Development and Implementation of Low Inductance Capacitor for Pulsed Power Applications

Uday Kommajoshyula[1], Rachana Thatipamula[2], Shruti Nema[3], RK Sharma[4]
Department of Electrical Engineering, LTCOE, KoparKhairane, Navi Mumbai[1,2,3]
BARC Mumbai[4]
HBNI Navi Mumbai[4]

Abstract: ***There are many types of capacitors available today, called electrolytic capacitors or DC film capacitors, that are designed and manufactured for mounting on circuit boards or other electronic devices. Large capacitors are useful in applications such as AC drives and cooling equipment. High voltage capacitors used in 50 Hz circuits are usually made of paper or polypropylene or some combination with or without liquid impregnation. All of these areas have grown significantly over the last decade. This research paper focuses on the description of capacitors for small size and high energy storage for electronic applications. Capacitors used in these applications use thin aluminium foil electrodes to conduct current through the capacitor***

I.Introduction

This research paper focuses on developing a capacitor that has the potential to store high energy. High voltage pulse power supply is a science and technology that stores energy for a long time. This energy is instantly released in the form of current or voltage, thus providing instant energy.A pulse generator is a combination of multiple electrical energy storage transformers (variable lines/tubes) that conduct electricity simultaneously and have low-impedance electrical connections to all electrical equipment (electrical load).This is commonly used in starters and detonators for high-voltage devices.Rules regarding commitment, hope, and longevity are also important. One application is MPW (metalized polypropylene film capacitors) using HVPPS (High Voltage Pulse Power System). In this project polypropylene film capacitor is used having a dielectric constant of 2.2.

MPW is a technology that uses electronic devices that are essentially the main components of HVPPS and have special rules for generating pulses. 100µs to ms, KA current 100 seconds, lifespan more than 105 times longer. A tank consisting of film capacitors with an energy capacity of 15KJ has been specially designed and developed for MPW-type applications[1].

The "Development and Implementation of Low Inductance Capacitor for Pulsed Power Applications" project represents a major effort to design and implement a low-inductance capacitor which will be reliable and efficient for pulsed power applications. A thin aluminium foil is used as a dielectric material in making electrical equipment. In the case of film and foil the electrodes are not used as in metalized capacitors, but the dielectric is wound like a metal sheet. tDue to the low failure rate, products produced in this way have excellent impact and current carrying capacity as well as high insulation[1].

The film foil model is only used for capacitors with small capacitance values. The advantage of this construction principle is easy access to metal electrodes and good impact. To avoid damage caused by weak points in the dielectric, the selected film is always thicker than the required thickness, which is determined by the specific strength of the product. Capacitance is a particular problem in data or signal cables. When electrical signals are transmitted through twisted pairs or coaxial cables, charges accumulate in the insulation of the conductors. The amount that accumulates in the cable over time is due to natural capacitance. This causes delays that can disrupt signal transmission. Due to acceleration and release, the square digital data pulses become a "sawtooth"-like shape, making the circuit unrecognizable from the pulses[1].

D.M. Tagare R(2001) has provided useful information regarding the properties of various dielectric materials used for development of capacitors.It also explained various technical terms associated with a dielectric phenomenon . Detailed the importance of losses (tan δ),voltage stresses and partial discharges related to dielectric materials. It has described mechanical and electrical properties of pp film, process of impregnation,capacitor deterioration.

B.L Theraja and A.K Theraja (2001) are referred to acquire knowledge about the method of charging and discharging of the capacitor. It has provided useful information regarding the nature of the waveform developed in the charging and discharging process of the capacitor.

The choice of dielectric material significantly affects the inductance of capacitors. Material selection for capacitor electrodes is crucial in minimising inductance. Distributed capacitance techniques involve strategically placing capacitive elements within the circuit to counteract inductance.Effective shielding and grounding strategies play a vital role in mitigating parasitic inductance.Low inductance capacitors find extensive use in pulsed power systems, where rapid energy discharge is paramount.In particle accelerators and other high-energy physics experiments, low inductance capacitors are indispensable for achieving precise control of energy release.

This research paper underscores the critical role of low inductance capacitors in pulse power applications by examining design principles, inductance reduction techniques, and real-world applications.This paper provides a comprehensive overview for engineers, researchers, and enthusiasts working in fields reliant on high-speed energy discharge.

II. Development Process

The structure of the capacitor is achieved by the following production process:-

1.Film stretching and metallization:- A special extrusion process is used to stretch polypropylene film to increase the capacitance value of the capacitor. The film is stretched both longitudinally and transversely(as shown in Fig.1),the frame is as thin as technically possible and at the required breakdown voltage allowed. The thickness of this film can be as small as 0.6 µm.It is then wound on a mandrel with a specific width

2. Film slicing - Then films wound on the mandrel are cut into small strips of polypropylene film of the required width(Fig.1)..

3.Winding:- The two pieces of film are wound together to form a cylindrical roll. Two metalized films allow the capacitor winding to be slightly offset from each other so that the metallization edge at both ends of the winding extends behind the preparation of the electrodes(Fig.1) .This process is carried on a capacitor winding machine as shown in Fig.2.[1]

4. Flattening:- Windings are usually flattened into a rectangular shape using a mechanical pressure machine. Since the cost of the printed board is calculated per square millimetre, the small capacitor footprint reduces the total cost of the circuit.(Fig.1) .[1]

5. Application of metal plating ("schoopage") - the tips of the electrodes are coated with liquified contact metal (tin, zinc, or lead), which is blown with compressed air during the winding(Fig.1). This metallization process is named after the Swiss engineer Max Schoop.[1]

6. Healing:- Existing windings connected together from the schoopage process are needed to be healed.This is done by using an accurately calibrated amount of the voltage to ensure that the faults are "burned" away as shown in Fig. 1 [1]

7. Impregnation - To enhance the protection of the capacitor against environmental influences (especially moisture), the windings are impregnated with an insulating liquid such as resin oil. Impregnation is an important process which is done to improve the electrical insulation and thermal properties of film-foil capacitors. This process involves:

A. Resin Selection:Resins generally used in this process include epoxy, polyurethane, or silicone-based compounds. The selection of any one of the materials depends on the required thermal stability, dielectric properties, and mechanical strength.

B. Vacuum Impregnation: The capacitors are kept in a vacuum chamber where air and moisture within the capacitor are removed. Then, the resin is filled in the chamber. The vacuum enables the resin to penetrate deeply into the small gaps within the winding or layers.

C.Pressure Impregnation: Instead of performing vacuum impregnation, pressure can be applied so that the resin fills up all gaps or voids, completely encasing the internal structures as shown in Fig.1

Thermal Curing

After completing impregnation, the resin is cured to form a solid, stable structure that keeps the components intact and gives rise to a rigid, protective shell around them. This involves:

A. Heating: The impregnated capacitors are heated in an oven at a controlled temperature.The specific temperature is 105 degree celsius.

B. Cooling: After curing, the capacitors are allowed to cool down till it reaches the room temperature in order to avoid thermal stresses that could lead to cracks or warping of the resin.

The thermal curing process solidifies the resin, keeping the foil and film layers intact and in their place, improving mechanical strength, and ensuring a stable, durable capacitor structure.This process of thermal curing is carried out in the setup as shown in Fig.3.

8. Connection of terminals - The terminals of the capacitor are welded which therefore act as a protection layer for the windings(Fig.1). [1]

9. Coating- The capacitor is then coated with a particular material or substance in order to improve its protection against scratches/marks/dents(Fig.1). [1]

10. Final Electrical Testing - All capacitors should be checked for all the important electrical parameters: capacitance (C), dissipation factor (tanδ losses), and impedance (Z)(Fig.1).[1]

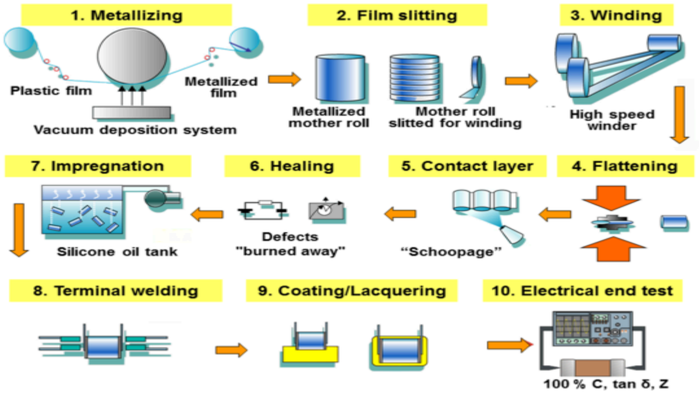

Fig.1 Steps of development of capacitor [2]

Fig.2 Capacitor Development Process [3]

Fig.3 Filtration,Implementation, and Thermal curing Plant at BARC [4]

4uF, 10KV, 20nH Hollow Cylindrical Capacitor

0.15 µF, 40KV, 20nH Flat-format Capacitor

Hollow Flat Format 3.5µF, 5KV, 10nH Capacitor,

Fig.4 Different types of Capacitor

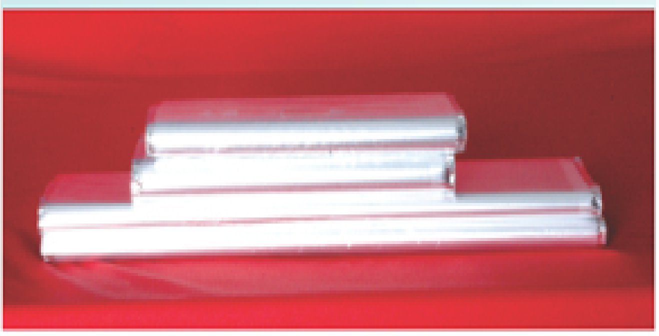

Fig.5 Flat plate Capacitor

TABLE 1 presents the properties of different dielectric materials. In this research paper polypropylene film has been used as the dielectric material of the capacitor. The dielectric constant (K) of this material is 2.26 as projected in TABLE 1.

TABLE 1. Properties of various dielectric material

Capacitor's type	K	Dielectric Strength	DF (%)	Volume Resistivity (Ohms.com)	Max .Oper.Temp(^{o}C)	Energy Density(Jcc)		Energy Density of Intrinsic
Polycarbonate (PC)	2.8	350	<1	$2x10^{17}$	150	3.6	0.5-1	28
Polypropylene (PP)	2.2	500	<0.1	$1x10^{18}$	105	4.1	1-1.5	36
Polyester (PET)	3.3	400	<1.5	$1x10^{17}$	125	4.9	1-1.5	30
Polyvinylidene Fluoride (PVDF)	12	200	1.5	$1x10^{15}$	105	19.1	2.4	12
Polyethylene Naphthalate (PEN)	3.2	440	<1	$1x10^{17}$	137	4.4	1-1-5	34
Polyphenylene Sulfide (PPS)	3.0	360	<0.2	$5x10^{17}$	200	4.1	1-1.5	36

Polypropylene film/PP film Properties-

1.Dielectric constant(K) - It is a term that determines how much of the charge can be stored and transferred in a capacitor.It is related to the number of dipoles available in a given geometry(2.2).[2]
2.Dielectric strength(V/µm) - It is the maximum electric field which a capacitor can endure without breaking down.[5]
3.Dissipation factor/DF(%) - It is the reciprocal of the ratio between the insulating material's capacitive reactance to its resistance(Equivalent series resistance or ESR) at a specified frequency(<0.1).[5]
4.Volume resistivity(Ohm/cm)-Volume resistivity is the resistance to leakage current through the body of an insulating material. The higher the surface/volume resistivity, the lower the leakage current and the less conductive the material is(1x10^18)[5]
5.Maximum operating temperature(^{O}C)- 105[5]
6.Energy density/D(J/cm^{3})- The amount of energy in a system per unit volume is called energy density(Intrinsic-4.1,practical-1 to 1.5).[5]

$$D = \frac{1}{2} CV^{2}$$

To increase energy density (D)following things can be done:-
1.decreasing the distance between two conducting plates(d)
2.increasing the area of the capacitor
3.increasing the Voltage
4.increasing the K(Dielectric Constant)[5]

III. Hardware Implementation:

In this section hardware equipment which has been used while conducting the experiment of recharging and discharging are shown and also the set up of the experiment is shown.

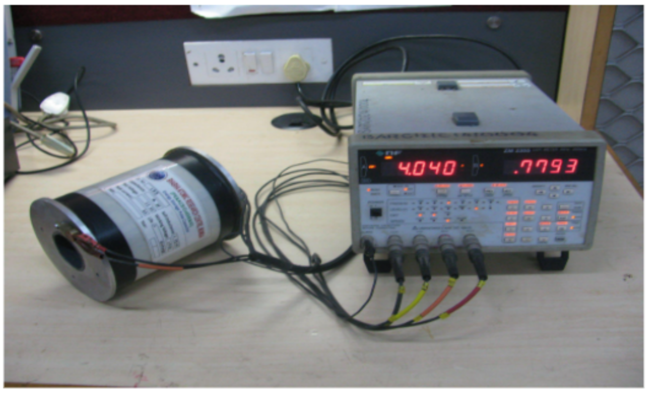

Fig 6 (a) Hollow Cylindrical Capacitor connected to LCR metre

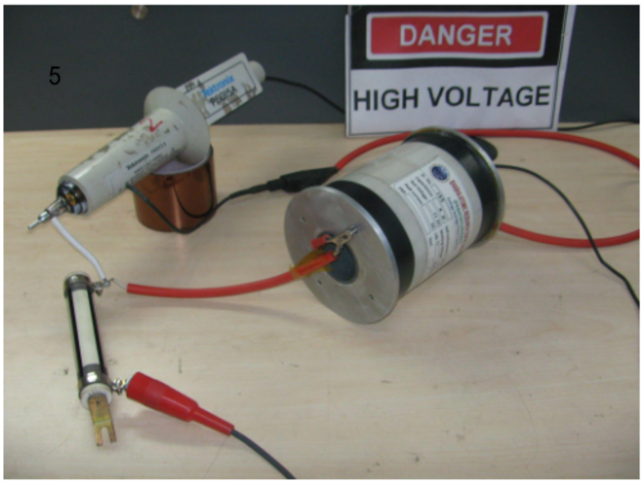

Fig 6 (b)Probe P6015 connected to the setup

Fig 6 (c) Digital Oscilloscope

Components Name :
1=Hollow Cylindrical Capacitor
2=LCR metre ZM2355
3=Discharge Rod
4=Resistor
5=Probe P6015
6=Power supply To Charge The Capacitor
7=Connecting Wire

The development of the capacitor has led to the character analysis by testing it for its charging characteristics.

TEST 1 :-

In test 1, following values are considered for the various parameters involved in the testing process:
$V_s = 5kV$, $R = 1.04M\Omega$ $I = 5mA$

Settings:- EST:- 300 Test type:-DCW,5kv,
Max Limit:- 7500µA, Min Limit:-0A
Ramp Up:- 0.1s, Dwell Time:-60s, Ramp down:-20s
A.c detect:- On, A.c sense:- 9

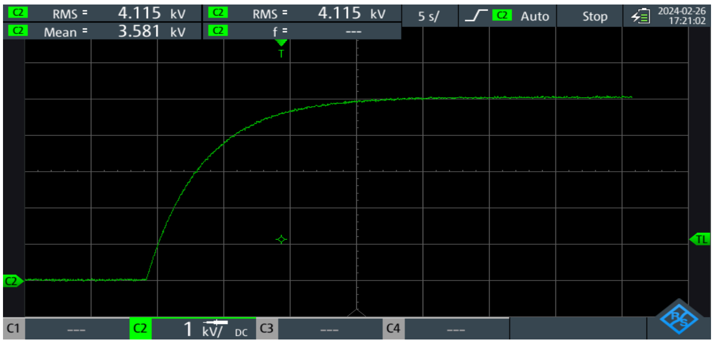

Fig. **7.** Waveforms for the RC charging of capacitor (4.04uF,5kV,1.04MΩ)

Fig,7 shows an exponentially increasing waveform for capacitor voltage values

TABLE 2.
Observed values of Time constant (sec) and capacitor voltage(kv))

$V_s = 5kV$	$R = 1.04M\Omega$	$I = 5mA$
SR. NO.	TIME CONSTANT(sec)	VOLTAGE(kV)
1	4.2016	3.235
2	8.703	4.365
3	12.6048	4.78
4	16.8	4.961
5	21	5.008
FINAL VOLTAGE		5.071

Hand Calculation:
In the capacitor charging phenomenon, capacitance is calculated by using the following formula, derived earlier from the capacitor charging derivation.
Therefore,
by Formula:-

$$C = -\frac{t}{ln(\frac{V-Vc}{V})R} \text{ F} \qquad (1)$$

By using the above formula,the capacitance value of the following capacitor is obtained as:-

$C_1 = 3.87\mu F$, $C_2 = 4.06\mu F$
$C_3 = 3.88\mu F$

In the Test 1, three values of the capacitor ratings(C_1,C_2&C_3) have been considered in order to find out the difference between actual value of the capacitor and the calculated value of it, using the above-mentioned formula.

$$C_{Avg} = \frac{C_1+C_2+C_3}{3}$$

$$C_{Avg} = 3.94\mu F$$

Then, the tolerance value has been counted by finding the percentage difference between the calculated and actual value of the capacitor rating.

$$\text{Tolerance} = \frac{4.04\mu f - 3.94\mu f}{4.04\mu f} * 100\ \%$$

Tolerance= 2.75%

Test No. 2:-

$V_s = 2kV$, $R = 1.04M\Omega$ $I = 5mA$

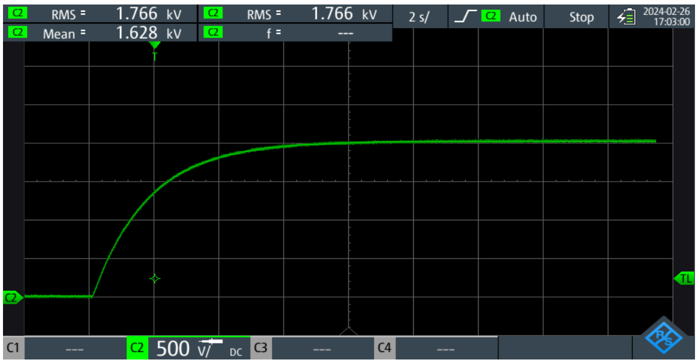

Fig.8 Waveforms for the RC charging of (4.04uF,5kV,433kΩ)

Fig.8 also shows an exponentially increasing waveform for capacitor voltage values

TABLE 3

Observed values of Time constant (sec) and capacitor voltage(kv)

$V_s = 2kV$	$R = 1.04M\Omega$	$I = 5mA$
SR. NO.	TIME CONSTANT (sec)	VOLTAGE (kv)
1	4.25	1.28
2	8.4	1.743
3	12.6	1.916
4	16.8	1.986
5	21	2.01
FINAL VOLTAGE		2.018

Hand Calculation

In the capacitor charging phenomenon, capacitance is calculated by using the following formula, derived earlier from the capacitor charging derivation.

Therefore,

by Formula:-

$$C = -\frac{t}{ln(\frac{V-Vc}{V})R}\ \text{F}$$

By using the above formula we have got the capacitance value of the following capacitor as:-

$C = 3.95\mu F$, $C_2 = 3.936\ \mu F$

$C_3 = 3.8217\mu F$

Similar to the first test ,in Test 2, three values of capacitor ratings(C_1,C_2&C_3) have been considered in order to find out the difference between actual value of t8he capacitor and the calculated value of it, using the above-mentioned formula.

$$C_{Avg} = \frac{C_1+C_2+C_3}{3}$$

$$C_{Avg} = 3.903\ F$$

Then, the tolerance value has been counted by finding the percentage difference between the calculated and actual value of the capacitor rating.

$$\text{Tolerance} = \frac{4.04\mu f - 3.903\mu f}{4.04\mu f} * 100\ \%$$

Tolerance= 3.40%

Test No. 3:-

$V_s = 2kV$, $R = 433k\Omega$ $I = 5mA$

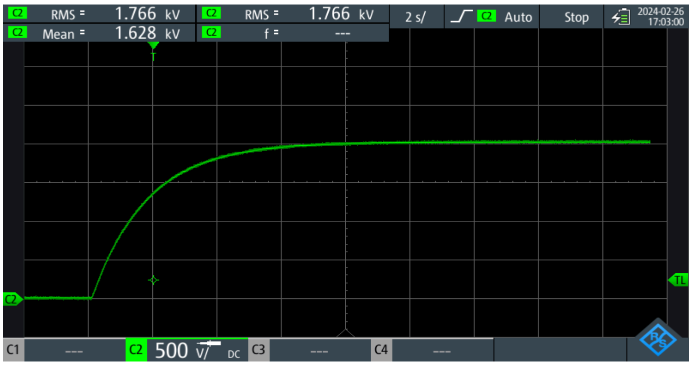

Fig. 9 Waveforms for the RC charging of High voltage film foil energy storage capacitor 4.04uF,2kV,1.04MΩ

Fig.9 shows an exponentially increasing waveform for capacitor voltage values

TABLE 4

Observed values of Time constant (sec) and capacitor voltage(kv)

$_s = 2kV$	$R = 433k\Omega$	$= 5mA$
SR. NO.	TIME CONSTANT (sec)	VOLTAGE (kv)
1 1	1.749	1.312
2 2	3.498	1.767
3 3	5.247	1.947
4 4	6.996	1.986
5 5	8.745	2. 033
FINAL VOLTAGE		041

Hand Calculation

In the capacitor charging phenomenon, capacitance is calculated by using the following formula, derived earlier from the capacitor charging derivation.

Therefore,

by Formula:-

$$C = -\frac{t}{ln(\frac{V-Vc}{V})R}\ \text{F}$$

By using the above formula we have got the capacitance value of the following capacitor as:-

$C_1 = 3.78\mu F$, $C_2 = 3.75\mu F$ and $C_3 = 3.33\mu F$

Similar to the first Test 1 & Test 2, in Test 3, three values of capacitor ratings(C_1,C_2&C_3) have been considered in order to find out the difference between actual value of the capacitor and the calculated value of it, using the above-mentioned formula.

$$C_{Avg} = \frac{C_1+C_2+C_3}{3}$$

$$C_{Avg} = 3.62\mu F$$

Then, the tolerance value has been counted by finding the percentage difference between the calculated and actual value of the capacitor rating.

$$\text{Tolerance} = \frac{4.04\mu f - 3.62\mu f}{4.04\mu f} * 100\ \%$$

$$\text{Tolerance} = 10.40\%$$

By observation it is found that the calculated values and the actual rated values have a slight difference.This is due to the following factors which can take place during the development process of the capacitor or even in later stages:

1. Flattening error: The difference between aluminium foils will increase the thickness, thus causing the capacitance value error.
2. Overlap error: If the lead sheets are overlapped incorrectly or overlapped at the wrong angle, this will affect the distance between the two conductive plates, causing an error in the value capacitance.
3. Impregnation: If not impregnated, moisture will not be removed and will shorten the entire life of the product.
4. Formation of pores, rust stains, stains, and wrinkles: If there are pores, rust stains, or wrinkles, air particles will accumulate on the product surface, causing the overall breakdown voltage level of the product to decrease and therefore causing errors in the capacitance value.
5. Dust particle accumulation: If dust particles are accumulated on the surface of the capacitor having their breakdown voltage level lesser than the film & foil ,it causes the breakdown voltage of the entire capacitor to decrease, resulting in an error in the capacitance value.

Capacitor Charging:

The battery is connected to the resistor and capacitor in series. The charge from one plate of the capacitor to the other is transferred and therefore the initial current is high. As the battery supplies voltage the current approaches zero and the capacitor becomes charged (Fig.10). The capacitor then stores energy in the electric field between the capacitor plates. The rate of charging is described in terms of a time constant RC($i.e.$ τ).[6]

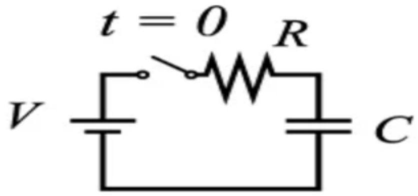

Fig.10 Circuit diagram of the charging capacitor[7]

Therefore by applying KVL to this circuit,
We obtain:

$$V = i_c R + V_c \text{..................}\textbf{(i)}$$

$Where,$

Q = CV

$$i_c = \frac{dq}{dt} = \frac{dC(V_c)}{dt}$$

$$i_c = \frac{CdV_C}{dt}$$

$$V = V_C + RC\frac{dV_C}{dt}$$

$$-\frac{dV_c}{V-V_c} = -\frac{dt}{RC}$$

$$\int -\frac{V_c}{V-V_c} = -\frac{t}{RC}\int dt$$

$$log_e(V - V_c) = \frac{t}{RC} + K \text{ .... }\textbf{(iii)}$$

At, $V_c = 0$

putting this above value in equation no iii

We get

$$log_e V = K$$

$$log_e(V - V_c) = -\frac{t}{RC} + log_e V$$

$$log_e(\frac{V-V_c}{V}) = -\frac{t}{RC} = -\frac{t}{\tau}$$

Where $\tau = RC$

$$\frac{V-V_c}{V} = e^{-\frac{t}{RC}} = e^{-\frac{t}{\tau}}$$

$$V_c = V(1 - e^{-\frac{t}{\tau}})\text{..................}\textbf{(iv)}[3]$$

From equation no 4

$$V_c = V(1 - e^{-\frac{t}{\tau}})\ Volts\ [2]$$

$$V_c = V - Ve^{-\frac{t}{\tau}}$$

$$V_c - V = -Ve^{-\frac{t}{\tau}}$$

$$V - V_c = Ve^{-\frac{t}{\tau}}$$

$$\frac{V-V_c}{V} = e^{-\frac{t}{\tau}}$$

$$ln(\frac{V-V_c}{V}) = -\frac{t}{\tau}$$

Where $\tau = RC$

$$ln(\frac{V-V_c}{V}) = -\frac{t}{RC}$$

$$C = -\frac{t}{ln(\frac{V-V_c}{V})R} \quad F$$

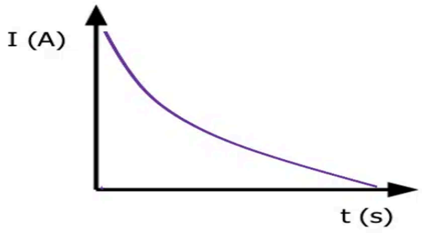

Fig 11: Current waveform[8]
Above figure shows an exponentially decreasing current waveform

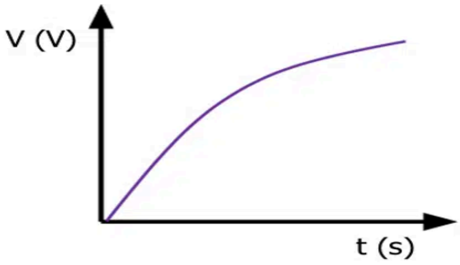

Fig 12: Voltage waveform[8]
Above figure shows an exponentially increasing voltage waveform

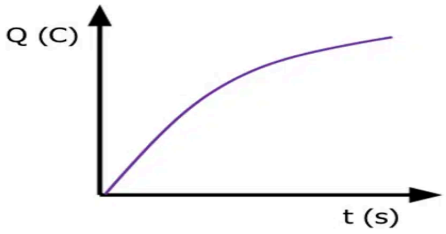

Fig 13: Charging waveform[8]
Above figure shows an exponentially increasing charging waveform

Fig.11 shows an exponentially decreasing current waveform.Whereas Fig.12 & Fig.13 show exponentially increasing voltage and charge waveforms respectively

But it is important that some precautions should always be taken while performing the above tests.These are:

1. Before testing

The capacitor specifications must be known.Inspection of capacitors and other testing equipment must be done to check for any physical damage, functioning, and calibration. Before testing, the capacitor must be discharged. The testing area should be isolated.

2. During testing

Monitoring must be done on the equipment during the test to prevent any emergencies. Connections must be properly insulated. The capacitor's rated voltage should not be changed during the testing. Capacitors should be monitored during the testing. All the readings taken during the test will be recorded.

3. After the test

Capacitors should be discharged fully before handling. Equipment must be shut down in a sequence and allowed to cool down, then capacitors shall be stored safely.

IV. Conclusion:

Working on a research paper based on the simulation and design of low-inductance capacitors for pulsed power applications provided a wide range of valuable learning experiences, skills, and knowledge and also helped to gain a deep understanding of the principles, components, and functioning of capacitors, which are crucial in electrical engineering. The designing phase helped to conceptualise, plan, and create engineering solutions and become adept at selecting materials and considering safety factors.
The testing phase allowed one to gain hands-on experience with the real-world equipment and testing procedures that are followed and also to learn how to set up experiments, collect data, and interpret results. Working on capacitors' design and testing challenges helped to solve complex engineering problems.Calculations were compared with actual calculated values by online calculators[9]. It developed strong teamwork and communication skills, which are essential in professional settings. Engaging in a project like this encourages one to think critically and innovatively, explore new ideas and find solutions to improve capacitor design. This project allows one to apply theoretical knowledge gained in the classroom to a real-world engineering challenge, bridging the gap between academia and practical application.

References:

[1] Uday. K, Rachana .T, Sumit. S, Aman kumar. B, Shruti. N, " Investigation on Low Inductance Capacitor for Pulsed Power Applications ", ICATM-2024 , 2nd International Conference on Advances in Technology and Management, April 2024.
[2]https://www.globalspec.com/learnmore/electrical_electroniccomponents/electronic_components/film_capacitors
[3]https://www.ae-mechatronics.com/application.php

[4]https://barc.gov.in/barc_nl/2023/2023010209.pdf
[5].D.M. Tagare R(2001).Electrical Power Capacitors:Design and Manufacture. McGraw-Hill Education (India) Pvt Limited)
[6]. B.L. Theraja & A.K. Theraja (2001). A Textbook Of Electrical Technology In S.I. Units (Volume-1). S.Chand & Company LTD
[7]http://hyperphysics.phy-astr.gsu.edu/hbase/electric/capchg.html
[8]https://mmerevise.co.uk/a-level-physics-revision/capacitor-charge-and-discharge/
[9]https://www.allaboutcircuits.com/tools/capacitor-Charge-and-time-constant-calculator/