals are essentially in phase so that approximately a half cycle of no channel signal exists. This is used to permit the fault relays to trip their respective breakers at each terminal.

3.9.1 Station bus protection

Occurance of bus faults are extremely rare. Statistics show that bus-fault occurance is about one in 15 years per installation. Statistics collected in U.K. shows that the causes of faults are as given below:

50 percent - Equipment insulation failure and flashovers due to lighting.

35 percent - Human error

10-15 percent - Falling objects, circuit breaker failures etc.

Therefore bus protection deserves very careful attention, since bus failures are, as a rule, the most serious that can occure to an electrical system. Unless properly isolated, a bus fault could result in complete shutdown of a station. Many methods are employed to protect the station buses. Amont them are the use of over current relays, back up protection by relays of adjacent protective zones, directional comparison scheme, etc. By far the most effective and preferred method used to protect buses consists of percentage differential relaying, using either current or voltage differential relays. The differential relaying is preferred because it is fast, selective, and sensitive. The relays are available in either electromechanical or solid-state units featuring some what higher speed and sensitivity than are available in the electromechanical models. operating times of 5 to 8 ms can be achieved with solid-state bus differential relays.

3.9.2 Transformer protection

Different types of faults which affect transformers are may be due to short circuit between phase and ground open circuits, turn-to-turn short circuit or due to overheating. Interphase short circuits are rare and seldom develop as such initially, since the phase windings are usually well separated in a 3-phase transformer. Faults usually begin as turn-to-turn failures and frequently develop into faults involving ground. Differential protection is the preferred type of transformer protection due to its simplicity, sensitivity, selectivity, and speed of operation. If the current transformer ratios are not perfectly matched, taking into account the voltage ratios of the transformer, autotransformers or auxiliary current transformers are required in the current transformer.Secondary circuits to match the units properly so that no appreciable current will flow in the relay operating coil, except for internal fault conditions.

3.9.3 Voltage-load tap-charging(LTC) transformer protection

L.T.C. transformer may also be protected by the same principles of applying differential protection to other transformers. It is necessary to select the differential relay in such a way that the unbalance in the current transformer. Secondary circuits will not in any case be sufficient to operate the relay under normal condition. Therefore it is suggested that the current transformers be matched at the midpoint of the tap-changing range. In this case, for the maximum tap position in either direction, the error in the current transformer will be minimum.

3.9.4 Over current protection

This protection should be applied to transformers as the primary protection where a differential scheme can not be justified or as back-up protection if differential is used. In this scheme of protection, power-directional relays are preferred for faster relaying.

3.9.5 Transformer overheating protection

This type of protection is sometimes provided to give an indication of over temperature, rarely to trip automatically. Replica type of overload relays may be connected in the current-transformer circuit to detect overloading of the unit. Others operate on top-oil temperature, and still others operate on top-oil temperature supplemented with heat from an adjucent resistor connected to a current transformer in the circuit. This latter relay is adjusted to operate on a simulated winding hot spot temperature. To indicate winding faults which produce gas or sudden pressure waves in the oil, gas-or oil pressure relays are available for attachment to the top or side of transformer tanks. Due to short circuits in the winding, rapid collection of gas or pressure waves in the oil will produce fast operation. In united states, this type of protection has gained a great popularity.

3.9.6 Circuit-Breaker protection

Circuit breaker failure can be caused by loss of d.c. trip supply, blown trip fuses, trip coil failure, failure of break-trip linkages, or failure of the breaker current-interrupting mechanism. The two basic types of failures are:

(1) Mechanical failure and

(2) Electrical failure

In order to clear faults for these two types of breaker failure, two different schemes of protection can be employed. The more conventional breaker-failure schemes consist of using instantaneous current-operated fault detectors which pick up to start a timer when fault relays operate. If the breaker fails to operate to clear the fault, the timer times out and trips necessary breakers to clear the fault. However, if the breaker operates correctly to clear the fault, enough time must be allowed in the timer setting to ensure reset of the fault detector relay. Total clearing times at EHV Using this scheme are quite fast and usually take 10 to 12 cycles from the time of fault until the fault is cleared.

There is a faster scheme for those faults where mechanical failure of the breakers occurs. This scheme depends on a breaker auxiliary switch (normally open type 52-A contact) to initiate a fast timer. The auxiliary switch is specially located to operate from breaker trip linkages to sense actual movement of the breaker mechanism. If the breaker failure is mechanical, the breaker failure timer is actuated through the auxiliary switch when the protective relays operate. The advantage of using the auxiliary switch is the extremely fast reset time of the breaker-failure timer that can be realized when the breaker operates correctly(1,2,3).

3.10 Substation Grounding

Provision of adequate grounding in a substation is extremely important for the safety of the operating personnel as well as proper system operation. The functions of a grounding system are listed below:

(a) provide the ground connection for the grounded neutral for transformers, reactors, and capacitors.

(b) provide the discharge path for lightening rods, arresters, gaps, and similar devices.

(c) Ensure safety to operating personnel by limiting potential differences which can exist in a substation.

(d) provide a means of discharging and deenergizing equipment in order to proceed with maintenance on the equipment.

(e) provide a sufficientely low resistance path to ground to minimize rise in ground potential with respect to remote ground.

Many electrical accidents occure due to electric shock caused by accidental contact of personnel with non-current carrying metallic parts of an equipment. Therefore it is very important to design the earth mat so as to give the minimum possible resistance (less than 1.0 ohm) required for the safety of equipment and operating personnel. In view of very high short circuits to be experienced in 400 kV Substations an effort should be made to design the earthing system in such a way that minimum value of earth resistance is obtained. The step and touch potentials should be within safe limits. Also the problems due to transferred potential or potential gradient in the vicinity of the substation should be examined carefully(1,2,3).

3.10.1 Design of Earth mat

In designing the earth mat following factors are to be considered:

(i) Magnitude of fault current

(ii) Duration of fault current or fault clearing time

(iii) Soil resistivity of the area

(iv) Resistivity of the material

(v) Materials of earth electrode

The size of the earthing conductor is determined by considerations of potential difference and temperature rise. The approximate formula for determining the size is given below:

$$\frac{A}{I} = \left[\frac{4050\, \rho\, \alpha t}{\delta\, S\, \mathrm{Log}\, \frac{1+\theta_m}{1+\theta_e}} \right]^{1/2}$$

where,

A = cross section in circular milt.

I = current in amperes

α = resistance temperature coefficient of material in per $^{\circ}C$.

t = time in seconds during which current is applied.

δ = density of material in gm/cm^3

S = specific heat of the material in $cal/gm/^{\circ}C$

θ_m = maximum allowable temperature in $^{\circ}C$

θ_e = ambient temperature in $^{\circ}C$

ρ = resistivity of material in micro ohm-cm.

The values of various constant in the above equation as applicable for steel are given below

α = 0.00423 per ^{o}C

t = 3 seconds

δ = 7.86 gm/cm^3

S = 0.114 cal./gm/^{o}C

θ_m = 900^{o}C for brazed joints
500^{o}C for bolted joints

ρ = 15.0 micro ohm-cm

θ_e = taken as 40^{o}C

Substituting the values of constant, the size of earth mat-conductor is given by:

A(steel) = 26 x I x $\sqrt{t}$ for bolted joints

= 21.6 x I$\sqrt{t}$ for welded joints.

The permissible values of step and touch potentials are given by the formulate::

$$E_{step} = \frac{165 + \rho_s}{\sqrt{T}} \text{ Volts}$$

$$E_{touch} = \frac{165 + 0.25\rho_s}{\sqrt{T}} \text{ Volts}$$

where $_s$ soil resistivity in ohm meters just beneath the feet of person (usually taken as 3000 ohm meters for crushed rock)

T = fault clearing time in seconds

The resistance of the earth mat is given by

$$R = \frac{\rho}{4r} + \frac{\rho}{L}$$

where, R = Resistance in ohms

ρ = Soil resistivity in ohm meters

r = equivalent radius of the substation area in meters

L = Total length of buried conductor in meters.

Another important point to be examined is whether the design is safe for sustained ground current which should be below the let go value of the body current (taken as 9 milliamperes) which gives the value of E_{touch} as follows:

$$E_{touch}(\text{sustained}) = R_K + 3/2\ \rho_s)\text{x}\ 9/1000 \text{ Volts}$$

where, R_K = Body resistance taken as 1000 Ohms.

ρ_s = Soil resistivity below the surface of the feet.

The mesh potential of the grid should be less than the

$$E_{touch} = \frac{K_m K_i \rho I}{L} \text{ Volts}$$

K_m = Factor depending upon the size, spacing, depth and number of parallel grid conductors.

K_i = Irregularity factor (0.65 + 0.172 n) n being number of parallel conductors.

In all the substations provisions are made for earthing the following preferably by duplicate earth connections.

(1) Equipment Frame work and other non current carrying parts.

(2) All the metallic structures and supports.

(3) Neutral point of each transformer or separate system.

(4) Lighting arresters. These are usually provided with independent earth grid which in turn is connected to main grounding grid.

(5) Substation fence earthed at regular intervals.

(6) Transformer rail track.

It is common practice to cover the area of switchyard with about 10 cm(4 in.) of gravel or crushed rock which helps in making the area safe for operating personnel against hazard due to shocks(1,2,3,5,6).

3.11 Substation auxiliary facilities

Besides the main equipment as discussed before, following auxiliaries, equipments and services have to be provided within a substation:

(1) Shielding against lightening by overhead shield wires or masts

(2) Compressed air supply.

(3) A.C. auxiliary supply

(4) O.C. auxiliary supply

(5) Illumination of switchyard and control room

(6) Facilities for oil filteration

(7) Fire fighting equipment

(8) Overhead travelling crane

(9) Power and control cables

(10) Carrier Communication equipment.

CHAPTER-4

E.H.V. SUBSTATION DESIGN CRITERIA

One of the important factor which influence the design of substation is consideration of technoeconomic criteria which involves that the design should provide a high level of service continuity as well as provision for further expansion, flexibility of operation and low initial and ultimate cost. Means should be provided for maintaining lines, breaker and switches with no service interruptions or hazard to personnel. The physical orientation of the transmission-line routes often dictates the substations'location and bus arrangement. The selected site should be such that a convenient arrangement of the line can be accomplished. For reliability the substation design should prevent total substation shutdown caused by breaker failure or bus faults and should be such as to permit rapid restoration of service after a fault occurs. The object of this chapter is therefore to define criteria for the design of substations and to review some of the published articles on this work. An attempt is made to collect and define the technical and economic criteria affecting the choice of substation designs. Further the details of a suitable method to evaluate the mathematical models, e.g., tie-set and cut-set method have also been discussed. This survey has been restricted to transmission substations. Detailed consideration of substation associated with generating station is excluded from this review as they are often more complicated and their number is fewer than the first mentioned. The technical and related criteria regarding substation designs are briefly described here.

4.1 Technical and Related Criteria

When choosing a substation design many technical and related criteria must be considered some of the important points related to these criterias are reviewed as follow:

4.1.1 Technical criteria

(a) Operational flexibility: In the operation of a substation, flexibility is concerned chiefly with the possibility of achieving the various different switching arrangements which may be required and the case of changing from one arrangement to another as in the case of inverted bus arrangement as already has been explained in article

(b) Limitation of short circuit levels - It may be necessary to divide the substation into two or more parts to limit the short circuit current if it is necessary. To achieve this and the required operational flexibility, simple arrangement such as single bus bar must be excluded.

(c) Protection arrangement - In case of simple arrangement few current and voltage transformers are required which therefore result in reducing the number of possible fault-sources. But in the case of very complicated arrangement, switching of protection devices are required for changing the power flow which therefore result in increasing failure possibilities.

4.1.2 Related criteria affecting design

(a) Maintenance - The relevant technical criteria for the layout of substation are:

- which part of the substation must be taken out of service and for how long The security of the system is there by affiected.
- Is it necessary to switch in spare units without interruption or is some outage time permissible In the latter case relatively simple means can be used, such as by-passing a circuit-breaker to permit its maintenance.

Another important question affecting maintenance is the proximity of live equipment. The design of the substation has a large influence, for instance the otherwise very useful arrangement of separated phases hampers maintenance work. The need for special transport, access and lifting devices, and the layout of transport routes will be affected by the substation design.

(b) Required Land Area: The requirements for selection of the land area in a substation are, width, length and height from technical criteria only under certain conditions, such as very poor-sub-oil or steeply sloping or uneven ground. The required land area may however present economic or other problems, should land be very expensive.

(c) Ease of Extension - Another technical criteria regarding design is the feasibility of extending an existing substation. If there is an unforceen rise in the demand for electrical energy in the locality this point will be important. The space for, and technical feasibility of an extension is important and also, whether it is possible to extend with only minimal shut-down of the existing substation.

(d) Environment - Selection of site for the substation has an influence on its technical design. For example, the sites near to and subjected to a prevailing wind from the sea, other heavy atmospheric polution or areas threatened by earth-quake. These negative influences can be overcome by technical means or, at least, their effects diminished. On the other hand the substation itself may be considered to have a deleterious effect on the environment and this must be minimised as for as is practicible polution of the sub-soil and noise are two well known pollutants but it may also be necessary to adjust the substation design to the locality from an aesthetical point of view. This adaption will probably play in increasing role in the future and will be a technical criteria when, for example, determining the permissible hight of substation.

4.2 Economic Consideration

One of the primary requirements of a good substation is that it should be as economical as possible, which is particularly important at present keeping in view the rising costs of materials and labour and the comparatively large programme for expansion of transmission and distribution facilities.

In consideration of costs, it is necessary to differentiage between the capital cost and running cost. The latter consists mainly of maintenance costs and amounts in general to an annual cost of 2-3 percent of the capital cost[17]. Further consideration of running costs is therefore omitted from this part, and attention is concentrated on capital cost. Before going into details, the basic assumption is elimination of costs for acquiring the land. In some cases the cost of the land approaches that of the total installation, thus swamping the relative costs of different technical solutions. In all countries prices have increased over the past few years so that the year of erection might have a significant influence on the cost of a substation of a particular type. Furthermore comparisons on an international level have taken into account currency problems. It is better, therefore to base comparisons on another criterion. One method is to establish the cost in each country for one particular design as 100 percent and then compare the relative costs of other designs. In many countries the arrangement with double busbars is the most widely used and therefore provides a suitable basis. Of course, it is appreciated that some countries do not use double busbar and that substation arrangement vary in different countries, but the arrangements considered are the most common. In order to establish a medium of comparison it is assumed that each substation is equipped with:

4 bays for line circuits

2 bays for transformer circuits

Table(4.1)

Relative costs of outdoor, Air Insulated substation[18]

Diagram	type	Maximum Service Voltage		
		110/170KV	245/300 KV	420 KV
Figure 2.1	Single bus	73	75	72
2.2	Sectionalised single bus	74	76	74
2.4	Single bus with by-pass bus	98	98	98
2.7	Ring bus	-	88	-
2.6	Duplicate bus	100	100	100
2.5	Duplicate bus with by-pas bus	112	112	111
-	Multiple bus	113	112	-
2.8	One and-a-half circuit breaker	-	-	115

1 bay for coupling or sectioning

Each substation is telecontrolled and the necessary equipment is included in price. The results obtained from an international questionnaire are given in Table (4.1).

Bearing in mind that these figures are mean-values, some trends can be recognized. Single-bus design (Fig.2.1) costs about 70 percent of double-bus system (Fig.2.6). Single bus system with by-pass(Fig.2.4) is however only a little cheaper than double-bus(Fig.2.6), whereas double bus with by-pass (Fig.2.5) and multiple bus are about ten percent more expensive.

When analysing costs it is very important to know the influence of the cost of the main components. An investigation carried out for this purpose gave the following results:

Table(4.2)

Influence of the cost of main equipments and components in a substation[18].

1	Cost for high-voltage-equipment	48
2	Cost for structual and supporting material as well as structual work above and below ground level	26
3	Cost for protection, measurement devices and telecommunication	16
4	Cost for assembly	10

The figures are averages for a substation with double busbars 110-170 KV(17,18).

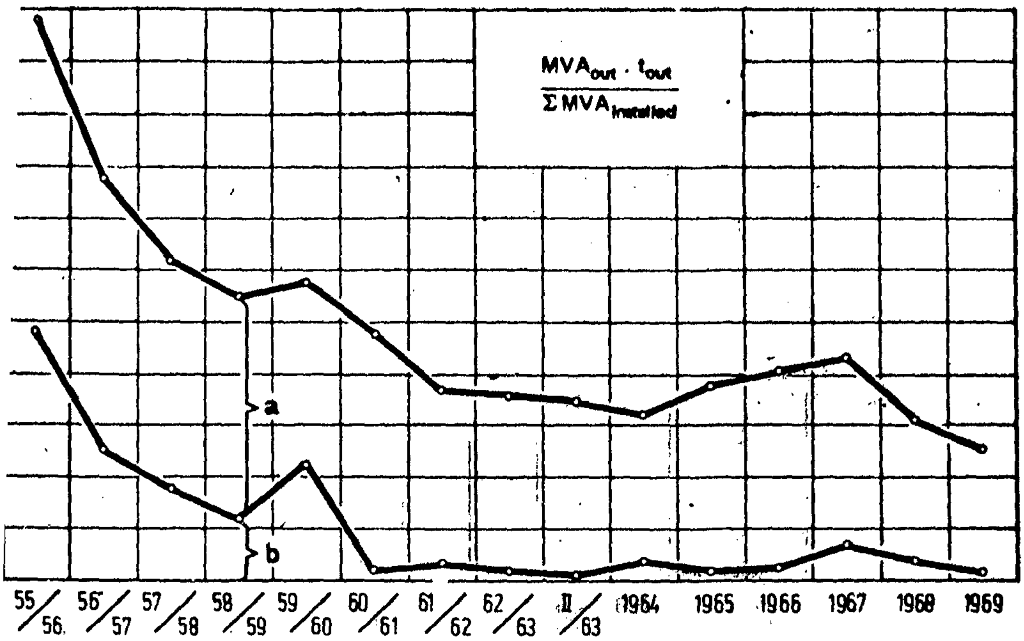
It is clear that the main part of expenditure for a substation lies in high-voltage equipment and structural work and material on the other hand account must be taken of the probable increase of the proportion of costs for protection and telecommunication equipment in the future.

4.3 Reliability as a Criterion for Substation Design

High reliability value of a power system is of utmost importance in the developed countries, now a days, the reliability of power system is so high, that it might seem unnecessary to discuss whether the value is equal to 99.99 percent or 99.999 percent. In other words the outage time of power system is extremely low. Fig (4.1) shows as example the improvement of the outage time in the grid of the Federal Republic of Germany after the second world war[17]. One can recognize from the diagram that the main part of outage time arises in the intermediate voltage level (6 KV to 30 KV) whilst that of the high voltage (110 KV and higher) is very small. This example is confirmed by experience in Great Britain which shows that in highly integrated network faults at higher voltages have little effect on supplies to consumers:

Percentage of faults causing interruptions of supply for the year 1970/71(18):

132 KV	11.0 %
275 KV	0.9 %
400 KV	0.6 %



ıre4.1 – Outage time of the total capacity of transformers, alled in the intermediate voltage grid of the Federal ıublic of Germany

a) failure in the intermediate voltage grid

b) failure in the high voltage grid

In a study conducted by Devenport et al.[18], it has been shown that the existance of higher voltage networks tends to restrict lower voltage system to a distribution function with a corresponding influence on substation design. The important criteria for higher voltage transmissions, e.g. flexibility becomes less important whereas the influence of the substations on the reliability of supply to the consumer increases. Study of distribution networks reveals that substation arrangements are simpler (e.g. single bus), than for transmission networks. Furthermore, as the supply approaches the consumer there is less provision for alternative supply. Thus it can be stated that the higher the voltage the lower the significance of reliability of supply to consumers.
In the same study, it is mentioned that out of 181 faults of all types on a 400 KV system in Great Britain over a period of 5 years only one caused interruption of supply and that fault was not in a substation. Even so, there were only 45 component failures in 400 KV substations. In such networks improved reliability of substations will have little effect on reliability of supply to consumers. Greater reliability is neverthless desirable and the benefits will include:

(1) The opportunity to simplify and cheaper the layout and equipment, including protection inside the substation.

(2) Net-work stability

(3) Optimization of generation and distribution cost

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(4) Flexibility of alternative connections between generators and network due to substation arrangement.

(5) Greater security for generators.

Although the functions of substations controlling generators are •omplex it can be readily appreciated that there is a direct relationship between reliability of substation components and the security of generators.

4.3.1 Theory of reliability applied to substations

The basic characteristic and methods of reliability analysis as applicable to substation are discussed briefly in this review. A suitable method to evaluate the mathematical models, e.g. tie and cut-set method has been discussed in detail.

(a) Reliability characteristics - The reliability of a system is determined by:

(i) The function of the components of the system and the function of the compoents in the system.

(ii) The failure and repair rate of the components.

In our case the substation is the system. The components of the system are the circuit breakers, the disconnect switches, bus bars, etc. The function of the substation is given by the scheme and the operation mode.

The failure rate of a component characterizes its reliability. The repairability to defined by its repair rate . In general, and are dependent on the operating age of the component and the stress applied during that time. As an example Fig(4.2) shows the failure rate as a function of age for electronic components (bathtub-curve)[17]. Similarly curves seem to be applicable for substations as in the next chapter will be shown.

In practical applications, constant failure and repair rates are assumed for several reasons. These assumptions are permissible if no wear-out is present, or if preventive maintenance is scheduled in order to prevent wear-out.

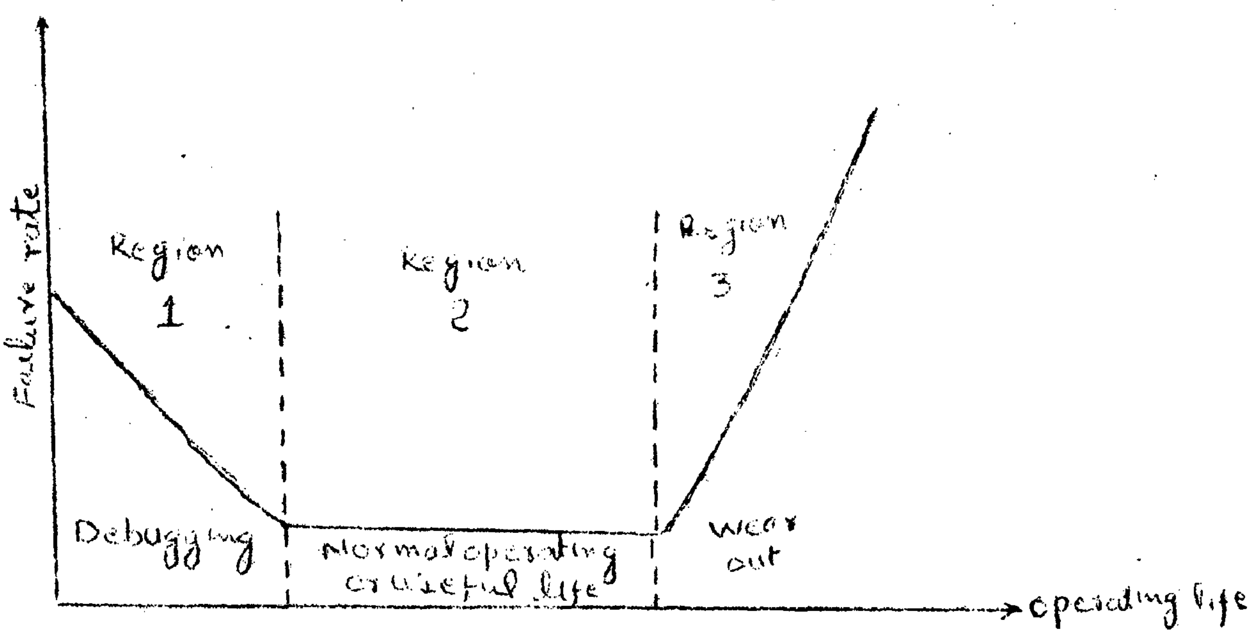


Fig (4.2) - Typical Electronic Component Failure Rate as a Function of Age[17].

A failure rate (t) can also be defined for a system. This system failure rate is generally time dependent even if the compoent failure rates are constant system function, failure and repair rate is the input of any advanced reliability analysis.

(b) Methods of reliability system analysis and system design

A reliability system analysis is performed according to the following steps:

(i) Defining the reliability goals and corresponding reliability characteristics.

(ii) Failure mode and Effect Analysis(FMEA), development of physical reliability models, determination of the failure and repair rates.

(iii) Choice of mathematical reliability models with a corresponding symbolic representation, e.g. reliability block diagram.

(iv) Choice of a suitable method to evaluate the mathematical models, e.g. tie and cutset method or Semimarkove process.

(v) Evaluation of the mathematical models and discussion of results.

In the following section, the tie-set and cut-set method has been discussed in detail.

4.3.2 Cut-set and tie-set method[11]

Avery efficient method for computing the reliability of any system not containing dependent failures can be developed from the properties of the reliability graph. The reliability graph consists of a set of branches which represent the n elements. There must be at least n branches in the graph, but there can be more if the same branch must be repeated in more than one path. The probability of element success is written above each branch. The nodes of the graph tie the branches together and form the structure. The term tie-set rather than path is common in graph nomenclature. A tie set is a group of branches which forms a connection between input and output when traversed in the arrow direction. We shall primarily be concerned with minimal tie sets, which are those containing a minimum number of elements. If no node is traversed more than once in tracing out a tie set, the tie set is minimal. If a system has i minimal tie sets denoted by T_1, $T_2,\ldots,T_i$, then the system has a connection between input and output if at least one tie set is intact. The system reliability is thus given by

$$R = P(T_1 + T_2 + \ldots + T_i) \tag{4.1}$$

The above equation is nothing more than a more precise statement of the path tracing method.

One can define a cutset of a graph as a set of branches which interrupts all connections between input and output when removed from the graph. The minimal cutsets are a group of distinct cut sets containing a minimum number of terms. All system failures can be represented by the removal of at least one minimal cut set from the graph. The probability of system failure is, therefore, given by the probability that at least one minimal cut set fails. If we let C_1, $C_2,\ldots,C_j$ represent the j minimal cut sets and C_j the failure of the jth cutset, the system reliability is given by :

$$R_f = P(C_1 + C_2 + \ldots + \overline{C}_j)$$

are non-minimal since they are both contained in cutset C_1 using Eq.(4.2),

$$R = 1 - P(\overline{C}_1 + \overline{C}_2 + \overline{C}_3 + \overline{C}_4) = 1 - P(\overline{x}_1\overline{x}_4 + \overline{x}_1\overline{x}_5\overline{x}_4 + \overline{x}_3\overline{x}_6\overline{x}_2) \quad (4.4)$$

The reader may verify by direct expansion the fact that if T_5 were included in Eq.(4.3) or if C_3 and C_5 were included in Eq.(4.4), the algebra would become more difficult but the correct result would still be obtained.

In a large problem there will be many cut sets and tie-sets, and although Eqs.(4.2) and (4.3) are easily formulated the expansion of either equation is a formidable task. (If there are n events in a union, the expansion of the probability of the union involves $2^n - 1$ terms). One of the approximation which is useful in simplifying the computations is discussed below.

We consider the following expression and its expansion

$$P(A + B + C) = P(A) + P(B) + P(C) - P(AB) - P(AC) - P(BC) + P(ABC) \quad (4.5)$$

where events A,B, and C are made up of products of other subevents.

For the example of Fig (   ), Eq.(4.3) yields

$$\begin{aligned} R = {} & P(x_1x_2) + P(x_3x_4) + P(x_1x_6x_4) + P(x_3x_5x_2) - P(x_1x_2x_3x_4) \\ & - P(x_1x_2x_4x_6) - P(x_1x_2x_3x_5) - P(x_1x_3x_4x_6) - P(x_2x_3x_4x_5) \\ & - P(x_1x_2x_3x_4x_5x_6) + P(x_1x_2x_3x_4x_5x_6) + P(x_1x_2x_3x_4x_5x_6) \\ & + P(x_1x_2x_3x_4x_5x_6) + P(x_1x_2x_3x_4x_5x_6) - P(x_1x_2x_3x_4x_5x_6) \end{aligned}$$

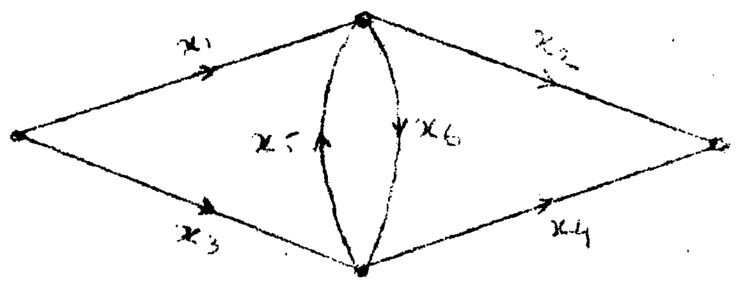
$$R = 1 - P_f = 1 - P(\overline{C}_1 + \overline{C}_2 + \ldots, \overline{C}_j) \qquad (4.2)$$

As an example of the application of cut-set and tie-set analysis we consider the graph given in Fig (4.3). The following combinations of branches are all tie-sets of the system:

$$T_1 = x_1x_2 \qquad T_2 = x_3x_4 \qquad T_3 = x_1x_6x_4 \qquad T_4 = x_3x_5x_2$$
$$T_5 = x_1x_6x_5x_2$$

Tie sets T_1, T_2, T_3 and T_4 are minimal tie sets. Tie set T_5 is nonminimal since the top node is encountered twice in traversing the path from equation (4.1)

$$R = P(T_1 + T_2 + T_3 + T_4) = P(x_1x_2 + x_3x_4 + x_1x_6x_4 + x_3x_5x_2) \qquad (4.3)$$



Fig(4.3) Reliability Graph for a Six-Element System

Similarly we may list some cut-sets of the structure

$$C_1 = x_1x_3 \qquad C_2 = x_2x_4 \qquad C_3 = x_1x_5x_3 \qquad C_4 = x_1x_5x_4$$
$$C_5 = x_3x_6x_1 \qquad C_6 = x_3x_6x_2$$

Cut-sets C_1, C_2, C_4 and C_6 are minimal. Cut sets C_3 and C_4

If all the x's are identical and independent with $P(x) = P$,

$$R = 2P^2 + 2P^3 - 5P^4 + 2P^5 \tag{4.6}$$

CIGRE Committee on substation design criteria[17], conducted reliability calculation and made use of tie and cut set method for evaluating the reliability of substation for various bus-bar arrangements. Two cases were considered (when the load was fed from one transformer and two transformers) and the results were obtained.

In the same article the improvements on the substation reliability evaluation have been suggested which are mentioned below.

4.3.3 Improvement of substation reliability evaluation[17]

(a) One of main difficulty for the evaluation of substation reliability is the deficiencies in the available failure statistics. In some countries the data available is sufficient for application to the design of substations but internationally the great differences in the bases of the statistics make it difficult, if not in possible, to use them constructively. It is clearly desirable to work towards a common basis for such statistics.

(b) For the main purpose of establishing criteria which should be capable of processing to give useful and accurate information, the acceptable and soundly based definitions are necessary. Some countries have established fault reporting (data collecting) system but each is unique and the value of comparisons of published data is doubtful. Of course, some of these systems are far from perfect. The availability of computers has only recently made it possible to process such large quantities of data and several years data must be assembled before processing can proceed with any hope of discovering useful conclusions. It is only after such processing that the shortcomings of the data become clear. The value of the processed data depends entirely on the accuracy of the stored information and also on clear definition.

(c) The data for reliability calculations should be chosen carefully so that the results obtained are realistic. The period covered by the data should not be too long as the results obtained with older designs of equipment will not be representative of future design, operation and maintenance procedures may have changed and the data collection procedures improved. The preceding five year period is suggested as a limit, the figures being adapted annually. Failure outage and maintenance experience with new designs of equipment (e.g. circuit breakers) may not be normal until several years have passed due to deething' troubles which may take several years to eradicate. As an example the fault rate for circuit-breakers on a new 400 KV system was as follows:

Mean annual fault rate	
Ist year	7%
2nd year	5%
3rd year	3.6%

Examination of subsequent data suggests that the rate will remain in the region of 3.6 percent. These results suggest that the bathtube curve (Fig 4.1) applies to substation components.

(d) The publication of reliability data can have two purposes: To demonstrate methods of analysis or use of data; To further international study means to improve the reliability of transmission systems.

If the latter above is the primary purpose, then it is necessary that the data be based on one set of criteria so that the data has a common meaning to all users. However, there are a number of reasons why, even if one set of definitions is achieved, the data will not be completely comparable. Some countries manufacture substation equipment and all or most of the transmission substations in these countries have equipment of home manufacture and therefore very little variety of types. Other countries do not manufacture and therefore purchase substation equipment from the manufacturing countries. There may be a great variety of types due to a policy of purchasing the cheapest equipment.

It is to be expected that equipment in the former category will be more reliable than that in the latter. Even with one design of equipment it is to be expected that reliability will vary in different countries depending on the quality and frequency of maintenance, the local environmental conditions and the geographical distance from the manufacturers' work.

(e) The collection, processing and analysis of fault statistics has a high cost which can only be justified by corresponding benefits, the greatest use of such information has so far been to asses the design of economic and reliable transmission and distribution system. Another use is to asses with the choice of the best substation diagram, which is the subject of this report. A third application is to improve the cost and reliability of transmission equipment such as lines, cable, transformers and switch gear.

(f) The statistical criteria relevant to substation design are as follow:

(i) Failure rate

(ii) Repair time or repair rate for all components of substation.

This information should be obtained for the following components:

(i) Circuit breakers

(ii) Load break switches

(iii) disconnectors

(iv) Earthing (grounding) switches

(v) Current transformers

(vi) Voltage transformers (wound type and capacitor type)

(vii) Surge divertors

(viii) Bus-bars

Protection equipment

Control equipment

Power transformers

CHAPTER-5

RESULT AND DISCUSSION

The economic and reliability criteria related to the substation design has been considered in detail. The approximate total costs of substations excluding the cost of land, power transformers and reactors for different bus-bar arrangements have been evaluated. The theory of reliability has been applied to the same bus-bar arrangements for evaluation of its reliability index for given values of component reliability. The relationship between substation reliability and component failure rate has also been studied. Repair time and maintenance time have not been taken into account in the calculation and only the major components are included in the analysis. A comparison of cost and reliability of different bus-bar schemes has also been discussed.

5.1 Cost Consideration

The approximate costs of different bus-bar arrangement have been estimated and shown in table(5.1). The cost for equipments and components has been collected from the U.P. electricity board. The total cost of substation includes i) the cost of high voltage equipments (excluding the cost of power transformer and reactor), ii) the structual work and material, iii) protection, measurement devices and telecommunication and, iv) the cost for assembly. For comparison

TABLE (5.1): Cost estimation of different bus-bar arrangements in lacs Rupees

Sl. No.	Particulars	Single bus	Sectionalised Single bus	Main and transfer bus	Double main and transfer bus	Double bus single breaker	Double bus double breaker	Ring bus	Breaker and-a-half
	0	1	2	3	4	5	6	7	8
1	High voltage equipments excluding power transformer and reactor	144.5	160.5	196.13	256.06	211.39	303.89	191.53	272.49
2	Structual and supporting materials as well as structual work above and below ground level	69.69	73.83	97.21	110.78	98.459	139.78	88.103	117.34
3	Protection, measurement devices and telecommunication	26.87	29.53	38.08	41.11	39.183	55.91	35.24	46.138
4	Cost for assembly	18.56	18.60	25,73	27.68	26.315	35.22	22.20	28.58
5	Total cost of substation	259.62 (70%)	282.46 (75%)	357.15 (97%)	435.63 (115%)	375.347 (100%)	534.87 (140%)	337.073 (88%)	464.548 (120%)

of different bus-bar arrangements, the cost of one particular design (duplicate bus) has been considered as the base cost i.e. 100 percent, and the other arrangements have been compared with respect to the base value. It has been assumed that the substations are having two incoming and two outgoing with the result it has been found that single bus design costs about 70 percent of double bus single breaker system. Main and transfer bus is however a little cheaper than double bus, where as double main and transfer bus is about 15 percent and that of breaker and-a-half, 20 percent costlier. These costs estimated here are quite close to the costs taken from ref.(18) as is evident in table (4.1). The cost of equipments and components given in table 4.1 are relevant to western countries. Since in India also the cost of some of high voltage equipments for example circuit breaker are quite comparable to the cost of the equipments used abroad and cost of the high voltage equipments being the dominant factor in total cost evaluation (being around 60 percent of the total), it is understandable that the relative cost of various bus arrangements are talling with international figure given in ref.(18). As it is seen that the cost of high voltage equipments are the dominant factor, it would worth-while to have these costs reduced by (i) limiting the overvoltage, (ii) judicious insulation co-ordination, (iii) development of cheaper equipment, these aspects are not however studied in detail.

It may perhaps be mentioned that the cost of high voltage transformer and reactor put together would be equal to the total substation cost. It would be worth-while to have these costs reduced by the means mentioned above.

5.2 Reliability Considerations

It was necessary to calculate the substation reliability value after considering a particular bus arrangement. The input data for the calculation of reliability would be the failure rates of individual equipments and components. This quantitative computation was done for various bus arrangements using path set and cut set method for the same number of times as in cost consideration. It was necessary to first formulate the reliability block diagrams[17], as shown in Fig(5.1-5.4). The failure rates of bus-bar, isolator and circuit breaker were used in these computations. The use of computer programme was allowed by Dr. J.D. Sharma for these calculations. The results are shown in Fig.(5.5) and in table (5.2). It is seen from Fig (5.5) that the reliability of substation having a single bus system falls too rapidly with time. Also the reliability of substation using sectionalised single bus system decreases at a faster rate beyond 10 years as compared to reliability using ring bus system or duplicate bus system. The reliability of ring bus system is higher than reliability of duplicate bus system our results tally well with those given in ref.(17).

TABLE (5.2): Reliability evaluation of different bus-bar arrangement with time periods varying from 5 years to 20 years

S.No.	Specification	System Reliability			
		5	10	15	20
1	Ring bus	0.997	0.986	0.960	0.921
2	Duplicate bus	0.996	0.980	0.950	0.909
3.	Sectionalised single bus	0.942	0.802	0.635	0.478
4	Single bus system	0.732	0.506	0.337	0.220

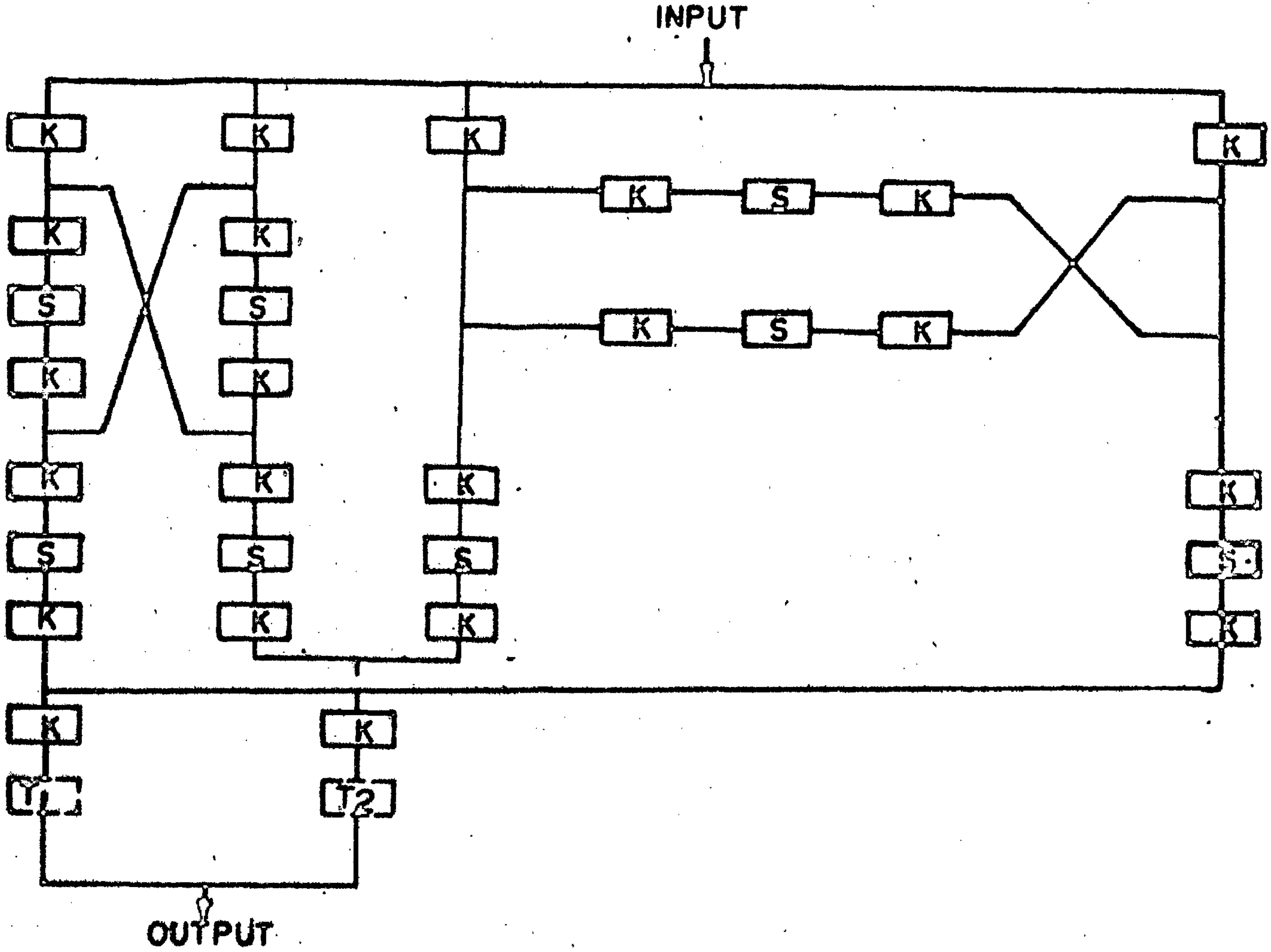


FIGURE. (5·1) RELIABILITY BLOCK DIAGRAM OF RING BUS ARRANGEMENT

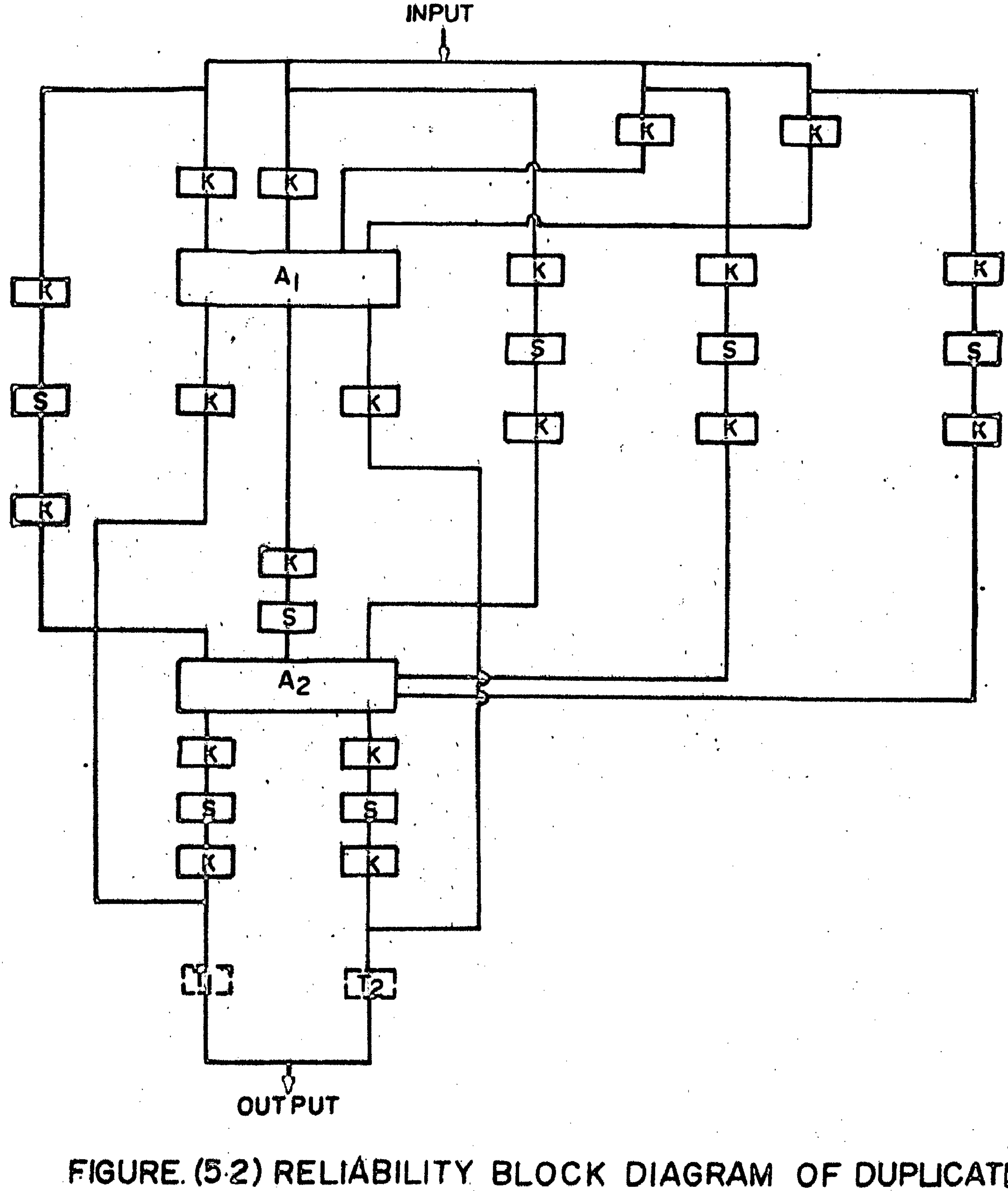


FIGURE. (5.2) RELIABILITY BLOCK DIAGRAM OF DUPLICATE BUS ARRANGEMENT.

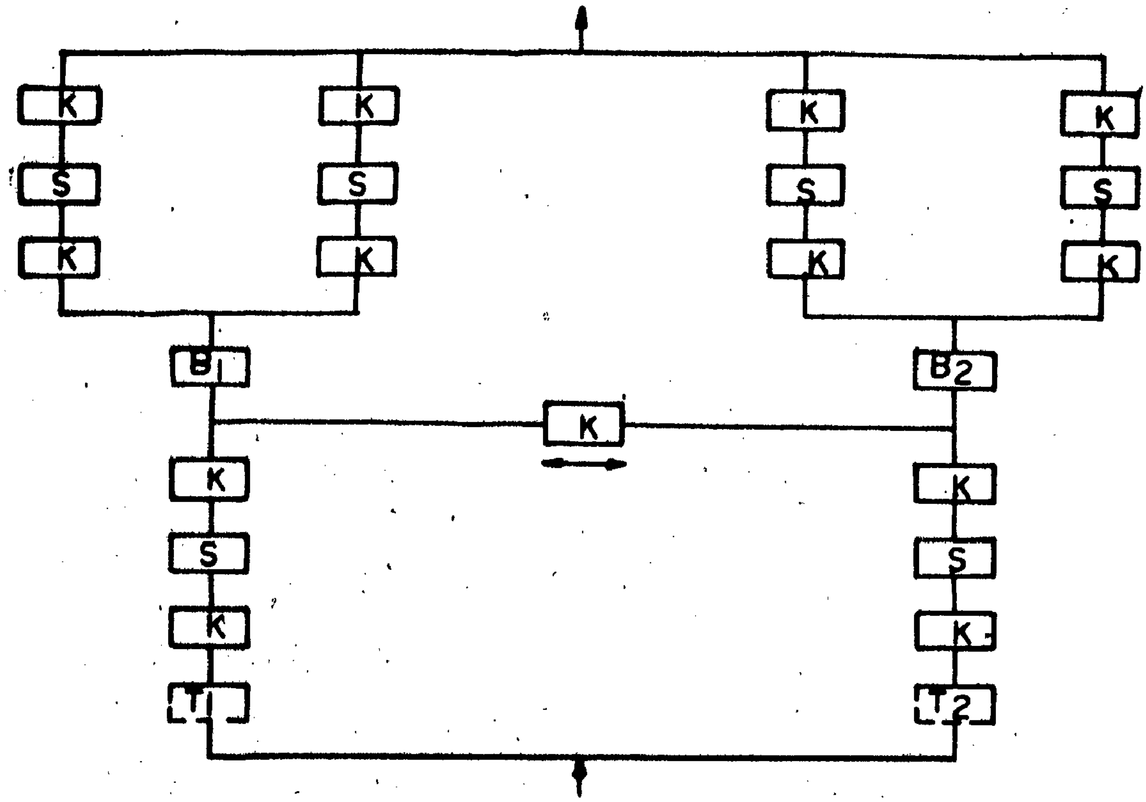


FIGURE. (5.3) RELIABILITY BLOCK DIAGRAM OF SECTIONALISED SINGLE BUS ARRANGEMENT.

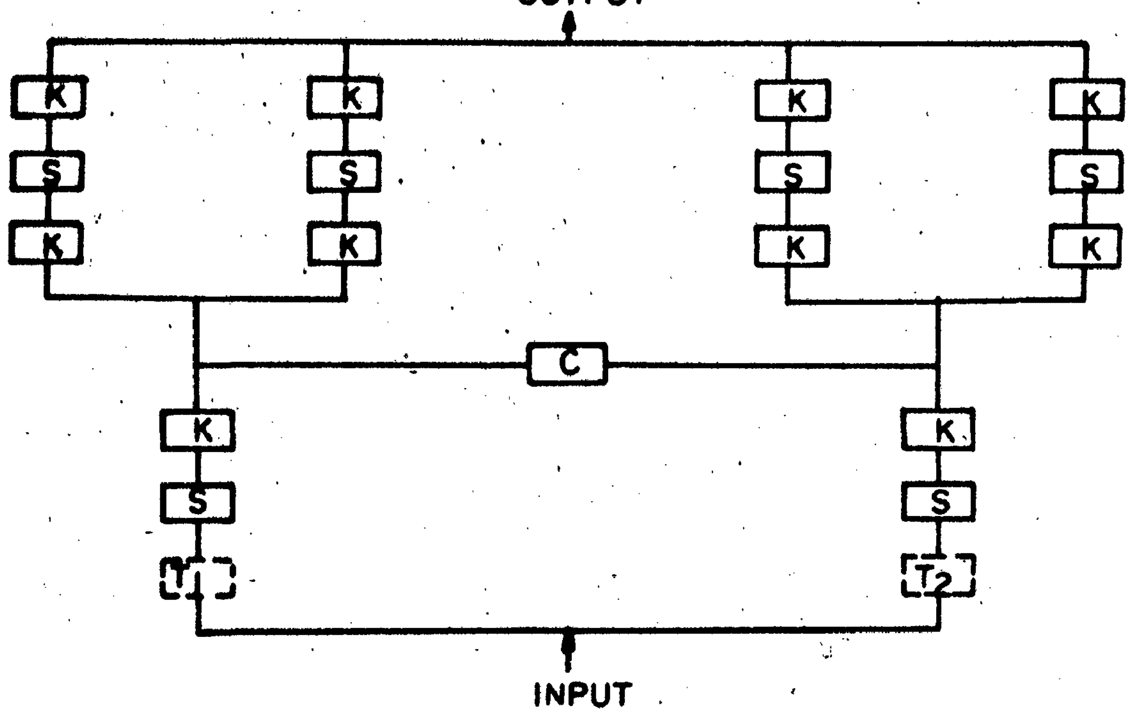


FIGURE. (5.4) RELIABILITY BLOCK DIAGRAM OF SINGLE BUS ARRANGEMENT.

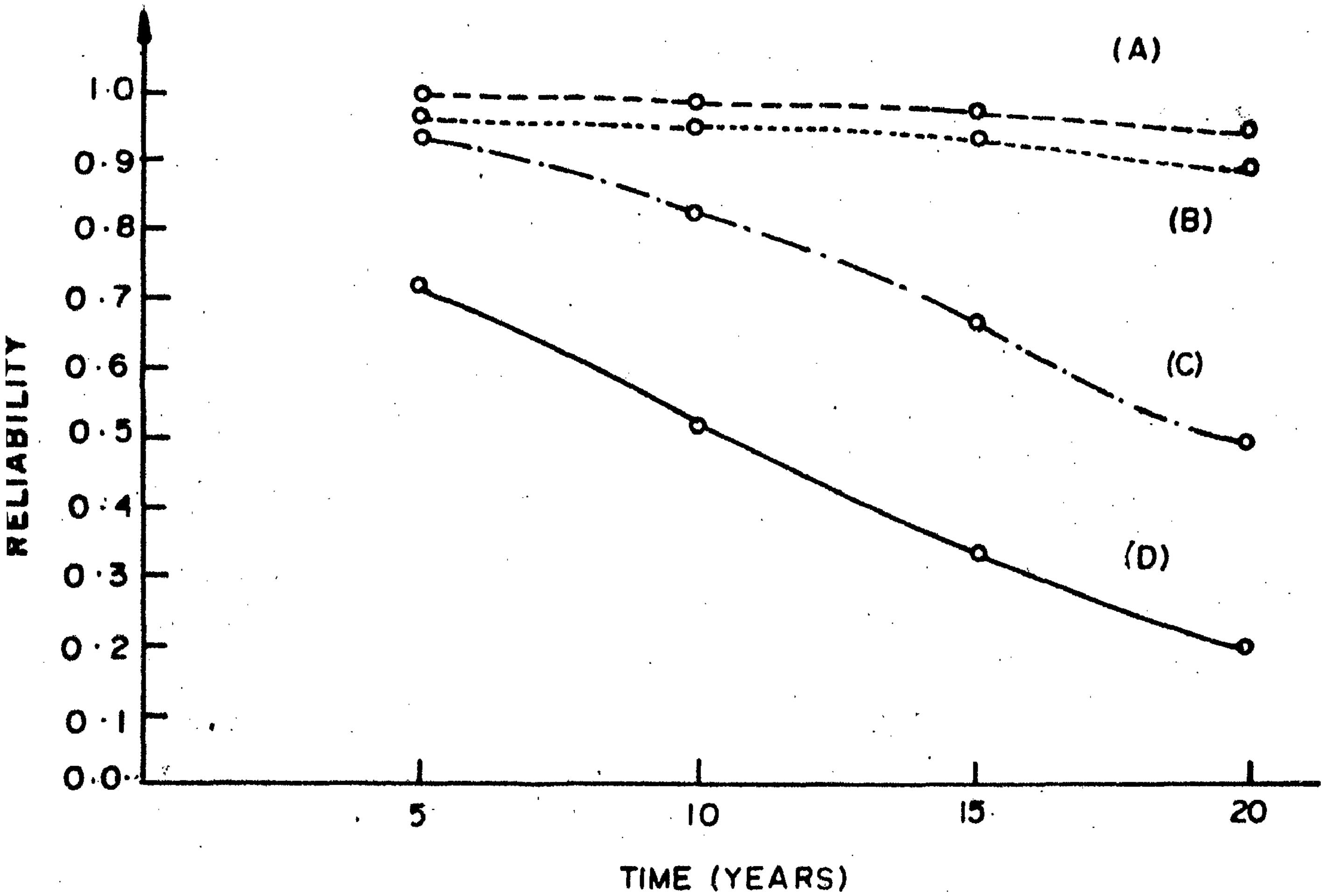


FIGURE.(5·5) RELIABILITY COMPARISON OF DIFFERENT BUS ARRANGEMENT.

(A) — RELIABILITY CHARACTERISTIC OF RING BUS

(B) — " " " " DUPLICATE BUS

(C) — " " " " SECTIONALISED SINGLE BUS

(D) — " " " " SINGLE BUS

5.2.1 Dependence of substation reliability on different Component failure rates.

It is also necessary to know the dependence of system reliability on the failure rate of individual components so that the system reliability is to be improved. It would be possible to make that improvement by lowering the failure rate of component which gives a high sensitivity to substation reliability. With the same view the dependence of reliability in substation on bus-bar, isolator, and circuit breaker failure rate was evaluated. In the following tables and graphs, is the failure rate and R is the reliability. K, S, and B, subscripts designate isolator, circuit breaker and bus-bar respectively. The reliability of various bus arrangements has been calculated for the time periods ranging from 5 to 25 years with an interval of 5 years. The computer programme for thise computations was developed and shown in Appendix (1). The reliability block diagram of a simple sectionalizes single bus arrangement used for these studies is shown in Fig (5.6). The results have been shown in Figures (5.7 - 5.12).

5.2.1.(a) Dependence of substation reliability on bus-bar failure rate

The reliability characteristics of the system corresponding to the different values of failure rate of bus-bar have been drawn and shown in Fig.(5.7). It shows the change of system reliability with respect to different values of failure rates i.e., $B_{(a)} = 0.045$, $B_{(b)} = 0.009$ and $B_{(c)} = 0.018$. As bus-bar failure rate changes, the system reliability does not show a large variation. The curves in fig (5.7) show that the system reliability is marginally sensitive to the variation in bus-bar failure rate. This is because of two sections of bus bars in the system. Even if one section fails, the remaining section of the bus-bar can be utilized. This results in an increase in system reliability and makes the system reliability less sensitive to bus-bar failure rate.

5.2.1(b) Dependence of substation reliability on isolator failure rate

The reliability of the system considering the different values of failure rate of isolator have been shown in fig (5.8). We can see from the figure that when we varry the isolator failure rate, there is a large variation in substation reliability. From the block diagram of sectionalised bus arrangement fig(5.5), we can see that the number of isolator used in the system is large and the series combination of these isolators give more sensitivity of substation reliability on isolator failure rate.

5.2.1(c) Dependence of substation reliability on circuit breaker failure rate

The system reliability corresponding to different values of failure rate of circuit breaker is shown in Fig (5.9).

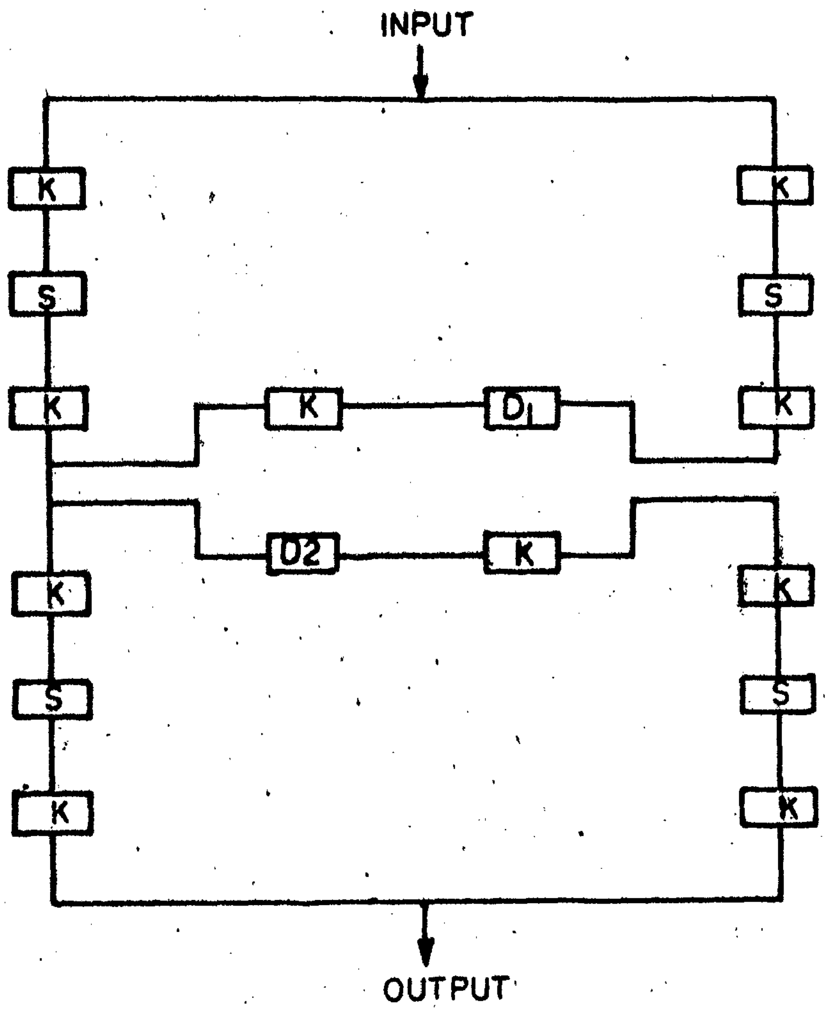


FIGURE. (5·6) RELIABILITY BLOCK DIAGRAM OF A SIMPLE SECTIONALISED SINGLE BUS ARRANGEMENT.

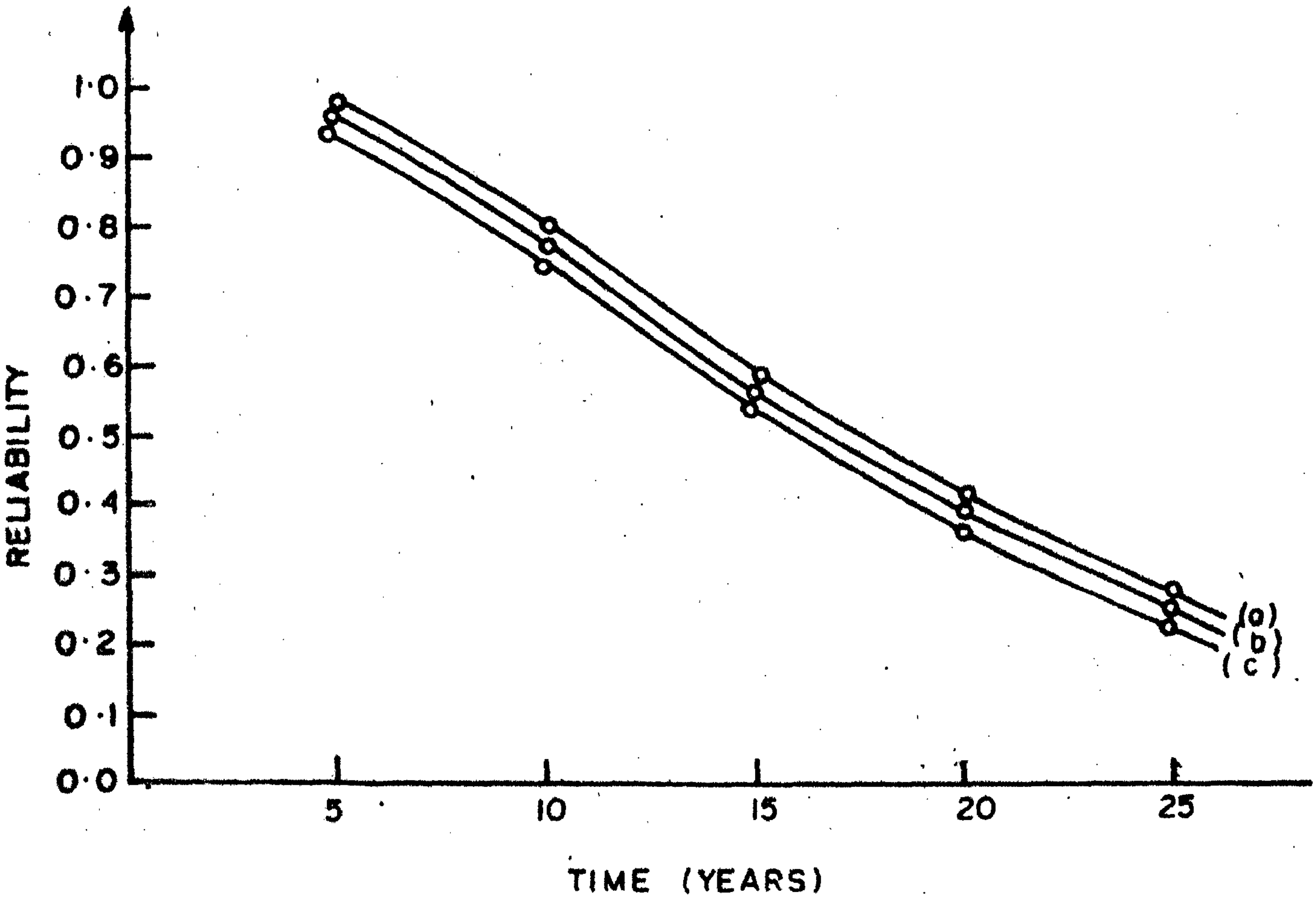


FIGURE. (5.7) DEPENDENCE OF SYSTEM RELIABILITY ON BUS-BAR FAILURE RATE.

λ_B (a) = 0·0045

λ_B (b) = 0·009

λ_B (c) = 0·018

λ_K & λ_S = 0·005 0·035

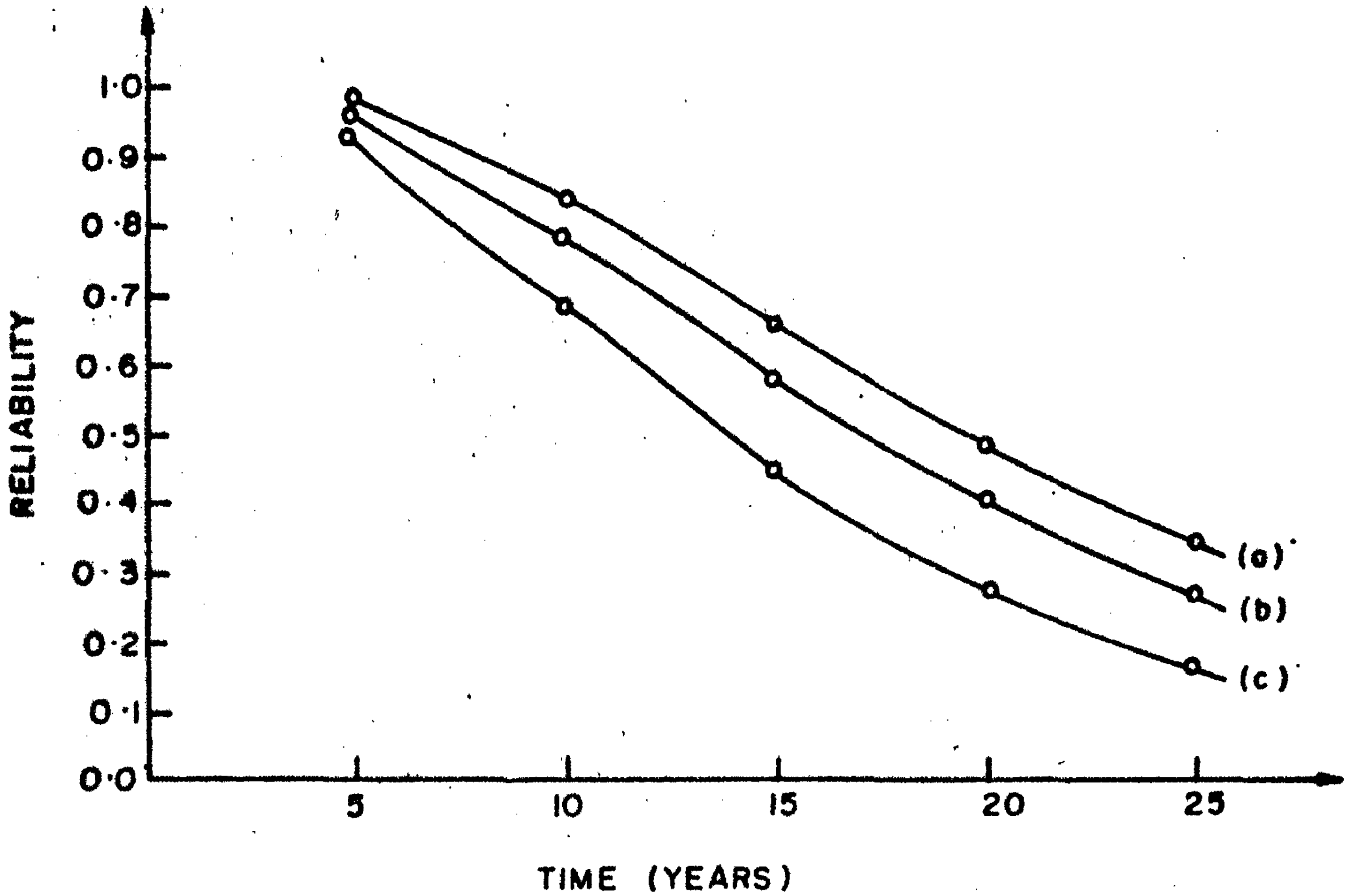


FIGURE. (5·8) DEPENDENCE OF SYSTEM RELIABILITY ON ISOLATOR FAILURE RATE.

λK (a) = 0·0025

λK (b) = 0·005

λK (C) = 0·01

λS & λB = 0·035, 0·009

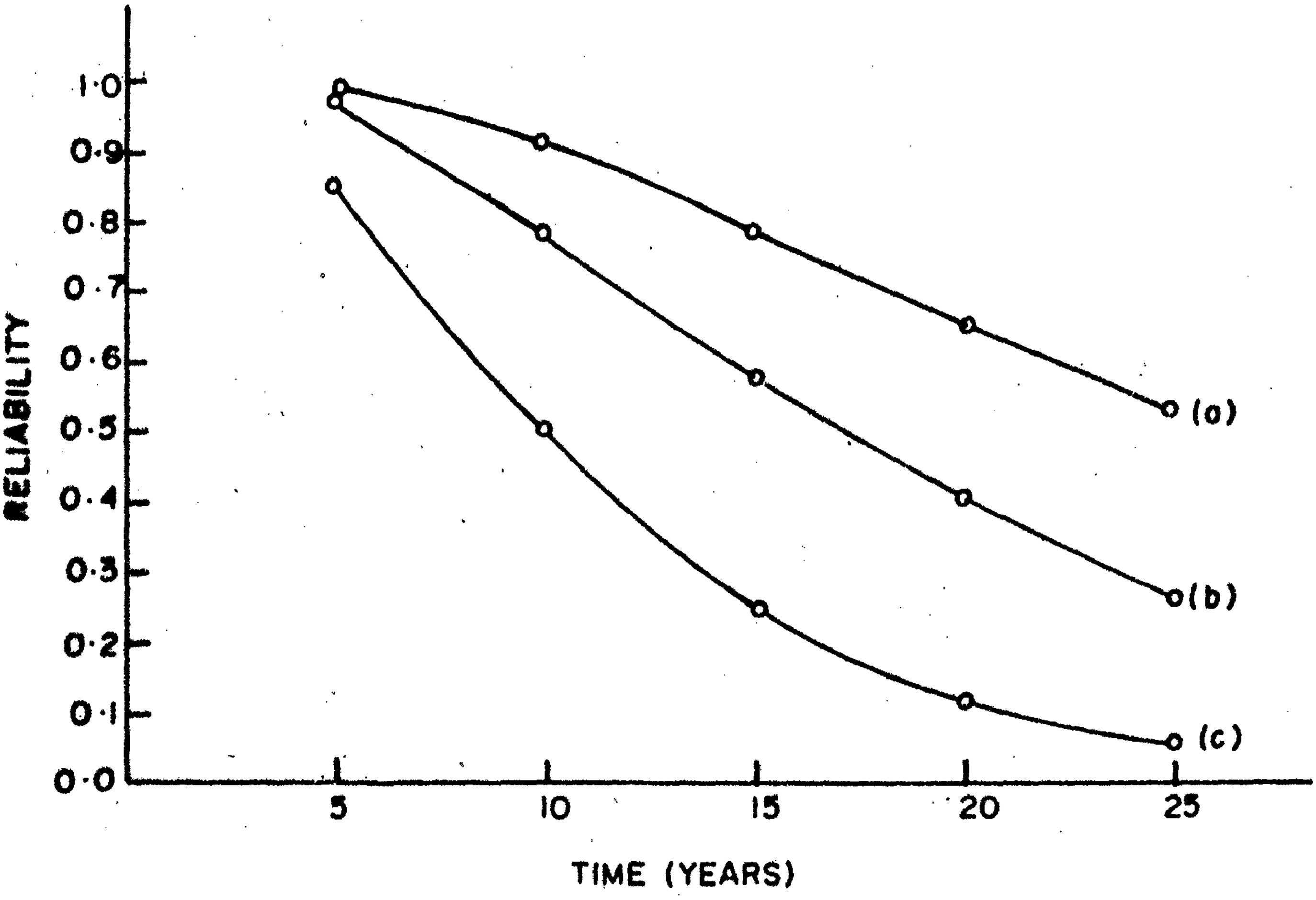


FIGURE. (5·9) DEPENDENCE OF SYSTEM RELIABILITY ON CIRCUIT-BREAKER FAILURE RATE

λ_S (a) = 0·0175

λ_S (b) = 0·035

λ_S (c) = 0·07

λ_K & λ_B = 0·005, 0·009

It shows that the system reliability is more sensitive because of higher value of circuit breaker failure rate. From the graph we can see that when the failure rate of circuit breaker is high the decrease in substation reliability is very sharp. This is because of series combination of high failure rate of component.

5.2.2 Dependence of reliability of two different bus arrangements on component failure rate

The variation of component failure rate gives different sensitivity of variation of substation reliability for different bus bar arrangements. Comparative study on this aspect was conducted on sectionalised bus and double bus arrangement. The reliability of system have been calculated after 15 years. From the table (5.3) and Figures (5.10-5.12), it can be observed that duplicate bus arrangement (A) is less sensitive to the failure rate of different components i.e. bus-bar, isolator, circuit breaker, than sectionalised single bus arrangement. The sectionalised bus arrangement is more sensitive to the failure rate of circuit breaker as compared to failure rate of isolator and bus-bar.

5.3 Most economical bus arrangement

The relative cost and reliability for various bus-bar arrangements of 400 KV substation have been calculated and given in table (5.4). It shows the cost of single bus arrangement is least as compared to other arrangements and its reliability is minimum. This is an undesirable failure

TABLE (5.3): Dependence of Two different system reliability on component failure rate.

S.No.	Specification	Component Failure Rate K	S	B	Reliability 15 Years
1	SECTIONALISED SINGLE BUS	0.0025	0.035	0.009	0.691
		0.005	0.035	0.009	0.635
		0.01	0.035	0.009	0.525
		0.005	0.0175	0.009	0.805
		0.005	0.035	0.009	0.635
		0.005	0.07	0.009	0.352
		0.005	0.035	0.0045	0.661
		0.005	0.035	0.009	0.635
		0.005	0.035	0.018	0.588
2	DOUBLE BUS	0.0025	0.035	0.009	0.957
		0.005	0.035	0.009	0.950
		0.01	0.035	0.009	0.934
		0.005	0.0175	0.009	0.969
		0.005	0.035	0.009	0.950
		0.005	0.07	0.009	0.913
		0.005	0.035	0.0045	0.976
		0.005	0.035	0.009	0.950
		0.005	0.035	0.018	0.890

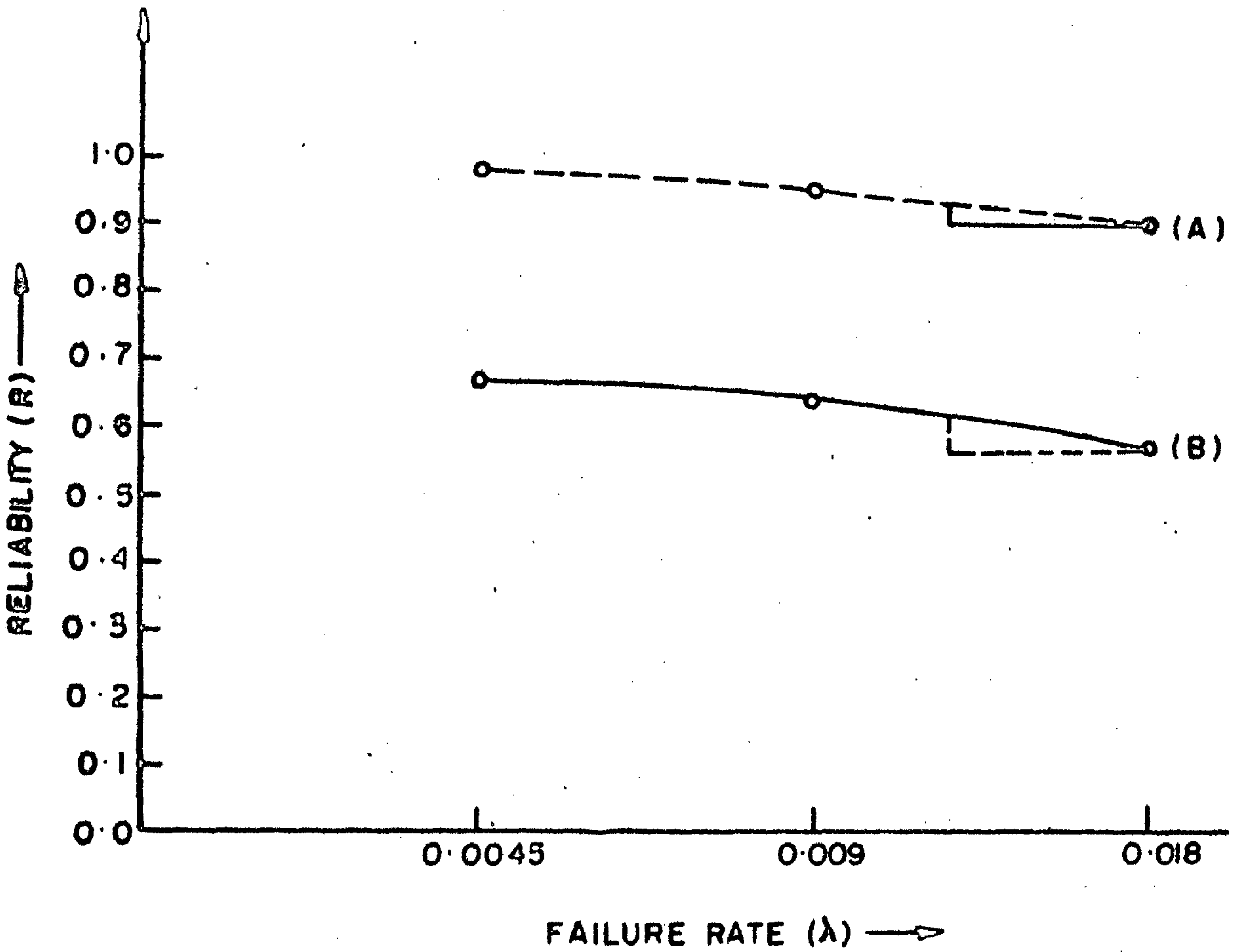


FIGURE. (5·10) DEPENDENCE OF - RELIABILITY OF TWO DEFFERENT ARRANGEMENT ON BUS BAR FAILURE RATE

λB_1 = 0·0045
λB_2 = 0·009
λB_3 = 0·018
λk = 0·005
λs = 0·035
λT = 15 Years

(A) = DUPLICATE BUS SYSTEM
(B) = SECTIONALISED SINGLE BUS SYSTEM
λK = ISOLATOR FAILURE RATE
λB = BUS-BAR FAILURE RATE
λT = FAILURE TIME

(I·V)

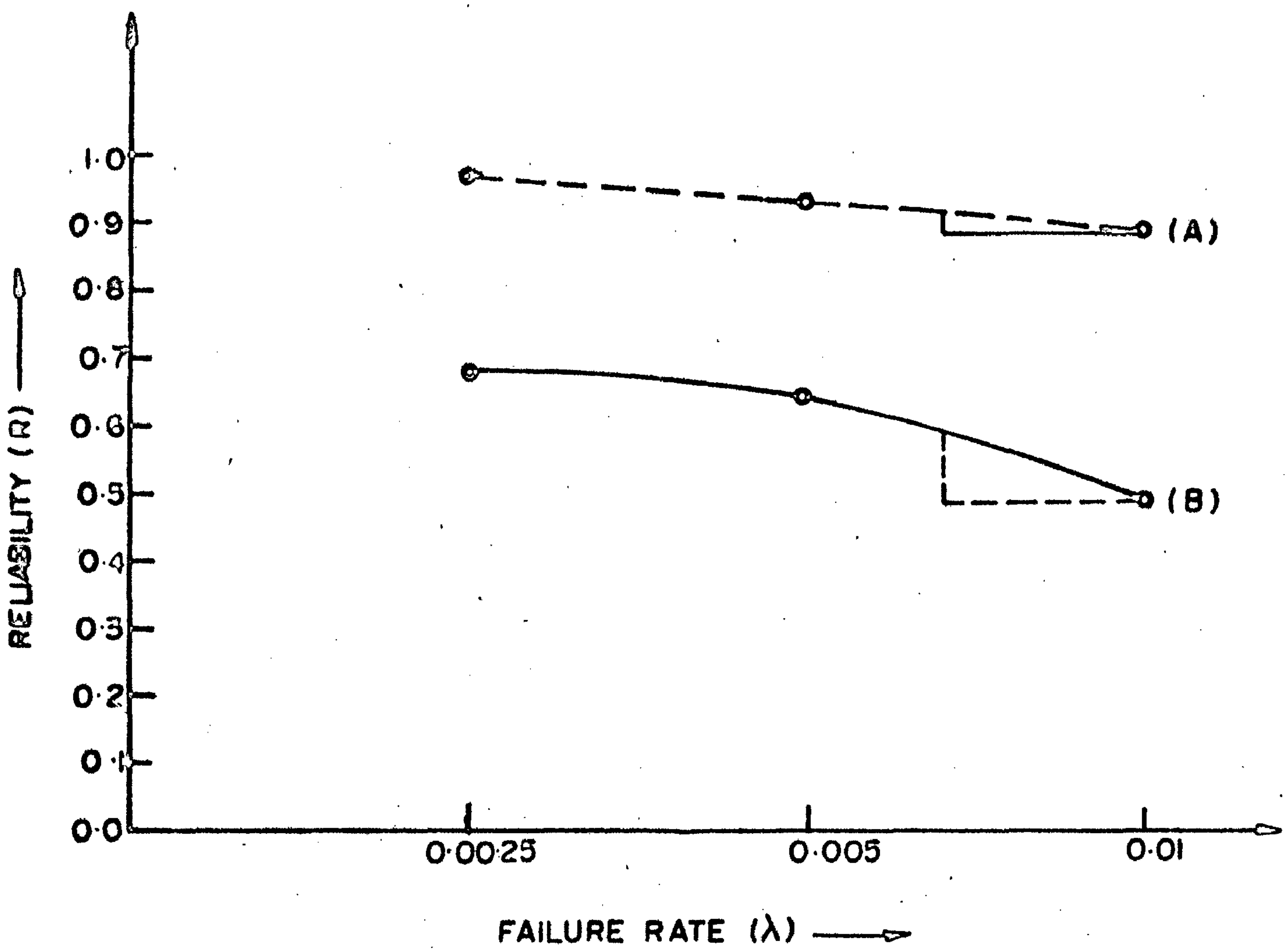


FIGURE.(5·11) DEPENDENCE OF RELIABILITY OF TWO ARRANGE-
-MENT SYSTEMS ON ISOLATOR FAILURE RATE.

λ_{K_1} = 0·0025	(A) = DUPLICATE BUS SYSTEM
λ_{K_2} = 0·005	(B) = SECTIONALISED SINGLE BUS SYSTEM
λ_{K_3} = 0·01	λ_K = ISOLATOR FAILURE RATE
λ_S = 0·35	λ_S = CIRCUIT BREAKER FAILURE RATE
λ_B = 0·009	λ_B = BUS-BAR FAILURE RATE
λ_T = 15 Years	λ_T = FAILURE TIME.

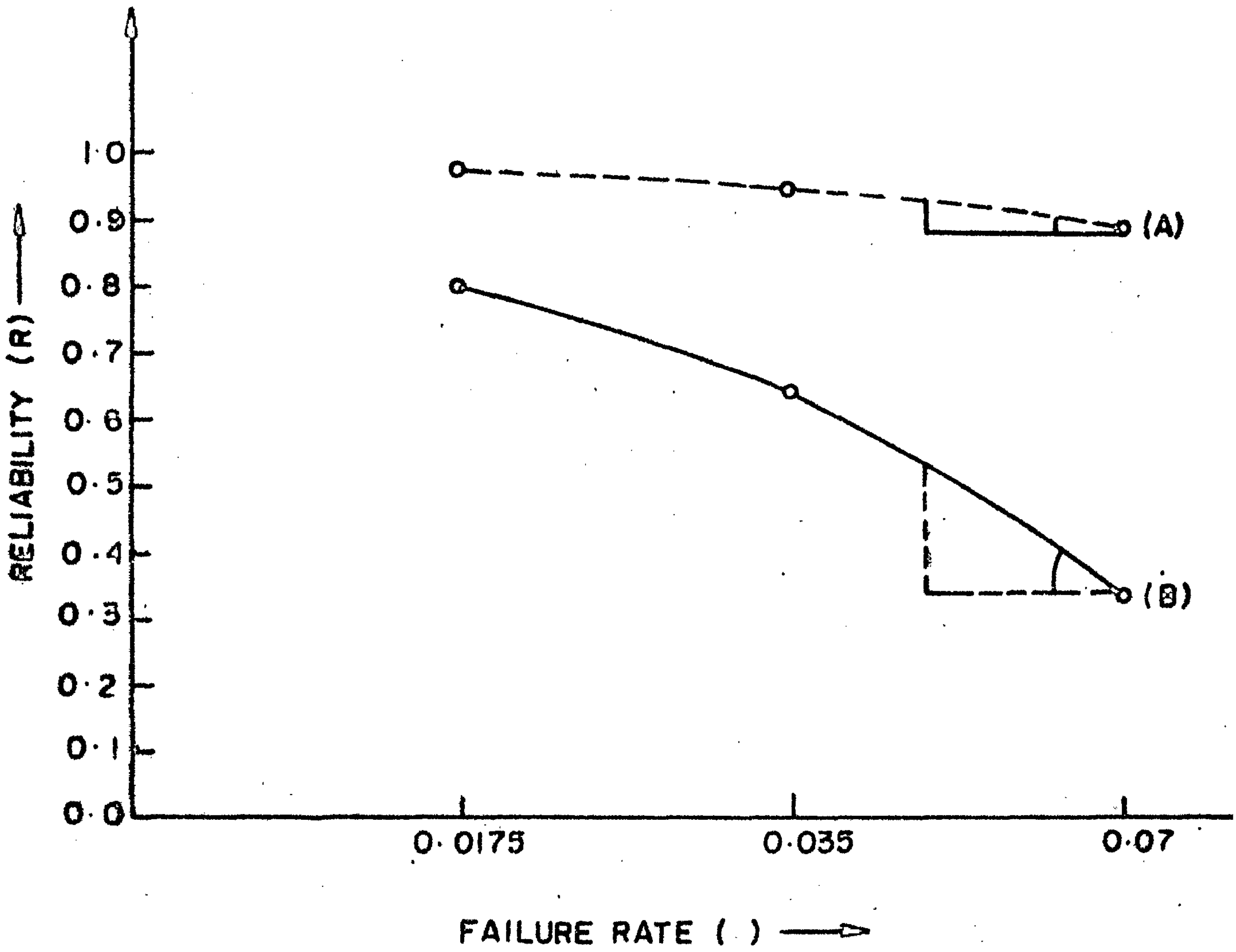


FIGURE. (5·12) DEPENDENCE OF RELIABILITY OF TWO DIFFERENT ARRANGEMENTS ON CIRCUIT BREAKER FAILURE RATE.

λ_S = 0·0175	(A) I DUPLICATE BUS SYSTEM.
λ_S - 0·035	(B) - SECTIONALISED SINGLE BUS SYSTEM
λ_S = 0·07	λ_K - ISOLATOR FAILURE RATE
λ_K - 0·009	λ_S - CIRCUIT BREAKER FAILURE RATE
λ_B - 0·009	λ_B - BUS-BAR FAILURE RATE
λ_T = 15 Years.	λ_T - FAILURE TIME

of single bus arrangement.

The ring bus system has got the higher cost compared to the sectionalised single bus, but its reliability, (R = 0.635), is higher as compared to sectionalised bus, (R = 0.635), which is an advantage over previous arrangement. In the case of duplicate bus arrangement, the cost is maximum and its reliability (R = 0.950), is lesser as compared to the ring bus arrangement. The reduction in reliability of ring bus arrangement with passage of time is least. Its reliability is always more than any other system in the time periods varying from 5 years to 20 years. The cost and reliability of this system is more than that of sectionalised bus, but in the long run (after 20 years) the reliability of sectionalised single bus system is 49 percent, while the reduction in ring bus system is only 10 percent. Hence it can be seen that ring bus is the most economical arrangement.

TBALE (5.4): Relative cost and reliability for various bus-bar arrangements of a 400 KV substation

S.No.	Particulars	Cost	Reliability			
		400 KV w.r.t table(5.1) (percent)	5 Years	10 Years	15 Years	20 Years
1	Ring bus	88	0.997	0.96	0.96	0.921
2	Duplicate bus	100	0.996	0.980	0.950	0.909
3	Sectionalised single bus	75	0.942	0.802	0.635	0.478
4	Single bus	70	0.732	0.506	0.337	0.220

CHAPTER-6

CONCLUSION

1. The relative cost of substations considering various bus arrangements are the same in Indian Conditions as in other western countries.

2. Taking the double bus arrangement as base, single bus arrangement is the lowest, but its reliability is also the lowest. Therefore this cheapest option can not be acceptable for EHV substations even though lowering the reliability in EHV interconnected system does not bring about a much reduction in reliability of supply to consumers as the lowering of reliability of distribution sub-stations would.

3. The relative cost of ring main system is considerably lower than all other options that is breaker and-a-half, double bus double breaker, double bus single breaker, double main and transfer bus and main and transfer bus:

4. From the reliability point of view, the ring bus system has the highest reliability after five years as well as after 20 years in comparison to other systems.

5. The reliability values of ring bus and duplicate bus arrangement are greater than 0.9 after 20 years and therefore, both these system should be acceptable from reliability point of view.

6. The substation reliability depends on the failure rates of individual components depending upon the magnitude of these failure rates. Substation reliability is not sensitive to the failure rate of bus-bar when the failure rate is double and half. Substation reliability is more sensitive to failure rate of isolator and is most sensitive for the failure rate of circuit breaker and extent of sensitivity increases with increasing value of circuit breaker failure rate.

7. The sensitivity of the reliability of substation with the variation of component failure rate is different for different bus arrangements in the range in which the failure rate of bus-bar, isolator and circuit breaker were varied. Reliability of duplicate bus arrangement was less sensitive than the reliability of sectionalised bus arrangement.

Suggestion for future work

1. This study is only a preliminarily x position design aspect of EHV substation of which there are three main aspects i) Technical criteria, ii) the cost consideration, iii) reliability consideration. There is much more scope to make detail studies on all these three aspects.

2. In cost consideration, detailed evaluation of cost taking into account cost of the land and the cost of transformer and reactor and running cost can be made.

3. For reliability computations, the failure rates of component should be obtained from the experience in Indian conditions and this should be used for computation.

4. The reliability computation of one and-a-half, breaker, double bus with transfer bus, double bus double breaker may also be carried out.

5. The failure rates of transformers, reactors, and lightening arrestor may also be taken into consideration for reliability calculations.

Appendix A

Definition of Terms and Reliability Indices

Reliability

Reliability R(t) is normally defined as the probability that a substation is able to supply for the period of time (t) under the condition that at least one component of the substation is nonrepairable during operation.

Availability

Availability A(t) (point-availability) is the probability that the substation is able to supply energy within tolerances at a given instant of time t.

General Terms

Component

A component is a piece of equipment, a line, a section of line or a group of items which is viewed as an entity for the purpose of reporting, analyzing and predicting outages.

System

A system is a group of components connected or associated in a fixed configuration to perform a specified function.

Outage Terms

Outage

An outage describes the state of a component when it is not available to perform its intended function due to some event directly associated with that component. An outage may or may not cause an interruption of service to consumers depending on system configuration.

Failure

A failure describes the state of a component when it is not available to perform its intended function due to the malfunction of that component. A component failure results in a component outage but a component outage can occure without a component failure.

Switching time

Switching time is the period from the time a switching operation is required due to a forced outage until that switching operation is performed.

Exposure time

Exposure time is the time during which a component is performing its intended function and is subjected to outage.

Outage Rate

The outage rate for a particular classification of outage and type of component is the mean number of outages per unit exposure time per component. A section of line averaging one outage every 10 years has an annual outage rate $= \frac{1}{10}$ 0.10.

Outage Duration

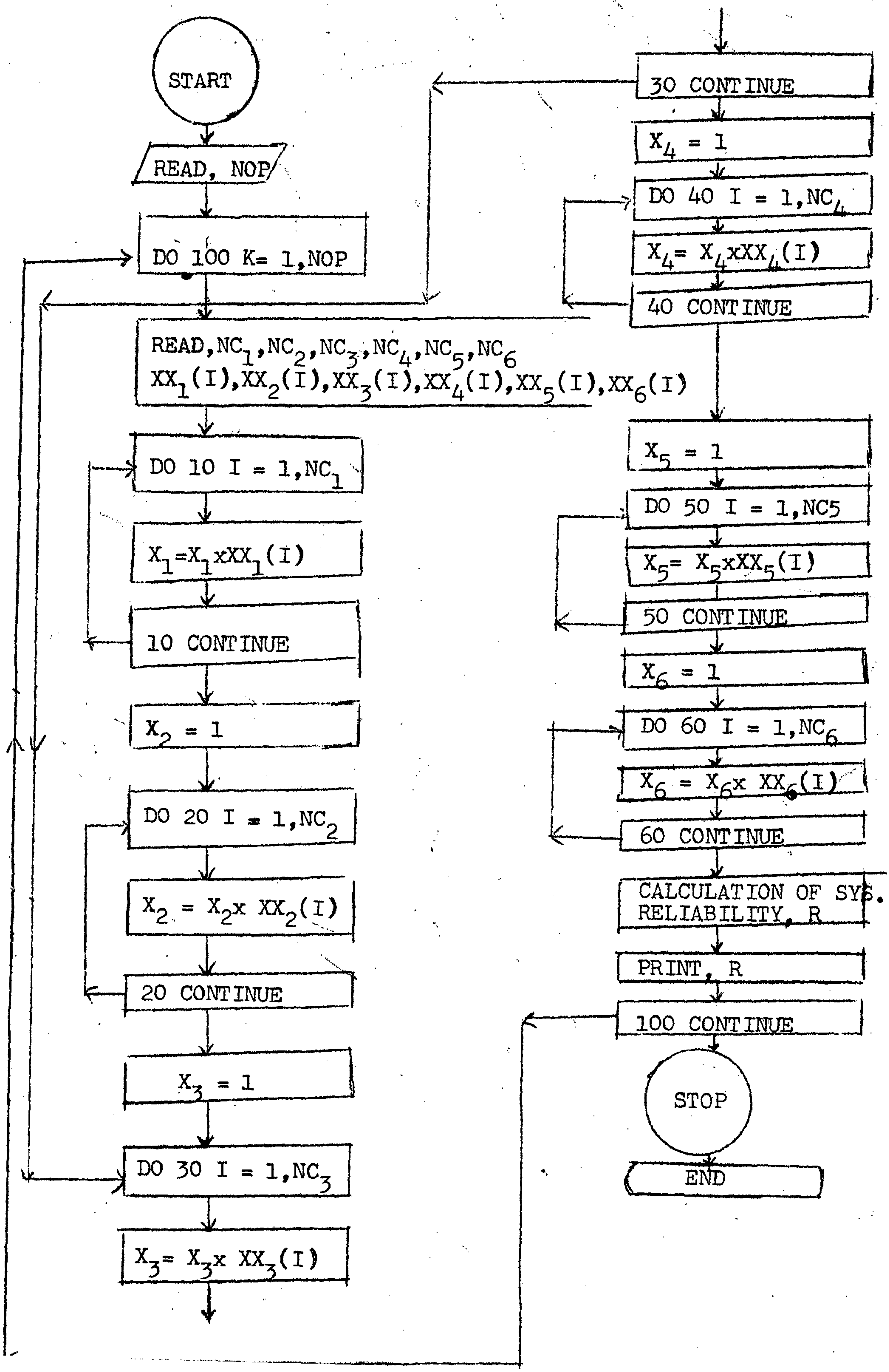
Outage duration is the period from the initiation of an outage untill the affected component or its replaced once again becomes available to perform its intended function.

Interruption Term

Interruption

An interruption is the loss of service to one or more customers and is the result of one or more component outages.

FLOW CHART



START
READ, NOP
DO 100 K= 1,NOP
READ,NC1,NC2,NC3,NC4,NC5,NC6
XX1(I),XX2(I),XX3(I),XX4(I),XX5(I),XX6(I)
DO 10 I = 1,NC1
X1=X1xXX1(I)
10 CONTINUE
X2 = 1
DO 20 I = 1,NC2
X2 = X2x XX2(I)
20 CONTINUE
X3 = 1
DO 30 I = 1,NC3
X3= X3x XX3(I)
30 CONTINUE
X4 = 1
DO 40 I = 1,NC4
X4= X4xXX4(I)
40 CONTINUE
X5 = 1
DO 50 I = 1,NC5
X5= X5xXX5(I)
50 CONTINUE
X6 = 1
DO 60 I = 1,NC6
X6 = X6x XX6(I)
60 CONTINUE
CALCULATION OF SYS.
RELIABILITY, R
PRINT, R
100 CONTINUE
STOP
END

```
C-----------------------------------------------------------------
C       PROGRAM TO EVALUATE SYSTEM RELIABILITY USING PATH-SET
C       AND CUT-SET METHOD.
C-----------------------------------------------------------------


C*****************************************************************
C       INFORMATION ABOUT INPUT DATA
C       ---------------------------
C       NOP=NO. OF PROBLEMS
C       NC1=NO. OF COMPONENT IN ARM NO. 1
C       NC2=NO. OF COMPONENT IN ARM NO. 2
C       NC3=NO. OF COMPONENT IN ARM NO. 3
C       NC4=NO. OF COMPONENT IN ARM NO. 4
C       NC5=NO. OF COMPONENT IN ARM NO. 5
C       NC6=NO. OF COMPONENT IN ARM NO. 6
C       XX1=RELIABILITY OF EACH COMPONENT IN ARM 1
C       XX2=RELIABILITY OF EACH COMPONENT IN ARM 2
C       XX3=RELIABILITY OF EACH COMPONENT IN ARM 3
C       XX4=RELIABILITY OF EACH COMPONENT IN ARM 4
C       XX5=RELIABILITY OF EACH COMPONENT IN ARM 5
C       XX6=RELIABILITY OF EACH COMPONENT IN ARM 6
C*****************************************************************
        DIMENSION XX1(25),XX2(25),XX3(25),XX4(25),XX5(25),XX6(25
        1)
        OPEN(UNIT=1,DEVICE='DSK',DIALOG)
        READ(1,*) NOP
        DO 100 K=1,NOP
        READ(1,*) NC1,NC2,NC3,NC4,NC5,NC6
        READ(1,*) (XX1(I),I=1,NC1)
        READ(1,*) (XX2(I),I=1,NC2)
        READ(1,*) (XX3(I),I=1,NC3)
        READ(1,*) (XX4(I),I=1,NC4)
        READ(1,*) (XX5(I),I=1,NC5)
        READ(1,*) (XX6(I),I=1,NC6)
        X1=1.
```

```
          DO 10 I=1,NC1
          X1=X1*XX1(I)
   10     CONTINUE
          X2=1.
          DO 20 I=1,NC2
          X2=X2*XX2(I)
   20     CONTINUE
          X3=1.
          DO 30 I=1,NC3
          X3=X3*XX3(I)
   30     CONTINUE
          X4=1.
          DO 40 I=1,NC4
          X4=X4*XX4(I)
   40     CONTINUE
          X5=1.
          DO 50 I=1,NC5
          X5=X5*XX5(I)
   50     CONTINUE
          X6=1.
          DO 60 I=1,NC6
          X6=X6*XX6(I)
   60     CONTINUE
          A1=X1*X2
          A2=X1*X3
          A3=X1*X4
          A5=X2*X5
          A6=X2*X6
          A7=X3*X4
          A8=X3*X6
C-----------------------------------------------------------------------
C         CALCULATION OF SYSTEM RELIABILITY.
C-----------------------------------------------------------------------
          R=A1+A7+(A3*X6)+(A5*X3)-(A1*A7)-(A6*A3)-(A2*A5)-(A3*A8)-
          1(A5*A7)+(A1*A7*X6)+(A5*A7*X5)
          RU=A1+A7+(A3*X6)+(A5*X3)
```

```
      XB1=1.-X1
      XB2=1.-X2
      XB3=1.-X3
      XB4=1.-X4
      XB5=1.-X5
      XB6=1.-X6
      RL=1.-((XB1*XB3)+(XB2*XB4)+(XB1*XB5*XB4)+(XB3*XB6*XB
     12))
      PRINT70
   70 FORMAT(/////,30X,'RESULTS',/,25X,'*****************',/
     1/,5X,'-----------------------------------------',/)
      PRINT80,R,RU,RL
   80 FORMAT(5X,'SYSTEM RELIABILITY= ',F9.6,///,5X,'UPPER BOUN
     1D= ',F9.6,///,5X,'LOWER BOUND= ',F9.6,/,5X,'-----------
     2------------------------------')
  100 CONTINUE
      STOP
      END
C*************************************************************************
```

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