GENERAL DESIGN AND OPERATING ASPECTS
OF A HIGH VOLTAGE DIRECT CURRENT
INVERTER STATION

A Thesis

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by

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PREFACE

While the concept of high voltage direct current transmission is very old, it is only recently that the technique has been applied in practice.

Until the introduction of extra high voltage long lines power transmission by alternating current was more adequate. Rapid growth of electric power consumption and large and complex interconnected load areas have demanded a corresponding increase in stability and reliability of the whole system. This necessitated transmission of power in large blocks over long distances by means of extra high voltage overhead transmission lines; underground and/or underwater cables; stable and reliable tie lines between systems; etc. Transmission of power under these conditions might be found to be more economical and stable by means of direct current. A d.c. tie line usually is also attractive not only from reliability and stability point of view but because it allows the interconnection of two or more a.c. systems which may be running at different frequencies.

This thesis concerns itself with the design and operating aspects of an inverter terminal station which is

necessary in any high voltage direct current transmission scheme to convert the d.c. transmitted power back into a.c. at the end of d.c. transmission line.

The author wishes to acknowledge the valuable guidance and keen interest taken by Professor M.Z. Tarnawecky throughout this work. His advice was always a source of inspiration. Whole hearted thanks to Messrs. C.J. Bulcock and G.T. Davies of English Electric Co. Ltd., England; Mr. H. Martensen and Dr. E. Uhlmann of ASEA, Sweden; Mr. D.T. Braymer, editor Electrical World; Dr. N.G. Hingorani and Mr. E.C. Starr of B.P.A., U.S.A.; Canadian ASEA Electric Co. Ltd., Montreal, Mr. E. F. Glass of Canadian Westinghouse Co., Winnipeg and Mr. J.W.J. Lewis of Power and Mine Co., Winnipeg for supplying valuable technical papers. Many thanks are due to Messrs. C.J. Goodwin, H.E. Wichert and C.V. Thio of Manitoba Hydro, Winnipeg, for providing some valuable information. Also sincere thanks to Misses Irene Reid and Judith Benson for excellent typing.

ABSTRACT

The layout of an H.V.D.C. inverter station is analysed using high voltage multi-anode mercury arc valves. Various converting equipment is compared. The design and operating aspects of the pertinent equipment in the inverter station are studied.

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TO MY WIFE

whose patience, understanding and encouragement were invaluable towards the completion of this thesis.

CHAPTER I

GENERAL CONSIDERATIONS

1.1 INTRODUCTION:

Transmission of energy from one place to another may be carried out in the form of coal, oil or gas by means of rail, boat, roadway or pipeline; or, alternatively, as electricity by transmission line utilizing either alternating current or direct current techniques.

Direct current transmission is one of several forms of energy transportation. Electrical engineers have always acknowledged the fact that d.c. offers fundamental economic and technical advantages for the transmission of electric power over long distances. Nevertheless, alternating current has been used predominantly for the generation, transmission and utilization of electric energy since the early days of electric power invention. The reasons for this lie in the advantages a.c. offers in generation, distribution and use of power. Also a.c. can be easily transformed from one voltage to another and easily rectified locally when d.c. is needed. Thus there is no doubt that power stations, most motors and a majority of consumer appliances should be built for alternating current. The advantage of d.c. is realised mainly in point to point transmission of power with a.c. to d.c. and d.c. to a.c. conversion at the two ends. Tapping of d.c. power at the present stage of development is also under extensive investigation and a break-through even in this application does not appear too far.[1,2]

Recent developments in control techniques for the conversion at high voltages from a.c. to d.c. and d.c. to a.c. has made possible the practical application of high voltage direct current transmission (in short H.V.D.C.T.).

As an introduction this chapter describes the prospects and places of application of H.V.D.C. technique. In chapter II the single line diagram and layout of the inverter station is developed. Subsequent chapters, III to VI, deal with major equipment in detail. Chapter VII describes the control and protection schemes of the station.

1.2 STATEMENT OF THE PROBLEM:

This thesis deals with the general design and operating aspects of a high voltage direct current inverter station rated at ± 450 KV D.C., 1800 amps., 1620 MW, connected to a 230 KV A.C., 3-phase, 60 Hz bus. Reference to rectification is made only where necessary.

1.3 CHOICE OF H.V.D.C. TRANSMISSION:

The choice of d.c. transmission depends on its economical and/or technical advantages. Some aspects of the consideration of d.c. compared with a.c. for the same power transfer capability are mentioned here briefly.[3,4,5,6,7]

i) Overhead H.V.D.C. Transmission:

Inherently for a d.c. transmission line only one or two conductors are required; for an a.c. line three conductors are necessary. Furthermore, for a given power transfer capability the weight of conductor is less for d.c. than a.c. This reduced conductor weight and the use of fewer conductors permits simplified tower design and narrower right of way. Hence d.c. transmission line cost is less per unit length than corresponding a.c. line.

As against this, d.c. terminal stations are more expensive than a.c. stations. It follows that d.c. offers a cost advantage only when the line exceeds a certain length. The break-even distance varies with local conditions. At present this distance is generally about 500 miles.

Also, there is no stability limitation with d.c. transmission. This advantage increases with the length of transmission line. A.c. lines are sensitive and their stability decreases with increase in length.

ii) Underground and Underwater D.C. Cable Transmission:

Direct current transmission becomes particularly attractive when underground or underwater cable is used. The absence of a charging current, the reduced dielectric stress and fewer conductors make d.c. cables cheaper than corresponding a.c. cables. This cost difference is enhanced in the case of underwater cables where it becomes impractical to install compensating reactors for a.c. cables.

Transmission of power by d.c. cables as compared with a.c. cables becomes more economical at over 20-- 30 miles.

Continuous expansion of metropolitan areas with corresponding growth in concentrated loads is demanding the transmission of large amounts of power to these centres by means of cables, as overhead lines become impractical. In such cases transfer of power by d.c. cables may become a very economical and practical solution. Other possible applications may be d.c. underwater cable to a distant island and across lakes, rivers etc.

iii) Earth Return:

Earth is an excellent return conductor for direct current. The direct ground current following the path of least resistance, penetrates into the good-conducting interior of the earth, leaving noticeable effects on the ground surface only in the vicinity of the earth electrode.

Earth could be used as a permanent conductor in a mono-polar line design or as a spare conductor in a bi-polar line design. In a bi-polar line design, the mid-point is connected to earth at both terminals. Should one pole be taken out of service for any reason, the other pole will continue to carry at least its half of the total power by using earth as a return conductor. A bi-polar d.c. line with earth return is, therefore, equivalent to a double-circuit a.c. line from the viewpoint of reliability.

iv) Overvoltages:

Overvoltages in d.c. transmission lines due to switching surges are relatively lower than in the comparable a.c. transmission lines.

v) Insulation Level:

A d.c. transmission line can operate at higher voltages than a.c. for a given insulation level.

vi) Non-synchronous Tie Lines:

Two large electrical systems with an a.c. tie must run in synchronism. If a d.c. link is used, it acts like a fluid coupling between two mechanical systems, and power can flow in either direction with both the systems operating independently at different frequencies and voltages. With an a.c. tie line stability and control problems might be more complex as compared to the d.c. interconnection.

vii) Fault Capacity:

Whenever two a.c. systems are interconnected by an a.c. link, the total short circuit capacity is increased and the a.c. link is also a contributing factor to it. With a d.c. link power is fully controlled and thus power in excess of the station rating will not be supplied to the fault. Thus a d.c. link in itself does not increase the short circuit capacity of the two interconnected systems.

viii) Power Flow Control:

The control of power flow in a d.c. line is very fast and accurate by means of grid control. This is advantageous not only under fault conditions but opens up new possibilities for improved operating procedures.

ix) Reversal of Power:

The direction of d.c. power flow can be reversed with a fast control system which gives the system high reliability and stability.

x) Matching Capacity With Demand:

A d.c. terminal station normally consists of many converters connected in series on the d.c. side. These converters could be added in steps to raise the d.c. line voltage and hence the power capacity. In this way the investment rate can closely follow the growth of load in the system. In an a.c. system since the major first cost is the line itself, this matching of capacity with demand is less pronounced.

xi) Possible Economy in Generation:

With the availibility of economical and reliable d.c. transmission, the design engineers should consider the overall concept of generation and transmission of power. It might be possible to generate power at frequencies other than 50 Hz or 60 Hz more economically and transmit it by non-synchronous d.c. line to the load centres.

From this evaluation it can be concluded that d.c. transmission has bright prospects. Already several d.c. schemes have been built in different parts of the world, many are in progress, and more are proposed. A list of these d.c. schemes is given in appendix I.

CHAPTER II

SINGLE LINE DIAGRAM AND VARIOUS STATION LAYOUTS

2.1 INTRODUCTION:

The first step in the design of an electrical station is the development of the single line circuit diagram. This diagram contains the essential information and is prepared to give a complete, clear and comprehensive picture of the electrical connections and apparatus involved. It does not necessarily give the relative physical locations of the equipment in the station, but conveys full information on electrical aspects of the station at a glance.

Before studying the single line circuit diagram of an inverter station, the overall performance of d.c. power transmission is considered.

A complete H.V.D.C. scheme typically consists of a "sending end station" linked by a d.c. transmission line to a "receiving end station". The conversion units at both the stations (mercury arc or thyristor valves) are connected in three-phase bridge circuits. These are also known as "valve groups". At the sending end, the units are phased to operate as "rectifier" and at the receiving end as "inverter". A simple arrangement is shown in FIG. 2.1.

The a.c. power generated at the rectifier end is applied to the rectifier bridge in the manner shown in FIG. 2.1. The rectifier units act simply as switches to turn the power on and off at appropriate times in order to produce a unidirectional current. The d.c. transmission line (overhead line or underground cable) transmits this power to the inverter station where the units commutate to invert the direct current back to alternating current.

2.2 SINGLE LINE CIRCUIT DIAGRAM:

The single line diagram of the inverter station is shown in DWG. 2A*. All the major equipment used is shown.[8,9,10,11]

It can be seen from this diagram that the inverter station is divided into two major sections:

1. d.c. Section;
2. a.c. Section;

The d.c. section is the core of an inverter station and it is this section which makes an inverter station appear so different from the familiar a.c. terminal stations. The a.c. section is very much similar to the conventional a.c. stations

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* See large drawing in back pocket of thesis.

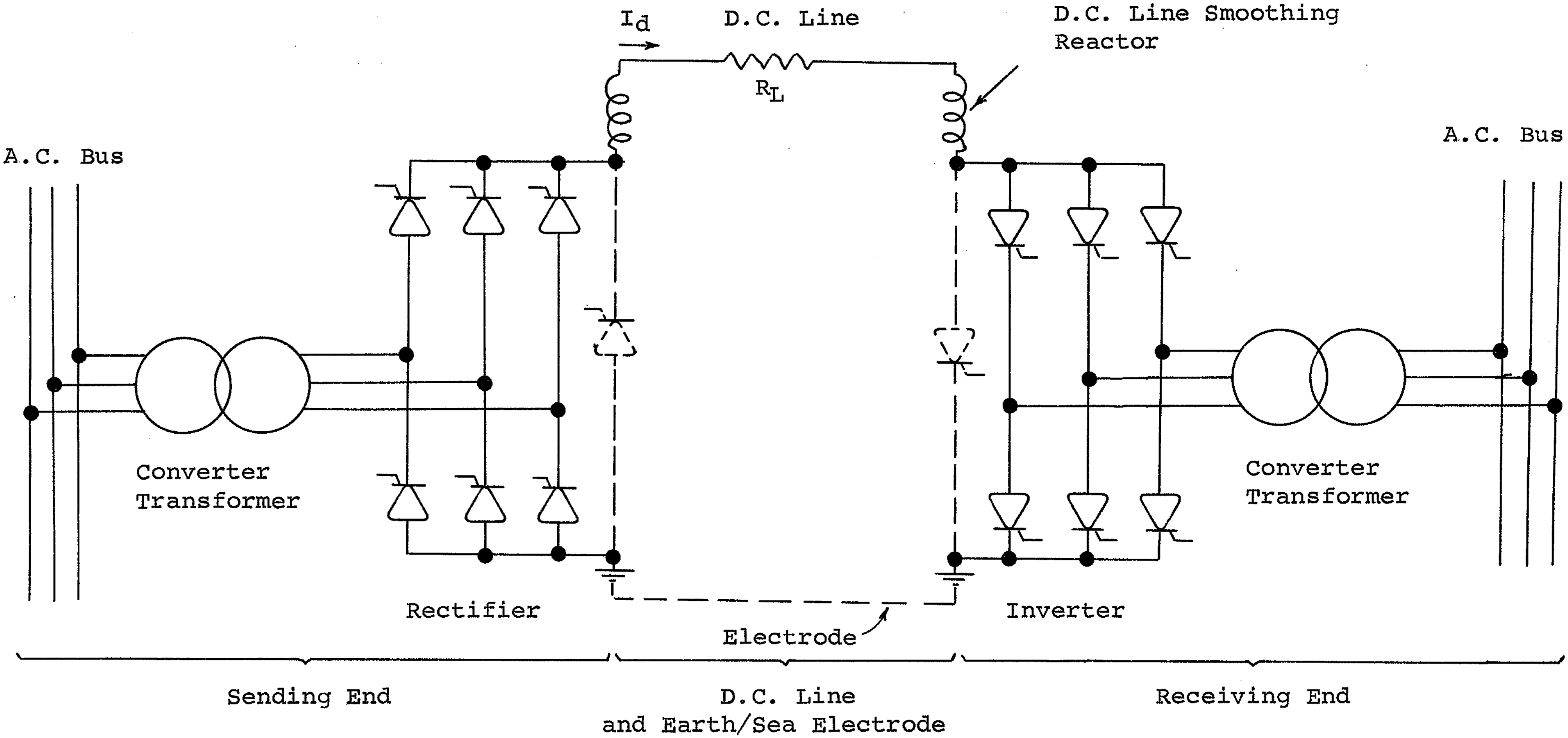

FIG. 2.1

A TYPICAL D.C. TRANSMISSION SCHEME

with the exception of a.c. harmonic filters, damping equipment and synchronous condensers.

2.2.1 Brief Description of Major Equipment:

Each equipment will be dealt with in detail in later chapters. Here it is desired to give only a short description of the equipment involved stating their purpose and general performance.

i) Valve Group and Auxiliaries:

These include the following equipment:

a) Valves:

Valves (item 1, DWG. 2A) are considered as the "heart" of d.c. transmission and are responsible for the inversion of electrical power from direct to alternating voltage in an inverter station.

In the single line diagram three valve groups, each of 150 KV, 1800 amps. rating are connected in series per pole in order to achieve a bi-polar terminal rating of $\pm$ 450 KV d.c., 1800 amps., 1620 MW.

b) By-Pass Valve and By-Pass Switch:

By-pass valves (item 2, DWG. 2A) are necessary only when mercury arc valves are used and not with thyristors. One by-pass valve is connected across the d.c. terminals of each bridge and is operated only during the time when the bridge is blocked momentarily because of any fault.

For sustained faults or during valve maintenance periods the by-pass switch (item b, DWG. 2A) is closed. The main and by-pass valves are isolated from the system.

By-pass switches are required with both mercury-arc and thyristor valves.

c) Valve Grid Control Equipment:

For proper control of firing of each valve it is necessary to have adequate valve grid control equipment. Each valve-group is provided with a firing control equipment.

d) Damping Equipment:

During normal operation of valves sudden voltage and current changes take place due to commutation. These trigger extra voltage oscillations and current surges in the converter transformer windings and other associated equipment. Special equipment is needed to limit these oscillations and surges.

Voltage oscillations are suppressed by installing "damping circuits" (item 3, DWG. 2A). Current surges are suppressed by installing "anode reactors" (item 4, DWG. 2A).

e) Cathode Reactor:

Cathode reactors (item 5, DWG. 2A) are installed to suppress radio noise and corona discharges from the conductors caused by current surges arising out of commutation.

ii) Converter Transformer:

Each valve group is connected to one three-phase or three single-phase converter transformers (item 6, DWG. 2A).

The primary windings of these transformers (windings connected to a.c. bus) are usually connected in grounded star. The secondary windings (windings connected across valve - group) are connected alternately in star and delta to achieve twelve-pulse operation. Converter transformers in inverter stations are normally provided with tertiary windings also. These windings are used for the connection of "synchronous condensers" (item 9, DWG. 2A). Tertiary windings are generally connected in delta to suppress transformer third harmonic voltages.

iii) A.C. Harmonic Filters:

Because of switching action (commutation) of valves the current wave shape of the a.c. side of the bridge is not sinusoidal. It consists of short discontinuous pulses and, due to the damping effect of the d.c. line reactor, has a rather flat top in the conducting region. Thus the shape of the pulsating output current approximates to a rectangular wave. This wave shape can be resolved, by Fourier series analysis[17,18] into a fundamental (60 Hz) component and harmonics, given by:

$$H_{ac} = pn \pm 1 \quad \ldots \quad \ldots \quad \ldots \qquad (2.1)$$

where, p = number of pulses (6, 12, etc.)

n = an integer (1, 2, 3, etc.)

Any bridge alone provides six-pulse output. Therefore, from equation (2.1), the a.c. wave shape can be analysed into current harmonics of the order $6n \pm 1$. With twelve-pulse operation 5th, 7th, 17th, 19th, 29th ... etc. harmonics are confined from entering into the a.c. system and only 11th, 13th, 23rd, 25th ... etc. harmonics would enter. Nevertheless, on occassions when one bridge is out of service, say, for maintenance, all six-pulse harmonic currents would flow into the system.

A.c. harmonic filters (item 7, DWG. 2A) are provided to by-pass these harmonics from flowing into the a.c. system. Otherwise they may become harmful under resonance conditions.

The resultant impedance of a.c. harmonic filters is "capacitive" at fundamental power frequency, thus these filters also serve as a source of reactive power supply.

iv) D.C. Harmonic Filters:

Valve switching action also generates voltage harmonics which would appear in the d.c. line. These are usually known as "d.c. harmonics" and are given by: [17,18]

$$H_{dc} = np \quad \ldots \quad \ldots \quad \ldots \quad \ldots (2.2)$$

where, p = number of pulses (6, 12,..., etc.)

n = an integer (1, 2, 3,..., etc.)

For six-pulse operation d.c. harmonics would be of the order of 6, 12, 18, 24, ..., etc. Of these the 6th, 18th, ..., etc, harmonics would be confined with twelve-pulse operation. Hence only 12th, 24th, ..., etc. harmonics would be present.

D.c. harmonic filters (item 8, DWG. 2A) are installed to short circuit these harmonics.

The above a.c. and d.c. harmonics are generally referred to as "theoretical", "classical" or "characteristic" harmonics of the classical converter theory.

V) Synchronous Condenser and Static Capacitors:

The current in an inverter bridge leads its voltage partly due to the process of commutation and partly due to the grid control. The bridge, therefore, absorbs reactive power during its operation*.

Any additional reactive power required by the bridge

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* In a rectifier bridge voltage leads current and reactive power is consumed during this operation also.

can be supplied by synchronous condensers (item 9, DWG. 2A) and/or static capacitors.

It is desirable to have the short circuit level of the a.c. bus about 3 to 6 times the d.c. transmitted power. This is to minimize the inverter station a.c. bus voltage fluctuations due to corresponding variations in a.c. system voltages and hence to improve commutation. Thus synchronous condensers installed at the inverter station contribute to this short circuit level (MVA) of the a.c. bus.

There is no single answer as to the required rating of synchronous condensers and static capacitors installation. Accordingly, each case has to be considered separately.

vi) D.C. Line Smoothing Reactor:

A smoothing reactor is installed at both ends of the d.c. transmission line for various purposes.

The reactor serves to smooth out the ripples in the direct voltage output from the converters. It acts as a damper and provides electrical inertia. This limits violent changes in currents and voltages due to switching operations and eliminates, almost completely, discontinuities in direct current during normal operating conditions.

The damping characteristic of the reactor is useful in limiting the rate of change of current and voltage during certain faults, such as valve and d.c. line faults. This enables the control and protective circuits to distinguish between the two types of faults and act accordingly. The smoothing reactor also limits the line discharge currents through the by-pass valve.

In some applications only line smoothing reactors have been used to suppress d.c. harmonics. Examples are: Benmore - Haywards H.V.D.C. transmission scheme, New Zealand [9] and Pacific H.V.D.C. intertie, U.S.A.[11]

A d.c. line smoothing reactor is placed in series with the d.c. line (item 10, DWG. 2A). The reactor must, therefore, be designed to carry full line current at all times. It should also withstand the most severe electrical and mechanical stresses due to d.c. harmonics and line current surges and the windings must be insulated for full line to earth voltage.

vii) A.C. Circuit Breaker:

These breakers follow conventional a.c. designs and layouts except that they should be properly designed for harmonic currents arising out of valve switching.

These are installed at the a.c. bus on the primary side of the converter transformers.

viii) Lightning Arresters or Surge Diverters:

The purpose of lightning arresters or surge diverters is to limit the surge voltage that may be applied to the apparatus they protect and by-pass the surge to ground. They must withstand the rated power voltage for which they are designed. The arresters are connected across d.c. and a.c. lines, valve groups, converter transformers and other major equipment for their respective protection.

ix) Disconnecting and Isolating Switches:

These switches are required both in a.c. and d.c. sections of the inverter station. Their purpose is to isolate and/or ground any desired piece of equipment or section under predetermined conditions such as faults, maintenance, etc.

x) Auxiliary Equipment:

Various equipment such as voltage-dividers, current transductors and current and voltage transformers, etc. are incorporated for metering, control, relaying, protection and operating purposes of all associated equipment in the station.

This completes the brief description of major equipment in an inverter station. Consideration will now be given to the economical layout of these equipment.

2.3 FACTORS AFFECTING STATION LAYOUT:

Most d.c. inverter stations follow the same basic pattern. Nevertheless every layout has to be decided on its own merits.[19,20,21,22] Any layout is governed by the following main factors:

i) Physical:

a. Available land and location.

b. Cost of land.

c. Condition of land.

d. Cost of building construction.

e. Climate of area.

ii) Electrical:

a. Rating of station.

b. Insulation levels of equipment.

c. Impulse withstand level and creepage distance required.

d. Permissible radio interference levels of equipment.

e. Type of equipment available.

All the above factors vary a great deal from one location to the other and for two similar locations the two layouts may still be quite different from each other because of possible different electrical ratings of the stations.

2.4 DEVELOPMENT OF INVERTER STATION LAYOUT:

Inverter terminal station layouts may be of three types:

1. Completely indoor.
2. Completely outdoor.
3. Mixed, i.e. a combination of indoor and outdoor equipment.

A completely indoor station would be most expensive because, in general, building costs exceed by far the cost of open land.

The necessity of a completely indoor station layout would arise in areas where:

1. the stations are to be located in an already builtup area, such as a metropolitan city;

or

2. where the climatic conditions are such that they force indoor equipment installations, such as reas of heavy precipitation or pollution.

A completely outdoor station is neither possible nor desirable when considering mercury arc valves. With thyristors the layout may be completely outdoors as the thyristor units immersed in oil can be completely encapsulated and installed outdoors. For mercury arc valves the surrounding air has to be relatively clean and within certain temperature limits to protect sensitive valve parts such as the voltage divider, insulating surfaces, etc. and to ensure proper operation.

These considerations make it economical to house the valves and their auxiliary equipment in a building whereas other major equipment such as transformers, disconnects, breakers, etc. can be arranged outdoors.

2.5 ALTERNATIVE ARRANGEMENTS OF EQUIPMENT:

The major equipment in any inverter station may be arranged in four possible ways:[23]

i) Narrow Base Layout;

ii) Compact Layout;

iii) Parallel or Back to Back Layout;

iv) Straight Layout.

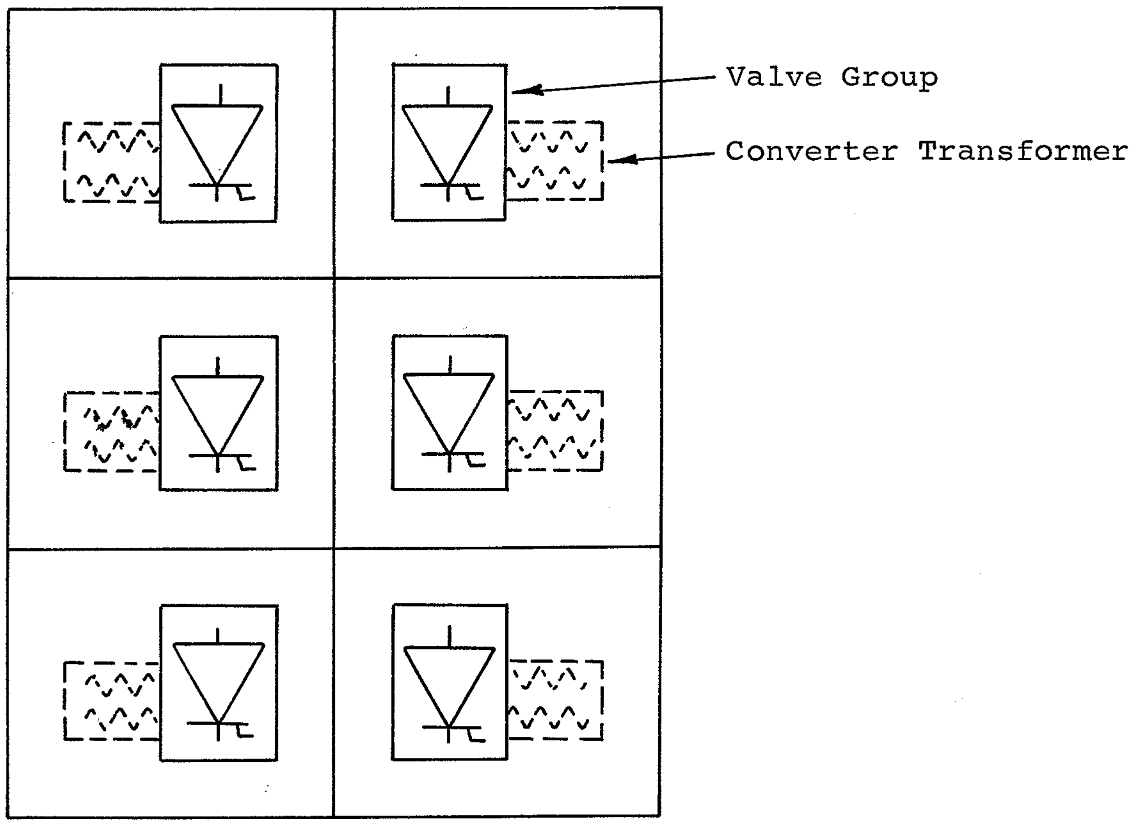
i) Narrow Base Layout: (FIG. 2.2)

In narrow base layout the valves are arranged in two levels and the converter transformers are placed on a third level below the valves. Other equipment may be installed on top of the building. Such a layout requires minimum land area and maximum building volume and so is very expensive.

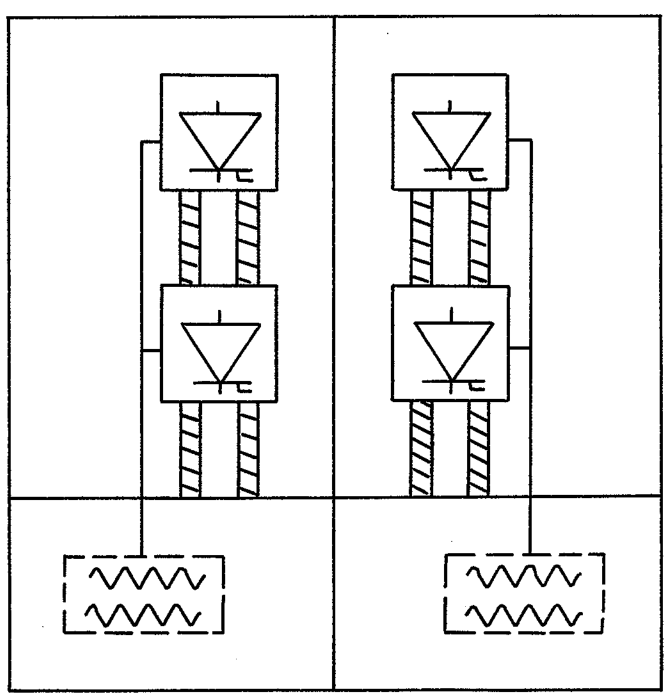
Besides being expensive, this layout offers less easy access to the valves and other equipment for service and maintenance. On the other hand the building can be completely screened thus greatly reducing radio wave emission and making it suitable for urban locations.

ii) Compact Layout: (FIG. 2.3)

In this type of layout the valves are arranged in parallel or back-to-back on both sides of the transport aisle. The converter transformers are enclosed separately adjacent to the valve building. A.c. circuit breakers may also be installed indoors. All other equipment can be installed on the top of



Plan

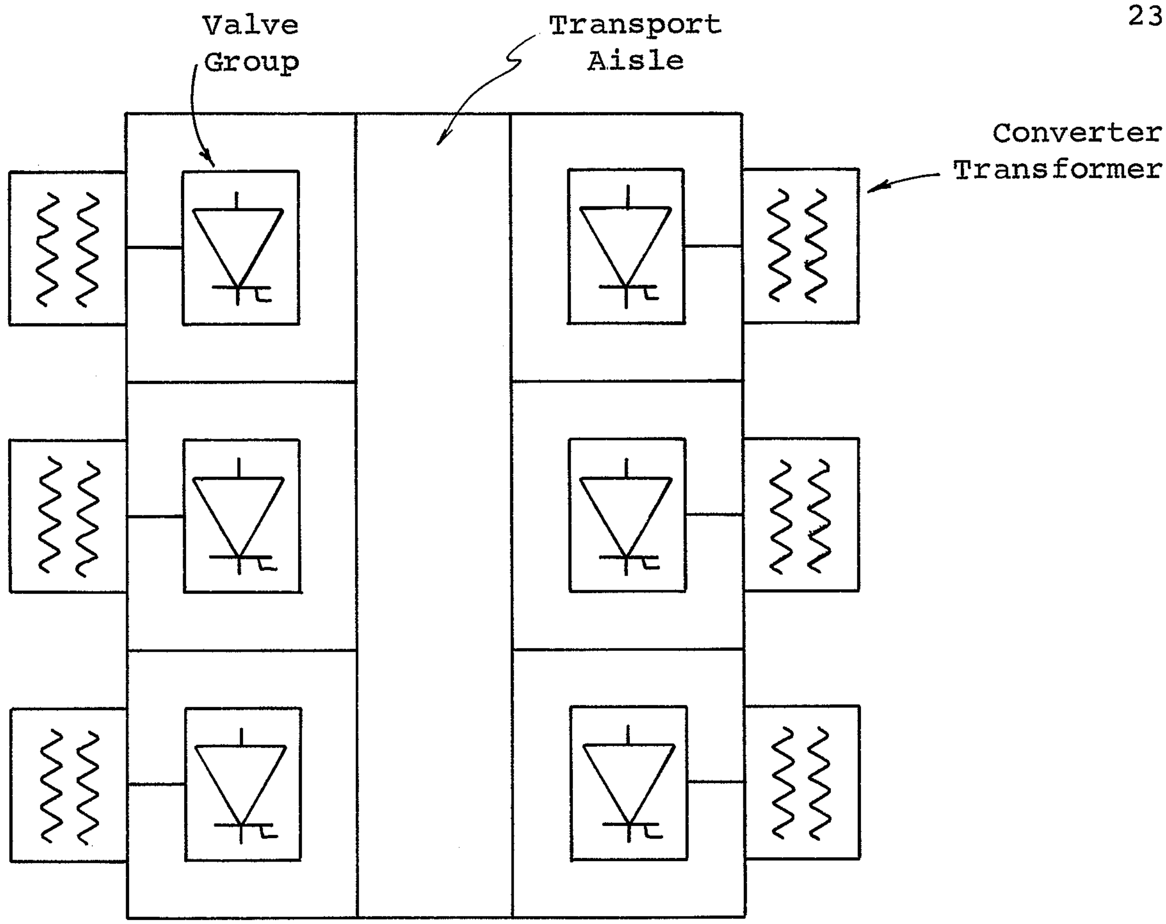


Elevation

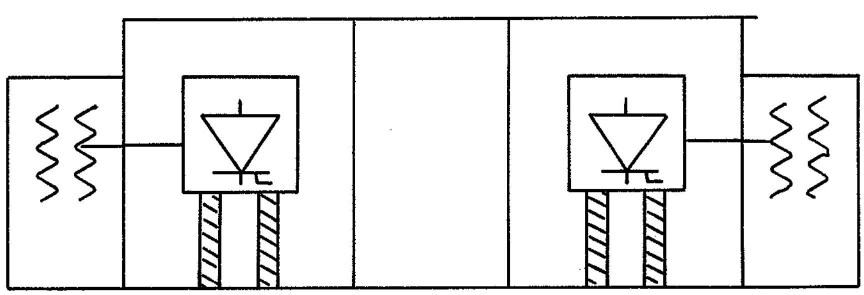
FIG. 2.2

NARROW BASE LAYOUT [23]

(for two bi-polar converter station)



PLAN



ELEVATION

FIG. 2.3

COMPACT LAYOUT 23

(for one bi-polar converter station)

the building.

This layout has similar applications as the narrow base alyout. However compact layout requires more land area than the narrow base layout (about 35-45%) whereas the building volume is reduced by about 50-60%. So compact layout is slightly less expensive. Also due to the parallel arrangement of valves, the compact layout offers comparatively easy access to the valves and other equipment for service and maintenance.

iii) Parallel or Back to Back Layout: (FIG. 2.4)

This layout is similar to the compact layout in so far as the arrangement of the valves is concerned. Other major equipment is arranged outside on two sides of the building. No equipment is installed on top of the valve building.

Parallel layout utilizes the smallest building volume as can be seen from the curves on FIG. 2.6. On the other hand, since the switchyard has to be arranged on both sides of the valve building, an adequate interconnection of the two sides of the switchyard is necessary. The total land area is, therefore, larger than any other layout.

This layout is considered suitable for terminals of large ratings when land is available at low cost. An additional advantage is when a bi-polar scheme is used since valve group platforms of equal voltage level can be arranged opposite to each other simplifying the construction of the building.

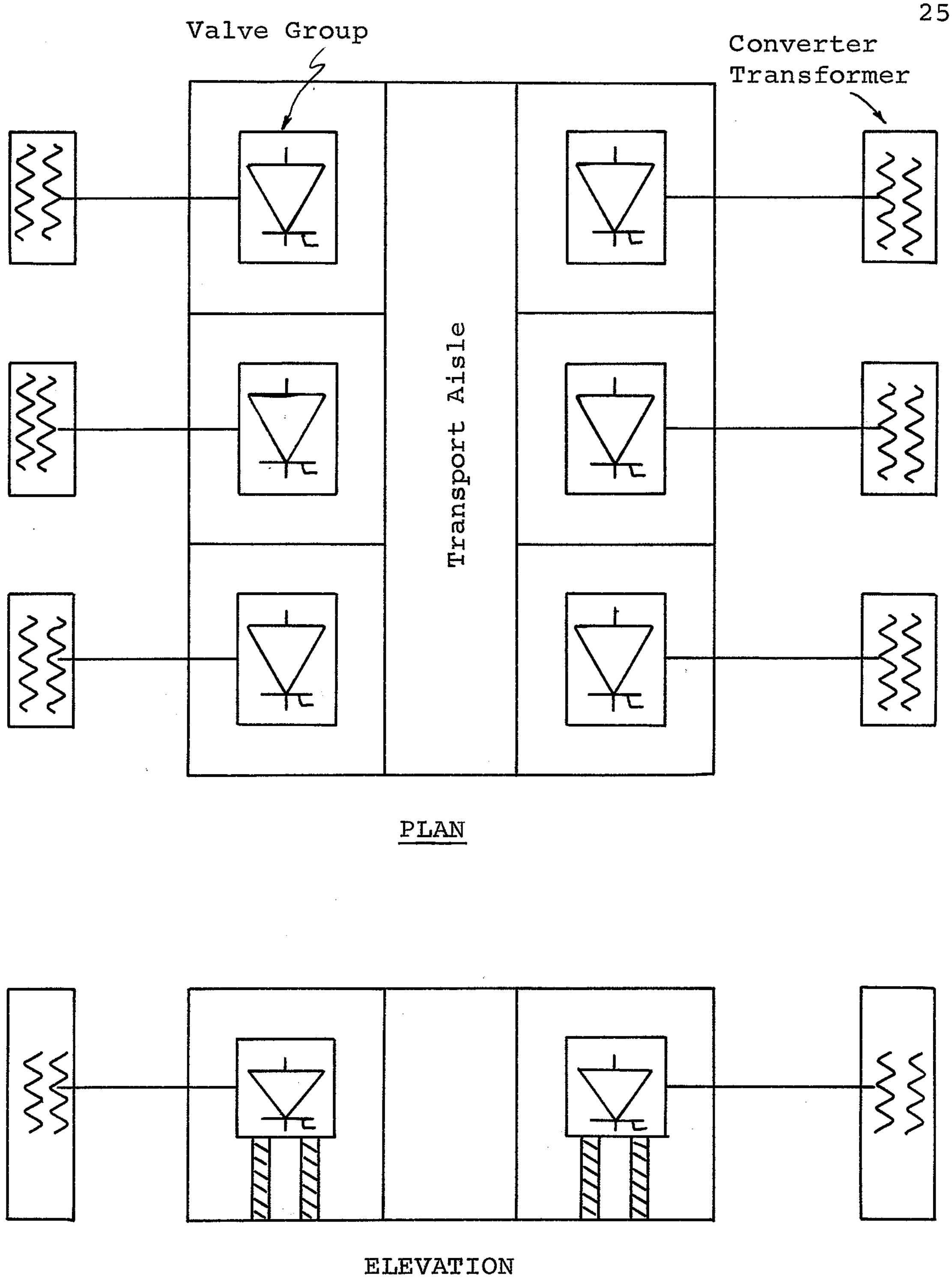


FIG. 2.4

PARALLEL OR BACK TO BACK LAYOUT [23]

(for one bi-polar converter station)

iv) Straight Layout: (FIG. 2.5)

This is the most simple layout and so far all the existing d.c. terminal stations constructed are of this type with the exception of the Celilo-Sylmar converter stations of the Pacific H.V.D.C. intertie, which are parallel type. The main feature of a straight layout is the arrangement of all the valves in a row on one level alongside a transport aisle. Other equipment is installed outdoors in a siwtchyard.

The straight layout provides a clear and easy arrangement for installation and maintenance of all equipment. Referring to FIGS. 2.6 and 2.7 this layout is competive from the point of view of building volume but requires considerable land area. It is the most economical layout where plain ground is available at low cost.

The above four converter station arrangements considered allow for a wide degree of variation in area and building requirements. The land area requirements vary approximately from 1 to 10 between "narrow base" and "parallel" layout, and the building volume requirements from 2 to 1 for the corresponding layouts.[23]

A.c. filters have a great and prominent influence on the design and layout of any inverter station. The land area required for these filters is considerable and hence is shown

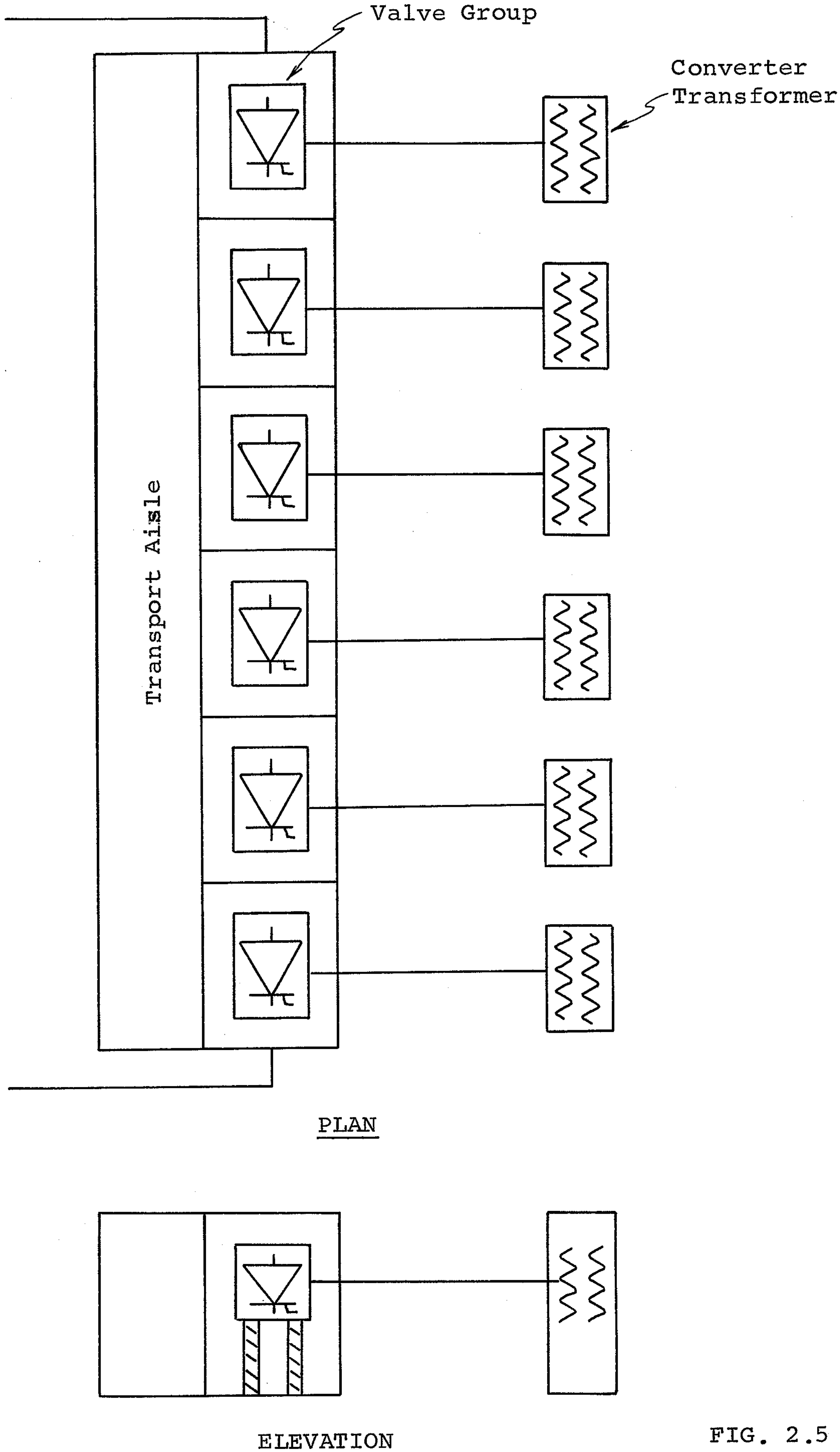


FIG. 2.5

STRAIGHT LAYOUT 23

(for one bi-polar converter station)

separately in FIG. 2.8.

The total land area actually required for all equipment and building, including a.c. filters, in an inverter station is, therefore, the summation of areas obtained from corresponding curves on FIGS. 2.7 and 2.8 for any given voltage rating and the building volume can be obtained from FIG. 2.6.

Table (II-1) is prepared from these curves and gives a comparison of ground area and building volume requirements for different types of station layouts for a bi-polar, $\pm$ 450 KVDC, inverter station with valve group ratings of 150 KV, 1800 amps.

The curves of FIGS. 2.6, 2.7 and 2.8 give the areas and volumes that are actually occupied by d.c. converter station equipment and building. These do not include areas and volumes required for terminations of a.c. lines, access roads, parking, staff, and visitors buildings, etc. These requirements vary greatly from case to case. A utility making an investigation of an H.V.D.C. installation is in the best position to make estimates from these additional areas tailored to its requirements.

2.6 DETERMINATION OF A SUITABLE LAYOUT:

As stated before every layout has to be decided entirely on its own environments and the factors affecting the

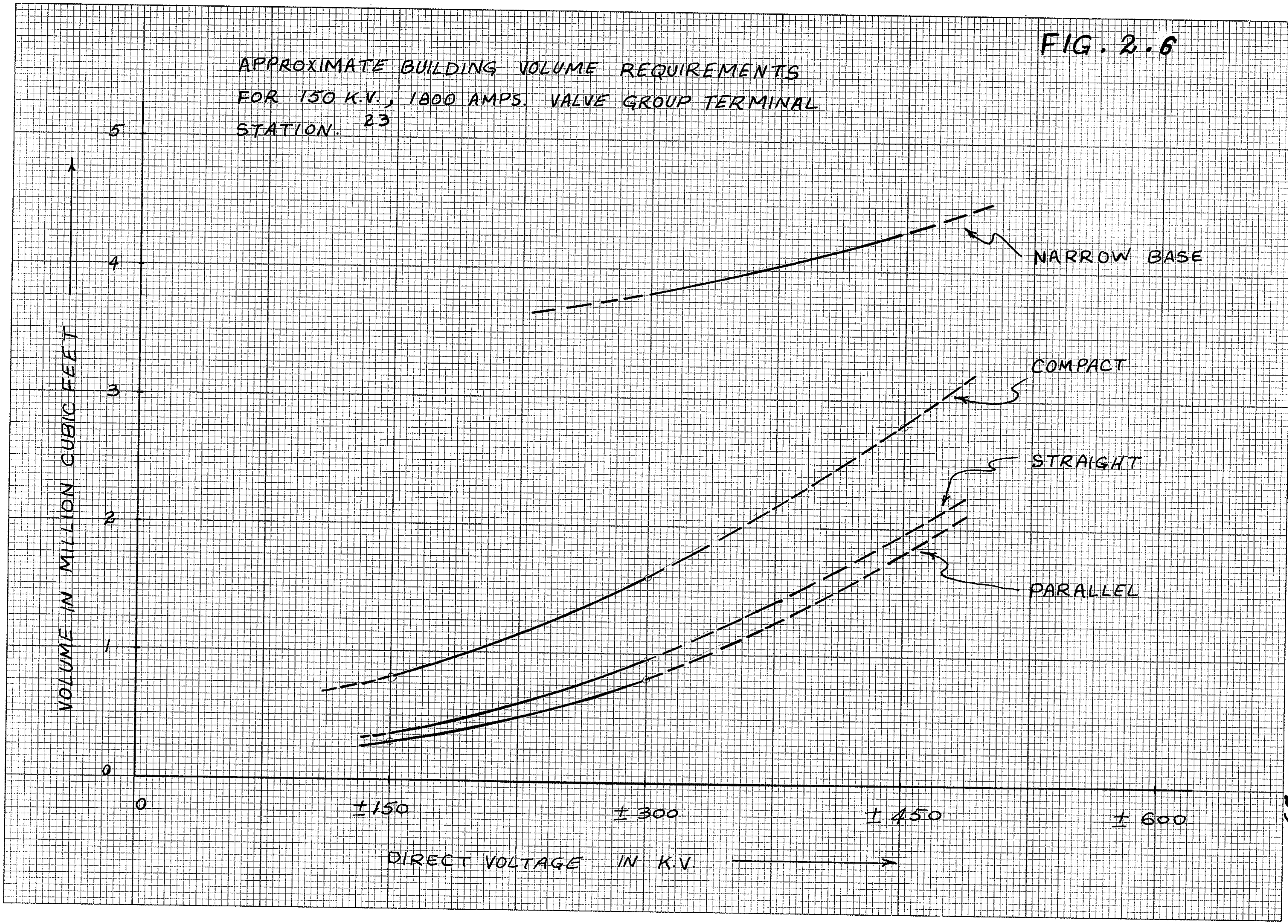


FIG. 2.6

APPROXIMATE BUILDING VOLUME REQUIREMENTS FOR 150 K.V., 1800 AMPS. VALVE GROUP TERMINAL STATION.[23]

FIG. 2.7

APPROXIMATE LAND AREA REQUIREMENT AT DIFFERENT VOLTAGES FOR 150 K.V. 1800 A., VALVE-GROUP INVERTER STATIONS. (A.C. FILTER AREA NOT INCLUDED).[23]

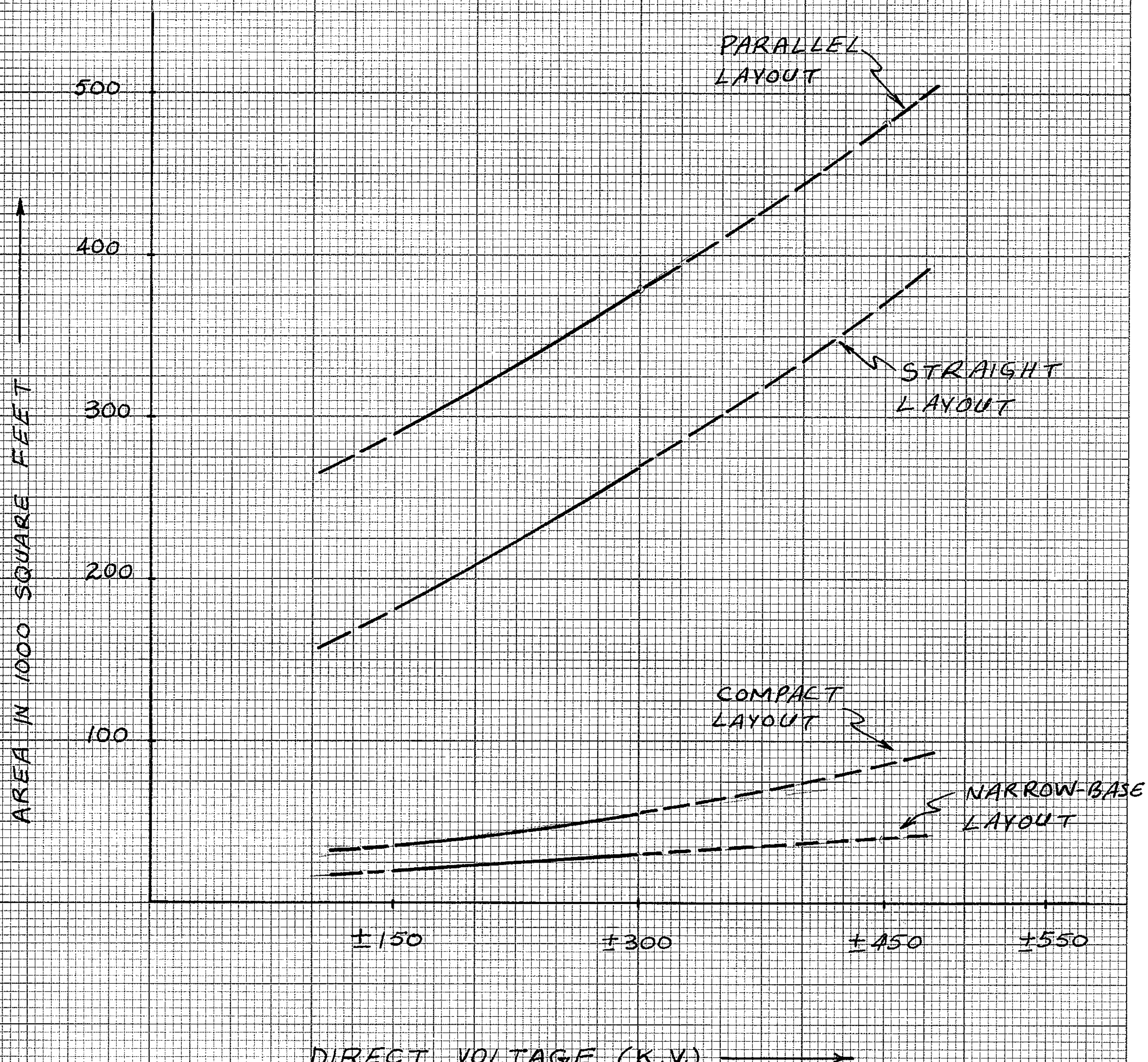


FIG. 2.8

APPROXIMATE LAND AREA REQUIREMENTS FOR A.C. FILTERS FOR DIFFERENT TYPES OF LAYOUTS AT DIFFERENT VOLTAGES.[23]

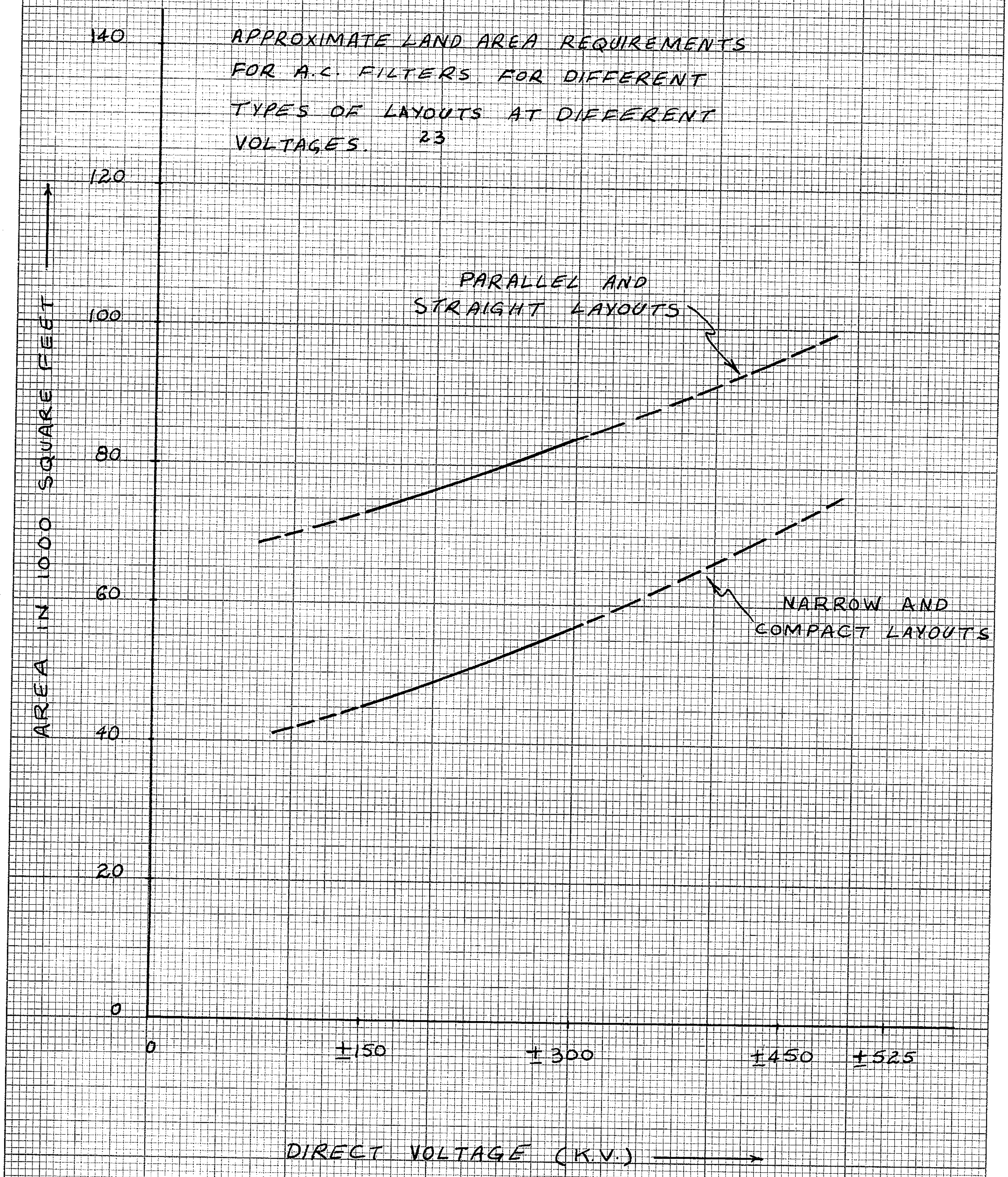


Table (II-1)
Comparison of land area and building volume requirements for different types of layout of same rating (± 450 KV D.C.)

Type of Layout	Required Land Area			Building Volume Million Ft^3
	Switchyard $Ft.^2$	A.C. Filters & Capacitors $Ft.^2$	Total Ft^2	
Narrow Base	40,000	71,000	111,000	4.3
Compact	85,000	71,000	156,000	2.8
Parallel	480,000	96,000	576,000	1.8
Straight	370,000	96,000	466,000	1.95

Notes:

1) Switchyard area includes - building, converter transformer banks, d.c. line and electrode line equipment a.c. switchyard (bus bar only, not including A.C. termination).

2) Building volume includes - Valve hall, transport aisle, Valve servicing and preparation rooms, Relay and Control rooms, offices, etc.

layout for the particular site concerned. Nevertheless, the straight layout offers many attractions as compared to other layouts.

1. D.c. terminal stations are usually built for the transmission of large blocks of power over long distances. Thus for safety and economic reasons they should be located away from populated areas where abundant land is available at a much lower cost. The narrow or the compact layout would be quite uneconomical in such locations.

2. In a straight layout, the switchyard is simple and neat and offers straight, uncomplicated and very economical bus work. The switchyard of the parallel layout is complicated and expensive.

3. Although the building volume required for a straight layout is slightly more (about 8-10%) than for the parallel layout, it is offset by smaller (about 20-25%) overall land area required.

4. In North America (U.S.A. and Canada) large areas of flat land are not scarce and a straight layout would prove the most practical and economical in the majority of cases.

Based on the above reasons it has been decided to consider a straight layout for the purposes of this thesis. One such layout is shown in DWG. 2B.*

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* See large drawing in the back pocket of thesis.

2.7 BASIC IMPULSE LEVEL, CLEARANCE AND CREEPAGE DISTANCE:

When considering the layout of an a.c. electrical station it is necessary to arrive at an economical and electrically acceptable value of basic impulse levels (BIL) of all equipment and clearances and creepage distances required for the desired rated voltages. Same is true for H.V.D.C. terminal station. BIL is defined as: [24]

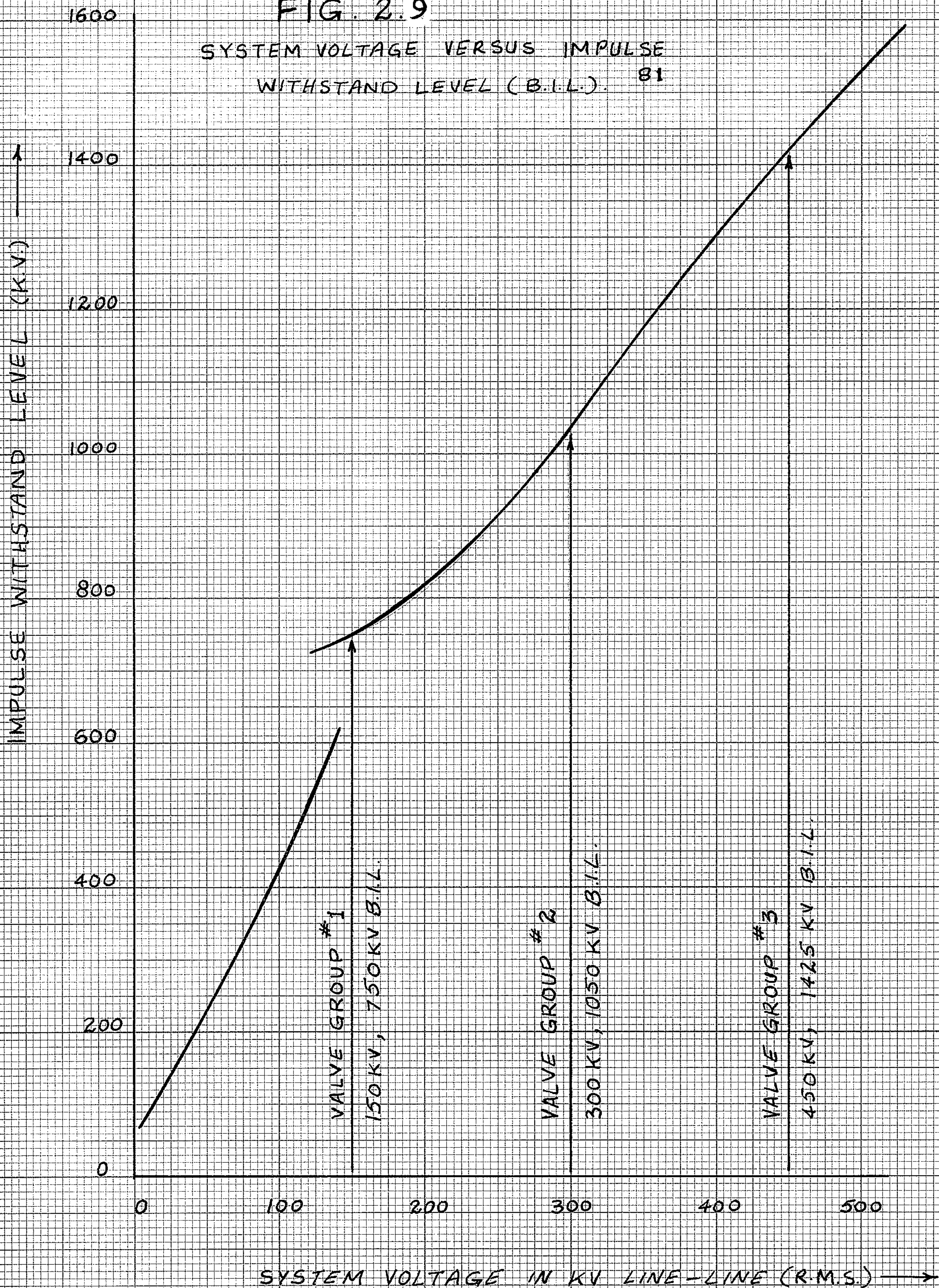
"Basic impulse insulation levels are reference levels expressed in impulse crest voltage with a standard wave not longer than 1.5 x 40 micro-second wave. Apparatus insulation as demonstrated by suitable tests shall be equal to or greater than the basic impulse insulation level."

As clearances are related to impulse withstand levels it follows that the choice of these levels is a principal factor influencing the design of layout of the station. The objective, therefore, is to determine the lowest values consistent with security of operation and consistent with good engineering practice.

Establishment of the impulse level for an equipment is quite involved. Extensive work has been done and experience gained by research engineers over a period of several years. The BIL value of an equipment is principally governed by the type and properties of protective equipment, lightning arresters and sparkgap settings. In the case of d.c. there is no established

FIG. 2.9

SYSTEM VOLTAGE VERSUS IMPULSE WITHSTAND LEVEL (B.I.L.) 81



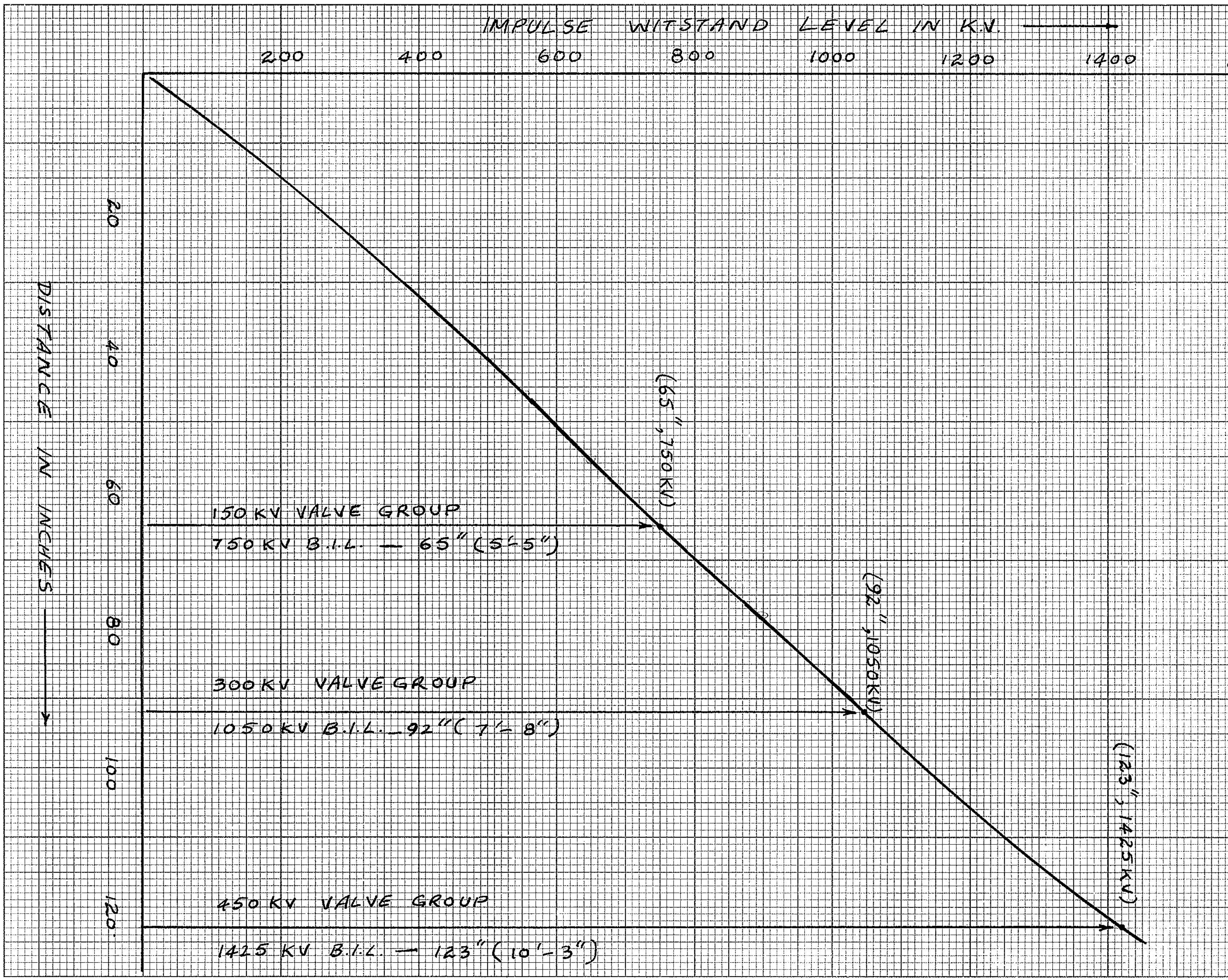


FIG. 2.10

B.I.L. VERSUS CLEARANCE

81

universally adopted standard as yet and extensive investigation is being done at the moment by different concerns including Teshmont Consultants Ltd., Winnipeg. The philosophy for establishing basic impulse levels for H.V.D.C. equipment may be stated as follows:

For any particular voltage level and circuit arrangement, the maximum dynamic overvoltage that can be generated within the system is calculated. This overvoltage is then taken as the lowest voltage against which the lightning arrester must reseal. From the lightning arrester manufacturer's data an arrester can be selected to meet this reseal voltage. Furthermore the maximum withstand voltage that can occur in the station is calculated from which a BIL is selected for the equipment from the standard table.

In FIG. 2.9 the curves show the I.E.C. recommended values of system voltage vs. impulse withstand level and the curve on FIG. 2.10 gives the criterion for determining clearances that have generally been adopted by I.E.C. for d.c. terminal stations. The values of BIL and clearances determined from these curves for a particular voltage would be subject to the following conditions:

1. The values determined may be varied by 20-30% to arrive at a standard value of BIL and/or clearance.

2. The values refer to an altitude of less than 3300 ft. (1000 meter) and take into account the most unfavourable conditions which may result from atmospheric pressure variations, temperature and moisture.

3. Above 3300 ft. and up to 10,000 ft. clearances should be increased by 1.25% for approximately every 330 ft.

4. In the case of outdoor installations the clearances may be slightly increased (typically up to 1.4%)

5. When the configurations of line and earthed parts are exceptionally unfavourable, it may be desirable to check the distance by a direct impulse test on a model structure incorporating the elements involved.

6. For insulating switches the insulation level should be increased by about 15-20% from those determined from the curves.

Basic Impulse Levels for 150 KV, 1800 amps. valve groups considered here are determined from the curve of FIG. 2.9 and are tabulated in table II-2 below.

Group No.	Rated Direct Voltage (KV)	BIL (KV)
1	150	750
2	300	1050
3	450	1425
Neutral	0	150

81
Table II-2
Recommended Values of BIL for Different Rated Voltages

Creepage distance is the total length along the surface of the insulator through which a spark has to creep, due to overvoltages, in order to cause a flashover.

For indoor installations, creepage distances present no problems and standard a.c. substation insulators may be used. However for outdoors the subject of creepage distance is rather complicated. Flashover voltage of a polluted insulator is proportional to the creepage distances, provided there is adequate clearance between live parts at different potentials. It can happen that on a, say, 550 KV BIL insulator there is insufficient creepage and one has to use a 750 KV BIL insulator.

The minimum creepage distance depends on climatic conditions, location of station, and system operating conditions. Typical minimum creepage values for a fairly clean place can be taken as below:

For Indoor Installations = 1 to 1.8 cm/K.V.P.*

For Outdoor Installations = 2.3 cm/K.V.P.

For a polluted area such as industrial or sea coast, the minimum creepage distance for outdoor installations could increase up to about 4.0 cm/K.V.P.

These values are based on laboratory and field tests and on experience from installations in operation.[20]

FIG. 2.11 gives the working voltages and corresponding impulse voltage values of different items of equipment in an inverter terminal station obtained from curves on FIG. 2.9 for the d.c. section, and from the NEMA standard for the a.c. section.

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* P = Peak

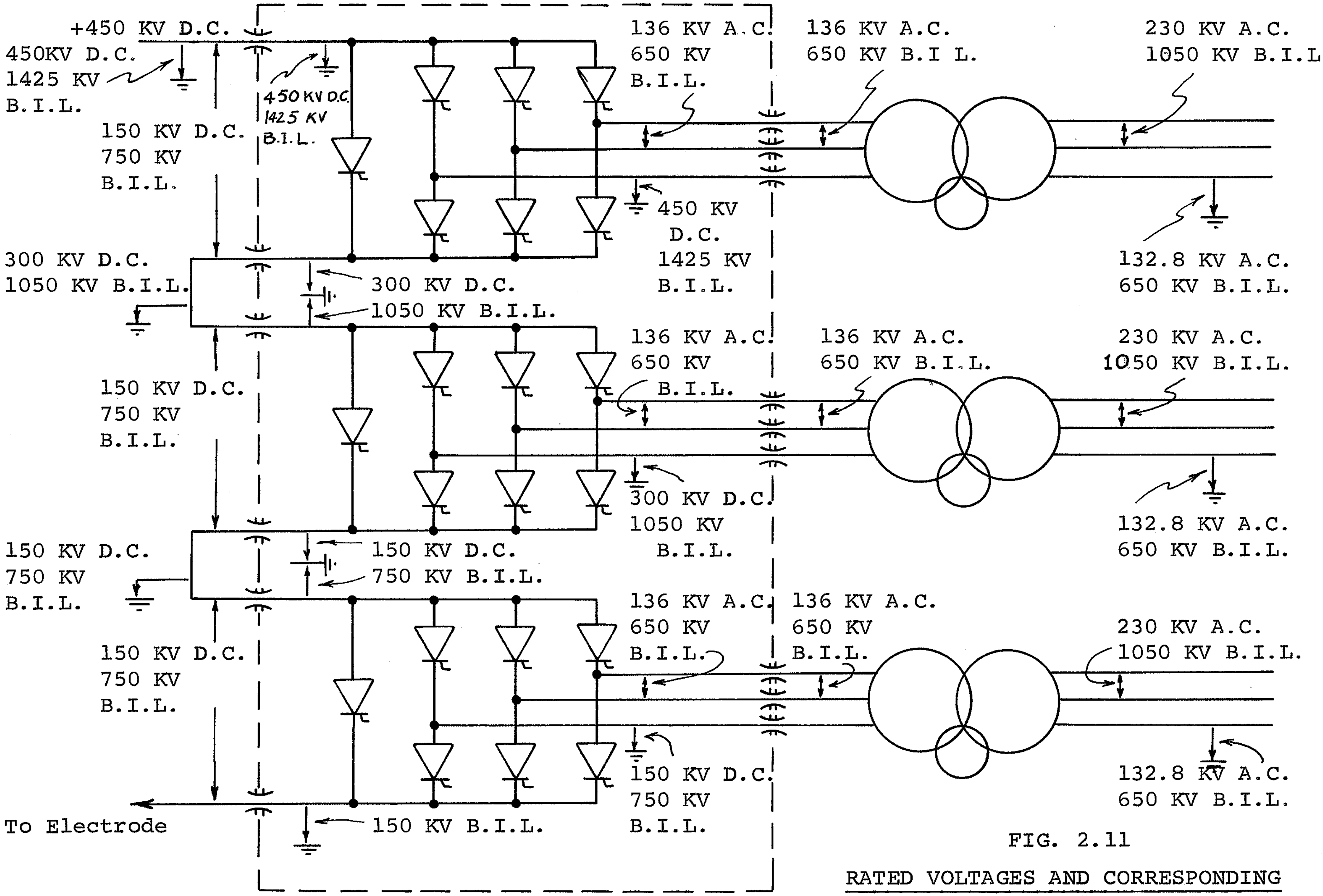


FIG. 2.11

RATED VOLTAGES AND CORRESPONDING BASIC IMPULSE LEVELS.

CHAPTER III

CONVERTING EQUIPMENT

3.1 INTRODUCTION:

Conversion of electrical power can be carried out by means of a special switching arrangement such as the "Transverter System" developed in England in the early 1920's or the "Swedish Glesum System" developed in Sweden in the early 1930's.[25] Such switching systems, although they might work quite satisfactorily under steady state conditions, cannot operate fast enough to respond to the rather frequent transient phenomena taking place in the connected a.c. system during faults or sudden variations of loads.

The only suitable electric switching devices, which can be made to respond to a.c. system transients and load variations are:

1. mercury arc valves; or
2. diodes and/or thyristors.

These devices have the inherent characteristic of facilitating conduction of current during the period when anode is at higher potential (positive) with respect to its cathode. The current could only be interrupted when the anode is at zero or lower potential (negative) with respect to its cathode.

3.2 JUSTIFICATION OF MERCURY ARC VALVES:

Due to the development of thyristors, the converter industry at the present time is going through a major revolution. In the majority of applications which require uncontrolled rectification, silicon and germanium diodes have already almost completely replaced mercury arc valves. In power inversion applications and grid controlled rectifications the mercury arc valves are still holding their leading position. However, in these fields also, thyristors have made progress and it is argued [16,26] that the day is not too far when most of the applications involving rectification and inversion will employ thyristors.

At present considerable research is being carried out in the development of thyristors for H.V.D.C. applications.[16,27,28,29] As a result the design engineer today has the choice between thyristors and mercury arc valves.

3.2.1 Comparison of Mercury Arc Valves with Thyristor Valves:

a) According to some manufacturers, thyristors are more expensive to manufacture at the present time than the mercury arc valves of equivalent ratings. It is claimed:[31]

"If a converter station using thyristor valve equivalents was built and successfully tested tomorrow, it would be quite uneconomic compared with one using mercury arc valves. The forward voltage drop across the thyristors would be too high and the thyristors themselves too costly."

b) Another investigation [29] shows that an H.V.D.C. terminal station with thyristors would be about 25% cheaper than with mercury arc valves. The main features in favour of thyristors are claimed to be:

1. Thyristors can be of outdoor type thus reducing building costs (refer to Chapter II, Section 2.4).

2. No arc-backs present and no by-pass valve required with thyristors (Chapter II, Section 2.2.1.b).

3. Thyristors can operate at much smaller angle of deionization (5-10^{o}) as compared to mercury arc valves (15-18^{o}), thus resulting in reduced reactive power consumption.

4. Thyristors do not require any warm up time.

5. Maintenance cost is lower on thyristors and they do not deteriorate in service.

c) At present thyristors are rated about 2 to 4 KV each. Thus in H.V.D.C. applications a large number of modules must be connected in series. All the thyristors have to be fired simultaneously and require uniform voltage distribution. This necessitates very accurate voltage dividers and complex firing circuitry.[32]

d) In recent years there have been several H.V.D.C. systems installed. They all have been based upon multi-anode high voltage mercury arc valve technology, including the Nelson River - Winnipeg Transmission scheme.[14,15] There is no commercial operating experience available at the present with thyristors used in H.V.D.C. schemes.

e) Grid controlled multi-anode mercury arc valves for bridge ratings up to 1800 amps., 150 KV (270 MW) are commercially available and such valves for operation at 200 KV are being developed by the English Electric Co. and ASEA.[12] In addition the English Electric Co. has also built a high power thyristor valve using 144 thyristors in series with a stack bridge rating approaching 100 KV, 450 amps.; General Electric Co. has built a 200 KV, 2000 amps. thyristor valve[16]; and HVDCT - Working Group (AEG, BBC, Siemens) in Europe has built experimental thyristor valves using up to 180 thyristors in series with bridge ratings of 100 KV, 1200 amps.[27]

Thus it can be safely stated that future installations will utilize thyristor techniques.

3.2.2 Comparison of Mercury Arc Multi-Anode Valve with Single-Anode Valve:

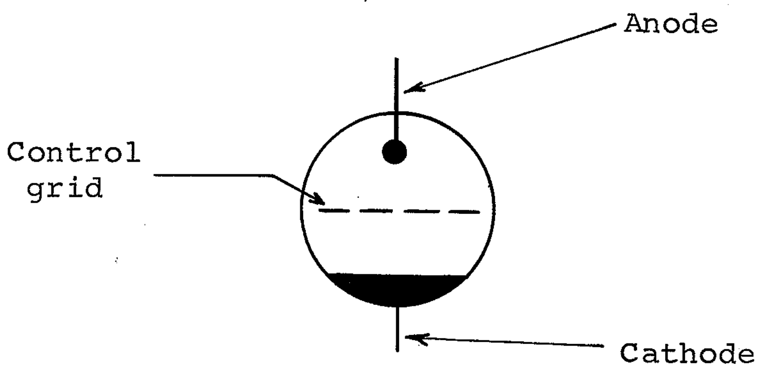
Until now all H.V.D.C. installations used the multi-anode mercury arc valves. But now a single-anode, single-grid mercury arc valve is being developed. The C.E.G.B. and General Electric Co. of England are developing such a valve (type E3175).[30] This valve is claimed to be capable of an output of about 70 KV, 1000 amps. A bridge using 18 such valves with 3 in series per leg would be capable of about 200 KV, 1000 amps. output. This valve is expected to have following advantages:

1. Lower cost per KW.
2. Smaller size per KW.
3. Suitable for outdoor installations (hence reduced building cost).

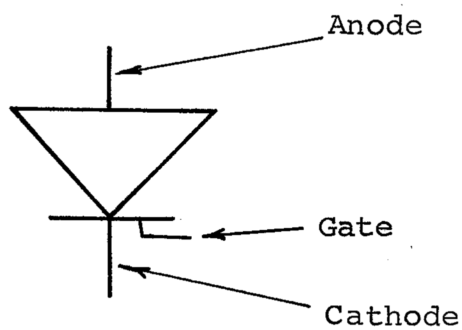
It is therefore considered very strongly that single-anode, single-grid type valves may also be available in future H.V.D.C. applications.

For the purposes of this thesis the multi-anode high voltage mercury arc valve has been chosen and from here on only this type of valve is considered.

The symbol used for mercury arc valve is as below:



In this thesis, for the sake of simplicity in illustrations the symbol shown below has also been used to represent high voltage multi-anode mercury arc valve.



3.3 MERCURY ARC VALVE:*

Mercury arc valves and their auxiliaries represent about 30% of the total cost of the terminal equipment of an H.V.D.C. transmission link.

Before considering the design of the inverter station

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* The terms "Valve", "H.V.D.C. Valve" or "Mercury-arc valve" will be used elsewhere for "High Voltage Multi-Anode Mercury Arc Valve" unless otherwise specified.

it is desirable to appreciate the research work that has gone into valve development.[10,15,25,34,36,37] The basic parts of a modern valve are mentioned below:

3.4 MAJOR CONSTITUENT PARTS OF A VALVE:

Today's valve consists of five major parts:

1. Anode Assembly;
2. Voltage Divider;
3. Current Divider;
4. Vacuum Tank and Mercury Pool Cathode;
5. Auxiliary Equipment.

The anode assembly consists of an anode, a series of grids called "grading electrodes" inserted between the anode and cathode, the control grid and the porcelain tube supporting the anode.

The anode assembly is mounted on top of the stainless steel vacuum tank. The mercury pool cathode is contained in the bottom of the vacuum tank. The assembly is mounted within a steel chasis which is generally supported on wheels. The chasis also contains fans, heaters and the vacuum system equipment.

FIG. 3.1 illustrates the main parts of a valve based on an ASEA design and FIG. 3.2 shows the circuit arrangement for the current divider in a six anode valve (1800 amps., 150 KV).

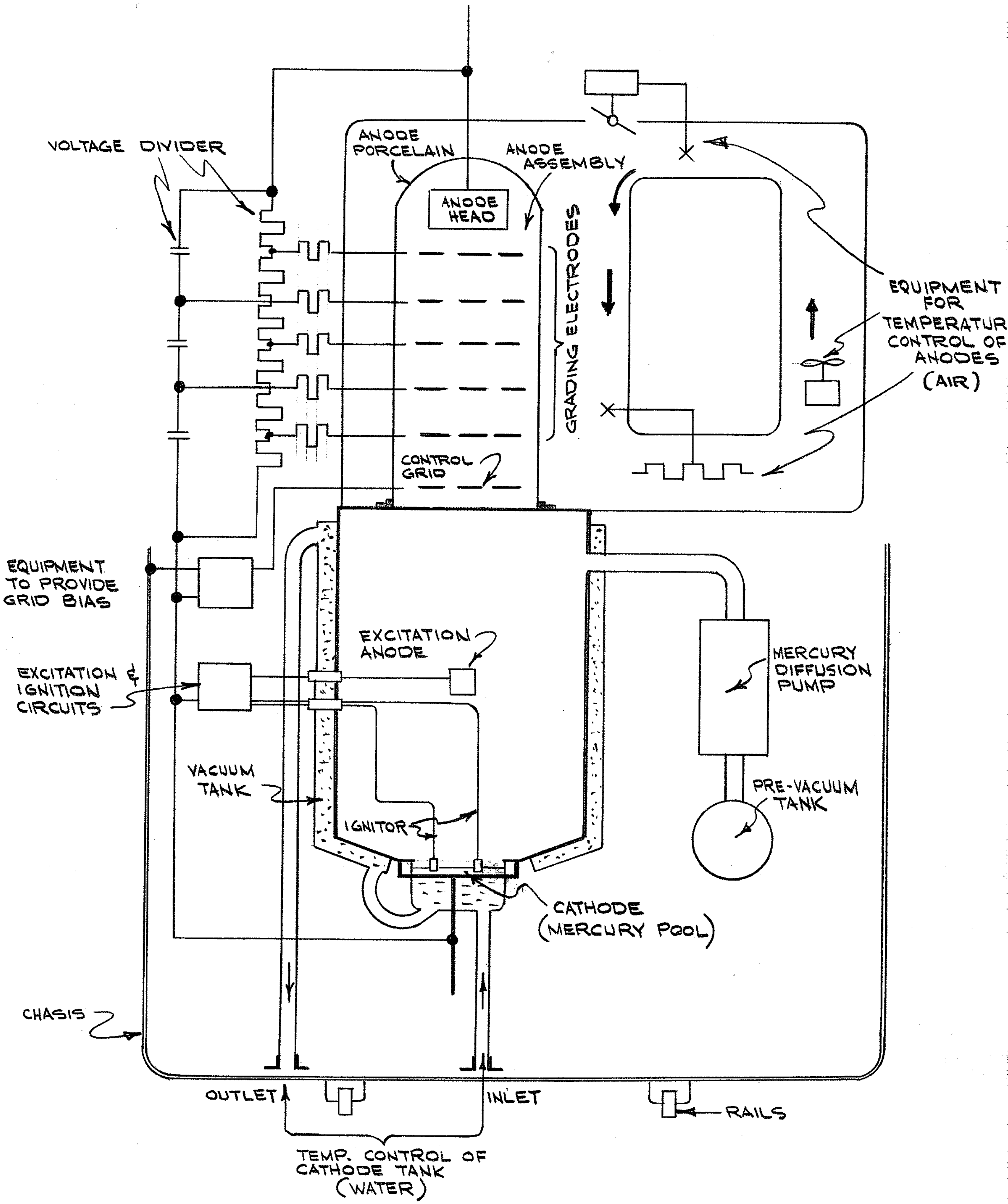


FIG. 3.1
(A TYPICAL HIGH VOLTAGE MERCURY ARC VALVE)

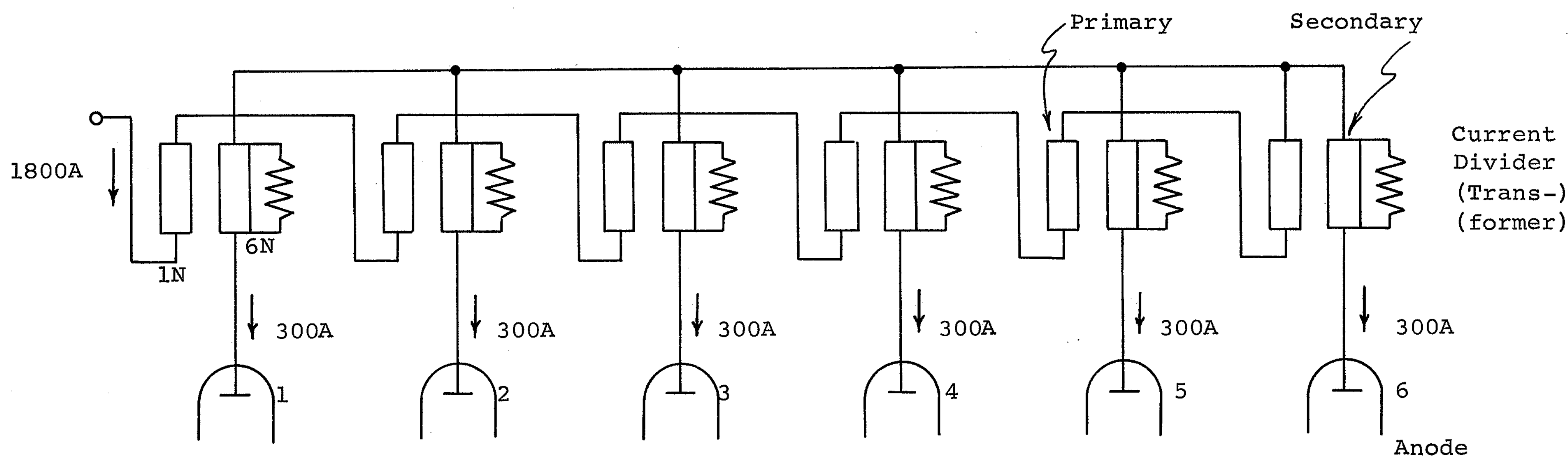


FIG. 3.2

CIRCUIT ARRANGEMENT FOR CURRENT DIVIDER IN A SIX ANODE VALVE [13]

3.5 ARRANGEMENT OF VALVE PARTS:

Two different arrangements of a complete six anode valve are shown in FIG. 3.3 and 3.4. In FIG. 3.3 all six anode assemblies are arranged in one line, whereas FIG. 3.4 has two parallel rows of anode assemblies with three anode assemblies in each row.

Arrangement of all anodes in one line presents several disadvantages, some of which are given below:

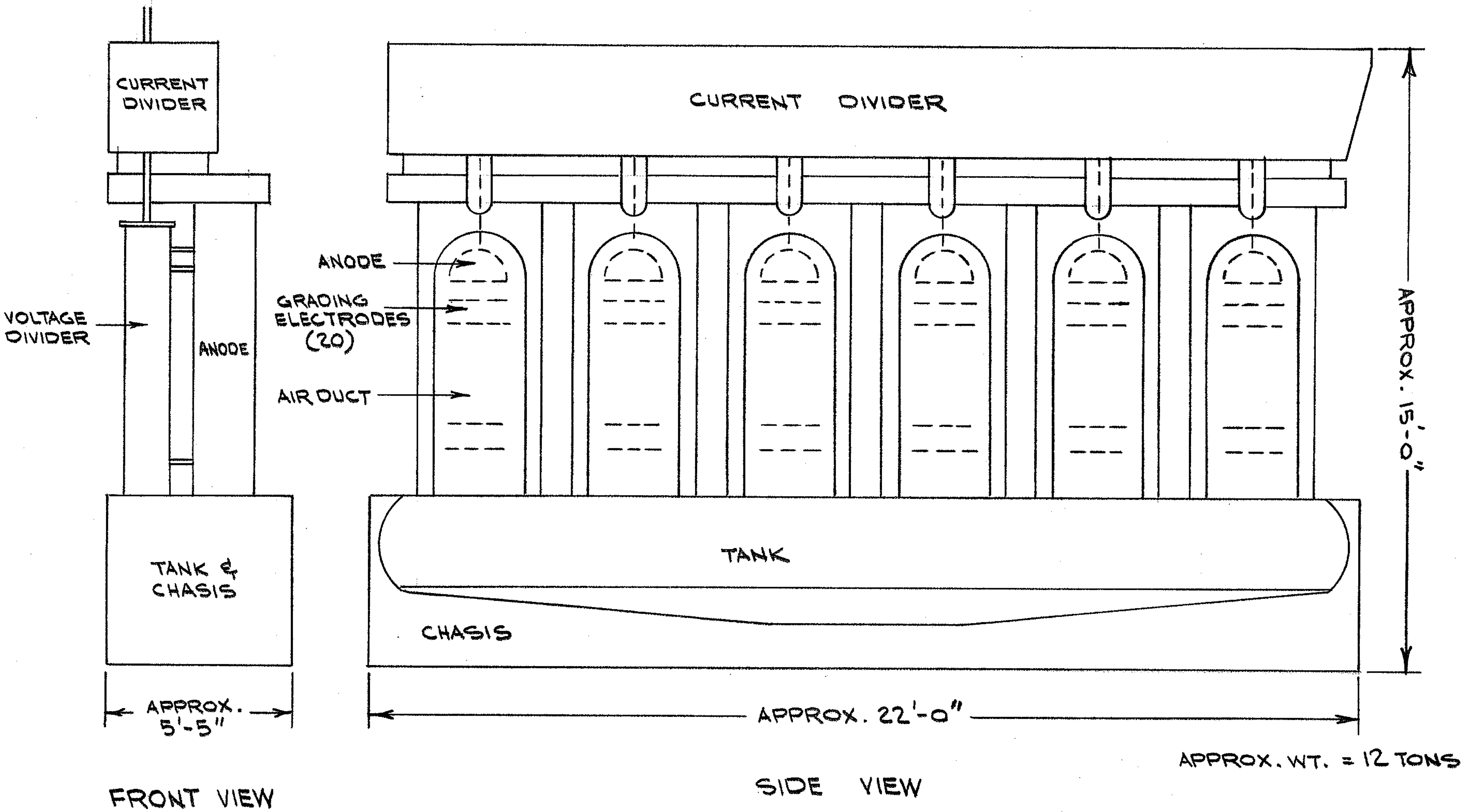
a) A narrow and long tank and a very long voltage divider assembly is more difficult and expensive to manufacture than a shorter and wider one.

b) Cooling arrangements in a narrow valve would be less efficient and more expensive.

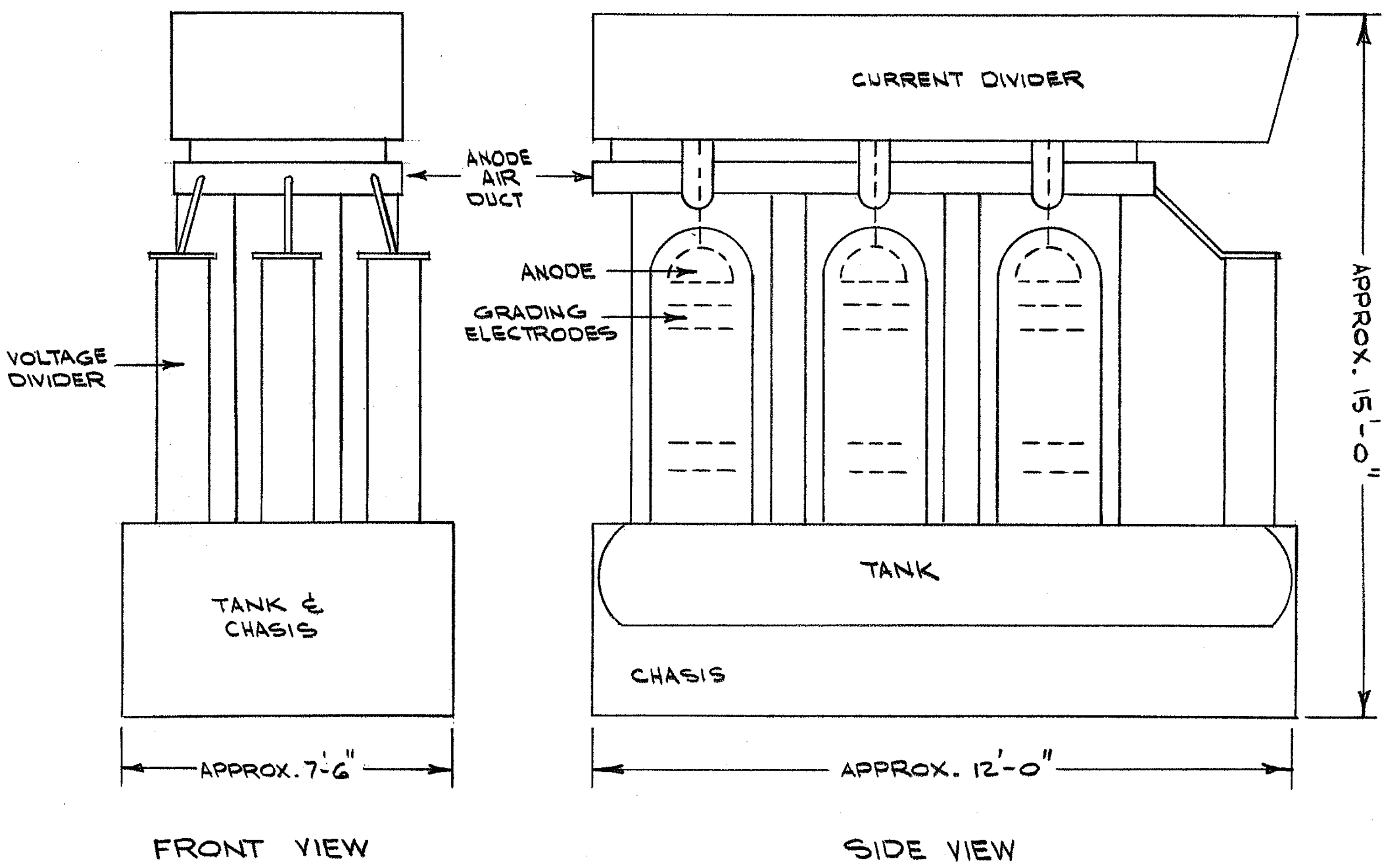
c) More valve withdrawl space is needed with long valves resulting in wider aisles and consequently bigger and more expensive valve buildings.

d) Transportation of a narrow and long valve is more difficult.

These reasons speak well in favour of parallel arrangement of anodes as shown in FIG. 3.4. Both ASEA valve JVKA6 used in the Pacific intertie [ΦΦ] and the proposed English Electric valve ARBJ6 for the Nelson River - Winnipeg scheme[13,14,15] are based on this design. A photograph of a typical High Voltage



(FIG. 3.3)
MULTI ANODE MERCURY ARC VALVE
150 K.V. 1800 A



APPROX. WT. = 12 TONS

(FIG. 3.4)
MULTI ANODE MERCURY ARC VALVE
150 K.V. 1800 A

mercury arc valve is shown in FIG. 3.5.

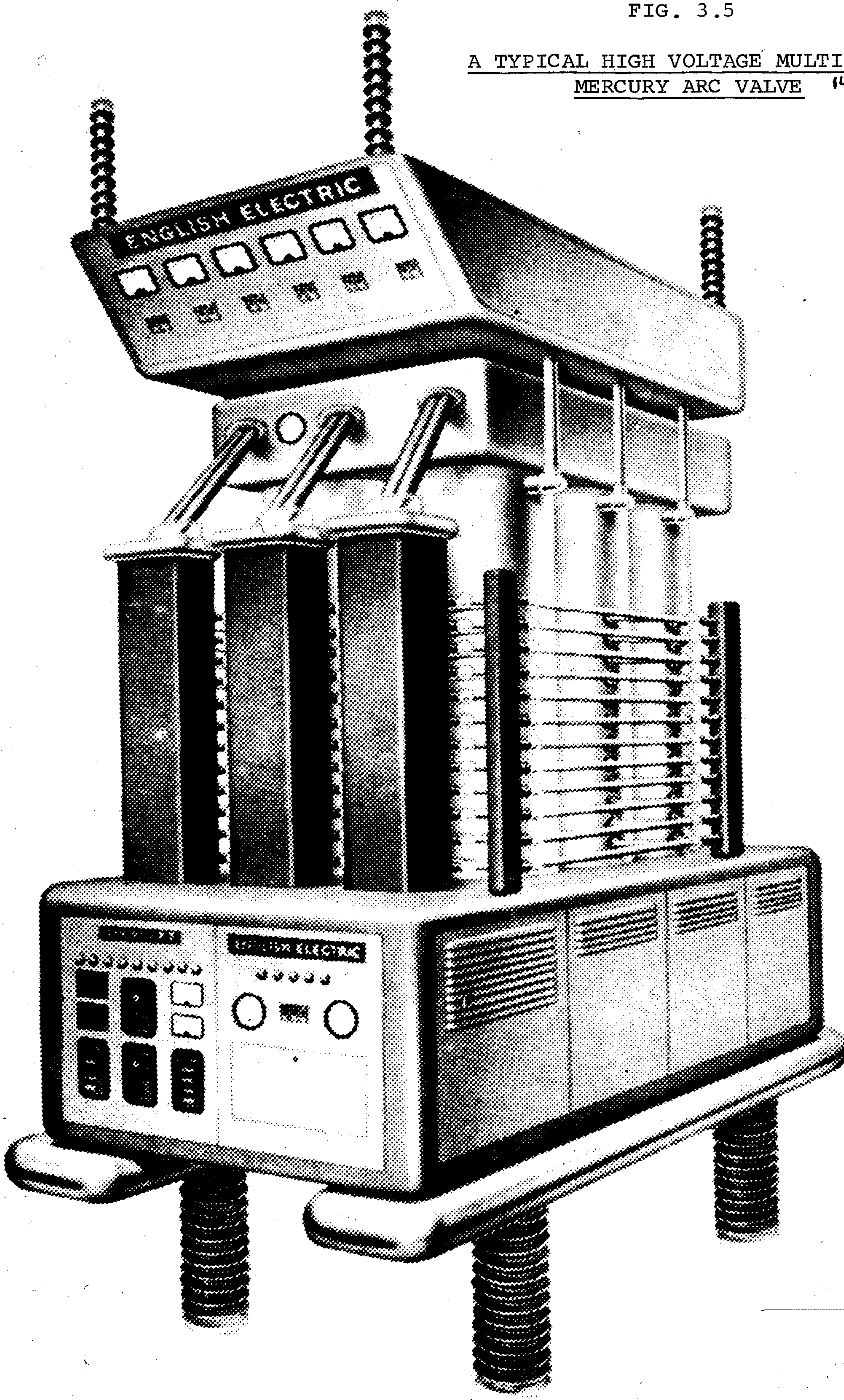
3.6 OPERATION OF VALVE:

The mercury pool cathode is the source of electrons and mercury vapour. The cathode is excited by means of ignition electrodes which are the source of excitation current creating the cathode spot.

The valve is held in the off position, i.e., blocked by maintaining its control grid at a negative voltage (about 300 V) with respect to its cathode. In order to fire the valve a positive pulse is superimposed on the control grid, which begins to attract the electrons. These electrons now pass into the field of the anode and the grading electrodes. On their way the electrons collide with neutral atoms of mercury vapour producing positive mercury ions. These positive ions are attracted towards the cathode. The presence of the positive ions neutralizes the electron space charge, which results in the low arc voltage drop. The valve now starts conducting. Once conduction starts, the control grid loses its control and the valve can only be blocked by bringing the anode voltage to zero or negative thus reducing its arc current to zero. Time must be allowed to deionise the valve before the control grid can become effective in preventing conduction of valve.

FIG. 3.5

A TYPICAL HIGH VOLTAGE MULTI ANODE MERCURY ARC VALVE [14]



3.7 THREE PHASE H.V.D.C. MERCURY ARC BRIDGE (VALVE GROUP):

In H.V.D.C. transmission three phase bridge connection has been accepted as the best connection for conversion of electrical power.[17,26,38] This is mainly because the bridge connection provides the best utilization factor for the transformer, as high as 95%.[25] Also, for the same output voltage, the maximum valve voltage is half that corresponding to other valve arrangements such as "double star" or "six-phase half wave" connections, and the valve current is double. This is advantageous from the point of view of valve rating and design.

FIG. 3.6 shows a typical bridge in its simplest form, connected as inverter. The circuit involves the series operation of two three-phase half wave bridges, 180^{o} out of phase. The top three valves (namely 4, 6 & 2) operate as one half and the bottom three (namely 1, 3 & 5) operate as the other half. Together they provide an output which is twice that of each half.

For the operation of the bridge it is necessary that the valves must be fired in a predetermined sequence and that the firing of valves must be controlled and timed accurately.* One of the valves is fired every 60^{o} and keeps conducting during roughly one third of a cycle (approximately 120^{o}).

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* Firing sequence tables for rectifier and inverter bridges are given in appendix II.

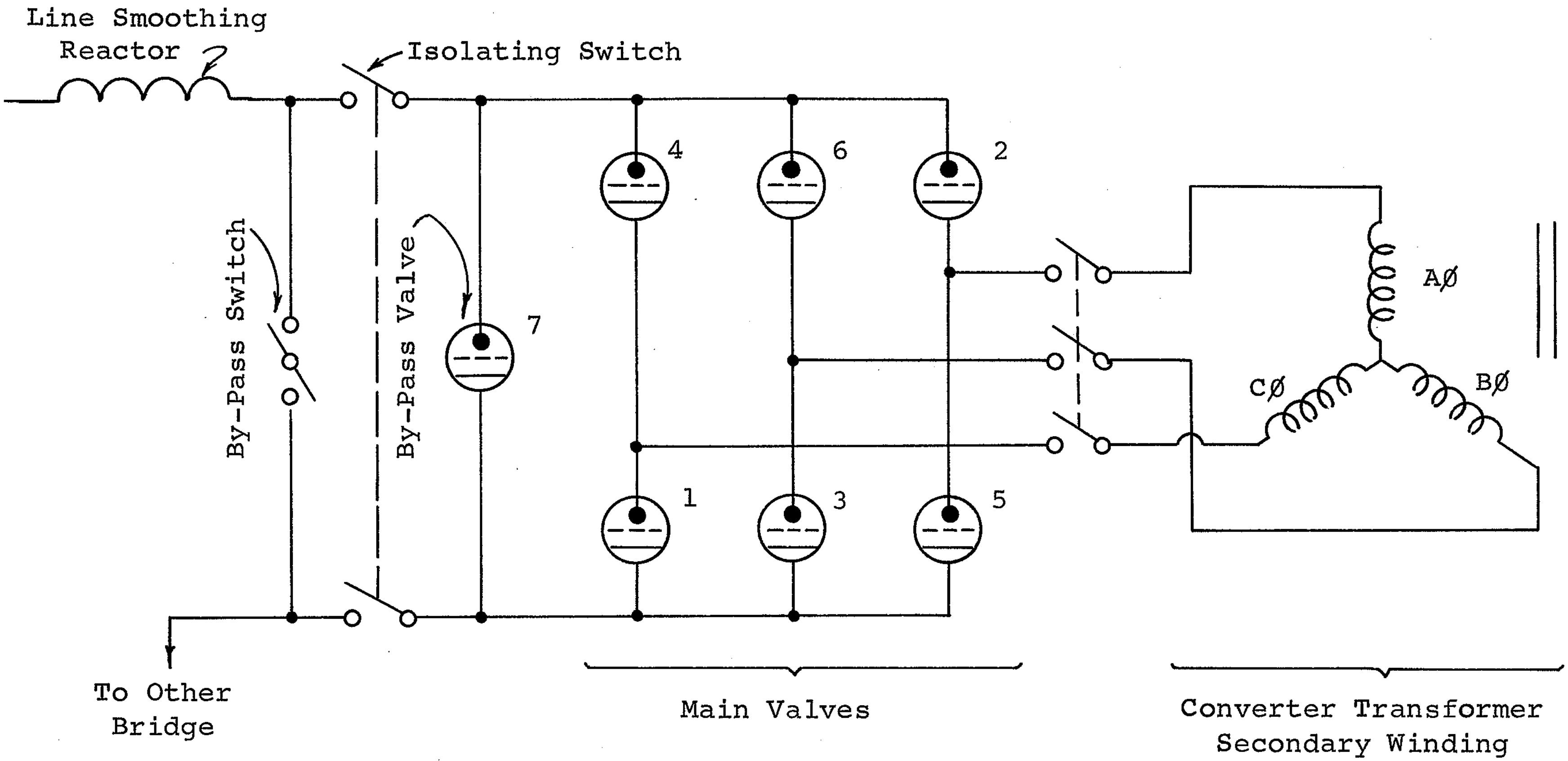

FIG. 3.6

THREE - PHASE BRIDGE ARRANGEMENT

Thus two valves conduct simultaneously in series (for 120°). During the remaining part of the cycle, the valve is first exposed to high inverse voltage and then to high positive voltage until the time when the arc is released by the control grid. The proportion between the time of inverse voltage and the time of positive blocking voltage depends upon the degree of phase retardation by grid control. In rectifier operation the inverse-voltage period is dominant, while in inverter operation the blocking voltage period is dominant. (FIG. 3.7)

The by-pass valve is similar to the main valves in construction and design, the only difference being that it is capable of carrying full line current usually for 30 to 60 seconds continuously.

Reference to Chapter II, section 2.2.b, the by-pass valve serves to by-pass the main valves of the bridge. During normal operation, this valve stays blocked. Due to any internal disturbance such as, commutation failure, fire through, arc back, arc quenching, etc., the main valves fail to operate. During this time the bridge is blocked temporarily, the by-pass valve unblocked and the direct current is transferred to the by-pass valve. The flow of current is, therefore, uninterrupted. As soon as the disturbance is cleared, the by-pass valve is blocked and the main valves unblocked to take over normal operation.

Although H.V.D.C. theory states that the temporary

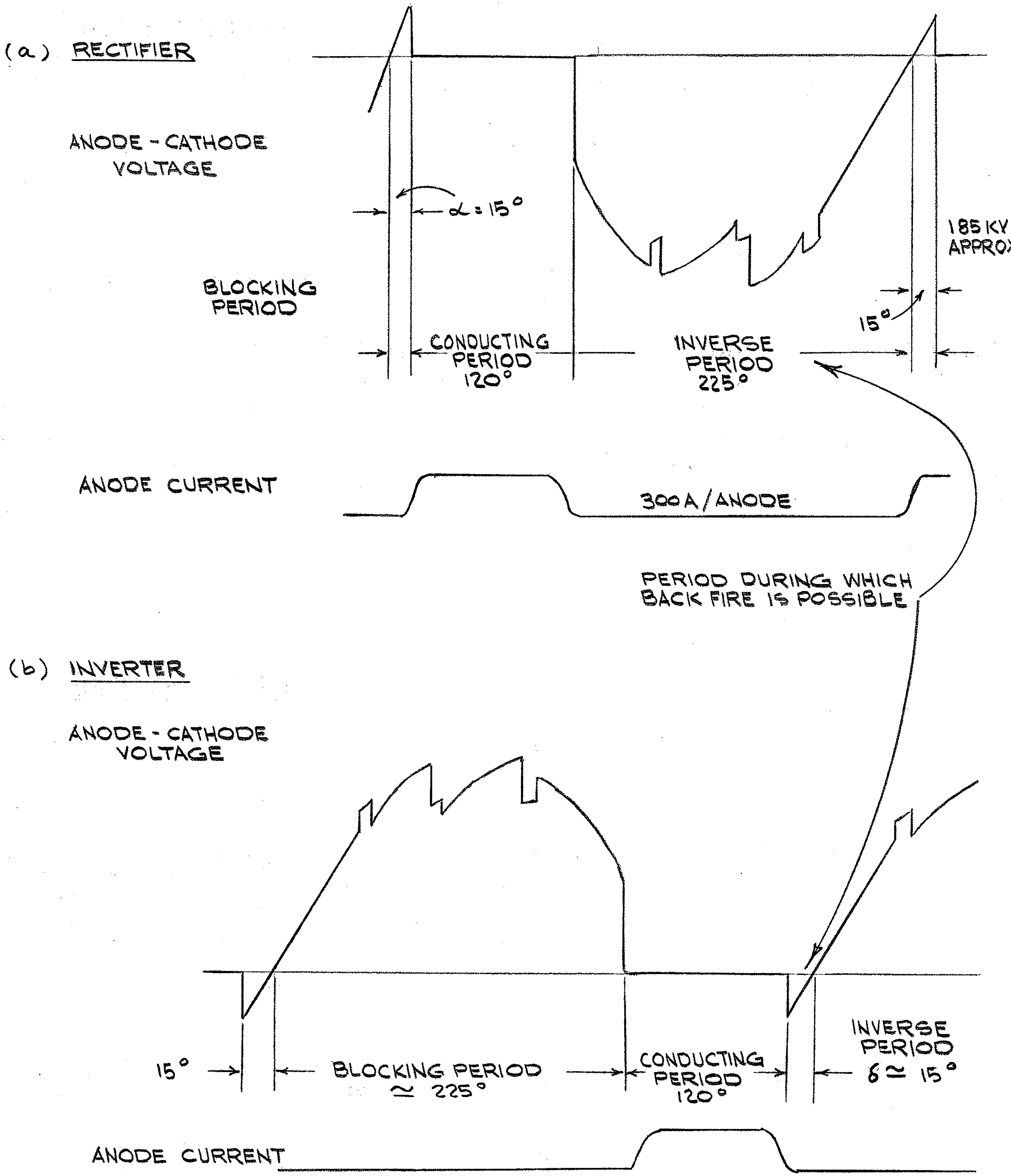

FIG. 3-7
TYPICAL VALVE VOLTAGE AND CURRENT WAVE FORMS IN 3 PHASE BRIDGE (RECTIFIER & INVERTER)

35

blocking-unblocking sequence can be accomplished in about 5 cycles (about 80 milliseconds), in actual practice this time may be more than that. The control circuit generally goes through a checking cycle to make sure that conditions for unblocking are satisfactory. For this reason longer blocking-unblocking time will be required.

The main reason for providing a by-pass valve is because the mercury arc valves cannot be designed to be entirely free from "arc-backs". The design of a mercury arc valve free of arc-backs has not been realised yet. But if it is, the elimination of the by-pass valve may be foreseen.

The theory of operation of a bridge has been dealt with in detail in several papers and books.[12,17,18,38] DWG. 3A* is drawn to define and identify the terms used in H.V.D.C. terminology and also for reference purposes. A list of the symbols used in this thesis is given in appendix III.

3.8 DAMPING CIRCUITS, ANODE REACTOR AND CATHODE REACTOR:

At the instant a valve starts conducting the voltage between its anode and cathode rapidly collapses to zero and the forward anode current rises very steeply to its full value. On the other hand, at the instant when a valve stops conducting

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* See large drawing in back pocket of thesis.

the anode current suddenly drops to zero value and the inverse anode - cathode voltage (rectifier) or blocking voltage (inverter) rises rapidly to its full value. This rate of sudden voltage and current change depends on the angle of delay and overlap. The greater the values of these angles the greater is the sudden change. Methods to limit these sudden changes are discussed below:

i) Damping Circuits:

At the beginning and the end of commutation, the high voltage step to which a valve is exposed creates high frequency oscillations in circuits which are mainly comprised of the leakage inductance of the converter transformers, and stray capacitances of the transformers, conductors and wall bushings. These voltage oscillations may be in the range of 10-60 KHz and may cause a back fire or extinguish the excitation arc. The recovery voltage across the valve may swing to dangerous values and cause severe voltage stresses on the valve (about 150-160% of normal value) making its operation impossible. In order to reduce these voltage stresses to reasonable values, say 110-120%, it is necessary that the energy stored in the leakage reactances and stray capacitances should be dissipated. This is done either in a long train of oscillating waves or more quickly in the resistor of a resistance-capacitance damping circuit.[9,25]

Of several methods of damping,[17,39] the use of series resistance-capacitance (R-C) damping circuits is the most simple and practical for H.V.D.C. terminal stations. These damping circuits can be connected either across each valve or across the converter transformer windings or both. Connection of one damping circuit across each valve results in lower losses, about 15%, as compared to other arrangements and is therefore most preferred.

With proper damping the voltage wave forms in the valves of a bridge are expected to be as shown in FIG. 3.7 and the electrical connections of these R-C circuits are shown in DWG. 2A (back pocket). The resistors of the damping circuits are connected in star and the common point is connected to one of the d.c. terminals of the group. The other terminals of the star connected resistors are connected to the bus on the a.c. side of the group via damping capacitors. The entire R-C damping circuit must be insulated from ground for the corresponding group voltages. This can be achieved by supporting resistors and capacitors on insulators.

Damping involves dissipation of energy in the damping resistors. This necessitates adequate cooling of these resistors. These damping circuits can be installed outside the valve hall and placed as close to the valves as practically possible.

ii) Anode and Cathode Reactors:

At the instant of commutation, the collapse of voltage between the anode and cathode causes current oscillations with such a high amplitude in relation to the rising main valve current that the resulting arc current may pass through zero several times before the oscillation is damped out.

The principal range of these current oscillation frequencies is about 20-60 KHz due to converter transformer self capacitance and capacitance of the transformer bushings; and also in the range of 0.5-10 MHz due to capacitances of the valve itself.

In FIG. 3.8 typical current waveforms in a valve are shown. These are:

1. The fundamental frequency current wave (FIG. 3.8.a).
2. The damped medium frequency current oscillations, say 20-60 KHz, superimposed on the fundamental frequency current wave (FIG. 3.8.b).
3. The high frequency component, say 0.5-10 MHz, current oscillations superimposed on the fundamental frequency current wave (FIG. 3.8.c).

These medium and high frequency oscillations do not cause any inconvenience to other equipment,[25] but they may force the valve into reverse conduction which would cause the

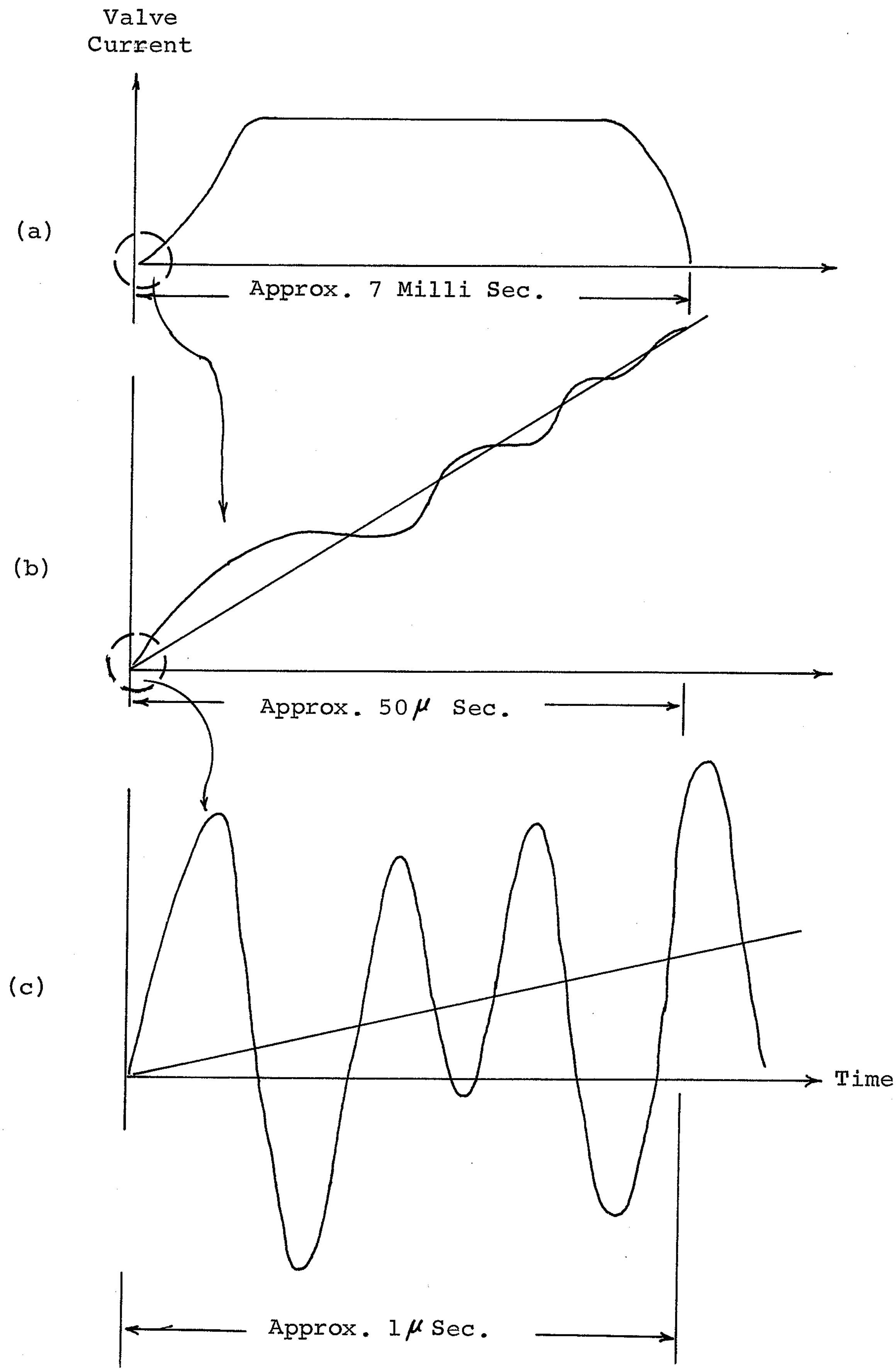

FIG. 3.8

<u>CURRENT WAVE-FORMS IN A VALVE</u> 8

excitation arc and hence the cathode spot to be extinguished and the valve conduction interrupted. These sudden bursts of valve current could cause radio noise and corona in the vicinity of the converter station.

If an inductance (anode reactor) is inserted in series with the anode as close as possible to the anode, the current oscillations can be effectively damped.[10] This is illustrated in DWG. 2A.

Anode reactors also contribute to some extent in suppressing radio emission due to commutation. Nevertheless, separate dampers such as cathode reactors are installed specially to dampen radio frequency oscillations being radiated through the bushings to the yard. These reactors are inserted in series with the cathode of each valve (see DWG. 2A).

A typical anode reactor is constructed of an air core inductor coil damped by parallel resistors mounted inside. Normally the inductor is air cooled. Cathode reactors are usually of the same design or, alternatively, could consist of rings of magnetic material such as "ferrite" through which cathode conductors pass.

3.9 METHODS OF VALVE FIRING:

There are four types of firing systems available at the present time. These are:

1. Constant α Control System;
2. Inverse Cosine Control System;
3. Constant Extinction Angle (γ) Control System;
4. Phase Locked Oscillator Control System.

The first three systems of controlling the firing pulses, or "conventional types of control systems", [40] contain six independent delay circuits per bridge, timed successively from the a.c. line voltages. The control voltage is usually obtained from an automatic negative feed back loop, proportional to the actual d.c. line current and a reference signal. Alternatively the controlled quantity may be power, or a.c. system frequency. Thus the firing pulses are dependent directly on a.c. line voltage and its distortion.

The fourth method, namely, phase locked oscillator [41] is based on the principle of generation of firing pulses at highly accurate relative intervals of 60^{o}, independent of a.c. waveform. A free running oscillator for each valve group is locked in frequency to six times the fundamental a.c. frequency and the relative phase can be shifted by a signal derived from the current control loop. The oscillator drives a six way ring counter which moves on one step per input pulse.

FIG. 3.9 illustrates the principle of operation of phase locked oscillator control system. This method was developed in England by Mr. J. D. Ainsworth of English Electric

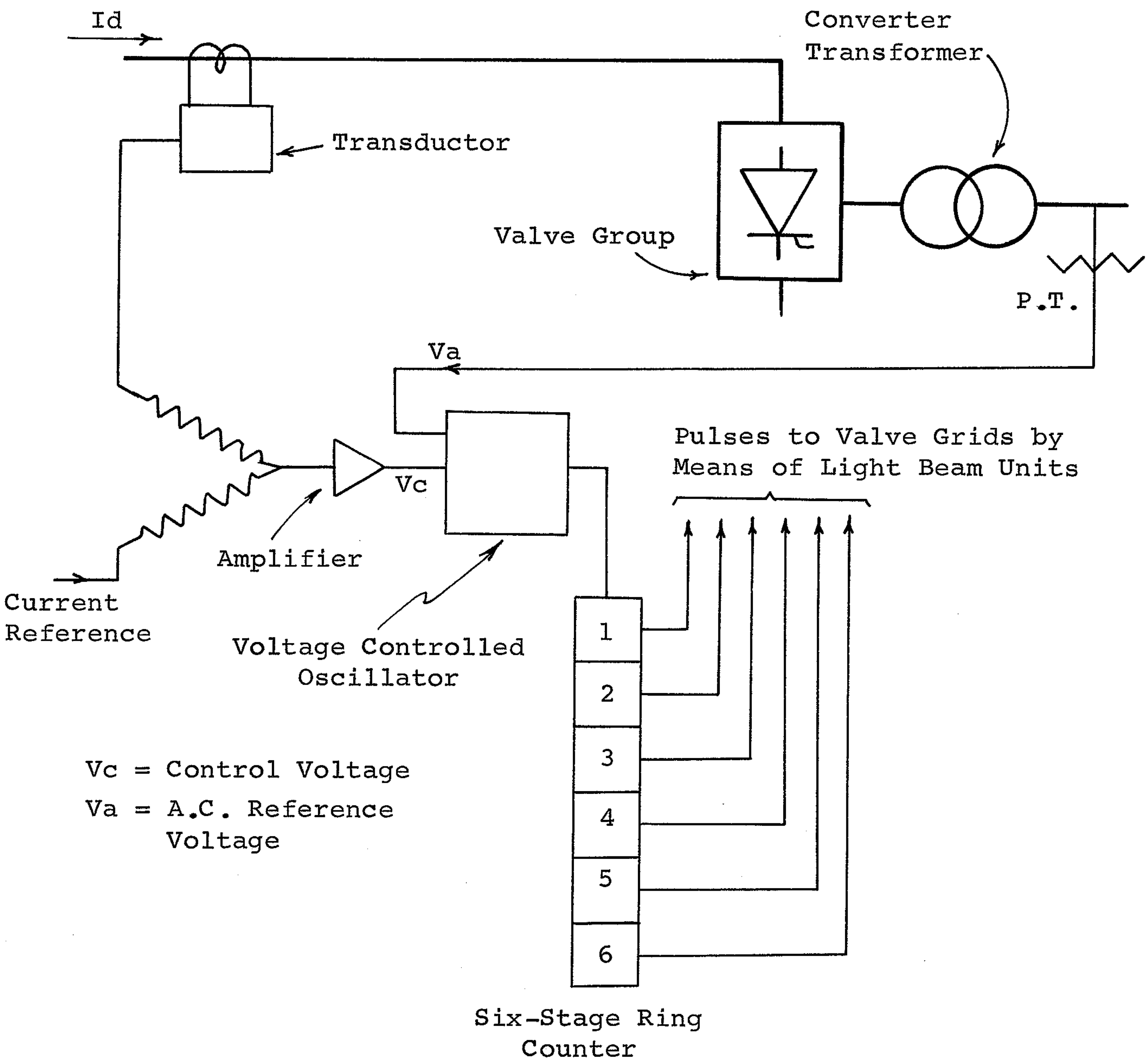

FIG. 3.9

PRINCIPLE OF PHASE-LOCKED OSCILLATOR CONTROL SYSTEM [40,41]

Co. Ltd., and has been extensively tested successfully on an H.V.D.C. simulator.[42] It has been accepted to be used in Kingsnorth H.V.D.C. scheme and also in the Nelson River - Winnipeg H.V.D.C. scheme.

The conventional control systems suffer from several disadvantages and operational difficulties which have been overcome by the phase locked oscillator control system. These are:

a) In conventional control systems, since the firing pulses depend directly on a.c. line voltage, any distortion in the a.c. system is transmitted into the pulse control system. This results in inaccuracy of the firing pulses which, in turn, cause the generation of a.c. and d.c. abnormal harmonics in addition to the theoretical harmonics. These "abnormal harmonics" may be of the order of 1, 2, 3 etc. on the d.c. side and 2, 3, 4 etc. on the a.c. side.

Such harmonics have been found in several H.V.D.C. installations [43,44,45,46] causing excessive interference and have resulted in adding expensive special filters in addition to the filters required for the attenuation of theoretical harmonics.

b) On the a.c. side, these abnormal harmonics and small amounts of other abnormal voltage harmonics present due to, say, generators etc., will cause further irregularity of firing pulses. These irregular pulses generate abnormal current harmonics which magnify the original voltage harmonics by flowing in the a.c. system impedance. This repeated magnification can readily rise to a high value resulting in harmonic instability.

c) The situation is made worse by the fact that firing angle irregularity, in general, produces d.c. components in the converter transformer secondary windings. This tends to saturate the core, producing further harmonics and hence further distortion from primary megnetising currents.

d) Another disadvantage of the conventional control systems is their inability to operate a converter on a very "weak"* a.c. system. Abnormal harmonic magnification becomes excessive and may prevent stable operation of converters.

The harmonic instability can be improved by adding a "control system filter" in the supply of a.c. voltages from the main system to the control system. Theoretically this method should provide sufficient attenuation, but in actual practice has resulted in several disadvantages of its own.

The filter has a phase error which varies with system

---

* The term "weak" a.c. system means a system whose short circuit capacity is less than, say 3 times the d.c. transfer capability.

frequency, and it cannot attenuate negative-sequence fundamental voltages. The effect of these is also to cause irregular firing-pulses, resulting in the generation of more abnormal harmonics by the converter. In addition, the filter ignores the presence of harmonics on the a.c. system voltages, whereas the valves respond to the actual voltage reaching them, including harmonics, and hence repeated commutation failure in the inverter may occur. The control system filter also does not prevent transformer saturation.

The phase-locked oscillator control system is primarily designed to prevent harmonic instability. Since the pulse timing is not directly dependent on a.c. line voltage, it can be adjusted to fire the valves very accurately every 60° and is not affected by the disturbances in the a.c. system. This practically eliminates the generation of abnormal harmonics and harmonic instability.

Because of this design feature, the phase-locked oscillator is credited with several other advantages, some of which are:

a) The method is more economical as additional filters for the attenuation of abnormal harmonics are not required.

b) Due to the absence of irregularity of firing pulses, the converter transformer saturation effect is also very small.

c) Since no harmonic instability is expected with this system, the need for a control system filter with its associated disadvantages is also eliminated. This further reduces the cost.

d) With this method of firing the operation of converters on "weak" a.c. systems is possible without harmonic instability.

Thus it is concluded that the phase locked oscillator control system offers the most economical and effective method of firing.

3.10 BUILDING AND VALVE HALL:

The building for an H.V.D.C. terminal station includes valves (valve-hall), their auxiliaries, rooms for cleaning, degassing, preparing, etc. and offices for operating personnel.

To suppress radio wave emissions from the valves, the valve hall is completely shrouded in a copper wire mesh cage forming a screen all around. The screen is generally built within the walls, roof and floor of the hall and grounded.

A typical arrangement of a valve and its auxiliaries is shown in FIG. 3.10, and the layout of a complete valve group in a valve hall with its d.c. and a.c. bus arrangement can be seen in FIG. 3.11.[20,47]

The valves are to be insulated from ground for their

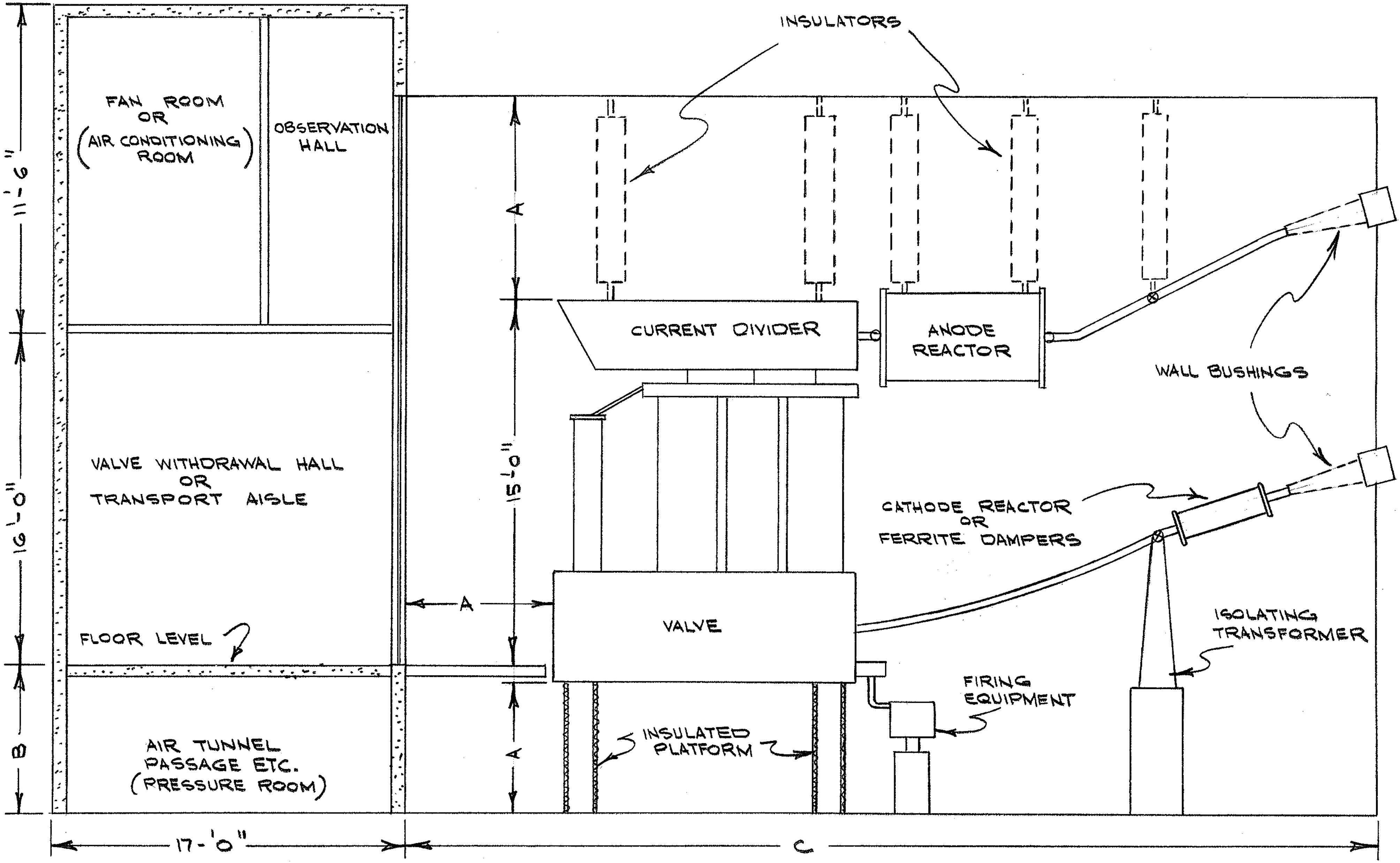

FIG. 3.10 [20]
(SIDE VIEW OF VALVE HALL)

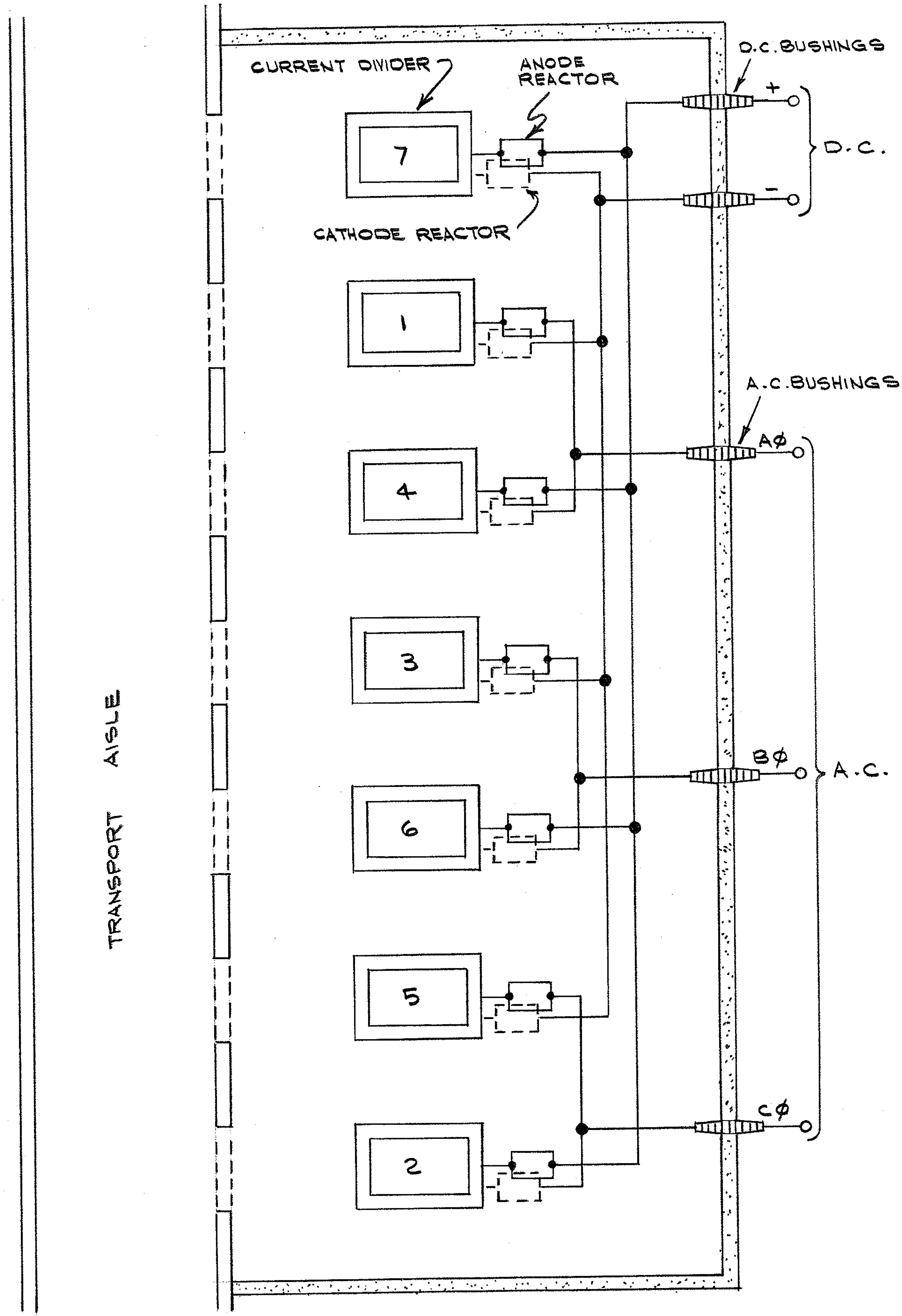

FIG. 3.11
(PLAN OF VALVE HALL)

corresponding voltages and therefore, should be installed on platforms supported on insulators. Suggested clearances are given in table III-1.

It is desirable to keep the floor height of the transport aisle and valve platforms at the same level throughout so that the valves can be easily moved on rails from service rooms to their platforms in the valve-hall and vice versa. This is achieved by making the floors of 300 KV valves lower than the floors of 150 KV valves and the floors of 450 KV valves still lower than those of 300 KV valves. Supporting insulators of appropriate heights are used to keep all valve platforms at uniform height. A cross-section of the valve-hall is shown in FIG. 3.12 giving respective clearances to ground.

Other equipment and facilities included inside the building are:

i) Air Conditioning and Ventilating Equipment Room:

These contain equipment for the control of temperature of valve halls and air ventilation.

ii) Transport Aisle:

The transport aisle is equipped with rails as a means of transporting valves between valve-hall and the service rooms. This aisle can also serve as a walkway for personnel and operators in the station.

TABLE III-1

Voltage / Dimension	150 KV D.C. (750 KV BIL)	300 KV D.C. (1050 KV BIL)	450 KV D.C. (1425 KV BIL)
A	5' - 5"	7' - 8"	10' - 3"
B	6' - 1"	8' - 4"	10' - 11"
C	45' - 0"	53' - 0"	57' - 0"

Suggested clearance and dimensions for valve halls. Dimension A is obtained from curve on FIG. 2.10 in Chapter II.

Dimensions refer to FIG. 3.10.

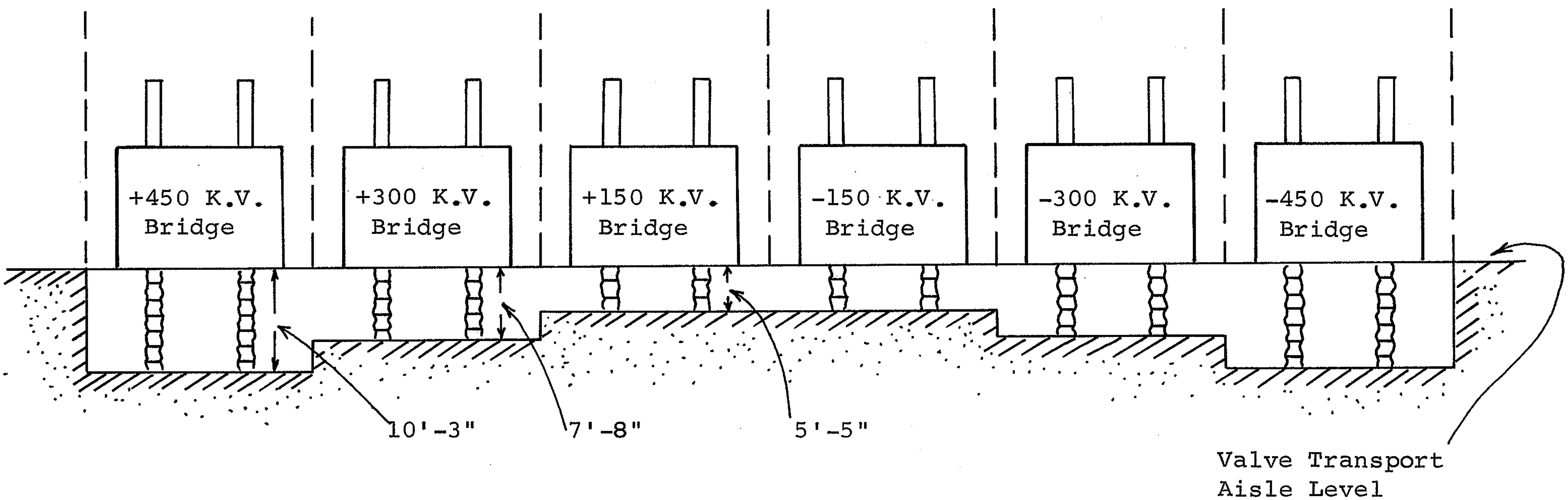

FIG. 3.12

CROSS-SECTION OF VALVE HALL

iii) Pressure Rooms:

These contain the pipes and tunnels etc. for air ventilation in the valve halls. Water cooling equipment for the valves may also be installed in these rooms.

iv) Valve Service Rooms:

These are necessary for cleaning, assembly and degassing of the valves. After degassing the valves are put in the preparation room where they are kept ready to go in service at any instant.

v) Control Room:

A control room is required for the equipment for control, relaying, protection and indication of the system.

vi) Offices, Stores & Workshops:

Offices for the staff, operators and other personnel are necessary. Proper stores and workshops are required for storage, repair and maintenance of equipment.

CHAPTER IV

LIGHTNING ARRESTERS, DISCONNECTS AND MEASURING EQUIPMENT

4.1 OVERVOLTAGES IN THE INVERTER STATION:

As in a.c. transmission, overvoltages of short durations also arise in a d.c. system both due to normal, as well as, abnormal operation of valves. Overvoltages generated during normal operation of valves have been discussed in chapter III, section 3.8. Here voltage transients only due to abnormal operations are discussed.

Overvoltages in a d.c. station can be divided into two classes.[48]

i) External Overvoltages;

ii) Internal Overvoltages.

These overvoltages are generated in both d.c. and a.c. systems and affect all equipment in the station.

i) External Overvoltages:

External overvoltages are caused by lightning strokes on the overhead lines, outdoor equipment, and switching surges in the a.c. section which may enter the d.c. equipment.

ii) Internal Overvoltages:

These are the result of various operating conditions of the d.c. transmission system such as inverter, and rectifier faults, blocking and unblocking operations, starting and interrupting the d.c. transmission etc.

4.2 OVERVOLTAGES IN D.C. SECTION:

The d.c. section of the inverter station is subjected to overvoltages due to following:

a) If the voltage on one group, in series with other groups, suddenly collapses due to, say, commutation failure, fire-through, back-fire or blocking and unblocking operations, the other healthy groups are subjected to overvoltages determined by the stray capacitances and the system voltage at the instant of collapse. The magnitude of these overvoltages may be in the order of about 1.5 to 1.7 times the normal no load voltage V_o.

b) Other valve group faults, such as arc-quenching, cause overvoltages across the faulty valve itself, anode reactor and converter transformer secondary windings.

c) Lightning strokes and switching surges result in overvoltages on the d.c. line and other d.c. equipment in the station.

4.3 OVERVOLTAGES IN A.C. SECTION:

Overvoltages arising in the a.c. section of the inverter station are transmitted into the d.c. section through converter transformers and associated valve damping equipment. Beside switching operations, other sources of overvoltages in the a.c. section are:

a) The sudden collapse of a.c. system voltage connected to the inverter station results in a dynamic overvoltage on the d.c. side. The magnitude of this voltage is influenced by the choice of synchronous condenser. A value of about 1.3 to 1.5 times V_o may be safely assumed for the magnitude of dynamic overvoltages.

b) A.c. harmonic filters produce overvoltages at the time of switching with a longer wave-front (about one millisecond) which are normally not present in a pure a.c. system.

The exact magnitude of the overvoltage transmitted into the d.c. section of the inverter station depends on the actual converter transformer design, its connection i.e. wye-wye or delta-wye, time in the cycle at which the overvoltage occurred, the phase which is affected and the system voltage at the instant.

4.4 PROTECTION AGAINST OVERVOLTAGES:

The insulation of the line and all other equipment in the inverter station should be designed to withstand voltage transients encountered by them. An economical protection level is as low as possible and steps must be taken to protect the equipment from damage from these surges. Various methods are adopted for protection against overvoltages depending on the location and type of equipment. Ground wires, rod-gaps, lightning arresters, surge capacitors, isolating switches and voltage and current measuring devices are used to achieve proper protection and render the station reasonably economical. In practical cases a compromise has to be found between financial and technical considerations.

i) Overhead Lines Protection:

D.c. overhead lines can be best protected against lightning strokes by running an earthwire on top of the towers. In the case of long lines it may be necessary to connect a surge capacitor just before the line termination. By providing an overhead ground wire and surge capacitor the effect of lightning storkes on line and other equipment in the station is reduced.

ii) Station Bus and Equipment Protection:

Two types of protective devices are most suitable for the protection of terminal equipment against overvoltages.

a) Protective Rod-Gaps:

These are simple and very economical, but have a long time lag for short duration impulses. For this reason it is difficult to select suitable settings for proper protection. Rod-gaps are also not very accurate. In actual service, considerable variation of sparkover voltage can occur due to slight differences in dimensions and shape of rods and also due to weather conditions, which also makes the setting of gaps difficult.

b) Lightning Arrestors:

These provide most effective protection against surges, both on the d.c. and the a.c. sides of the inverter station.

On the a.c. side the lightning arrester operates as a spark gap with a precise firing voltage, connected in series with non-linear resistors which tend to hold the line voltage near its original level while follow current flows. At a current zero, the arc is extinguished and the arresters reseal.

The absence of current zero on the d.c. side makes the process of extinguishing the arc difficult. A lightning arrester has to be designed specially for d.c. applications say, by providing a diverter that will reseal at reasonable current, or a protection arrangement to blow out, extend or reduce the arc current to zero when the arresters fire.

4.5 LOCATIONS OF LIGHTNING ARRESTERS:

DWG. 4A* shows the possible optimum locations[49,50] where lightning arresters may be connected. These are:

i) D.C. Line Lightning Arresters:

These arresters are installed for the protection of equipment connected to the d.c. line terminals (item 1, DWG. 4A). Lightning and switching surges on transmission lines may travel into the terminal station and cause damage. D.C. line arresters by-pass these surges to earth.

ii) D.C. Line Smoothing Reactor Lightning Arresters:

These are connected across the smoothing reactor (item 2, DWG. 4A) and are designed to protect the reactor from overvoltages.

iii) Valve Group Lightning Arresters:

These arresters are connected across the by-pass valve just outside the valve hall (item 3, DWG. 4A). The purpose of these arresters is to protect by-pass valves and also main vlaves of the group from overvoltages on the a.c. system and valve faults. These arresters also protect the by-pass valves from sudden overvoltages due to d.c. line reactor arrester operations.

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* See large drawing in back pocket of thesis.

iv) Valve Winding Arresters - Line to Line:

In a d.c. terminal station both a.c. and d.c. surges are impressed on connections between the a.c. side of the valve groups and the secondary windings of the converter transformers. Overvoltages on one phase create unbalancing among the three phases. A set of arresters connected in delta across the three phases (item 4, DWG. 4A) acts to correct the unbalancing by equally distributing the surges in all three phases.

v) Valve Winding Arresters - Line to Ground:

These arresters (item 5, DWG. 4A) are required for the protection of secondary windings of converter transformers and associated equipment from surges originiating on a.c. side of the station. They are connected close to the secondary windings of converter transformers.

vi) Electrode Line Lightning Arrester:

Under normal conditions no current flows in the electrode line. If one pole is blocked the current in the other pole will flow into the electrode line. An arrester (item 6, DWG. 4A) installed on this line protects it from overvoltages caused by blocking of one pole and also lightning surges.

vii) A.C. System Lightning Arresters:

These arresters are installed to protect converter transformers from lightning strokes and switching surges on the a.c. system and are connected on the primary side of the transformers (item 7, DWG. 4A).

4.6 LOCATIONS OF A.C. DISCONNECTS AND D.C. ISOLATORS:

DWG. 4A also shows locations of a.c. and d.c. switches together with their desirable BIL ratings.

All the switches are to be motor operated with remote, local as well as local hand operation facilities. These are:

i) D.C. Line Isolator and Grounding Switches: (item a, DWG. 4A)

These switches are installed for the isolation of the d.c. line for maintenance and under faults. These are not load breaking switches. The direct current must drop to zero before they can be operated. Each d.c. line switch is mechanically and electrically interlocked with its grounding switch so that when the line switch is opened its grounding switch is closed simultaneously to ground the line and vice versa.

The line switch must have a continuous current rating of at least 1800 amps. A rating of 2160 amps (120% of 1800 amps.) may be given for safety reasons. The grounding switch is not needed to have a continuous rating of 2160 amps but must be able to carry this current for at least a few milli-seconds.

ii) By-Pass Switches (b), Valve Group d.c. Isolators (c), Valve Group Grounding Switches (d) and (h) and a.c.

Disconnecting Switches (e): (all items refer to DWG. 4A)

These switches are for the isolation and grounding of the corresponding valve groups. Under normal operating conditions switches (c) and (e) stay closed while switches (b), (h) and (d) are open.

Referring to chapter II, section 2.2.1.b, permanent blocking of a valve group is achieved by closing the by-pass switch (b) which takes over current from the by-pass valve. Now the valve group d.c. isolators (c) are opened. The group is also isolated from the a.c. side by opening the a.c. disconnects (e) and effectively grounded by closing grounding switches (d) and (h). The a.c. disconnects (e) are interlocked with the a.c. grounding switches (d).

The by-pass switches (b), valve group d.c. isolators (c) and a.c. disconnecting switches (e) should have a continuous rating of 2160 amps. Other switches namely, valve group grounding switches (d) can be designed to carry full load current for a very short time only, say a few milli-seconds.

iii) Electrode Line and Ground Switches:

The purpose and function of these switches (item f, DWG. 4A) are similar to the d.c. line and ground switches (item a, DWG. 4A).

4.7 VOLTAGE AND CURRENT MEASURING EQUIPMENT:

In the a.c. section of the inverter station the desired voltages and currents are measured by conventional alternating voltage and current transformers at suitable locations, such as, C.T.'s in transformer and circuit breaker bushings and P.T.'s on the a.c. bus.

In the d.c. section it is not possible to use such voltage and current transformers, instead voltage dividers and current transductors are used.

i) Voltage Divider:

The direct voltage is measured by means of high resistance voltage dividers. Each divider must be insulated for the basic impulse level of the section to which it is connected and must be capable of withstanding full line voltage to ground continuously. The tap-off voltage is a small fraction of the total voltage drop across the full length of the divider. This voltage can be amplified and applied to a voltmeter, calibrated in terms of actual line voltage, or used for control and protection circuits.

ii) Direct Current Transformers: (Transductor)

The magnitude of direct current is measured by means of direct current transformers known as "transductors". A transductor provides an output which is instantaneously and continuously proportional to the primary current. Several forms of transductors are available.[51,52]

CHAPTER V

REACTIVE POWER REQUIREMENT AND HARMONIC FILTERS

5.1 INTRODUCTION:

While designing a.c. terminal stations little attention is paid to the question of harmonics, since harmonic levels in a.c. power networks are generally found to be acceptably low. However, in the case of an H.V.D.C. terminal station, harmonics cannot be ignored. The operation of inverter, and rectifier, bridges is characterised by two main features;

1. Consumption of reactive power;
2. Generation of a.c. and d.c. harmonics.

This chapter concerns itself with the reactive power requirements and harmonic suppression methods in the inverter station.

5.2 MAGNITUDE OF REACTIVE POWER:

Various methods are available[17,18,53,54] to determine the amount of reactive power required for the operation of bridges. One typical illustration is given below

For inverter operation:[17,54]

Power factor (p.f.)

$$\cos \phi = 1/2\ (\cos \delta + \cos \beta)^* \quad \ldots \quad (5.1)$$

Considering a typical case, when

$$\delta = 15^\circ$$

$$\gamma = 20^\circ$$

$$\beta = \gamma + \delta = 35^\circ$$

From equation (5.1),

$$\text{p.f.} = 0.8925 \quad \ldots \quad \ldots \quad \ldots \quad (5.2)$$

The reactive power consumed per unit of the active power is given by:

$$\frac{\text{reactive power}}{\text{active power}} = \frac{VI \sin \phi}{VI \cos \phi}$$

$$= \tan \phi \quad (5.3)$$

So, for the above value of p.f.;

Reactive power consumed

= 50.55% of active power.

The value of advance angle β depends on load, β increasing with load. From equations (5.1) and (5.3) it can be seen that reactive power consumed as a percentage of active power (i.e. a.c. load) increases with increase of load. This suggests that every attempt should be made to keep β minimum.[55] The curve on FIG. 5.1 illustrates the change in reactive power consumption by a bridge with load.

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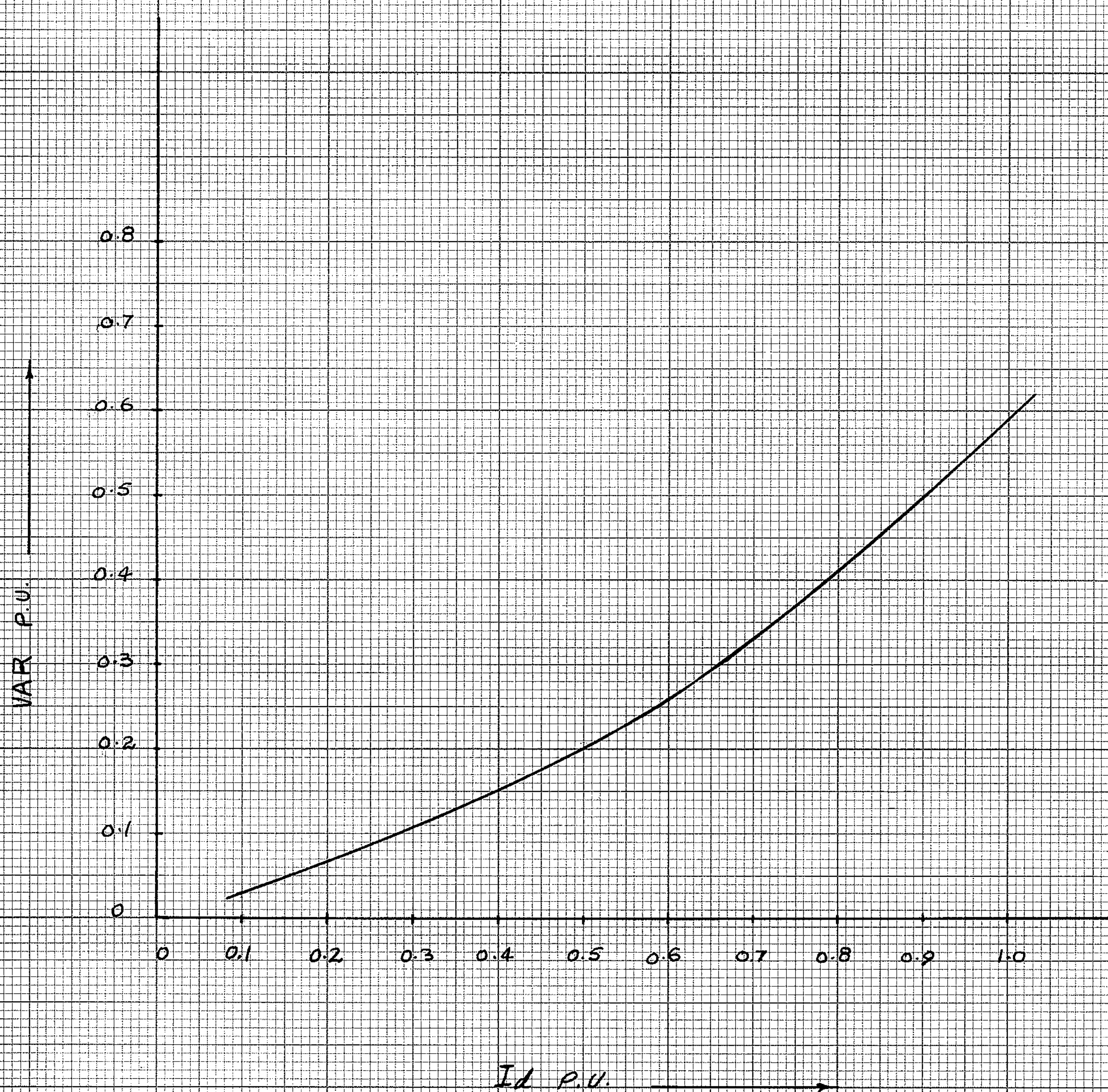
* For definitions of various symbols refer to appendix III.

FIG. 5.1

CHANGE IN REACTIVE POWER CONSUMPTION BY A BRIDGE WITH LOAD UNDER NORMAL OPERATING CONDITIONS.[53]



Even with an angle of advance automatically maintained at the minimum for safe commutation, in actual practice the reactive power consumption of valves may be as much as 50 - 60% [54,55] of the real power output. Therefore, for a bridge of, say, 270 MW output the reactive power consumed could be 135 MVAR to 162 MVAR.

The design engineer is confronted with the question of providing ways and means of the required reactive power for valves.

5.3 SOURCES OF REACTIVE POWER:

The sources of reactive power may be as follows:

1. A.C. harmonic filters;
2. Reactive power available from the connected a.c. system;
3. Additional static capacitors;
4. Synchronous condenser.

The sources of reactive power in the a.c. system may be:

1. Long transmission lines;
2. Synchronous generators; and
3. Capacitor banks for voltage correction.

A large a.c. system is generally capable of supplying enough reactive power. If the system cannot supply total reactive power required by the bridges, it becomes necessary to install synchronous condensers, additional shunt capacitors or a.c. harmonic filters of a larger "size".*

Filters of large sizes are not suitable since the amount of reactive power consumed by the valves increases with the power transmitted. There will, therefore, be an excess of MVAR at light loads.

Additional capacitors have the advantage over large size a.c. filters as they can be easily switched off under light load conditions when reactive power requirements are less.

The synchronous condenser is a better source of reactive power from the point of view of MVAR control. It provides stepless control throughout the entire output range, improves stability and a.c. system voltage control. In a weak a.c. system the synchronous condenser by virtue of its inertia, provides the a.c. source which enables the d.c link to ride through a.c. system disturbances.[45,46] Synchronous condenser also occupies less space and is designed for outdoor installation. As stated before (in chapter II) the synchronous condenser helps to increase the a.c. bus short circuit level.

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* "Size of filter" - It is the amount of reactive power which a harmonic filter can supply at fundamental frequency under normal system conditions.

As against these, the condenser is noisy, more expensive than capacitors and suffers from higher losses (about 1.5 - 2.0%) and more maintenance cost. Losses in capacitors are about 0.2 - 0.25%.

In most cases the reactive power source consists of a.c. filters, synchronous condenser, static capacitors or a combination of all. Usually the prime purpose of synchronous condenser is to increase the short circuit level of the inverter a.c. bus.

5.4 SYNCHRONOUS CONDENSER:

FIG. 5.2 illustrates the connection of a synchronous condenser to the tertiary windings of the converter transformer. For physical location of the condenser refer to DWG. 2B in the back pocket. Economy dictates that the synchronous condenser must be of lower voltage ratings, say, 10 - 20 KV.[10,57] Converter transformer tertiary windings are most suitable for synchronous condenser connections.

The synchronous condenser is connected to the converter transformer by means of a circuit breaker and line isolating switch. The breaker and the switch are required for the protection and isolation of the condenser.

A complete synchronous condenser assembly is normally equipped with stator and rotor windings, main and pilot exciters, starting generator, automatic voltage regulator and voltage

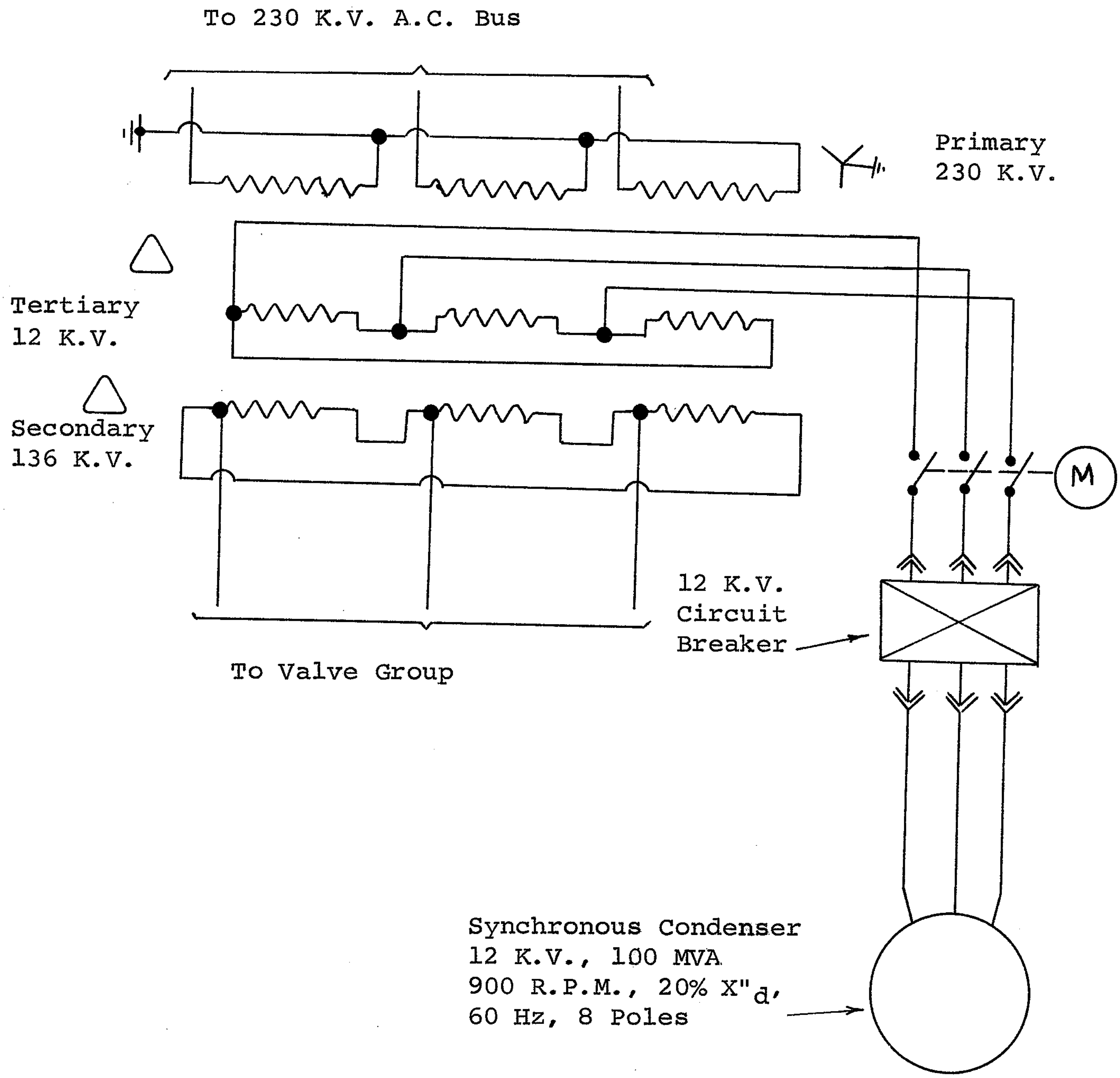


FIG. 5.2

CONNECTION OF SYNCHRONOUS CONDENSER

matching and synchronising equipment. Adequate cooling arrangements must also be provided. The condenser should be installed as close to the converter transformers as practically possible.

5.4.1 Characteristic and Rating of Synchronous Condenser:

The synchronous condenser must be designed to withstand continuously, under normal and abnormal conditions, the harmonic currents resulting from six-pulse operation of the associated group. Typical parameters of the condenser may be:[56]

Synchronous reactance (X_d)	$\simeq$	1.6 p.u.
Transient reactance, X'_d	$\simeq$	0.3 p.u.
Sub-transient reactance, X''_d	$\simeq$	0.2 p.u.
Stator leakage reactance, X_1	$\simeq$	0.2 p.u.
Inertia factor, (H)	$\simeq$	1.5-2 KW sec/KVA
Frequency	=	60 Hz
Speed	=	900 r.p.m.
Number of poles	=	8

Reactive power supplied by a.c. filters is about 20 - 30% of total MW output of the inverter station at full load. The remaining MVAR could be supplied by the synchronous condensers. The rating of the synchronous condenser in the inverter station may be determined as:

Assuming:	Total d.c. power transfer	=	1620 MW
	Approximate reactive power consumption at full load	=	60% of 1620 MW (970 MVAR)
	Available short-circuit capacity at inverter a.c. bus	=	2000 MVA
	Desired short-circuit capacity	=	3 x d.c. power transfer
		=	3 x 1600
		≃	5000 MVA
Therefore:	Synchronous condenser should provide (5000-2000)	=	3000 MVA
	Rated MVA output of synchronous condenser ($X''_d = 0.2$)	=	(3000) (0.2) MVA
		=	600 MVA
	Required balance of reactive power	=	970 - 600 MVAR
		=	370 MVAR
	Available reactive power from a.c. filters (20 to 30% of 1620)	=	324 to 486 MVAR

If one synchronous condenser is connected per valve group, then each condenser is expected to provide about 100 MVA for inverter consumption.

5.5 MAGNITUDE OF HARMONICS:

i) A.C. Harmonics:

The magnitude of the fundamental component I_s of a.c. output current is given by [17,18]

$$I_s \simeq 0.78\, I_d \qquad \ldots \qquad \ldots \qquad \ldots \quad (5.3)$$

where, I_d = d.c. line current

= 1800 amps.

Also, the magnitude of the harmonic current H_{ac} at $\gamma = 0$ and $\alpha = 0$ is given by:

$$H_{ac} = \frac{I_s}{n} \qquad \ldots \qquad \ldots \qquad \ldots \quad (5.4)$$

where, n = order of harmonics (5,7,11,13,etc.)

The curve on FIG. 5.3 is plotted to show the magnitude of theoretical a.c. harmonic current as a percentage of I_s. (See appendix IVa)

ii) D.C. Harmonics:

The magnitude of the d.c. harmonics is given by: [17,18]

$$H_{dc} = \frac{V_o \sqrt{2}}{(n^2 - 1)} \qquad (5.5)$$

where, V_o = No load d.c. voltage;

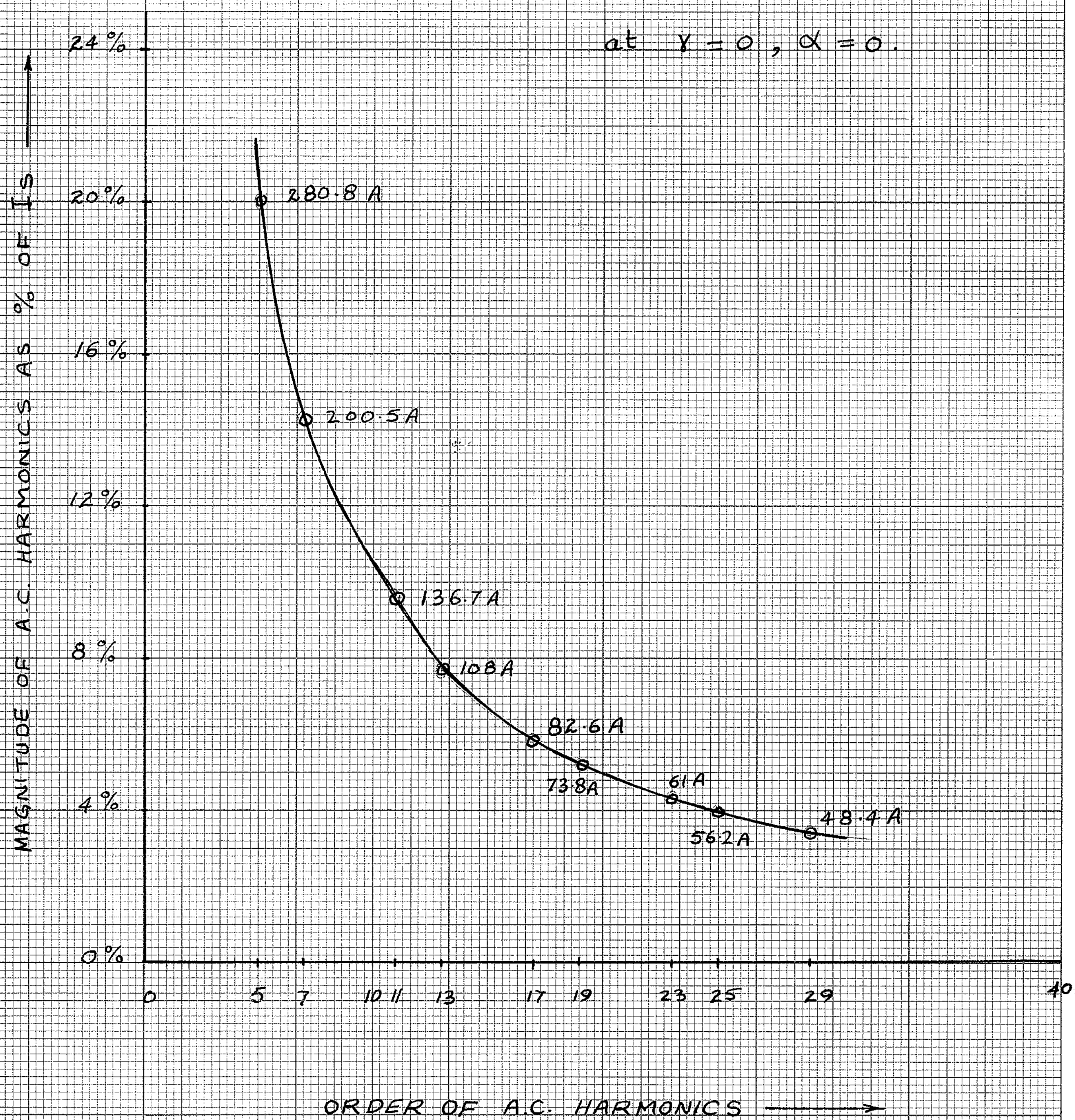
n = Order of harmonics, (6,12,18 etc.)

The curve of FIG. 5.4 is plotted to show the magnitude of theoretical d.c. harmonics as a percentage of V_o. (See appendix IVb).

FIG. 5.3

VARIATION OF A.C. HARMONIC CURRENT WITH THE ORDER OF HARMONIC.

at $\gamma = 0$, $\alpha = 0$.



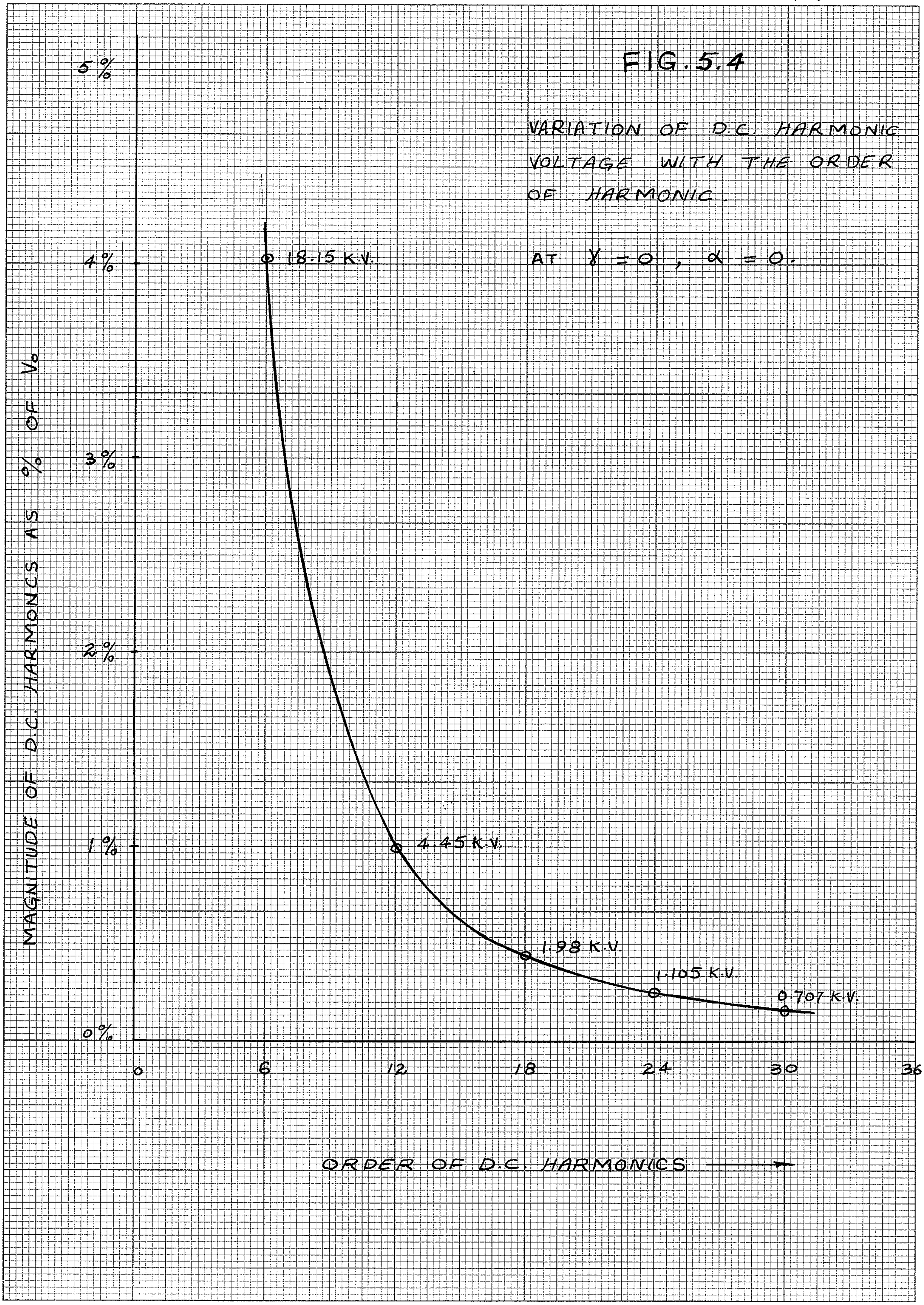


FIG. 5.4
VARIATION OF D.C. HARMONIC VOLTAGE WITH THE ORDER OF HARMONIC.
AT γ = 0 , α = 0.
MAGNITUDE OF D.C. HARMONICS AS % OF V₀
5%
4%
3%
2%
1%
0%
18.15 K.V.
4.45 K.V.
1.98 K.V.
1.105 K.V.
0.707 K.V.
0
6
12
18
24
30
36
ORDER OF D.C. HARMONICS

To appreciate the necessity of harmonic suppression the effect of these harmonics on the system and various equipment are considered.

5.6 EFFECTS OF HARMONICS: [17,18,58,59]

a) D.C. line harmonics cause interference due to electro-magnetic or electro-static coupling with communication circuits, such as telephone, telegraph and electric train signal circuits, if they fall in close vicinity of the d.c. power line.

b) On the d.c. as well as the a.c. side of inverter station a short line behaves as an electrically long line at high harmonic frequencies. Harmonics may cause nodes and antinodes, with very high voltages at nodes where the line behaves as if open circuited and very high currents at antinodes where the line behaves as if short-circuited.

c) A. C. harmonics cause additional losses in the rotor windings of induction and synchronous motors.

d) On the a.c. side, induction motors in parallel with power factor correcting capacitor banks may form parallel resonating circuits and result in excessive losses.

e) A. C. harmonics cause poor working of fluorescent lamps, errors in instrument readings, interference with protective equipment, disturbance to ripple control systems operating at audio frequencies in distribution networks, and additional power losses in the network.

f) In the a.c. system wherever resonance occurs, very high voltages will appear which could cause serious damages to connected equipment.

From above it is understandable that suppression of harmonics to harmless levels is a desired feature of the design of the inverter station.

5.7 METHODS OF CONTROLLING HARMONICS:

Harmonic filters are most suited for the control of a.c. and d.c. harmonics. These filters must be designed and connected for adequate suppression of harmonics at minimum cost.

Harmonic suppression can also be achieved by several other methods. These methods are:

i) Installing capacitor banks on the inverter station a.c. bus;

ii) Improved methods of valve firing;

iii) Increasing the number of pulses;

Various merits and demerits of these methods are:

i) Installing Capacitor Banks:

Sometimes shunt capacitor banks are installed for power factor correction purposes on the a.c. side. Such banks can, in principle, be used to attenuate a.c. harmonics (and also to supply reactive power). However, this method is not economically suitable for harmonic suppression as it is very expensive to reduce the leakage reactance of capacitors sufficiently to be effective for adequate harmonic suppression.

ii) Improved Methods of Valve Firing:

By improved methods of valve firing, such as the phase locked oscillator system, the generation of abnormal harmonics could either be eliminated completely or reduced to a harmless low level. (Refer to chapter III, section 3.9).

For interference from abnormal harmonics one may follow the "wait and see" policy. After the completion of the inverter station, if interference from abnormal harmonics is objectionable, proper steps may then be taken to rectify the same.

iii) Increasing the Number of Pulses:

With twelve-pulse operation of bridges the number of harmonics present in the a.c. system and d.c line are reduced (refer to chapter II, section 2.2.1, article iii and iv).

In the same way 24-pulse operation can be achieved if four bridges were operated together with the secondary windings of their converter transformers shifted in phase by 15^{o}. Most of the harmonics can be suppressed and the only harmonics present would be:

a.c. harmonics: 23rd, 25th, 47th, 49th, etc.

d.c. harmonics: 24th, 48th, etc.

Theoretically it is quite possible to operate the bridges in such a way that no harmonics can enter the system. This, however, has practical limitations and economic objections, as explained below.

a) To increase the pulse numbers to more than twelve, it becomes necessary to provide phase shifting transformers. These additional transformers increase the cost of the station.

b) For 24-pulse operation four bridges have to operate together; for 48-pulse operation eight bridges have to operate together; and so on. Therefore, in order to suppress all harmonics, the number of bridges to operate together will have to be 4, 8, 16, etc. This not only increases the cost of the station considerably but also presents serious outage problems in case of emergency.

c) Due to constant research and development, valves of higher ratings are expected to be available, which would increase the tendency of building terminal station of higher ratings with less number of bridges. It is very hard to visualise a terminal station with 16 or 32 bridges, as the stations with so many bridges would be impractical.

From above it can be safely concluded that the most practical and economical way is to operate bridges in twelve-pulse and use harmonic filters to suppress these harmonics.

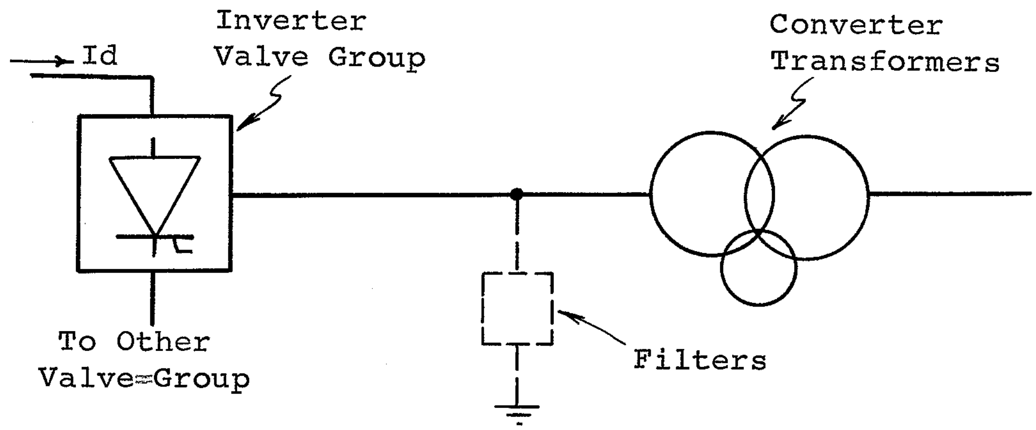
5.8 LOCATION OF HARMONIC FILTERS:

A. C. filters may be located at three possible places (FIG. 5.5). These locations are:

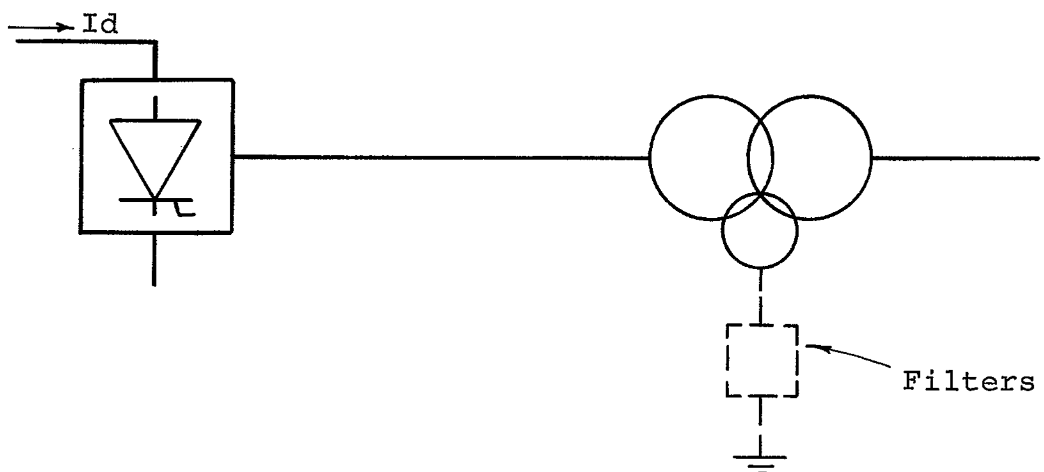
1. Secondary side of converter transformer;
2. Tertiary side of converter transformer;
3. Primary side of converter transformer.

Connection of filters on the secondary side of the transformer is not practical. Such a filter essentially shunts the transformer windings and the total commutating reactance of the valve is reduced.

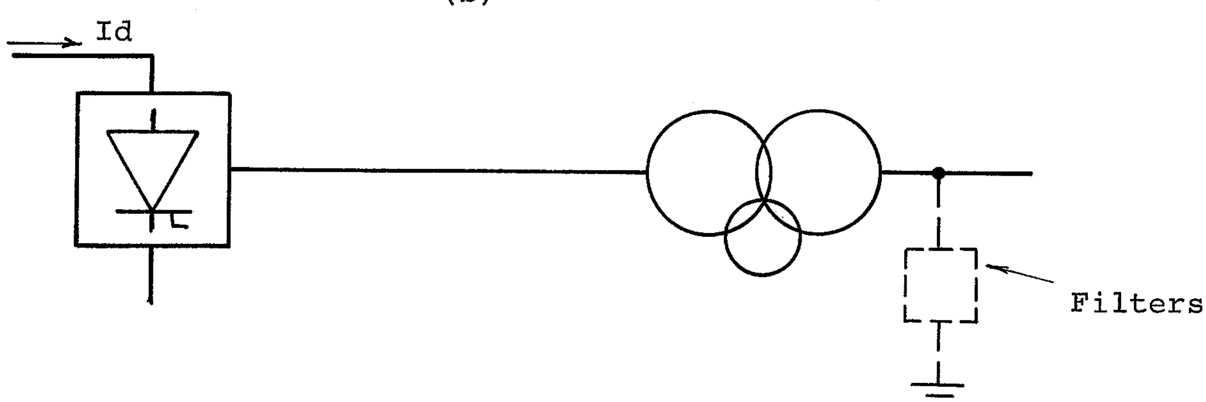
The value of commutating reactance is detrimental for the valve operation. Commutating reactance is the summation of reactances of converter transformer, system reactance and the anode reactors of valves, of which the former is the most predominant. For successful operation, the valves require a particular minimum commutating reactance. A value of about 12% is considered safe.[54] With harmonic filters on the secondary side of the converter transformer, this reactance drops too low, lower than the minimum safe value. As a result the valves would be subjected to excessive rate of change of current ($\frac{di}{dt}$) at the time of commutation, i.e.,



A.C. Filters on Secondary Side of
Converter Transformer
(a)



A.C. Filters on Tertiary Side of
Converter Transformer
(b)



A.C. Filters on Primary Side of
Converter Transformer
(c)

FIG. 5.5

POSSIBLE LOCATIONS OF A.C. HARMONIC FILTERS higher voltage stresses, and increased arc-back frequency.

Filters connected to the tertiary windings of the transformer would be economical, since they can be of low voltage rating. However, this connection also suffers from several disadvantages. The commutating reactance would be reduced from the total transformer reactance to about the reactance of the secondary side only. Further there would be a possibility of 5th harmonic filters resonating with the 3rd harmonic transformer reactance. If the filters are connected to the tertiary windings of the transformer, the transformer reactance on the secondary side should be specially increased. Such filters are used on the British end of the Cross-Channel H.V.D.C. scheme.[60] Abnormally high transformer reactance means higher transformer cost.

Too high commutating reactance should also be avoided since it causes larger overlap angle resulting in a higher voltage loss, increased VAR consumption and higher stresses on the valves. The desirable condition is to maintain the commutating reactance slightly above the minimum safe valve, say 16%.

If self-tuning filters are installed on the a.c. side of the transformers, the total commutating reactance would be the transformer reactance only. If the filters are not self-tuned then the a.c. system short circuit reactance (X_s) should be added to transformer reactance. Thus with self-tuning filters any change in the a.c. system reactance would not change the equivalent commutating reactance provided that the tuning range is adequately large. Although the filters on the transformer primary side must be insulated for the high a.c. bus voltage, the transformer cost is not increased.

From above the connection of a.c. filters on the a.c. side of the converter transformer is considered most suitable and has been adopted in this thesis (FIG. 5.5c).

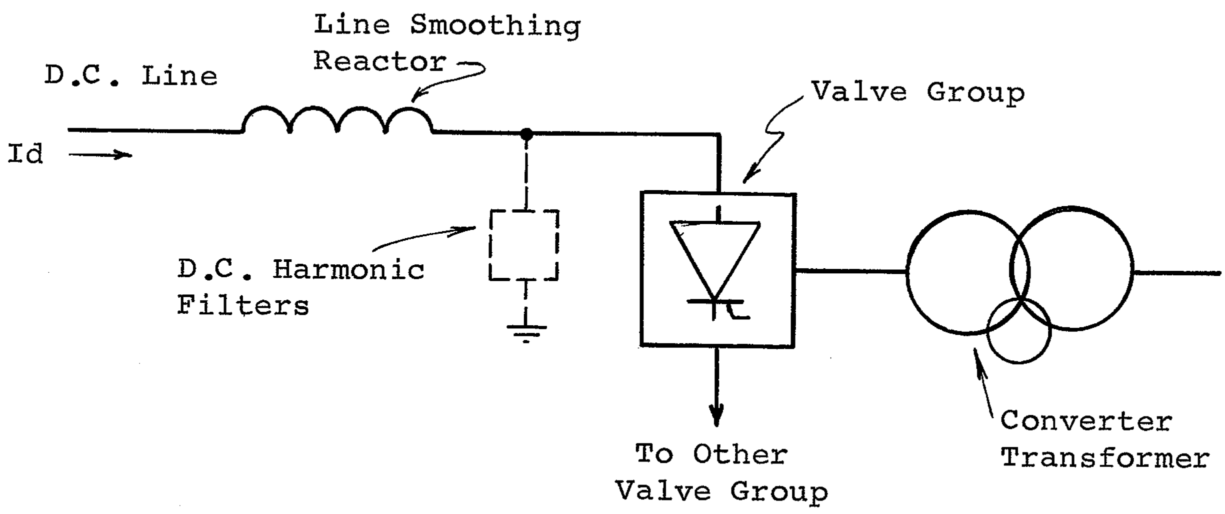
The choice of locating d.c. filters is simple. Two possible locations are shown in FIG. 5.6. Filters located between the line smoothing reactor and the bridge (FIG. 5.6a) would be large and expensive since they would be directly subjected to d.c. ripples and other transients due to commutation. For these reasons these filters are installed on the line side of smoothing reactor (FIG. 5.6b).

5.9 DESIGN, CONNECTION AND RATING OF HARMONIC FILTERS:

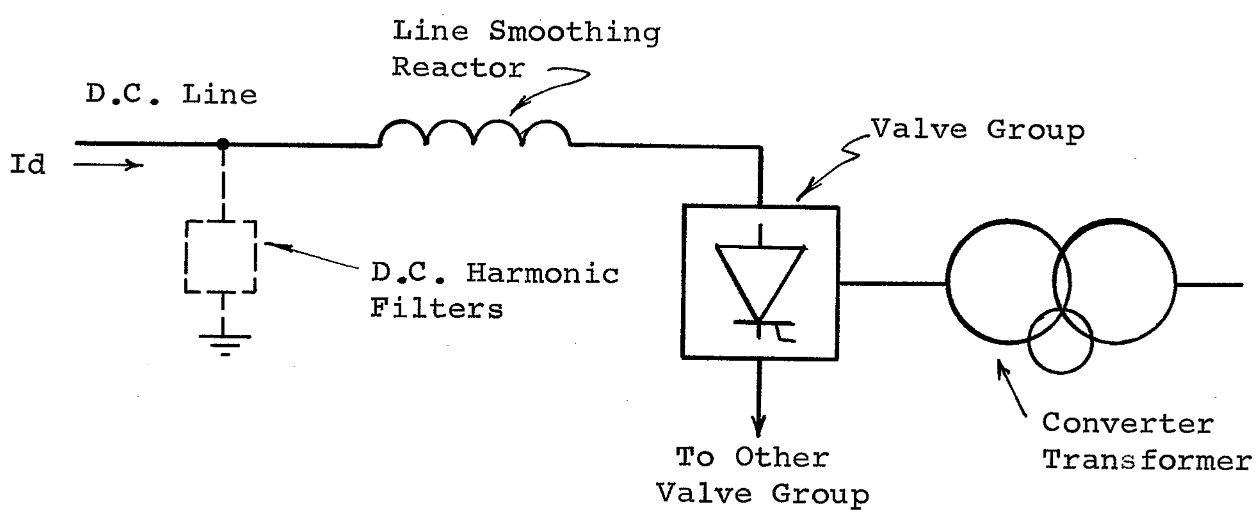
There are two types of filters suitable for H.V.D.C. applications. These are [58,61,62]

1. High - Q tuned filters; and
2. Damped high-pass filters.

Ideally filter arms tuned to every harmonic should be installed to suppress each harmonic individually. However,



(a)



(b)

FIG. 5.6

POSSIBLE LOCATIONS OF D.C. HARMONIC FILTERS for economical reasons and because of numerous uncertainties about the behaviour of system elements, and the generation of harmonics by generators, transformers, industrial rectifiers, and corona affects of lines, etc., it is difficult to calculate exactly the circulation of harmonics in a network. Nevertheless, it is the lower order of harmonics which, because of their amplitude, cause most distortion of the system waveform. Harmonics of higher orders, say, above 25th are of smaller magnitudes and do not cause any appreciable disturbance.[53,58] Therefore, it is practical to install filters tuned only to major harmonics, such as 5th, 7th, 11th, and 13th, etc. a.c. harmoncis and 6th, 12th and 18th, etc. d.c. harmonics and one set each of high-pass filters on the a.c. as well as the d.c. side for respective higher order harmonics suppression. These filters could be connected in shunt, series, or in a combination of both.

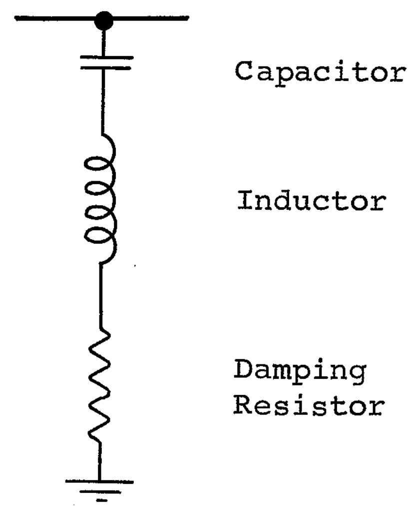
In order to consider design and rating aspects of these filters let us consider a.c. and d.c. filters separately.

5.9.1 A.C. Harmonic Filters:

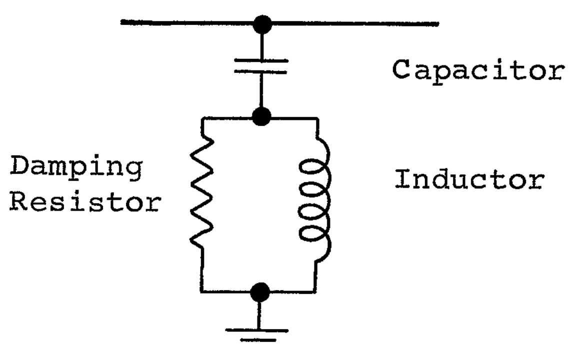
An a.c. filter connected in shunt is particularly effective for the harmonic for which it is tuned if the a.c. system impedance is high at that frequency.

Series connected filters are not used because they suffer from the disadvantage of increasing the commutating reactance and have a low inductive impedance at low frequencies. Also no reactive power can be supplied by these filters. Series filters are also expensive since all the component parts have to be designed for full line insulation and current ratings. A combination of series and shunt filters appears attractive in that they can reduce harmonics entering the a.c. system, whether the a.c. system impedance is high or low at a particular harmonic frequency. But this combination would also be expensive because of the series connected filters. For these reasons shunt filters are found most suitable.

Out of a wide choice of types of filter circuits available,[18,58] single tuned filters and high-pass filters of the types shown in FIG. 5.7 are most simple and economical. The tuned filters (for 5th, 7th, 11th and 13th harmonics) have a high Q which could lie between 50 - 100[53,58] depending on the steepness to which the individual arms are tuned. These consist of series connected inductor and capacitor components with damping resistors. The high-pass filters are designed to offer a low impedance at high frequencies (17th and above) and are not sharply tuned to any particular frequency. These filters, therefore, can be of lower Q. These consist of capacitors connected in series with damping resistors in parallel with the inductors.



Single Tuned A.C. Filter
(a)



A.C. High-Pass Filter
(b)

FIG. 5.7

A.C. HARMONIC SHUNT FILTERS

Capacitors are the most expensive part of the filters. The filter capacitors generally consist of many relatively small units connected in series and parallel combination and have to be insulated for the a.c. bus voltage and mounted on insulators. The voltage, position and space available dictates the arrangement of the capacitor banks of the filters. One end of the damping resistors is grounded and the inductors are connected between the capacitor banks and the resistors. For self-tuning filters the reactance of reactors is varied automatically.

FIG. 5.8 shows the connection of a.c. filters to the a.c. bus. The arms of each filter are connected in star with neutral grounded. With this arrangement, harmonics of all phases are suppressed and also the total cost of insulating filter components is reduced.

Two sets of a.c. filters, one for each pole, are installed and connected as per FIG. 5.8. The single line diagram (DWG. 2A) shows arrangement of both the sets. The current in any filter arm consists largely of the harmonic current from the inverter at the resonant frequency, plus some current at fundamental frequency. Referring to section 5.4.1, these filters should be of such "size" that their MVAR rating at fundamental frequency approximates 20 - 30% of rated real power (370 MVAR). This suggests that each set of the filters may have a size of approximately 200 MVAR.

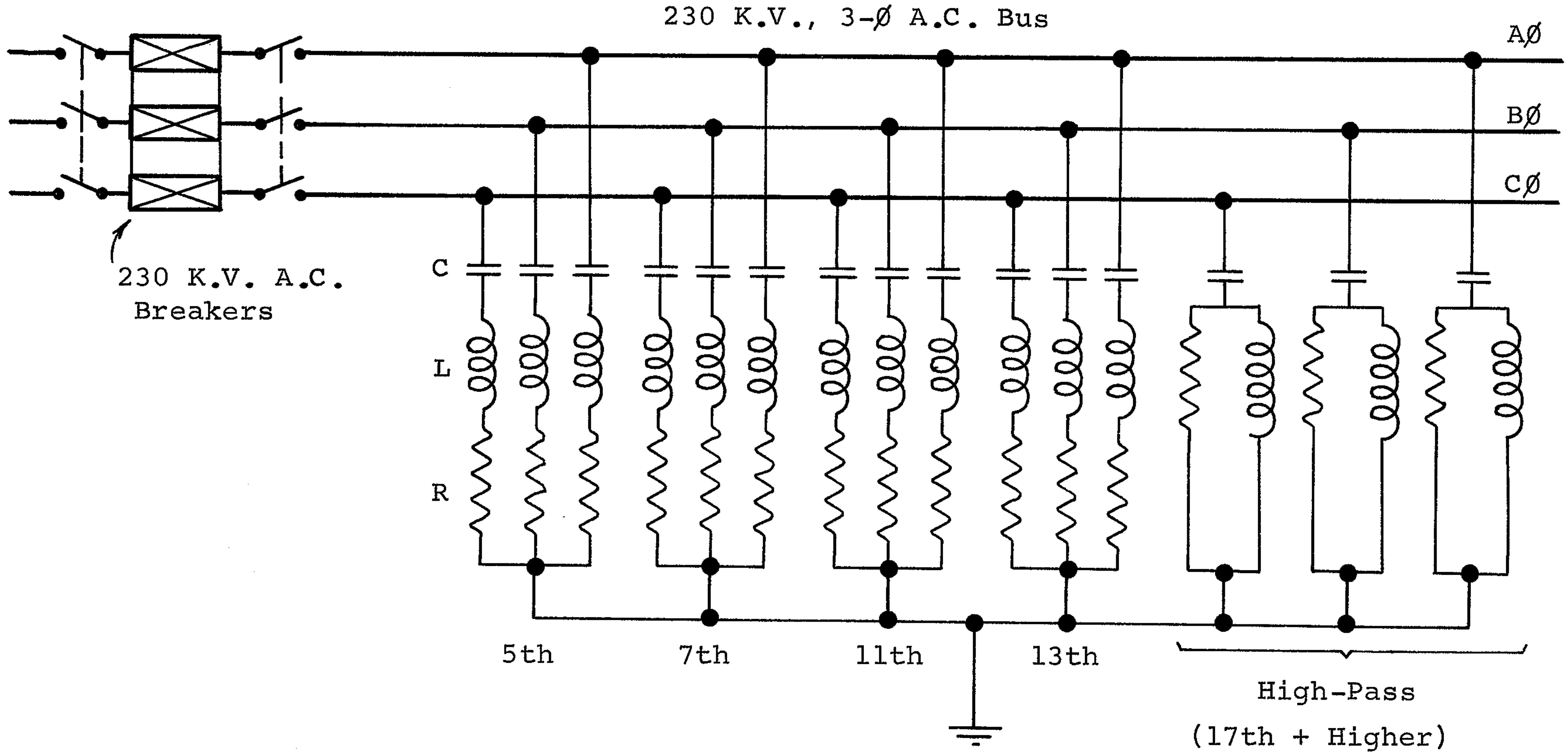


FIG. 5.8

CONNECTION OF A.C. HARMONIC FILTERS TO A.C. BUS

5.9.2 D.C. Harmonic Filters:

The application of d.c harmonic filters is mainly governed by the type and length of the d.c. line. A d.c. line may be of two types:

1. Underground or underwater cables;
2. Overhead transmission lines.

Let us consider an overhead transmission line, say, 600 miles long. Assuming a single conductor parallel to earth with zero earth resistivity, and assuming no flux within the conductor, the velocity of propagation of electromagnetic waves would be:[63,64]

$$\text{Velocity} = \lambda f$$

$$= 186{,}000 \text{ miles/second}$$

where, λ = wave length

f = frequency

= 60 Hz.

Therefore, λ = 3,100 miles.

Now considering the d.c. harmonics on the line,

for 6th harmonic,

$$\lambda = \frac{3100}{6} \simeq 517 \text{ miles}$$

for 12th harmonic,

$$\lambda = \frac{3100}{12} \simeq 258 \text{ miles}$$

for 18th harmonic,

$$\lambda = \frac{3100}{18} \simeq 172 \text{ miles}$$

and so on.

Thus a 600 mile long d.c. transmission line becomes electrically approximately 1.16, 2.33 and 3.5 wave lengths long for 6th, 12th and 18th harmonics respectively and would have corresponding lengths of only 129.25, 64.5 and 43.00 miles representing a quarter wave length. These harmonic voltages would be superimposed on the rated d.c. line voltage and would result in nodes and antinodes on the line. Because of these, the insulation level of the line would have to be increased resulting in longer insulator strings, higher towers and longer crossarms.

If a transmission line is less than one quarter wave length long at the highest harmonic frequency, d.c. harmonic filters will not be required. But for longer lines these harmonics must be suppressed by installing properly designed harmonic filters. D. C. cables are usually of very short lengths, and the smoothing effect of the d.c. line reactor is generally adequate for higher order harmonics. Even if the d.c. cable is long, the resonant frequency between the line reactor and cable capacitance would be relatively low, of the order of fundamental frequency, and there would be considerable attenuation of the major harmonics. In general, therefore, with cables, no further filtering would be needed.

D. C. harmonic filters may also be connected in series or, alternatively, in shunt. The series arrangement is not very useful because the line smoothing reactor is normally a high impedance compared to the transmission line. Also series filters will be expensive as all the component parts will have to be designed for line insulation. Shunt filters are more suitable and are quite practical.

The design of d.c. filters is similar to a.c. filters. A typical d.c. filter is shown in FIG. 5.9. The only difference from an a.c. filter is that there is a capacitor C' in parallel with the inductor and resistor units. This arrangement has the advantage that it acts like a lightning surge absorber, reducing the amplitude and steepness of surges. It also reduces, by voltage division, the surges reaching the smoothing reactor.[80]

FIG. 5.10 shows the connection of d.c.filters to the line. Tuned filters with high Q are required for 6th, and 12th harmonics whereas a high-pass filter is connected for higher order harmonics. As in the case of a.c. filters, two sets of d.c. filters are installed, one for each pole. The connection of the filters of both poles is shown in the single line diagram (DWG. 2A).

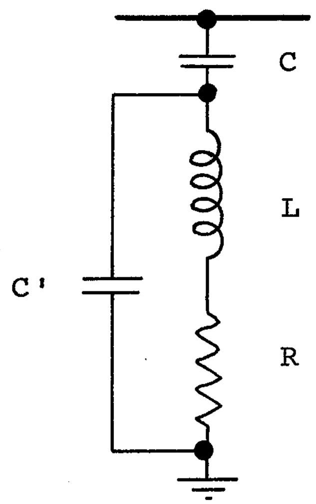


FIG. 5.9

TUNED D.C. HARMONIC FILTER [80]

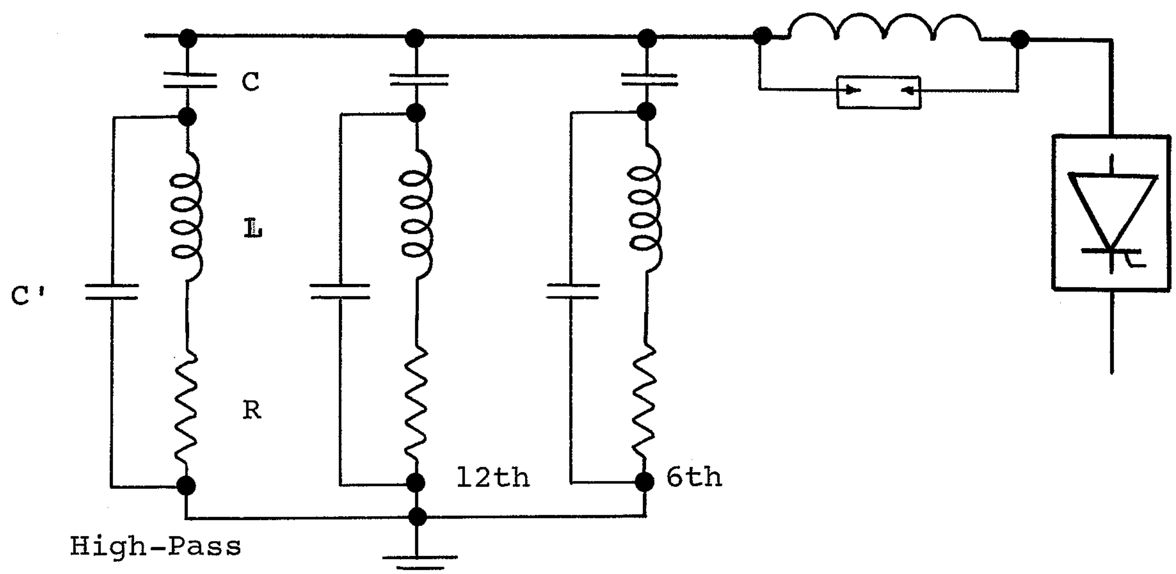


FIG. 5.10

CONNECTION OF D.C. HARMONIC FILTERS [80]
TO D.C. LINE

CHAPTER VI

CONVERTER TRANSFORMER & A.C. CIRCUIT BREAKER

6.1 CONVERTER TRANSFORMERS:

The equipment discussed so far pertains to the d.c. section of the inverter station, with the exception of the a.c. filters and disconnects. Converter transformers serve as liaison between d.c. and a.c. sections of the station. The arrangement of two transformer bank windings for twelve-pulse performance is shown schematically in FIG. 6.1.

Converter transformers for H.V.D.C. applications operate under voltage stresses different from normal a.c. applications. The stresses appearing across the transformer insulation could vary from pure d.c. to a combination of d.c. and a.c. voltages.[65]

Forces due to the alternating current act outwards away from the core creating pulling forces on the copper and supporting braces. As against this, forces due to the direct current have compressing effects towards the centre of the core. These two kinds of opposing forces, therefore, create twisting effects on the transformer windings, their supporting braces and spacers, which may ultimately loosen

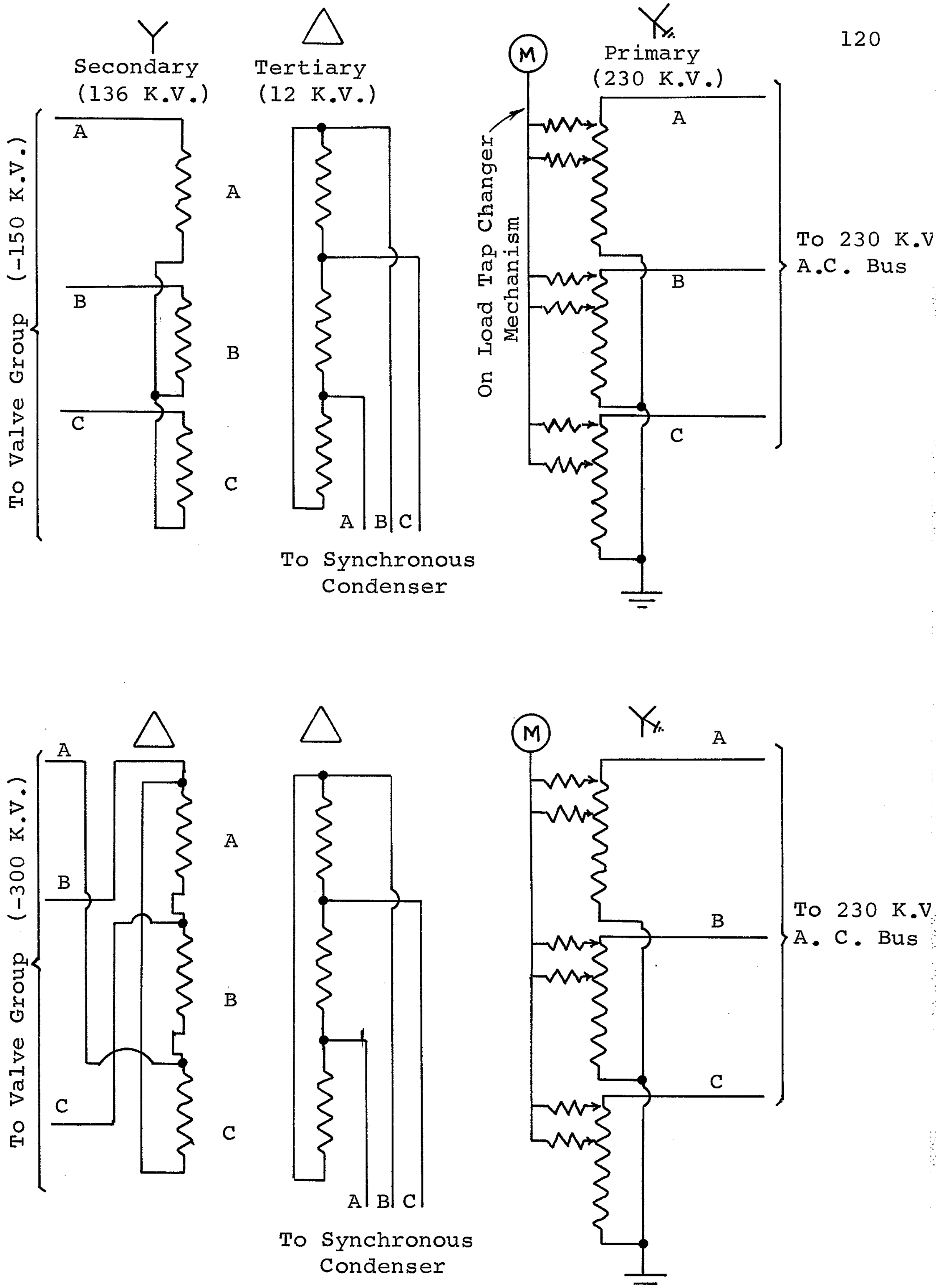


FIG. 6.1

CONNECTION OF TWO CONVERTER TRANSFORMERS FOR 12 - PULSE PERFORMANCE the whole assembly and the windings might fall down to the bottom of the tank.

Due to the presence of these forces special care has to be taken in the construction of converter transformers. Their windings must be adequately braced and have sufficient supports and spacers so that they could withstand these forces and also forces due to harmonics and short circuit impulses.[66]

6.2 RATING OF CONVERTER TRANSFORMER:

The converter transformers must be capable of transforming the pulsating a.c. input to their secondary windings from the associated valve group to the full rated voltage of the a.c. bus. They also have to carry full load current at all times.

Typical MVA and nominal voltage ratings of a three-phase converter transformer bank for each bridge connection at the inverter station may be as given below. (See appendix V for calculations).

Capacity	=	345 MVA
Secondary Voltage Rating	=	136 KV
Primary Voltage Rating	=	230 KV ($\pm$ 10%)
Tertiary Voltage Rating	=	12 KV
Frequency	=	60 Hz

BIL rating for the above voltages as obtained from NEMA standard would be:

Transformer winding	Voltage Rating (KV)	BIL (KV)
Primary	230	1050
Secondary	136	650
Tertiary	12	110

Table VI-1
Rated Voltage and Corresponding BIL Ratings of Converter Transformer

A transformer having the above ratings would be fairly large in size. Therefore, to facilitate ease in manufacture, shipment and installation, these transformers should be built separately in single-phase units. After shipment and installation in the field, three transformers will have to be connected to form a three phase bank as required for bridge operations. Each of the single-phase units in the three-phase bank arrangement would contain tertiary windings placed inside its tank. All the transformers to be equipped with conventional auxiliaries for their proper operation and protection.

A single-phase unit of the bank of the above ratings is expected to have an approximate height of 35'-0" and a ground area of about 300 square feet.

6.2.1 Tap Changer Mechanism:

The primary windings of converter transformers are equipped with an automatic fast acting on-load tap changer mechanism. Tap changers may be connected to secondary windings also. In order to achieve smooth variation in voltage it is desirable to keep the tap change steps as small as possible. The high and low limits of the tap changer mechanism depend on the particular station requirements. A typical regulating range may be taken as ± 10% in 20 setps of 1% each. For such a range the voltage regulation would be*:

-10%	Nominal	+10%
207 KV	230 KV	253 KV

and the tap changer would have 21 positions including one neutral position.

The tap changer mechanism must have some operating delay to keep it from operating during transient disturbances. Also an interlocking is advantageous to prevent the tap changer

---

* On load tap changer range in:

1. Cross-channel ... ... ± 15%
2. Nelson River ... ... - 7%, + 25%

from moving to the neutral tap due to loss of power to the tap changer controls.

6.3 A.C. CIRCUIT BREAKER:

The other major equipment included in the a.c. section of the inverter station is the a.c. circuit breaker.

The prime purpose of the a.c. breaker is to protect and isolate the a.c. bus section under abnormal or fault conditions. The a.c. breakers in the inverter station are also interlocked with the associated valve groups. Whenever a permanent blocking of a bridge is called for, its associated a.c. breakers are tripped to isolate the whole section. For example, supposing the + 450 KV bridge is blocked permanently. At this instant the breakers 1 and 2 (DWG. 2A) would also be tripped in order to completely isolate the affected section without interrupting the power supply.

The arrangement of breakers in the a.c. bus and their connections to converter transformers is shown in the single line diagram (DWG. 2A). One and one third (1-1/3) breakers per element have been selected. This arrangement is very economical and the power supply is not interrupted if the corresponding breakers are tripped due to an a.c. bus fault or bridge blocking.

6.3.1 Characteristics and Rating of Circuit Breaker:

The circuit breakers must be designed to carry continuously full load current at rated voltage and frequency under all conditions, electrical and otherwise, prevailing at the station. They must also be capable of interrupting and quenching the short circuit current in the shortest possible time.

Single phase, high speed, outdoor type, air-blast or oil-less type a.c. breakers have been developed [67,68] for the application of high voltages, say, 60-725 KV. These breakers are designed to have an interrupting time of as fast as two cycles.

The breakers also incorporate a fast reclosing mechanism. These reclosures may be set for one or more (1-5) operations, as desired, before permanent tripping. In the case of tripping due to bridge blocking, no reclosure operation would be required.

Typical ratings of the breaker for the inverter station may be:

continuous voltage rating	=	230 KV, (three-phase, 60 Hz.)
continuous current rating	=	2000 A
interrupting capacity	=	5000 MVA
BIL	=	1050 MVA

A single phase breaker of the above rating is expected to have physical dimensions in the neighbourhood of, say, 15'-0" high, 11'-0" long and 2'-0" wide.

CHAPTER VII

OPERATION, CONTROL & PROTECTION OF INVERTER STATION

7.1 BASIC CONTROL SCHEME:

Power flow in a d.c. transmission depends primarily on its controls which can be easily adjusted to almost any requirement.[69,70,71]

In an H.V.D.C. transmission scheme the basic requirement is to control continuously the transmitted current I_d to obtain the desired power.

$$I_d = \frac{V_{dr} - V_{di}}{R} \quad \dots \quad \dots \quad \dots (7.1)$$

where,

V_{dr} = direct voltage at rectifier station;

V_{di} = direct voltage at inverter station;

R = resistance of d.c. transmission line.

The voltages V_{dr} and V_{di} have to be continuously controlled for correct operation. If V_{dr} is too small or V_{di} too large, no current can flow. On the other hand if V_{dr} is too large or V_{di} too small, I_d may become too large.

FIG. 7.1 shows a simplified block diagram of a general control scheme. This is basically a closed loop current control in which the direct voltage at the inverter station is kept

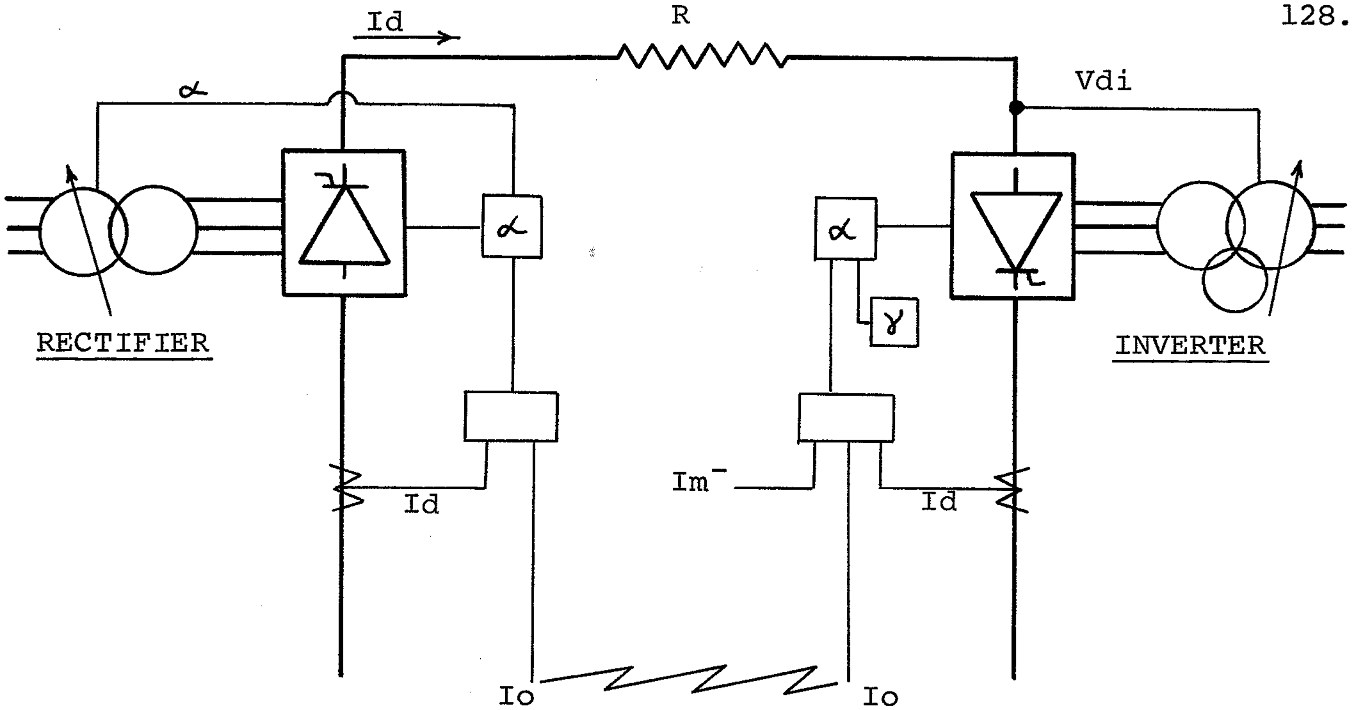


FIG. 7.1

BASIC CONTROL SCHEME OF D.C. TRANSMISSION SYSTEM [12]

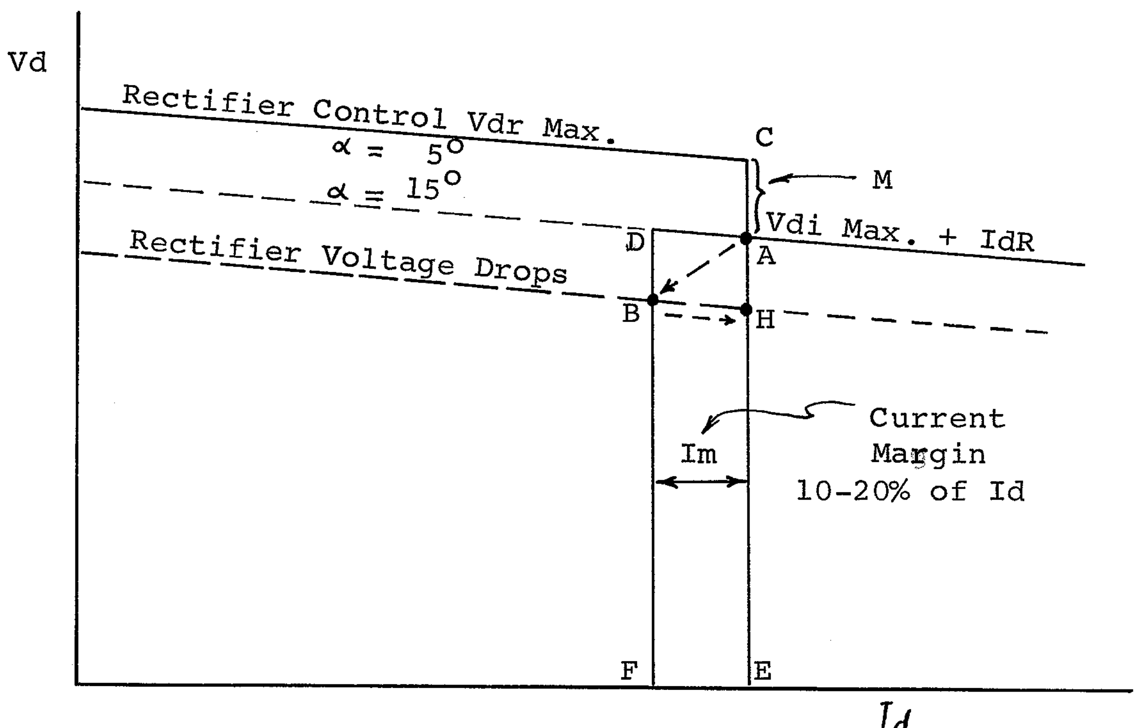


FIG. 7.2

VOLTAGE - CURRENT CHARACTERISTICS FOR THE CONTROL OF D.C. POLES [12] constant at a high value and the desired power is obtained by varying the transmitted current at the rectifier station which in turn is varied by the timing at which the grids allow the valves to conduct. In this control system the inverter station has commutation margin control also, known as "constant extinction angle control".[72,73] The inverter determines operating voltage and the rectifier operating current.

The control scheme is designed for:

7.1.1 Steady State Operation or When Rectifier is in Control:

7.1.2 Abnormal Operation or When Inverter is in Control.

7.1.1 <u>Steady State Operation or When Rectifier is in Control:</u>

In steady state operation:

a) Voltage V_{di} is kept at its highest possible design value by following operations:

1. Commutation margin angle γ is kept constant, and to minimize the reactive power consumption, it is kept at its minimum safe value, say, $\gamma_o \simeq 15^o$ or 18^o. By doing this the highest direct voltage V_{di} max. is obtained for existing value of I_d.

2. The inverter transformer tap changer is operated in such a way as to keep V_{di} at the rated value.

b) I_d is controlled by the rectifier delay angle α and hence V_{dr} to obtain the desired power. This is normal

"Rectifier control" which follows the line C-A-H-E in FIG. 7.2.

c) The rectifier transformer tap-changer is controlled to keep the rectifier delay angle α and therefore the voltage "M" (FIG. 7.2) within preset limits ($\alpha = 5^{\circ} - 15^{\circ}$). This also keeps the stresses down in the valve and the rectifier reactive power consumption to the minimum. The greater the value of M, i.e., α , the higher the rectifier reactive power consumption and electrical stresses on the valve. The optimum value of M is $10^{\circ} - 15^{\circ}$. M is necessary for rectifier operation in order to avoid frequent inverter control due to any small variation of a.c. system voltages.

7.1.2 Abnormal Operation or When Inverter is in Control:

Due to the slow action of converter transformer tap changers, a situation might arise where:

$$V_{dr} \text{ max.} \leq V_{di} \text{ max.}$$

so that, $I_d \longrightarrow 0$

and the transmission of power might be interrupted.

The above situation may arise under two conditions:

a) The voltages in the two a.c. systems, a.c. system before rectification and a.c. system after inversion, might become such that $V_{dr} \leq V_{di}$.

b) One bridge on the rectifier end is blocked reducing V_{dr} max.

To prevent the interruption of power transmission, the inverter station is also provided with a current regulator. This regulator is set to a value slightly lower than the current setting of the rectifier end. The difference, called current margin I_m, is generally 10%-20% of I_d (FIG. 7.2).

Referring to the rectifier and inverter voltage-current characteristic curves of FIG. 7.2, point 'A' represents normal operating conditions under "steady state" control. If V_{dr} falls below V_{di}, i.e., the voltage change is greater than M, the current I_d and hence the transmitted power would have become zero. However at this instant the inverter control system comes into action and reduces the inverter voltage V_{di} below V_{di} max. by increasing the advance angle β . The control is now taken over by the inverter and 'B' becomes the new operating point. Now the control takes place along the line D-B-F. Although the power transmitted at the point B is less than A, it is not interrupted. This reduction of power may result in the reference current I_o being increased in an attempt to restore the original power and the operating point 'B' may move to the right to point H. Within a few seconds tap-changers get time to operate and help to restore normal operation to point A.

For the transmission of a certain amount of power, the required reference I_o can be preset in both the stations and the transmission will continue as shown in FIG. 7.2.

7.2 H.V.D.C. TRANSMISSION CONTROL SCHEME:

A complete control scheme for H.V.D.C. transmission may be divided into three major sections.

7.2.1 Master Controller or Power Flow Control Circuits;

7.2.2 Pole Control Circuits;

7.2.3 Valve Group Control Circuits.

FIG. 7.3 shows a block diagram of these controls.

7.2.1 Master Controllers or Power Flow Control Circuits:

Master control equipment incorporates circuits whose output is either the current order I_o or power order P_o, or frequency order f_o , depending upon the type of control used.

Thus master control can be achieved in three ways:

i) Constant Current Control:

ii) Constant Power Control:

iii) Constant Frequency Control.

i) Constant Current Control:

FIG. 7.4 shows the basic arrangement for this scheme. Here the direct current I_d, and the order current I_o are applied to the controlling circuit. I_o is varied by the master

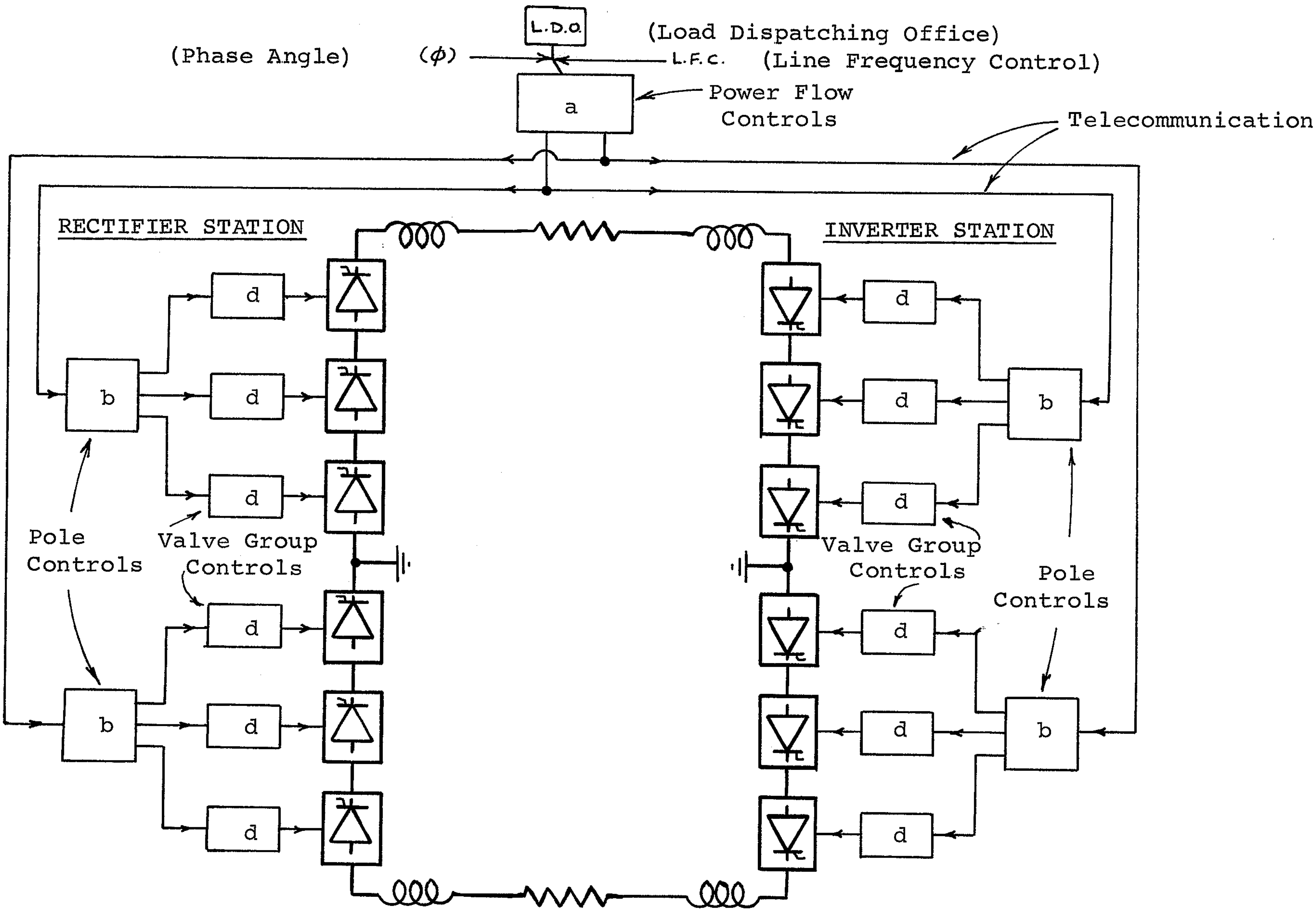


FIG. 7.3

A COMPLETE H.V.D.C. TRANSMISSION CONTROL SCHEME controller according to the power requirement so that the required amount of current and hence power is transmitted at all times.

If any change in power is required at the receiving end the signal is sent to the rectifier station by means of the communication channel to vary I_o accordingly. This order is then sent to the pole controls to increase or decrease the power flow by changing the angle α .

ii) Constant Power Control:

In this control system, in addition to the direct current I_d, the direct voltage V_d is also obtained by means of a voltage divider. The basic circuit is shown in FIG. 7.5. Now the power order P_o is varied which sends commands to the pole controls to change transmitted power.

iii) Constant Frequency Control:

This system is similar to the constant power control except that the direct power P_d and order power P_o are expressed in terms of the frequency of the receiving a.c. system. Power flow is controlled, not by means of any change in current or power, but by a change of the receiving end frequency.

One set of Master controller equipment is required for a complete bi-polar H.V.D.C. transmission scheme (Item "a" FIG. 7.3). This equipment can be installed at either station.

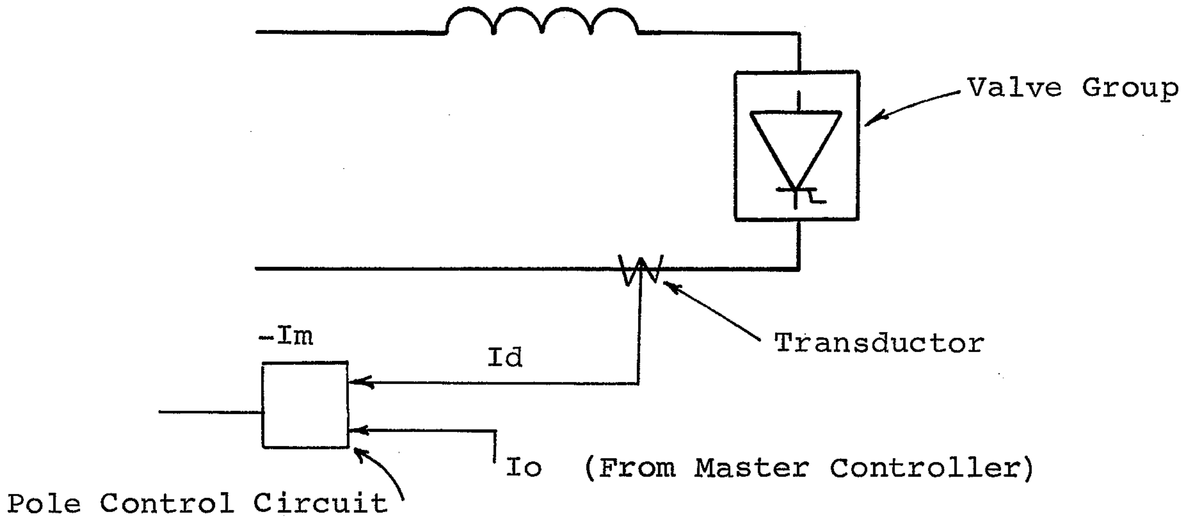


FIG. 7.4

CONSTANT CURRENT CONTROL

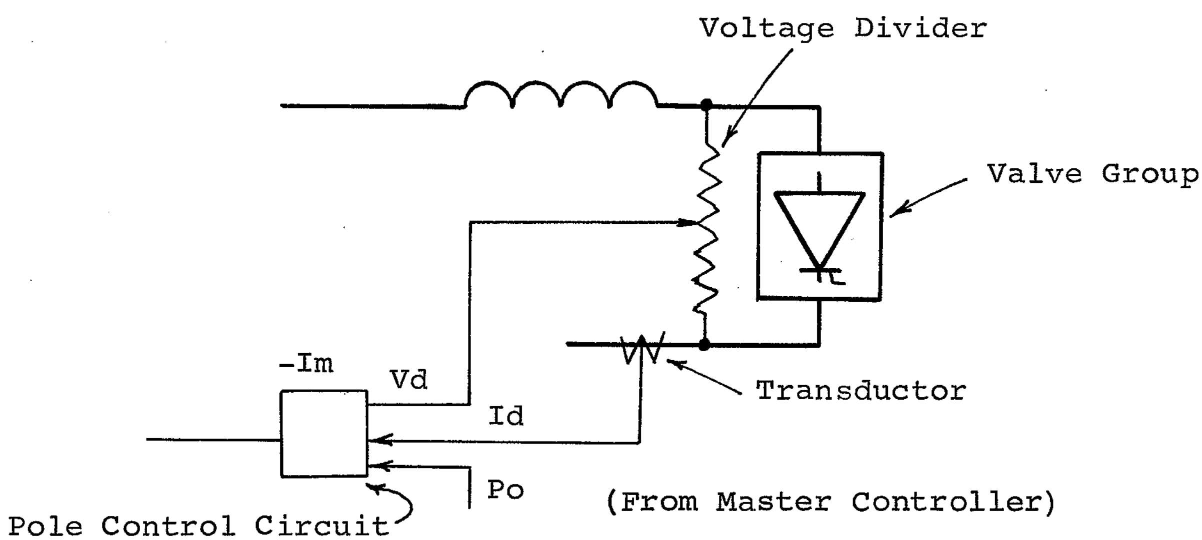


FIG. 7.5

CONSTANT POWER CONTROL

Sometimes a combination of two or all methods is also used, such as for the Sardinia-Italian mainland scheme which has constant current and constant frequency types of controls.

As stated earlier, for efficient operation, master controller equipment relys on a modern and reliable communication system e.g., microwave, pilot wire or short wave radio etc. A microwave communication system is most efficient and reliable.

If the power setting is to be altered, this has to take place in such a way that an increase of the setting must always be made first at the rectifier station; whereas if the decrease of power is desired it should be made first at the inverter station. If this sequence is not followed, the margin would be lost. The proper timing between the power settings is also controlled by the telecommunication system, which is set to order the right operating sequence when a power order change is given from one station.

7.2.2 Pole Control Circuits:

These include circuits for the control of each pole of the d.c. station. One set of such circuits per pole at each station is required (Item "b", FIG. 7.3).

Pole control equipment also incorporates protective circuits. The functions of the control circuits are to control the closed loop current, compounding of voltage, converter transformer tap-changer mechanism, d.c. line current, current margin setting, rectifier and inverter voltage settings, reversal of power flow direction, etc. These are described below:

a) The current order I_o fed from the master controller is compared with I_d and in the case of inverter, also with I_m. The difference between these signals is amplified and the output is fed to valve control circuits to control firing of the phaselocked oscillator.

b) The values of V_{dr} and V_{di} differ because of line drop. For the transformer tap-changer control it is necessary to obtain a voltage signal referred to a common point on the line. This reference could be either at the rectifier end or at the mid-point of the line. Generally transmission line mid-point voltage regulation is preferred. The advantage of such regulation is that the line voltage drops are shared equally between both the terminal stations. Inverter transformer tap-changer mechanisms are controlled so as to keep the voltage of this point at the highest safe limit.

c) Pole control circuits control the transmitted current I_d within the prescribed limits. The minimum and maximum values of this current are those between which the valve groups can be operated satisfactorily. These limits usually are between 10% and 110% of the rated current.

d) Pole controls also control the current margin setting I_m at the inverter end for the inverter control operation whenever rectifier control is lost.

e) Pole controls keep the inverter voltage lower than rectifier voltage by an amount M (FIG. 7.2). This is achieved by controlling the rectifier transformer tap-changer mechanism (Section 7.1.1 c).

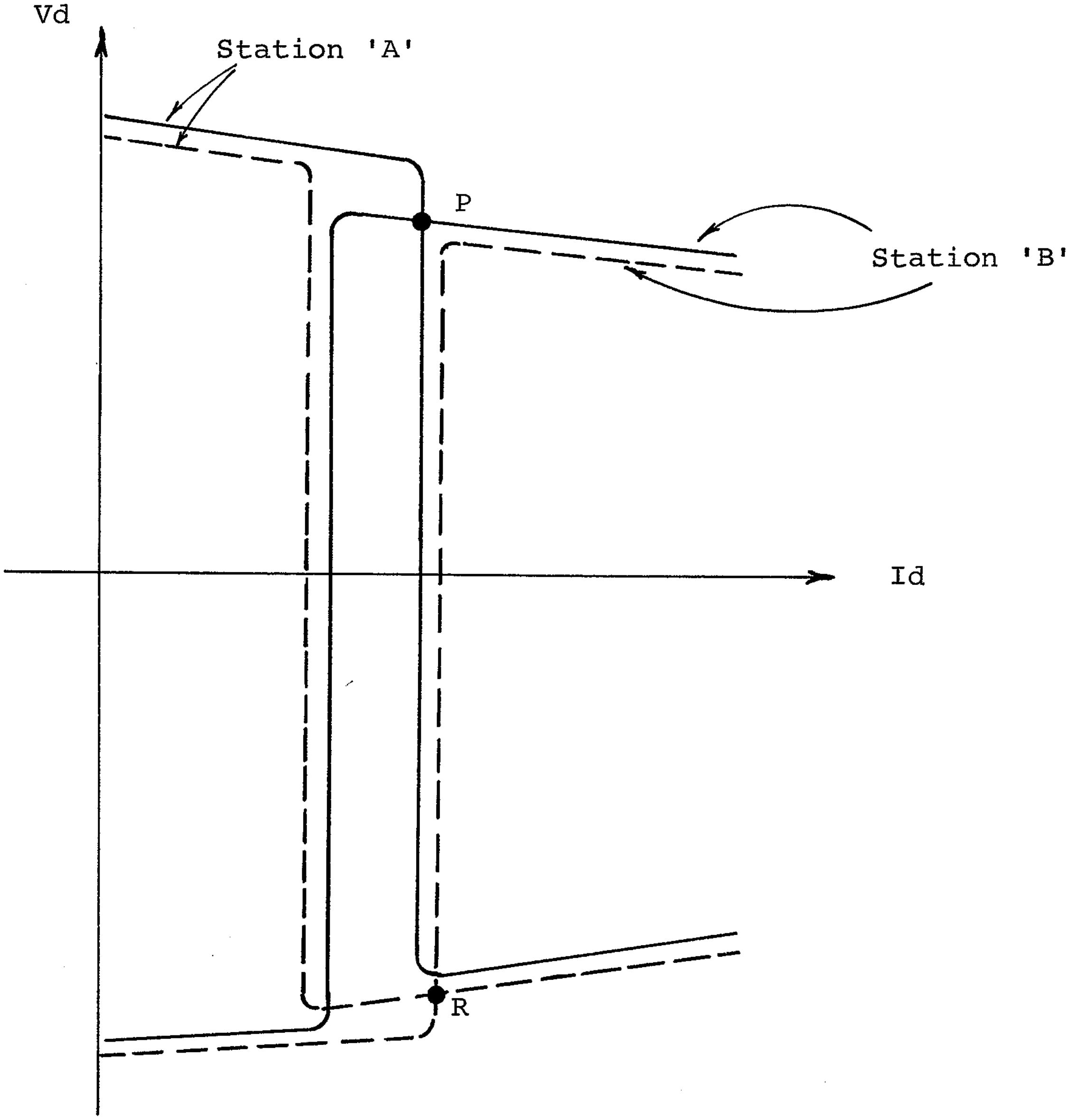
f) Reversal of power flow is also controlled by pole controls. This is achieved by shifting the inverter to rectifier operation and vice versa. FIG. 7.6 shows this process

Supposing that station A is operating as rectifier and station B as inverter. The load characteristics for this set up are shown in solid lines and "P" is the normal operating point. In order to reverse the power flow d.c. pole controls operate to make the following changes:

1. A signal is sent to both the stations, which sets current margin in station A and resets it from station B.

2. Minimum delay angle α setting is changed from station A to station B.

3. Tap-changer control of station A is changed to regulate the transmission line mid-point voltage and that of B to



————	(Solid Lines):	Station 'A' operating as rectifier and Station 'B' as inverter. "P" is normal operating point.
---------	(Broken Lines):	Station 'A' operating as inverter and Station 'B' as rectifier. "R" is normal operating point.

FIG. 7.6

<u>REVERSAL OF POWER FLOW</u> 70

keep α at a safe minimum.

4. Indicating circuits are changed accordingly.

5. D.C. line protection is changed to suit the corresponding operation.

After performing the above operations the load characteristics are changed as shown by dotted lines in FIG. 7.6 and R becomes the new operating point. Station B now operates as a rectifier as station A as an inverter.

The protective relays in the pole control scheme are incorporated for:

a) If the d.c. line voltage falls below the preset value, say, about 60% of normal voltage, the protective relays operate to block the rectifier pole and inverter pole control takes over. If this condition persists for a longer period, say, about a minute, the permanent blocking signal is sent to the inverter station and both corresponding poles are blocked.

b) Differential protection is provided to compare the d.c. incoming and outgoing currents at both ends. If the difference increases beyond a certain preset value, the valve groups are blocked. In case of a persistent or greater difference it is necessary to block both the poles.

c) It is necessary to provide relays to detect whether due to different combinations of bridge or pole blocking the rating of a.c. harmonic filters is not exceeded. If such a condition occurs and persists, pole control relays operate to isolate the filters and, if necessary, shut down the whole station.

7.2.3 Valve Group Control Circuits:

These include circuits for the control and protection of each valve group of inverter and rectifier stations. One set each of this equipment is required for every valve group (item "d" in FIG. 7.3).

The output from the d.c. pole control amplifier is used to control the firing of the valves. The voltage control oscillator is located in the control room and the signal is sent from the ring counter to each valve where it energizes the neon lights located near the foot of the valve supporting platform at earth potential. These light pulses are transferred to the top of valve by means of light guides. At the top of the light guides the photo cells detect the beams and convert them into potentials. These are then amplified and applied to the pulse transformers supplying firing circuit for grid pulse generator. The grid pulse generator generates pulses of required magnitude which are applied to the valve control grid to raise or lower its potential to + 300V or

-300V with respect to the valve cathode.

7.3 FAULTS AND PROTECTION:

Inverter station faults may be divided into three major groups:

7.3.1 Inverter Faults:

7.3.2 D.C. Line Faults:

7.3.3 A.C. System Faults.

D.C. protection schemes should be very fast. Conventional a.c. relays are slow and are not suitable for d.c. protection. For this reason d.c. protective circuits are all electronic relays which react very quickly and send protective signals for prompt action.

7.3.1 Inverter Faults:

In an a.c. system the circuit breaker is the basis of protection because of current zero twice every cycle. Since there is no current zero in the case of d.c., practical sizes of d.c. circuit breakers are not yet possible. However, the absence of a d.c. breaker is somewhat mitigated by fast acting grid control, especially in point to point transmission. The valve grid control has faster speed of operation and provides greater protection than can be achieved with circuit breakers. Even if d.c. breakers become available, it may not be advantageous to abandon grid control in their favour, except perhaps for tapping purposes.

Inverter faults are characterised by departure from normal conducting periods. Either a valve fails to conduct when it is normally supposed to do so or, alternatively, it conducts outside its normal pulse-controlled period.[16,17,71,74,75]

These faults are:

i) Commutation Failures:

ii) Arc Quenching:

iii) Arc-through or Fire-through; and

iv) Back-fire or Arc-back.

i) Commutation Failure:

When a valve fails to commutate (i.e. misfire) at its normal conducting time, the fault is called commutation failure.

Commutation failure causes a short circuit on the d.c. side of the valve group. Thus during commutation failure, direct current exceeds alternating current on the valve side of the transformer.

All kinds of commutation failures, viz. single commutation failure (s.c.f.), double-successive commutation failure (d.s.c.f.), and double-not-successive commutation failure (d.n.s.c.f.), usually correct themselves in the next cycle; no action on the part of protective circuits is necessary and the receiving a.c. system is not disturbed. If the fault persists and repeats itself, then it becomes necessary to block the bridge temporarily (refer to chapter III, section 3.7). If the fault still persists, then the bridge is blocked permanently and its associated a.c. breakers tripped, thus shutting the faulty bridge down completely.

The protective circuit for commutation failure is shown in FIG. 7.7. Here the direct current I_d and the alternating current I_a (rectified) are applied to a current level detector circuit. When I_d exceeds I_a, a blocking signal is sent to the valve group control equipment to block the bridge. A delay circuit is introduced to delay the blocking signal and give a chance to the faulty valve(s) to recover itself. For a persistent fault the signal circuit sends a permanent blocking signal and its a.c. breakers are tripped. The bridge is completely isolated and locked out. It will now be necessary for the operating personnel to detect and correct the fault before putting it back into service.

ii) Arc-quenching: (inability to pick-up commutation)

If the firing arc of a valve is extinguished it is called arc-quenching. Arc-quenching results in commutation failure and therefore the same protective circuits (FIG. 7.7) and methods are used to protect the equipment from this fault.

iii) Arc-through or Fire-through: (valve fires prematurely - inability of valve grid to control)

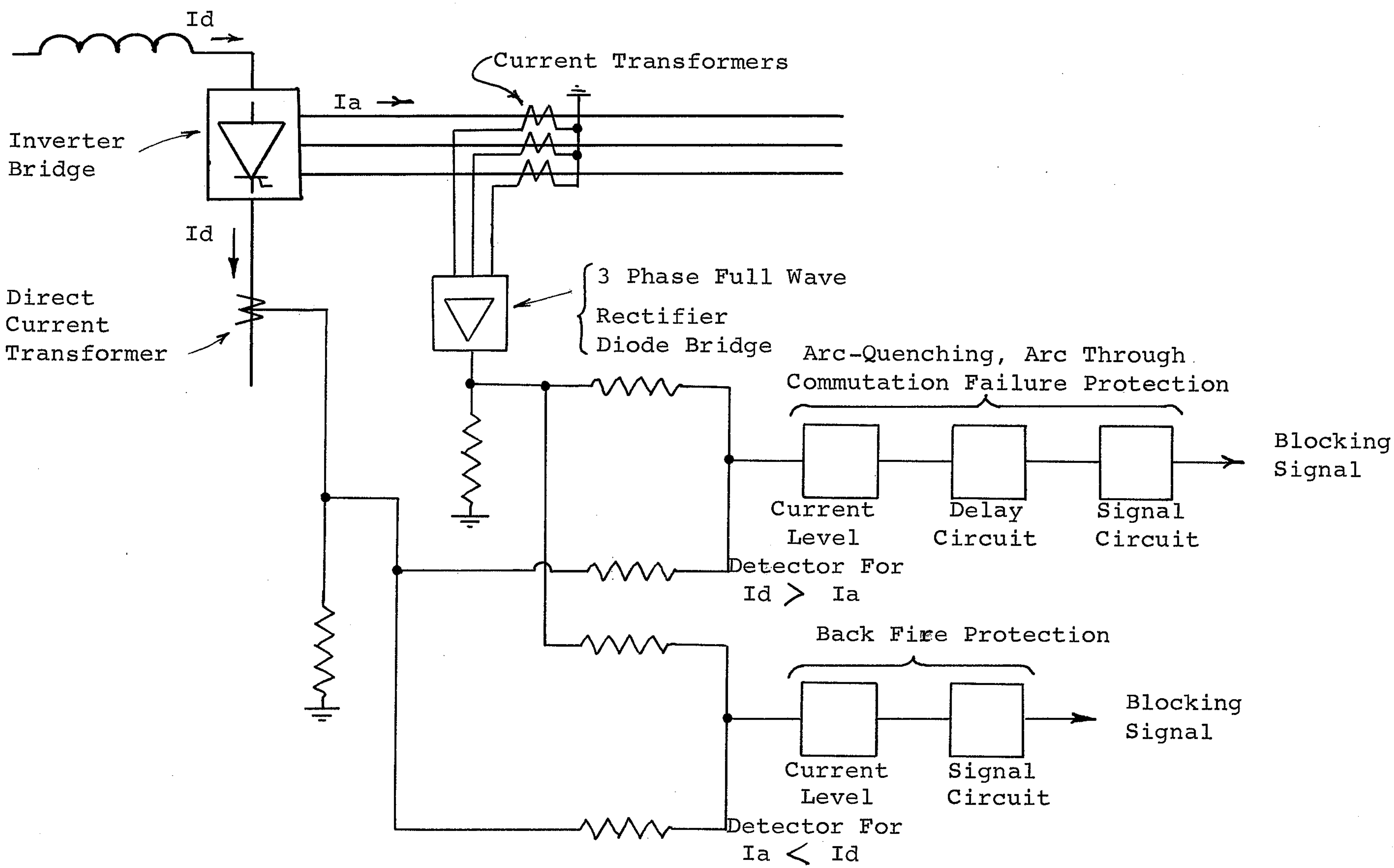


FIG. 7.7

BLOCK DIAGRAM SHOWING INVERTER FAULTS PROTECTION SCHEME

When a valve fires in the forward direction, during its non-conducting period, the fault is called arc-through or fire-through. The repercussions are similar to that of commutation failure and in this case also commutation protection circuits (FIG. 7.7) come in action and protect the equipment.

iv) Back-fire or Arc-back:

During the normal non-conducting period, a valve may conduct incorrectly in the reverse direction, from cathode to anode. This condition is called back-fire or arc-back. This type of fault in an inverter is very rare. This is so because during inverter operation, the anode voltage is negative with respect to its cathode only for a relatively very short period and the voltage is too small to cause back-fire. But sometimes, under inverter operation, when its angle may be large, back-fire might occur. Back-fire results in the short-circuit of two transformer phase windings on the valve side (secondary windings). The reverse current in the back-fired valve comes to its peak when the transformer secondary phase to phase voltage comes to zero, before which the faulty valve would have de-ionized in the case of normal operation. Therefore when the reverse current in the faulty valve comes to zero, the event extends to commutation failure. Thus the result of an inverter back-fire is that alternating current exceeds direct current for one part of the cycle and direct current exceeds alternating current for the other part of the cycle. The bridge should be blocked immediately.

FIG. 7.7 also shows the protective circuit for the faults resulting in back-fire. The scheme has a current level detector circuit which compares I_d and I_a. Whenever I_a exceeds I_d, a blocking signal is immediately sent to the valve group control equipment, and the bridge is blocked temporarily. For a persistent fault, permanent blocking is achieved and the associated a.c. circuit breakers tripped.

In the inverter fault detection scheme it is also desirable to determine, as fast as possible, the faulty valve. In order to achieve this the current level detector circuits include digital logic circuits [76,77] which determine the catagory of fault, the valve involved and the region in the cycle where the fault occurred and send indicating and protective signals.

7.3.2 D.C. Line Faults:

D.C. line faults can occur due to the following reasons:

In overhead lines:

1. Broken line conductors;
2. Broken or contaminated insulators;
3. Falling tree branches across the conductors;

4. Icing on the insulators;

5. Overvoltages on the line.

In underground or underwater cables:

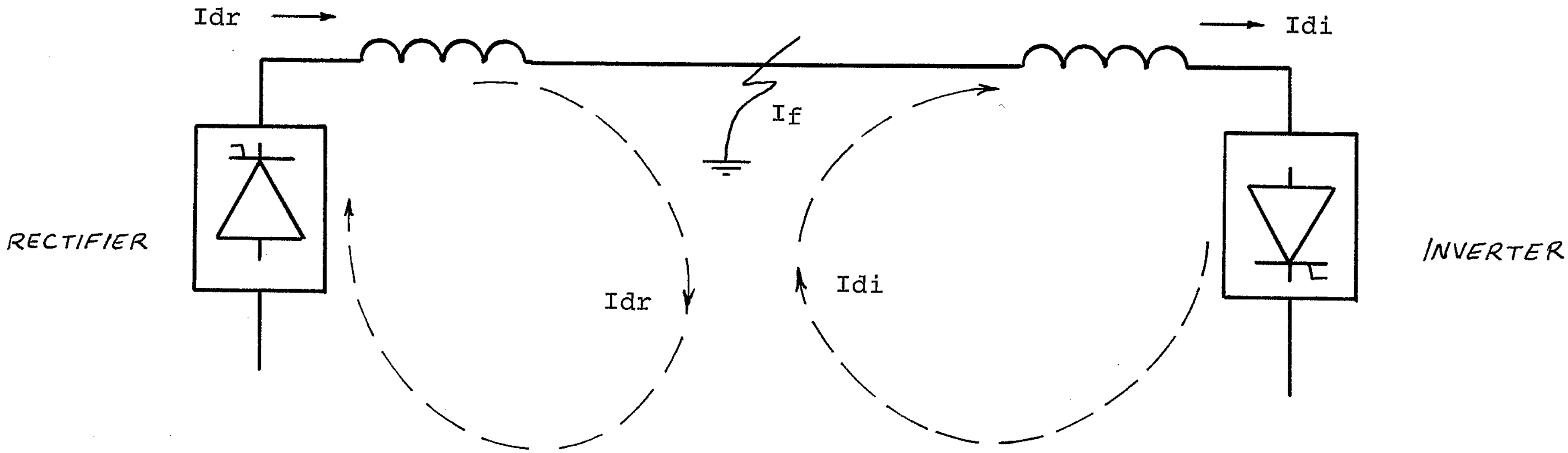
1. Insulation failure;

2. Accidental slicing, etc.

D.c. line faults, say, line to ground faults, result in the collapse of transmitting voltage. The current from the rectifier tends to rise and the current into the inverter tends to fall. One of the methods that could be employed at the inverter station is to reverse its voltage polarity by advancing the angle β to more than 90°. The inverter now starts conducting as the rectifier and forces its current I_{di} through the fault in the opposite direction into the line (FIG. 7.8). On the other hand the rectifier increases its angle α to maintain its current I_{dr} into the line. I_{dr} also flows into the fault but in a direction opposite to I_{di}. The current through the fault, therefore, will consist of a discharge transient current from the line, as the line capacitance discharges through the fault at the instant of fault, and the difference between currents I_{dr} and I_{di}. After the time for transients (a few milli-seconds) the fault current I_f is given by:

$$I_f = I_m = I_{dr} - I_{di} \quad \ldots \quad \ldots \quad (7.1)$$

A fault on the d.c. line, therefore, does not give rise



I_f = Im = Idr - Idi

——— Solid Lines Indicate Normal Current Flow

- - - Dotted Lines Indicate Current Flow During Fault

FIG. 7.8

D.C. LINE FAULT

to any dangerous overcurrents, but in order to avoid transmission interruption as far as possible, it is essential that the fault be cleared rapidly. The d.c. line fault current is a "d.c. arc" and it cannot be extinguished by itself.[78,79] To clear the fault it is necessary to reduce the fault current to zero for a time sufficient to deionize the arc in the fault and then resume transmission with minimum delay.

As has been said before, the line fault results in collapse of line voltage. On the other hand inverter faults and inverter blocking also appear as a d.c. short ciurcuit and loss of line voltage when viewed from the rectifier end. Thus it is necessary to distinguish between the line and the inverter faults. Here the d.c. line smoothing reactors installed at both ends of the line play an important role. The blocking of the inverter valves and firing of their by-pass valve appears as a fault beyond the two smoothing reactors, whereas the line fault is beyond only one reactor. This means that due to only one smoothing reactor, the rate of change of voltage dv/dt due to a line fault will be higher than due to the faults at the inverter station. So discrimination can be achieved by careful detection by dv/dt and prohibiting the line fault detecting circuits from acting for inverter faults.

FIG. 7.9 shows a d.c. line protection scheme in block diagram form. As soon as the line fault is detected by the level

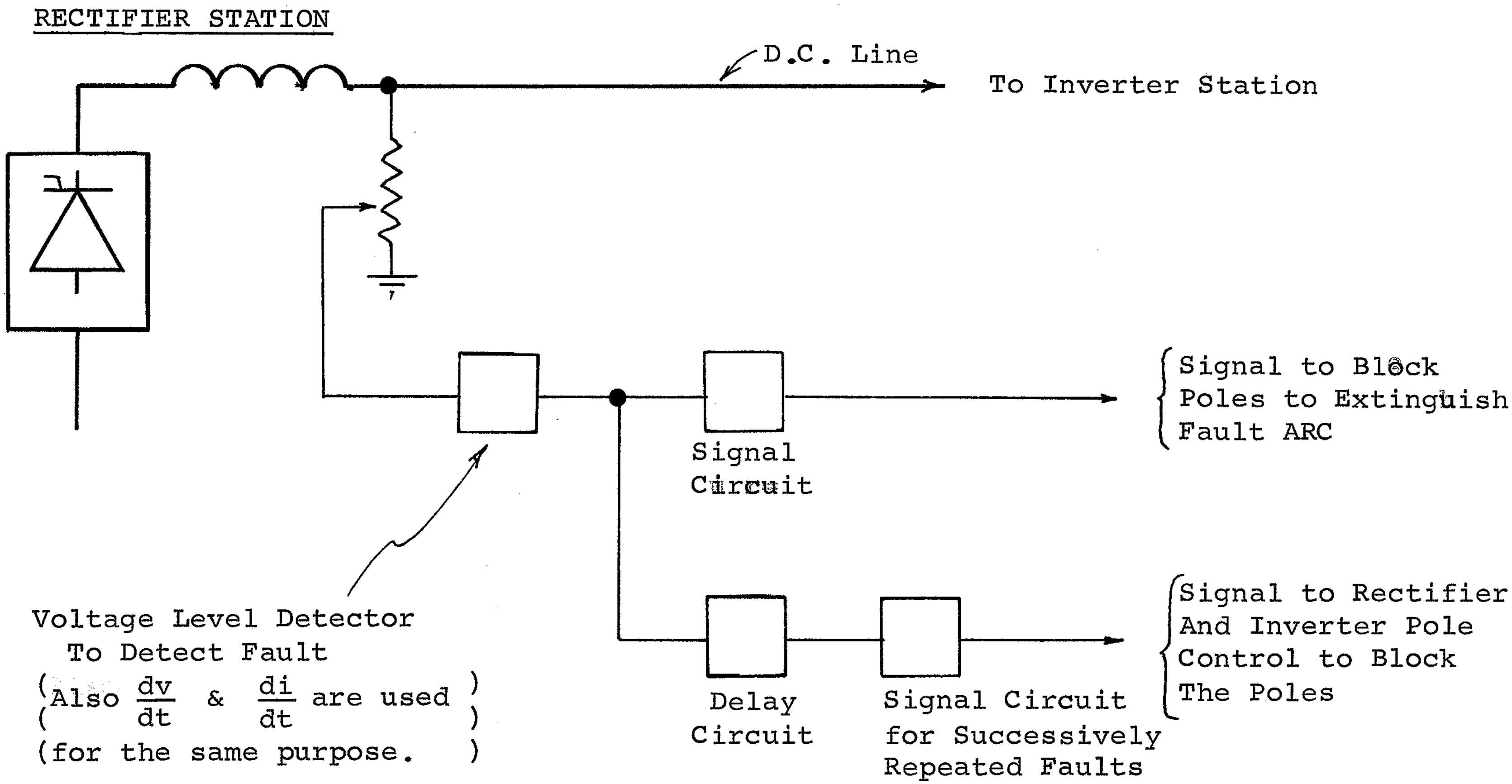


FIG. 7.9

D.C. LINE PROTECTION SCHEME 74

detector the signal circuit sends a command to the corresponding pole controls to block both rectifier and inverter poles. After the arc is extinguished the poles are unblocked and, if the fault is of temporary nature, normal transmission is resumed. If the fault persists, the cycle repeats a few times, depending on the setting of the delay circuit. after which a signal is sent to the pole controls to block the poles permanently and the corresponding a.c. breakers are tripped both at inverter and rectifier stations and locked out. Total time for clearing a d.c. line fault, say, line to ground fault, from the instant of detecting the fault to the clearing time is approximately 300-500 milli-seconds[75] depending upon the fault and protection circuit settings and the restoring sequence.

It is good design practice to provide spare lines or lines with higher capacities to ensure continuity of power supply. In such cases it is not necessary to lockout poles completely. Instead a switching arrangement may be provided to switch the poles to a spare line.

7.3.3. A.C. System Faults:

Alternating voltage fluctuations on the a.c. side would cause corresponding direct voltage fluctuations but, due to constant current regulation, these fluctuations are taken care of automatically by changing the current order I_o to the inverter and rectifier power flow controls. Thus provided the current limits do not change beyond the preset values (both minimum and maximum), the d.c. power transmission is not affected. The alternating voltage fluctuations might even drive the pole controls to inverter control operation, but still the d.c. power transmission is not interrupted and transformer tap changers operate, in time, to resume normal operation (rectifier control).

FIG. 7.10 shows in block diagram, the protection scheme from a.c. bus disturbances. When alternating current increases beyond the set value, becuase of, say, an a.c. bus fault at the inverter station, the over-current protection circuit sends a signal to trip the corresponding breakers and isolate the faulty bus. All other sections would not be affected and transmission of power to healthy sections is uninterrupted. Generally reclosing can be provided to take care of the transient faults and disturbances. If the fault is permanent, the breakers are tripped permanently and a fault alarm signal comes on.

Under-current protection circuits are also provided for similar reasons. These protect the affected equipment if the alternating current falls below the set value due to violent voltage fluctuations.

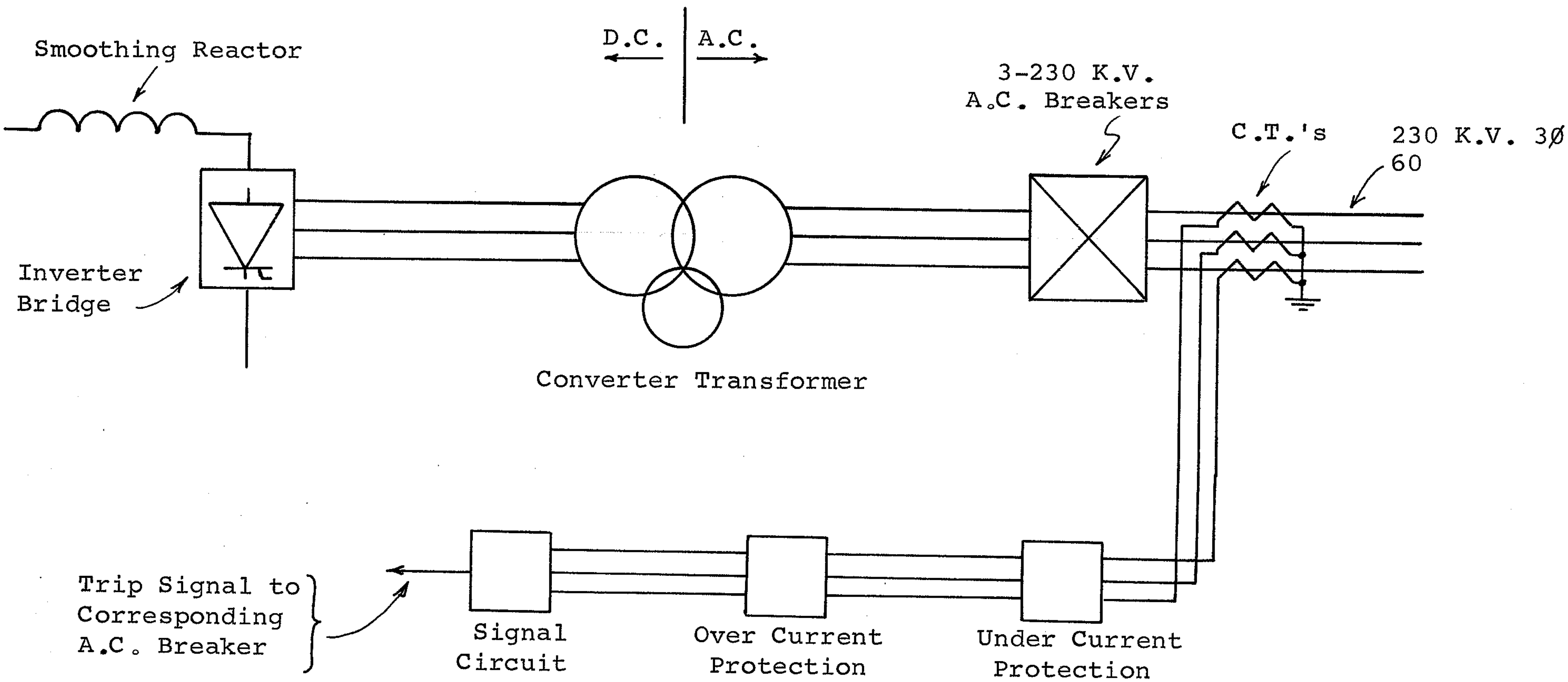


FIG. 7.10

A.C. BUS FAULT PROTECTION

CHAPTER VIII

CONCLUSION

i) This thesis has presented a broad survy of the design and operating aspects of a high voltage direct current inverter station.

Although only the inverter station was considered, the design and operation of a rectifier terminal station would be similar.

ii) In describing the behaviour of different equipment, the theory of operation and formulae used are not included, because these are easily accessible in various textbooks. The emphasis is on the arrangement of the equipment and its function in the station.

iii) The initial capital costs of H.V.D.C. terminal stations are higher than comparable a.c. stations (same rating). Indications are that refinement of engineering design would bring the cost of d.c. stations more in line.

iv) Control and protection techniques of d.c. equipment are more involved than those of the a.c. equipment. This would be a rewarding area for further study.

v) An H.V.D.C. circuit breaker does not exist at the present time. With the development of such a breaker it may be possible to design future d.c. stations with simpler and more effective protection and control schemes.

From this thesis it is seen that d.c. breakers are not required for point to point d.c. transmission. A d.c. breaker would be useful in more complex d.c. transmission networks.

vi) Overhead transmission lines, underground and underwater cables and earth and sea electrodes for H.V.D.C. transmission are not covered in this thesis. These are major fields of study by themselves.

vii) Telecommunication requirements for efficient control of power flow and protection are also not covered. This may be a subject for further study.

viii) Only multi-anode mercury arc valves are considered. The technology of such valves is highly developed. Single anode mercury arc valves and thyristors have not been studied in this thesis. These would be suitable subjects for other theses.

ix) Some of the topics discussed in this thesis could be subjects of further research. Such as:

1. Development of Layouts of H.V.D.C. Terminal Stations.
2. Application of Harmonic Filters and Reactive Power Requirement in an H.V.D.C. Terminal Station.

3. Design Aspects of H.V.D.C. Valves.
4. Lightning Arrestors for High Voltage Direct Current Applications.
5. Application of Damping Equipment in an H.V.D.C. Terminal Station.

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Appendix I

H.V.D.C. Schemes Around the World - Existing and Proposed

	Year in Service	Power Rating	Direct Voltage	Direct Current	Valve Groups	Anodes Per Valve	Voltage Per Group	Type of Line	Length of Line	Station Location	A.C. Grid Voltage
		M.W.	K.V.	AMPS.			K.V.		MILES		K.V.
Gotland (Sweden)	1954	20	100	200	2	2	50	U.G.	60	Vastervik	130
										Visby	30
Cross-Channel	1961	160	±100	800	2	4	100	U.G.	40	Lydd	275
										Boulogne	225
U.S.S.R.	1964	750	±400	900	8		100	U.G.	2	Volgograd	220
								O.H.	294	Donbass	220
Japan	1965	300	±125	1200	2	4	300	0	0	Sakuma	275
Sweden-Denmark	1965	250	250	1000	2	4	125	U.G.	54	Gothenburg	130
								O.H.	53	Alborg	150
New Zealand	1965	600	±250	1200	4	4	125	U.G.	25	Benmore	16
									354	Haywards	110

Appendix I (continued)

	Year in Service	Power Rating M.W.	Direct Voltage K.V.	Direct Current AMPS.	Valve Groups	Anodes per Valve	Voltage Per Group K.V.	Type of Line	Length of Line MILES	Station Location	A.C. Grid Voltage K.V.
Italy	1966	200	+200 or -200	1000	2	4	100	U.G. O.H.	72 180	Codron- Gianos	230
										San Dalmazio	220
Canada	1969	78 (312 ultimate)	130 260 (ulti- mate)	1200	2	4	130 (ulti- mate)	U.G. O.H.	175 28	Arnott Stratford	230 230
U.S.A. (Pacific Intertie 1)	1969	1440	$\pm$400	1800	6	6	133	O.H.	853	Celilo Sylmar	230 230
England	1970	640	$\pm$266	1200	4	4	133	U.G.	52	Kingsnorth	132
					2 2			U.G.	14	London Willesden	132 132
U.S.A. (Pacific Intertie 2)	1971	1400	$\pm$400	1800	6	6	133	O.H.	820	Celilo Mead	230 230

Appendix I (continued)

	Year in Service	Power Rating	Direct Voltage	Direct Current	Valve Groups	Anodes per Valve	Voltage Per Group	Type of Line	Length of Line	Station Location	A.C. Grid Voltage
		M.W.	K.V.	AMPS.			K.V.		MILES		K.V.
Canada (Stage 1)	1971	810	+150 -300	1800	3	6	150	O.H.	565	Kettle Dorsey (Winnipeg)	120 230
Canada (Final Stage)	1976 (Proposed)	1620	±450	1800	6	6	150	O.H.	565	Kettle Dorsey (Winnipeg)	120 230
U.S.A. (Alaska)	1972 (Future)	80			2			O.H. Under-water		Snettisham Juneau	
Canada (Newfound-land)	Proposed										
Canada (New Brunswick)	(Proposed) 1972	320			2+2			Tie	Tie		230
South Africa (Stage 1)	(Proposed) 1975	960	±267	1800	4		133	O.H.	900	Cabora Bassa (Mozambique) Joheunesburg (South Africa)	275
South Africa (Final Stage)	(Proposed) 1979	1920	±533	1800	8		133			Same as above	

Appendix I (continued)

	Year in Service	Power Rating	Direct Voltage	Direct Current	Valve Groups	Anodes per Valve	Voltage per Group	Type of Line	Length of Line	Station Location	A.C. Grid Voltage
		M.W.	K.V.	AMPS.			K.V.		MILES		K.V.
Spain - Morroco	Proposed	200	±220					U.G.	20		
Italy - Yugoslavia	Proposed	720	±300					O.H.	135		
U.S.S.R. (East - West)	Proposed	12,000	±750					O.H.	1,560		

Appendix II

a.

Time	Valves Conducting	Valve fires After 60^{o}	Commutation Takes Place	Valves Conducting After Commutation
0^{o}	1 and 2	3	from 1 to 3	3 and 2
60^{o}	3 and 2	4	from 2 to 4	3 and 4
120^{o}	3 and 4	5	from 3 to 5	5 and 4
180^{o}	5 and 4	6	from 4 to 6	5 and 6
240^{o}	5 and 6	1	from 5 to 1	1 and 6
300^{o}	1 and 6	2	from 6 to 2	1 and 2
360^{o}	1 and 2	cycle repeats		

Rectifier Bridge Firing Sequence

Appendix II

b.

Time	Valves Conducting	Valve Fires After 60°	Commutation Takes Place	Valves Conducting After Commutation
0°	4 and 5	6	from 4 to 6	6 and 5
60°	6 and 5	1	from 5 to 1	6 and 1
120°	6 and 1	2	from 6 to 2	2 and 1
180°	2 and 1	3	from 1 to 3	2 and 3
240°	2 and 3	4	from 2 to 4	4 and 3
300°	4 and 3	5	from 3 to 5	4 and 5
360°	4 and - cycle repeats.			

Inverter Bridge Firing Sequence

Appendix III

I_o = Reference current

V_o = No load d.c. voltage

V_{ar} = Rectifier RMS Alternating voltage L-L 3Ø

V_{ai} = Inverter RMS Alternating Voltage L-L 3Ø

I_{ar} = Rectifier RMS Alternating Current L-L 3Ø

I_{ai} = Inverter RMS Alternating Current L-L 3Ø

V_{dr} = Rectifier Direct Voltage Output

V_{di} = Inverter Direct Voltage Input

I_{dr} = Rectifier Direct Current

I_{di} = Inverter Direct Current

I_d = d.c. line current

I_s = magnitude of fundamental component of a.c. output current referred to transformer secondary

R = D. C. line resistance

α = Angle of delay

γ = Angle of commutation or angle of overlap

δ = Angle of extinction or dionization (angle between voltage zero and angle of commutation)

β = $\gamma + \delta$ = Angle of advance

γ_o = minimum value of γ at $\alpha \simeq 0$

H_{ac} = magnitude of a.c. harmonics (current harmonics)

H_{dc} = magnitude of d.c. harmonics (voltage harmonics)

λ = wave length

X_s = A.C. system short circuit reactance

Appendix IV

a) Magnitude of A.C. Harmonic:

$$I_s = \frac{\sqrt{6}}{\pi} I_d = (0.78)\ I_d$$

$$I_d = 1800\ A.$$

$$I_s = 1404\ A.$$

$$H_n = \frac{I_s}{n}$$

where, n = order of harminic, vis 5,7,11,13 etc.

$$H_5 = \frac{1404}{5} = 280.8A \simeq 20\%\ of\ I_s$$

$$H_7 = \frac{1404}{7} = 200.5A \simeq 14.3\%\ of\ I_s$$

$$H_{11} = \frac{1404}{11} = 136.7A \simeq 9.7\%\ of\ I_s$$

$$H_{13} = \frac{1404}{13} = 108A \simeq 7.7\%\ of\ I_s$$

$$H_{17} = \frac{1404}{17} = 82.6A \simeq 5.9\%\ of\ I_s$$

$$H_{19} = \frac{1404}{19} = 73.8A \simeq 5.26\%\ of\ I_s$$

$$H_{23} = \frac{1404}{23} = 61.0A \simeq 4.35\%\ of\ I_s$$

$$H_{25} = \frac{1404}{25} = 56.2A \simeq 4\%\ of\ I_s$$

$$H_{29} = \frac{1404}{29} = 48.4 \simeq 3.45\%\ of\ I_s$$

Appendix IV

b) Magnitude of D. C. Harmonics:

$$H_n = \frac{V_o\sqrt{2}}{(n^2-1)}$$

where, n = order of harminic, vis, 6, 12, 18 etc.

V_o = no load output d.c. voltage = 450 KV

$$H_6 = \frac{450\sqrt{2}}{35} = 18.15 \text{ KV} = 4.04\% \text{ of } V_o$$

$$H_{12} = \frac{450\sqrt{2}}{143} = 4.45 \text{ KV} = 0.99\% \text{ of } V_o$$

$$H_{18} = \frac{450\sqrt{2}}{321} = 1.98 \text{ KV} = 0.44\% \text{ of } V_o$$

$$H_{24} = \frac{450\sqrt{2}}{575} = 1.105 \text{ KV} = 0.24\% \text{ of } V_o$$

$$H_{30} = \frac{450\sqrt{2}}{899} = 0.707 \text{ KV} = 0.157\% \text{ of } V_o$$

Appendix V

i) **Converter Transformer Rating:**

$$MVA = 1.047\ V_o\ I_d \qquad \text{----(1)}$$

Also, $V_d = V_o \cos\beta$ ----(2)

For inverter station under consideration.

V_d = d.c. line voltage = 150 KV

I_d = d.c. line current = 1800 A

β = Angle of advance $\simeq 35^o$

= 0.81915

from equations (1) & (2)

$$\text{Transformer rating} = 1.047 \frac{V_d\ I_d}{\cos\beta}$$

$$= \frac{(1.047)(150{,}000)(1800)}{0.81915}$$

$$\simeq 345 \text{ MVA}$$

ii) **Converter Transformer Secondary Voltage rating:**

Let, E = r.m.s. line to line voltage of transformer secondary

Now, we have,

$$V_o = 1.35\ E \qquad \text{----- (3)}$$

from equations (2) and (3) we can write

$$V_d = 1.35\ E \cos\beta$$

$$E = \frac{V_d}{(1.35)\cos\beta}$$

or, $E = \dfrac{150{,}000}{(1.35)(0.81915)}$

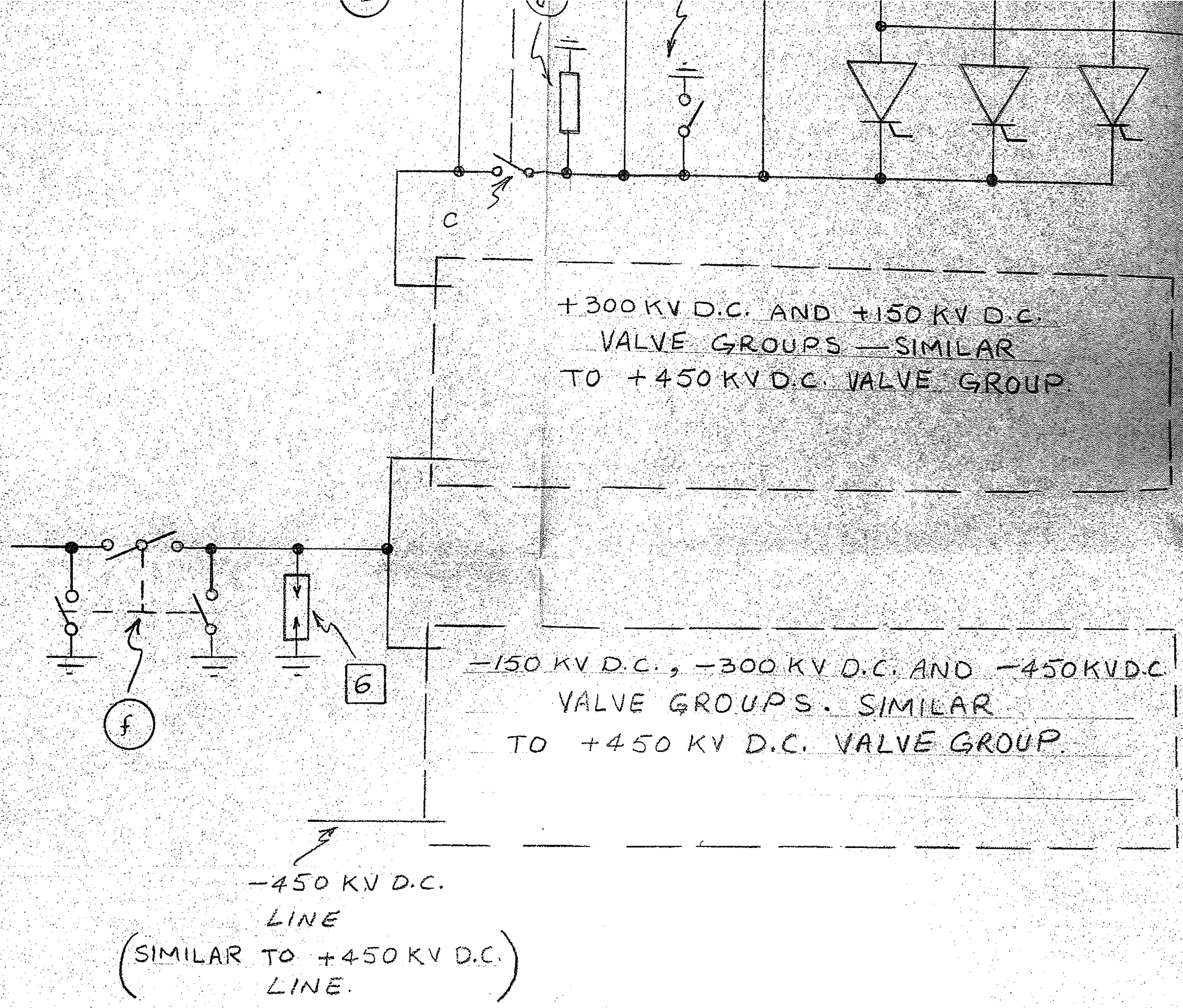
136.0 KV

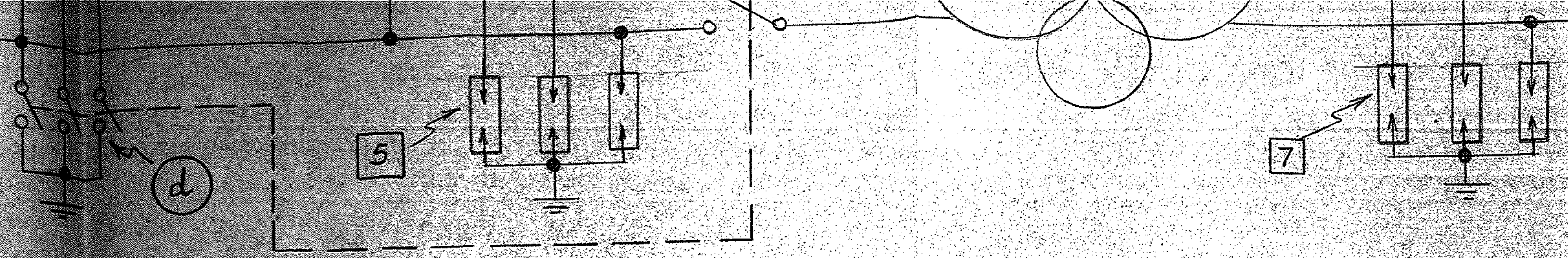
Appendix V (continued)

The voltage ratings of tertiary and primary windings have been taken as:

Tertiary windings: 12 KV, three-phase, 60 H_z

Primary windings: 230 KV, three-phase, 60 H_z





DRAWING # 4A

LOCATIONS OF LIGHTNING ARRESTERS
SWITCHES
AND
MEASURING EQUIPMENT

LEGEND

1 D.C. LINE LIGHTNING ARRESTER

2 D.C. LINE SMOOTHING REACTOR LIGHTNING ARRESTER

3 VALVE GROUP LIGHTNING ARRESTER

4 VALVE WINDING LIGHTNING ARRESTER – (LINE TO LINE)

5 VALVE WINDING LIGHTNING ARRESTER – (LINE TO GROUND)

6 ELECTRODE LINE LIGHTNING ARRESTER

7 A.C. SYSTEM LIGHTNING ARRESTER

(a) D.C. LINE ISOLATOR AND GROUNDING SWITCHES

(b) BY-PASS SWITCH

(c) VALVE GROUP D.C. ISOLATORS

(d) VALVE GROUP GROUNDING SWITCH (A.C. SIDE)

(e) A.C. DISCONNECTING SWITCHES

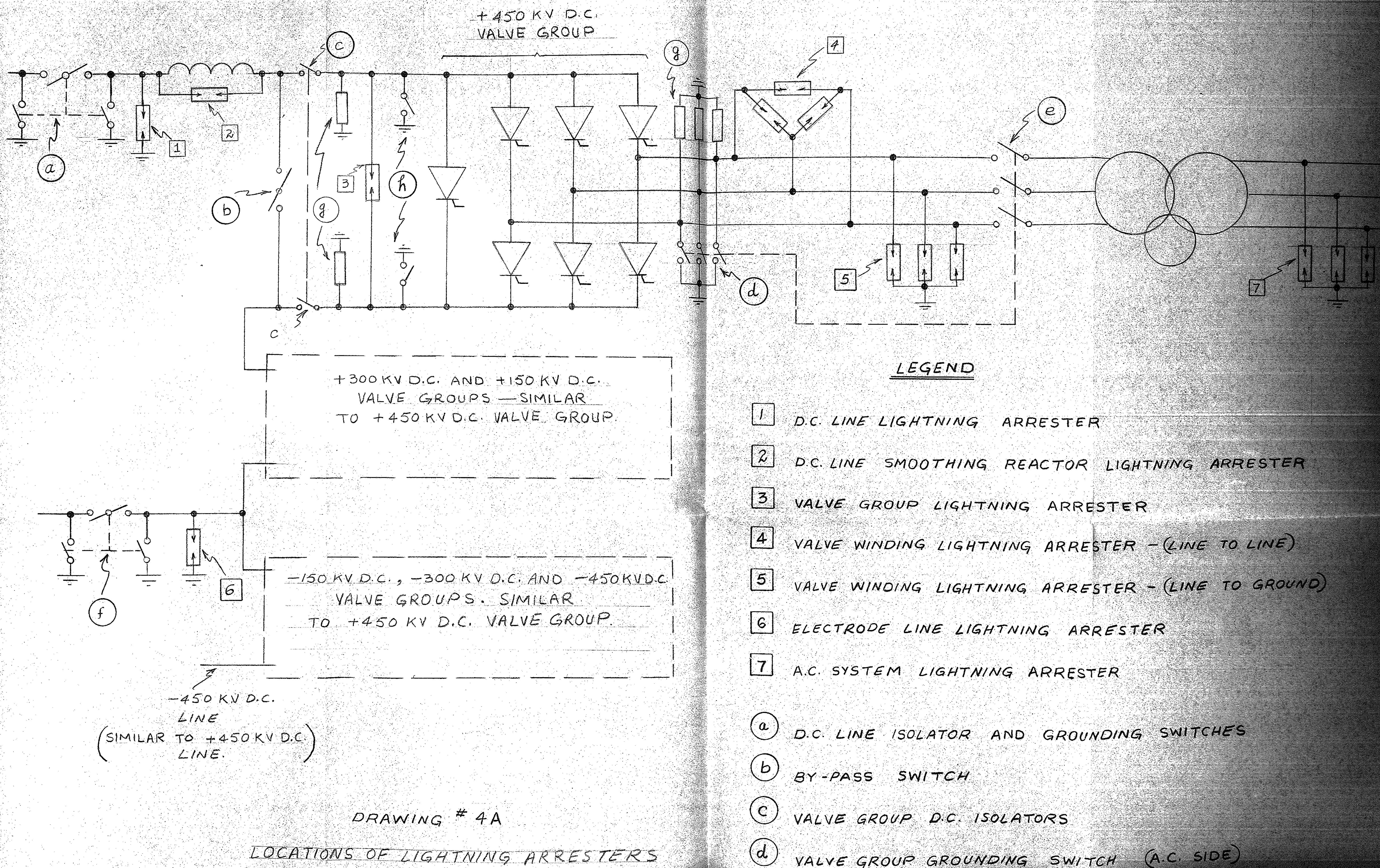
(f) ELECTRODE LINE AND GROUND SWITCHES

(g) VOLTAGE DIVIDER

(h) VALVE GROUP GROUNDING SWITCH (D.C. SIDE)

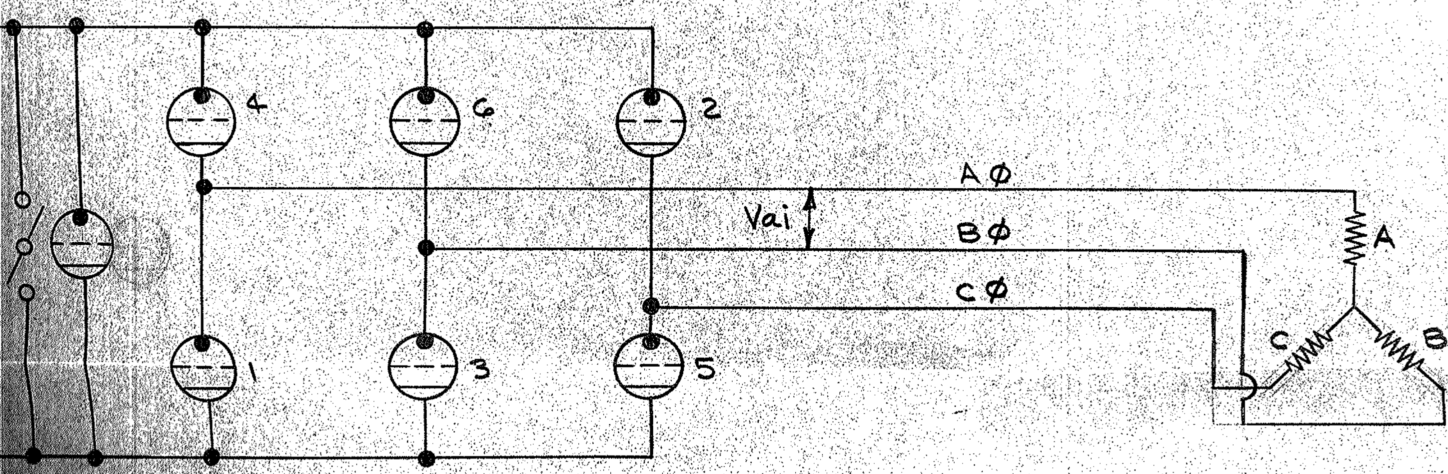
S.M.H. NAQVI, ELECT. ENGG., M.Sc. THESIS, FEB. 1970

DWG. # 4A

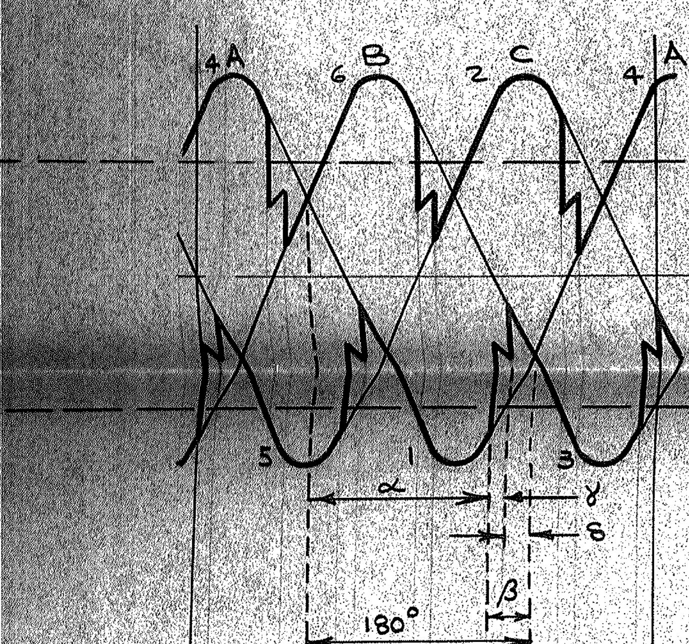


DRAWING # 4A

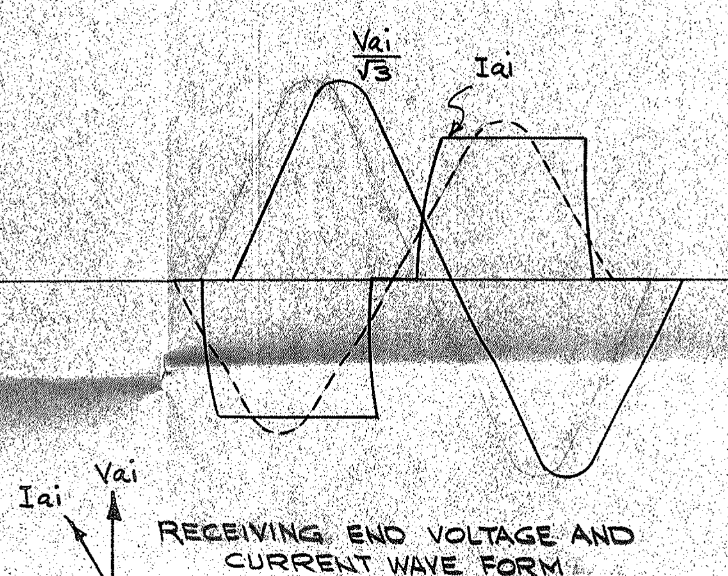
LOCATIONS OF LIGHTNING ARRESTERS



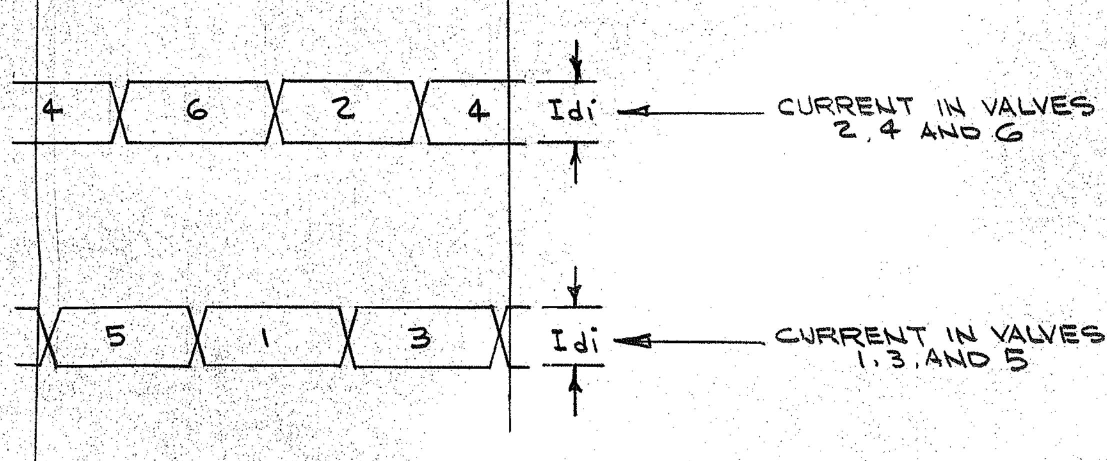
INVERTER BRIDGE



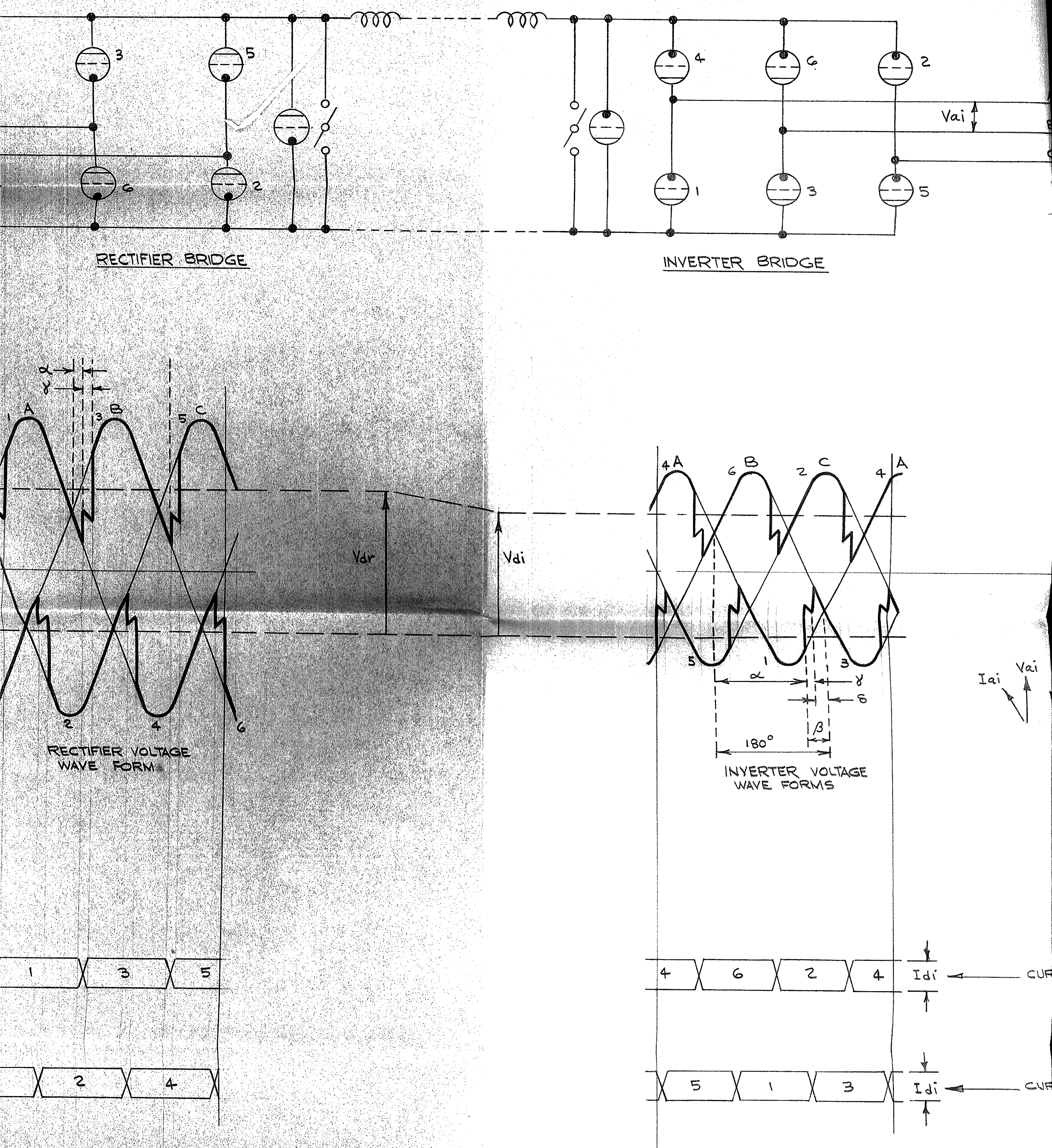
INVERTER VOLTAGE WAVE FORMS



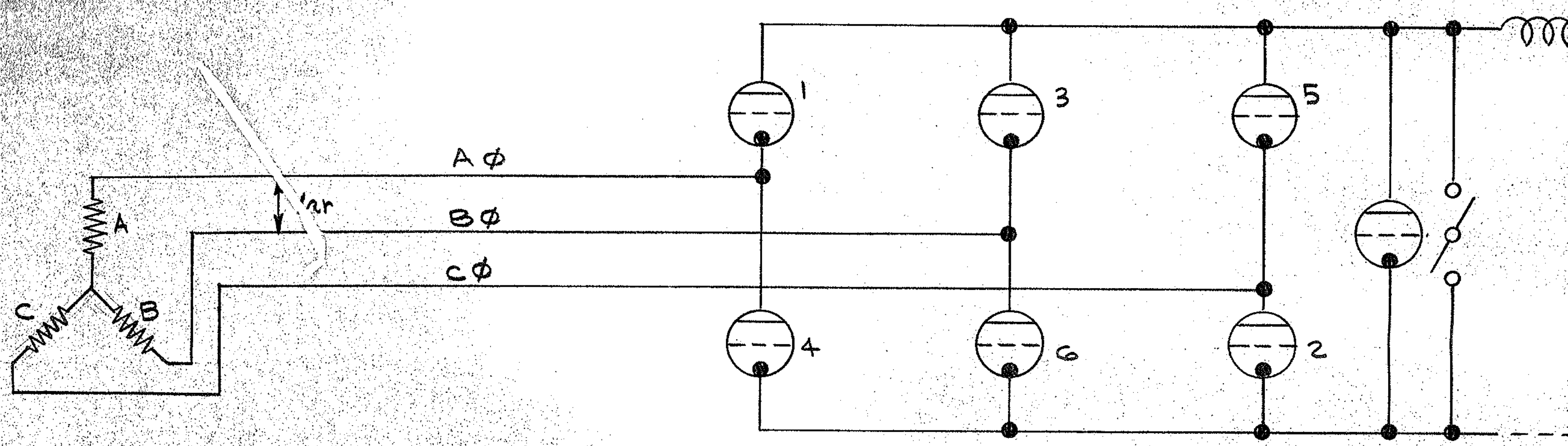
RECEIVING END VOLTAGE AND CURRENT WAVE FORM



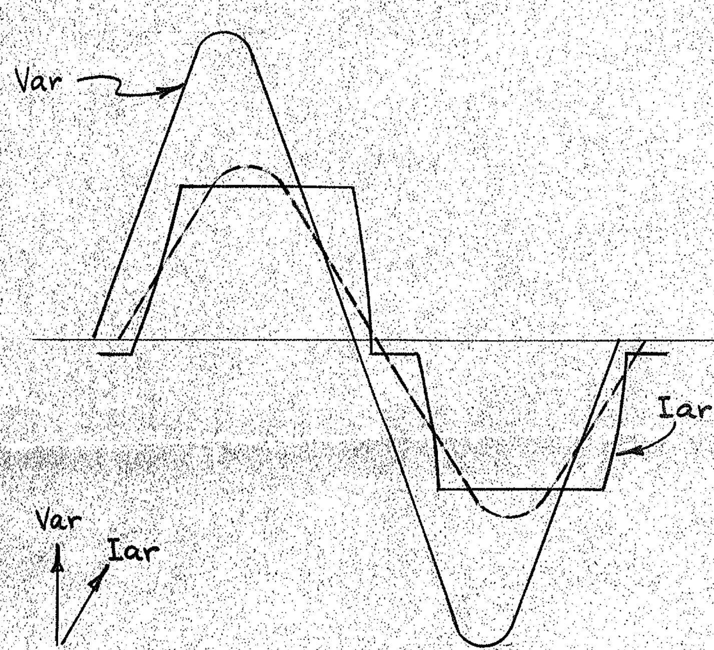
INVERTER CURRENT WAVE FORMS



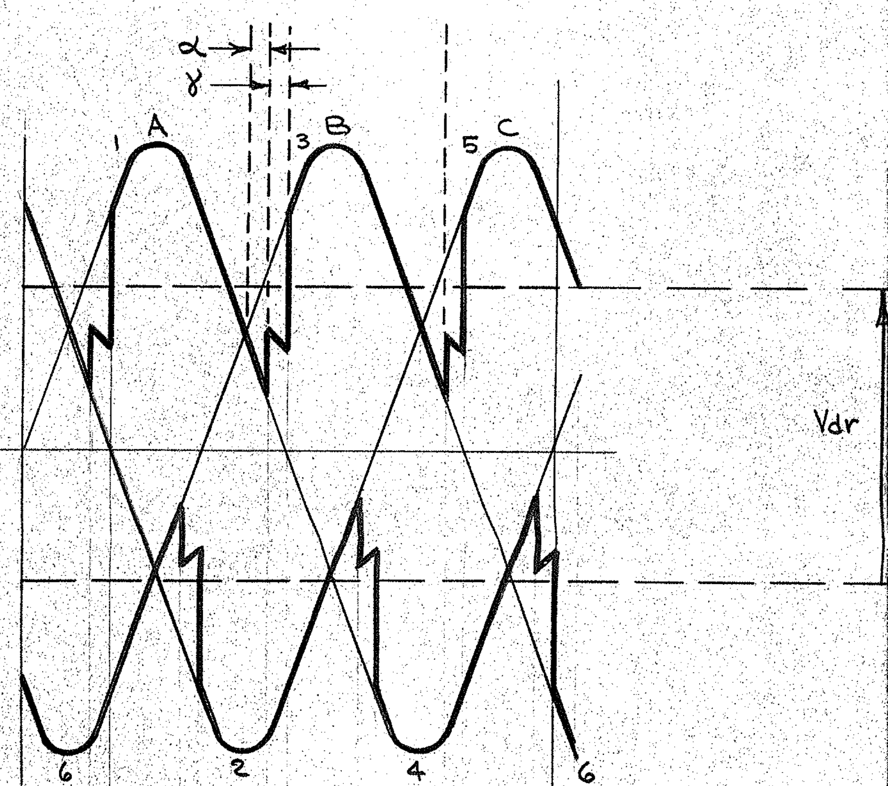
DRAWING # 3A
OPERATION OF CONVERTER BRIDGES



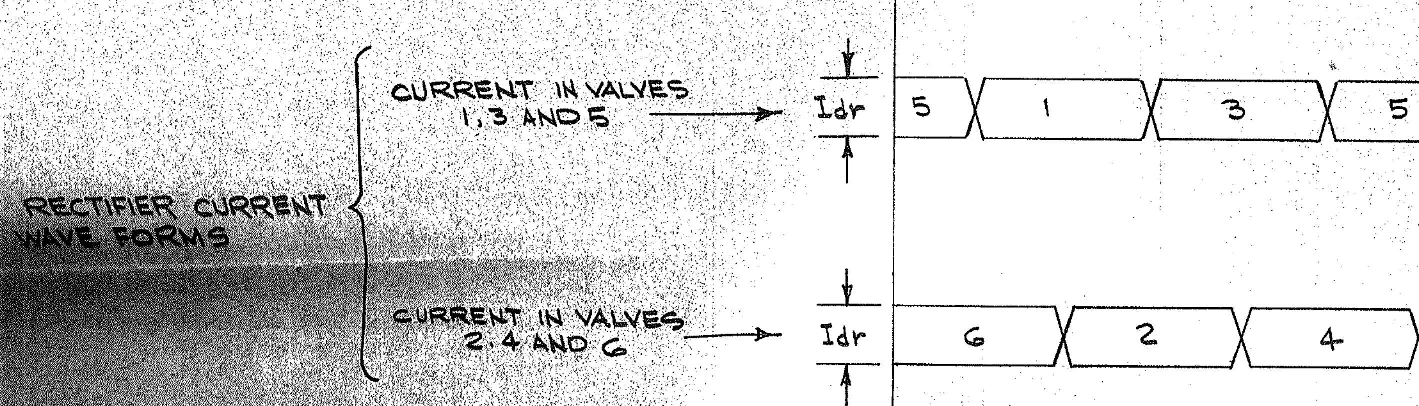
RECTIFIER BRIDGE



SENDING END VOLTAGE AND CURRENT
WAVE FORM



RECTIFIER VOLTAGE
WAVE FORM



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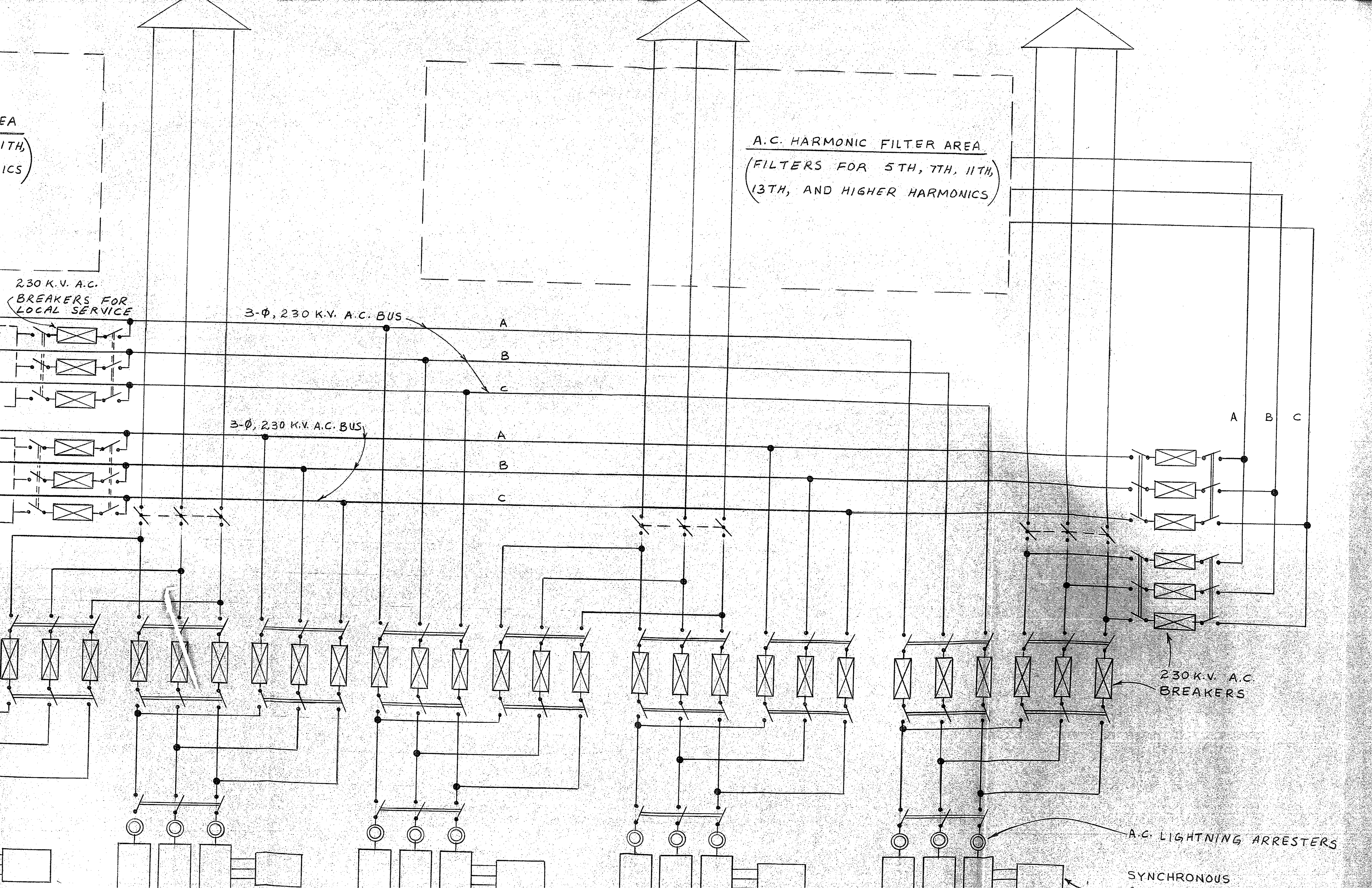
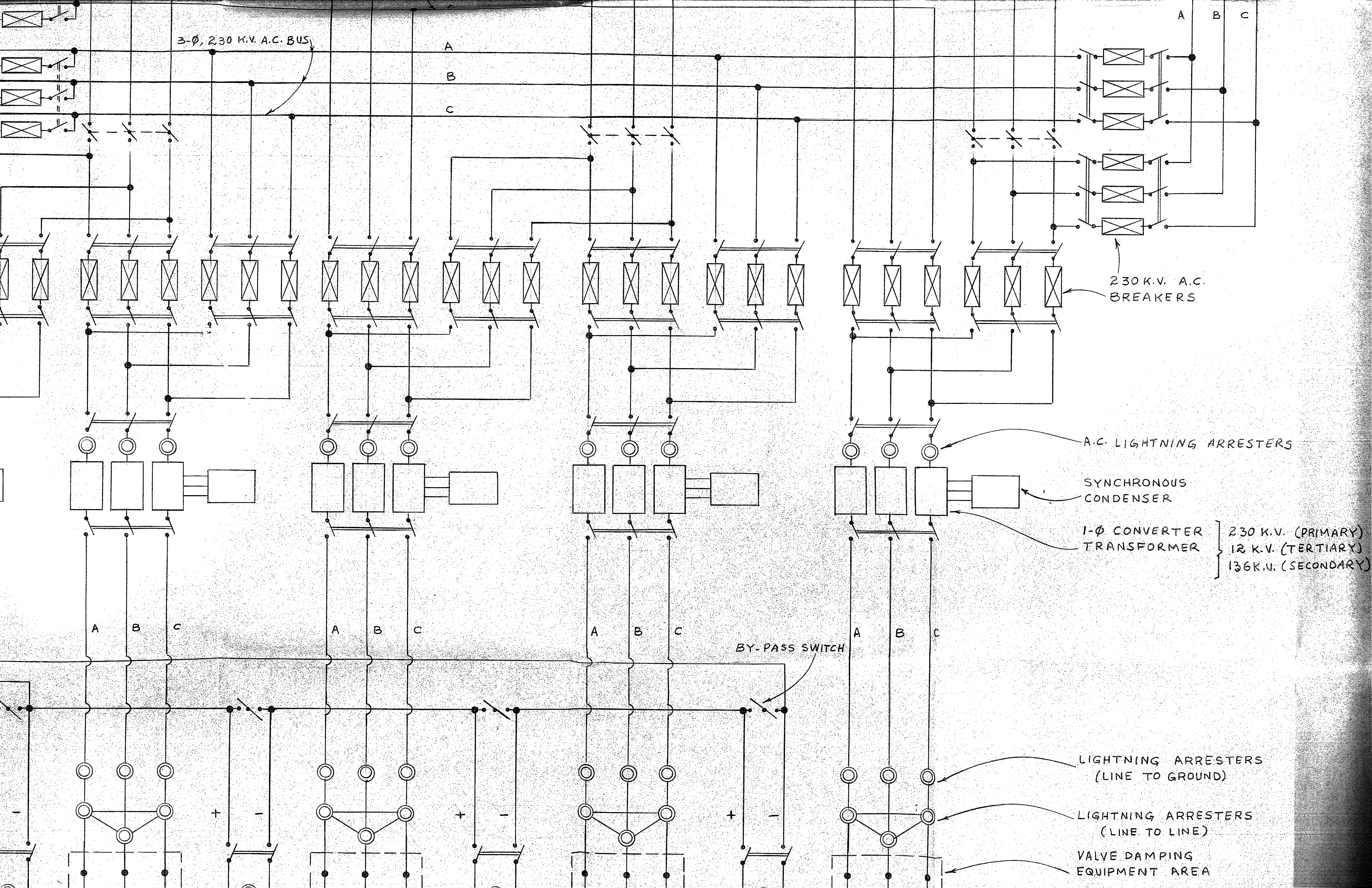
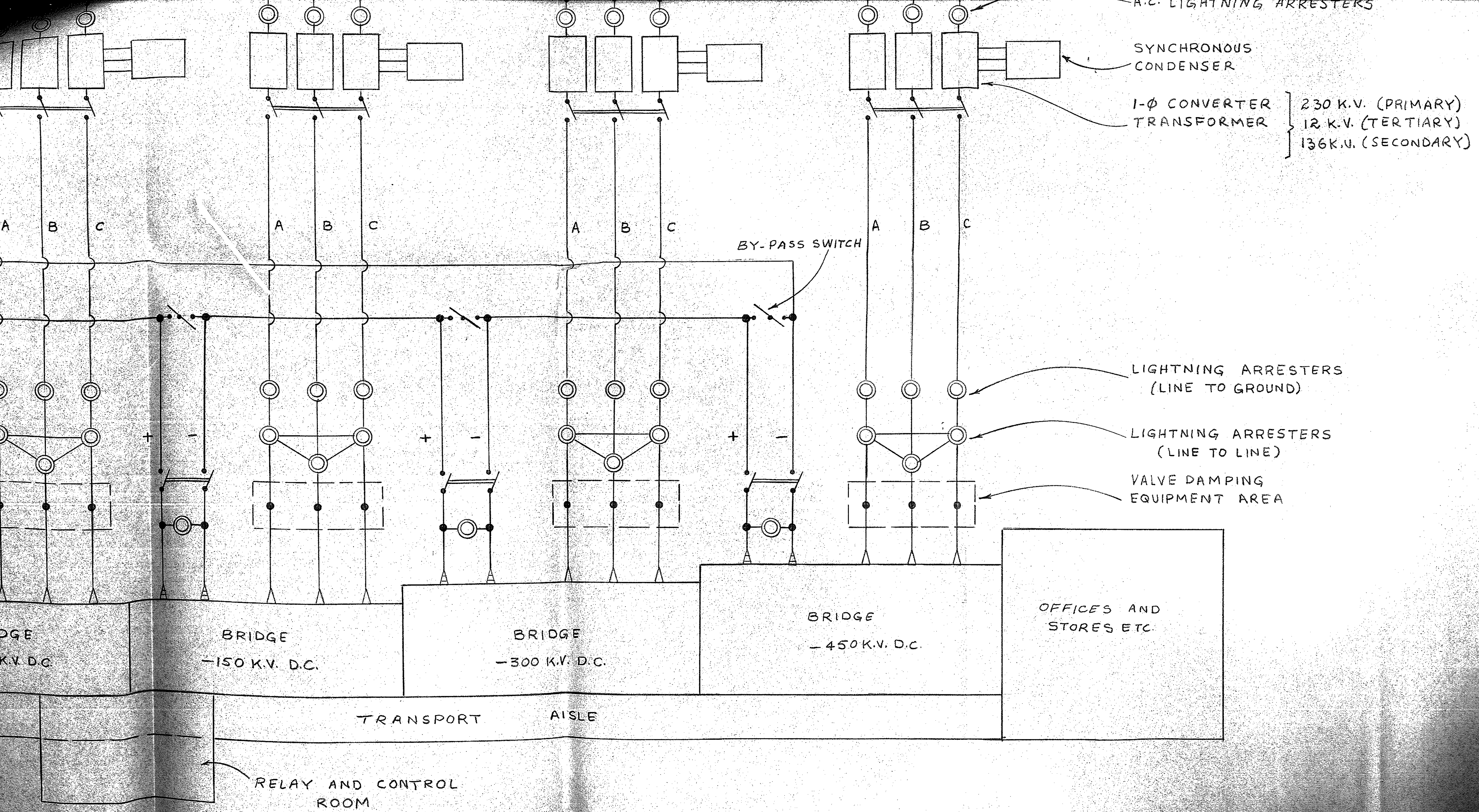
OPERATION OF CO


EA
ITH,
ICS
230 K.V. A.C. BREAKERS FOR LOCAL SERVICE
3-Φ, 230 K.V. A.C. BUS
A
B
C
3-Φ, 230 K.V. A.C. BUS
A
B
C
A.C. HARMONIC FILTER AREA
(FILTERS FOR 5TH, 7TH, 11TH, 13TH, AND HIGHER HARMONICS)
A B C
230 K.V. A.C. BREAKERS
A.C. LIGHTNING ARRESTERS
SYNCHRONOUS

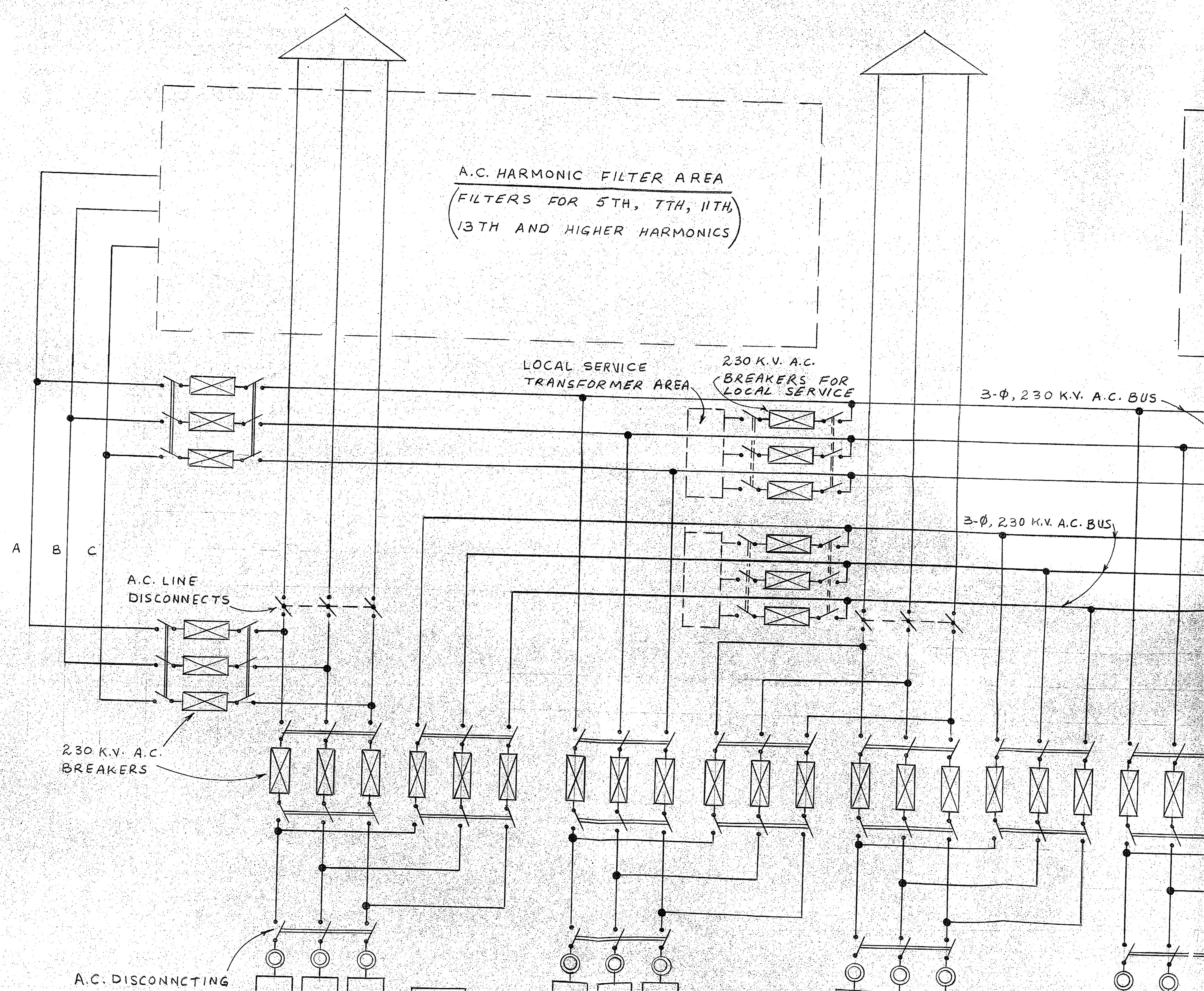

3-Ø, 230 K.V. A.C. BUS
A
B
C
230 K.V. A.C. BREAKERS
A.C. LIGHTNING ARRESTERS
SYNCHRONOUS CONDENSER
1-Ø CONVERTER TRANSFORMER
230 K.V. (PRIMARY)
12 K.V. (TERTIARY)
136 K.V. (SECONDARY)
BY-PASS SWITCH
LIGHTNING ARRESTERS (LINE TO GROUND)
LIGHTNING ARRESTERS (LINE TO LINE)
VALVE DAMPING EQUIPMENT AREA

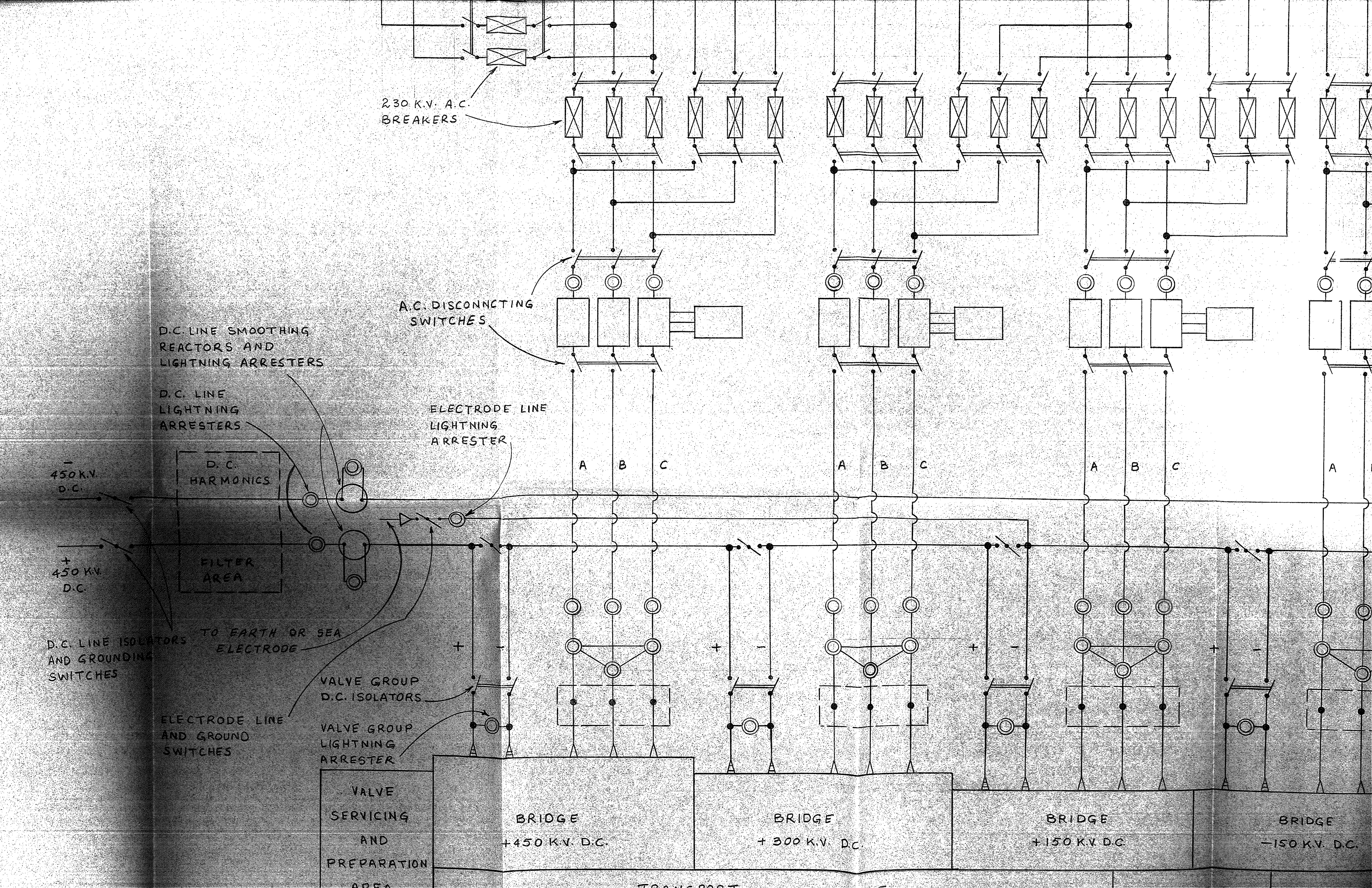


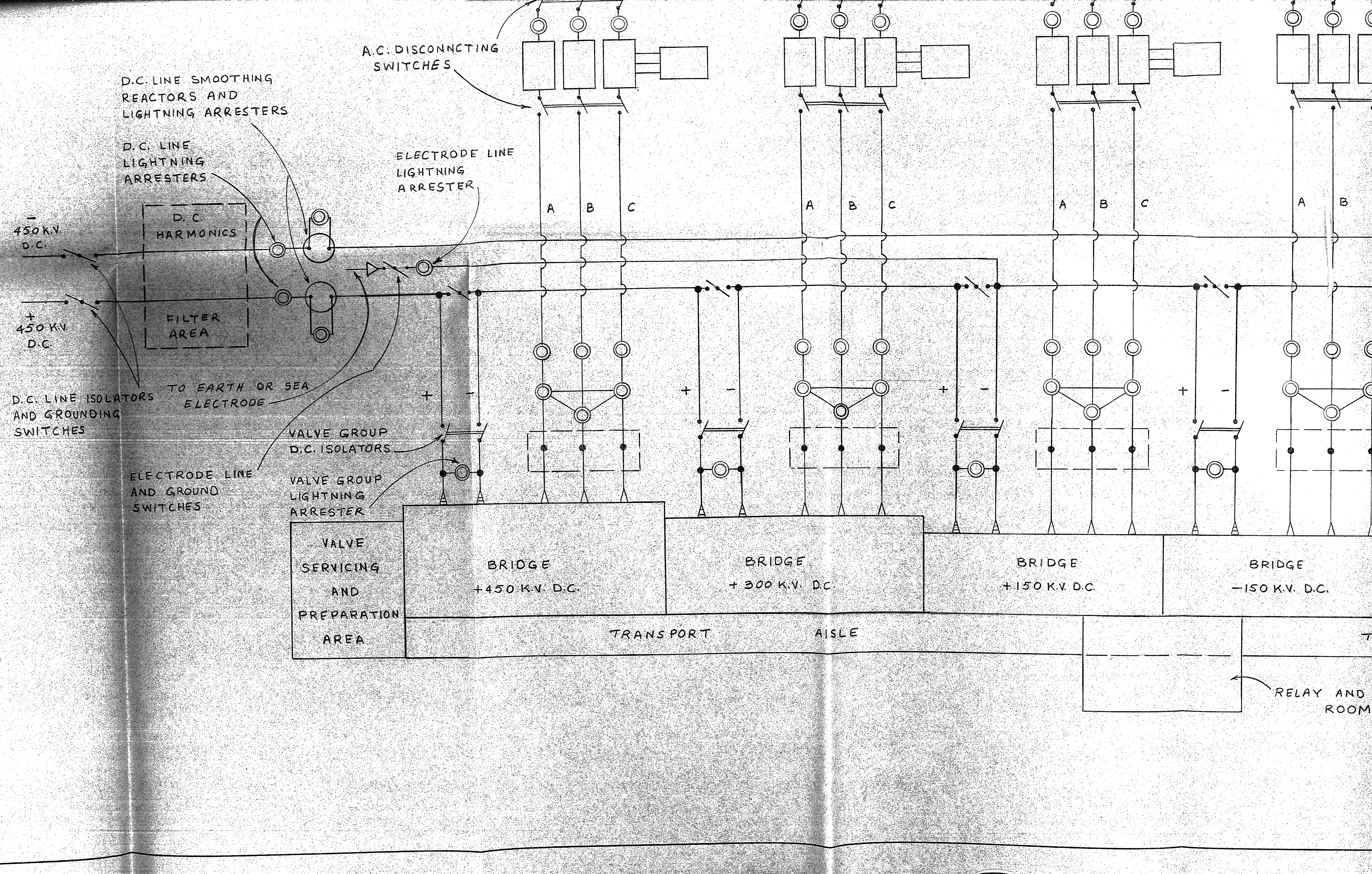
DRAWING #2 B

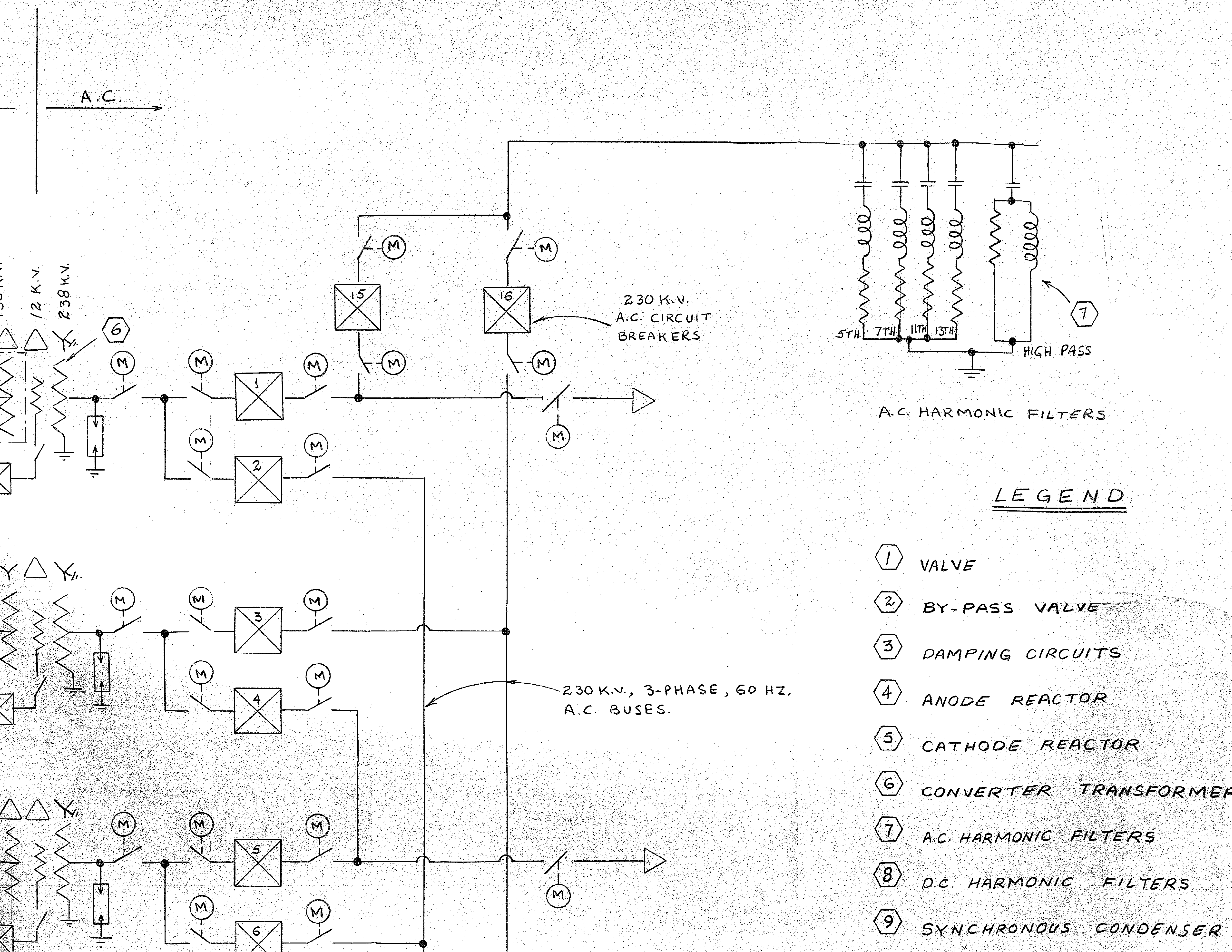
LAYOUT OF INVERTER STATION

S.M.H. NAQVI, ELECT. ENGG., M.SC. THE

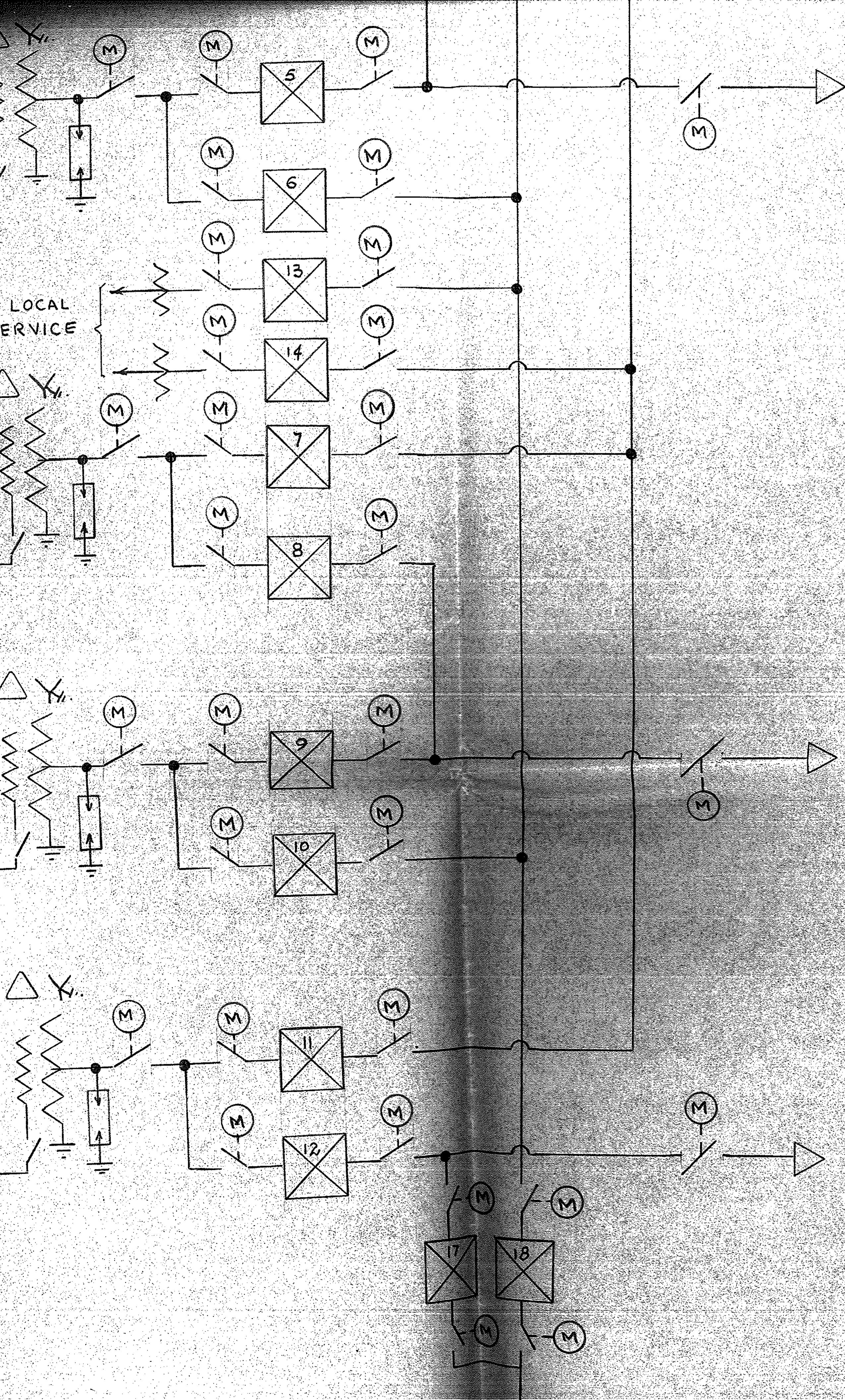

A.C. HARMONIC FILTER AREA
(FILTERS FOR 5TH, 7TH, 11TH, 13TH AND HIGHER HARMONICS)
LOCAL SERVICE TRANSFORMER AREA
230 K.V. A.C. BREAKERS FOR LOCAL SERVICE
3-Φ, 230 K.V. A.C. BUS
3-Φ, 230 K.V. A.C. BUS
A
B
C
A.C. LINE DISCONNECTS
230 K.V. A.C. BREAKERS
A.C. DISCONNCTING


230 K.V. A.C.
BREAKERS
A.C. DISCONNCTING
SWITCHES
D.C. LINE SMOOTHING
REACTORS AND
LIGHTNING ARRESTERS
D.C. LINE
LIGHTNING
ARRESTERS
ELECTRODE LINE
LIGHTNING
ARRESTER
A B C
A B C
A B C
A
−
450 K.V.
D.C.
D.C.
HARMONICS
FILTER
AREA
+
450 K.V.
D.C.
D.C. LINE ISOLATORS
AND GROUNDING
SWITCHES
TO EARTH OR SEA
ELECTRODE
+ −
+ −
+ −
+ −
VALVE GROUP
D.C. ISOLATORS
ELECTRODE LINE
AND GROUND
SWITCHES
VALVE GROUP
LIGHTNING
ARRESTER
VALVE
SERVICING
AND
PREPARATION
BRIDGE
+450 K.V. D.C.
BRIDGE
+300 K.V. D.C.
BRIDGE
+150 K.V. D.C.
BRIDGE
−150 K.V. D.C.


A.C. DISCONNECTING SWITCHES
D.C. LINE SMOOTHING REACTORS AND LIGHTNING ARRESTERS
D.C. LINE LIGHTNING ARRESTERS
ELECTRODE LINE LIGHTNING ARRESTER
- 450 K.V. D.C.
+ 450 K.V. D.C.
D.C. HARMONICS
FILTER AREA
A B C
A B C
A B C
A B
D.C. LINE ISOLATORS AND GROUNDING SWITCHES
TO EARTH OR SEA ELECTRODE
VALVE GROUP D.C. ISOLATORS
ELECTRODE LINE AND GROUND SWITCHES
VALVE GROUP LIGHTNING ARRESTER
VALVE SERVICING AND PREPARATION AREA
BRIDGE +450 K.V. D.C.
BRIDGE + 300 K.V. D.C.
BRIDGE +150 K.V. D.C.
BRIDGE -150 K.V. D.C.
TRANSPORT AISLE
RELAY AND
ROOM



A.C.
12 K.V.
238 K.V.
230 K.V.
A.C. CIRCUIT
BREAKERS
5TH
7TH
11TH
13TH
HIGH PASS
A.C. HARMONIC FILTERS
230 K.V., 3-PHASE, 60 HZ.
A.C. BUSES.
LEGEND
1 VALVE
2 BY-PASS VALVE
3 DAMPING CIRCUITS
4 ANODE REACTOR
5 CATHODE REACTOR
6 CONVERTER TRANSFORMER
7 A.C. HARMONIC FILTERS
8 D.C. HARMONIC FILTERS
9 SYNCHRONOUS CONDENSER



⟨7⟩ A.C. HARMONIC FILTERS

⟨8⟩ D.C. HARMONIC FILTERS

⟨9⟩ SYNCHRONOUS CONDENSER

⟨10⟩ D.C. LINE SMOOTHING REACTOR AND ITS LIGHTNING ARRESTER

ⓐ D.C. LINE ISOLATOR AND GROUNDING SWITCHES

ⓑ BY-PASS SWITCH

ⓒ VALVE GROUP D.C. ISOLATORS

ⓓ VALVE GROUP GROUNDING SWITCHES (A.C. SIDE)

ⓔ A.C. DISCONNECTING SWITCHES

ⓕ ELECTRODE LINE AND GROUNDING SWITCHES

ⓗ VALVE GROUP GROUNDING SWITCHES (D.C. SIDE)

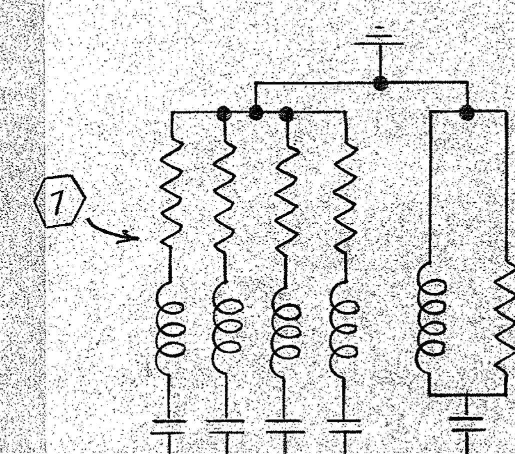
⊠ A.C. CIRCUIT BREAKER

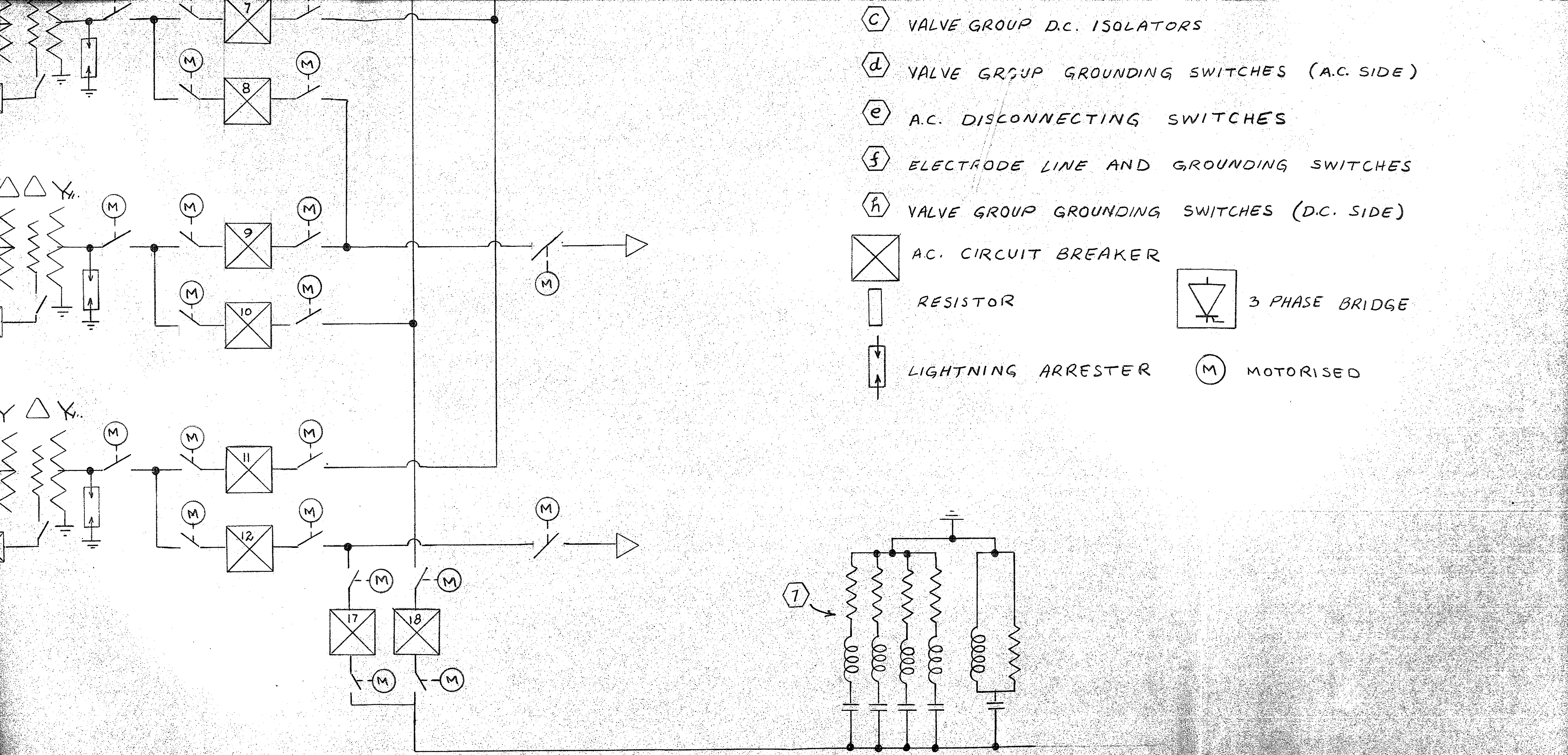
RESISTOR

3 PHASE BRIDGE

LIGHTNING ARRESTER

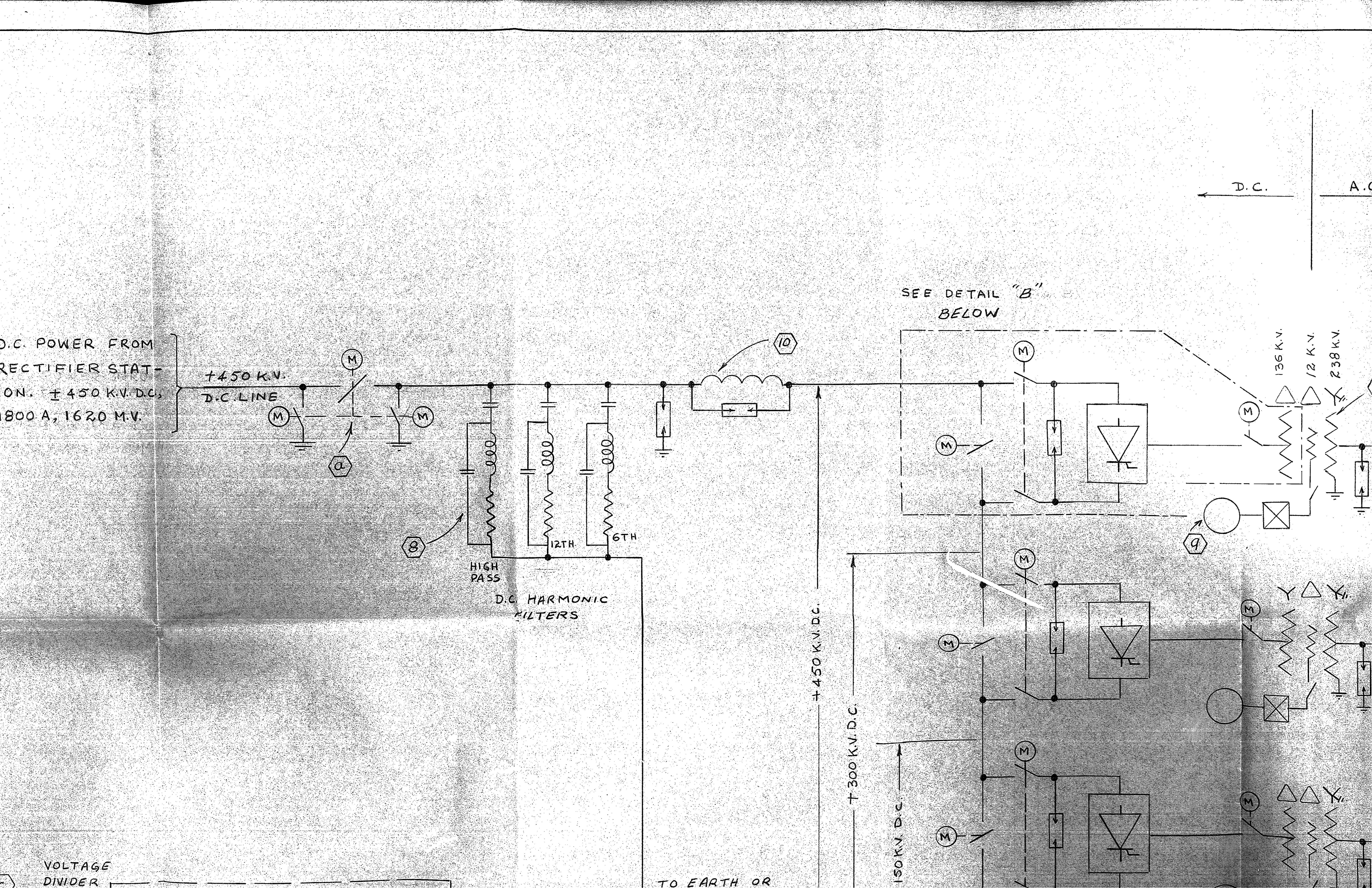
Ⓜ MOTORISED



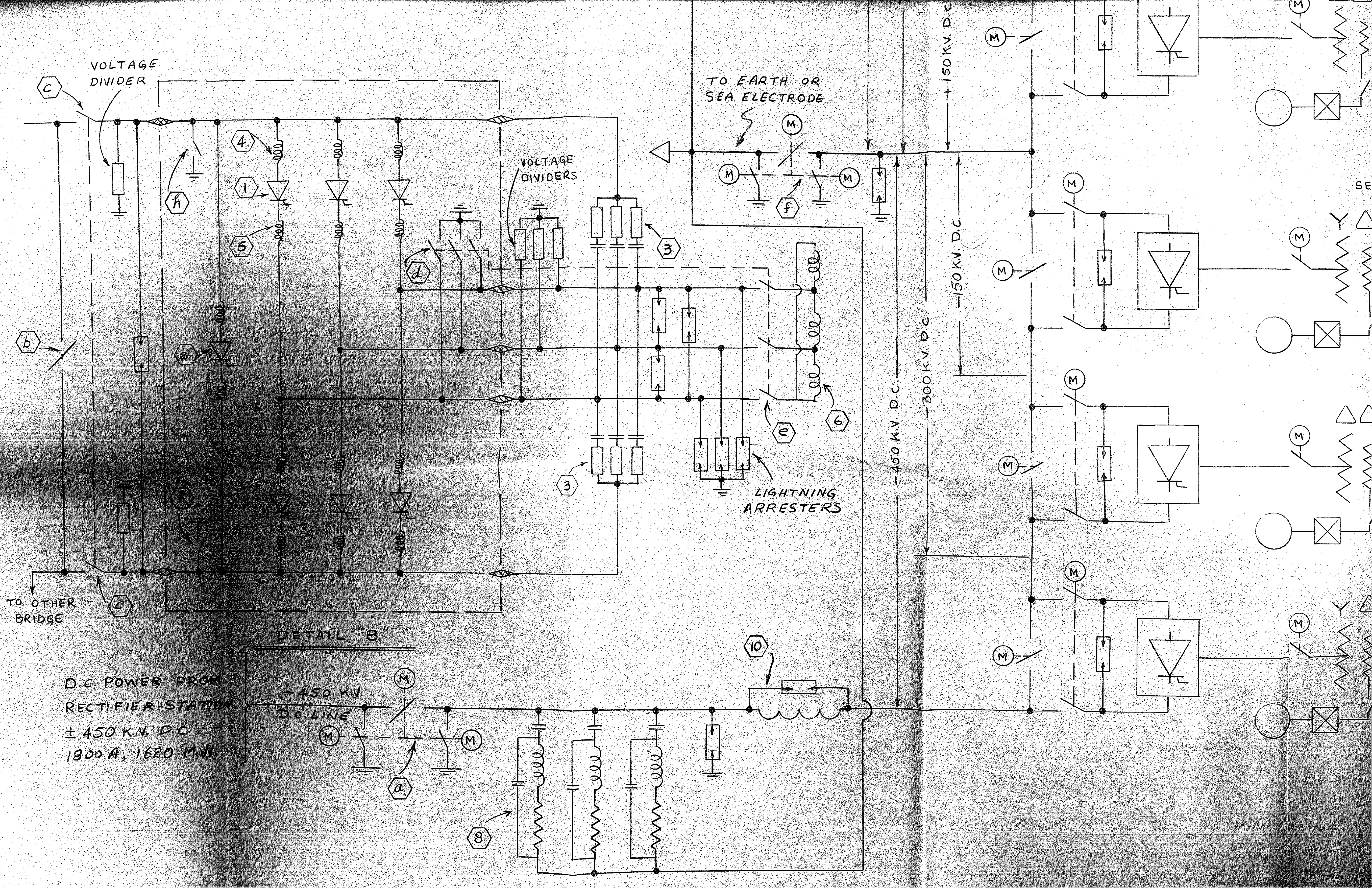


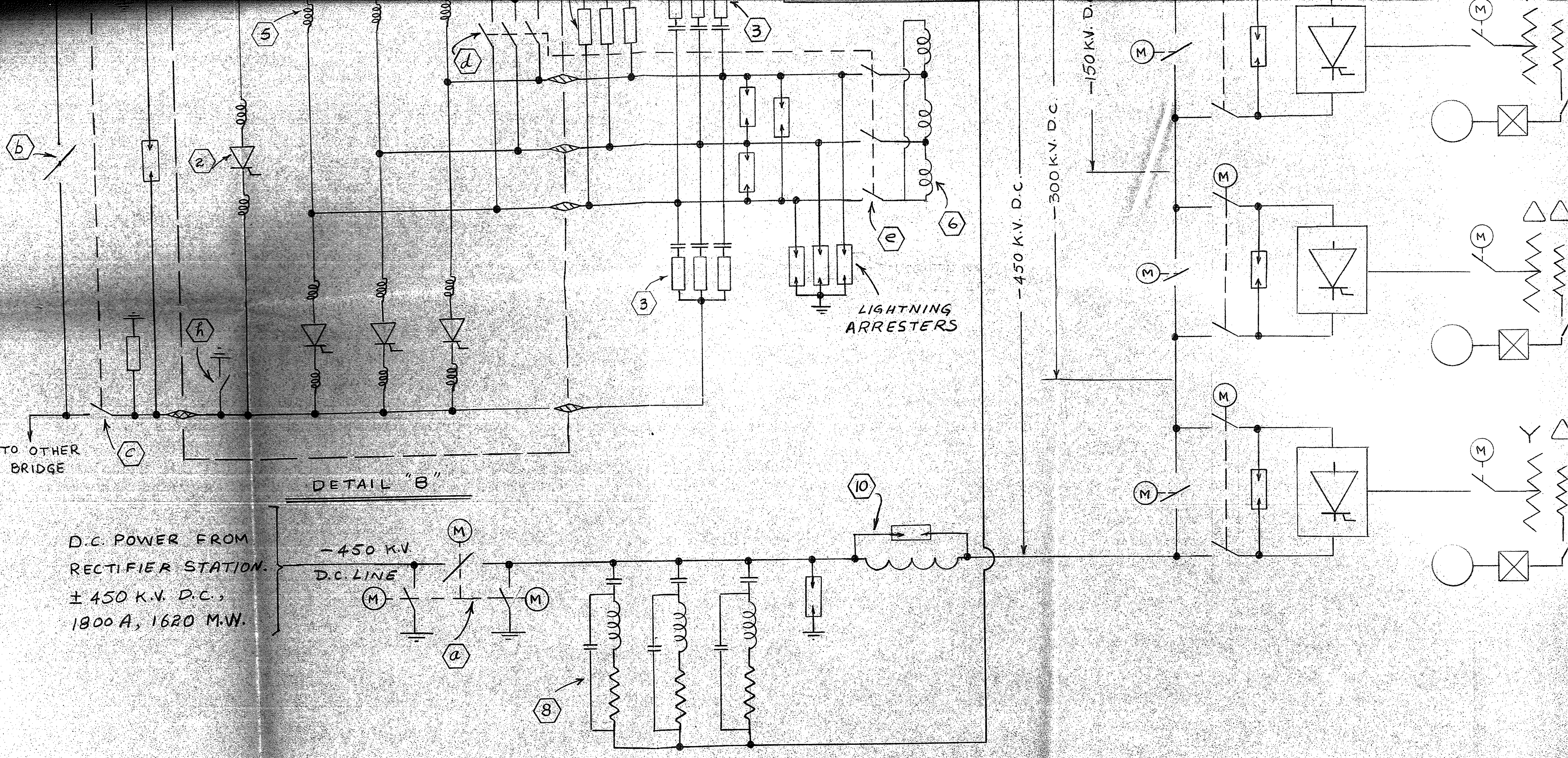
S.M.H. NAQVI, ELECT. ENGG., M.SC. THESIS, FEB. 1970

DWG. #2A



D.C. POWER FROM
RECTIFIER STAT-
ON. ±450 K.V. D.C.,
1800 A, 1620 M.V.
+450 K.V.
D.C LINE
M
a
8
HIGH
PASS
12TH
6TH
D.C HARMONIC
FILTERS
10
+450 K.V. D.C.
+300 K.V. D.C.
150 K.V. D.C.
SEE DETAIL "B"
BELOW
D.C.
A.C
136 K.V.
12 K.V.
238 K.V.
9
VOLTAGE
DIVIDER
TO EARTH OR


VOLTAGE DIVIDER
TO EARTH OR SEA ELECTRODE
+150 K.V. D.C.
VOLTAGE DIVIDERS
-150 K.V. D.C.
300 K.V. D.C.
-450 K.V. D.C.
LIGHTNING ARRESTERS
TO OTHER BRIDGE
DETAIL "B"
D.C. POWER FROM RECTIFIER STATION. ± 450 K.V. D.C., 1800 A, 1620 M.W.
-450 K.V. D.C. LINE



DRAWING #2 A

SINGLE LINE CIRCUIT DIAGRAM