# DESIGN AND DEVELOPMENT OF 150 KV PORTABLE IMPULSE GENERATOR

A DISSERTATION
*submitted in partial fulfilment of the*
*requirements for the award of the degree*
*of*
MASTER OF ENGINEERING
*in*
ELECTRICAL ENGINEERING
(Power System Engg.)

*By*

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# CERTIFICATE

Certified that the Dissertation entitled '' Design and Development of 150 KV Portable Impulse Generator'' which is being submitted by Mr. D.K.Goel in Partial fulfilment for the award of the degree Master of Engineering in Electrical Engineering ( Power System Engineering) of the University of Roorkee,Roorkee is a record of the students own work carried out by him under our supervision and Guidance. The matter embodied in this dissertation has not been submitted for the award of any other Degree or Diploma. This is to further certify that he has worked for a period of five.. months...... from.15th..Jan.1980. to.11th.June.1980.for dessertation at this University.

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# FOREWORD

The advances made within the realm of Electrical Engineering during the twentieth century have been phenomenal. Tremendous advances and increased power demand spurred more and more power transfer at longer distances and hence at higher voltage. In India 400 KV lines are already in operation and it is estimated that up to the end of sixth five years plan about 900 Km length of 400 KV line will be in operation.

Thus with large number of high voltage and extra high voltage transmission lines being constructed all over the country as part of large power developments programme, expensive electrical equipments are put into service. Consequently it has become necessary to ensure that such equipments are capable of withstanding the overvoltage met with in service due to lightning and switching transient. In order to simulate these over voltage conditions all the power transmission and distribution apparatus are frequently subjected to high voltage impulse or surge tests which are performed by the impulse generator.

Thus impulse generator is used to study the insulation behaviour under ~~all~~ certain conditions which the apparatus is likely to encounter. Tests are also made with higher impulse voltage than normal working voltage to determine factor of safety over working conditions. Impulse generator simulates the lightning and switching impulses for research and development purpose.

To make an exercise in using the latest design for developing a 150 KV impulse generator which could be easily accomodated in existing H.V. lab. and could be used for training, testing, research and development; I have undertaken this particular job.

The arrangement of the thesis is as follows: first the definitions, which are usually considered to be most irksome and exasperating adjunct of any literature, have been dealt with. After considering the theoretical analysis of impulse generator the evolution of multistage generator has been described. The operation of multistage discharge circuit is analysed and the photographs of various components made for 150 KV impulse generator are shown. A full photograph of complete 150 KV impulse generator assembly constracted is also attached. In addition some of the auxiliary equipments needed are briefly discussed. The thesis concludes with discussion. Bibliography also appears at the end of the thesis.

## SUMMARY

High impulse voltages are required mainly for testing purposes to simulate over voltages that occur in power systems due to lightning and switching. Lack of well written literature about impulse generator has been a handicap. Here the theoretical analysis of impulse generator circuit has been discussed. The evolution of modern multistage generator circuit was studied and the design of 150 KV impulse generator was decided on the basis of latest type of impulse generator.

Since the components of impulse generator i.e. spark gap assembly, non inductive resistances, charging circuit triggering circuit, connections etc. have special specifications, it was necessary to design and fabricate some of them. The resistance has been designed and fabricated with non inductive winding to have minimum inductance. Spark gap assembly has been designed and fabricated to have 1.5 cm axial movement and at the same time there is provision that spheres can be taken out for cleaning and polishing purpose. The sparking plug in trigatron gap assembly can also be taken out easily for cleaning purpose.

The charging sets for trigatron triggering device as well as for charging the impulse generator capacitors have been designed and fabricated separately. The thesis contains the details about all these components as well as total assembly of impulse generator, which is made as a portable unit. The commissioning and testing of impulse generator is also discussed there in.

# CONTENTS

## INTRODUCTION

Despite the great strides made in equipment design in recent years, the weak link in the chain of reliability is still the insulation. The importance of sound electrical equipments has been recognised from the early days of electricity. The necessity for improved testing was emphasized by damage caused by flashover of equipment by lightning strokes, transients caused by switching surges etc. etc. As the years rolled by and the electrical industries expanded, various machines, transmission lines and cables become larger, methods of impulse voltage testing improved and test equipment itself grew larger to keep pace with the equipment that had to be tested.

There is an increasing demand for impulse voltage tests, particularly when it is directly employed in the transmission of power. Impulse voltage tests are recommended with the object of determining the effect of voltage surges of short duration on electrical installations and on their individual parts because to ensure satisfactory operation, power transmission equipment must successfully withstand not only the working voltage but also overvoltages to which it may be subjected as a result of switching operations and lightning strokes. From the knowledge already obtained of the nature and magnitude of the surges occuring in practice it is now possible to specify appropriate impulse strengths for the insulation of the apparatus. Impulse voltage testing is concerned with the investigation of the electric strength of such new equipment. It is apparant that, as the knowledge of surge phenomena is increasing the purpose of testing electrical apparatus is better served by tests which are more appropriate to the characteritics of the surges to be guarded against, and thds impulse voltage tests are replacing some of alternating over voltage tests. Although, of course the latter will be required perhaps in a modified form as a check on the characteristics of apparatus when power frequency voltages are applied.

The testing and certification of power apparatus have gained considerable recognition and importance during last few years. The reliability of a power system is very much linked with the apparatus and equipment used. It is therefore essential that the power apparatus are tested in a recognized laboratory and certified that the design incorporated in power apparatus adequately meets the requirement of standards. This is a well recognized approach abroad and in fact no manufacturer markets his product unless this step has been completed. In the past lack of laboratory facilities has been the major constraint. At present a host of H.V. laboratories are coming up to perform various impulse voltage and other tests. Really speaking the performance of impulse tests on power transmission and distribution equipments, probably absorbs a large proportion of total effort in the field of high voltage technology.

The high voltage laboratory equipments are very costly and in addition requires big and expensive building to accommodate them. It was decided to build 150 KV impulse generator as one of the equipment which could be used for training, testing, research and development purposes. D.C. supplies made, i.e. 30 KV and 11 KV, are used for charging impulse generator capacitors and trigatron triggering device respectively, in addition these can be used for other purposes as well.

## 2 DEFINATIONS AND STANDARDS OF WAVE SHAPE TERMS

Impulse is the properly employed term to denote a controlled surge, such as is obtainable in standard form from an impulse generator. To understand properly the concepts of literature concerning impulse generator, it is essential to get familiar with the basic terms. Hence in this chapter I would like to give an idea of most of the terms.

### 2.1 IMPULSE VOLTAGE

Impulse voltage is a unidirectional voltage which, without appreciable oscillations rises rapidly to a maximum value and falls more or less rapidly to zero. Ideally it approximates a double exponential form. Other forms, such as damped oscillatory impulse and impulses which approximate a rectangular form, are sometimes used for special purposes.

### 2.2 LIGHTNING AND SWITCHING IMPULSE

An arbitrary distinction is made between lightning impulses and switching impulses on the basis of the duration of the wave front Impulses with front durations from ~~less than~~ one up to some tens of microseconds are in general considered as lightning impulses a those having front durations of some tens up to hundreds of microseconds, as switching impulses. In general, switching impuls are characterized by considerably longer total durations than those of lightning impulses.

## 2.3 PEAK VALUE

The maximum value is called the peak value of the impulse and the impulse voltage is specified by this value.

## 2.4 FULL IMPULSE VOLTAGE

If an impulse voltage develops without causing flashover or puncture it is called a full impulse voltage.

## 2.5 CHOPIED IMPULSE VOLTAGE

If flashover or puncture occurs, thus causing a sudden collapse of the impulse voltage, it is called a chopped impulse voltage. The collapse can occur on the wavefront, at the peak or on the tail.

## 2.6 WAVE FRONT

The wave front of an impulse voltage is the rising portion of the voltage time characteristic of the impulse voltage.

## 2.7 WAVE TAIL

The wave tail of an impulse voltage is the falling portion of the voltage time characteristic of the impulse voltage.

## 2.8 DEFINITION APPLICABLE ONLY TO FULL IMPULSES[9]

For these definitions we will refer to fig. 2.8

### 2.8.1 Virtual Front Duration $T_1$

The virtual front duration $T_1$ is defined as 1.67 times the time

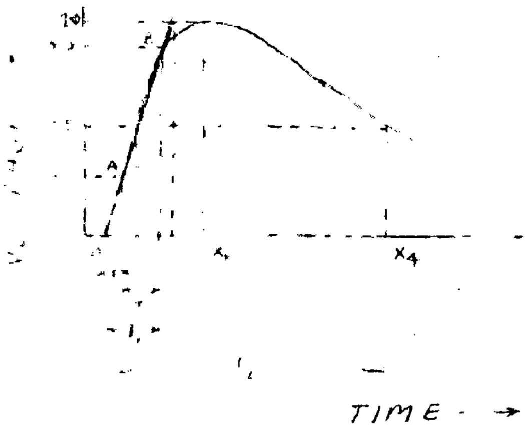

FIG 2.8 : IMPULSE WAVE SHAPE

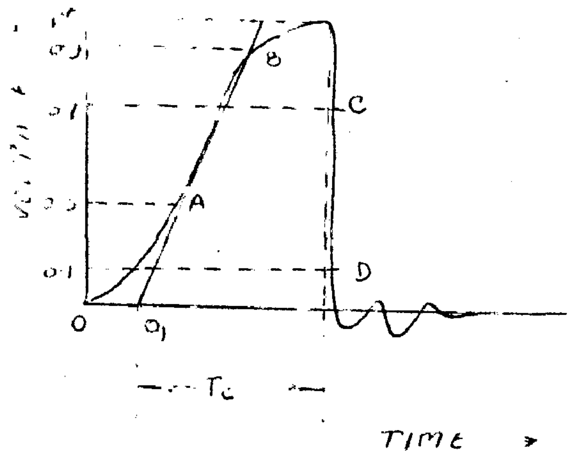

FIG 2.9 a : IMPULSE VOLTAGE CHOPPED ON THE FRONT

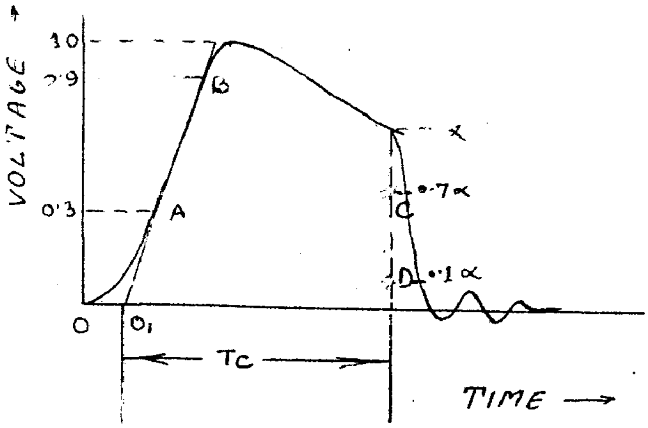

FIG 2.9 b : IMPULSE VOLTAGE CHOPPED ON THE TAIL

interval T between the instants when the impulse is 30% and 90% of the peak value. If oscillations are present on the wave front, the points A and B should be taken on the mean curve drawn through these oscillations.

### 2.8.2 Virtual Origin of An Impulse

The virtual origin of an impulse is defined as the instant preceeding that corresponding to the point A by a time 0.3 $T_1$. For oscillograms having linear time sweeps, this is the intersection with X axis of a straight line drawn through the reference point A and B on the wave front.

### 2.8.3 Virtual Time To Half Value $T_2$

The virtual time to half value $T_2$ of an impulse is the time interval between the virtual origin and the instant of the tail, when the voltage has decreased to half of the peak value.

### 2.8.4 Virtual Steepness of Wave Front

The virtual steepness of wavefront of an impulse voltage is the average rate of rise of voltage measured between the points on the wave front where the voltage is 30% and 90% of peak value respectively.

### 2.8.5 Indian Standards For Lightning and Switching Impulse

| | | |
|---|---|---|
| Standard Lightning Impulse | | 1.2/50 μs |
| Tolerances: | Peak value | ± 3% |
| | Front time | ± 30% |

| | | |
|---|---|---|
| Tail time (Time to half value) | | ± 20% |
| Standard Switching Impulse | | 250/2500 μs |
| Tolerances: | Peak value | ± 3% |
| | Front time | ± 20% |
| Tail time (Time to half value) | | ± 60% |

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## 2.9 DEFINITIONS APPLICABLE ONLY TO CHOPPED IMPULSES

Ideally the chopping of an impulse is characterised by an initial discontinuity which decreases the voltage. The voltage than continues to decrease to zero or nearly zero, either directly or via oscillations.

### 2.9.1 Virtual Time of Voltage Collapse During Chopping

The virtual time of voltage collapse during chopping is 1.67 times the time interval between points C and D (see Fig.2.9 'a) and 2.9b)

### 2.9.2 Instant Of Chopping

The instant of chopping is the instant when the initial discontinuity occurs.

### 2.9.3 Virtual Time $T_c$ to Chopping

The virtual time $T_c$ to chopping is the time interval between the virtual origin O, and the virtual instant of chopping.

### 2.9.4 Virtual Steepness of Voltage During Chopping

The virtual steepness during chopping is the quotient of the estimated voltage at the instant of chopping and virtual time of voltage collapse.

## 2.10 IMPULSE FLASH OVER VOLTAGE

In this we have two categories as follows:

### 2.10.1 50 Percent Impulse Flash Over Voltage

The 50 percent impulse flashover voltage is the peak value of that impulse voltage which causes flashover of the object under test for about half the number of applied impulses. Flashover occurs at an instant subsequent to the attainment of the peak value. The value of the impulse flashover voltage depends on the polarity, the wavefront and the wavetail of the applied impulse voltage.

### 2.10.2 In Excess of The 50 Percent Impulse Flash Over Voltage

The impulse flashover voltage for flashover on the wave-tail is the peak value of the impulse voltage which causes flashover on the wave tail. Similarly impulse flashover voltage for flashover on the wavefront is the value of impulse voltage at the instant of flashover on the wavefront.

## 2.11 IMPULSE PUNCTURE VOLTAGE

Impulse puncture voltage is the peak value of that impulse voltage which causes puncture of the object under test when puncture occurs on the wave tail and is the value of the voltage at the instant of puncture when puncture occurs on wavefront.

## 2.12 IMPULSE RATIO FOR FLASHOVER

It is the ratio of the impulse flashover voltage to the peak value of the power frequency flashover voltage.

### 2.13 MINIMUM IMPULSE RATIO

For a given wave shape the minimum impulse ratio is the ratio obtained from a 50% impulse flashover voltage.

The impulse ratio is not constant for any particular object, but depends upon the shape and polarity of the impulse voltage the characteristics of which should be specified when impulse ratios are quoted.

### 2.14 IMPULSE RATIO FOR PUNCTURE

The impulse ratio for puncture is the ratio of the impulse puncture voltage to the peak value of power frequency puncture voltage.

The impulse ratio is not a constant for any particular object but depends upon the shape, and manner of application of the impulse voltage and on the manner of application of the power frequency voltage. Information on these points should be given when impulse ratios are quoted.

### 2.15 TIME TO FLASH OVER AND TIME TO PUNCTURE

The time to flashover and time to puncture are the durations of the impulse voltage prior to being chopped by flashover or puncture respectively. For the sake of convenience, the nominal times are measured from the nominal start of the wage to the instant when chopping occurs.

## 2.16 TIME LAG OF FLASHOVER[9]

The expression'time lag of flashover' is some times used; it is generally the time from the instant when the peak value of the power frequency flashover voltage is reached on the wavefront to the occurence of the impulse flashover.

## OVER VOLTAGES

Any time dependent voltage between two points with peak value exceeding the normal working peak value between them is known as over voltage. Over voltages are always transitory phenomena. A rough distinction may be made between highly damped overvoltages of relatively short duration and undamped or weakly damped overvoltages of relatively long duration. The border line between these two groups can't be clearly fixed.

In addition to power frequency voltage stress under normal operating conditions, the equipment has to withstand following classes of over voltages:

a. Temporary over voltages
b. Switching over voltage and
c. Lightning overvoltages

## 2.17 DIELECTRIC TEST

The following types of dielectric tests are generally considered

a. Short duration (one minute) power frequency tests.
b. Long duration power frequency tests

c. Switching impulse tests and

d. Lightning impulse tests.

Power frequency tests are intended to verify, as far as practicable, that there will be no significant deterioration of the insulator due to partial discharges during the expected working life of equipment and that in the most severe conditions the insulator is not liable to thermal instability. Long duration power frequency tests intended to demonstrate the behaviour of equipment with respect to ageing of internal insulation or to contamination of external insulation. The switching and lightning impulse tests are needed to check the performance under switching and lightning overvoltages.

## 2.18 STANDARD INSULATION LEVELS FOR EQUIPMENT

The standardized values of the highest voltage for equipment are divided into three ranges:

Range A: above 1 KV and less than 52 KV.

Range B: from 52 KV to less than 300 KV, and

Range C: 300 KV and above.

The selection of dielectric tests is different in voltage range 'A','B' and C.

For range A and B the performance under power frequency over voltage, temporary overvoltages and switching over voltages is checked in general by a short duration power frequency test. The performance under lightning overvoltage is checked by a lightning impulse test. Aging of internal insulation and contamination of external insulation require long duration power frequency tests.

For range C the performance under power frequency operating voltages and temporary overvoltages is checked by long duration power frequency tests, aiming at demonstrating the suitability of the equipment with respect either to ageing or to contamination, according to which is the case. The performance under switching and lightning overvoltages is checked by switching and lightning impulse tests.

Following section shows the recommended values of the short duration power frequency test voltages and of the switching and lightning impulse withstand voltages; for long duration power frequency tests, the general guidance is given in I.S.2165-1977.

All specifications concerning the values of the test voltages, as well as the test procedure and the test conditions, should be decided by the relevant equipment Committee in agreement with these indications and conforming to IS 2071-1974.

### 2.18.1 Standard Insulation Levels For Range 'A'

The standard insulation levels are given in table 1 below:

**TABLE-1:** STANDARD INSULATION LEVEL FOR 1 KV<Um<52KV 'ii'

| Highest Voltage for equipment Um(rms) KV | Rated Lightning Impulse withstand voltage (peak) KV | | Rated Power frequency short duration withstand voltage (rms) KV |
|---|---|---|---|
| | List 1 | List 2 | |
| 3.6 | 20 | 40 | 10 |
| 7.2 | 40 | 60 | 20 |
| 12 | 60 | 75 | 28 |
| 17.5 | 75 | 95 | 38 |
| 24 | 95 | 125 | 50 |
| 36 | 145 | 170 | 70 |

The choice between list 1 and list 2 should be made by considering the degree of exposure to lightning and switching over voltages, the type of system neutral earthing and, where applicable, the type of over voltage protective device.

2.18.2 Standard Insulation Levels For Range B

The standard insulation levels are given in table 2 below:

**TABLE 2:** STANDARD INSULATION LEVEL FOR 52 KV<Um<300 KV

| Highest voltage for equipment Um(rms) (KV) | Rated lightning impulse withstand voltage (peak) (KV) | Rated power frequency short duration withstand voltage (rms) (KV) |
|---|---|---|
| 52 | 250 | 95 |
| 72.5 | 325 | 140 |
| 123 | 450,550 | 185,230 |
| 145 | 450,550,650 | 185,230,275 |
| 170 | 550,650,750 | 230,275,325 |
| 170 | 650,750,850,950,1050 | 275,325,360,395,46 |

From 145 KV upwards, two or more lower values of insulation are given. The choice of a lower value of insulation supposes that the equipment is adequately protected against surges.

### 2.18.3 Standard Insulation Levels For Range C

The standard insulation levels are given in table 3 below:

TABLE 3: STANDARD INSULATION LEVELS FOR Um > 300 KV

| Higest voltage for equipment Um (rms) KV | Rated switching Impulse withstand voltage (Peak) KV | Rated lightning impulse withstand voltage (peak) KV |
|---|---|---|
| 420 | 950 | 1050,1175 |
| | 1050 | 1175,1300,1425 |
| 525 | 1050 | 1175,1300,1425 |
| | 1175 | 1300,1425,1550 |
| 765 | 1300 | 1425,1550,1800 |
| | 1425 | 1550,1800,2100 |
| | 1550 | 1800,1950,2400 |

As the table 3 shows several insulation levels may exist in the same system, appropriate to installations situated in different locations or to various equipment situated in the same insulation. The selection of insulation level in relation to the particular conditions of the installation can be had from Indian Standards.

(IS 3716 – 1978)

## 3 THEORETICAL ANALYSIS OF IMPULSE GENERATOR CIRCUIT

It is usually necessary to analyse the circuit performance theoretically before we jump to the practical aspects. A single stage impulse generator circuit which corresponds approximately with practical conditions is shown in Fig. 3.1.

$C_1$- Discharging capacitor of impulse generator
$L_1$- Inherent inductance of generator
$R_1$- Resistance for control of wave front
$R_2$ or $R'_2$- Resistance for control of wave tail
$L_2$ - external inductance of load and connections
$C_2$ - load capacitance

There are other variants not amenable to practical considerations If the circuit of figure 3.1 is examined, it will be found that the expression for the load side voltage is an equation of the forth order, and in that form is little more than of academic interest, although quartic differential equation can be solved by laborious methods. For simplicity, hence, if $L_2$ is made zero or in effect combined with $L_1$, the equation is reduced to one involving no power higher than the third.

Let us presume, then, that $L_2$ is zero and $R_2$ is in its position $R'_2$ (shown dotted). The voltage across the load $C_2$ is then across the parallel $R_2C_2$ branch, which combined give.

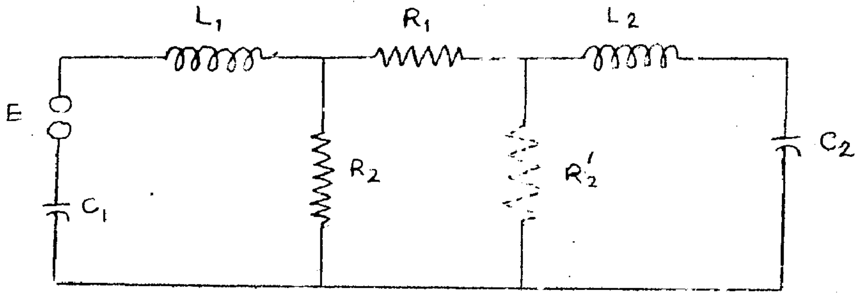


FIG 3·1 : THE EQUIVALENT IMPULSE VOLTAGE TESTING CIRCUIT.

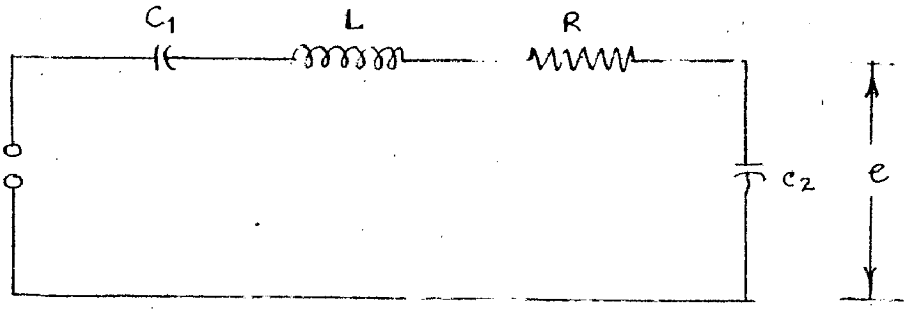


FIG 3·2 : SIMPLIFIED CIRCUIT OF IMPULSE GENERATOR AND LOAD FOR CALCULATION OF WAVE FRONT.

an impedance $Z_2 = \frac{R_2}{1+PC_2R_2}$

The total circuit impedance is then

$$Z = \frac{1}{PC_1} + PL_1 + R_1 + \frac{R_2}{1+PC_2R_2}$$

$$= \frac{P^3C_1C_2R_2L_1 + P^2(C_1L_1 + C_1C_2\overset{R_2}{\cancel{R_1}}L_2 + P \quad C_1R_1 + C_1R_2 + C_2R_2 \; +1}{P\,C_1(1 + PC_2R_2)}$$

...(1)

Voltage across load $e = \frac{Z_2 . E}{Z}$

$$= \frac{P\,C_1R_2E}{P^3C_1C_2R_2L_1 + P^2(C_1L_1 + C_1C_2R_1R_2) + P(C_1R_1 + C_1R_2 + C_2R_2) + 1}$$

For evaluating the critical resistance $R_1$ necessary to supress any oscillations in the circuit, $R_2$ can be neglected. Because of this omission the results of calculations are slightly pessimistic as $R_2$ will absorb energy and will therefore tend to prevent oscillation in the circuit.

Then

$$e = \frac{\cancel{P}C_1}{P^3C_1C_2L_1 + P^2C_1C_2R_1 + P(C_1 + C_2)} . E$$

$$= \frac{C_1}{P^2C_1C_2L_1 + P\,C_1C_2R_1 + (C_1 + C_2)} . E$$

For critical damping resistance

$$(C_1C_2R_1)^2 = 4.\ C_1C_2L_1.(C_1+C_2)$$

$$R_1 = 2\sqrt{\frac{L_1(C_1+C_2)}{C_1C_2}}$$

hence $R_1$ must be greater than this value.

If $R_2$ is on generator side of $R_1$, i.e. in the position $R_2$ in Fig. 3.1 the parameters in eqn.(1) are slightly different but the equation is of the same form. Even more complicated representations have been examined by so many persons but the resulting expressions are of little more than academic or mathematical interest especially as the stray capacitances and inductances are distributed throughout the circuit and no precise numerical values can be designed to them.

In practice it is convenient to simplify the calculations and four cases are examined in the following sections.

## 3.1 NON INDUCTIVE CIRCUIT

Now let us consider the same circuit shown in Fig.3.1 to be non inductive one, then $L_1$ and $L_2$ both be zero. Considerfirst when wave tail resister $R_2$ is one the load side of $R_1$ i.e. in $R_2'$ position (shown dotted). The Laplace transform of output voltage is given by expression

$$\overset{*}{e(s)} = \frac{E}{S} \cdot \frac{Z_2}{Z_1 + Z_2}$$

where $Z_1 = \frac{1}{C_1S} + R_1,$

$$Z_2 = \frac{R_2/C_2S}{R_2 + \frac{1}{C_2S}}$$

By substitution: $e(s) = \frac{E}{S} \cdot \frac{R_2/(1+R_2C_2S)}{R_1 + \frac{1}{C_1S} + \frac{R_2}{R_2C_2S} + 1}$

$$= \frac{E}{S} \frac{R_2}{(R_1 + 1/C_1S)\ (1 + R_2C_2S)\ + R_2}$$

$$= \frac{E}{R_1C_2} \frac{1}{S^2 + (\frac{1}{R_1C_1} + \frac{1}{R_2C_2} + \frac{1}{R_1C_2})S + \frac{1}{R_1R_2C_1C_2}}$$

or $e(s) = \frac{E}{R_1C_2} \cdot \frac{1}{S^2 + as + b}$

where $a = (\frac{1}{R_1C_1} + \frac{1}{R_2C_2} + \frac{1}{R_1C_2})$

and $b = \frac{1}{R_1R_2C_1C_2}$

$$e(s) = \frac{E}{R_1C_1} \cdot \frac{1}{(\alpha_1 - \alpha_2)} \left[ \frac{1}{S-\alpha_1} - \frac{1}{S-\alpha_2} \right]$$

where $\alpha_1$ and $\alpha_2$ are the roots of the equation $S^2 + as+b=0$ and both will be negative. Hence we get

---

* S and P have been used interchangably

$$e(t) = \frac{E}{R_1C_2(\alpha_1-\alpha_2)} \cdot ( e^{+\alpha_1 t} - e^{+\alpha_2 t} )$$

The actual time for the voltage e to rise to its peak value is given by

$$t_1 = \frac{\log_e (\alpha_2/\alpha_1)}{(\alpha_1 - \alpha_2)}$$

and the voltage effeciency, $\eta$, of the generator is given by

$$e_{max}/E \quad \text{i.e.} \quad \eta = \frac{e^{\alpha_1 t} - e^{\alpha_2 t}}{R_1C_2(\alpha_1 - \alpha_2)}$$

The values of $t_1$ and $\eta$ will be determined in the same manner as when $R_2$ is on the generator side of $R_1$.

The position of $R_1$ may sometimes be of great practical importance. It will be apparant from figure 3.1 that when $R_2$ is on the load side of $R_1$ the resistor $R_1$ and $R_2$ form a potential divider and the output voltage is reduced. No such reduction takes place when $R_2$ is on generator side of $R_1$.

When $R_2$ is on load side of $R_1$ the effeciency is very low for small values of $C_2/C_1$, but when the circuit is so arranged that $R_2$ is on generator side of $R_1$ the effeciency is highest when the load is zero, and the latter circuit should be used wherever possible, especially when the resistance of $R_1$ is not very small when compared with that of $R_2$.

## 3.2 SIMPLIFIED NON OSCILLATORY INDUCTIVE CIRCUIT

If the tail of the wave is long as compared with its front ( as it is for 1/50 wave) then very little error result from ignoring the wave tail resistance when calculating the wave front duration.

The circuit is then simplified as shown in Fig. 3.2 in which

$$Z = \frac{1}{PC_1} + PL + R + \frac{1}{PC_2}$$

$$= \frac{C_2 + P^2C_1C_2L + PC_1C_2R + C_1}{P\,C_1C_2}$$

$$e = \frac{1}{PC_2}\,\frac{P.C_1C_2.\,E}{P^2C_1C_2L + P\,C_1C_2R + (C_1+C_2)}$$

$$= \frac{1}{C_2.L} \cdot \frac{1}{P^2+2\alpha P+\omega_.^2}\,E \quad \text{where } \alpha = \frac{R}{2L}\,, \quad \omega_.^2 = \frac{1}{LC}$$

$$e(t) = \frac{E}{C_2.L}\left[LC\left\{1-e^{-at}\,(1+at)\right\}\right]$$

If circuit in critically damped then

$$C_1^2C_2^2R^2 = \underline{4\,(C_1+C_2).\,C_1C_2L}$$

$$R = \sqrt{4\;\frac{C_1+C_2}{C_1C_2}\;.\,L}$$

Voltage across $C_2$ can then be expressed explicitly as follows:

$$e = \frac{CE}{C_2} \left\{ 1 - e^{-\frac{2t}{2L}} \left( 1 + \frac{R.t}{2L} \right) \right\} \qquad \left[ C = \frac{C_1 C_2}{C_1 C_2} \right]$$

If the inductance is reduced to zero now, then

$$e = \frac{CE}{C_2} \left( 1 - e^{-t/RC} \right)$$

now for standard wave

$$.3 = 1 - e^{-t_1/RC}$$

$$.9 = 1 - e^{+t_2/RC}$$

Therefore $t_1/RC = \log_e \frac{1}{0.7}$

and $t_2/RC = \log_e \frac{1}{0.1}$

Substracting $(t_2 - t_1) = RC \, (\log_e 7)$

$= 1.945 \, RC$

When circuit is critically damped then wavefront $= 2.\overset{5}{\cancel{1}}$ RC

With the impulse generators in normal industrial use, it is imperative that the total circuit inductance be as low as possible; and even then, with large capacitive loads, it is virtually impossible to attain normal wave fronts as low as $1 \mu s$ in duration.

In practice fairly accurate results are obtained by computing first the value of ~~$R_2$~~ $e_1$ required to make the circuit shown in Fig.3.1 non oscillatory when $R_2$ is absent. Then the value of $R_1$ ( if > $\sqrt{4L/C}$) required to give the desired wave front and finally the value of $R_2$ required to give required wave tail when $R_2$ is on generator side of $R_1$ in the circuit shown in Fig. 3.1.

## 4 MODERN MULTI STAGE GENERATOR CIRCUITS

A high voltage generator could be provided by a single capacitor charged from a high direct voltage source, but it is expensive hence we have to go in for multstage impulse generators. The additional advantage in multistage generator is that its capacitance as well as output can be varied depending upon connections

### 4.1 EVOLUTION OF MULTISTAGE GENERATOR CIRCUITS :

In 1915, Peek produced 200 KV just by employing a transformer to supply high alternating voltage for charging a condenser which was then used as a single stage impulse generato Since the impulse wave shape could not be measured it was calculated by means of whose validity was very questionable.[4] Moreover polarity of impulse was not readily controllable. In 1921, Grunewald described a single stage circuit in which an electrostatic generator charged a condenser, which was then discharged across a sparkgap in series with a load.

In 1923 Marx published a simple circuit which effectiv solved the fundamental problem by eleminating the need for any individual components to operate at more than a small fraction of the desired voltage output. The most convincing proof of th merit of his invention is that after the lapse of more than half a century, the circuit, without any basic change, is still invariably used, although important modifications have been made to the details.

Fig.4.1a shows Marx's so called 'voltage doubling circuit', fitted with a spark heating condenser $C_3$ across the

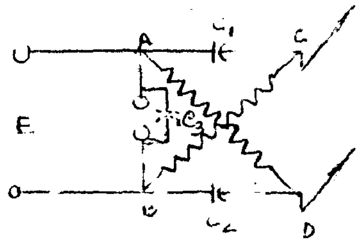


FIG 4·1a MARX ORIGINAL VOLTAGE DOUBLING CIRCUIT 4

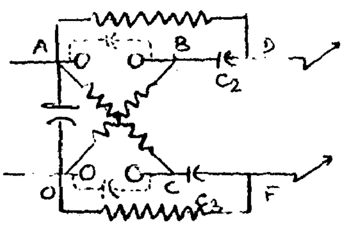


FIG 4·1 b MARX ORIGINAL VOLTAGE TRIPLING CKT.

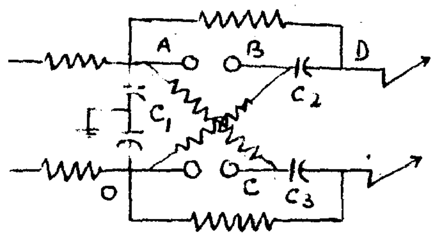


FIG 4·1 C MARX MODIFIED VOLTAGE TRIPLING CIRCUIT WITHOUT SPARK HEATING CONDENSERS.

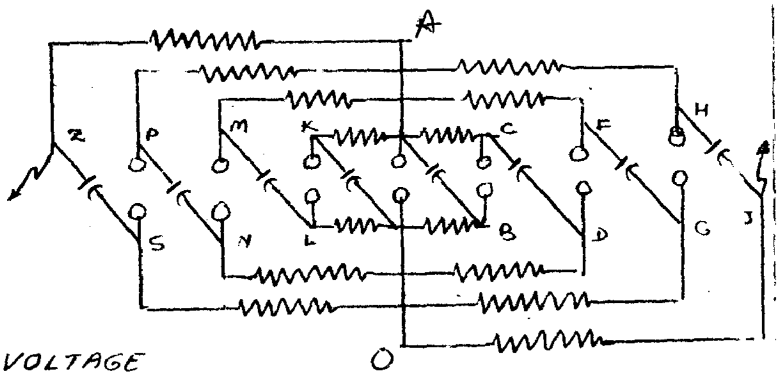


FIG 4·1 d MARX ORIGINAL MULTISTAGE GENERATOR DRAWN FOR 8 STAGES

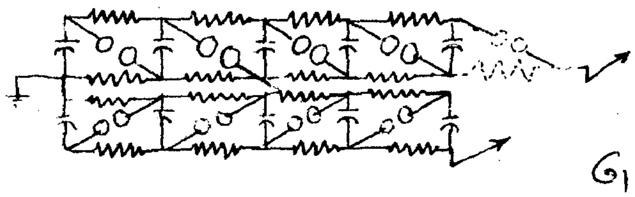


FIG 4·1 E : MARX'S ORIGINAL DOUBLE MULTI STAGE GENERATOR

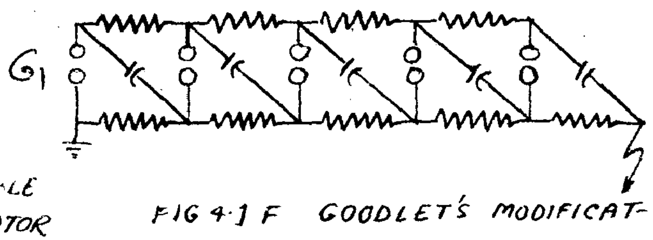


FIG 4·1 F GOODLET'S MODIFICATION OF MARX CIRCUIT sparkgap to accomplish the breakdown of sparkgap. The inherent disadvantage of this circuit is that there is at least a voltage V across the test specimen all the time.

Marx described voltage trippling circuit, and a little later to it he modified his circuit slightly. The new circuit had an earth point but no spark heating condensers (see Fig. 4.1b and 4.1c ).

The circuit of Fig. 4.1d shows Marx's 8 stage generato If the point O were earthed, the left hand side of the Fig. would show a four stage circuit with a steady voltage E is superimposed when the spark gap breaks down. The right hand side is an entirely different four stage circuit with the load earthed at the point J through the resistor connected between the points J and O during the charging period, an impulse voltage of 4E being applied to J when four right hand spark gaps breakdown.

If the point J is earthed the sparkgap GH must be arranged to fail first and the voltage on Z( initially E) rises to 8 E.

Fig. 4.1E illustrates a circuit which is noteworthy, it has an earth point and two quite separable circuits. The charging voltage is applied to the load but if Marx had taken only the right hand side of the circuit shown in Fig. 4.1 and connected the charging resisters in the manner shown in Fig. 4.1E, he would have had an entirely satisfactory circuit as shown in Fig. 4.1F with the load earthed during the chargir period and with the polarity of impulse voltage opposite to that of the charging voltage. This later circuit is described by Goodlet. Alternatively he could have added another gap and another resistor to the top half of the circuit of Fig. 4.1I (as shown dotted) and obtained another equally satisfactory circuit with the charging voltage and impulse voltage of same polarity.

Some of the points regarding Fig. 4.1F are that specimen is earthed during the charging period as well and hence there is no need of the spark gap to isolate the specimen from the generator. The polarity is reversed and both the spheres of first stage attain zero voltage during discharge.

In 1929 Peek gave a circuit[4] shown in Fig. 4.1G, it should be noted that resistor $R_4$ has to withstand the full output voltage.

Miner also published some comments on Marx circuit and extended the circuit shown in Fig. 4.1a to obtain two interconnected circuits which have been separated and redrawn in Fig. 4.1H; at a later date he added isolating gaps at the points p and Q.

Later Marx's original circuit has been extended by Mark and other investigators. Fig. 4.9 and 4.15 shows such two circuits[4]. Fig;4.15 shows a rather inconvenient way of short circuiting the load during the charging cycle. In Fig. 4.1 J the test specimen is separated from the impulse generator by spark gap G and specimen is earthed through a resistance $R_0$ during charging period. After breakdown of

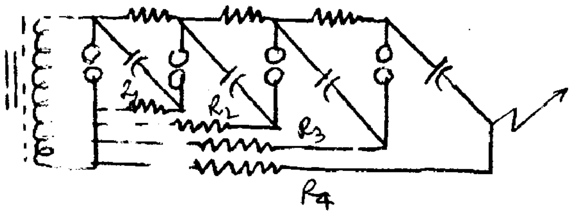


FIG 4·1G PEEK'S MULTI STAGE IMPULSE GENERATOR

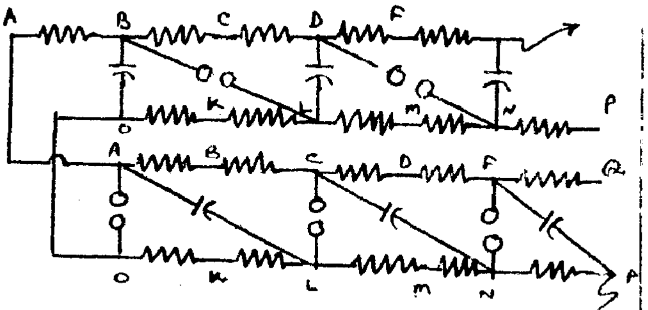


FIG 4·1H MINER'S EXTENSION OF MARX'S VOLTAGE DOUBLING CIRCUIT

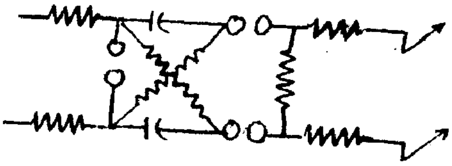


FIG 4·1I MARX'S LATER VOLTAGE DOUBLING CIRCUIT WITH ISOLATING GAPS AND LOAD EARTHED DURING DISCHARGING

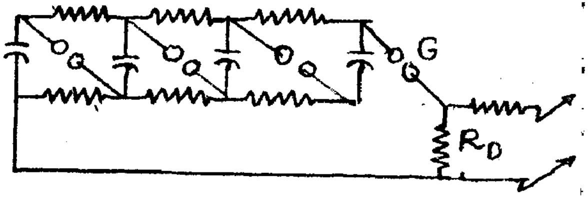


FIG 4·1J MARX'S LATER MULTI STAGE GENERATOR WITH ISOLATING GAP

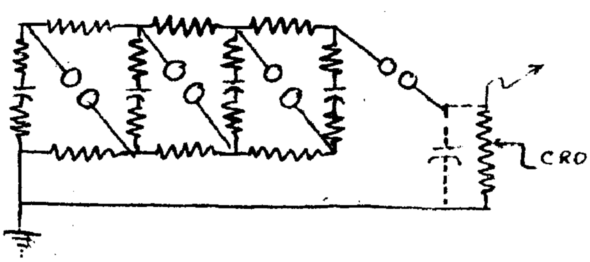


FIG 4·1K BOUWER'S MULTISTAGE CIRCUIT SHOWING DISTRIBUTED SERIES RESISTORS

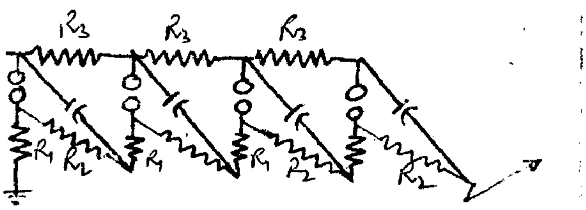


FIG 4·1L : MODERN MULTI STAGE CIRCUIT SHOWING DISTRIBUTED SERIES RESISTORS CONNECTED TO GIVE MAX. EFFECIENCY gap G impulse voltage appears across resistance $R_D$ and hence across specimen. The polarity, of course, across the specimen remains the same as that of charging voltage.

Bouwer also reviewed various impulse generator circuit.[4] Fig. 4.1K shows such a circuit, where the series resistors are distributed throughout the generator. This arrangement reduces the need for an external resistance capable of withstanding the full output voltage of the impulse generator. Usually half the resistance is placed outside the generator and the load while the remaining half is distributed among the generator stages. This helps to obtain a perfectly damped impulse wave form. The polarity remains unchanged.

A method of using distributed wave front resistors and also obtaining high effeciency has been developed by Edwards[4] and Scoles the circuit is shown in Fig. 4.1L. The essential feature is that $R_3$ is large compared with $R_1$ and $R_2$ is made as small as necessary to give the required wave tail. Under these conditions the current through $R_2$ does not flow through $R_1$ and so has no effect in reducing the initial generator output voltage, no matter how small $R_2$ or how large $R_1$ may be. The polarity is reversed. Thus this circuit includes all the good features of Fig. 4.1F and 4.1 K, and hence is widely used now a days.

## 4.2 CIRCUITS IN MODERN IMPULSE GENERATORS

Fig. 4.2a, 4.2b,and4.2c and 4.2d shows four different impulse generator circuits of modern multistage generators.[5,6,15] Let us discuss the different features of every type of circuits.

### a. Range of Impulse Voltage

The circuit 4.2a produces impulse voltage from 200 to 10,000 KV circuit 4.2b is used in ~~pm~~ impulse generators for producing a voltage impulse from 100 to 1600 KV. Circuits 4.2c and 4.2d are used for 200 to 1600 KV impulse voltage generator.

### b. Capacitors

Oil impregnated capacitors have higher working stress than Hollow cylinders of varnished paper with concentric metallic layers inserted at suitable intervals. The capacitors should be higher stability and low inductance. Circuits shown in Fig. 4.2 a and 4.2b use oil impregnated capacitors, impregnated with high grade castor oil. Circuits 4.2c and 4.2d use oil impregnated paper type capacitors with protruding foils.

### c. Resistors

Circuits shown in figure 4.2a and 4.2b use wire wound resistors cast in epoxy resin and equipped with plug in end contacts. The series parallel resistors are of identical size and can be used interchangeably. In control of some of the circuits

| | |
|---|---|
| $C_s$ | 100 kV impulse capacitor |
| $R_s$ | Series resistor |
| $R_{p1}$ | Parallel resistor for lighining impulse mode |
| $R_{p2}$ | Parallel resistor for switching impulse mode |
| $R_L$ | Charging resistor |
| $R_{pot}$ | Potential resistor |
| $R_{erd}$ | Discharge resistor |
| SF | Switching spark gap |
| ES | Grounding switch |
| PF | Parallel spark gap |
| $C_z$ | Fir[illegible] capacitor |

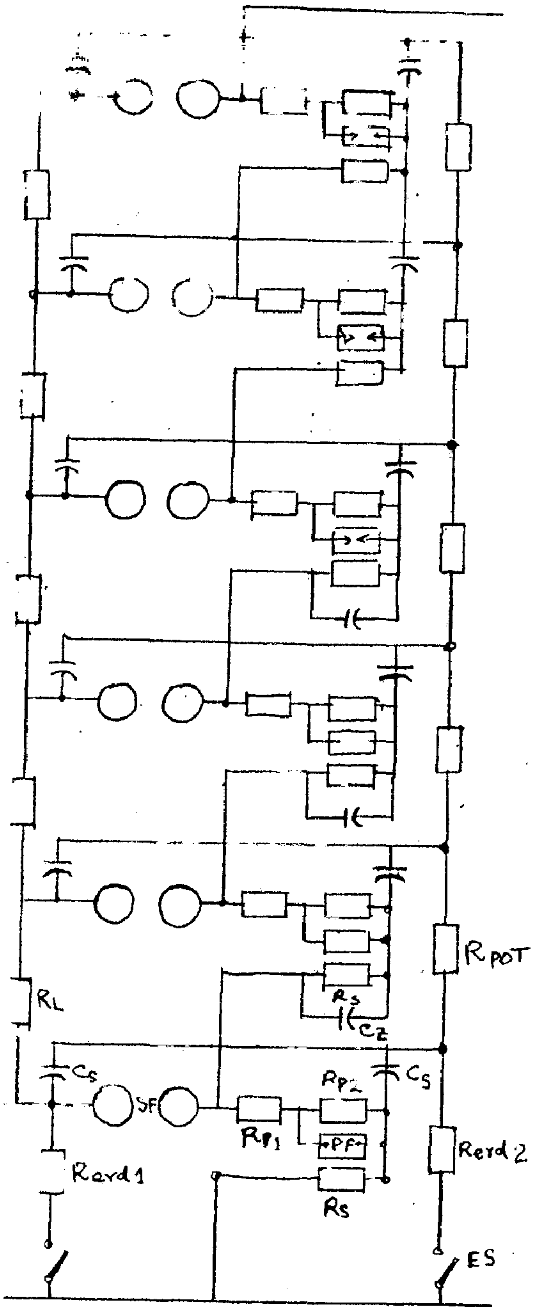
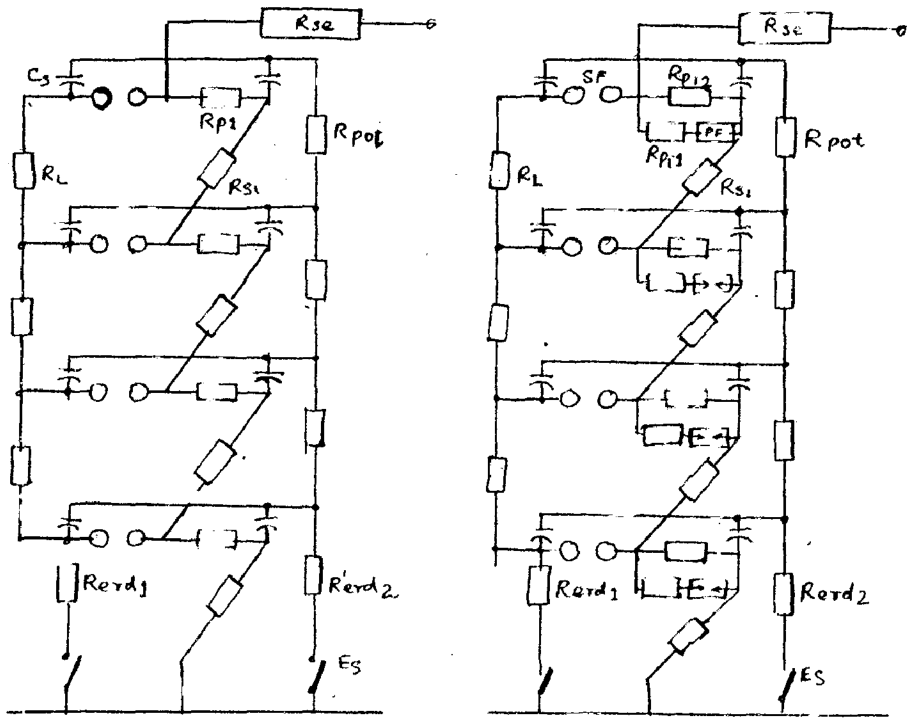
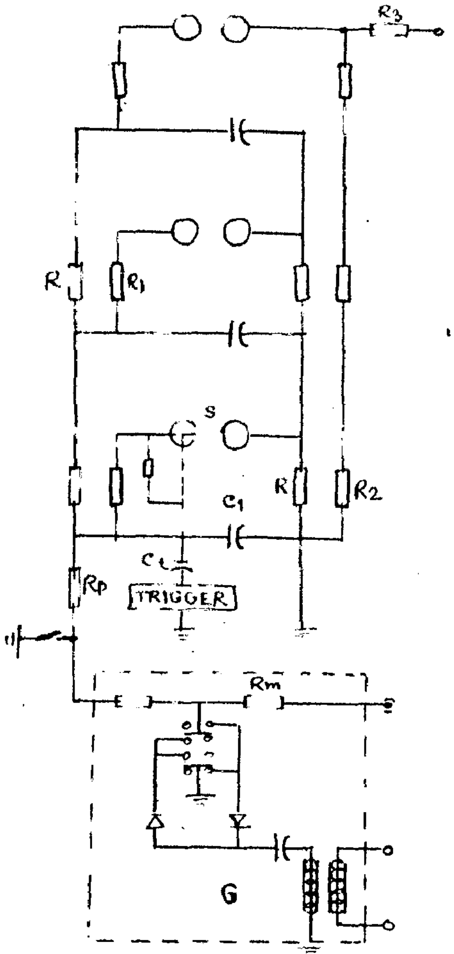


FIG 4.2 a : BASIC DIAGRAM OF IMPULSE GEN. (STAGE VOLTAGE 200KV)[5]



| | |
|---|---|
| $C_s$ | Impulse capacitor |
| $R_{s_i}$ | Internal series resistor |
| $R_{se}$ | External series resistor for lightning and switching |
| $R_{pi_1}$ | Internal parallel resistor for lightning |
| $R_{pi_2}$ | Internal parallel resistor for switching |
| $R_L$ | Charging resistor |
| $R_{pot}$ | Potential resistor |
| $R_{erd}$ | Discharge resistor |
| SF | Switching spark gap |
| ES | Grounding switch |
| PF | Parallel spark gap |

FIG 4.2 b : IMPULSE GEN CIRCUIT WITHOUT & WITH PARALLEL SPARK GAPS ( STAGE VOLTAGE 100KV)[6]



| | |
|---|---|
| C1 | capacitor |
| Ct | trigetion capacitor |
| G | DC generator |
| R | charging resistor |
| $R_1$ | front resistor |
| $R_2$ | tail resistor |
| $R_3$ | output resistor |
| $R_m$ | measuring resistor |
| $R_p$ | protection resistor |
| S | spark gap |
| $C_i$ | interstage capacitor |
| I | pneumatic interstage connection |
| U | grounding device |

FIG 4 2 C GENERAL LAYOUT OF IMPULSE GEN (STAGE VOLTAGE 100 KV)[5]

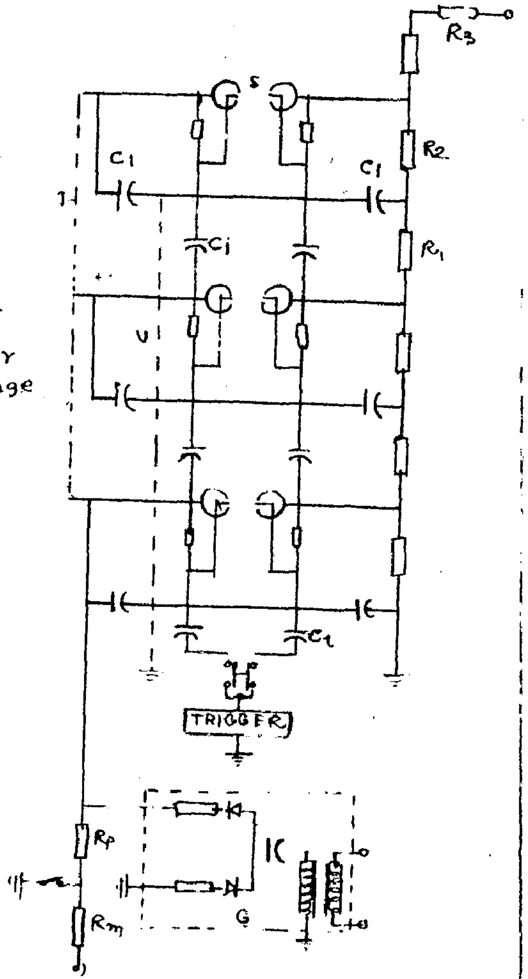


FIG 4.2 d : LAYOUT OF IMPULSE GENERATOR WITH COMPRESSED AIR SPARK GAPS ( STAGE VOLTAGE 100 KV)

some time a push button change from lightning to switching surge is provided. This is achieved by shorting some of the resistors required for either of wave form. For research and development a manual change of resistors is preferred in which case spring loaded contact enable easy change of resistors. We must realize that for voltage as high as 10,000 KV and the no of stages 50, the height could be as high as 35 m. In order to be able to change the resistors of each stage not only a permanent ladder to reach the higher stages is provided ~~by~~ but also space to store various values of resistors on each stage. Circuit 4.2c and 4.2d use Nickel chrome wire on resin glass stem for resistances.

### d. Indoor / out door Operation

All of the generator circuits shown are for indoor operation outdoor operation is a must for equipments having high level of insulation, which require extra big laboratories. Outdoor operation gives difficulties like rain snow and wind etc. We adopt a self carrying monolithic structure having sufficient mechanical strength. An air conditioning plant inside the generator ensures proper humidity and temperature conditions.

### e. Per Stage Voltage

The per stage voltage must be a compromise between conflicting requirements. A low per stage voltage permits the use of a small and cheap d.c. charging set but requires increased no. of stages. The total cost of condensers having a given energy storage capacity will not usually vary widely with no. of stages. The per stage voltage for circuits shown in fig. 4.2a and 4.2d is 200 KV, while for rest of the circuits, per stage voltage is 100 KV.

### f. Firing Capacitors

As the no. of stages increase we use firing capacitors in some of the lower stages for consistancy of firing. For circuit shown in figure 4.2a firing capacitors are used for lower stages if the total no. of stage increases beyond six.

### g. Supports

The insulating supports in case of circuit of fig. 4.2a are made up of bakelized paper. If more than 15 stages are to be installed than epoxy resin is used. In case of circuit of figure 4.2b porcelain pin insulators have been used with spacer plate made up of galvanised sheet steel.

### ~~f~~ h. Dia. of Spheres

The standard sphere dia. are 2,5,6,10,12.5,15,25,50,75,100,150 and 200 cms in use. The usual separation of two spheres should not exceed the dia. of the sphere. No measurement should be taken with spacing less than 5% of radius. The sphere diameters used in circuits 4.2a and 4.2b are 250 mm and 150 mm respectively.

### i. Energy Per Stage

Energy per stage will affect the capability of circuit being utilized for standard as well as other switching surges. Higher is the energy better is the effeciency for production of switching surges as compared to lightning impulse. Fig. 4.2 I shows effeciency versus load curves for lightning impulse. The energy per stage in circuits of fig. 4.2a, 4.2b and 4.2d are 2.5 to 30 KJ; 1 to 5 KJ; 2.5 to 5 KJ and 5 to 20 KJ respectively.

### j. Spark Gaps

For higher rating impulse generators spark gap column is enclosed. The enclosure contains U.V. lamp for U.V. illumination for consistancy of firing and compressed air supply which is used for brushing offdust before starting impulse generation. In circuit of fig. 4.2a and 4.2b protective bakelised paper cylinder encloses all spark gaps. In case of circuit of fig. 4.2d compressed gas resin glass cylinder casing has been used.

### k. Portability

Stationary impulse generators are almost exclusively used for routine test systems. Modern H.V. lab use mobile test systems. The main advantage lies in improved utilization of available

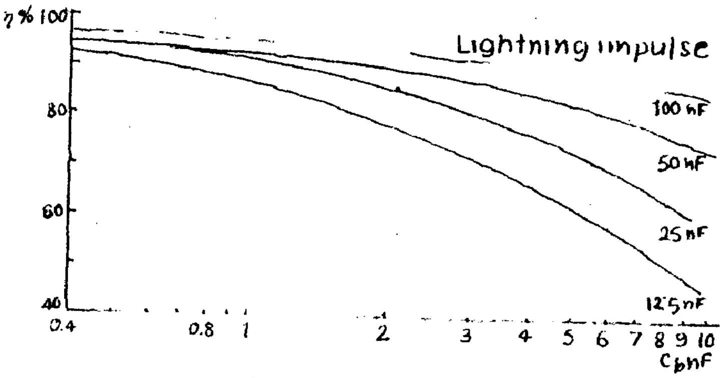


FIG 4.21 : EFFECIENCY η VERSUS LOAD CAPACITANCE $C_b$ [5]

space and in greater flexibility for different types of test configurations. Modern impulse generators are displaced to desired location by cushioning created by compressed air supply.

## 5 GENERAL FEATURES OF MULTISTAGE IMPULSE GENERATOR

In principle the impulse generator is an extremely simple piece of equipment. It consists of a charged capacitor which at an appropriate instant discharges into an external network. For good performance of impulse generator certain requirements of impulse generator are required to be met.

### 5.1 REQUIREMENT OF AN IMPULSE GENERATOR

The first and very basic requirement of impulse generator is that it should have low inductance so that steep front waves could be generated as well. Secondly the height of impulse generator should be as low as possible as it saves building cost. The third requirement is that the construction of impulse generator should be good. It should be robust and mechanical stable. And lastly there should be ease of access and of adjustment of movable or moving parts and ease of extension.

### 5.2 FACTORS INFLUENCING THE DESIGN AND SAFETY ASPECTS

First of all we have to choose the charging voltage. There are conflicting requirements in choosing and hence we have to make a compromise. A low charging voltage permits the use of a small and cheap d.c. charging set but requires an increased no. of stages. The total cost of condensers also sometimes gets affected in the two above mentioned cases. The charging voltage selected should be about 10-15 percent less than the open circuit voltage of D.C. set used if the time of charging is to be kept down to a reasonable value.

There are certain advantages in having a multistage generator instead of single stage. There are as follows:

a. D.C. set can be used for other purposes also.

b. Higher is the charging voltage greater is the difficulty and cost of supressing corona discharges from the leads during the charging period.

c. Multistage generator has greater flexibility as by the rearrangement of connection between stages, large variations in the output voltage and capacitance are possible for the same charging voltage.

As we know the length of wave tail depends upon the discharge resistance ($R_2$), the generator discharge capacitance ($C_1$) and load capacitance ($C_2$), we should have a set of discharg resistance so that wave tail variation within ± variation is assured with varying load values.

As the ratio of $C_1$ to $C_2$ is increased the open circuit voltage required for a given output voltage across load decreases and the circuit characteristics becomes less dependent on the external load. However for economic reasons it is desirable to limit the ratio.

If V is open circuit voltage of generator, of output capacitance $C_1$, and $V_c$ is crest value of voltage (assumed to be non oscillatory) reaching the load then $V=V_c\ (1 + \frac{C_2}{C_1})$.

From the above equation it is clear that an increase in $C_1/C_2$ from 1 to 2 causes a reduction in $V/C_c$ of 0.5. An increase from 2 to 3 causes a further reduction in $V/V_c$ of 0.17. For successive equal increments in $C_1/C_2$ the corrosponding reductions in $V/V_c$ are extremely small when $C_1/C_2$ exceeds 5, and in practice this ratio is rarely exceeded when $C_2$ is maximum load expected.

The power output of testing plant (or the stored energy in case of impulse generator) is determined by the capacitance, inductance and resistance of the test sample. In most cases the capacitance term predominates. The following table shows the order of magnitude of the capacitance of different types of apparatus:

Table 4: Capacitance of Different Test Objects

| Name of Test Object | Order of Capacitance Value |
|---|---|
| Line insulators, pin insulators | Several pF |
| Bushings | 150 - 400 pF |
| Current Transformers | 200 - 600 pF |
| Transformers upto 1000 KVA | Approx. 1000 pF |
| Transformers over 1000 KVA | 1000 - 4000 pF |
| Cable per meter length | 150 - 300 pF |

The rating of impulse generator should be about 30 percent higher than the desired maximum output. With increasing load capacitance, higher and higher generator capacitance is required to obtain a good efficiency of the generator. The accumulated energy of generator is given by

$$W = \frac{(\underline{n}\cdot V_{dc})^2 \cdot C_g \cdot 10^{-3}}{2} \quad KJ$$

where $V_{dc}$ → d.c. voltage per stage

$n$ → no. of stages

$C_g$ → capacitance of generator

The possible lethal effects of high voltage make extreme caution and safety awareness essential elements of testing. Not only the equipments but all aspects of entire testing should be as safe as possible to minimize danger to personnel. Even a poor bodily contact is very dangerous in case of equipments supplying many thousands of volts. As the size of unit increases we have to include more and more safety features in it. Following are some of the essentials which facilitate the use of equipment and some are essential for the safety of its user.

1. We should have a main on off switch and a pilot light to indicate the application of primary power.
2. There should be a fuse or circuit breaker in the primary circuit to shut off power in the event of internal shorts or protected overloads.
3. There should be three wire input line cord, so that the unit can be grounded right at the power line.
4. A voltmeter should be connected directly at the output so that its reading at all times is a true indication of voltage at the Terminals. ( Voltmeter accuracies of 2% of full scale for d.c. and 3% of full scale for a.c. are commonly available and are adequate for most applications).
5. There should be no buzz or hum from transformer or busling at maximum setting of voltage.
6. Functional layout with all controls should be clearly marked so that their operation can't be misunderstood.
7. Provision should be made for bleeding off any charge left on the capacitors or load after the completion of the test.
8. A test cage preferably with a sufficiently large clear area of glass or plastic to permit the viewing the equipment under test should be included whenever possible.

In addition to being rugged constructed of high quality and Villa uses special oil impregnated paper type with protruding foils to minimise inductance and assure a sturdy inter connection. Haefely uses capacitors impregnated with high grade caster oil. The welded can is equipped with Porelain bushing.

At low voltage carbon resistors can be used but at high volta we should use non inductively wire wound resistors and we should avoid the carbon film type. Resistances may be composed of liquids or solids in the form of rod as well. Liquids have high hea capacity but their resistance is unstable. The generator resistance in common withthose normally employed in H.V. lab. generators, are composed of 'silido' resistance ribon fixed length wire along varnished paper tubes, then taped up with linen tape, and finally treated with several coats of special hard water proof varnish. It is important that the enamelled wire should be wound on to its support, free from strain and that turns electrically remote from each other should also be physically remote.

The best way for wavefront resistor is to distribute it in all stages within the generator itself. One more practical reason for distributing the wavefront resistors is that the need is then diminished for an external resistor capable of withstanding the full voltage. Wave tail resistors also perform function of charging resistances and distributed throughout the generator. However it is usual to arrange for part of the wave tail resistance

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8. A test cage preferably with a sufficiently large clear area of glass or plastic to permit the viewing the equipment under test should be included whenever possible.

In addition to being rugged constructed of high quality components and conservatively rated, the unit should present a pleasing appearance with all operating controls and meters arranged in a neat, functional manner. The output voltage should be capable of being smoothly from a low value to the maximum. The operator is responsible for the safety of all personnel while using the equipment. It is therefore very necessary that he should follow all accepted safety practices, proceed with caution and do all as power to assure safety. In general in order to prevent flashover to the extraneous structures, it is necessary to keep the clearance greater than minimum values given in the specifications. The safe distances for A.C. is 50 cms for every 100 KV; similarly for lightning impulse safe distance is 20 cms for every 100 KV.

## 5.3 THE GENERAL CONSTRUCTION OF IMPULSE GENERATOR

The method of construction is largely governed by the type of condensers used. Three main types of condensers are used in the construction of impulse generators. Hollow cylinders of varnished paper with concentric metalic layers inserted at suitable intervals are rarely used now a days. Since these have low working stress and inconvenient shape and require expensive frame work. Oil impregnated in metal tank have higher stress than the above mention and can be made weather proof. Most recently impulse generators use oil impregnated capacitors in insulating containers. Passoni and Villa uses special oil impregnated paper type with protruding foils to minimise inductance and assure a sturdy inter connection. Haefely uses capacitors impregnated with high grade caster oil. The welded can is equipped with Porelain bushing.

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The best way for wavefront resistor is to distribute it in all stages within the generator itself. One more practical reason for distributing the wavefront resistors is that the need is then diminished for an external resistor capable of withstanding the full voltage. Wave tail resistors also perform function of charging resistances and distributed throughout the generator. However it is usual to arrange for part of the wave tail resistance to be placed outside the generator as then it can be used also to serve the purpose of potential divider.

For H.V. connections it is unnecessary to use starp or thick gause wire. A 24-gause copper strand is a convenient size of wire for the purpose, and a single touching contact is all that can be desired.

## 5.4 OPERATION OF DISCHARGE CIRCUIT[1]

Referring to Fig. 5.4 when first spark gap $G_1$ fires the stray capacitance betweem B and ground is very rapidly charged from $C_1$ through spark. The stray capacitance at D, however, must be charged through the resistance B.D. which slows down the process. Thus, while B quickly assumes the potential of A, D is slower in responding. Meanwhile, the voltage across $C_2$ can't suddenly charge so that C rises with B. A consequence of this is that a voltage approaching 2V appears across the second gap CD and it breaks down. The stray capacitance between D and ground can now be charged directly through two sparks, so D quickly assumes the potential of C. The process then repeats with $C_3$, the gap EF coming into the act. The whole process is cumulative, so that in short order all gaps fire and the output terminal flies up in potential to a value approaching nV, where n is no. of stages and V is charging voltage. For consistant operation it is found

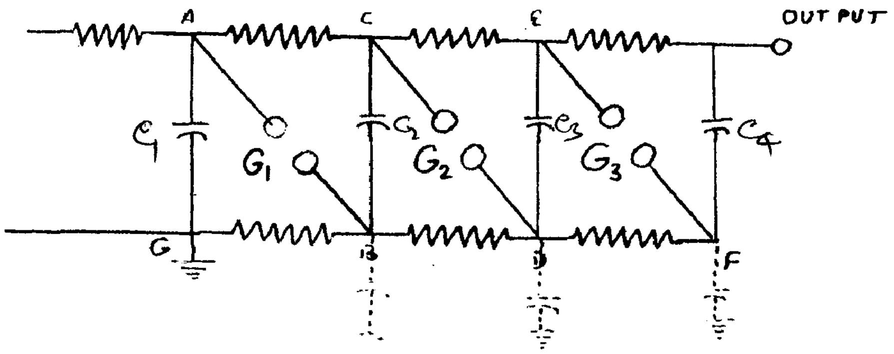

FIG 5·4: MARX MULTISTAGE IMPULSE GENERATOR CIRCUIT advisable to irrediate the gaps. This can be done by an ultra voilet lamp etc. It is also customary to put the gaps as line of sight of each other, for then the radiation from the spark in the lower gaps help to trigger the upper gaps.

Although the theory outlined above goes a long way towards an explanation of the observed phenomena, it is still very imperfect and does not amount for the extremely erratic behaviour of impulse generator when the resistances have been made very small in order to produce a very short - tailed wave. Let us reconsider Fig. 5.4. The stray capacitance immediately begin to receive or loose charge through the resistors, so that the over voltage across next gap quickly reaches to zero. Since the capacitance are normall of the order of tens of micro micro farads, the time constants of the local circuits are likely to be small; e.g. if the resistances are of 1000 $\Omega$ each, then the time constants will be of the order of $10^{-2}$ to $10^{-1}$ micro sec. and corrospondingly less for lower values of resistance. The values of stray capacitances depend upon the physical construction of the generator, but can be increased artificially, whilst resistance values are fixed by the capacitance and required wave shape. The over voltage across the second spark gap is reduced even more as the current flowing through resistance after the breakdown of first gap causes a drop as voltage applied to second one.

## 5.5 EFFECT OF DUST AND ILLUMINATION ON CONSISTENCY OF BREAK-DOWN OF GAPS [3]

The presence of dust can cause irregular operating a multistage generator. We can't set the subsequent gaps to breakdown at a voltage much higher than that at which first spark gap breaks down, as the available overvoltage is small and of brief duration. The dispersion of d.c. breakdown voltage in presence of dust may be great.

To overcome this difficulty, experiments have beenmade with each gap enclosed in a cylindrical shroud made of press board and greased on the inside. The first gap showed the great regularity but none of the othergap broke down. The later can be explained as the ultra violet illumination from the spark in the first gap was prevented from reaching the othergaps,and consequently there were insufficient electrons to initiate breakdown during the brief period when the gaps were subjected to overvoltage. Narrow slits were then introduced at the top and bottom of each shroud so as to facilitate irrediation from gap to gap. The performance was satisfactory now. Further it was found that a slight horizontal displacement from vertical plane is the alternate gaps reduced the intensity of illumination to adjacent gap, and this resulted in irregular firing sometimes. The gaps arranged in vertical line gave reliable performance.

## 5.6 MEASUREMENT ASPECTS

There are four basic methods of measurement of impulse voltage.

a. Resistance divider and C.R.O.

b. Capacitance divider and C.R.O.

c. Sphere gaps

d. Peak voltmeter.

In resistance potential divider the impulse voltage is applied to the C.R.O. through a coaxial cable, terminated in as resistance R of magnitude equal to the surge impedance of the cable to avoid reflections.

The main disadvantage of capacitance divider is that the load inductance with the capacitance forms a resonant circuit. This has to be supressed by damping resistor.

Sphere gaps and peak voltmeter of course are used to see the peak value of impulse voltage. The sphere gap is tobe connected directly as parallel to the test object. A resistor should not be used in series with the sphere gap, as the capacitance of later modifies the wave shape and leads further inaccuracies in the measurement. The sphere gap probably includes superiposed oscillations as well if there are present. It is possible however, that such oscillations would have a different quantitative effect in flashing over or breaking down other type of air gap or insulation, and it is for this reason that the presence of superimposed oscillations in undesirable.

Thus single sweep cathode ray oscillograph is the most suitable and satisfactory means of examining the shape of an impulse wave; it may be used to obtain visual or photographic recods of the wave trace.

## 6 DESIGN OF 150 KV IMPULSE VOLTAGE GENERATOR

The high voltage laboratory equipments are costly and at the same time requires large and expensive building for placement. Seeing the present laboratory having moderate size of hall; it was decided to build a portable 150 KV impulse generator with fire stages.

### 6.1 SCOPE OF PRESENT PORTABLE GENERATOR

The impulse generator charging set has a charging voltage up to 30 KV. Thus the range of applications extends up to 150 KV impulse voltage generator. Thus this portable impulse voltage generator can be used for training, testing research and developmen purposes in the laboratory. This is also suitable for the point of view of clear layout and techniqcality. The unit is expandable, and we can have more stages by utilizing additional resistors. The generator is designed for indoor operation.

As shown in Fig. 6.1 we have adopted the most modern marx multiplier circuit. The reliability and accuracy to triggering is improved by the reciprocal irrediation of spark gaps with the ultraviolet light of the discharge spark. The first stage is triggered with the help of triggering device.

All registors are distributed among the stages within the generator. This concept guarantees minimum space requirements

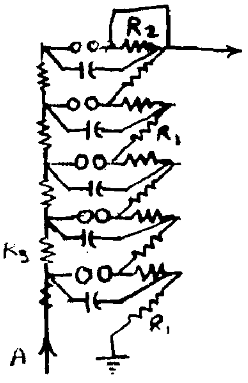

FIG 6.1 BASIC IMPULSE GENERATOR CKt

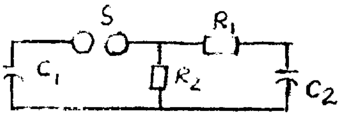

FIG.6.2a : EQUIVALENT DIAGRAM OF IMPULSE GENERATOR

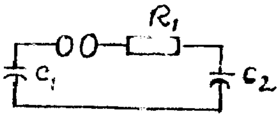

FIG 6.2b EQUIVALENT DIAGRAM OF WAVE FRONT

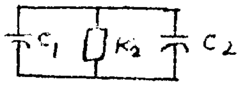

FIG. 6.2c : EQUIVALENT DIAGRAM OF WAVE TAIL

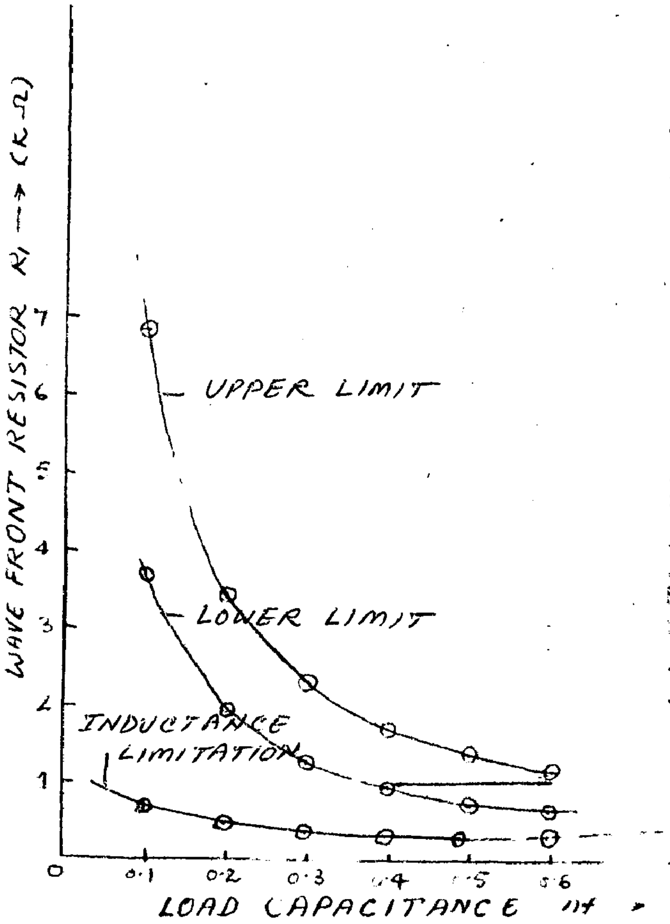

FIG.6.22a. : R1 RANGE FOR LIGHTNING IMPULSE

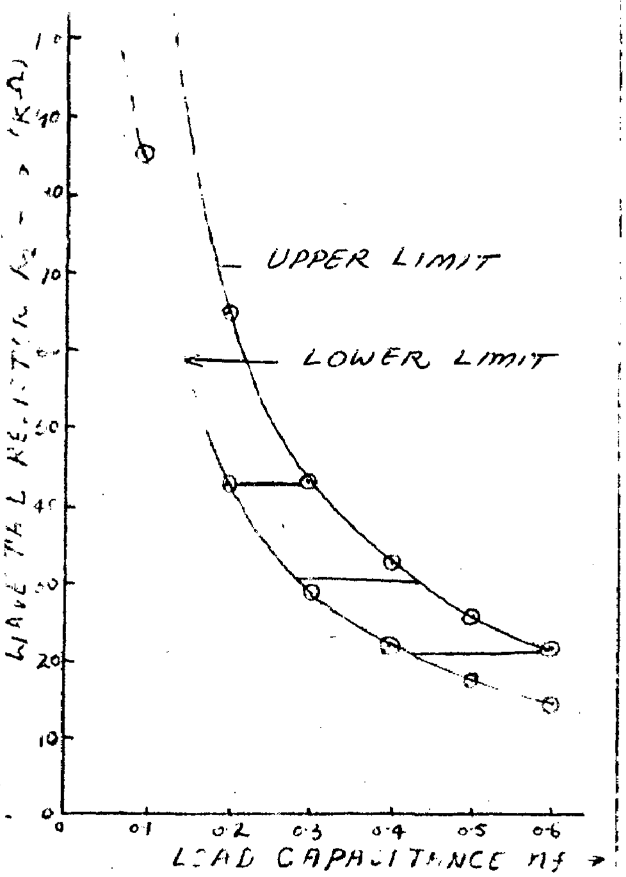

FIG 6.22b R2 RANGE FOR LIGHTNING IMPULSE

and low impulse circuit inductance. All series and parallel resistances are interchangeable.

## 6.2 DESIGN OF 150 KV IMPULSE GENERATOR

Let us consider the equivalent diagram of the impulse generator (Fig. 6.2a) where

$C_1$($\mu$F): equivalent capacitance of generator

$C_2$($\mu$F): Capacitance of load + divider

$R_1$(ohm) front resistor ( sum of series resistances of stages and output resistance if any)

$R_2$)ohm) tail resistor ( sum of parallel resistors of the stages)

$T_1$ and $T_2$ are front and tail times of wave in $\mu$ sec.

Capacitor $C_1$, charged at voltage E, discharges across capacitor $C_2$ through resistance $R_1$. The voltage $V_1$ reached by both capacitors, is lower than the E charging value. The theoretical efficiency is yielded by the equality of the charge quantities:

$$\eta = \frac{V}{E} = \frac{C_1}{C_1+C_2}$$

which evidences the need of having $C_1$ for bigger than $C_2$. For instances in order to have 85/ efficiency $C_1$ must five times bigger than $C_2$. By consequence, the energy value to be given to the generator is thus determined.

For design we will keep in mind the Indian standard specifications ( I.S. 2071, 1974). For the wave front, the equivalent circuit may be as shown in Fig. 6.2b. For 1.2150 wave, the duration of wavefront

$$T_1 = 2.7\, R_1 \quad \frac{C_1 C_2}{C_1 + C_2} \qquad \ldots(1)$$

Similarly for wave tail resistance we will consider the diagram shown in Fig. 6.2c.

Capacitors $C_1$ and $C_2$, discharge in parallel across resistanc $R_2$, following an exponential law with a $\tau = R_2(C_1+C_2)$ time constant. To reach half of the voltage time needed is

$$T_2 = 0.7\, R_2\, (C_1+C_2) \qquad \ldots(2)$$

### 6.2.1 Technical Data

As we will use 2 capacitors of 10,000 PF in parallel.energy

$$\text{energy} = \frac{1}{2}\; \frac{20.000\text{x}10^{-12}}{5} \text{ x } 150\text{x}150\text{x}10^{6} = 45 \text{ Joule}$$

Total stages = 5

Height of each stage = 25 cms.

### 6.2.2 Load Range OF Lightning Impulse Tests

The standard lightning impulse is 1.2/50

Tolerences are peak value = ± 3%

Front time ± 30%

time to half value ± 20%

hence according to eqn.(1) $T_1 = 2.7\, R_1 \frac{C_1 C_2}{C_1 + C_2}$ ; considering the hypothesis, to have $C_1 = 5.66\, C_2$; i.e. 85% efficiency and considering wave front as 1.2µS ± 30%.

$$0.366 < R_1 C_2 < 0.680$$

TABLE 6.2.2.a WAVE FRONT RESISTOR RANGE FOR VARYING LOAD

| $C_2$(µF) | .0001 | .0002 | .0003 | .0004 | .0005 | .0006 |
|---|---|---|---|---|---|---|
| $R_1$ (Ω) Upper limit | 6797 | 3399 | 2266 | 1699 | 1359 | 1133 |
| $R_1$ (Ω) Lower limit | 3660 | 1830 | 1220 | 915 | 732 | 610 |

Plot is shown in figure 6.2.2a

According to eqn. (2) $T_2 = 0.7\, R_2(C_1 + C_2)$

here also considering 95% efficiency i.e. $C_1 = 5.66\, C_2$

and considering ± 20 % tolerence

$$8.571 < R_2C_2 < 12.857$$

---

TABLE 6.2.2b <u>WAVE TAIL RESISTOR RANGE FOR VARIFYING LOAD</u>

| $_2(\mu F)$ | .0001 | .0002 | .0003 | .0004 | .0005 | .0006 |
|---|---|---|---|---|---|---|
| $_2$ ($\Omega$)<br>pper limit | 128570 | 64285 | 42856 | 32142 | 25714 | 21428 |
| $_2$ ($\Omega$)<br>ower limit | 85710 | 42855 | 28570 | 21427.5 | 17142 | 14285 |

Plot is shown in figure 6.2.2b

### 6.2.3 <u>Maximum Inductance Permissible</u>

Say the total inductance of impulse generator is L, then for circuit to be non oscillatory $R_1 > 1.25 \sqrt{L/C_2}$ (15)

$$\text{or} \qquad C_2 R_1^2 > (1.25)^2.L$$

following table 6.2.3 shows maximum permissible value of inductance for lightning impulse:

TABLE 6.2.3 <u>PERMISSIBLE VALUE OF INDUCTANCE</u>

| ) | .0001 | .0002 | .0003 | .0004 | .0005 | .0006 | .0007 | .0008 |
|---|---|---|---|---|---|---|---|---|
| )<br>value | 3660 | 1830 | 1220 | 915 | 732 | 610 | 522.85 | 457.8 |
| ) < | – | – | – | 214.32 | 171.46 | 142.88 | 122.07 | 106.93 |

## 6.3 CONSTRUCTION DETAILS:

The construction of impulse generator is not very complicated, all components are easily seen and accessible. The individual stages are erected one above the other on a modular system. The generator can be moved into the optimum testing position without the help of auxiliary equipment.

### 6.3.1 Frame Structure:

The basic movable frame structure is made up of mild steel. The welded steel section have protective rust proof coating. The base can be moved with castors in the base. The support frame for capacitors is made up of wood. The drawing of the metal frame is shown in figure 6.3.1.

### 6.3.2 Spark Gaps:

Five pairs of 50 mm brass spheres, are attached to insulating colomn supports. The gap setting can be adjusted by moving one of the spheres of each pair. The bottom spark gap is equipped with a special triggering sphere and electrode arrangement. The drawings are shown in figure 6.3.2a, and the photograph is shown in Fig. 6.3.2 b.

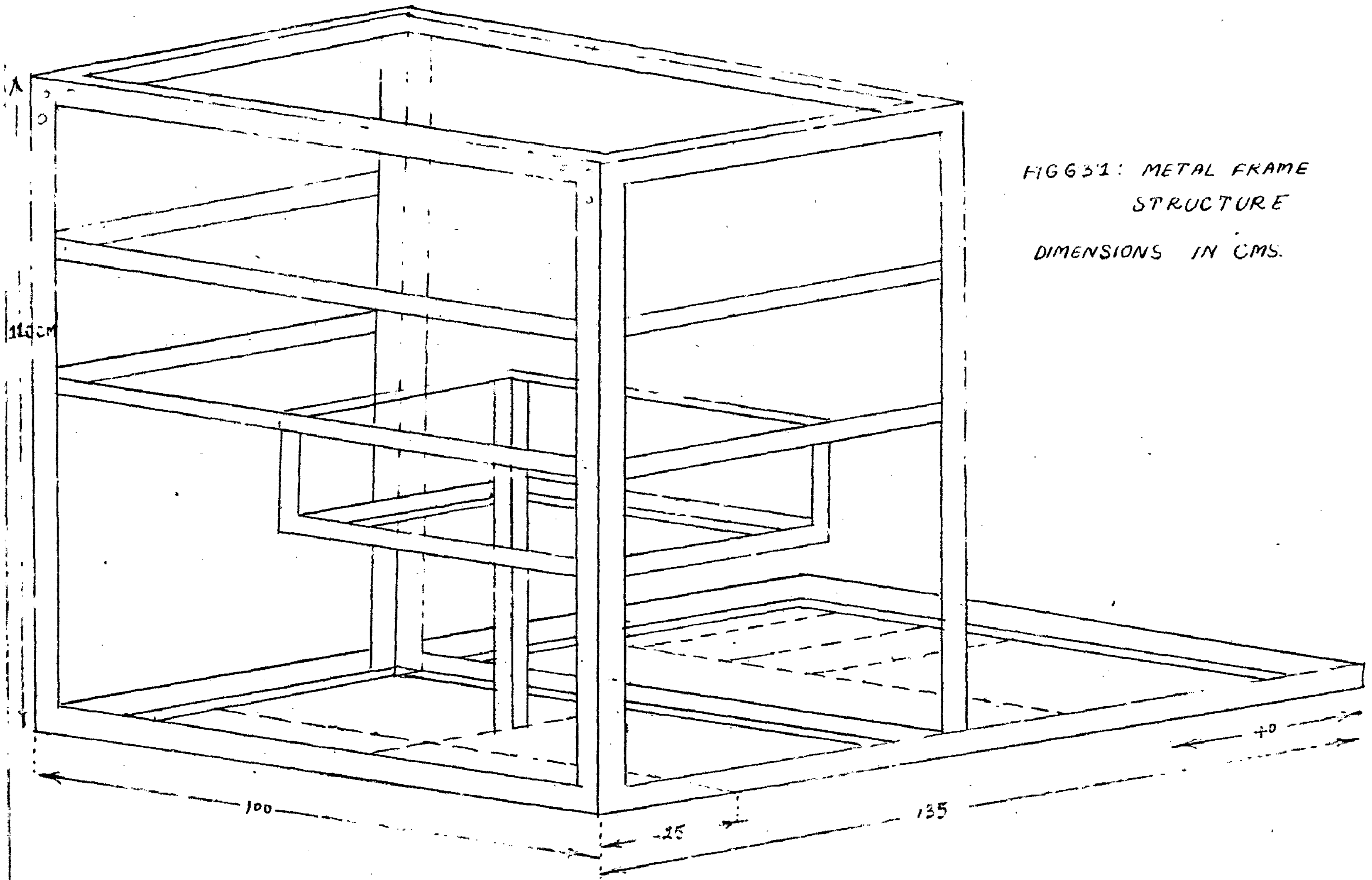

FIG 6.3.1: METAL FRAME STRUCTURE

DIMENSIONS IN CMS.

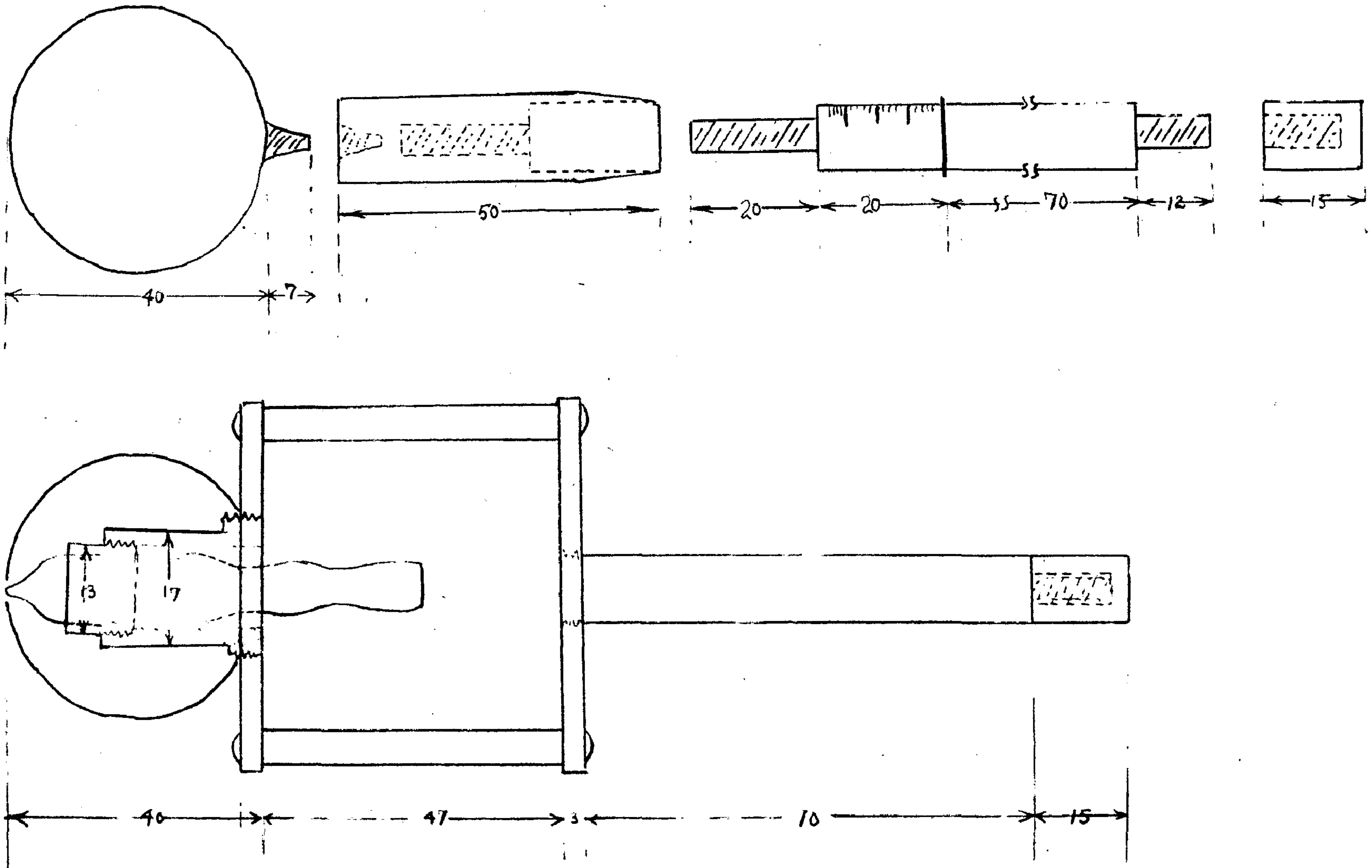

FIG 6·3·2 a : SPHERE GAP ASSEMBLY DRAWINGS.

(DIMENSIONS IN MM.)

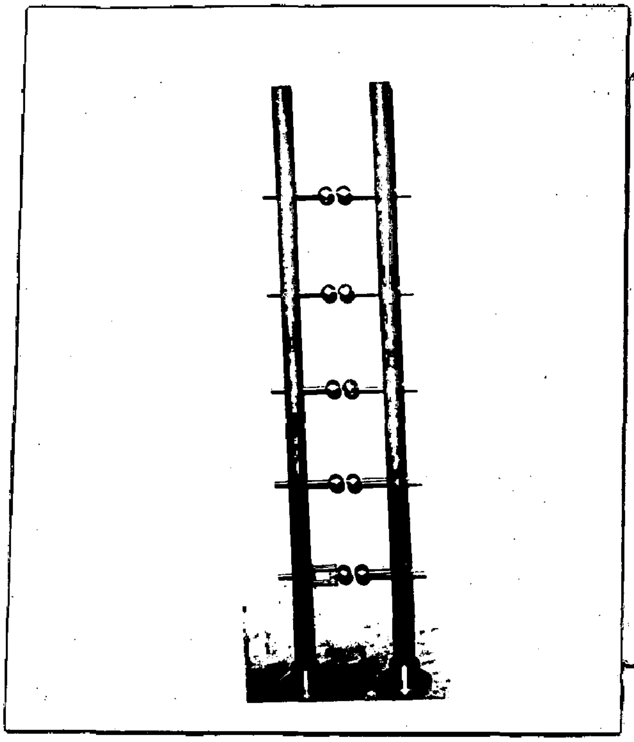

Fig.6.3.26- Insulating Supports.

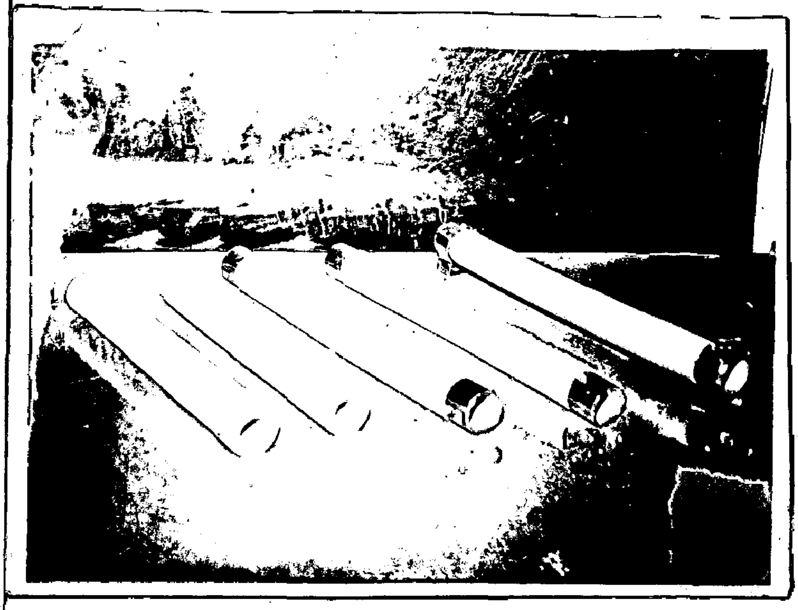

Fig. 6.3.4a- Different Stages of Wire Wound non Inductive Resistance.

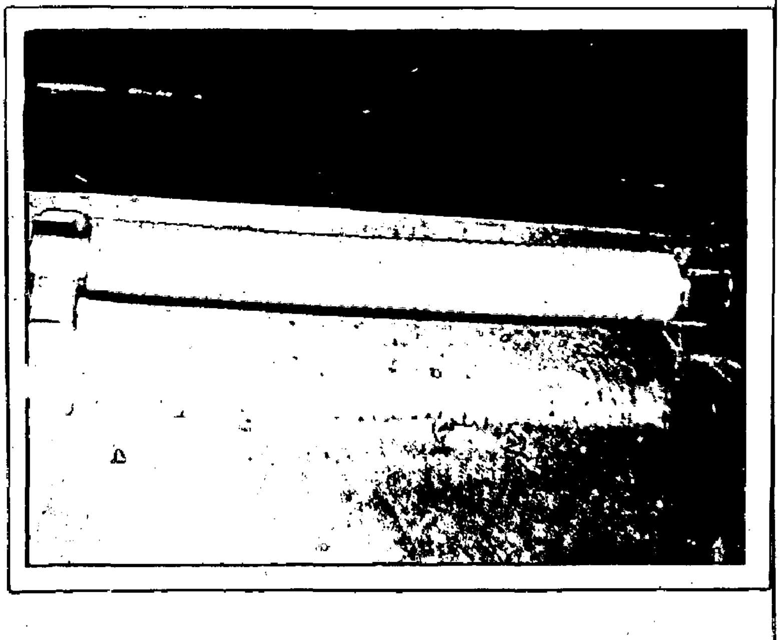

Fig. 6.3.4b- Wire Wound Resistance.

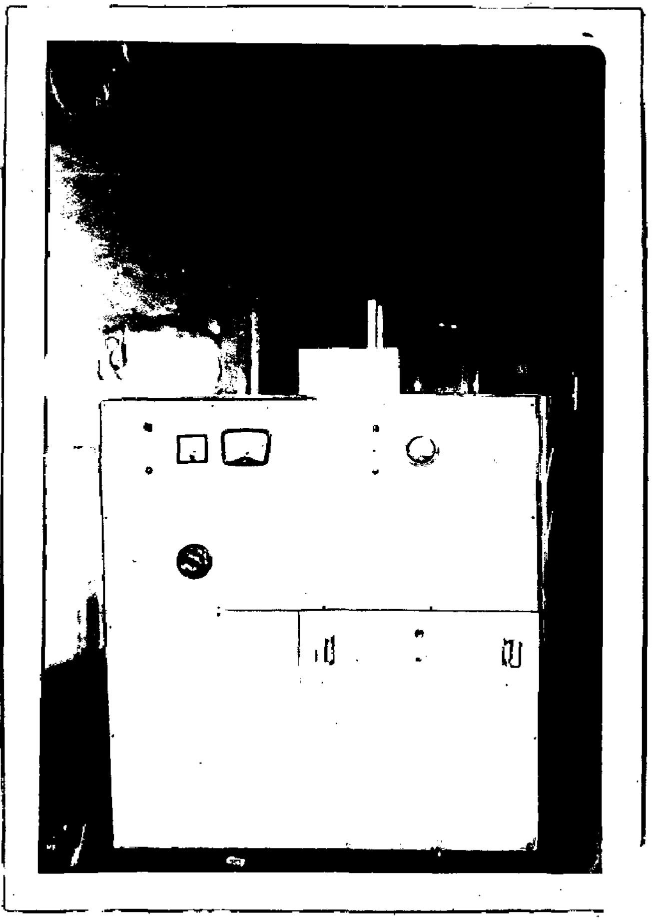

Fig.6.3.4c- 150 KV Porable Impulse Generator.

### 6.3.3 Impulse Capacitors :

The capacitors used at present are high voltage mica capacitors 0.1 $\mu$F, 5 KV, 1 PC. two in series. Impulse capacito feature low inductance, reliability and long service life. Two additional capacitors can be provided for generators, in order to double the energy at a later date and for increased load range. The rack is already built in advance to accomodate four capacitors.

### 6.3.4 Series Parellel Resistors :

The resistors are formed by nickel-chrome wires, wound contrary wise over a porcelain tube. These materials ensure constant resistances and can withstand mean temperature o 180°C, with peaks upto 250°C. The way wire is wound permits extra low inductance value. A coat of varnish protects the resistors against damages in transit. All resistors are dimentioned for easy handelling and feature specially designed and contacts for rapid exchanging. The photographs of resistances made are shown in Fig. 6.3.4a and 6.3.4b. These resistances have been made after many trials and the various possibilities of size, shape and material. First of all I made a single layer resistance on porcelain tube ~~valuing~~ Of 40 $\Omega$ . The values of

R and L on bridge came out to be as follows

L = 1.4 mH

R = 40 Ω

Thus we see single layer has quite a lot inductance so we have to adopt noninductive winding. Then I took a low resistan wire and wound it in different shapes to see the inductive effe as I was mainly concerned with inductance to keep it maximum.

1. Tube dia 5.8 cm, lenth of copper wire 630 cm and noninductive winding; The inductance came out to be 4.85 μH
2. On porcelain tube dia 2 cms length of wire 792 cms noninductive winding at less inter turn distance. The inductance came out to be 4 μH.
3. Porcelain tube 2 cm dia, total 49 turns, total length of wire = 352.8 cm Noninductive winding total
   resistance = 21 Ω
   inductance = 42.5 μH

   Wire used here was nichrome wire.

4. Then we measured the inductance of card resistances already available in the lab.

R = 1.4 KΩ

L = 65 μH

Then I tried for flat shape resistances. I took a special type of wooden frame and weaved a flat reistance with the help of wire and thread length of wire = 162 cm

$R = 20.25 \, \Omega$

$L = 205 \, \mu H$

5. As it was very difficult to weave, we thought the idea of having resistance on thick cloth ( Niwar); then I inserted wire in the thick cloth, in a way so that it will give minimum inductance. The result was as follows -

Length of wire = 273 cm.

$R = 34.10 \, \Omega$

$L = 1.1 \, mH$

Thus the inductance was very high.

As we know inductance $L \, \alpha \, N^2 r$

r → equivalent radie of cross section

N → no. of turns.

~~As we know for same cross sectional area i;e for same equivalent radie, square cross section has maximum periphery so ideally we should have square cross section of resistance rod so as to have minimum inductance.~~

Finally we decided resistances to be made on porcelain tube having outer dia 3 cm and length = 25 cm; based on the construction of impuse generator and availability of material.

The full photograph of impulse generator is shown in Fig. 6.3.3c.

## 6.4 AUXILIARY EQUIPMENTS :

Impulse generator consists of so many auxiliary equipments, which may be assembled with impulse generator for making a full unit complete in itself. Some of the auxiliaries like charging D.C. supply, trigetron triggering device along with its supply etc. we have made in one single unit. We will elaborate few auxiliary equipments in the following sections.

### 6.4.1. Charging Set :

Charging set is required for charging the capacitors of impulse generators. Since we need high voltage D.C. supply we have to have rectification techniques i.e. high voltage D.C. is obtained with the help of rectifiers from A.C. voltage. Again we have optio to use half wave rectifier circuit, full wave or bridge rectifier circuit or voltage doubler or cockraft walton circuit etc. Each type has its own advantages and disadvantages. For instance a bridge rectifier needs four diodes and transformer, while voltage doubler circuit needs only two diodes ( different rating than used in bridge rectifier circuit). Similarly the rating of transformer is also different for the same D.C. output in both cases. Seeing the overall economy i.e. in transformers and rectifiers, we have selected a bridge rectifier configuration for 30 KV D.C. charging set. At the same time we have provision for increasing this value.

### 6.4.1.1 Design Aspect:

We are having a transformer of following ratings - 230 V/50 KV, 0.5 KVA, as we know in bridge rectifier configuration if secondary A.C. voltage peak is $E_m$, then average D.C. output will be $\frac{2}{\pi} E_m$. Hence the maximum D.C. output upto which the capacitors could be charged is $50\sqrt{2}$ KV.

The maximum current of transformer secondary winding

$$= \frac{0.5 \text{ KVA}}{50 \text{ KV}} = 10 \text{ m.A.}$$

Hence minimum value of charging resistance $= \frac{30 \times 3.14}{2\sqrt{2} \times 10}$

(For 30 KV D.C. out put) $= 3.3 \text{ M}\Omega$

Charging time $\simeq$ 5 RC

$$= 5 \times 3.3 \times 10^6 \times C \text{ sec.}$$

### 6.4.1.2 Rectifiers and Transformers:

Most modern test sets employ selenium rectifiers when maximum output current is below 25 mA and silicon rectifiers when heavier currents are required. We can increase the voltage or current ratings by connecting the rectifiers in series or parellel respectively. Since the loads are capacitive the load impedance itself aids in the filtering.

While mounting the high voltage rectifiers, adequate spacing must be allowed between the assembly and any nearby grounded surfaces to prevent arching. Assemblies with ratings of 5 KV or below may be bolted directly to a mounting surface. Higher voltage assemblies should be spaced in minimum distance of one half the terminal spacing dimension from the grounded surface. For higher altitudes the voltage ratings must be reduced to prevent arcing between the insulating terminals. This is due the fact that air at high altitudes is rarefied and has lower insulating capabilities.

### 6.4.1.3 Operation :

The circuit diagram is shown in Fig. 6.4.1.3. When we press the switch $K_1$ the supply voltage of 230 volts comes the primary of low voltage auto transformer, which is indicated by red neon lamp. The output of the variac is directly fed to the primary of high voltage transformer, and the voltage fed is shown by voltmeter. In order to measure high voltage of secondary side a milliammeter is provided in series with a resistance. An overcurrent relay has been provided in the load circuit. When the current in the load circuit the preset value, the normally closed contact N.C. gets open and thus the supply to the primary side of variac is automatically switched off.

### 6.4.2 Grounding Device :

For the safety of operating personnel it is very necessary that the generator should be fitted with a device to earth the condensers, when equipment is not in active operatio

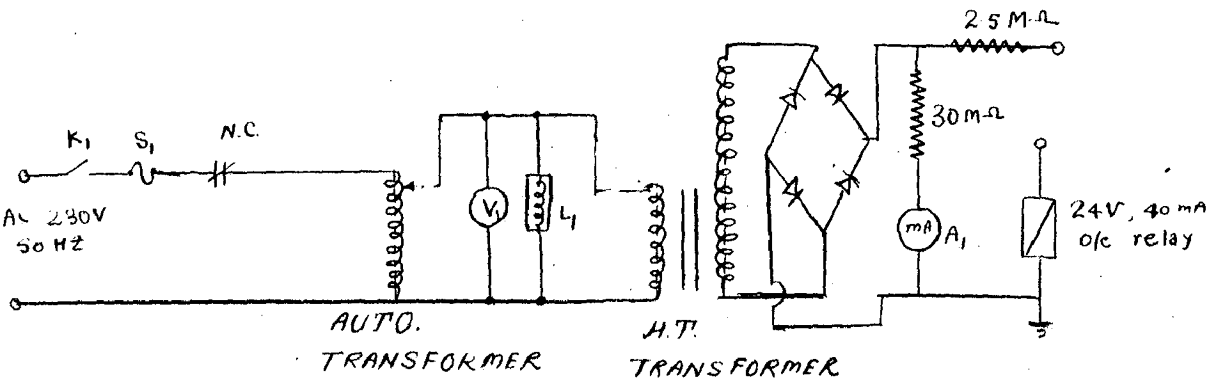

FIG 6·4·1·3   30 KV D.C SUPPLY CIRCUIT

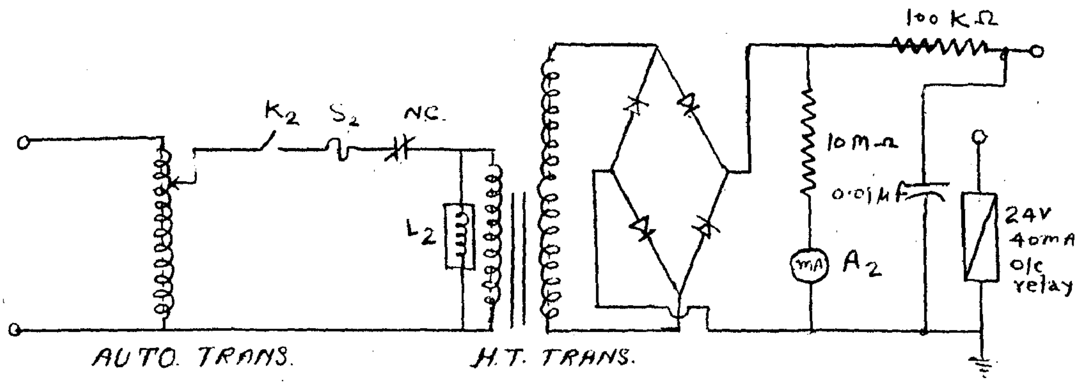

FIG. 6·4·3a  11 KV  D.C. SUPPLY CIRCUIT

The earthing device may have the form of suitable switch arm and could be operated mechanically or electrically. For more sophistication and advancement, the device may be provided with signal lamps and automatic interlocking. The switch arm may be applied to the charging point of impulse generator and then stages will be discharged through the various inter-stage resistors or all the stages may be connected directly to earth points.

During the operation of generator, sometimes, it may be necessary to earth the equipment when condensers are fully charged. If this is effected by short circuit switch, there will be a heavy spark hence one resistance is added in series with the arm of earthing switch.

We are using copper rod with insulating handle for grounding purpose. The series resistance is 75 K$\Omega$.

### 6.4.3 Triggaron Triggering Circuit

Triggering device has been assembled in a draw out cabinet and has been built by Miss Priti Dwivedi as a B.E. Project. Please refer to B.E. Project report 1980 by Priti Dwivedi. However 11 KV D.C. supply for this circuit has been built as an integral part of impulse generator with capacitance of 0.01 $\mu$F in the output circuit. The circuit diagram of 11 KV supply is shown in figure 6.4.3 a.

For the testing of triggatron circuit, 10 KV supply built by Mr. A.K.Shrivastava and Mr. Mohd. Fariduddin, M.E.II P.S.E. in 1978 was commissioned and calibrated. The circuit diagram is shown in figure 6.4.3 b and calibration table is given below:

Table 6.4.3 : Calibration Table

| S.No. | Ammeter Readings ($\mu$.A) | Output Voltage (KV) | Remark |
|---|---|---|---|
| 1. | 6 | 0.425 | Corresponding to zero position of variac |
| 2. | 12 | 1 | For input supply 180 Volts |
| 3. | 18 | 1.5 | -do- |
| 4. | 24 | 2 | -do- |
| 5. | 30 | 2.5 | -do- |

Linear hereafter till 5 KV.

We could not go beyond 5 KV as the capacitors of high voltage rating were not available. We have used capacitors of 0.25 $\mu$F, two in series.

### 6.4.4 U.V.Lamp:

For consistancy of firing of sphere gaps the gaps are arranged one above other so that the sparking irrediation of first gap will go to second gap and so on. To ensure regularity of firing we provide artificial radiations. We have used 220-230 Volts, 300 W ultra-voilet lamp for Providing radiations to the gaps.

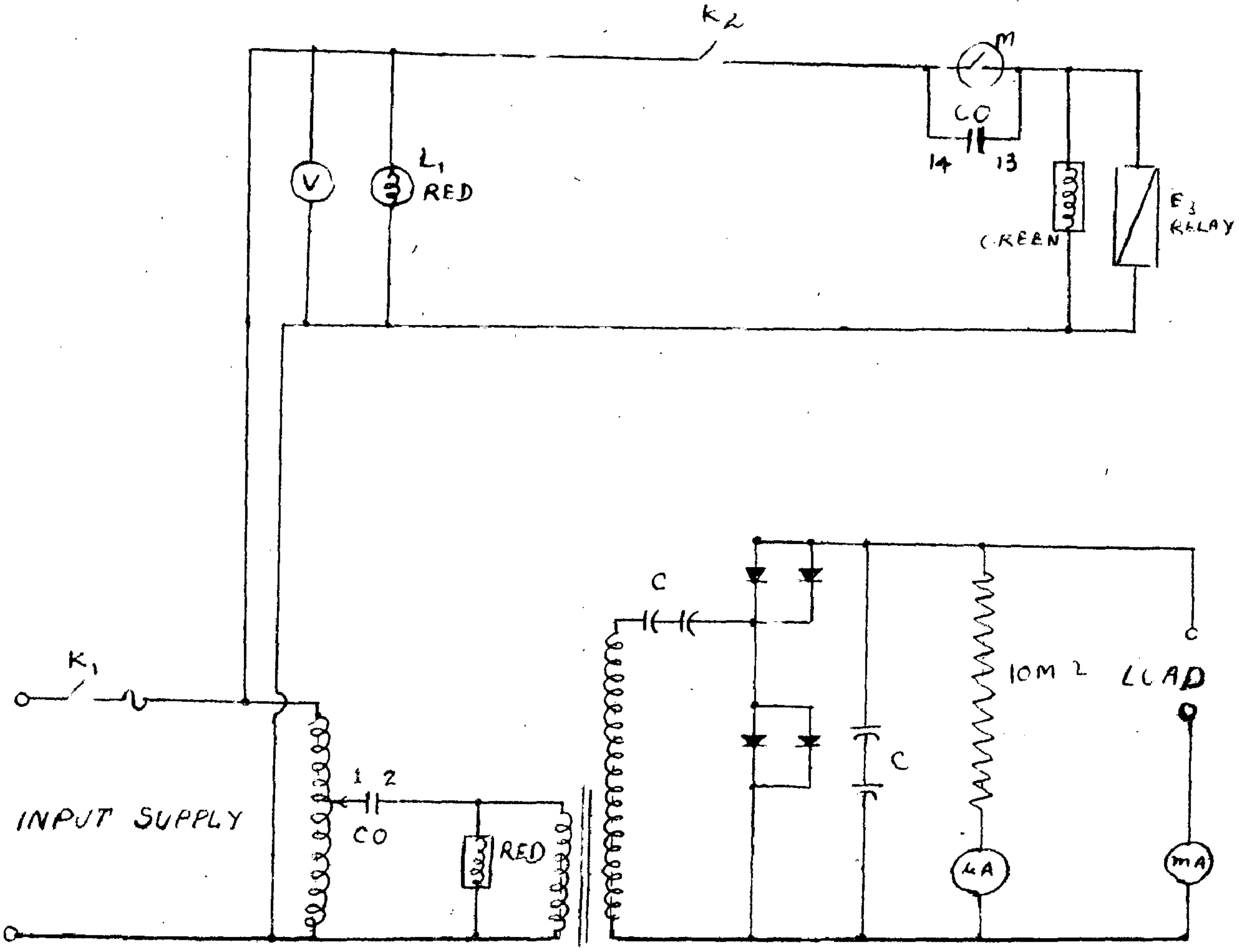

FIG. 6·4·3 b SUPPLY FOR TESTING OF TRIGGATRON TRIGGERING DEVICE

(CO : CONTACTS OF $E_3$ RELAY)

## 7 IMPULSE GENERATOR OPERATION

While operating the impulse generator following Sequence of instructions is to be followed:

### 1. For 30 KV Set

a. Earth one pole of generator and one pole of object.

b. Plug in the supply points into 3 way socket 1 on the front panel.

c. Keep the auto transformer at minimum position.

d. Switch on the switch $K_1$ on the board.

e. Move the auto slowly and thus high voltage 'ON' is indicated by red lamp $L_1$.

f. Increase the auto transformer putting slowly and make desired voltmeter reading after seeing calibration chart of d.c. voltage output Vs A.C. voltage input.

g. Check the output voltage reading with the help of calibrated chart ( D.C. voltage output Vs Ammeter current (mA) and ammeter $A_1$ reading.

### 2. For 11 KV Supply

a. Plug in the supply points into 3 way socket 2 on the front panel.

b. Switch on the switch $K_2$ on the board.

c. Check the output voltage reading with the help of calibrated chart (D.C. voltage output Vs Ammeter Ammeter current (mA) and ammeter $A_2$ reading.

### 3. For trigetron triggering device

a. Switch on the switch $K_3$ on the board.

b. Push button $P_1$ to trigger the spark gaps.

## 8 DISCUSSIONS

The evolution of multistage circuit from the original idea of Marx, now can meet any load conditions likely to occur in practice. Use of high voltage and a few stages is advantageous from the stand point of simplicity and economy, as multistage unit requiring a lower input voltage is less subjected to corona problems and offers further advantages of flexibility. In chapter 3 as we have shown the exact calculation is tedius to perform and the complication enormously increased if attempts are made to analyse the multistage circuit, with its many degrees of freedom, coupled with the difficulty of assigning precise values to many of the parameters such as stray capacitance to earth at different points in the circuit. Simple calculations such as those outlined, together with the use of C.R.O. permit considerable and rapid control of output wave shape of impulse generator.

A high voltage could be provided by a single capacitor charged from a high direct voltage source, but it is expensive.

As we know the capacitance of H.V. cables is roughly of the order of 0.2$\mu$F per 1000 yard; we have to test only a few yards of cable. However there are generators availablee which can be made to test complete manufacturing length. Such type are available in Switzerland, Germany and Denmark. They differ fundamentally; a high voltage cable is used in generator capacitance, so that much higher charging voltage can be employed with this system all the complications of marx i.e. series parellel, spark gaps, adjustments etc. can be eleminated entirely. In Felten und Guilleanme, Cologue. The main capacitanc comprises two drums of cable which are charged to 700 KV. The generator is for 1400 KV operation with a discharging energy 110 KW sec.

The resin bounded paper insulation is probably better than procelain from the leakage point of view in high humidity, but it may suffer damage through flashover, and its use therefore, should be confined to relatively easily replaceable components.

A 50 cycle test should be a type test on the complete apparatus or on component parts and may necessiatate testing to destruction, whilst the impulse testing purpose should be achieved by ordinary acceptance test, which should verify that the apparatus is sound but should avoid any unnecessary risk of damage.

According to Edwards and Perry use of solid resistors are better than wire wound but this must be giving problems of skin effect and at the moment of discharge passing. In case of wire wound resistance when their L/R rate is smaller than 0.1 $\mu$sec, the use of wire wound resistors are advantageous. The can be designed to have desired value of resistance, heat capacity and length simply by changing the size of conductor. The winding is of so called non inductive type giving sufficiently low values of inductance although not eleminating it entirely.

For a given power rating the capacitance of generator must be inversely proportional to the square of the voltage rating of the test object. Hence it is desirable to have a provision that the condensers of the generator should be readily arranged in parallel when testing low voltage objects.

The continued use of impulse generator will make the gaps pitted and oxidized. This will alter the uniformity of electrosta ic field in the gaps and could affect the generator stability in two ways:

a. By making the gaps slightly less sensitive to dust it could increase the generator stability.

b. By raising the impulse ratio of gaps it would make then more difficult to trigger on the very short duration over voltage available and might possibly lead to the necessity of making the gap smaller. This would decrease the generator stability.

We may think of single or two stages generator as it is attractive on account of its simplicity and possibility of its cost. However, there is first the fact the higher the charging voltage the greater is difficulty and expense of supressing discharge from the leads during charging. Secondly a few laboratories can allow themselves the luxury of a range of impulse generators and space. Most of the labs have to content themselves with one really big one only. This may be used very occationally at its full output voltage; for most of the time it is working at much lower voltage on a wide variety of loads. It is here that the flexibility and ease of extension of the multistage generator become valuable.

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