STUDY OF IMPULSE GENERATOR AND DETERMINATION OF IMULSE BREAKDOWN VOLTAGE OF SPHERE GAP (CRITICAL FLASHOVER VOLTAGE)

3rd Year UG Power System Lab

OBJECTIVE

- Study of impulse voltage generator
- Generation of standard impulse voltage and
- Determination of impulse breakdown voltage of sphere gap

Standard Impulse Voltage Waveform

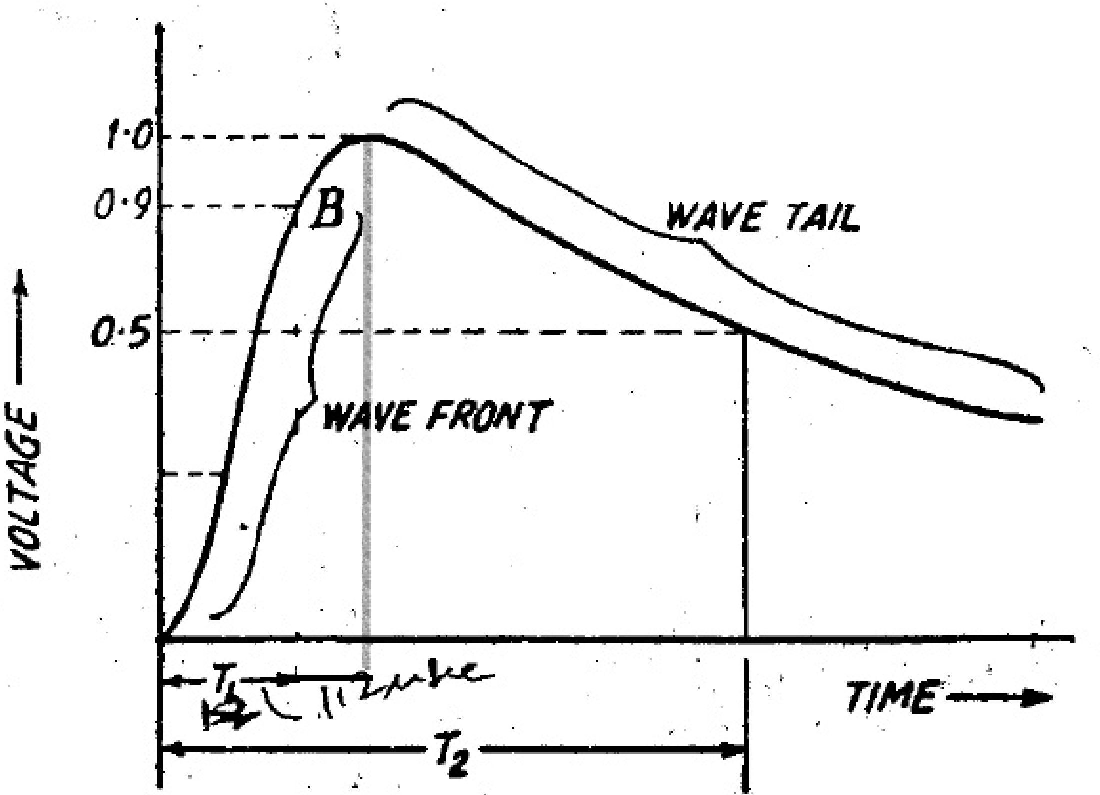


Fig. 1: 1.2/50 μs standard lightning impulse voltage

For standard lightning impulse voltage, T_1 = 1.2 μs and T_2 = 50 μs

Double exponential impulse voltage waveform: $V = V_0 \left[\exp(-\alpha t) - \exp(-\beta t)\right]$

For 1.2/50 μs, 1/ β << 1/ α

Principle of Impulse Voltage Generation

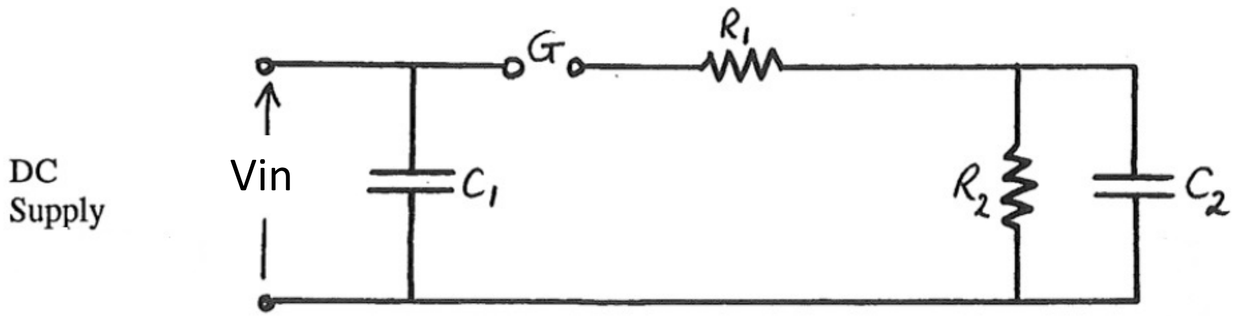
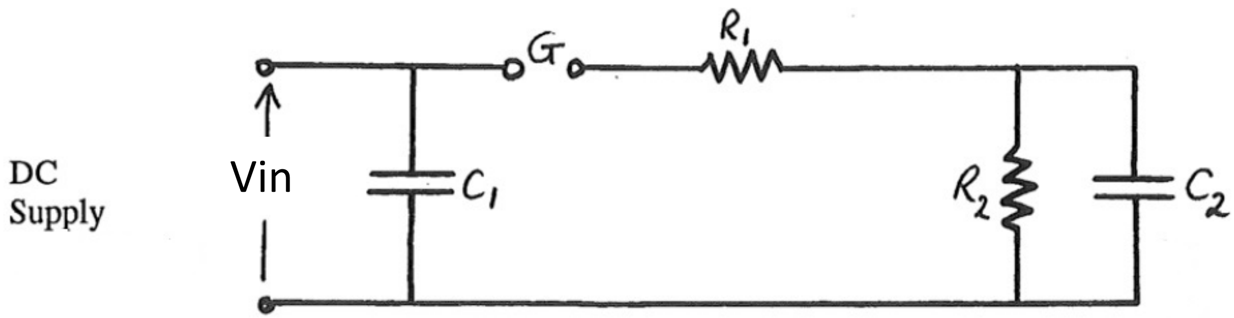


Fig. 2: R-C circuit for impulse voltage generation

- **C_1 = source capacitor (say C_1)**
- **C_2 = load capacitor (say C_2)**
- **R_1 = damping resistor or front resistance (R_1)**
- **R_2 = discharge resistance or tail resistance (R_2)**
- **V_t = Impulse voltage output across load capacitor C_b**
- **Double exponential impulse voltage,** $V = V_0\,[\exp(-\alpha t) - \exp(-\beta t)]$
  - **$\alpha + \beta = -(1/R_1C_1 + 1/R_2C_2 + 1/R_1C_2)$,**
  - **$\alpha * \beta = 1/R_1R_2C_1C_2$ and**
  - **$V_0 = V_{in} / R_1 * C_2$**
  - **for lightning impulse, $R_2 >> R_1$**

Important Parameters of Impulse Voltage Generator

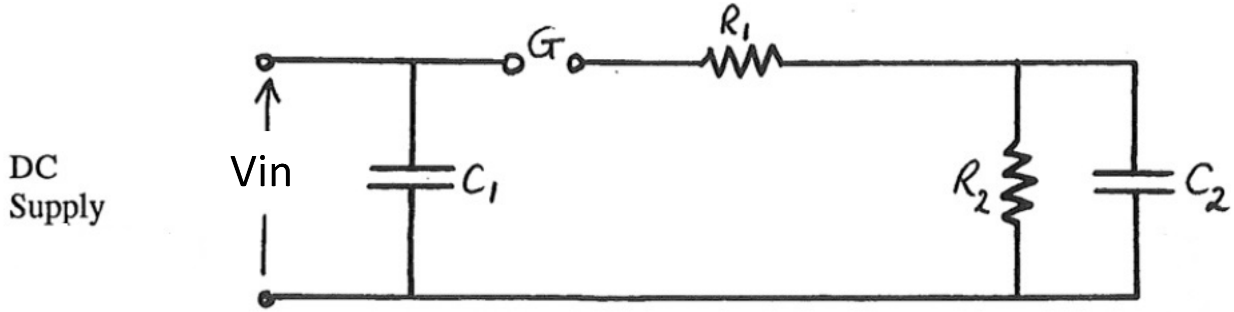


$$V = V_0 [\exp(-\alpha t) - \exp(-\beta t)]$$

- **Rise time T_1 (time to reach to peak value)**
- **Fall Time T_2 (time to fall to 50% of peak value)**
- **Peak Voltage V_p**
- **Voltage efficiency** $\eta = V_p/V_{in}$
- **Maximum stored energy = ½ * C_1 * V_{in}^2, this energy determines size and cost of imulse generator**

- **For 1.2/50 μs impulse voltage, 1/β = 0.405 and 1/ α = 68.1**

Approximation of **α and β**



$$V = V_0 \left[\exp(-\alpha t) - \exp(-\beta t)\right]$$

- **For fast rising and slow fall of impulse voltage waveform, R_2 is made very large compared to R_1 (i.e. R2 >> R1) and C_1 is also kept larger than C_2 (i.e. $C_1 >> C_2$)**
- **Therefore, C_2 gets charged mainly through R_1 and C_1 during front time and C_1 and C_2 both get discharged through R_2 during fall time**

Approximation of **α and β**

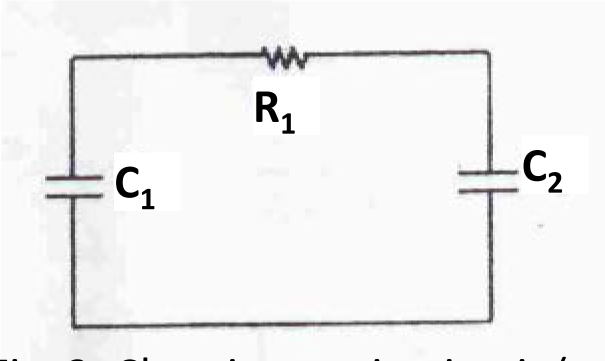


Fig. 3: Charging equiv. circuit (approx.)

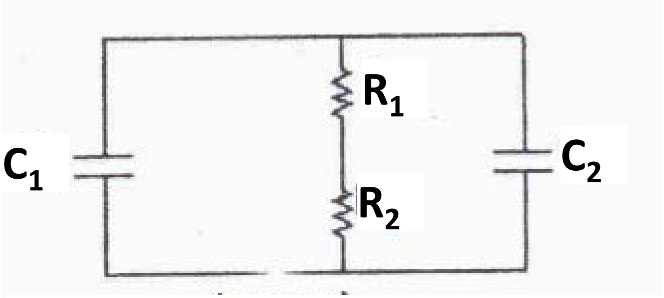


Fig. 4: Discharge equiv. circuit (approx.)

- **Charging time constant = $R_1 * (C_1*C_2/(C_1 + C_2)) \approx R_1*C_2$**
- **Discharge time constant = $(R_1+R_2)*(C_1 \,||\, C_2) = R_2*C_1$**

- **For double-exponential impulse voltage waveform, rise time is mostly dominated by β and fall time is dictated by α and therefore,**
- **$1/\beta = R_1*C_2$ and $1/\alpha = R_2*C_1$**

Limitation of single stage impulse voltage generator (for V_p > 200 kV)

- **Size of individual element will be large**
- **Difficulty in obtaining high DC voltage source for charging C_1**
- **Difficulties in using spark gap for switching at very high voltage**
- **Difficulties in suppressing corona discharges from the structural leads**

***** To overcome these difficulties, in 1923, Marx proposed a circuit where a number of source capacitors are charged in parallel and then discharged in series through spark gaps***

Marx Generator Circuit

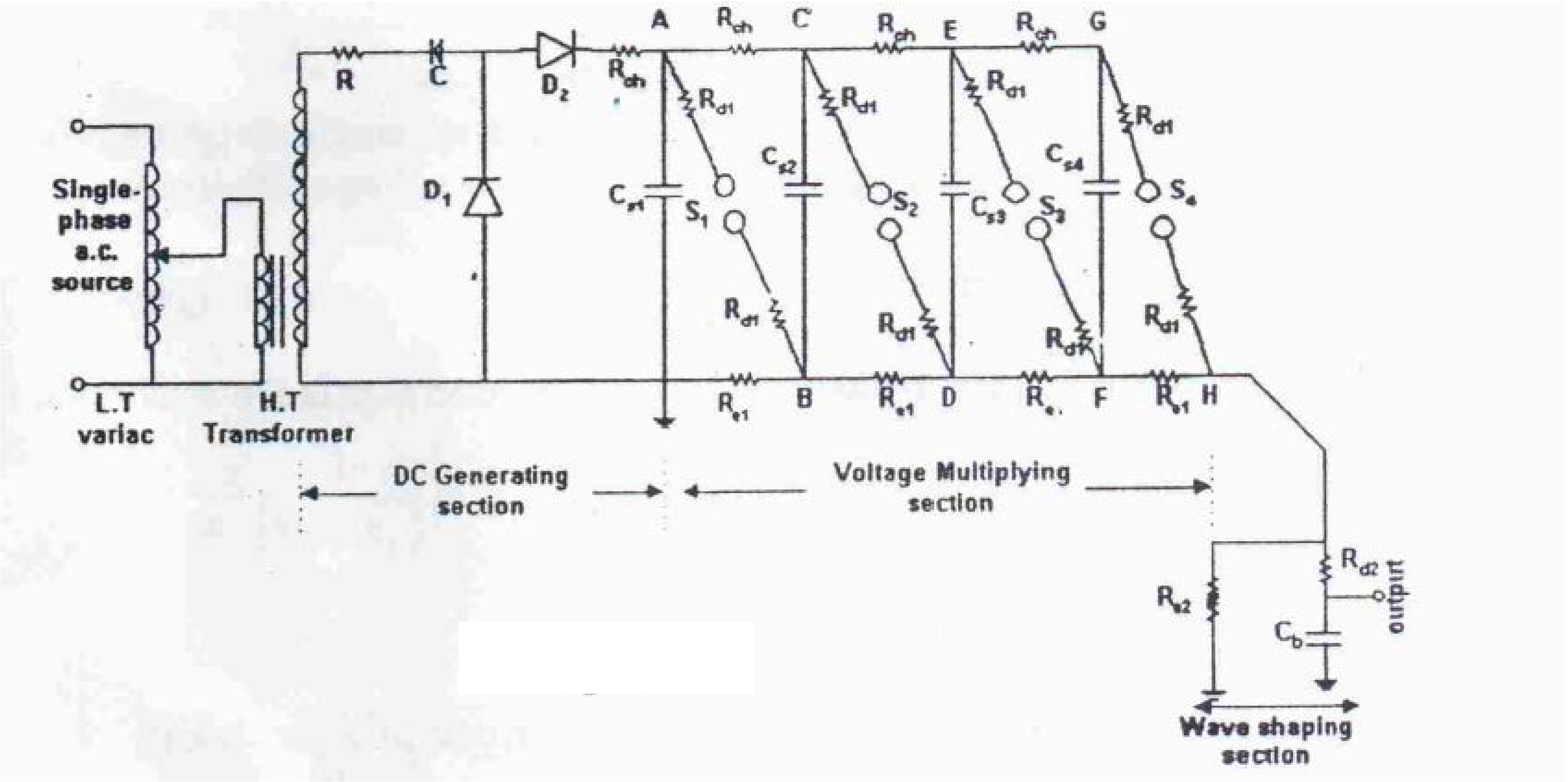
- 

Fig: 5-stage impulse voltage generator circuit

Marx Generator: Equivalent single stage generator

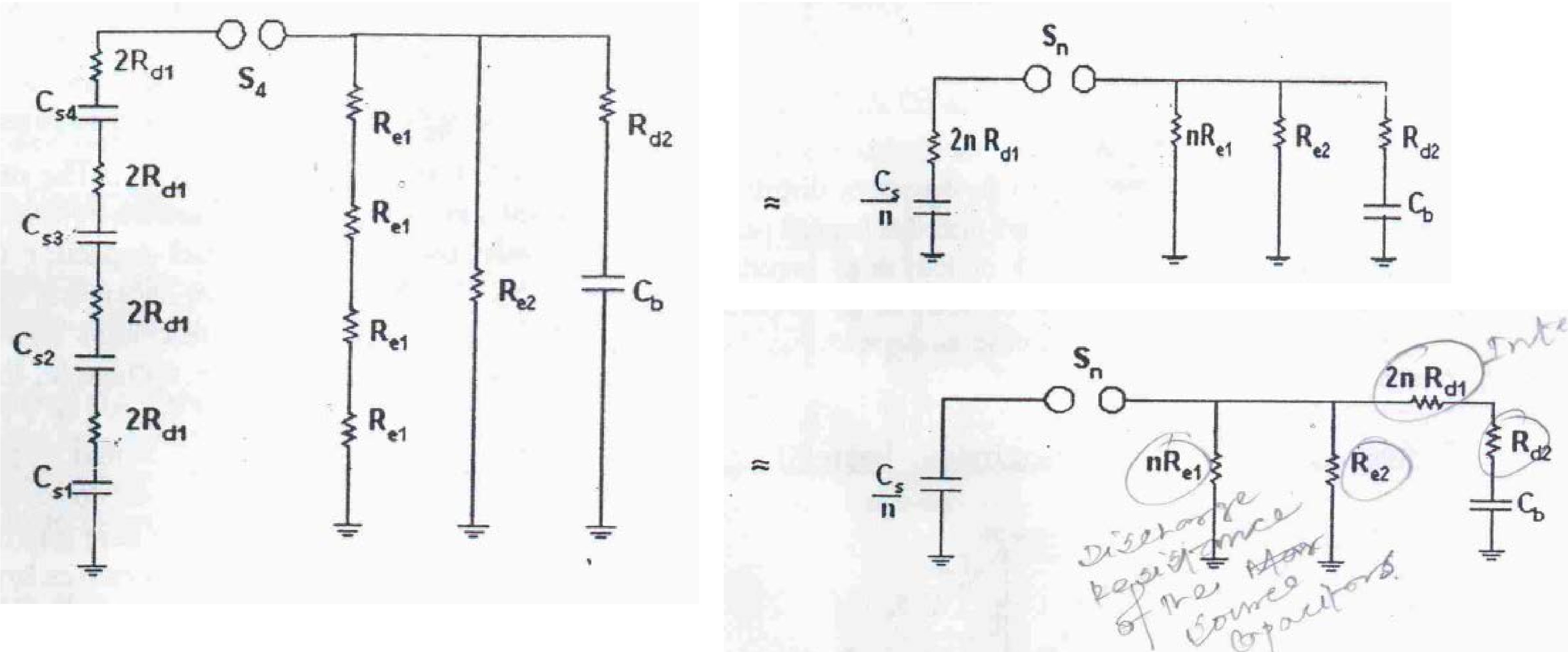


Fig. 6: Equivalent single stage circuit just after triggering the generator circuit

Marx Generator: Working Principle

1. **DC Generation:** Conventional Cockroft-Walton Voltage Doubler Circuit or even a single-phase half wave diode rectifier is used to generate DC voltage for charging source capacitors. Output DC voltage is usually kept between few tens of kV to maximum 200 kV
2. **Voltage Multiplying:**
   - During charging all source capacitors are charged to input DC voltage through R_{ch} and R_1.
   - All spark gaps are initially kept at a distance to withstand the charging voltage
   - To obtain impulse voltage across load capacitor, triggering of impulse generator is performed by causing breakdown of sphere gap S_1. (simply reduce the gap distance S_1)
   - Breakdown of S_1 causes automatic breakdown of sphere gaps S_2, S_3, and S_4 in succession.
   - Breakdown of S_4 leads to charging of load capacitor and discharging of source and load capacitors
   - Desired impulse voltage is generated across load capacitor

Marx Generator: Working Principle …

1. **Wave Shaping:**
   - **To achieve standard impulse wave-shape, external front and tail resistances are commonly changed**
   - **Equivalent front and tail resistances are also partially distributed within the impulse generator. If needed, these internal resistances are also changed to achieve standard impulse wave-shape.**

Six-Stage Marx Generator in High Voltage Lab (600 kV, 18 kJ)

Fig. 7: Six stage impulse voltage generator in HV Lab

Six-Stage Marx Generator in High Voltage Lab (600 kV, 18 kJ)

Diode

Single phase step up transformer

Fig. 8: Single phase half-wave diode rectifier for DC generation

Six-Stage Marx Generator in High Voltage Lab (600 kV, 18 kJ)

Fig 9: Six stage Marx generator for voltage multiplying

Sphere gap arrangement with resistive voltage divider

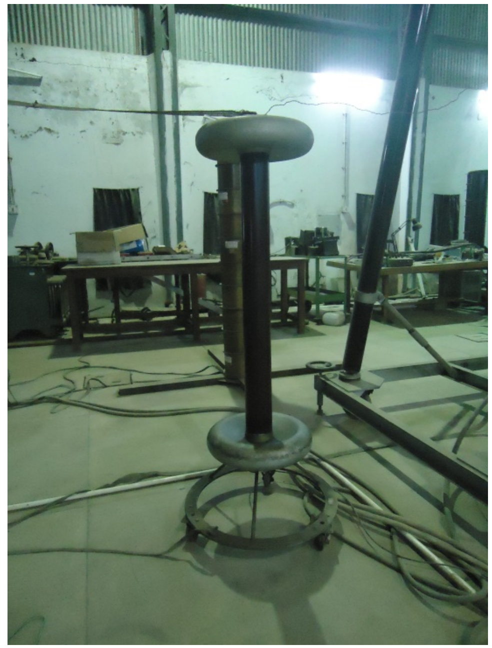


Fig 11: Resistive voltage divider

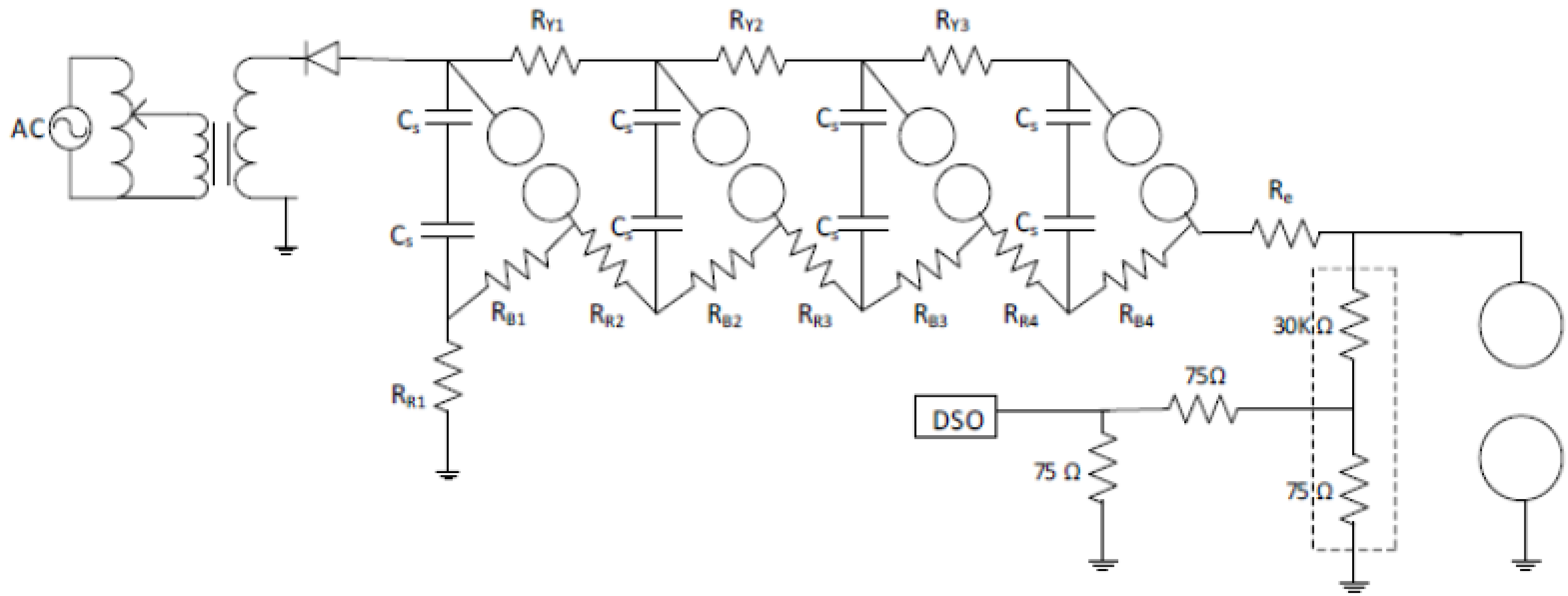
Fig 10: Sphere gap arrangement with resistive voltage divider

Fig 12: Sphere gap arrangement (70 mm gap)

Sphere gap arrangement with resistive voltage divider

Fig 13: Control panel with DSO

Equivalent Circuit of 4-Stage Generator



$R_{Y1} = R_{Y2} = R_{Y3} = 8.5k\ \Omega$, $R_{R1} = R_{R2} = R_{R3} = R_{R4} = 15\ \Omega$, $R_{B1} = R_{B2} = R_{B3} = R_{B4} = 115\ \Omega$, $R_e = 160\ \Omega$

C_S= Capacitor= 1.2 μ F, 50 KV

Fig 14: Circuit representation of 4-stage Marx generator in High Voltage Lab

Determining impulse breakdown voltage for sphere gap

BDV: Minimum applied voltage that causes breakdown of an insulation gap. BDV is always measured by the peak of the input voltage.

Air Breakdown Voltage: For uniform field gap, air breakdown voltage is 30 kV_P/cm

AC Breakdown Voltage vs Impulse Breakdown Voltage:

If the sinusoidal voltage is gradually increased across the gap, the breakdown occurs when the peak value of the applied voltage reaches the breakdown voltage (known a priori). Important observation is that the breakdown will always occur whenever the same voltage is applied across the gap. **THIS IS NOT THE CASE FOR IMPULSE BREAKDOWN… WHY??**

Breakdown of sphere gap under impulse voltage is probabilistic in nature: WHY?

Breakdown process and two steps of time-delay:

Breakdown mechanism is not an instantaneous phenomena and it requires certain amount of time to complete the process.

- **Statistical Time-Delay:** It is the time required for an initiating electron to appear in the sphere gap
- **Formative Time-Delay:** It is the time required for the establishment of breakdown after the appearance of initiating electron
- Sum of these two is approximately 2-3 μs
- *For 50 Hz sine-wave, peak value exists almost for a time duration of 0.2 ms which is large compared to the time required for breakdown. Hence, the breakdown always occurs for the same applied voltage. For impulse voltage, peak value exists only for a fraction of micro-second. Hence impulse breakdown is probabilistic in nature !!*

Discharge probability as a function of crest value

- **The behavior of air gap insulation is defined by the discharge probability as a function of crest value V_p**
- **Discharge probability is described by the normal distribution density function (Gaussian)**

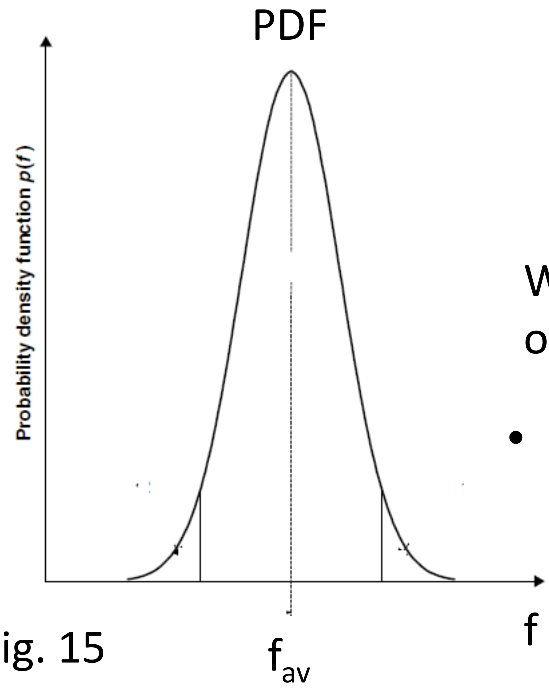


Fig. 15

- Normal distribution density function is given by:

$$p(f) = \frac{1}{\sigma\sqrt{2\pi}} e^{-((f_k - f_{av})^2/2\sigma^2)}$$

Where, f_k is the k^{th} value of the variable, f_{av} is the average or mean value and σ = standard deviation

- When crest value of applied voltage V becomes variable, probability density function becomes

$$p(V) = \frac{1}{\sigma\sqrt{2\pi}} e^{-((V - V_{50})^2/2\sigma^2)}$$

where, V_{50} is the voltage which leads to mean value or average value

Discharge probability as a function of crest value

- **More convenient form of normal distribution is the cumulative distribution function (CDF), the integral for eqn. 1 which has the form**

$$P(V) = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{V} e^{-(V-V_{50})^2/2\sigma} dV$$

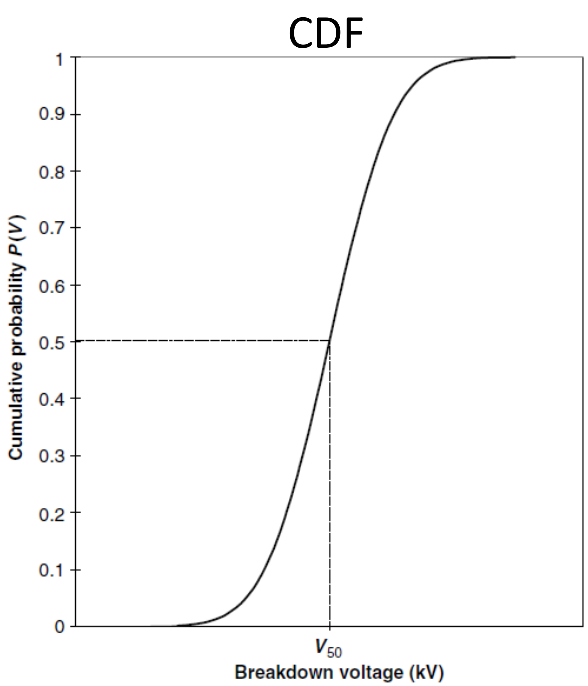
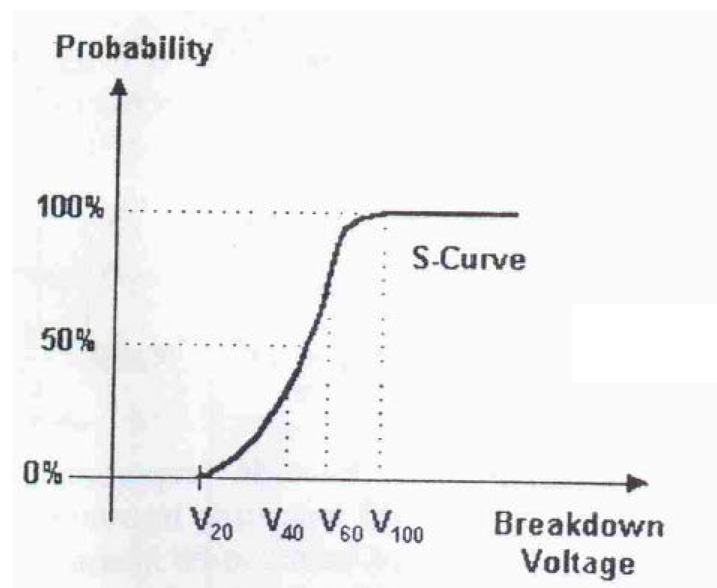


Fig 16: Gaussian cumulative distribution function



Curve is linear from 30% to 90%

** V_{50} is the voltage which leads to 50% probability of discharge

Experimental procedure to determine critical flashover voltage for sphere gap

- **Refer 'procedure' in instruction manual…..**

Table I

Record of Flashover

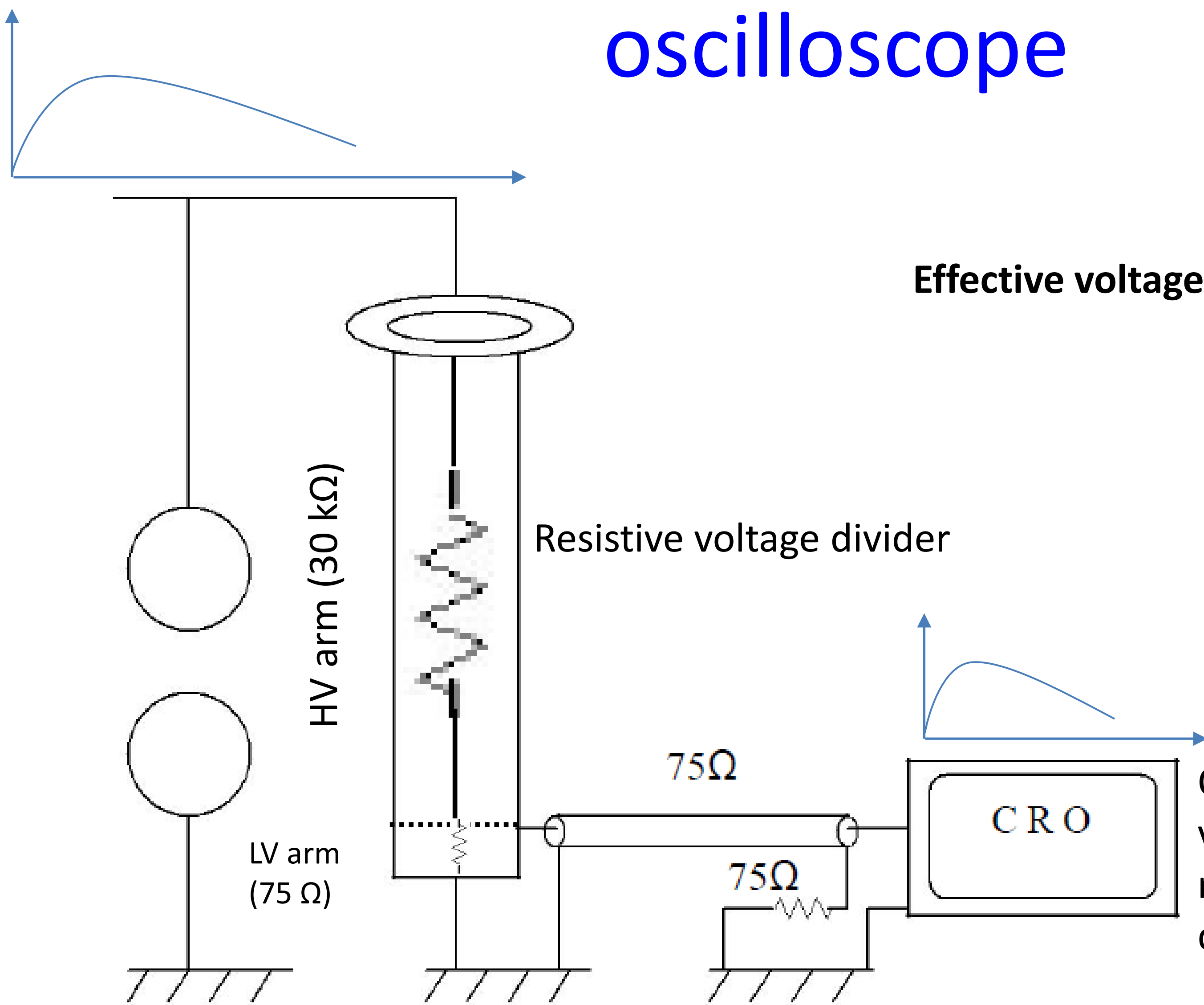
Voltage Level/ Stage kV	Pulse No.										Probability of Flashover
	1	2	3	4	5	6	7	8	9	10	
35	W	W	W	W	W	W	W	W	W	W	
37	W	W	W	W	F	W	W	W	W	W	
37.5	W	F	W	W	W	W	F	W	F	W	
37.7	W	F	W	F	F	F	F	W	F	F	

\# **F** - Flashover **W-** Withstand

Atmospheric Condition: (1) Pressure: 755 mm Hg (2) Temperature: 33°C

- Using voltage divider, measured impulse peak from DSO is 180.1 V for 37.5 kV stage voltage
- Using voltage divider, measured impulse peak from DSO is 181.67 V for 37.7 kV stage voltage

Measuring impulse voltage using oscilloscope



Effective voltage divider ratio = ??

CRO acquires the impulse voltage of reduced magnitude, but with no distortion

Fig. 17: Measurement circuit for impulse voltage

Atmospheric correction factor

- **Air density correction factor:** $K_1 = P_1/P_2 * (273+t_0)/(273 + t)$
- $V_{BD} = V_0 * K_1 * K_2$
- **Humidity correction factor (K2): No humidity correction factor for sphere-gap arrangement**
- ***Refer annexure for more details…***

Lab Report Preparation

- **Name of the experiment**
- **Objective**
- **Schematic diagram of experimental setup**
- **Draw a standard 1.2/50 μs lightning impulse voltage (100kV) on appropriate scale**
- **Compute probability and draw "Probability vs Breakdown Voltage" curve for the records in Table 1**
- **Determine CFO voltage for 70 mm sphere gap at STP from the experimental measurement**
- **Draw single stage equivalent circuit for 4-stage Marx generator in Fig. 14 and obtain equivalent parameters**
- **Also obtain the approximated expression for double exponential impulse voltage across load capacitor**

ANSWER THE FOLLOWING QUESTIONS

- **Why is the impulse breakdown of a sphere gap is statistical?**
- **How is the wave shape of impulse voltage is controlled?**
- **Why it is the capacitive storage, not the inductive storage for impulse voltage generator**
- **Describe, briefly, how the operator can vary the peak of the impulse voltage.**
- **Describe the concept of 50% flashover voltage and indicate how it can be determined for a test sample, such as an insulator**