SURGE PROTECTION OF SUBSTATIONS

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ABSTRACT

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The effective protection of substations against surges is an essential aspect of power system design. There are several phases of this protection problem, all of which are interrelated, but each requiring proper engineering consideration.

This paper provides a sufficient coverage of each phase of the subject through a review of existing literature in order to enable a good understanding of the basic principles for design of a reliable surge protection of substations. In the annexes, some examples are given as they have been studied by the author for a real application of insulation-coordination.

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PART I

OVERVIEW

PART I - OVERVIEW

1. INTRODUCTION

The insulation requirements of electric power systems are determined by lightning and switching overvoltages and not by the power frequency voltage. The reliability of supply provided by an electric power system, as judged by the frequency and duration of supply interruptions, depends to a great extent on the surge performance of the system. Although there are many other causes of interruptions, failure of insulation is one of the most frequent.

It is not always possible to provide insulation which will withstand the highest overvoltage stress that may occur. An economic limit intervenes well below the technical limit. The engineer places this limit at the point at which the cost of achieving a further improvement in reliability cannot be justified by the savings the reduced number of failures may bring.

The effective protection of substations against surges has ever increasing importance with the expansion of transmission systems and increased investments in more and larger substations serving the load area. Also the growing use of larger capacity power transformers, now commonly in sizes of 500 MVA, entails enormous loss in the event of a transformer failure. In the following, the selection of the insulation of substations and the protection against surges, and specifically against lightning surges, is considered for systems up to and including 230 kV.

2. OVERVOLTAGES

Overvoltages can be of an origin external to the power system, i.e. those caused by atmospheric (lightning) discharges or they can be generated within the system itself. Any change in system configuration, from one to another steady state, brought about by the opening or closing of switching devices (connections or disconnections of loads, interruptions of circuit elements) or by the initiation of interruption of short circuits is accompanied by transient and steady-state voltage variations. A transient condition will therefore be present between these two states giving rise to transient overvoltages. The parameters influencing the nature of the transient are the characteristics of the circuit before and after the switching operation, and the type and timing of the switching operation itself.

The switching transients are of a great variety of forms, magnitudes and durations. The overall picture is complicated since switching surges are travelling waves. The initial value changes with the time, in magnitude and form, due to the successive reflections and transmissions of the wave at the points of discontinuity.

The magnitude of lightning surges, appearing on transmission lines, increases only moderately with the height of the towers and the heights are much less than proportional to the operating voltages. The peaks of switching surges on the other hand are substantially proportional to the operating voltage. Up to a voltage of about 220 kV, the insulation design is governed by the need to guard against lightning surges, disregarding the steady-state phenomenon of insulator contamination. Beyond that voltage, in the extra high voltage range, both lightning and switching surges have to be taken into account. For the ultrahigh voltages of 765 kV and above, switching surges become the main criterion.

3. LIGHTNING SURGES

3.1 LIGHTNING PHENOMENA

Before considering the effect of lightning discharges on power systems, some of their natural characteristics will be discussed. The physical manifestations of lightning have been present from the remotest times, but only comparatively recently have the phenomena become even partly understood.

During thunderstorms, positive and negative charges become separated by the interplay of air currents, ice crystals in the upper part of the cloud and rain in the lower part. This process is the subject of many theories but it is the observable facts which are of interest: the great mass of cloud becomes negatively charged, with a layer of positive charge on the top, which may be 16 000 m high, and a small positive inclusion near the base. The negative charge centres may be from 450 to 10 000 m high; the cloud base may be as low as 150 m but in some instances the storm clouds may actually envelop mountains rising from a plain. The potential gradient in the region between cloud base and ground is of the order of 5 to 10 kV/m. A 3 000 m high cloud could thus have a potential of the order of 20 MV.

A lightning stroke to earth usually appears to the eye as a single luminous discharge although sometimes rapid fluctuations of light intensity can be seen. Photographs by rotating cameras reveal that most strokes are followed by repeat strokes which travel along the path established by the first discharge, at intervals of 0.5 to 500 ms.

The first component of a stroke is initiated by a "leader" which starts in a cloud region where a local charge concentration causes the voltage gradient to reach the critical breakdown value. In a region filled with water droplets this gradient is approximately 1 MV/m, a third of the value in dry air.

The leader consists of a thin conducting core or channel, which has the characteristics of an arc plasma. It is preceeded and surrounded by a corona envelope which has a diameter of about 30 m and extends about 45 m in front of the channel. The channel tip moves rapidly in steps of 10 to 80 m (average 50 m) and pauses after each step while streamers emanating from it charge the corona sheath that enables it to proceed. The average speed of propagation is 1/500 to 1/2 000 of the velocity of light (300 x 10^6m/sec). If the distance from stroke centre to ground is say 3 000 m it may take the leader 20 ms to bridge it.

The steps are straight but each new step changes direction. Branches appear which may terminate in midair, whilst the main channel continues a zigzag path to earth. During this relatively slow descent, the stepped leader deposits a negative charge along its path. As the head of the leader approaches the ground, the positive charges induced in the general target area intensify; however, the point of impact remains indeterminate until the leader has arrived at a certain striking distance from the ground surface. At this stage, short positive streamers rise from the earth, usually from high projections. At the instant the negative leader encounters the positive streamer, an intense luminous discharge starts from earth to cloud, travelling at a velocity varying from 10 to 50% of that of light.

This phenomenon is usually referred as the "return stroke". What happens is that the stationary negative charge laid down by the leader stroke along its path is being rapidly neutralized by the upward-moving positive charge previously induced in the ground and in objects on the ground. The luminous point indicates the boundary to which the positive charge has penetrated at any instant. The current which develops below that point can be considered either as a negative current flowing downwards or a positive current flowing upwards. For a relatively small proportion of lightning flashes, the downward current is positive.

The current in the return stroke varies from 1 000 to 200 000 A. It is very much higher than the current in the leader since the same quantity of charge is involved in both stages, the currents are in the ratio of their velocities.

As the cloud charge is lowered during the process of leader formation, the potential differences between this charge and other charge centres in the cloud increase. Streamers develop between them and create channels by which additional cloud charges are connected to the still ionized and heated path of the first stroke. A "dart" leader develops between cloud and earth which follows this path without branching, and at higher velocity than that of the leader; the velocity is about 1% of the light velocity. Upon striking the ground, a second stroke travels back to the cloud. This process may repeat itself several times.

It has been established that many more discharges take place from cloud to cloud than between cloud and ground. The ratio of cloud-cloud to cloud-ground strokes varies from (2 or 3) to 1 in temperate zones to (5 to 9) to 1 in tropical zones.

3.2 LIGHTNING STROKE CHARACTERISTICS AND ISOKERAUNIC LEVEL

A great number of field investigations was conducted to ascertain the characteristics of lightning which affect overall transmission line performance. The first important field studies of lightning voltages on transmission lines were begun in 1925 on 27 systems varying in voltage from 6.6 to 220 kV, (12). Subsequently other studies were begun in the United States, (13) (14), in South Africa and Japan (15).

Lightning current oscillograms indicate an initial high-current portion, which is characterised by short front times of up to 6 μs and time to half value of about 50 μs.

The front is usually concave upward. The high current portion is followed by a long-duration, low-current tail which may last hundreds of milliseconds and is responsible for thermal damage (Hot Lightning). A recorded lightning current oscillogram is shown in fig. I.3.1 .

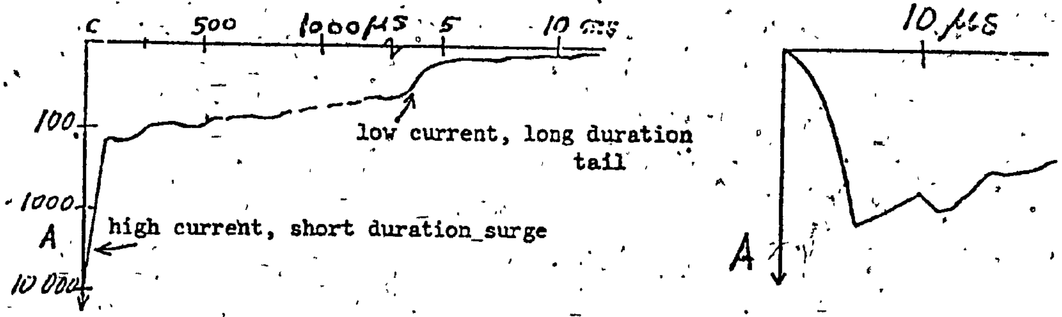

Fig. I.3.1 Typical lightning oscillogram (3).

Lightning currents are measured either directly on high towers or buildings, which are not typical of transmission lines, or on the four corner legs of transmission lines, which is inaccurate because of the unequal division of leg currents and the presence of ground wires and adjacent towers.

The only measure of thunderstorm activity available from meteorological services throughout the world is the isokeraunic level, defined as the number of days in a year when thunder is heard at any particular location. A weakness of this indicator is that it does not distinguish between strokes to the ground and strokes between clouds, and does not recognize the varying intensities of thunderstorm. The number of flashes in a storm can vary tremendously. Attempts are being made to remedy this situation by the installation of lightning flash counters. As these respond also to cloud-cloud flashes in different proportions, they have to be calibrated for ground flashes at each location. Until more data from this device become available, estimates of lightning performance continue to be based on isokeraunic levels.

The isokeraunic levels used today in Canada are those published by the "Ministry of Transport, Meteorological Department" (1), which are based on weather reports received from 230 principal weather stations across the country during years 1941 to 1960 inclusive. Fig. I.3.2 shows the isokeraunic level chart for all Canada. The isokeraunic level of Toronto is 22.6 while Montreal region is subjected to a level 20.5. For example there are 20.5 days per year with thunderstorms in Montreal. This is an average obtained over a period of 20 consecutive years.

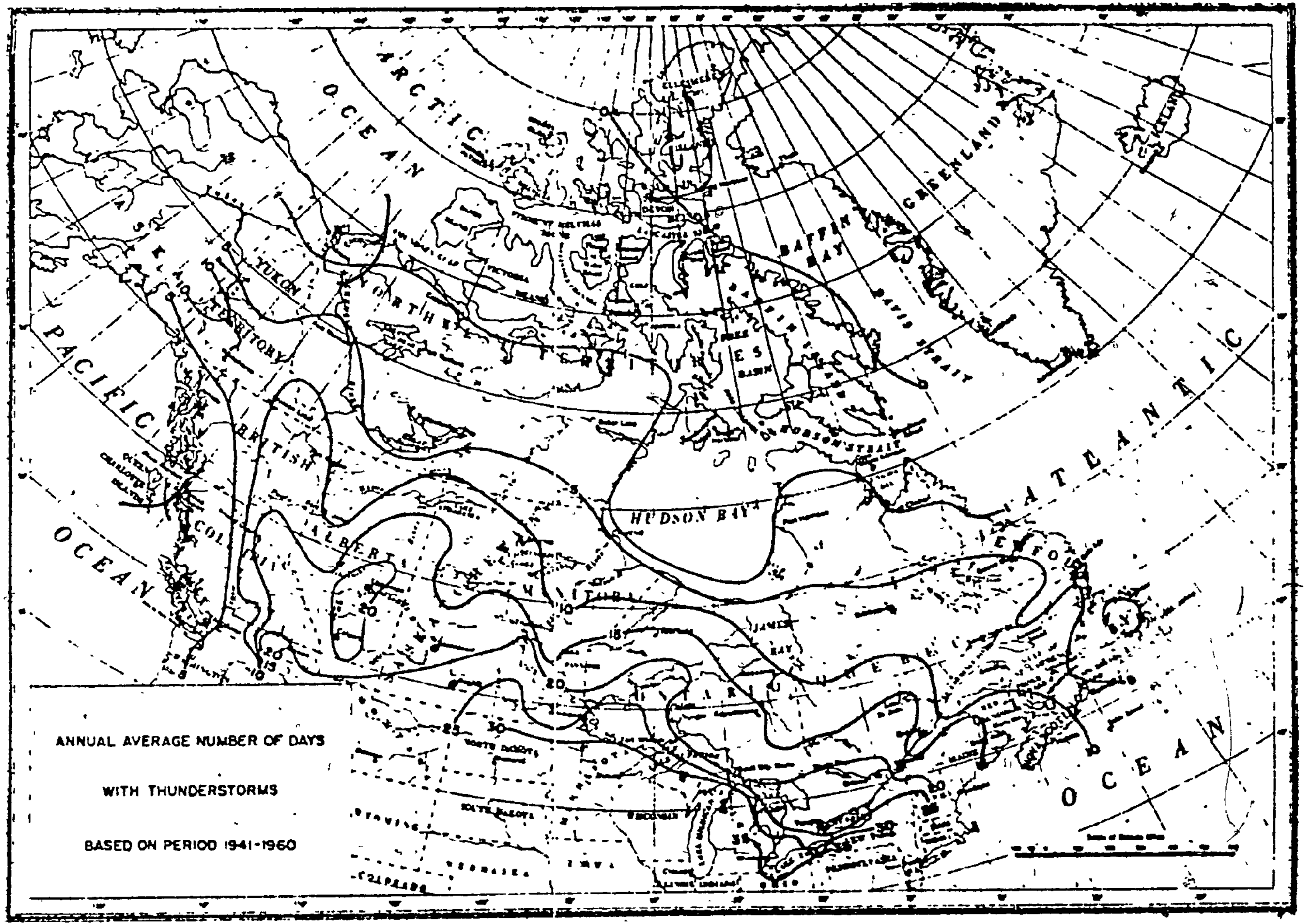

Fig. I.3.2 Isokeraunic level of Canada (1).

The number of thunderstorms per year in a given region is several times greater than its isokeraunic level as there can be several thunderstorms during the same day. The number of thunderstorms occuring in a given region varies from year to year. The isokeraunic level varies from almost zero in arctic regions to 100 or more in some tropical regions.

3.3 PROBABILITY OF BEING STRUCK

Of particular importance in evaluating lightning performance of a transmission line is the knowledge of probable number of strokes on it. It is possible to determine the order of magnitude of the frequency with which transmission and distribution lines, substations, buildings and towers are likely to be struck by lightning. Such exposure is called the "probability of being struck" and is based on a considerable number of actual field records. Of course, all strokes to lines do not produce flashover and all flashovers do not produce outages.

The probability of being struck for a given structure configuration depends on several factors such as the height and the area of structure and the isokeraunic level of the region where the structure is erected. Other factors such as the relative height and the distance of nearby buildings or surrounding hills and possibly the ground resistance have also a direct influence on the "probability of being struck".

Several researchers have installed since 1925 stroke measuring instruments on actual operating systems over a period of several years in different parts of the world to establish the number of strokes to transmission and distribution lines and to buildings and towers as well. Specialized instruments like klydonographs, magnetometers, Boy & Lichtenberg's camera, Fulchronographs, magnetic links, cathode-ray oscillograph, are some of the instruments commonly used. Reference (2), pages 551 to 556, gives a description of the instruments for the measurement of lightning surges and an extended bibliography on the subject.

The number of strokes per annum to a transmission line can be expected to be proportional to the number of ground flashes per square mile per year and the area of attraction of the line which increases with length and height. On the basis of long term observations on transmission lines equipped with magnetic links on every tower, supplemented by model studies, it is generally accepted that for an isokeraunic level of 30 and for a tower height of 30 m the number of strokes is 100 per 160 km of line per annum.

Based on the results of these investigations, an A.I.E.E. Committee (16) has produced the frequency distribution curve of fig. I.3.3 which is widely accepted for performance calculations. The probability curve of fig. I.3.3 is labelled directly in strokes per 100 miles-year for an isokeraunic level 30. For other isokeraunic levels, this curve is adjusted prorata. For heights other than 30 m, the correction factors of fig. I.3.4 apply (2).

Field investigations have also shown that approximately 60-90 per cent of the lightning voltages are of negative polarity. Most of the transmission line data show 80 to 90 per cent negative polarity, while measurements on distribution systems show about 60 per cent negative polarity. The latter figure is probably influenced by the recorded induced lightning voltage which is always of opposite polarity from the direct stroke voltage.

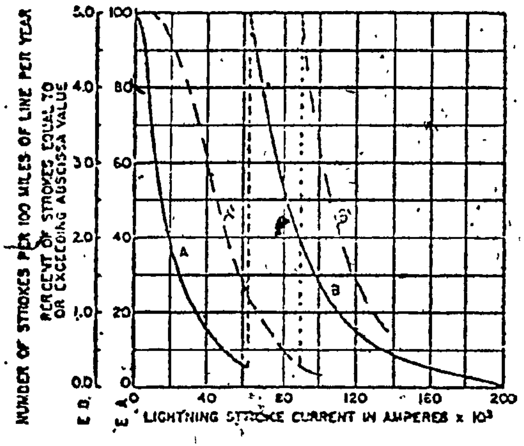

Fig. I.3.3 AIEE lightning stroke probability curve (2)
(=no. of strokes/100 mile year at TD=30 -Dashed curves from Ref.17)

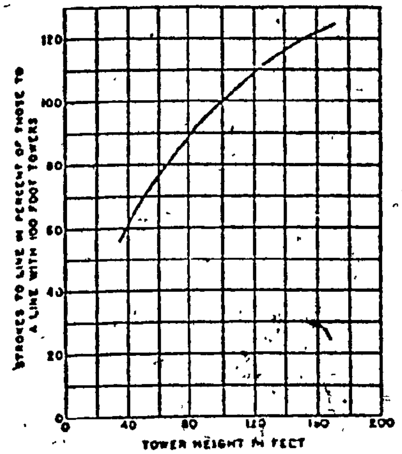

Fig. I.3.4 Variation in no. of strokes to line vs height (2).

3.4 SHIELDING AGAINST DIRECT STROKES TO PHASE CONDUCTORS

An impulse current of magnitude i_o, injected into a transmission line conductor, will produce a travelling wave propagating in both directions. The conductor potential will rise to approximately $1/2\ i_oZ$, where $Z=\sqrt{\frac{L}{C}}$ the surge impedance of the conductor. Taking a typical figure of Z=400 ohm, a stroke current as low as 10 kA, which is reached or exceeded 60 times a year for 160 km of line at an isokeraunic level 30, would cause a voltage of 2 000 kV. Only lines insulated for the highest operating voltages could withstand this stress. It is clear that, excluding areas of exceptionally low thunderstorm frequency the trip-out rate would be unacceptably high.

If a tower is struck, the impedance of the tower will be of concern. The voltage drop down the tower will appear across the line insulation. If this is excessive, flashover of the insulation will occur and a fault will be placed on the systems. The tower current of course flows in the ground. Therefore, the ground impedance of tower footing must be taken into consideration.

In an attempt to avoid this, one or more ground wires are strung on the towers above the line conductors. These serve to shield the phase conductors, that is they intercept the lightning strokes instead of the phase conductors and ~~conduct~~ them to ground.

The ground wires are grounded at every tower, and the grounding resistance is kept as low as possible. To achieve a high degree of success in preventing shielding failures, i.e. preventing strokes from by-passing the shielding wires and terminating on a phase conductor, it is necessary to keep the shielding angle low.

The higher the tower the lower must be the shielding angle for a given probability of shielding failure P_a expressed as a percentage of all strokes to line. A rule of thumb is to adopt a shielding angle of 20° to 30° for towers not exceeding 30 m. For portal type structures, two ground wires are needed to meet this requirement. Substations can be shielded by masts or horizontal ground wires, or both.

In the event of a stroke to a tower, the tower impedance is paralleled by the surge impedance of the ground wires, which extend away in both directions, so that the total impedance is reduced and the tower top potential is correspondingly less. A tower, for example, with a surge impedance of 125 Ω paralleled by two ground wires with a surge impedance of 400 ohm, might have an effective surge impedance of 75 ohm. Currents of the order of 20 kA lead to voltages of the order of 1 500 kV.

Finally there is considerable electric and magnetic coupling between ground wires and the phase conductor which tends to limit the voltage that can be established between them. These transient disturbances travel as waves along the line and ultimately reach a terminal where they are impressed across the equipment at that point. However, attenuation plays an important role so that damage to terminal equipment becomes likely only when lightning strikes close to the terminal.

3.5 INTERACTION BETWEEN LIGHTNING AND POWER SYSTEMS

It has been postulated that current, coming into a tower by lightning stroke from a cloud, disappears into the ground. Where does it finally return? A useful concept is to think of the cloud and earth as forming a vast capacitor which is being discharged by the stroke. The return circuit would then be completed by displacement current in the electric field. This is suggested by Fig. I.3.5.

It should be possible to calculate the capacitance and inductance from the size of the cloud and its height above the ground and find a surge impedance looking upon the assemblage as a lumped circuit. An example will show that such a simple computation can yield results in accordance with observable phenomena if it is recognized that damping will be present.

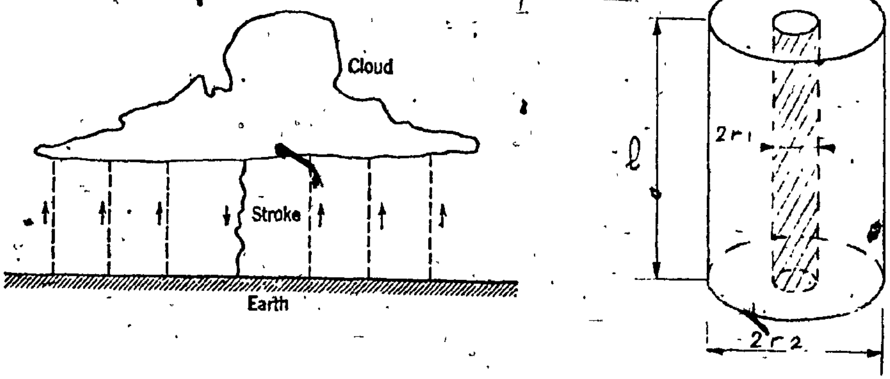

Fig. I.3.5 Lightning stroke from cloud to earth discharges a vast capacitor (4).

Suppose the cloud and earth are represented as a capacitor having parallel plates of circular shape with a radius of 1 km and a separation (height of cloud) of

1 km, and let the stroke be 20 cm in diameter.

$$L = \frac{\mu_0}{2\pi}\int_{r_1}^{r_2}\left(1-\frac{x^2}{r_2^2}\right)\frac{dx}{x} \quad \text{where} \quad \mu_0 = 4\pi\times 10^{-7}$$

$$L = 2\times 10^{-7}\int_{r_1}^{r_2}\left(1-\frac{x^2}{r^2}\right)\frac{dx}{x} \quad (H/m)$$

$$\simeq 2\times 10^{-7}\ \ln\frac{r_2}{r_1} \quad H/m \quad \text{approximately}$$

For $r_1=10$ cm, $r_2=1$ km and a path 1 km long the total inductance is L=1.84 mH

The capacitance is given by

$$C= \frac{\varepsilon_0 A}{d} = \frac{8.854 \times 10^{-12}\times\pi\times 10^{+6}}{10^3} = 27.8 \times 10^{-8}\ F$$

This gives a surge impedance

$$Z_0 = \sqrt{\frac{L}{C}} = 257.25 \text{ ohm}$$

$$f_0 = \frac{1}{2\pi\sqrt{LC}} = 22\ 253.01 \text{ Hz}$$

and the period of oscillation, if the current should oscillate

$$T_0 = \frac{1}{f_0} = \frac{1}{22\ 253.01} = 44.94\ \mu s.$$

The resistance of the ionized path would, however, damp the current. If this resistance amounted to 5 000 ohms (from the damped curve fig. 4.4 of ref. (4)) the current would approximate to a 1.5/50 μs wave. Although this approach may give us an insight into the current characteristics of the return stroke and conform to the kind of waveforms suggested by the A.I.E.E. Committee, it is clearly a very crude approximation for describing the phenomenon as a whole.

On the ground under a thundercloud, and on objects on the ground, such as power transmission lines, charge is induced by the proximity of the charged cloud. Whenever the charges in the cloud move or redistribute, the charges on the ground move or redistribute. Such motion represents current flow and momentarily potential differences are established on ground elements. These movements in the cloud are usually relatively slow, unless a discharge occurs. Consequently, the ground currents are very small.

Once a leader has established a conducting arc channel to ground, the return stroke represents a process of progressive neutralization of the charges of this channel. The neutralizing front moves up the channel with a velocity from 10 to 50% of that of light, as it has already been postulated in sect. 3.1. This rate and the quantity and disposition of the charge to be neutralized determine the magnitude and shape of the current. Thus if the current contains 1 mC/m and the stroke travels at 100 x 10^6m/s, the current involved would be I=1mC/mx100x10^6 m/s=10^5 A .

The electrostatically induced lightning surge, where bound charges on a line are suddenly released, are relatively harmless. Much more serious are electromagnetically induced surges which arise from lightning striking close to the line, but not actually striking the line itself. The surge produced in this way can be high enough to cause flashover. The distribution of peak amplitudes of lightning currents is shown in fig. I.3.6 taken from reference (10).

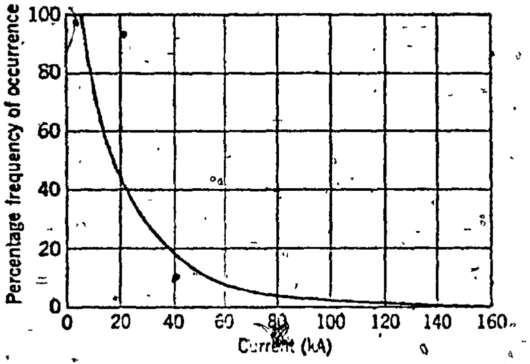

Fig. I.3.6 Frequency of occurence of lightning currents of 5 kA or greater.

System voltage plays an important role in the incidence of lightning problems on overhead lines. Generally the number of incidents diminishes as the voltage goes up because of the improved insulation. However, there are some exceptions to this trend, due to the design which is a very important factor.

4. SUBSTATION INSULATION

Surge protection entails two main objectives: to limit the lightning and switching surges to levels which will not damage nor depreciate the apparatus insulation and assure continuity of power service.

Substations possess a composite of several items of insulation which are electrically in parallel from line to ground. These include apparatus internal insulation and exposed insulation such as the line dead-end insulators, air-break switch insulators, bus support insulators, cable potheads, and the air gap between the line and ground. Each of these has a certain electrical strength against impulse voltages different from its continuous or 60 Hz voltage strenght.

In a broad sense, the voltage required to flashover or puncture a given insulation becomes higher the shorter the time of application of voltage. Furthermore, the insulation strenght varies with the shape of the applied impulse. This leads to the concept of an impulse volt-time characteristic, which shows how the impulse voltage varies with the length of time the voltage is applied.

Actually, the volt-time characteristics cannot be expressed by a single curve since the test points cover broad bands. Their shape is also influenced by the polarity of the impulse wave. The curves of fig. I.4.1 are average values and illustrate the impulse volt-time flashover characteristics of different items of insulation for 115 kV class systems. The polarity effects differ for various types of insulation.

Typical impulse volt-time curves are usually plotted over the time range from 0.5 μs to the critical flashover level which usually occurs in the range of 8 to 15 μs. It should be remembered that the lightning flashover level is not reduced by rain , dew or dirt contamination of the insulation (21) (22). However the switching surge flashover may be appreciably reduced by these effects.

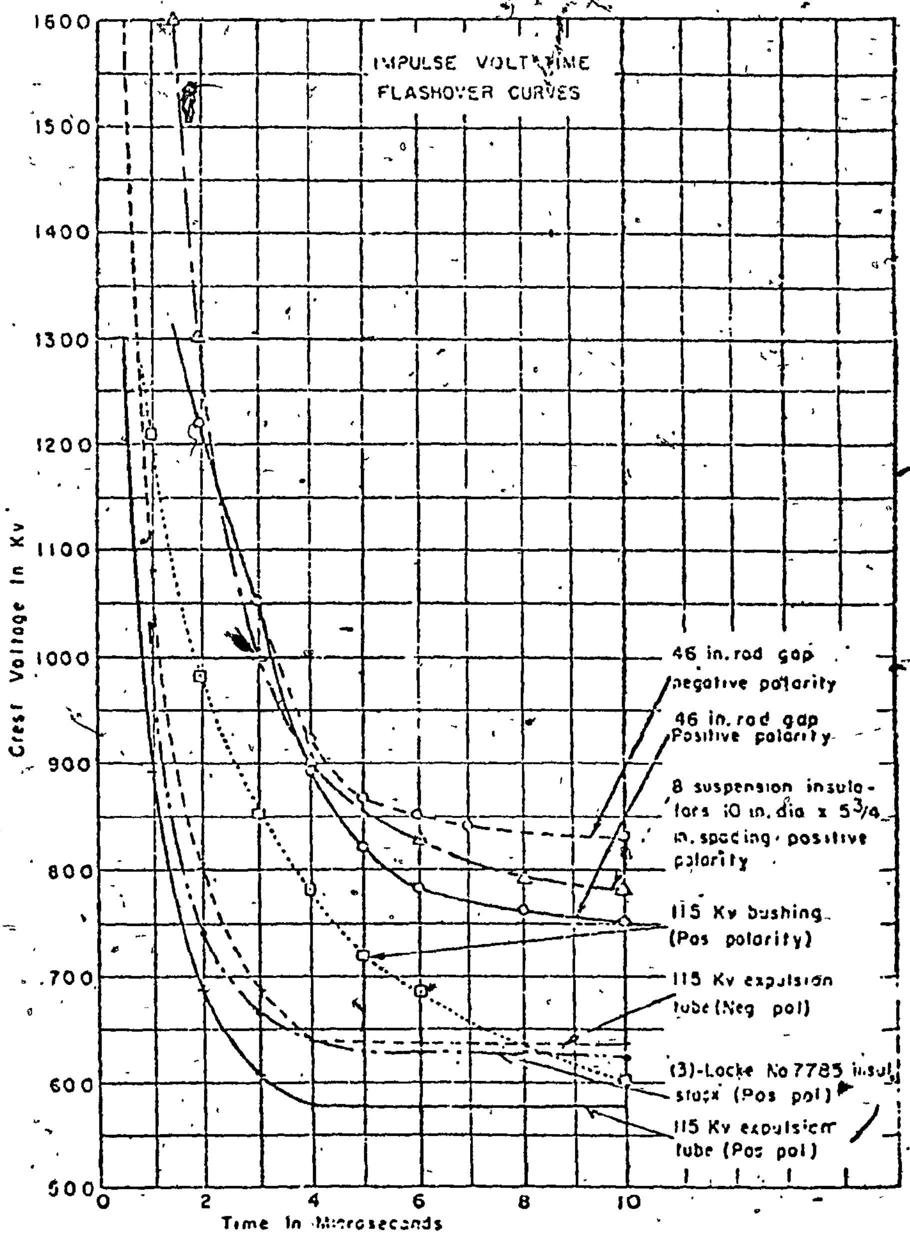

Fig. I.4.1 Impulse volt-time flash-over curves for 115 kV voltage class devices (25).

The critical flashover level is obtained by applying on the insulators the new international standard wave 1.2 x 50 μs and gradually increasing the crest voltage of the wave until the insulation flashes over on 50% of the test applications. This flashover occurs on the tail of the wave. The crest voltage which causes flashover on 50% of the applications is called the "Critical" impulse flashover voltage. The impulse full-wave "Withstand" voltage is a lower crest voltage of 1.2 x 50 μs wave which the insulation will withstand for several applications without flashover or damage.

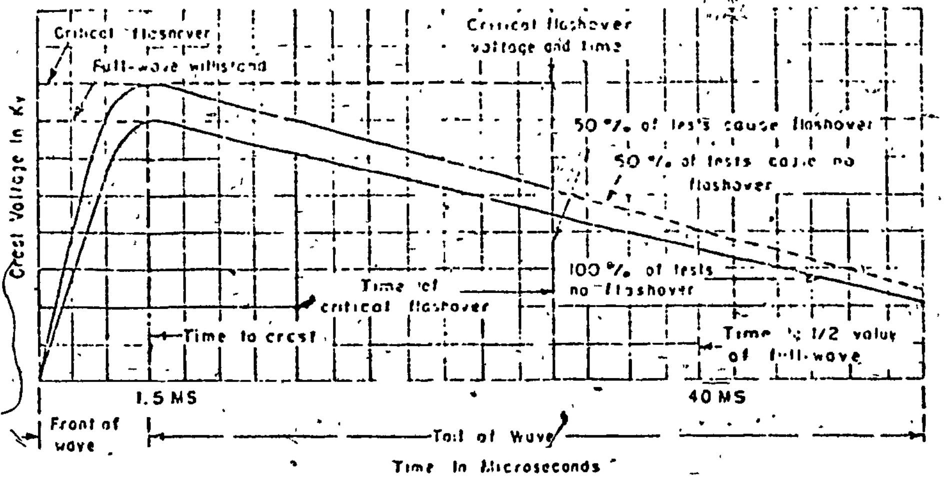

Fig. I.4.2 Illustration of 1½ x 40 μs full-wave withstand voltage and critical flashover voltage (25).

Fig. I.4.2 shows the critical and the withstand flashover voltages and the terminology involved. Fig.I.4.3 shows the method of designating significant characteristics of the wave. The impulse volt-time curve is obtained by applying the standard wave 1.2 x 50 µs with progressively higher crest voltage which will cause the flashover to occur at shorter times toward the front of the wave as shown in fig. I.4.4.

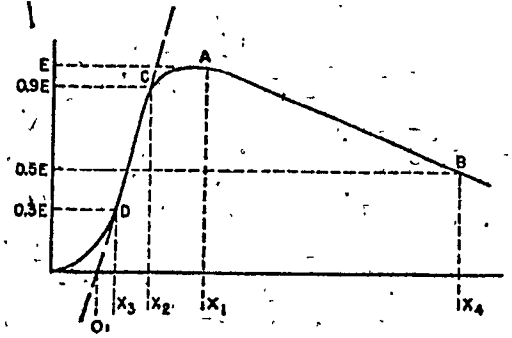

Fig. I.4.3 Method of designating an impulse wave (2).

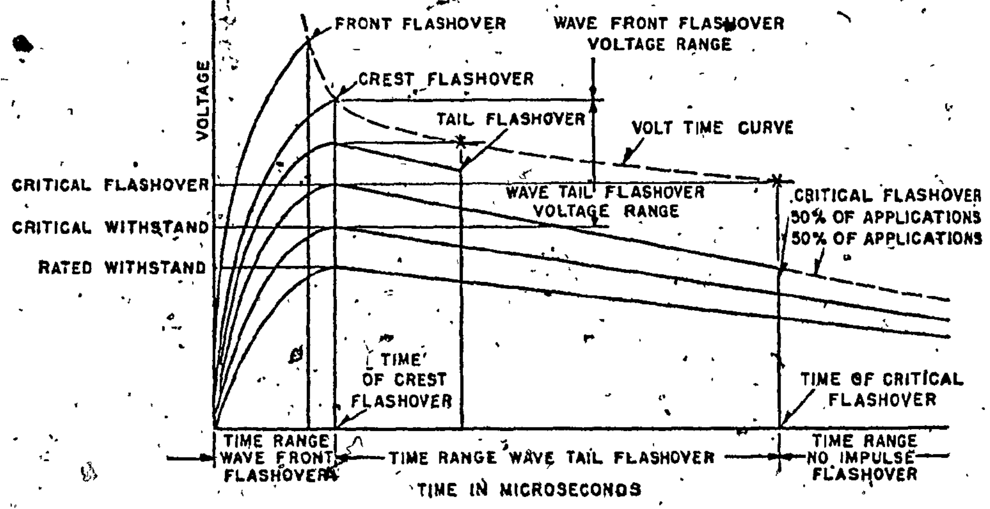

Fig. I.4.4 Series of impulse wave illustrating the terminology and definitions (2).

5. BASIC INSULATION LEVEL (BIL)

In 1930, the NEMA-NELA Joint Committee on Insulation Coordination was formed to consider laboratory testing technique and data, to determine the insulation levels in common use, to establish the insulation strength of all classes of equipment, and to establish insulation levels for various voltage classifications. After 10 years of study in 1941, the joint, AIEE-EEI-NEMA, Committee on Insulation-Coordination adopted basic impulse insulation levels according to the following definition:

> "Basic impulse insulation levels are reference levels expressed in impulse crest voltage with a standard wave no longer than $1\frac{1}{2} \times 40$ μs wave. Apparatus insulation as demonstrated by suitable tests shall be equal to or greater than the basic insulation level."

This requires that apparatus conforming to these levels shall have a withstand test value not less than the withstand test voltage. Table I.5.1 gives a summary of the BIL's for system voltage classes up to (and including) 330 kV, with the low frequency and impulse withstand tests for different types of apparatus. The values of Table I.5.1, column 2 were selected initially as the standard BIL's to be applied regardless of how the system was grounded and protected. If the system is grounded solidly or so as to limit the line-

System Voltage Class kV	Standard Basic Impulse Insulation Level BIl-kV		Typical Reduced BIls Below Standard kV	Outdoor Air Switches, Insulator Units and Bus Supports Tentative AIEE Std. Withstand Tests			Oil-Type Transformers Standard Withstand Tests							Bushings for Outdoor Apparatus Standard Withstand Tests					
				Low Freq. 1-min. Dry kV RMS	Low Freq. 10-sec. Wet RMS	Impulse Test 1.2x50 μs Full-Wave Pos or Neg kV Crest	Low Freq. 1-min. Test kV RMS	Impulse Tests						Low Frequency Test				Impulse Test	
								Chopped Wave Crest kV		Chopped Wave Min. Time to Flashover		Full-Wave 1.2x50 μs Crest kV		1-min Dry Test kV RMS		10 sec Wet Test kV RMS		1.2x50 μs Full-Wave kV Crest	
	Class Dist	Class Pwr					Dist&Pwr Classes	Class Dist	Class Pwr	Class Dist	Class Pwr	Class Dist	Class Pwr	Appar. Small	Appar. Large	Appar. Small	Appar. Large	Appar. Small	Appar. Large
1	2		3	4	5	6	7	8		9		10		11		12		13	
1.2	30	45					10	36	54	1.	1.5	30	45	10		6		30	
2.5	45	60						54	69	1.25	1.5	45	60	15	21	13	20	45	60
5.0	60	75					19	69	88	1.5	1.6	60	75	21	27	20	27	60	75
8.7	75	95					26	88	110	1.6	1.8	75	95	27	35	24	30	75	95
15	95	110		50	45	110	34	110	130	1.8	2.0	95	110	35	50	30	45	95	110
	Dist&Pwr							Dist&Pwr		Dist&Pwr		Dist&Pwr		Small Large		Small Large		Small Large	
23	150			70	60	150	50	175		3.0		150		70		60		150	
34.5	200			95	80	200	70	230		3.0		200		95		80		200	
46	250			120	100	250	95	290		3.0		250		120		100		250	
69	350			175	145	350	140	400		3.0		350		175		145		350	
115	550			280	230	550	230	630		3.0		550		280		230		550	
			450				185	520		3.0		450							
138	650			335	275	650	275	750		3.0		650		335		275		650	
			550				230	630		3.0		550							
161	750			385	315	750	325	865		3.0		750		385		315		750	
			650				275	750		3.0		650							
230	1050			545	445	1050	460	1210		3.0		1050		545		445		1050	
			900	465	385	900	395	1035		3.0		900		465		385		900	
			825				360	950		3.0		825		425		350		825	
287			1050			1050	460	1200		3.0		1050						1050	
330			1350			1350	600	1550		3.0		1350						1350	
			1175			1175	520	1360		3.0		1175						1175	

Table I.5.1 Basic impulse insulation levels, and impulse and power frequency withstand tests for representative apparatus insulation in substations.

to-ground voltage during ground faults ($X_0 / X_1 \leq 3$) the so called 80% or 75% arrester can be used, resulting in insulation with BIL's one or two classes lower as shown in table I.5.1, column 3.

6. IMPULSE CHARACTERISTICS OF TRANSFORMER INSULATION

The most valuable equipment must be protected most carefully. A power transformer is usually the most expensive equipment in a substation and its failure may mean a lengthy and costly outage; it is, therefore, investigated most critically from an insulation stand point.

The impulse level of a transformer can be determined by the breakdown voltage of the major internal insulation (insulation to ground), the breakdown voltage of the minor insulation (insulation between turns and windings) and the flashover voltage of the bushings. The impulse characteristic of the internal insulation in a transformer differs from flashover in air in two main respects. First of all the impulse ratio (the ratio of minimum breakdown on impulse to breakdown on 60 Hz peak) is higher, being from 2.1 to

2.2 for transformer insulation, whereas, it is 1.5 or less for rod gaps, insulators, bushings etc. Secondly the impulse breakdown of transformer insulation does not vary as much with time as seen from a typical volt-time curve, shown in fig. I.6.1. After three microseconds, the breakdown voltage is substantially constant.

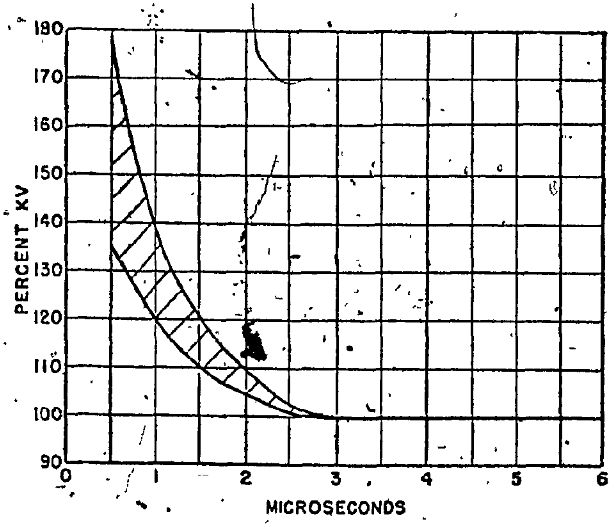

Fig. I.6.1 Volt-time curve of typical major insulation in transformers (2).

The insulation stress between turns or between coils is dependent largely upon the steepness of the surge wave front. To test the minor insulation of the transformers, the impulse withstand tests include a chopped-wave test in addition to the full wave withstand test.

The chopped wave withstand test involves a 1.2 x 50 μs impulse voltage wave (either positive or negative polarity), about 15% higher crest voltage than the full wave test. The wave is chopped by flashover of a gap in parallel with the transformer. This flashover of the gap and the resulting chopping of the wave must occur in not less than a specified time which ranges from 1.5 to 3 μs, depending on the transformer voltage class. The standard transformer impulse test sequence is ~~two~~ applications of chopped wave, followed by an application of the full wave.

It must be remembered that the impulse withstand tests in table I.5.1 are not the actual flashover or breakdown levels. The designer must incorporate some factor of safety, by which the ultimate insulation strength is suitably higher than the withstand test levels.

The volt time characteristics of the bushings on a transformer differ from the volt-time characteristics of the transformer internal insulation. In general, the bushings will have a higher flashover at short time lags than the transformer internal insulation . At long time lags, its flashover may be slightly more or slightly less than the transformer internal insulation as in fig. I.6.2.

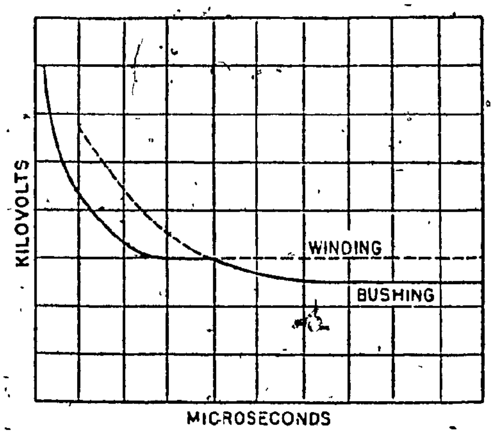

Fig. I.6.2 Typical volt-time curve of transformer winding and bushing (heavy solid line represents the overall volt-time curve of transformer, to be used when protecting against lightning surges) (2).

The impulse strength of the winding is essentially the same for positive or negative waves; whereas the bushing's critical flashover may be higher for one polarity than for the other. The manufacturer takes the overall characteristics of a transformer into account when giving its withstand voltage characteristic.

7. OVERVOLTAGE PROTECTIVE DEVICES

The function of the protective device is to see that the electrical strength of the protected apparatus is not exceeded at any time. Thus if a surge attempted to raise the voltage above the insulation capability, the protective device would have to by-pass the surge to ground and keep the voltage down to an acceptable level.

We shall treat here only the rod gaps and lightning arresters. Both are connected in parallel with the equipment insulation offering a by-pass to voltages dangerous to the insulation.

The use of lightning arresters for protection against switching surges is increasing, since they have reached a high-degree of perfection and provide the highest degree of protection of all protective devices. Rod gaps are inferior but they are inexpensive and have still a certain field of application.

7.1 REQUIREMENTS FOR PROTECTIVE DEVICES

These can be summarized as follows:

i. They must not spark over under dynamic voltages. Lightning arresters would be destroyed as their thermal capacity is small.

ii Their volt-time curve must lie below the withstand volt-time curve of the protected insulation. If these characteristics are bands rather than lines, then the highest value the protective device can clamp must lie below the lowest value at which the insulation it is protecting can fail.

The margin between the two curves must be adequate to allow for the effects of distance, polarity, relative air density, humidity, aging of the insulation and likely changes in the characteristics of the protective device.

iii They must be able to discharge high energy surges without changes in their protective levels or damage to themselves or adjacent insulation. When the protective device flashes over as a consequence of the surge voltage, the associated current is partially diverted into the device, thereby creating a voltage across it. The maximum voltage would be generated if all the current were so diverted. This condition would be approached if the line terminating impedance had a particularly high value. In this case, the maximum voltage would be: IZ_p where Z_p is the protective device impedance. It is this voltage, generated by the surge current, that must not exceed the safe value set for the protected equipment.

iv The forth important factor relates to their potential for storing or dissipating energy. When current is diverted into a lightning arrester, and voltage is generated across it, it is at the time absorbing energy. The amount of energy involved depends upon the magnitude and duration of the surge. The arrester must be capable of handling this energy by storing or dissipating it without damage to itself. It is not sufficient that it holds the voltage down to an acceptable level.

v After discharging a surge, the arrester should reseal (become non-conducting) in the presence of dynamic overvoltages.

7.2 ROD GAPS

Although rod gaps have the advantage of being extremely simple, they have several disadvantages from a protective standpoint. They do not meet the requirements of sect. 7.1.

First when they operate, they cause an outage on the system. The circuit must be deenergized to clear the flashover arc each time the gap operates. Second, their breakdown voltage rises more at short time lags than the impulse volt-time of most insulations which means that a relatively short gap is required to provide protection against surges having steep wave fronts. They would thus have a low flashover at long time lags, and would operate for a proportion of switching surges, causing a larger number of outages.

They are subjected to atmospheric conditions and respond differently to surges of positive and negative polarity. Their volt-time characteristic is therefore a quite broad band bending up sharply for short wave fronts. As a consequence, their protective level is not clearly defined.

The rod gap is, therefore, generally used only for back-up protection. They are used too, on circuits where the outages with short gaps can be tolerated or compensated for by high-speed reclosing of the circuit energizing breaker.

7.3 VALVE-TYPE ARRESTERS

7.3.1 Principles of Operation

The conventional valve-type arrester, provides the highest degree of protection of all protective devices. Its essentially flat volt-time characteristic makes it ideally suited for the protection of transformer insulation.

Arresters vary in sophistication depending upon their voltage class and duty but they gererally comprise a number of gap units, coil units and valve elements of non linear resistance material. These are stacked in series and hermetically sealed in porcelain housings. The principle of their operation can be understood by referring to fig. I.7.1 which shows schematically the circuit arrangement of the elements of a 6 kV valve-type arrester.

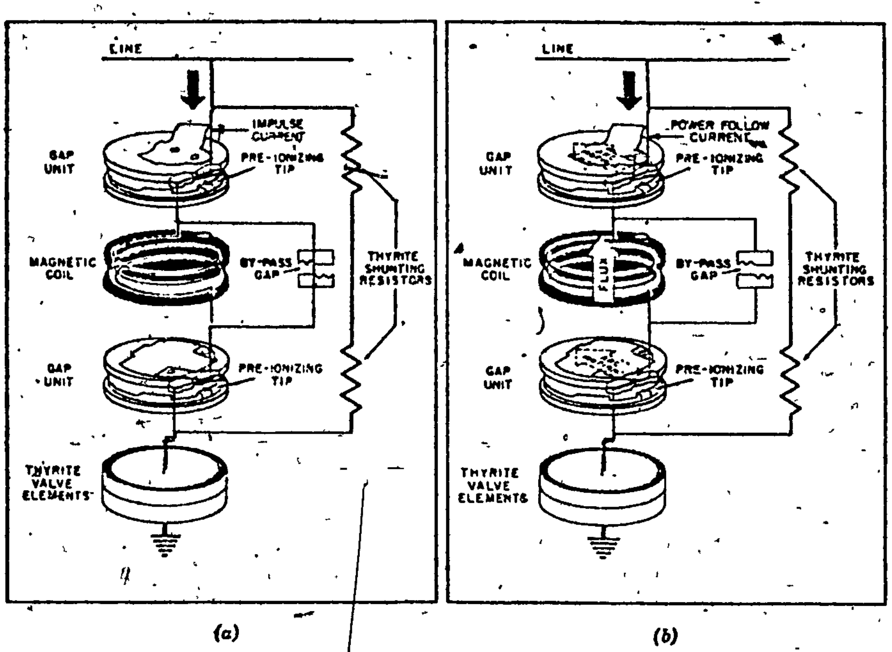

Fig. I.7.1 Schematic diagram of valve type arrester showing path of (a) surge current (b) Follow current (4).

When the arrester is connected to the power frequency source, it does not operate because its sparkover voltage is higher than the source voltage. When a transient voltage, such as a lightning surge reaches the arrester, the voltage across its terminals rises to sparkover voltage and causes the gap units to sparkover, thereby creating a path for the surge current through the coil and the valve element.

In the example shown, breakdown of the gaps is made more consistent by the inclusion of a "preionizing tip" which maintains a higher than normal number of electrons in the gap, ready to initiate a breakdown when overvoltage appears. The surge current quickly develops across the coil a voltage sufficient to cause the bypass gap to flashover. This removes the coil from the circuit and leaves only the impedance of the valve element. The flow of surge current through the valve element produces a discharge voltage which is a function of the surge current magnitude. Conditions at this time are those shown in fig. I.7.1 (a).

After a few microseconds, the surge discharge is completed, but current continues to flow through the arcs that have been established. The initial magnitude of the so-called power-follow current depends on the source voltage and impedance and the arrester valve element impedance.

When power frequency conditions are restored, following the passage of the surge current, the impedance of the coil is much lower. This causes the arc in the by-pass gap to become instable and extinguish. The current is transferred to the coil. This condition is shown in fig. I.7.1(b). The magnetic field created by the follow current in the coil reacts upon the current in the arcs of the gap assemblies, causing them to be driven into arc quenching chambers, which are an integral part of the gap units. This is the magnetic blow-out effect of the arrester current. Arc extinction is brought about at the first current zero by elongating and cooling the arc. The arrester returns to its quiescent state and the surge voltage has been successfully limited.

As shown in fig. I.7.1 the main gaps are shunted by other nonlinear resistance elements that provide automatic self regulation of the power frequency voltage across each set of gap elements. They reduce, thereby, any electrical effect of external surface deposits of stray fields.

7.3.2 Some Fundamental Consideration

Considerable control of the volt-time curve of arresters is possible by the resistive grading of the gaps, by which the voltage distribution across the gaps at low frequencies is controlled, and capacitive grading which affects the impulse voltage distribution. The preionization by corona points and ceramic auxiliary gaps assists in obtaining fast and consistent front-of-wave sparkover.

The most important property of the series gap is its ability to interrupt power follow current. For any design of spark-gap there is a maximum power follow current which it can safely interrupt at the first current zero. This critical current, which is of the order of 100 to 300 A, for arresters without magnetic blow-out effect, determines the resistance at rated voltage of the current limiting valve element and hence, the discharge voltage. A lowering of the discharge voltage can therefore be achieved by increasing the quenching current. This has led to the development of the "assisted" spark-gaps, using the magnetic "blow-out" effect of the arrester up to 1 000 A.

The non-linear characteristics of the valve element can be expressed by the relationship $I=kV^{\alpha}$ where " α " approaches 5. In modern heavy-duty arresters, the magnetically controlled arc in the series spark-gap consumes a substantially portion of the power frequency voltage. The resistance blocks can therefore be of lower resistance than for the arresters with natural arc extinction and as the arc voltage is substantially independent of current, this leads to lower discharge voltage than the given by the above relationship.

Requirement iii of sect. 7.1 calls for a high thermal capacity of the valve elements, since nearby direct lightning strokes may result in arrester currents of 100 kA or more, fortunately a very rare occurence. Field measurements indicate that - 10 to 30% exceed 2 000 A

3 to 10% exceed 5 000 A

1 to 4% exceed 10 000 A

Long duration, low current surges caused by the discharge of long lines are, however, a problem. They can reach peaks of 2 000 A and durations of 2 000 μs or more. The lighter design of arresters cannot cope with heavy current discharges. Therefore, the spark-gaps must not operate on switching surges. However heavy duty arresters are not so restricted. When operating on switching surges the slower rate of rise of the current permits a stronger blowout action to develop. Manufacturers claim that even dynamic power frequency exceeding the rated arrester voltage by as much as 35% for several seconds will not damage the arrester and will not prevent resealing. The use of arresters for protection against switching surges permits savings on insulation in the U.H.V. range and has been adopted in the planning of 765 kV system (18).

7.3.3 TERMS AND DEFINITIONS

The characteristic of lightning arresters are very carefully defined in Standard Specifications. In the following, a review of the most important of them is made.

<u>Rated Voltage</u>: According the IEC Recommendation (9), this definition reads:

> "The rated voltage of an arrester is the designated maximum permissible r.m.s. value of power-frequency voltage between its terminals at which it is designed to operate correctly. This voltage may be applied to the arrester continuously whithout changing its operating characteristics."

It is the voltage rating specified on the nameplate and at which the arrester is designated to perform its duty cycle. The technical data of a particular type of arrester is directly related to the Rated Voltage.

<u>Operating Duty Cycle Test</u>: According the IEC Recommendation (9), this definition reads:

> "This is a test in which service conditions are simulated by the application to the arrester of a stipulated number of specified impulses while it is energized by a power supply of specified frequency, voltage and impedance."

Power-follow current must be established by each impulse, and the arrester shall interrupt the follow current after each application of the impulse. After these tests, the sparkover voltages and the residual voltage shall not have changed by more than 10%.

Nominal Discharge Current: Lightning arresters are classified by their nominal discharge currents. According the IEC Recommendation (9), this definition reads:

> "The peak value of discharge current, having an 8/20 waveshape, which is used to classify an arrester. It is also the discharge current which is used to initiate follow current in the operating duty test."

With the same wave shape 8/20 µs, but varying current peaks of either 1.5, 2.5, 5 or 10 kA the nominal Discharge Current is determined from the peak value which is used throughout the operating duty test: i.e. a 10 kA arrester has been subjected to initiating impulses of 10 kA peak and 8/20 µs wave shape. The arresters, in addition, shall meet the performance characteristics listed in table I.7.1 .

CLASSIFICATION		TEST REQUIREMENTS		
ASA	IEC	Duty Cycle	Long Duration Current	High Current
Station	10kA heavy duty [1] 10kA light duty [1]	10kA, 8/20 μs	,2000 μs [3] 150 A, 2000 μs	100kA, 4/10 μs
Intermed. Distribution	5kA series A [2] 5kA series B [2]	5kA, 8/20 μs	75A, 1000 μs	65kA, 4/10μs
None	2.5kA	2.5kA, 8/20 μs	50A, 500 μs	25kA, 4/10 μs
Secondary	1.5kA	1.5kA, 8/20 μs	None	10kA, 4/10 μs

Table I.7.1 Arrester classification and test requirements (9).

Note 1: For the 10 000 A arrester, there are two types, light-duty and heavy-duty, which are differentiated by the amplitude of the long duration impulse current, which they are capable of withstanding.

Note 2: Series A arresters are based on performance characteristics in practice in all countries. Series B arresters are based on performance characteristics in practice in Canada and U.S.A.

Note 3: The peak current is defined in clause 63.3.2 of IEC recommendation (9).

Power-Follow Current: According the IEC Recommendation (9), this definition reads:

> "The current from the connected power source which flows through an arrester following the passage of discharge-current."

The standard impulse current 8x20 μs is of extremely short duration. It may be considered as having a duration of about 20 μs which is only 0.24% of the 60 Hz half wave duration. The thermal stress on an arrester is, therefore, to a great extent, determined by the power-follow current.

Discharge or Residual Voltage: According the IEC Recommendation (9), this definition reads:

> "The voltage that appears between the terminals of an arrester during the passage of discharge current."

Power-Frequency Sparkover Voltage (S.O.V.): According the IEC Recommendation (9), this definition reads:

> "The value of the power-frequency voltage measured as the peak value divided by $\sqrt{2}$ applied between the terminals of an arrester, which causes sparkover of all series gaps."

The IEC and ANSI standards (9) (10) specify, for all classes of arresters, except for 10 000 A station type arresters, a minimum power-frequency S.O.V. equal to 1.5 times the rated arrester voltage. This is a requirement to assure that the arrester does not discharge unnecessarily on system overvoltages.

Impulse Sparkover Voltage: According the IEC Recommendation (9), this definition reads:

> "The highest value of voltage attained before sparkover during an impulse of given waveshape and polarity applied between the terminals of an arrester."

This impulse S.O.V. is referred as a 100% value, i.e. at or above which a sparkover will always be obtained. The ANSI standards do not specify any limit. The IEC Recommendation specifies a certain maximum value (in kV crest) which, for ratings above 25 kV, is equal to 3 to 3.6 times the rated arrester voltage.

Front of Wave Sparkover Voltage: According the IEC Recommendation (9), this definition reads:

> "The impulse sparkover voltage obtained on the wavefront the voltage of which increases linearly with time."

A maximum value is specified, with factors in the range of 3.1 to 4.0 times the arrester rating, for a station class arrester. For other classes higher factors are specified.

Front of Wave Steepness: All the major standards (9) (10) specify a steepness of 8.3 kV/ μs, per kV of arrester rating.

Switching Surge Sparkover Voltage: According to IEC Recommendation (9), a switching voltage impulse is an impulse voltage having a virtual front time greater than 30 μs.

None of the standards have yet issued any specification regarding allowed S.O.V. limits for switching surges, but they are under consideration. The IEC standards specify a test for the switching voltage impulse sparkover voltage/time curve. This test is applicable only to heavy duty 10 kA arresters having a rated voltage above 100 kV and is intended to provide a uniform method of making the test so that data supplied by manufacturers will be comparable.

7.3.4 PROTECTIVE LEVEL

The protective level of an arrester is, according to the IEC Recommendation, a combination of the following:

a) Lightning-voltage impulse sparkover-voltage/time curve.
b) The residual-voltage/discharge current curve.
c) For 10 kA arresters rated 10 kV and higher, the switching-voltage impulse sparkover-voltage/time curve.

Modern station-type arresters are designed to have virtually the same impulse sparkover and discharge voltages for either positive or negative impulse waves, thereby assuring a protection level which is inaffected by polarity. Table I.7.2 gives the protective characteristics of Alugard Thyrite station type arresters.

Arrester Rating KV RMS	Max. USASI Std. Front-of-wave Sparkover KV Crest	Max. 1.2 x 50 μs 100% Sparkover KV Crest *	Max.# Switching Surge Protective Characteristic# KV Crest	Max. 60 Cycle Sparkover KV RMS **	Maximum Discharge Voltage (Crest KV) at Indicated Impulse Current, 8 x 20 μ Sec.					
					1.5 KA	3.0 KA	5.0 KA	10.0 KA	20.0 KA	40.0 KA
3.0	12	12	12	5.3	5.0	5.8	6.4	7.3	8.3	10.2
4.5	16	15	15	7.9	7.4	8.7	9.5	10.8	12.3	15.1
6.0	20	18	18	10.5	9.8	11.5	12.6	14.3	16.3	19.9
7.5	25	22	23	13.2	12.2	14.3	15.7	17.7	20.3	24.8
9.0	30	25	27	15.8	14.6	17.1	18.8	21.2	24.3	29.6
12.0	39	32	35	21.0	19.4	22.7	24.9	28.1	32.1	39.2
15.0	48	39	43	26.3	24.2	28.2	31.0	35.0	40.0	48.8
18.0	57	47	51	31.5	28.9	33.7	37.1	41.8	47.8	58.5
21.0	66	54	59	36.8	33.7	39.3	43.2	48.7	55.5	68.0
24.0	76	61	67	42.0	38.4	44.8	49.2	55.5	63.5	77.5
30.0	95	75	84	52.5	47.8	56.0	61.5	69.5	79.0	96.5
36.0	113	90	100	63.0	57.5	67.0	73.5	83.0	94.5	115.0
39.0	123	97	108	68.3	62.5	72.5	79.5	89.5	102.0	125.0
48.0	151	118	132	84.0	76.0	89.0	97.5	110	125	153
60.0	180	136	142	99.0	95.0	111.0	122.0	137	156	190
72.0	213	166	170	119	114	133	146	164	187	227
78.0	231	183	184	129	123	144	158	178	202	246
84.0	247	198	198	139	133	155	170	191	217	265
90.0	267	214	213	149	142	166	182	204	232	283
96.0	280	231	227	159	151	177	194	218	248	302
108.0	315	262	253	178	170	198	218	245	278	339
120.0	347	294	284	198	188	220	241	272	309	376
132.0	380	320	312	218	207	241	263	294	333	402
144.0	413	350	340	238	226	262	287	321	363	439
168.0	495	396	397	277	263	305	334	374	422	510
180.0	530	430	425	297	281	327	358	400	452	550
192.0	560	460	453	317	300	349	362	427	482	585
228.0	640	547	539	376	355	413	452	510	575	695
240.0	670	575	567	396	374	435	476	535	605	730
258.0	710	623	609	426	402	467	515	575	650	785
264.0	725	640	624	436	411	478	525	585	665	800
276.0	752	672	650	455	429	500	550	615	690	835
288.0	785	706	680	475	448	525	570	640	720	875
300.0	820	738	709	495	467	545	595	665	750	910
312.0	850	771	737	515	495	565	620	690	730	945

* The impulse voltage which, when applied to the arrester, causes sparkover at every application (IEC Standard 99-1).

† These values are also used for 10 microsecond to sparkover in protecting Ac rotating machinery.

** Minimum 60 cycle sparkover in KV, RMS is 1.5 times the arrester rating.

\# The protective characteristic includes both the maximum switching-surge sparkover and the maximum switching-surge discharge voltage for any switching-surge current magnitude.

Table I.7.2 Protective characteristics of of Alugard Thyrite Station Arresters (19).

7.4 LOCATION OF ARRESTERS

It is a good general rule that all protective devices be located as close as possible to the equipment they are to protect. If a steep-fronted surge approaches a transformer, that is protected by an arrester, the arrester will spark over when its sparkover voltage is reached. In doing so, it will let through a spike of voltage with a crest equal in magnitude to the sparkover voltage, which will travel on and impinge on the transformer terminals. If the arrester is close to the transformer, the voltage on the transformer will be limited to that same level. At the same time, a reflected wave will travel back down the line, modifying the incident wave. The transformer will present a comparatively high impedance to the surge so that the reflected voltage wave from the terminations will add to the incident wave. This results in the terminal voltage approaching twice the incident voltage. This voltage will persist until the reflected wave has returned to the arrester and a second negative reflected wave has propagated back from the arrester to the transformer. For a wave velocity of 300 x 10^6 m/s and a separation of 30 m, this duration results in $\frac{2 \times 30}{300}$ = 0.2 μs.

If the surge front has a steepness of 1 000 kV/µs, it will result in a gradient of $\frac{1\ 000\ \text{kV}/\mu\text{s}}{300\ \text{m}/\mu\text{s}} = 3.3\ \text{kV/m}$ on a conductor. Hence when the line to ground voltage is zero at one point, another point 30 m away may have approximately 100 kV to ground.

To illustrate the effect of arrester location, consider the 138 kV station shown schematically in fig. I.7.2 with the arrester located 30 m beyond the disconnect switch and 30 m ahead of the transformer. Consider a travelling wave having a rate of voltage rise of 1 000 kV/µs entering the station and an arrester which limits the voltage to 400 kV. In 0.1 µs after the wave reaches the switch, it reaches the lightning arrester and 0.1 µs later,

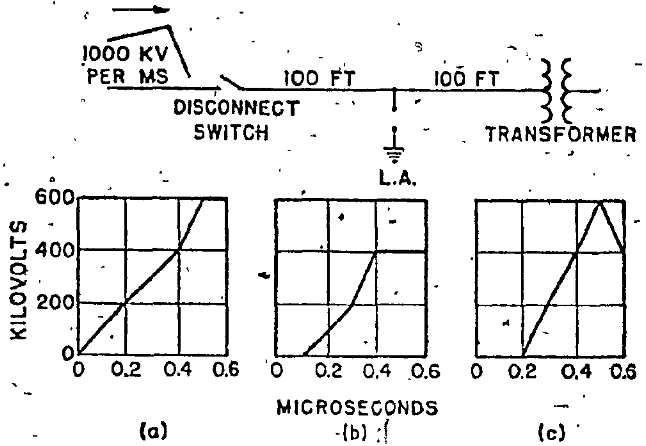

Fig. I.7.2 Voltages at 138 kV substation resulting from first reflection of traveling surge having 1000 kV per microsecond wave front (2).
a) At disconnect switch located 30 m ahead of arrester
b) At arrester
c) At transformer located 30 m beyond arrester.

or at the end of 0.2 µs, it reaches the transformer where it reflects and builds up at a rate of 2 000 kV per µs. At the end of 0.4 µs after the wave first reached the switch, the incoming wave and the reflected wave from the transformer would total to 400 kV at the arrester. As shown in fig. I.7.2, the voltages at the switch and at the transformer would also be 400 kV.

The reflected wave from the transformer has just reached the switch. The voltage at the arrester remains at 400 kV until the crest of the incoming wave is reached but the voltages at the switch and transformer continue to rise at 2 000 kV/ µs until the reflected negative waves from the arrester reaches the switch and transformer at the end of 0.5 µs.

Successive reflections occur until the wave spends itself by discharging through the arrester. As shown in fig I.7.2, the voltages at the switch and transformer resulting from the first reflections reach 600 kV or 50% more than the arrester voltage. The maximum voltage E_t at a transformer at the end of a line beyond an arrester as a result of the first reflections of a travelling wave, may be expressed mathematically as follows:

$$E_t = e_d + 2 \frac{de}{dt} \times \frac{L}{300}$$

up to a maximum of 2 e_d where:

e_d = arrester discharge or sparkover voltage

$\frac{de}{dt}$ = rate of rise of wave front in kV/ µs

L = distance between arrester and line terminum in meter.

The same expression can also be used to determine the voltage at a point on a line ahead of an arrester, due to a travelling wave. In this case, the voltage can reach as a maximum the crest of the travelling wave if the distance to the arrester is big enough or if the rate of rise of the wave front is sufficiently high.

The curves of fig. I.7.3 show the voltage in excess of the arrester voltage as a function of distance from the arrester for rates of rise of wave front of 100, 500 and 1 000 kV/ µs. The curves can be used to determine the actual voltage at a point ahead of an arrester or at a line terminum beyond an arrester by adding to the curve value the discharge or sparkover voltage of the arrester.

In the case of switching surges, the travelling wave effects can generally be neglected, considering that a

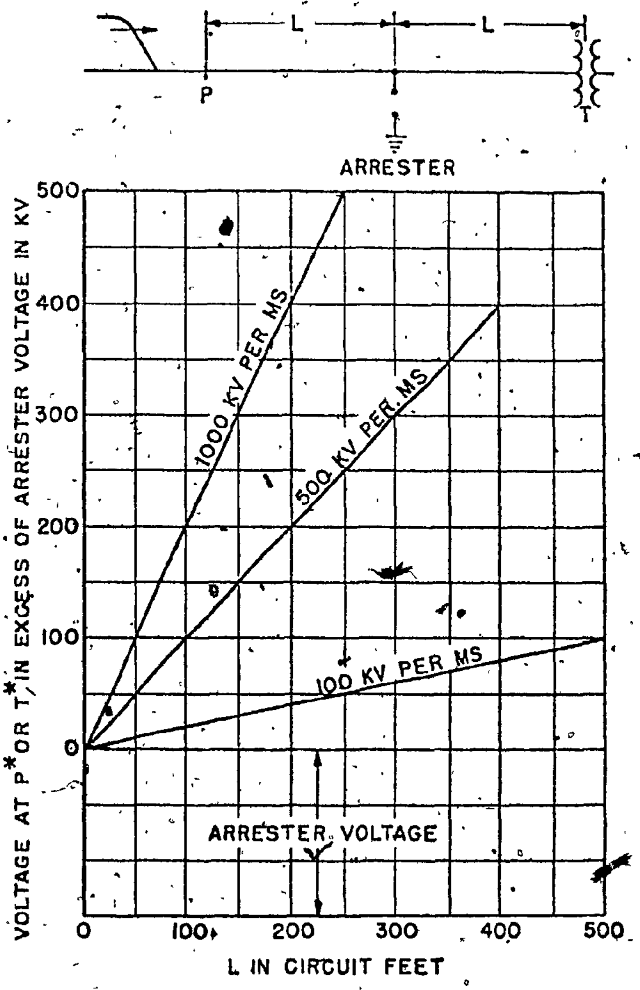

Fig. I.7.3 Maximum voltage due to first reflection of travelling wave as function of distance from arrester and steepness of wave front.(2).

front of only 50 µs is 15 km long. However, switching surges with abrupt changes do occur.

In addition to the reflected wave phenomena, it is quite possible that still higher peak voltages would exist at the apparatus as a result of oscillations caused by the inductance of the line between the arrester and the apparatus and the capacitance of the apparatus. Furthermore, the voltage drops in the lead from the line to the arrester and in the lead from the arrester to ground, add to the drop across the arrester.

In view of the above factors, it is important that the protective device be located close to the protected apparatus. The leads to the devices must be kept as short and direct as possible, and the arrester and apparatus grounds be interconnected and as low in resistance as possible, preferably one ohm or less.

With the arrester suitably close to the transformer, it is necessary to appraise the protection to breakers and switches located some distance from the transformer. It is desirable to assume the possibility of an incoming wave front of not less than 500 kV/ µs, or 3.30 kV higher stress at the switches for each meter of separation. The stress on a breaker located 30 m apart would be the arrester voltage plus 100 kV. Assuming a wave front of 1 000 kV/µs, the stress on the breaker would be the arrester voltage plus 200 kV. Therefore, efficient protection of the larger substations requires supplementary sets of arresters connected to the line side of the breakers and disconnecting switches.

The risk of trouble on switching equipment is not so serious as it may appear. Oil-filled breakers and disconnecting switches are so built that the internal impulse insulation strenght or the flashover distance over open switches is greater than that to ground from the terminal. Thus, a surge in excess of the insulation strenght is likely to flash to ground without damaging the apparatus. This may cause an outage but the probability is small.

7.5 SELECTING ARRESTER RATED VOLTAGE

The selection of the arrester rated voltage is a compromise between cost and safety. A lightning arrester is often called upon to operate during an earth fault somewhere in the system, and the rated voltage of the arrester must therefore be higher than the sound phase-to-ground voltage. Otherwise, the arrester will draw too high a power-follow current which may lead to thermal overloading and failure, or at least a reduction in the useful life of the arrester. On the other hand, the higher the rating, the higher the cost of the arrester and in addition, the higher the cost of the protected equipment, since the protective level and therefore the BIL of the equipment is higher.

The maximum phase-to-ground voltage applied to the arrester under fault condition is the real criterion in selecting the arrester rated voltage. When deciding upon a suitable arrester rating it is of major importance to know the degree of effectiveness of the system neutral grounding. Such information is usually given as the ratio of the zero and the positive sequence reactances. The system neutrals are considered to be effectively grounded when the coefficient of earthing does not exceed 80%. The earthing coefficient is defined as the ratio of the highest r.m.s. voltage to earth of the sound phase or phases, at the point of application of an arrester during a phase to earth fault (irrespective of the fault location), to the highest phase-to-phase r.m.s. voltage, expressed as a percentage of the latter voltage.

A value less than 80% is obtained, when for all system conditions the ratio of zero sequence reactance to positive sequence reactance $\frac{X_0}{X_1} = 0$ to +3, and the ratio of zero sequence resistance to positive sequence reactance $\frac{R_0}{X_1} = 0$ to +1. In this case, the arresters should have a rated voltage equal to at least 80% of the highest phase-to-phase system voltage (denoted as "80% arrester") corresponding to approximately 140% of system line to neutral voltage.

On many high voltage transmission systems, the coefficient of earthing will not exceed 75% when for all system conditions $\frac{X_0}{X_1} = 0$ to +1 and $\frac{R_0}{X_1} \leq 0.5$. Under these conditions, the arrester rated voltage may be 75% of the highest phase-to-phase system voltage, corresponding to approximately 130% of system phase to neutral voltage.

For ungrounded neutral systems, the 100% arrester should be used. It may be noted that in a non effectively grounded system, the reactance ratio $\frac{X_0}{X_1}$ lies between zero and minus forty, resonance conditions may exist and no general rule for the arrester rated voltage is practicable.

7.6 PROTECTIVE MARGIN

The difference which should exist between the B.I.L. of the insulation to be protected and the protective level of lightning arresters is a much discussed question (2) (3) (20). This difference is called the "Protective Margin". Allowance has to be made for adequate margin to take care of:

i The effect of separation between the protected apparatus and the arrester caused by travelling wave effects in case of short front lightning surges.

ii Voltage drops in the connecting leads from the line to the arrester high-voltage terminal and from the arrester ground terminal to the ground electrode.

iii The possibility of variations of arrester characteristics with time and reduction of insulation strength of the protected apparatus with time.

Common values of margins above protective level are 20 to 30%. In order to give higher margins at lower voltages, a figure of 15% + 30 kV is used, but the margin may have to be larger if the lightning arresters protect remote apparatus.

8. INSULATION COORDINATION OF H.V. SUBSTATIONS

Insulation coordination is a correlation of the insulation of the apparatus and the overvoltage that will be allowed by the protective device. The task is facilitated by the establishment of a protective voltage level by means of a lightning arrester. A general approach consists in comparing the volt-time insulation withstand curve of the apparatus to be protected with the volt-time protective level curve of the protective device. The withstand level of the insulation is to be above the protective level by the protective margin, dictated mainly by the distance of the equipment from the arrester. Hence equipment remote from arresters is often of higher withstand level than equipment close to them.

Although coordinated protection is important throughout the substation, it is most vital to the power transformers. Hence in the following, we shall consider the coordinated protection of power transformers.

From basic design data, it is known that the kV strength of modern transformers at 0.5 μs is about 50% greater than the B.I.L. Therefore the over-all impulse volt-time curve, defining the transformer withstand strength, is represented by a composite curve e.g. from 0.5 μs through 1.5 or 3.0 μs by the chopped-wave test point, and then through the full wave test level (B.I.L.).

The switching surge strength of the transformer depends on the duration of the switching surges. For the shorter duration switching surges, the insulation withstand strength will approach the impulse full wave withstand test kV level. As the switching surge duration extends into thousands of microseconds, a figure of 0.83 times the B.I.L. is generally taken in the literature (3) (19), as a probable withstand value against switching surges. These concepts of Insulation-Coordination are clarified in part II.

PART II

APPLICATION OF INSULATION CO-ORDINATION ON 230 kV, 161 kV, 115 kV, AND 34.5 kV INSULATION CLASS SYSTEMS

4

PART II - APPLICATION OF
INSULATION CO-ORDINATION
ON 230 kV, 161 kV, 115 kV AND 34.5 kV
INSULATION CLASS SYSTEMS

1. INTRODUCTION

This study refers to the selection of the impulse insulation level and the coordinated rating of the lightning arresters for the power transformers of the following insulation classes of transmission systems.

230 kV
161 kV
115 kV
34.5 kV

The protective efficiency of the modern station type arresters enables the reduced insulation approach which results in tremendous savings in apparatus cost. The reduced insulation concerns only the power transformers, with the arresters installed on the transformer bushings, and it is not applicable to the other outdoor apparatus, like circuit breakers, disconnect switches etc. These apparatus do not use the reduced insulation level because the advantages in savings resulting from reduced transformer winding insulation are not achieved and because, in many locations, the added margin against contamination is desirable. Furthermore, because of separation between the circuit breakers and arresters at the transformers, a higher insulation level for the breakers may be desirable.

2. GENERAL PROCEDURE

The following three steps are required for the coordinated protection of the transformers.

i PROTECTIVE LEVEL

The protective level is established by selecting the lightning arrester rated voltage and nominal discharge current. The rated voltage must be not less than the maximum power frequency voltage (r.m.s.) to ground, at the point of installation, under any fault or operating condition. As far as the nominal discharge current is concerned, 10 kA station type lightning arresters are selected for the present application, since they are intended to protect transmission power transformers.

The sparkover and discharge voltages of the arresters can now be determined from the manufacture data and the protective level be established. It will be noticed that commercially available lightning arresters have more favorable characteristics than the standards demand.

ii PROTECTIVE MARGIN

A protective margin of 20% is selected since the lightning arresters are installed on the transformer bushings.

iii IMPULSE AND SWITCHING WITHSTAND LEVELS OF THE TRANSFORMER.

It is now possible to select the basic insulation level (BIL) from the list of standard values of table II.2.1. The switching impulse level (SIL) is estimated at 83%* of the BIL (19). These levels (BIL and SIL) must exceed at least by 20% the protective level of the lightning arrester, established in step i.

It is not likely that the insulation class will be

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*NOTE: For voltages higher than 300 kV, table II.2.2 gives a proposition of I.E.C. for the switching impulse levels.

reduced more than one class, except in the case of transformers for 230 kV and higher. In the lower voltages, the savings are not great enough to justify the reduction by more than one class. Also, the 60 Hz strength of the equipment must be considered. The 60 Hz strength and BIL are related. There will be a minimum 60 Hz strength below which it is not safe to go for a particular system voltage. This, then, fixes the minimum impulse strength or BIL, regardless of whether the lightning protection might permit a lower BIL (20).

Highest Voltage for equipment	Impulse withstand Test voltage with standard full wave positive and negative polarity		Power frequency withstand Test voltage with respect to earth under standard conditions	
kV r.m.s.	Full insulation kV crest	Reduced insulation kV crest	Full insulation kV r.m.s.	Reduced insulation kV r.m.s.
72.5	350		140	
145	650	550 450	275	230 185
245	1050	900 825 750	460	395 360 325
362		1300 1175 1050		570 510 460
525		1800 1675 1550 1425		790 740 680 630

Table II.2.1 Impulse and Power - Frequency Withstand Test Voltages. (Extract from IEC Publication 71-1967).

Highest Voltage for equipment U_m	Base for p.u. values $U_m \frac{\sqrt{2}}{\sqrt{3}}$	Rated Switching impulse withstand voltage 250/2500 µs		Rated Lightning impulse withstand voltage	Ratio between Lightning and switching impulse withstand voltage
kV rms	kV	kV peak	(p.u.)	kV peak	
300	245	750	(3.06)	850 - 950	1.13 - 1.27
362	296	850	(3.45) (2.86)	950 - 1050	1.12 - 1.24
420	343	950	(3.20) (2.76)	1050 - 1175	1.12 - 1.24
525	429	1050	(3.06) (2.45)	1175-1300-1425	1.12 - 1.24 - 1
		1175	(2.74)	1300-1425-1550	1.11 - 1.21 - 1
765	625	1300 1425 1550	(2.08) (2.28) (2.48)	1425-1550-1800 1550-1800-2100 1800-1950-2400	1.10 - 1.19 - 1 1.09 - 1.26 - 1 1.16 - 1.26 - 1

Table II.2.2 Proposed standard insulation levels for $U_m \geq 300$ kV. (From IEC Document, Central office, 35, July 1970).

3. CO-ORDINATION CURVES

The curves on fig. II.3.1, II.3.2, II.3.3 and II.3.4 illustrate the co-ordination of transformers having various BIL's with the impulse and switching surge characteristics of different Thyrite station type arresters. The upper volt-time curve on each figure indicates the maximum lightning voltage that can be delivered to the substation by travelling waves reaching the station over the connected transmission line. Obviously any lightning voltage on the line exceeding the line insulation level will cause line flashover and a resulting chopped wave of voltage travelling to the station.

The lower curves on each figure are a similar representation of the arrester characteristics under impulse and switching surge conditions. The horizontal dotted lines at 80% of the selected BIL and SIL determines the desired margin of safety. Lightning and switching voltage stresses on the transformers should not exceed this kV-level. At the lower part of each figure, the maximum IR discharge voltages are shown in ladder form for various values of lightning currents.

On the same figure, the sparkover voltage curves for rod gaps of various spacings are shown. One can easily see that effective protection of the transformers cannot be achieved with rod gaps, for the reasons explained in sect. 7.2

4. MAXIMUM POWER FREQUENCY PHASE-TO-GROUND VOLTAGE

From system data, the maximum power frequency phase-to-ground voltages are known to be as follows:

System Insulation class	kV	230	161	115	34.5
Max. Power Frequency Phase-to-Ground Voltage	kV	185	125	75	27

5. SELECTION OF THE TRANSFORMER BIL's AND ARRESTER RATED VOLTAGE

For the Arrester Rated Voltage, the lowest standard rating above maximum power frequency phase-to-ground voltage, is selected. The BIL's of the transformers and the rated voltage of the arresters, which have been selected, are summarized in table II.5.1

System Insulation Class	kV	230	161	115	34.5
Nominal Operating Voltage	kV	225	150	90	33
Max. Power Frequency Phase-to-Ground Voltage	kV	185	125	75	27
Arrester Rated Voltage	kV	192	132	84	30
Transformer BIL	kV	825	650	450	200

Table II.5.1 Summary of Arrester Rated Voltage and Transformer BIL's

The appraisal of the co-ordinated protection of power transformers can be made easily through the curves of figures II.3.1, II.3.2, II.3.3 and II.3.4. A protective margin exceeding 20% is obtained for both lightning and switching surges with the selected BIL's of the transformers and the rated voltages of the arresters. It can be noted that the arresters will prevent lightning voltages from exceeding the safe allowable impulse stress even for lightning discharge currents of 40 kA.

CONCLUSION

The benefit to be derived from the application of the Insulation Co-ordination, in selecting the BIL's of the transformers and the rated voltage of the lightning arresters, is economic. For this application, it is imperative to know the maximum power frequency voltage to ground at the point of installation of the arresters. The selection of the proper lightning arresters enables the reduction of the BIL's of the transformers by one or two kV-classes below the standard BIL's. Important savings, thus, can be obtained in the apparatus cost , especially in the range of the extra high voltages.

For example, in the case of a 100 MVA, 230-161 kV power transformer, the standard BIL's are 1050 kV and 750 kV respectively. The reduction of the BIL's from 1050 kV to 825 kV and from 750 kV to 650 kV reduces the price of the transformer by 15% and 7 % respectively or a total reduction of approximately 22%. This represents an important saving, the price of the transformer with the standard BIL's being of the order of $600 000.00

The savings are more important in the case of larger transformers whose prices exceed $1 000 000.00. Further in the range of the extra high voltages, the percent difference of price from one to the next level is more than the assumed 7% of the example. In voltages lower than 150 kV, this percent difference of prices, being 2% or less, does not justify the reduction of the insulation by more than one class or even the reduced insulation concept.

The reduced insulation concept is not applicable to the Circuit-Breakers, Disconnect Switches and other apparatus of the substation. For these apparatus, the standard BIL's are used.

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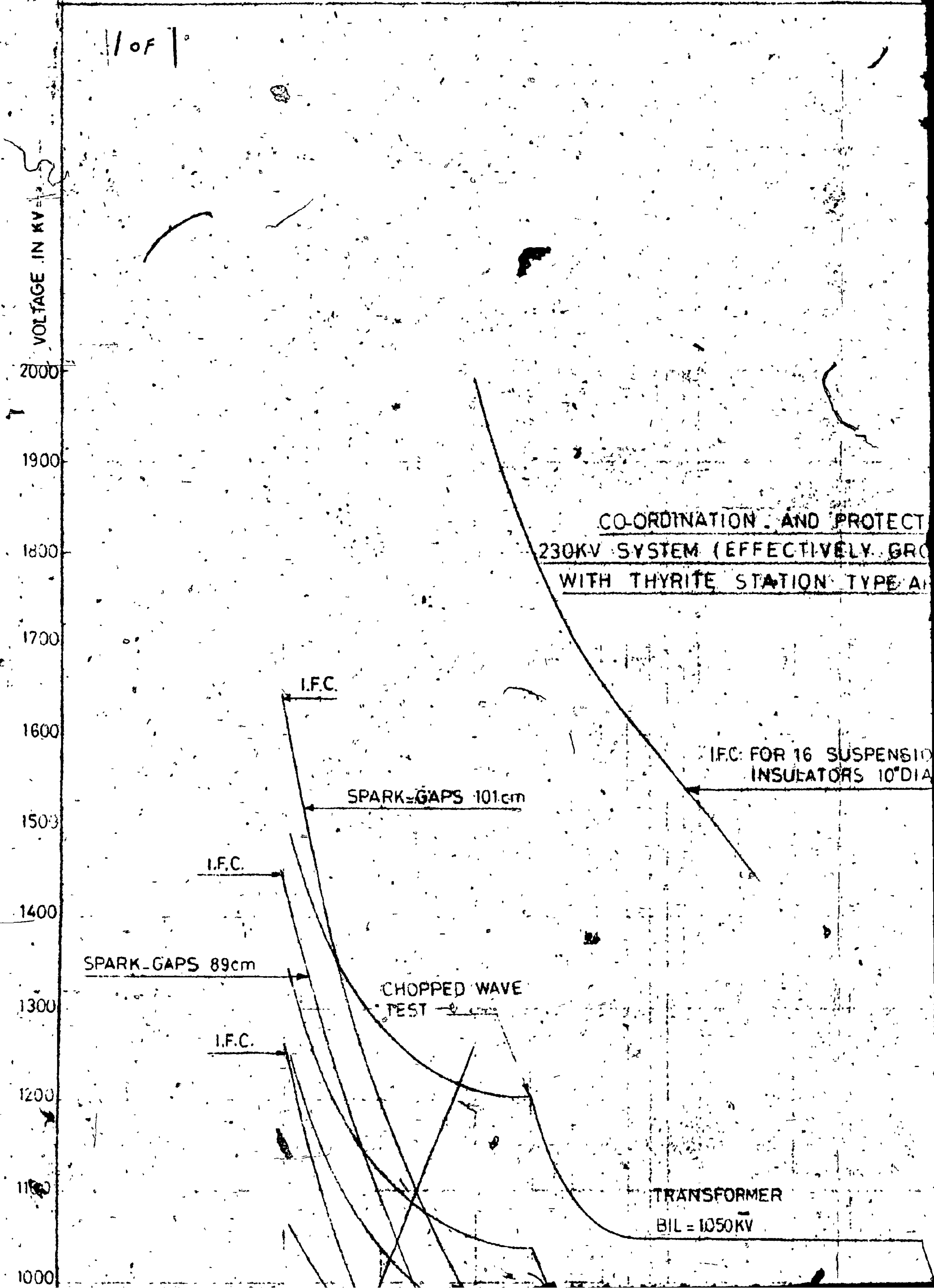


VOLTAGE IN KV
2000
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
CO-ORDINATION AND PROTECT
230KV SYSTEM (EFFECTIVELY GRO
WITH THYRITE STATION TYPE AI
I.F.C.
SPARK-GAPS 101cm
I.F.C.
SPARK-GAPS 89cm
I.F.C.
CHOPPED WAVE TEST
I.F.C. FOR 16 SUSPENSIO
INSULATORS 10"DIA
TRANSFORMER
BIL = 1050KV

| 2 OF |

AND PROTECTION
ECTIVELY GROUNDED)
TION TYPE ARRESTERS

R 16 SUSPENSION
SULATORS 10"DIAM×5 3/4"

NOTES: 1) *LIGHTNING ARRESTER IR VOLTAGES BASED ON CURRENT WAVE OF $8\times20\mu S$

2) M.P.M.= MINIMUM PROTECTION MARGIN

3) B.I.L.= B.I.L. AND FULL WAVE TEST

4) S.O.V = SPARK-OVER VOLTAGE

5) MINIMUM 60Hz SPARKOVER IN KV R.M.S IS 1.5 TIME THE ARRESTER RATING

6) FOR THE CHOPPED WAVE TEST THE MINIMUM TIME TO SPARKOVER IS TAKEN $3\mu S$

7) IFC = IMPULSE FLASHOVER CHARACTERISTICS (POS. POLARITY)

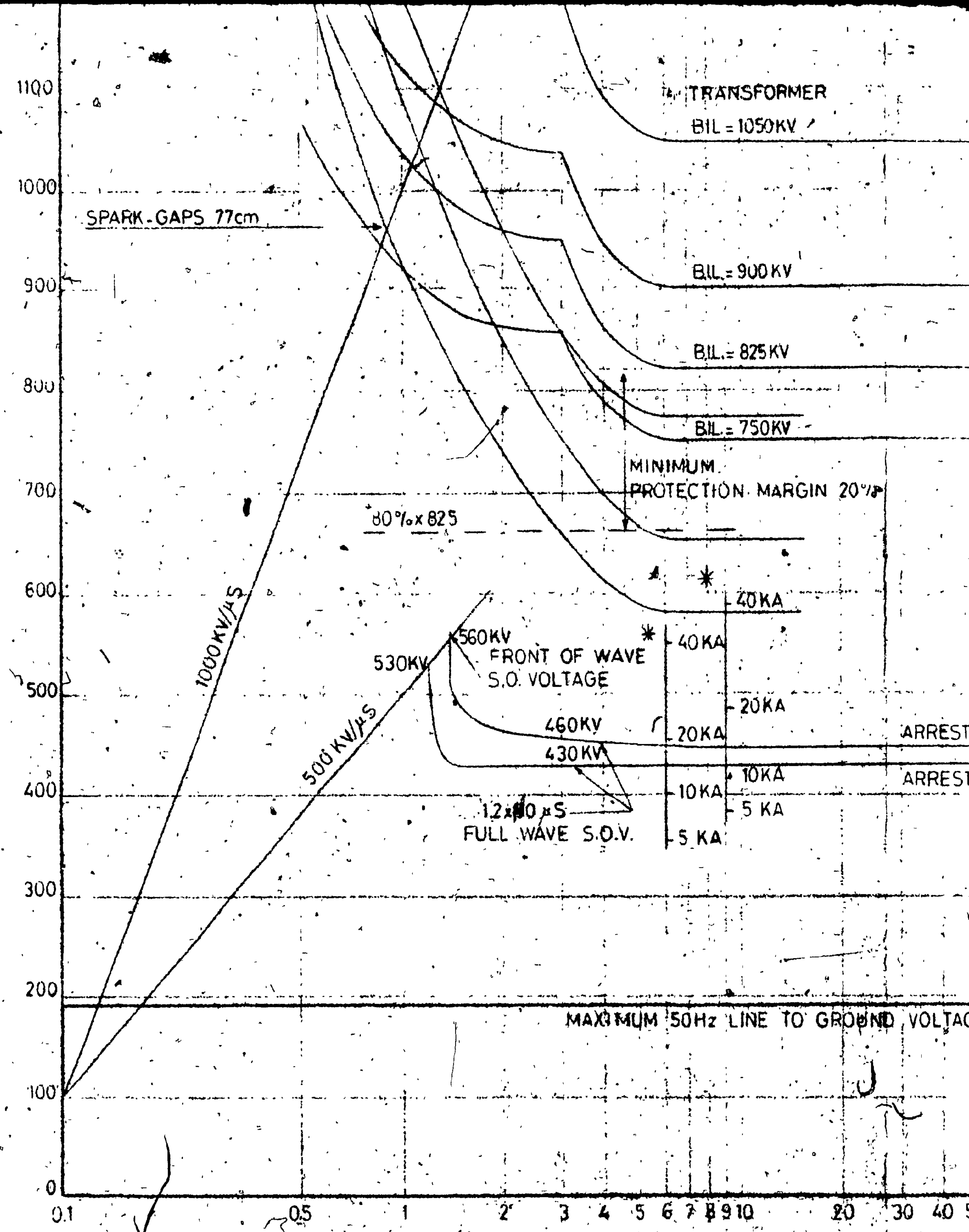


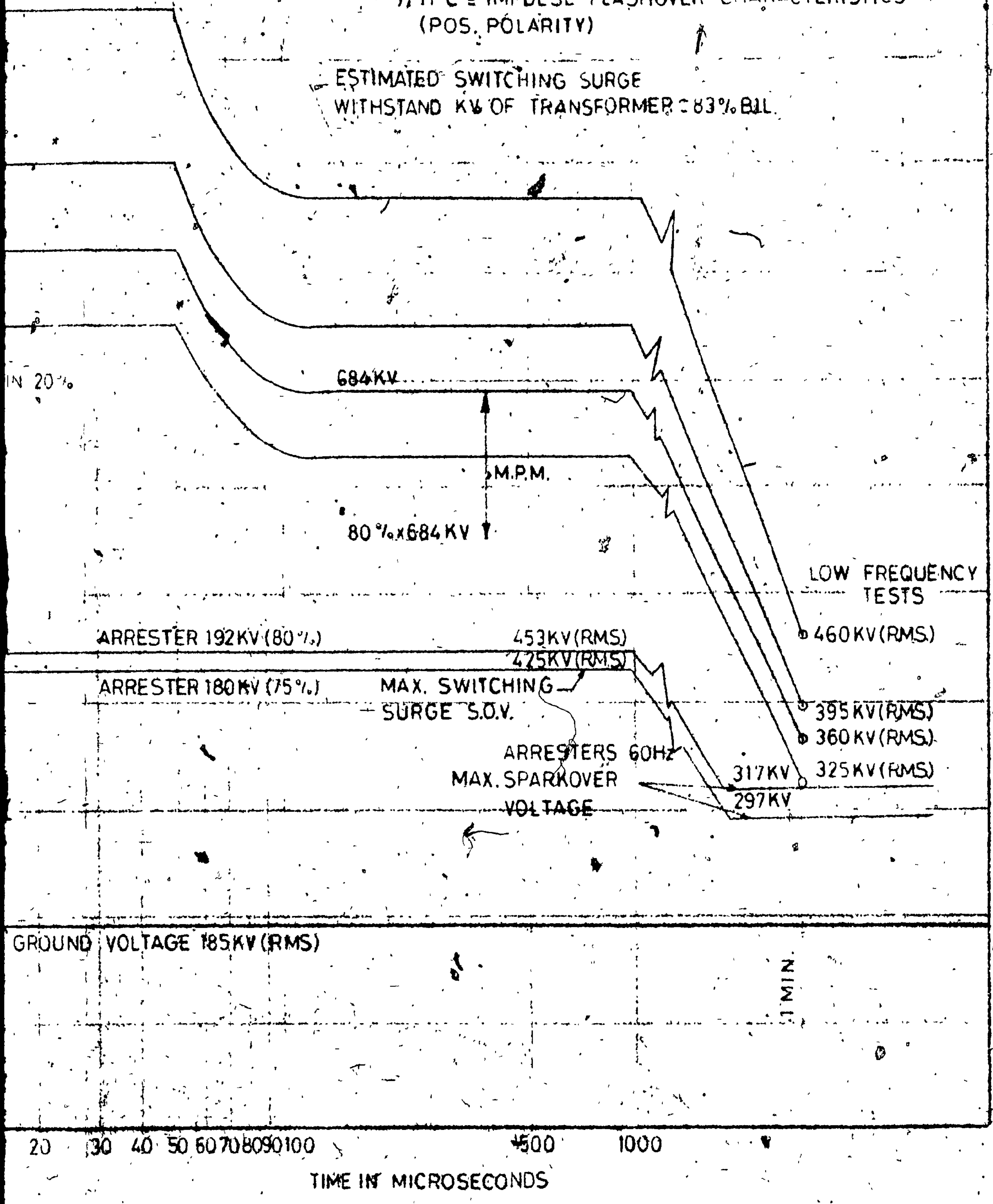
FIG Ⅱ.3.1 CO-ORDINATION AND PRO

3 OF

5) MINIMUM 60Hz SPARKOVER IN KV RMS IS 1.5 TIME THE ARRESTER RATING

6) FOR THE CHOPPED WAVE TEST THE MINIMUM TIME TO SPARKOVER IS TAKEN 3µS.

7) IFC = IMPULSE FLASHOVER CHARACTERISTICS (POS. POLARITY)



ATION AND PROTECTION 230 KV SYSTEM

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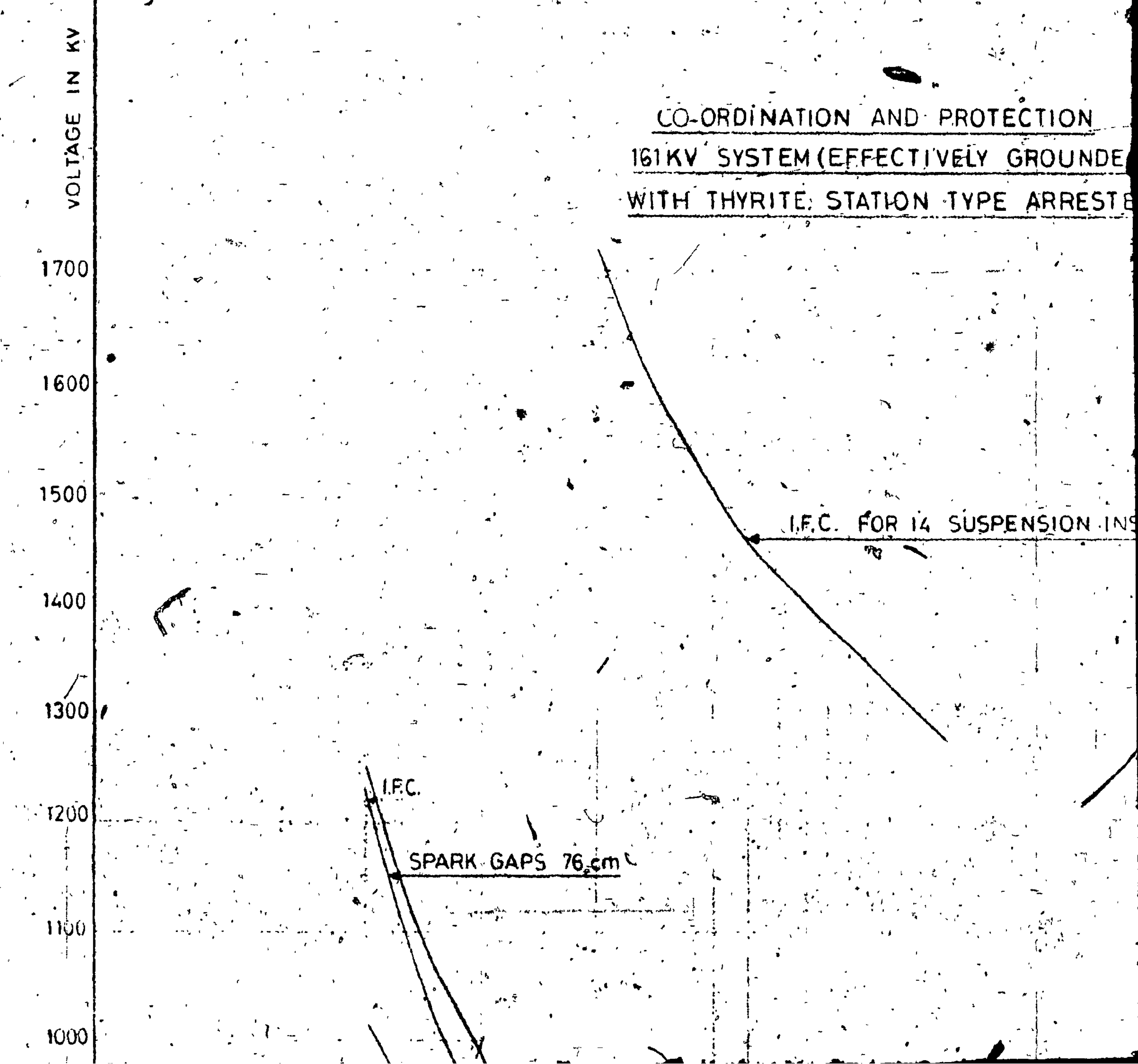


CO-ORDINATION AND PROTECTION
161KV SYSTEM (EFFECTIVELY GROUNDE
WITH THYRITE STATION TYPE ARRESTE

PROTECTION

VELY GROUNDED)

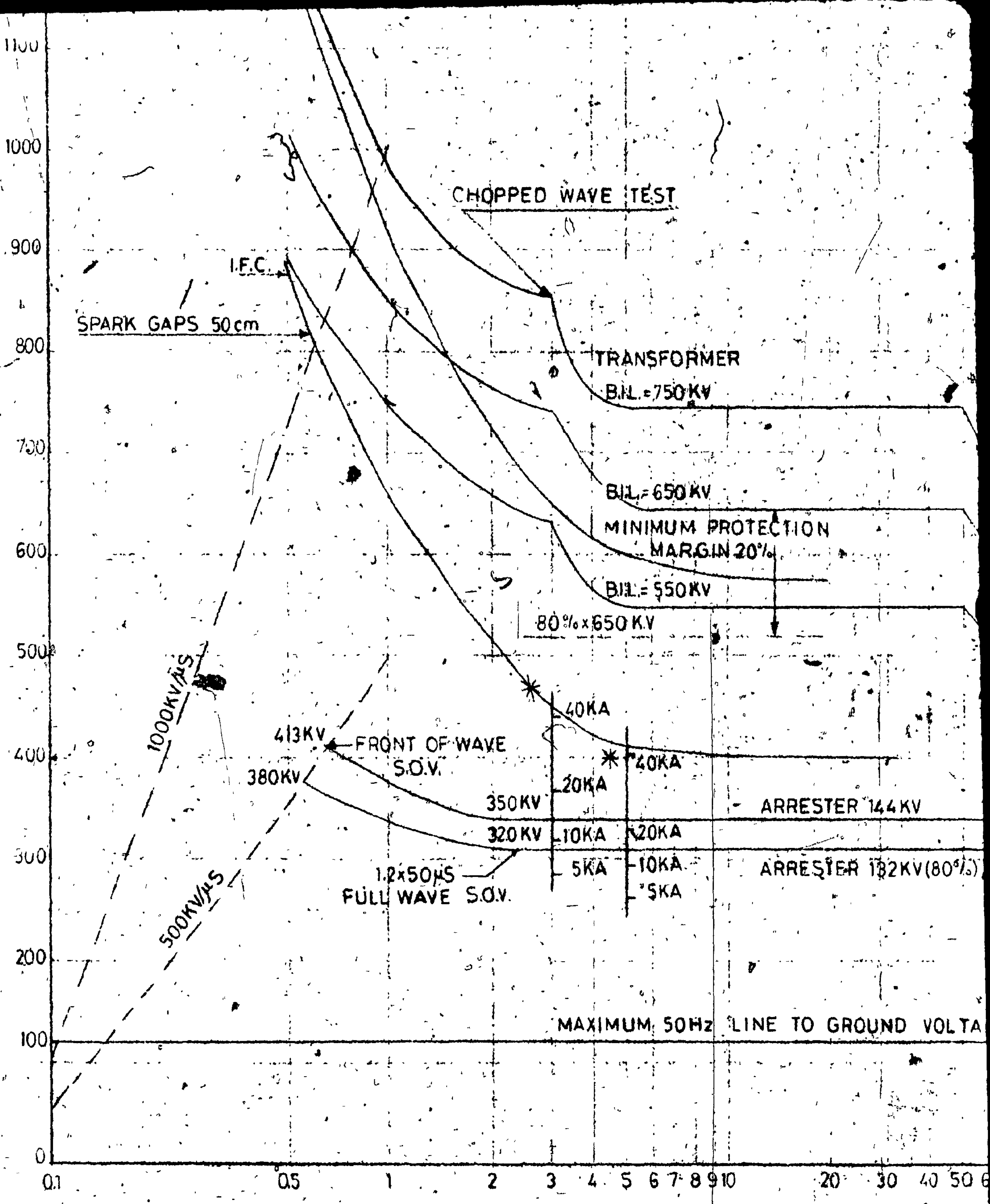
TYPE ARRESTERS

SUSPENSION INSULATORS 10" DIAM x 5 3/4"

NOTES: 1) * LIGHTNING ARRESTER IR VOLTAGES BASED ON CURRENT WAVE OF 8×20μS.

2) M.P.M. = MINIMUM PROTECTION MARGIN

3) B.I.L. = B.I.L. AND FULL WAVE TEST.



3 OF

FIG II . 3.2 CO-ORDINATION AND PROTEC

NOTES: 1) * LIGHTNING ARRESTER IR VOLTAGES BASED ON CURRENT WAVE OF 8×20μS.

2) M.P.M. = MINIMUM PROTECTION MARGIN.

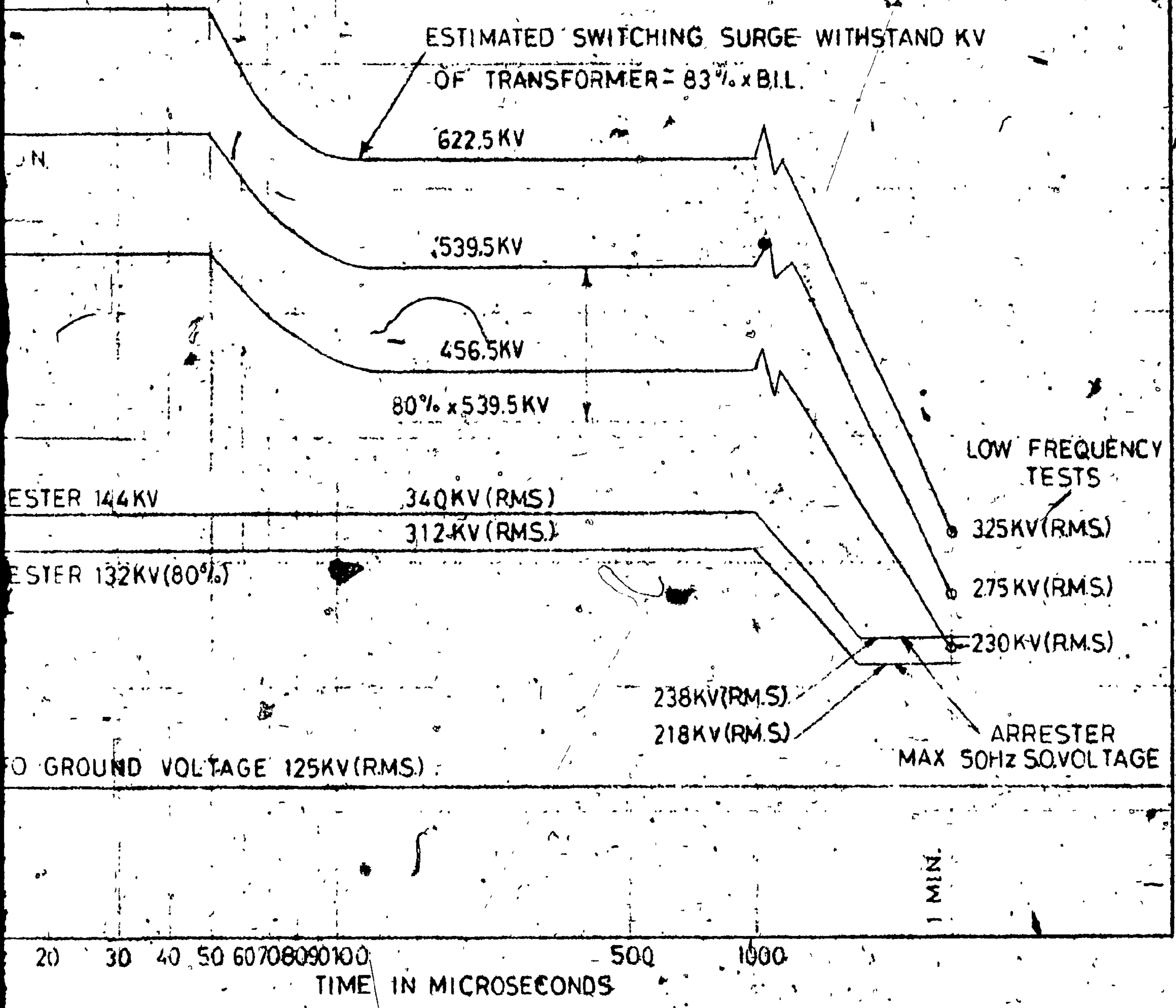
3) B.I.L. = B.I.L. AND FULL WAVE TEST.

4) S.O.V. = SPARK OVER VOLTAGE

5) MINIMUM 60Hz SPARKOVER IN KV RMS ~~IS 1.5 TIME THE ARRESTER RATING~~

6) FOR THE CHOPPED WAVE TEST THE MINIMUM TIME TO SPARKOVER IS TAKEN 3μS

7) I.F.C. = IMPULSE FLASHOVER CHARACTERISTICS (POS. POLARITY)



TION AND PROTECTION 161 KV SYSTEM

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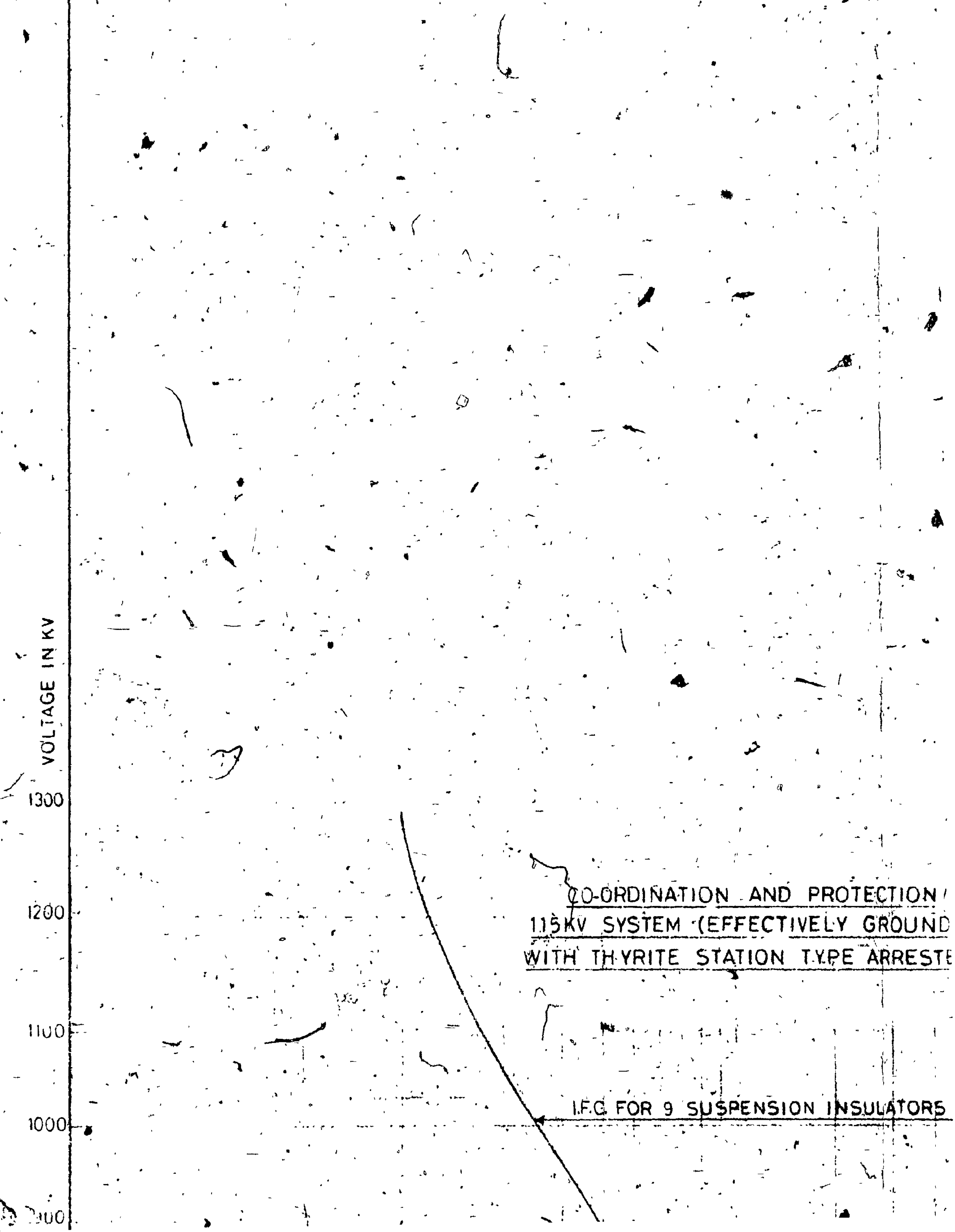
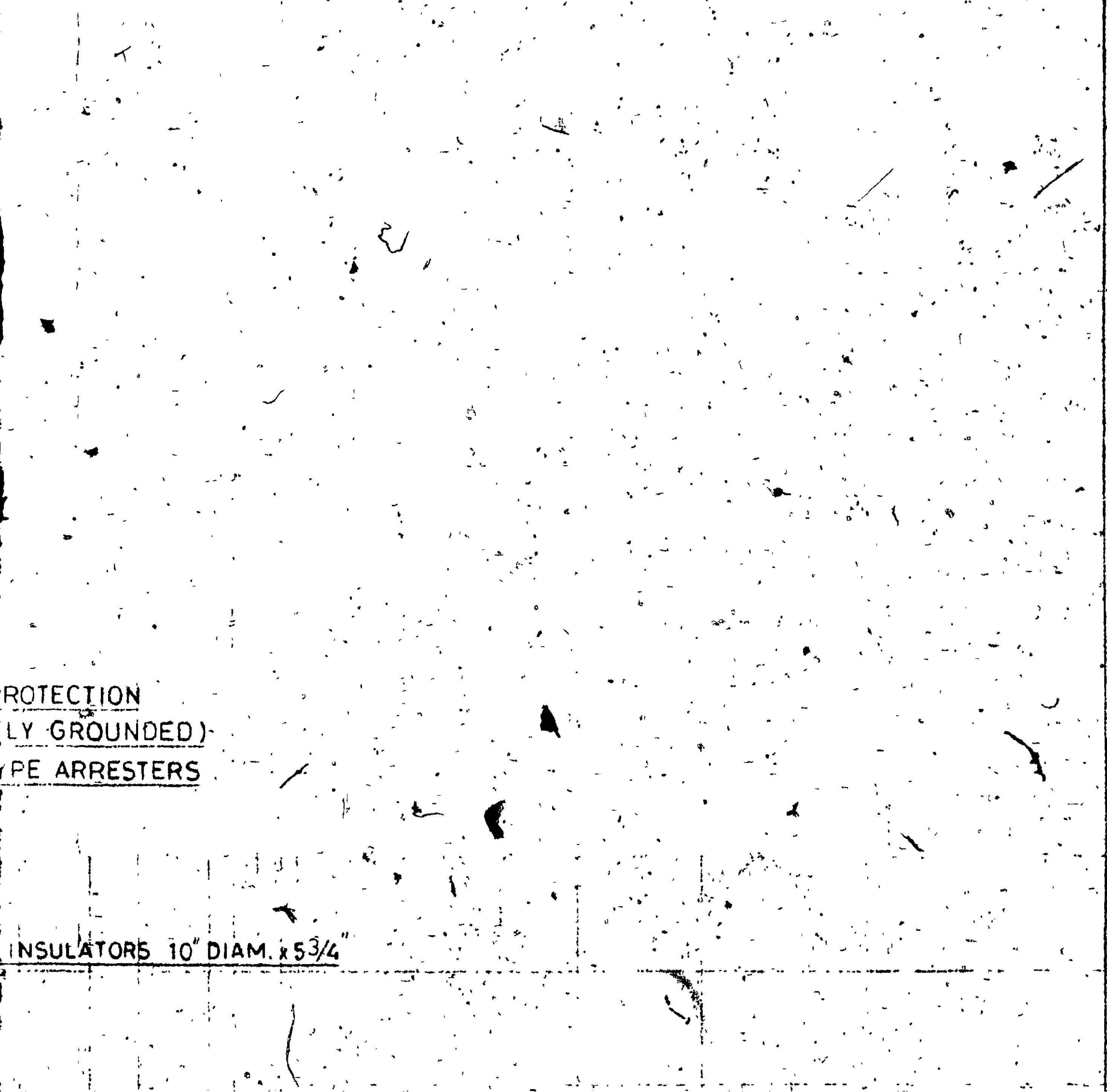
1 OF 1



CO-ORDINATION AND PROTECTION
115KV SYSTEM (EFFECTIVELY GROUND
WITH THYRITE STATION TYPE ARRESTE

2 OF


ROTECTION
LY GROUNDED)
PE ARRESTERS
INSULATORS 10" DIAM. x 5 3/4"

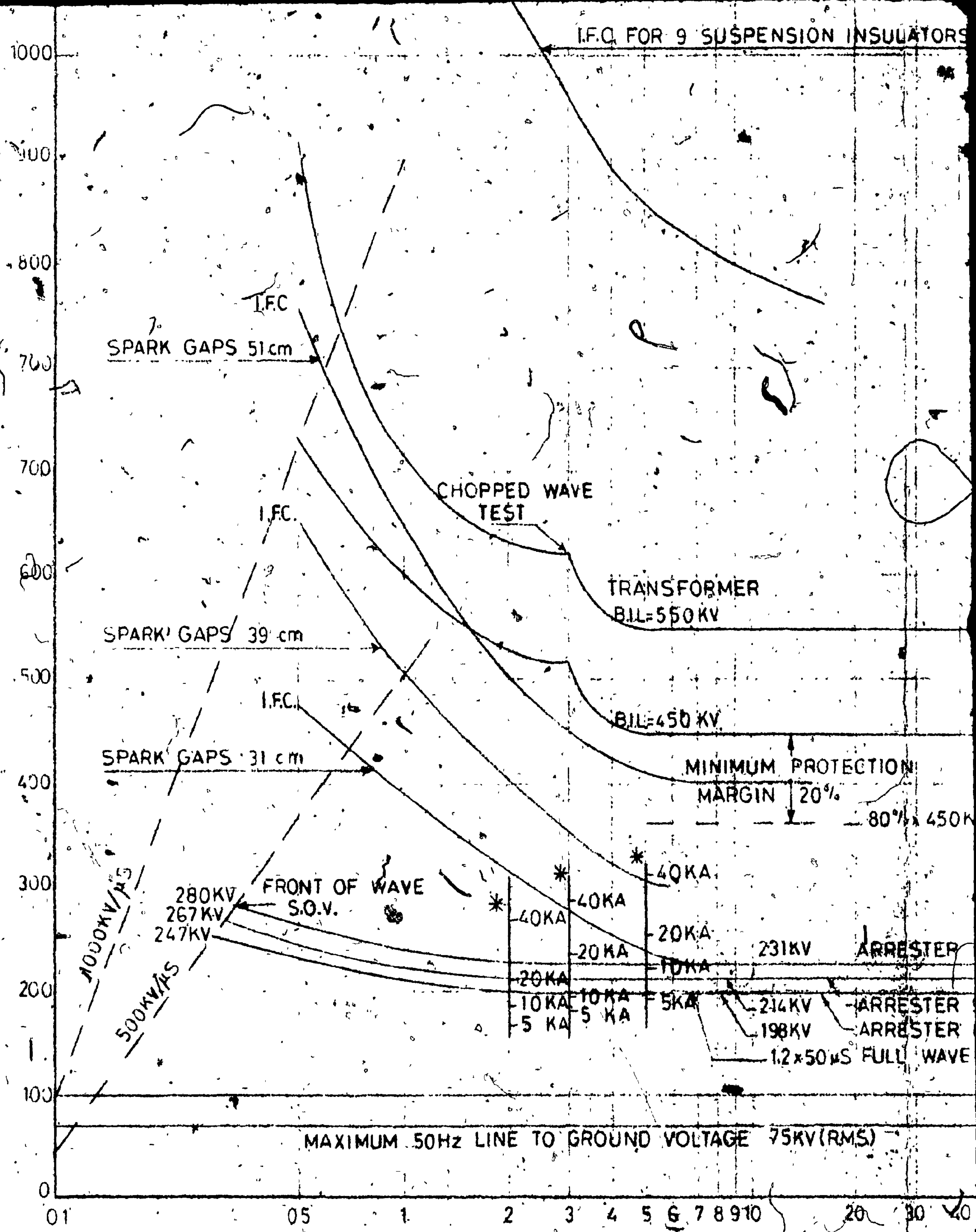
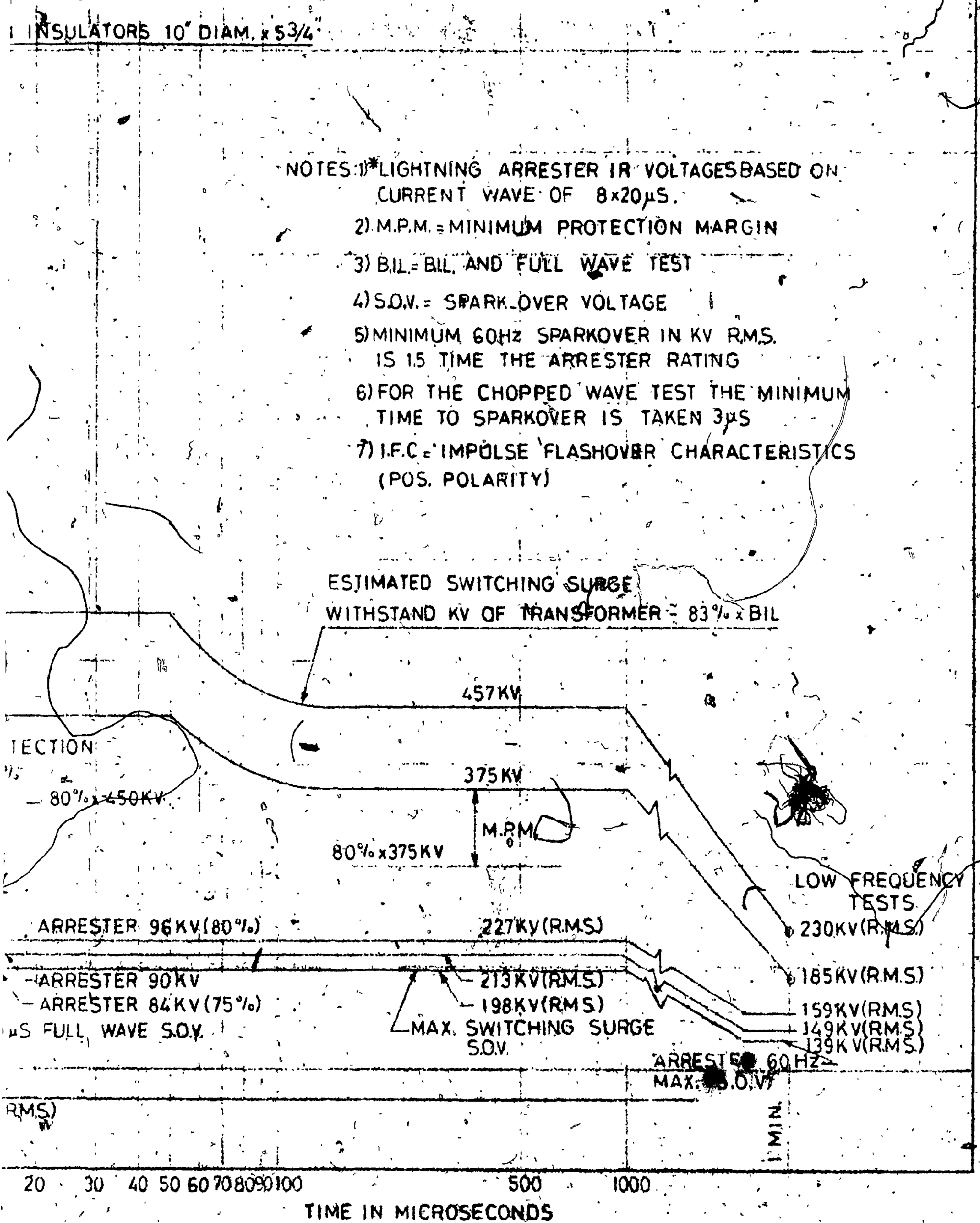


FIG II.3.3 CO-ORDINATION AND PROTEC

3 OF



NOTES: 1) *LIGHTNING ARRESTER IR VOLTAGES BASED ON CURRENT WAVE OF 8x20µS.

2) M.P.M. = MINIMUM PROTECTION MARGIN

3) B.I.L. = B.I.L. AND FULL WAVE TEST

4) S.O.V. = SPARK-OVER VOLTAGE

5) MINIMUM 60Hz SPARKOVER IN KV R.M.S. IS 1.5 TIME THE ARRESTER RATING

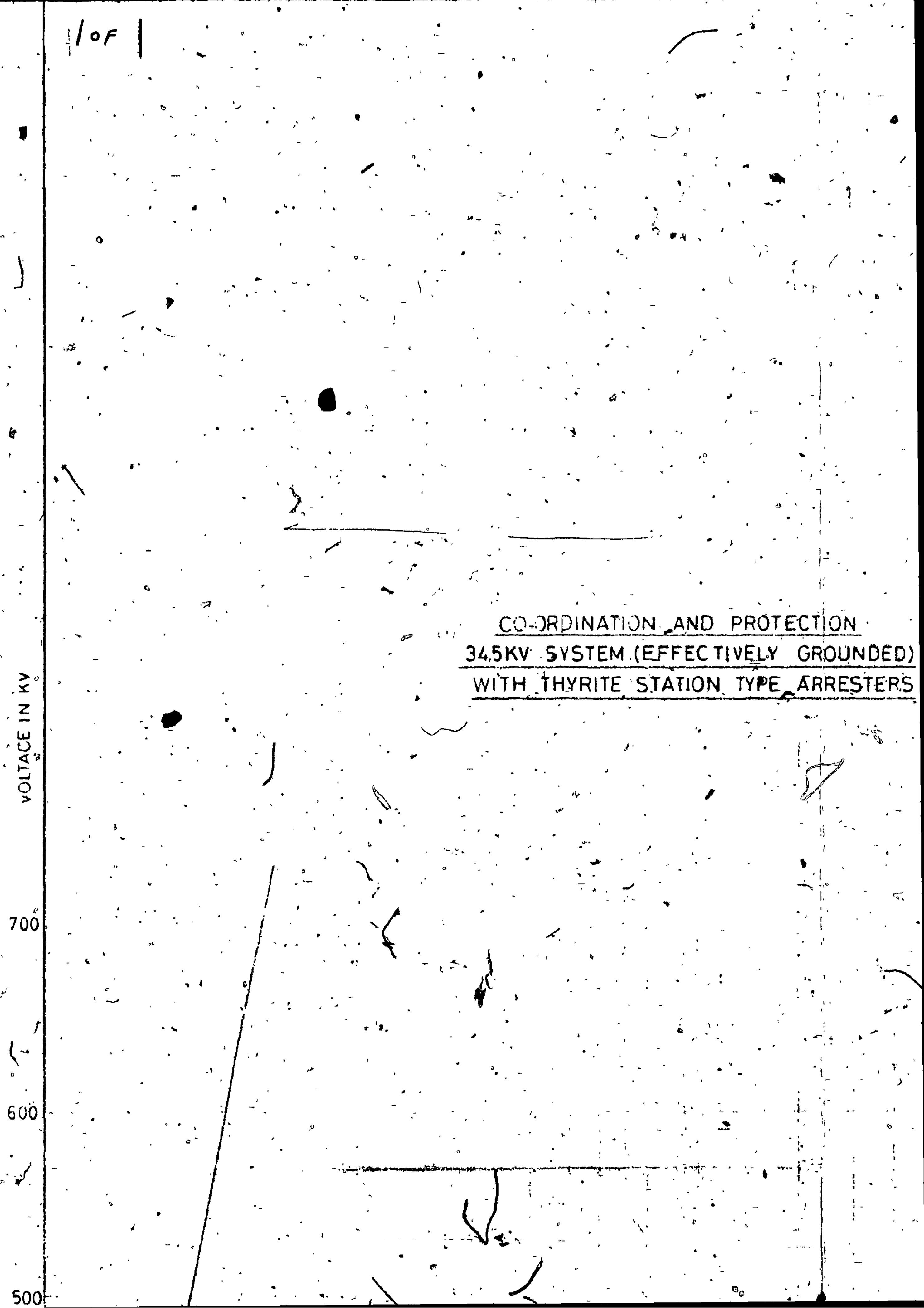
6) FOR THE CHOPPED WAVE TEST THE MINIMUM TIME TO SPARKOVER IS TAKEN 3µS

7) I.F.C. = IMPULSE FLASHOVER CHARACTERISTICS (POS. POLARITY)

N AND PROTECTION 115 KV SYSTEM

4 OF 4

1 OF 1



CO-ORDINATION AND PROTECTION
345KV SYSTEM (EFFECTIVELY GROUNDED)
WITH THYRITE STATION TYPE ARRESTERS

ROTECTION
VELY GROUNDED)
TYPE ARRESTERS

NOTES: 1) LIGHTNING ARRESTER IR VOLTAGES BASED ON CURRENT WAVE OF 8 x 20 µS

2) B.I.L. = B.I.L AND FULL WAVE TEST OF TRANSFORMER

3) S.O.V. = SPARK-OVER VOLTAGE

4) MINIMUM 60 Hz SPARKOVER IN KV. RMS IS 1 1/2 TIME THE ARRESTER RATING

5) FOR THE CHOPPED WAVE TEST THE MIN. TIME TO SPARKOVER IS TAKEN 3 µS.

6) I.F.C. = IMPULSE FLASHOVER CHARACTERISTICS (POS. POLARITY)

7) M.P.M. = MINIMUM PROTECTION MARGIN

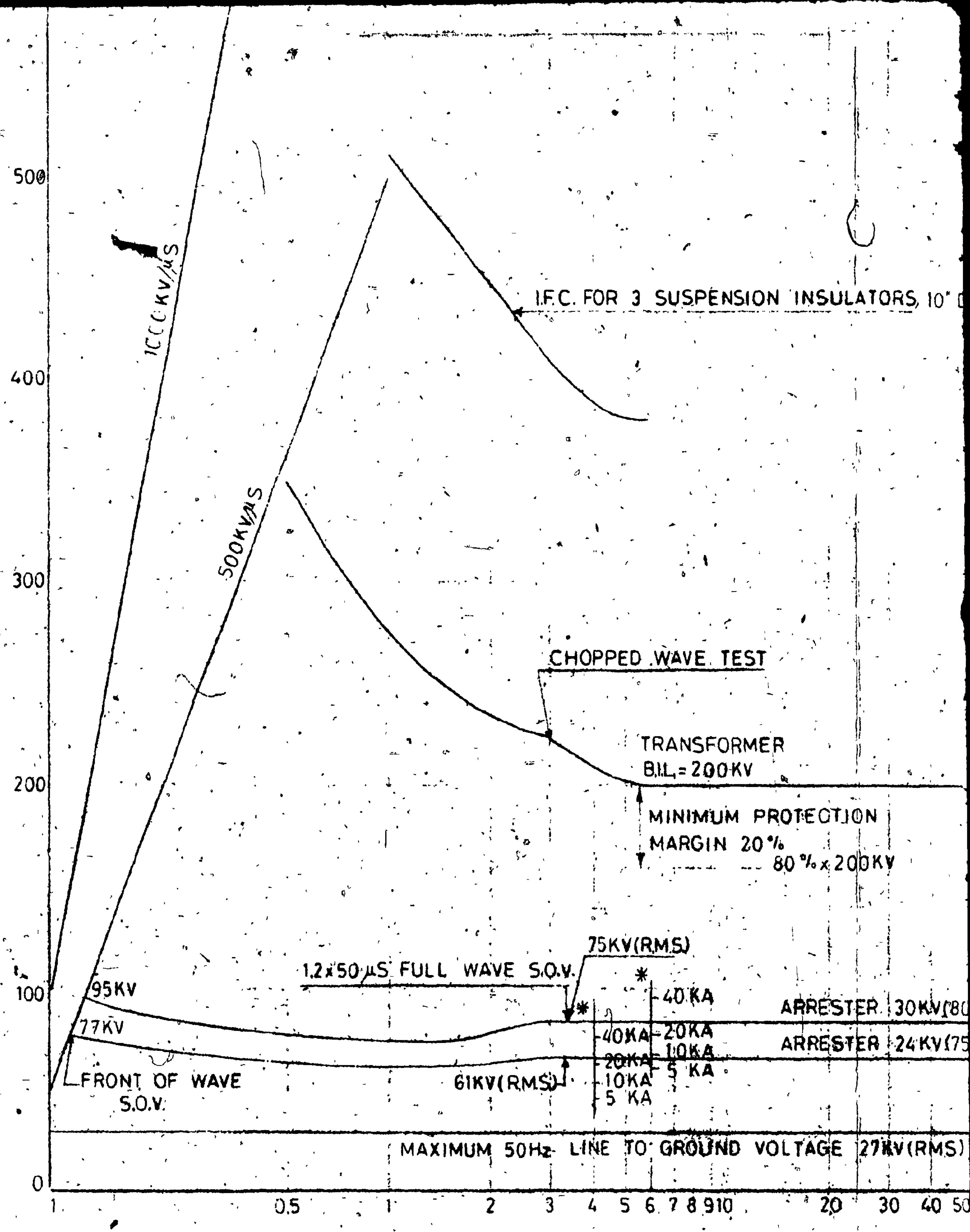


FIG II.3.4. CO-ORDINATION AND PROTECTIO

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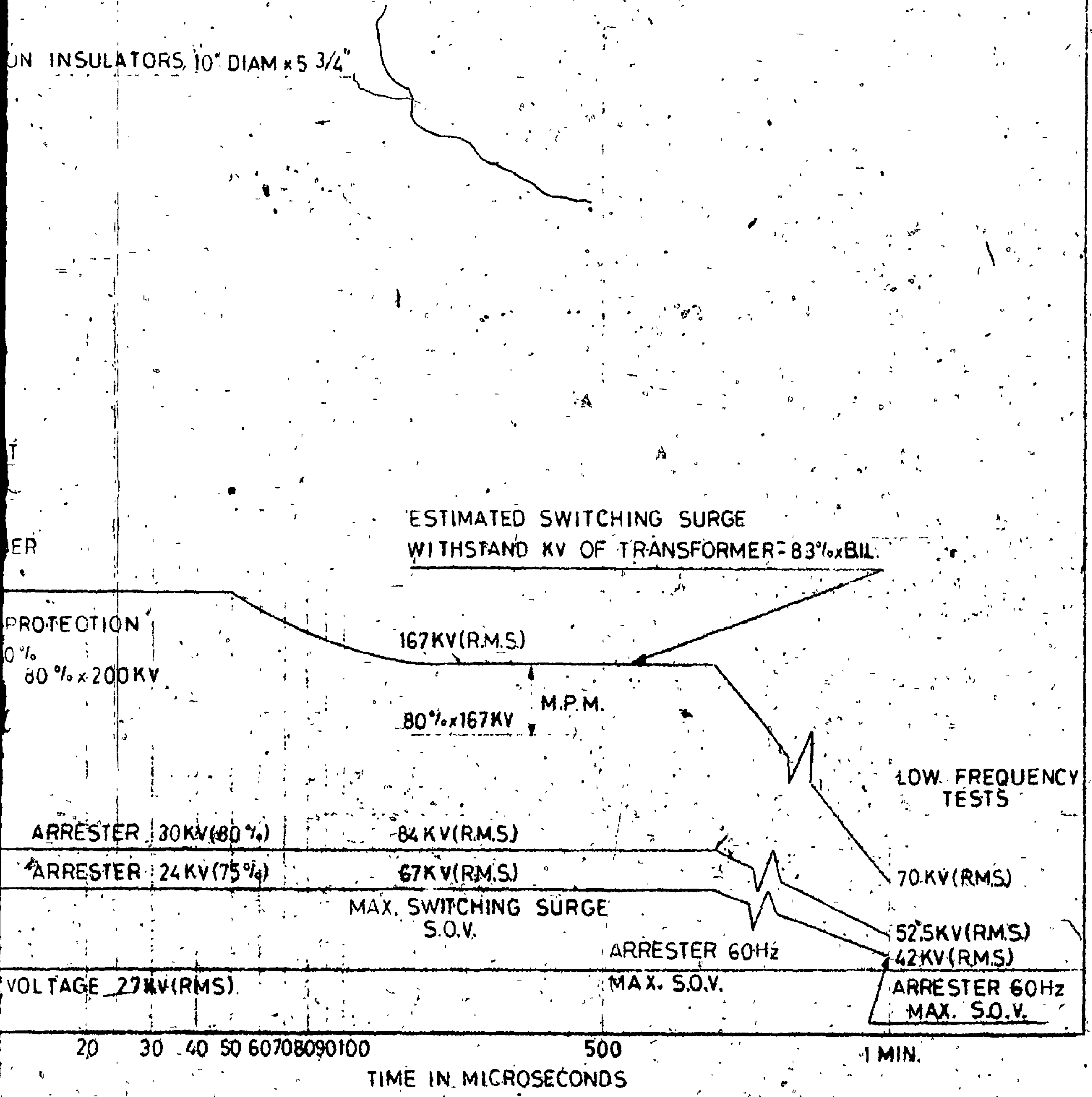
5) FOR THE CHOPPED WAVE TEST THE MIN. TIME TO SPARKOVER IS TAKEN 3μS.

6) I.F.C = IMPULSE FLASHOVER CHARACTERISTICS (POS. POLARITY)

7) M.P.M.= MINIMUM PROTECTION MARGIN



TION AND PROTECTION 34.5KV SYSTEM

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