

BREAKDOWN STUDY OF WATER WITH DIFFERENT CONDUCTIVITIES

¹S. THIVYA, ²V. GOWRI SREE

¹M.E. High Voltage Engineering, Department of Electrical and Electronics Engineering,
College of Engineering Guindy, Anna University, Chennai

²Associate Professor, Division of High Voltage Engineering, Department of Electrical and Electronics
Engineering, College of Engineering Guindy, Anna University, Chennai
E-mail: ¹thivya1012@gmail.com, ²vg_sree@annauniv.edu

Abstract— Water is the abundant source in nature and used in various aspects of mankind. This water is also used in many parts of pulsed power systems as a liquid dielectric. The major factor for the choice of water as dielectric is due to its high breakdown strength, high dielectric permittivity, high dielectric constant, self-restoring ability, low cost and ease of handling. This paper focuses on the breakdown strength of water such as Tap water and Distilled water with different conductivities under impulse voltage. The main aim of this paper is to determine the volt-time characteristics of water (i.e. Tap water & Distilled water) and Ionic solution (i.e. Sodium chloride and Copper sulfate solution) under impulse voltage. The effect of applied voltage polarity in breakdown phenomena, the breakdown strength of water is analyzed under positive and negative impulse voltage. This Breakdown study on ionic solution helps to know the breakdown strength of water with different conductivity level by suspending Sodium Chloride and Copper sulfate to the water. The prediction of Volt-time characteristics of Distilled water is also determined at various inter-electrode distances under needle-plane electrode configuration.

Index Terms—Breakdown Strength, Inter-electrode gap, Volt-time characteristics.

I. INTRODUCTION

Water is used as a liquid dielectric in many parts of pulsed power systems including intermediate stores in accelerators and pulsed forming lines of impulse generators. Plasma closing switches and the loads of electro-hydraulic and impulsive high-power ultrasound systems are often filled with water. This choice of water as a liquid dielectric is due to its high breakdown strength and high dielectric permittivity. Emerging pulsed power technologies for environmental and bio-medical applications also require information on breakdown strength and other characteristics of water stressed with high voltage impulse[1].

The breakdown voltage level of water under the impulse voltage of a given shape is not a constant parameter. The breakdown voltage of water depends on various factors such as nature of water, electrode geometry, polarity of applied voltage, gap length, electrode material etc. The breakdown study is done in Tap water, Distilled water and ionic solution under needle-plane electrode topology. The ionic solution is used as electrolyte in High-Power High-Voltage tight resistors. These resistors are made up of ionic solution (i.e. water solutions of salts, acids and their mixtures) where salt level is adjusted according to the required resistivity. In this paper the Breakdown characteristics of ionic solution and the volt-time characteristics of ionic solution is also determined [6]. There are various types of ionic solution used in high voltage resistors, among them the most commonly used ionic solution (i.e. copper sulfate and sodium chloride solution) is analyzed and the breakdown study is determined.

II. GENERATION OF IMPULSE VOLTAGES

The standard impulse voltage $1.2/50\mu\text{s}$ is generated as per Indian standard (IS 2071) and specification. The impulse waveform considered for analysis is within the tolerances specified in IS standards. The Fig1 is Marx circuit used for generation of standard lightning impulse of 140 kV, MWB (Mess Wandler-Bau) high voltage test kit available in the high voltage laboratory in College of Engineering, Guindy, Anna University, Chennai, is used to generate the impulse voltages. The waveforms are recorded using the Digital Storage Oscilloscope (DSO) TDS3054B at the sampling rate of 250 MSa/s.

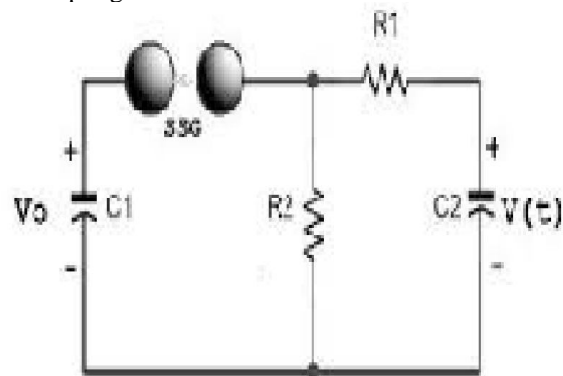


Fig1 Marx circuit

The capacitor C_1 is previously charged to a particular DC voltage and suddenly discharged into the wave shaping network through the sphere gap arrangement. The discharge voltage across the capacitor C_2 gives rise to the desired double exponential wave shape. The desired wave shapes are obtained by controlling wave shaping resistors (R_1 and R_2).

III. VOLT-TIME CHARACTERISTICS

The Electric field (E_b) can be used for characterization of the dielectric properties of liquid water. In the case of a low-divergent (uniform) electric field, the breakdown field can be evaluated as

$$E_b = V_b/d \quad (2)$$

Where d is the gap distance between the electrodes, V_b is Breakdown voltage. This relationship is called the volt-time (V-t) breakdown characteristic and such empirical scaling relationships are used in the design of high voltage and pulsed power systems in which water is employed as a dielectric or working fluid[3].

IV. V-t CHARACTERISTICS OF WATER UNDER NON-UNIFORM FIELD

The volt-time characteristics of Tap water and Distilled water under needle-plane electrode topology at different inter electrode distance (i.e. 2mm & 3mm) at both positive and negative impulse voltage is determined. The Fig 2 & Fig 3 shows the V-t curve of Tap water under positive impulse at 2mm & 3mm. The Fig 4 & Fig 5 shows the V-t curve of Tap water under negative impulse at 2mm & 3mm.

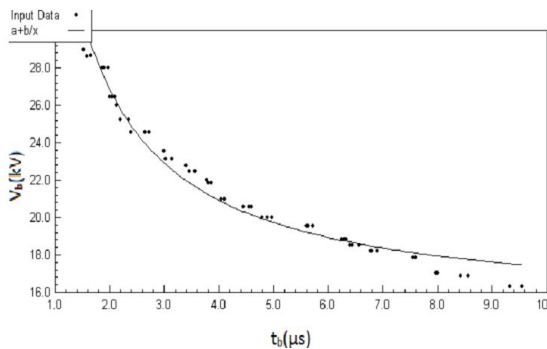


Fig 2. V-t characteristics of tap water under positive impulse at d=2mm

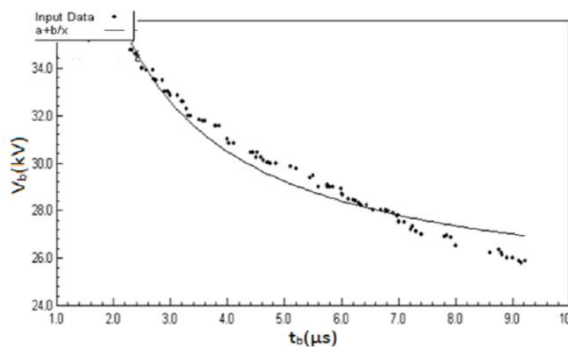


Fig 3. V-t characteristics of tap water under positive impulse at d=3mm

Fig 2 and Fig 3 is v-t curve of tap water under positive impulse at 2mm and 3mm inter electrode gap respectively. At 2mm inter electrode gap the minimum breakdown voltage of tap water is 18kV with breakdown time is 9.6 μs, as the voltage is increased from minimum breakdown voltage, the breakdown time starts to decreases gradually. At 3mm inter electrode gap the minimum breakdown

voltage tap water is 29kV with 9μs breakdown time. As per [5] if the voltage is increased above minimum breakdown voltage the breakdown time starts to decrease, this is followed in the v-t characteristics of tap water under positive impulse in needle-electrode topology.

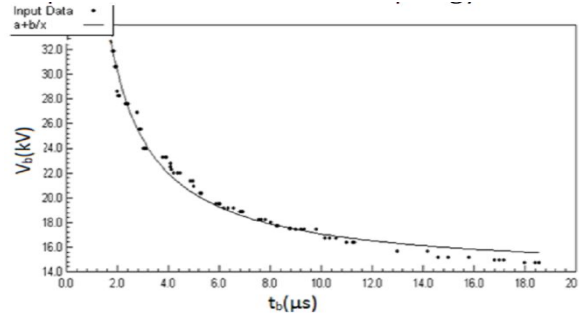


Fig 4. V-t characteristics of tap water under negative d=2mm

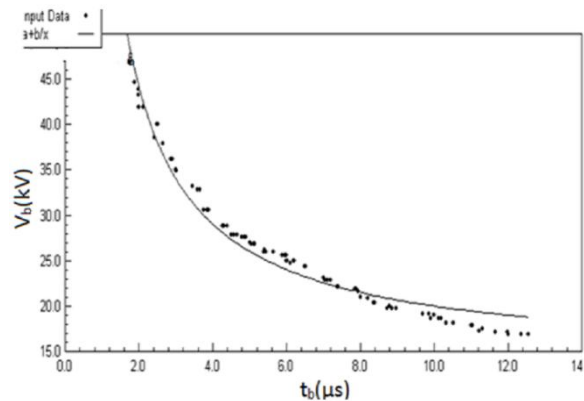


Fig 5. V-t characteristics of tap water under negative at d=3mm

Fig 4 and Fig 5 is V-t curve of tap water at 2mm and 3mm inter electrode gap respectively under negative impulse voltage. The minimum breakdown voltage of water at 2mm gap in negative impulse voltage is 16kV with 18μs breakdown time. As the voltage is increased above minimum breakdown voltage the time to breakdown started to decrease gradually. The breakdown voltage of Tap water is high under positive impulse than negative impulse. The breakdown occurs along front time for positive impulse whereas the breakdown occurs on the tail time of the negative impulse.

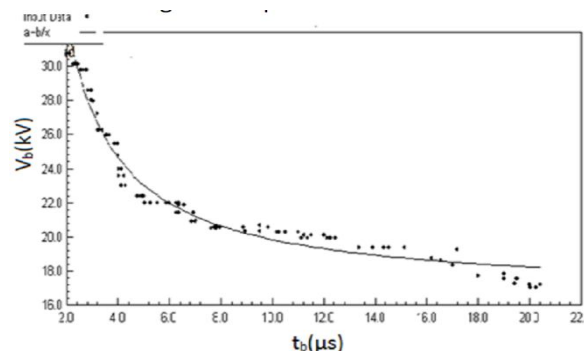


Fig6. V-t characteristics of distilled water under positive impulse at d=1mm

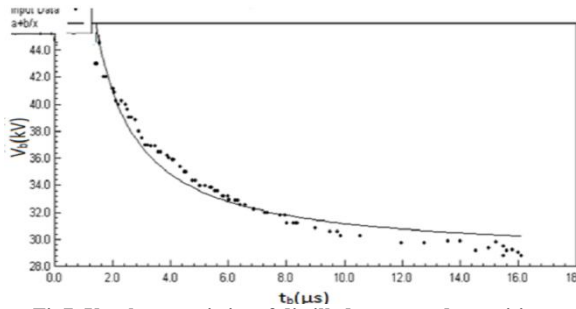


Fig. 7. V-t characteristics of distilled water under positive impulse at d=2mm

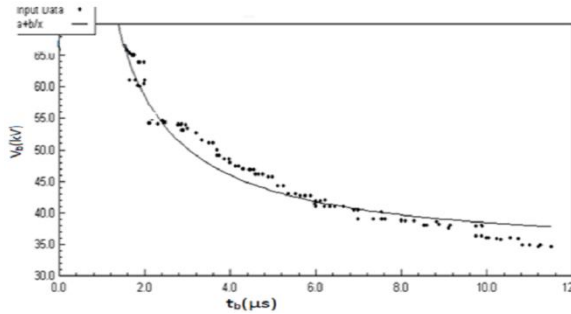


Fig. 8. V-t characteristics of distilled water under positive impulse at d=3mm

The Fig 7 and Fig 8 shows the Volt-time characteristics of distilled water under positive impulse at 2mm and 3mm inter electrode gap spacing respectively. The minimum breakdown voltage of distilled increase as the inter electrode gap increases. The minimum breakdown voltage of Distilled water under positive impulse at 2mm and 3mm electrode space is 30kV and 37kV respectively. The distilled water has higher breakdown strength than tap water under positive impulse.

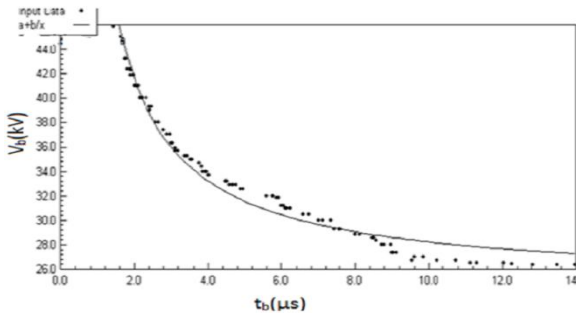


Fig. 9. V-t characteristics of distilled water under negative impulse at d=2mm

From Fig9 the minimum breakdown voltage of distilled water under negative impulse at 2mm inter electrode gap spacing is 27kV with 14μs breakdown time. The breakdown strength of distilled water is higher under positive impulse than negative impulse at same electrode gap spacing. The minimum breakdown voltage of distilled water under negative impulse at 3mm inter electrode space is 32kV with 15μs breakdown time. The breakdown strength is high under positive polarity impulse voltage in both tap and distilled water. Thus breakdown strength is also influenced by the distance between the

electrodes, as the distance increases the breakdown voltage increases both in tap and distilled water. The breakdown strength of distilled water is carried out under uniform and non-uniform field at 1mm inter electrode distance. The breakdown strength of distilled water is high under uniform field than under non uniform field distribution. This is due to high field stress across needle-plane electrode under both positive and negative impulse voltage. The breakdown strength is high while applying positive impulse than negative impulse voltage. Thus polarity of the impulse applied influences the breakdown of water. From Table I the breakdown strength of distilled water is compared under uniform and non-uniform.

Table I Breakdown Strength of Distilled water Property

Property	Breakdown Strength at	
	Uniform Field (kV/mm)	Non-Uniform Field (kV/mm)
Electrode Configuration	Hemisphere-Hemisphere	Needle-Plane
Positive impulse	25.5 kV/mm	17.8 kV/mm
Negative impulse	21.0 kV/mm	15.5 kV/mm

PREDICTION OF V-t CURVE OF DISTILLED WATER

From the experimental data of Volt- time characteristics of distilled water under three different inter electrode distance (i.e.1mm, 2mm&3mm) the breakdown voltage and breakdown time of distilled water at inter electrode distance between 1 to 3mm has been predicted. The V-t curve of three inter electrode distance are modelled as hyperbolic curves using Regression analysis, in order to predict the volt-time characteristics of distilled water. The Breakdown voltage under various inter electrode gap under positive impulse is shown in Table II

Table II Breakdown Voltage At Different Distance

Distance (mm)	1	2	3
Breakdown voltage (kV)	17.8	29	37

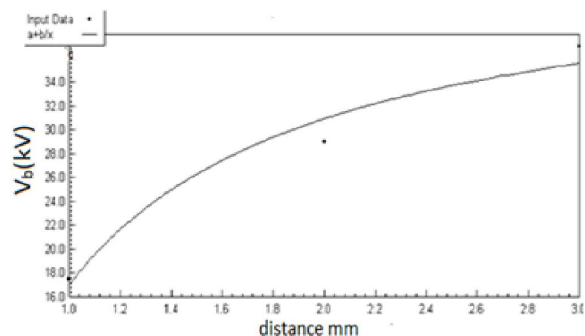


Fig. 10. Variation of Vb with distance

The Fig10 is drawn between the minimum breakdown voltage of distilled water with various inter electrode distance(1mm,2mm&3mm) of distilled water of each electrode gap spacing fits into the hyperbolic under positive impulse voltage. The points are fit under Hyperbolic equation(A+B/x) by regression analysis of the experimental data with the standard estimated error is found to be 2.45% .

$$V_b = A + B/x \quad (3)$$

In the above hyperbolic equation V_b is minimum breakdown voltage, x is a variable respect to distance mm, A and B are constant value 44.826 and -27.807 respectively which is obtained from the data fit information .On substituting A and B on the equation (3) with various x values the breakdown voltage for different distance between 1mm to 3 mm can be obtained.

Table III Prediction of Breakdown Voltage

Distance (mm)	Predicted Breakdown voltage (kV)	Actual Breakdown voltage (kV)	Error (%)
1.2	21.653	20.268	-6.3
1.5	26.288	25.637	-2.47
2.3	32.736	32.500	-0.72
2.5	33.703	33.087	-1.82

The percentage error between experimental and predicted breakdown voltage is calculated and found to be less than 10%. From the experimental data the of the V-t curve of inter electrode distance (1mm,2mm and 3mm) the breakdown time can be predicted using regression analysis.

The V-t curve equation.

$$V_b = C + D/t_b \quad (4)$$

In above equation (4) V_b is breakdown voltage, t_b is breakdown time and C and D are parameters of Breakdown voltage. The C and D parameter obtained for three V-t curves are tabulated below in Table IV .

Table IV Breakdown Voltage At Different Distance Distance mm

Distance mm	1	2	3
C (kV)	16.72	27.452	32.373
D (kV-μs)	30	31.990	59.4431

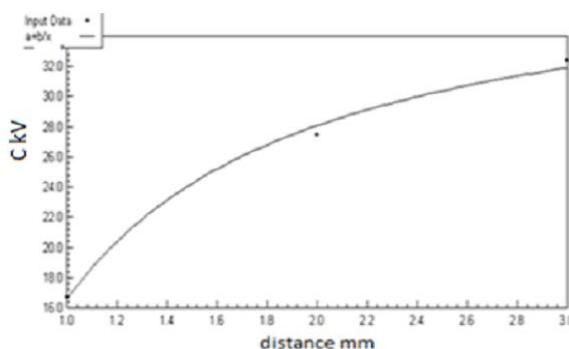


Fig 11 Variation of C with different distance

$$C = E + F/x \quad (4)$$

The breakdown voltage parameters C for three inter electrode distance fits in hyperbolic model. From the data fit information the value of E and F are obtained as 39.573 and -23.01438 respectively which is substituted in to obtain C .

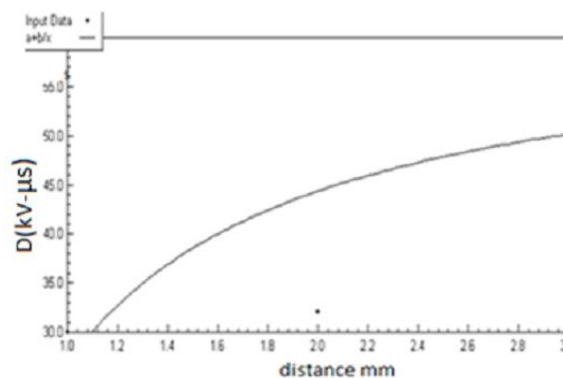


Fig 12 Variation of D with different distance

Similarly the voltage-time parameter D of three inter electrode distance is fitted under hyperbolic model with equation

$$D = G + H/x \quad (5)$$

The values G and H are 61.803 and -34.99 respectively which are obtained from data fit information. On substituting the E and F value in equation (4) and substituting G and H in equation (5)

$$C = 39.573 - 23.01/x \quad (6)$$

$$D = 61.803 - 34.99/x \quad (7)$$

The value of C and D for required inter electrode distance is measured by substituting the x value which lies between 1 to 3 mm. From the computed values of C and D the time to breakdown is calculated for various breakdown voltages and V-t curve is predicted[2].

Table V. Hyperbolic model parameters at different distance

Distance mm	1.5	2.5
C (kV)	24.233	30.38
D (kV-μs)	38.49	47.807
Predicted V_b (kV)	26.288	33.70

On substituting the V_b , C and D values in equation (4) the breakdown time t_b is obtained. The predicted breakdown time is compared with actual experimental data. The percentage error between experimental and predicted breakdown time is calculated and found to be less than 10%, which is as per the reference a

Table VI .Prediction of Vb and tb

Distance Mm	Predicted V _b (kV)	Predicted t _b (μs)	Actual t _b (μs)	Error %
1.5 mm	26.28	18.72	17.8	-4.91
	27	13.88	13.1	-5.61
	29	8.06	8.1	0.49
	30	6.67	6.4	-4.07
	35	3.57	3.9	9.24
	37	3.01	2.8	-6.9

V. V-t CHARACTERISTICS OF IONIC SOLUTION

The Aqueous Electrolyte Resistors are most widely used in High-Power High-Voltage tight resistors. These resistors are made up of ionic solution (i.e. water solutions of salts, acids and their mixtures) where salt level is adjusted according to the required resistivity .In this chapter the Breakdown characteristics of ionic solution and the volt-time characteristics of ionic solution is determined. There are various types of ionic solution used in high voltage resistors, among them the most commonly used ionic solution (i.e. copper sulfate and sodium chloride solution) is analyzed. The volt-time characteristic of sodium chloride solution is carried out in uniform field with Stainless Steel Hemisphere-Hemisphere electrode configuration. The inter electrode gap spacing is maintained at 1mm.The sodium chloride salt is added to distilled water until which it act as dielectric at 1mm electrode gap spacing without conducting. The conductivity of sodium chloride solution is kept at 0.65μS/cm above which the electrolyte acts as conductor at 1mm spacing of electrode.

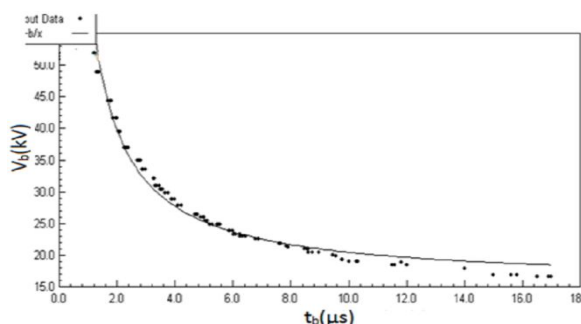


Fig12.V-t characteristics of sodium chloride solution under positive impulse at

Fig 12 is V-t curve of Sodium chloride solution at 1mm inter electrode spacing under positive impulse. The breakdown voltage of ionic solution is less than the distilled water due to increase in the conductivity of the solution. The minimum breakdown voltage of ionic solution under 1mm inter electrode gap spacing at positive impulse voltage is 18 kV (17μs).As the voltage is increased above the minimum breakdown voltage the breakdown time reduces. The breakdown time reduces to 2 microseconds when impulse voltage is raised above 50kV.

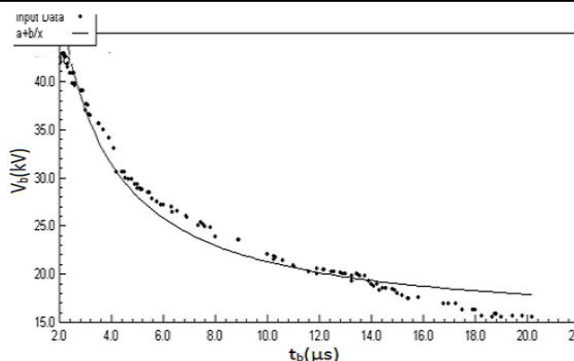


Fig13.V-t characteristics of sodium chloride solution under negative impulse

The Breakdown voltage of ionic solution is less than the distilled water due to increase in the conductivity of the solution. The minimum breakdown voltage of sodium chloride ionic solution under 1mm inter electrode gap spacing at negative impulse voltage is 16 kV (20μs) from Fig 13.

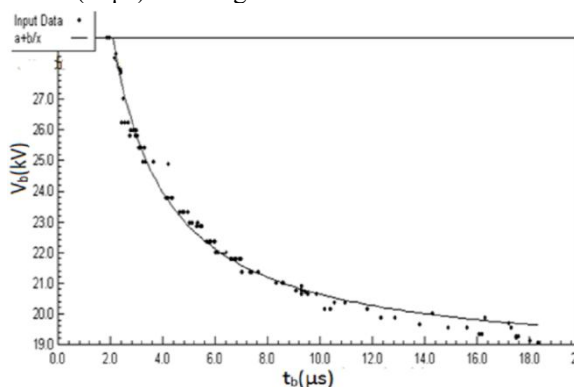


Fig 14.V-t characteristics of copper chloride solution under uniform field positive impulse

Copper sulfate resistors are widely used as high voltage resistors .Hence the breakdown characteristics of copper sulfate solution is determined under uniform and non uniform field at 1mm gap spacing of electrodes . The copper sulfate salt is diluted in distilled water until its conductivity reaches 0.6μS/cm above this conductivity the solution starts conducting at 1mm inter electrode distance. The breakdown analysis is done in copper electrodes.

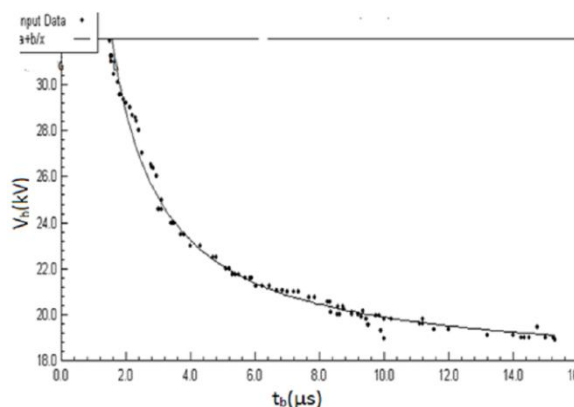


Fig 15.V-t characteristics of copper chloride solution under uniform field negative impulse

The breakdown voltage of copper sulfate solution under positive impulse voltage is higher than negative impulse which is similar in case of tap and distilled water. The minimum breakdown voltage for both ionic solutions is less under negative impulse.

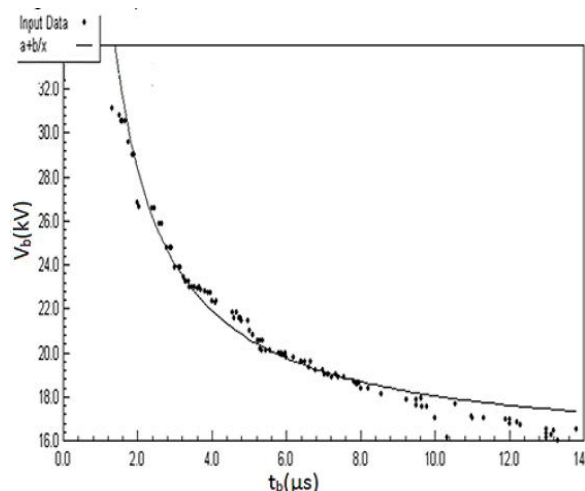


Fig.16.V-t characteristics of copper chloride solution under non-uniform field at positive impulse

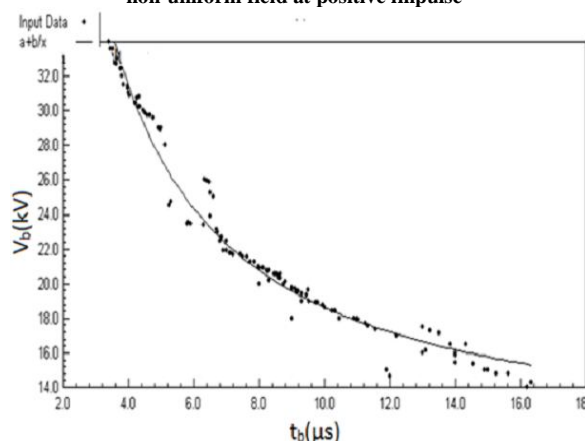


Fig.17.V-t characteristics of copper chloride solution under non-uniform field at negative impulse

Fig 18 is the volt-time characteristic curve of copper sulfate solution under non uniform field at 1mm electrode gap spacing negative impulse voltage. The minimum breakdown voltage under this set up is 15kV (16μs).

Under non-uniform field the copper sulfate solution have higher breakdown strength at positive impulse voltage than applying negative impulse voltage. The breakdown time is long when negative impulse is applied whereas it is comparatively less under positive impulse. The copper sulfate has higher breakdown strength than sodium chloride solution under both polarity impulse voltages hence it is widely used in high voltage resistors. The copper electrode used under breakdown study of copper under non-uniform field is subjected to corrosion and cracks after application of impulse voltage under copper sulfate solution. The surface of electrode is analyzed under Scanning electrode microscope to view the corroded surface.

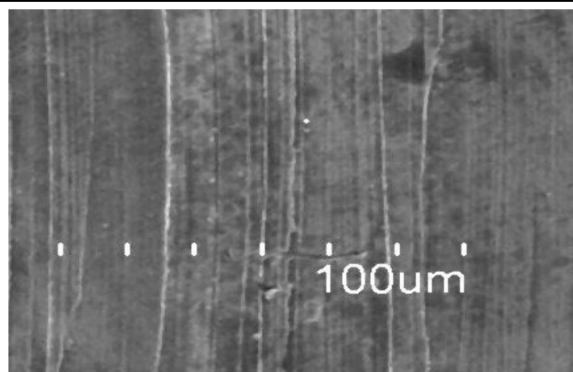


Fig.18. Microstructure of copper electrode

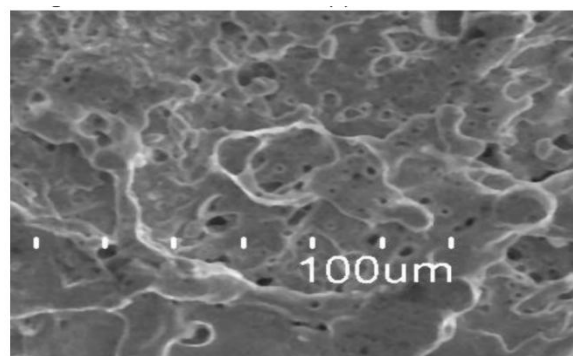


Fig.19. Microstructure of corroded copper electrode

The Fig 18 is the surface of electrode before applying impulse voltage, after the impulse voltage is applied the surface of electrode gets corroded which is shown in Fig19

CONCLUSION

The breakdown voltage of tap and distilled water increases as the distance between the electrodes increases under both polarity impulse. The breakdown voltage is high for positive impulse voltage than negative impulse voltage for Tap water, Distilled water and ionic solution. After application of high impulse voltage the bubbles formed near the high voltage electrode (needle electrode) which causes breakdown of water. And the tip point of needle electrode became blunt. The breakdown occurred in falling (tail) edge for negative impulse voltage and on rising slope for positive impulse. The Breakdown voltage of distilled water is found to be higher than tap water and ionic solution under both impulse voltages. The field distribution also shows effect towards breakdown of water and ionic solution. The distilled water and Copper sulphate solution are subjected to uniform and non uniform field distribution, the breakdown voltage under uniform field is found to be higher than non-uniform field. The Breakdown of liquid electrolyte are determined, each ionic solution have different breakdown voltage at same conductivity level. Copper sulfate solution has higher breakdown strength than Sodium chloride solution. The Breakdown time of Tap Water, Distilled Water and Ionic solution is high when

negative impulse voltage is applied than positive impulse voltage.

The copper electrode used under breakdown study of Non-uniform field distribution in copper sulfate solution is subjected to corrosion whereas the surface of brass electrode used for breakdown study of Distilled water under Non-uniform field distribution and Stainless Steel electrode used for breakdown study of Sodium chloride solution under uniform field does not have any cracks on its surface. The corrosion in the plane electrode is high at the point near the tip of needle electrode.

The volt-time characteristics of Distilled water under non-uniform positive impulse is predicted at 1.5mm inter electrode distance. The prediction of breakdown voltage and breakdown time has 10% error than actual value.

REFERENCES

- [1] Fouracre R A, Given M.J, Hogg M.G, MacGregor S.J ,Timoshkin I.V , Wilson M.P, T. Wang, (2012), 'Impulse Breakdown of Water with Different Conductivities', IEEE Transactions on Dielectrics and Electrical Insulation ,Vol. 19, No. 5.
- [2] Sharath B and Usa S,(2009), ' Prediction of Impulse Voltage-time Characteristics of Air and Oil Insulation for Different Wavefronts' IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 16, No. 6.
- [3] Given M.J, Fouracre R.A, MacGregor S.J, Timoshkin I.V, Wilson M.P, (2010) , 'Impulse Breakdown of Liquid Water ' Annual Report Conference on Electrical Insulation and Dielectric Phenomena
- [4] Usa .S , Venkatesan .S (2010), 'Volt-time Characteristics of small air gaps with Hyperbolic Curve' ,Electric Power System Research
- [5] Lehr J.M(1996) 'Effect of De-aeration on the Electrical Breakdown Characteristics of Water'.
- [6] Dapeng Liang, Nanchen Zheng, Ruobing Zhang ,Xian(2013), 'Effect of solution characteristics on the discharge in the PEF treatment chamber' Annual Report Conference on Electrical Insulation and Dielectric Phenomena.
- [7] H. M. Jones and E. E. Kunhardt (1994) 'The Influence of Pressure and Conductivity on the Pulsed Breakdown of Water' IEEE Transactions on Dielectrics and Electrical Insulation Vol. 1 No. 6.
- [8] Dapeng Liang, Gang Du, Jie Chen, Ruobing Zhang (2012), 'Research on the discharge characteristics of different types and micro-structures in the PEF treatment chamber', IEEE Conference.

★ ★ ★