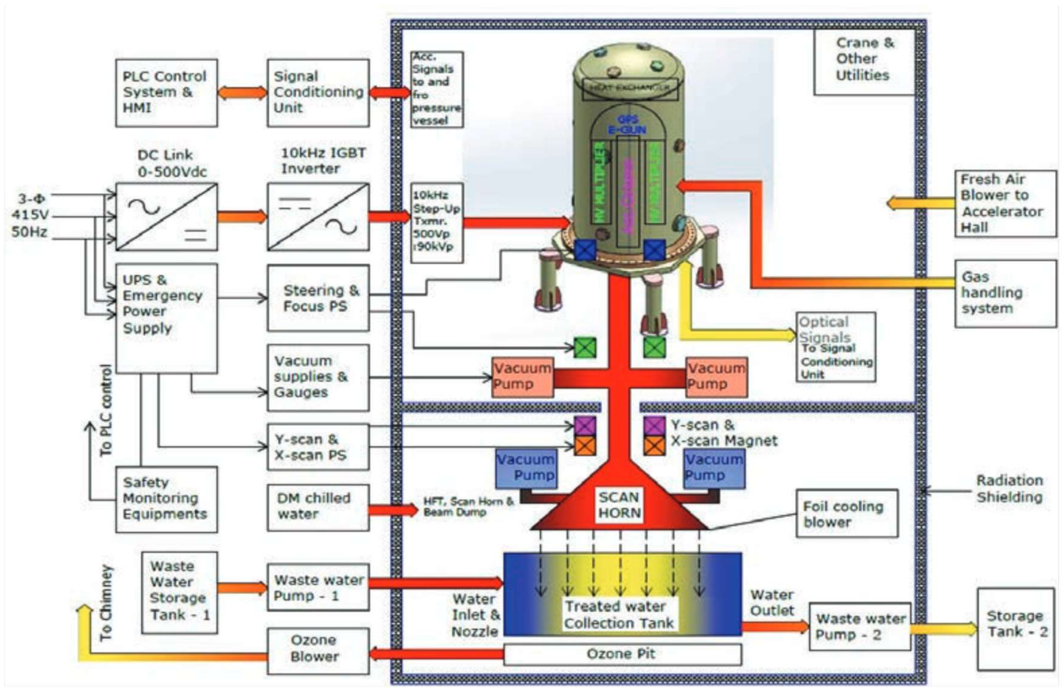
# BHABHA ATOMIC RESEARCH CENTRE

## ACCELERATOR AND PULSE POWER DIVISION




## *SIMULATION, ANALYSIS & TESTING OF HV MULTIPLIER CIRCUIT FOR DC ELECTRON BEAM ACCELERATOR*

**SUBMITTED BY:** DEBRAJ BHATTACHARJEE

**BRANCH-** ELECTRICAL ENGINEERING (2021-2025)

**ENROLLMENT NO.-**21UEE014

# NATIONAL INSTITUTE OF TECHNOLOGY, AGARTALA

# ACKNOWLEDGEMENT

I would like to express my gratitude to Shri. S. Dewangan without whose permission and wise counsel and able guidance it would have not been possible to pursue my Training in this manner.

I am very grateful to Shri S. Dewangan for providing academic inputs, guidance and encouragement throughout the Training Period.

I would also like to thank all officer/officials who guided and helped me at each and every step in the online training programme.

Yours Faithfully,
(Debraj Bhattacharjee)
(21UEE014,EE,NIT AGARTALA)

Date: Place: Electron Beam Centre

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## *CERTIFICATE*

*This is to certify that **Mr. Debraj Bhattacharjee**, a student of Electrical Engineering at **National Institute of Technology, Agartala** has successfully completed his summer training at **Bhabha Atomic Research Centre , APPD** from **12th May 2024 to 5th July 2024**. He has successfully completed his project work on **Simulation, Analysis & Testing of HV Multiplier Circuit for DC Electron Beam Accelerator** . During the training he took keen interest in the assigned work. We wish him all success in his academic endeavors and life.*

*Date:* *Mentor*

# INDEX

## Introduction to 1MeV 100KW DC Electron Accelerator

The Electron Beam Centre (EBC) Beam technology development group (BTDG, BARC) has designed and developed a dc accelerator in the energy range of 1-3MeV and beam current range of 0-100mA. One unit of DC electron accelerator in the energy range of 1MeV-3MeV, 30KW has been constructed and demonstrated for flue gas treatment, dye waste water treatment etc. Presently this accelerator is dismantled and a new high power accelerator in the energy range of 0.8Mev,100KW has been developed and installed at the existing pressure vessel of 3 MeV DC accelerator for demonstration. This machine can be considered as the workhorse for industrial radiation processing applications like modification of bulk polymers, cross linking of cables, degradation of scrap Teflon and cellulose materials, diamond colouring. EB treated hydro gel, small scale industrial flue gas treatment.

The 1.0MeV machine works on the principle of accelerating electron in a graded dc high voltage column developed by a Symmetrical Cockcroft Walton Voltage Multiplier.

The dc accelerating potential of 1.0MV is generated by a voltage multiplier scheme, based on capacitor-rectifier cascade circuit. The multiplier is driven by a high frequency power source fed from 3-$\varphi$ 415V, 50Hz mains. Power required for the electron gun located at the 1.0MV potential is derived from the multiplier column. The derived power is converted in to supplies of different ratings to energize the electron gun and the control circuits. Entire high voltage system consisting of voltage multiplier, accelerating column, electron gun and electron gun supplies are enclosed in a vessel filled with 95% $N_2$-5% $SF_6$ gas at 6kg/cm$^2$ pressure to obtain the required electrical insulation.

## Introduction to Voltage Multiplier Circuits

Cascaded voltage Doubler circuits for higher voltages are cumbersome and require too many supply and isolating transformers. It is possible to generate very high D.C. voltages from single supply transformers by extending the simple voltage doubler circuits. This is simple and compact Here we discuss about Cockcroft-Walton Voltage Multiplier.

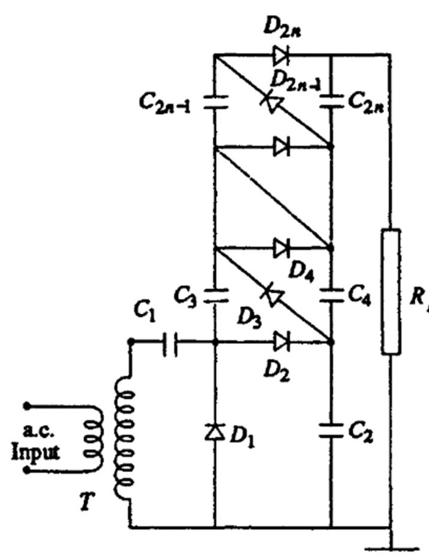



Figure-1: Cockcroft-Walton Voltage Multiplier Circuit

Voltage multiplier circuit using the Cockcroft-Walton principle is shown in Figure. The First Stage Consist of $D_1$, $D_2$, $C_1$, $C_2$, and transformer **T .** During the Positive Cycle, $C_1$ is Charged through $D_1$ to a voltage of +$V_{max}$ . During the Negative Cycle, $C_2$ is Charged through $D_2$ to a voltage of +$2V_{max}$ as $C_1$ is already charged to +$V_{max}$ and thus $C_1$ and T provides the $+2V_{max}$ voltage to $C_2$. Similarly, $C_3$ is charged to voltage of $+2V_{max}$ through $D_3$ and then $C_4$ is charged to voltage of +$4V_{max}$ with respect to ground and similarly $C_{2n}$ to +$2nV_{max}$ with respect to ground .But Voltage across any individual Capacitor or Diode is only $2V_{max}$. The Diodes $D_1$, $D_3$ , ... $D_{2n-1}$ shown in Figure operate and conduct during the positive half cycles while the Diodes $D_2$, $D_4$... $D_{2n}$ conduct during the negative half cycles. Typical current and voltage waveforms of such a circuit are shown in the below figure.

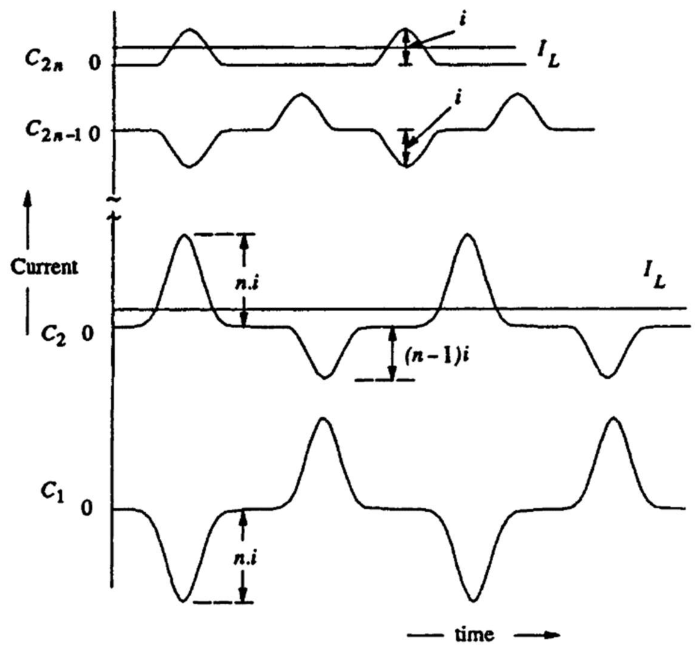



Figure-2: Schematic Current Waveform across the first and the last capacitor of the cascaded Voltage multiplier Circuit.

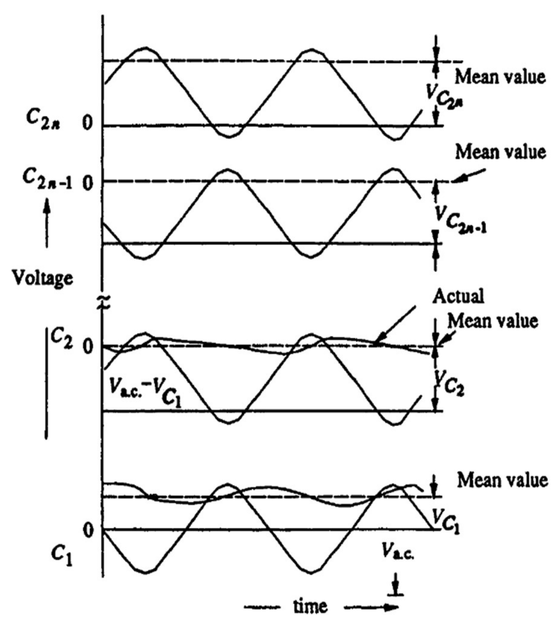



Figure-3: Schematic Voltage Waveform across the first and the last capacitor of the cascaded Voltage multiplier Circuit.

# High Voltage Multiplier rated for 1MV, 100mA

## Introduction

The electron beam is accelerated upto 1MeV energy using an Ultra High Voltage DC Power Source. This supplies the power needed for acceleration of electron beam and also develops the required Electric-field in the accelerating tubes for acceleration of electron beam.

The 1MV Voltage multiplier of 15 stages, Symmetrical Cockcroft-Walton scheme has been selected due to its simple design, easier fabrication & testing, high energy efficiency as well as rugged & reliable operation. The Voltage multiplier is located inside a pressure vessel filled with 95% $N_2$-5% $SF_6$ gas at 6kg/cm$^2$ pressure.

## Technical Specifications

The salient specifications of the High Voltage Generator are as follows:

| | |
|---|---|
| 1. Operating Voltage | 0.80MV - 1.00 MV |
| 3. Load current | 0-100 mA |
| 4. Voltage drop (Regulation) | 280 kV (max.) |
| 5. Ripple (p-p) | 10 kV (max.) |
| 6. Multiplier Scheme | Symmetrical Cockcroft-Walton |
| 7. Operating gas medium | 95% $N_2$-5% $SF_6$ gas at 6kg/cm$^2$ pressure |

## Design Considerations for Cascaded Voltage Multipliers

A simple cascade voltage multiplier circuit was discovered by Cockcroft and Walton, hence, known as Cockcroft-Walton multiplier after them. A comparison of various forms of voltage multipliers i.e conventional, symmetric and parallel coupled multiplier is given below through the formula of Output Voltage.

***Conventional Cockcroft-Walton Multiplier :***

$$V_L = 2NV_i - \frac{I}{fC}\left(\frac{2N^3}{3} + \frac{N^2}{2} - \frac{N}{4}\right) \pm \frac{N(N+1)I}{2f}$$

***Symmetrical Cockcroft-Walton Multiplier:***

$$V_L = 2NV_i - \frac{I}{fC}\left(\frac{N^3}{6} + \frac{N^2}{4} + \frac{N}{3}\right) \pm \frac{NI}{2fC}$$

**Parallel Cockcroft-Walton Multiplier:**

$$V_L = \frac{NV_i}{k} - \frac{NI}{KfC_{SE}} \pm \frac{I}{2fC_{SE}}$$

The main feature of all these voltage multipliers is that, input is high frequency AC voltage and output is high voltage DC. The first three circuits (i.e. conventional, balanced & symmetrical) utilize discrete capacitors and operate at moderate frequencies usually in 1-10 kHz range.

The parallel circuit was mastered by Radiation Dynamics Inc. and marketed as 'Dynamitron' type generator. This generator operates at 30-300 kHz input and utilizes geometrical (i.e. stray) capacitances formed between metal components (i.e. corona guards, RF Electrodes and rectifiers) for development of High Voltage.

## Selection Criteria for type of Generator

In general, Cockcroft-Walton circuits are used when relatively lower output voltage is required. A Conventional Circuit is used for relatively lower voltage and current, whereas, symmetrical Circuit is used when lower voltage but higher output current is desired. Parallel circuit utilizes geometric capacitances, which are of very low value (in pF), hence stored energy is low, even at much higher voltages. Therefore, parallel circuit is used for higher voltage usually in 2- 6 MV range.

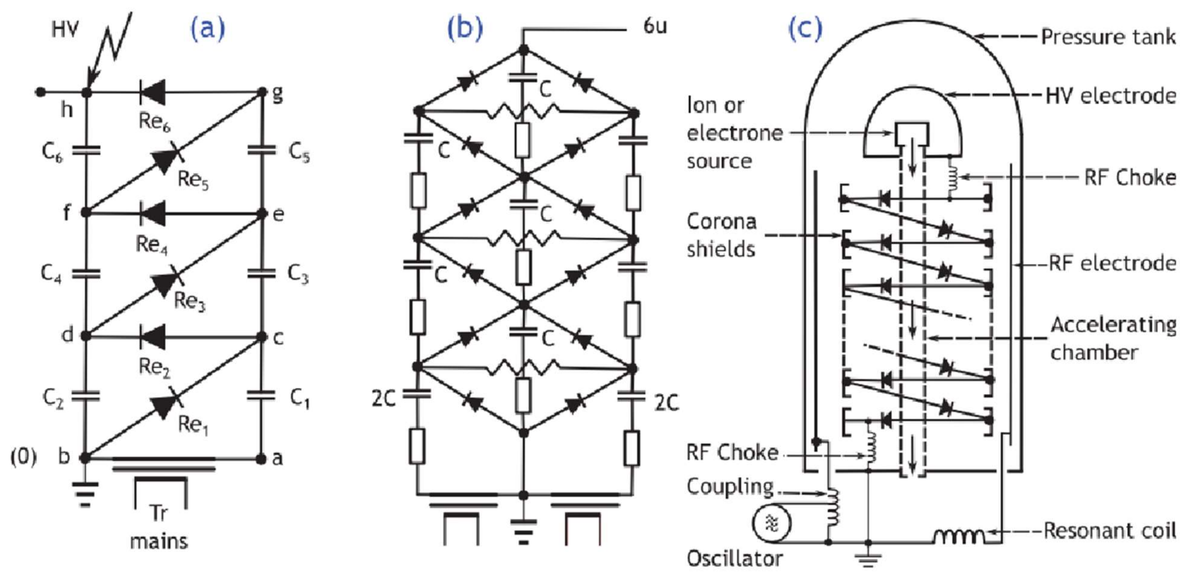
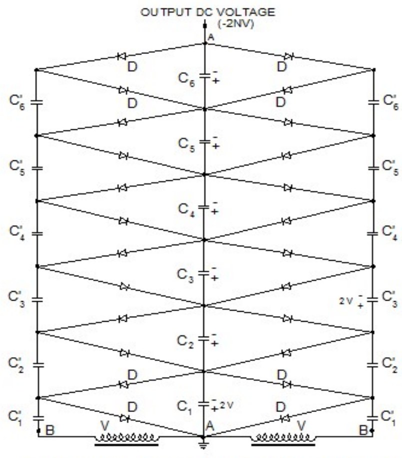
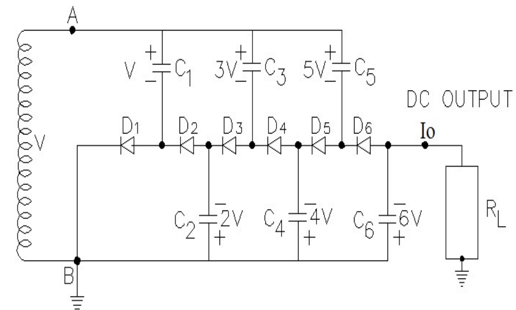



Figure : Electrical Scheme of the three types of voltage multiplier circuits: (a) conventional CW circuit, (b) symmetrical CW circuit, and (c) parallel (dynamitron) circuit.

# Detail Comparison of Symmetric and Parallel CW

| No. | Parameter | Cockcroft Walton Symmetrical Scheme | Parallel Coupled Multipler |
|---|---|---|---|
| 1 | Output Voltage | $V_L = 2NV_i - \frac{I}{fC}\left(\frac{N^3}{6}+\frac{N^2}{4}+\frac{N}{3}\right) \pm \frac{NI}{2fC}$<br>Input Voltage, $V_i$ = 40kV$_P$; N = 15; C = 20nF; I = 100mA | $V_L = \frac{NV_i}{k} - \frac{NI}{kfC_{SE}} \pm \frac{I}{2fC_{SE}}$<br>Input Voltage, $V_i$ = 150kV$_P$; N = 25; $C_{SE}$ = 16pF; I = 100mA |
| 2 | Scheme | <br>Fig.: SYMMETRICAL COCKCROFT WALTON CIRCUIT | <br>Fig. : SIMPLIFIED ELECTRICAL SCHAMATIC OF PARALLEL FED VOLTAGE MULTIPLIER |
| 3 | Frequency | 10kHZ | 100kHZ |
| 4 | Components | HV ceramic capacitors (40DKD33 x 54 Nos. per stage) & HV diodes (HVRW-4 with PIV-4kV, 1A, $T_{rr}$ = 150ns) | HV Distributed gas capacitor made of corona rings and RF electrode & HV diodes (UXFOB, 8kV, 0.5A with $T_{rr}$ = 50ns) |
| 5 | Principle | Series Capacitance charging | Parallel capacitance charging |
| 6 | Regulation | 28% | 30% |
| 7 | Ripple | ± 2.6% | ± 2% |
| 8 | Input Source | 40kV-0-40kVp, 10kHz, 104kW<br>A)Solid state inverter with $\eta$=95% OR<br>B)Triode based oscillator with $\eta$=70% | 75kV-0-75kVp, 100kHz, 103kW<br>Triode based oscillator with $\eta$=70% |
| 9 | Bulk Insulation | $SF_6/N_2$ gas at 6kg/cm$^2$ pressure | $SF_6/N_2$ gas at 6kg/cm$^2$ pressure |
| 10 | Stored Energy | 2.7kJ | 100-200J |

## Capacitor and diode rating & Connections

We currently have commercially available 3.3 nF capacitors rated at 40kV. However, for our Symmetrical Cockcroft Walton Generator aiming to achieve 1 MeV and 100 mA with 15 stages, we require 19.8nF per stage capacitance with a working voltage of 90kV (rating 120kV). To meet this requirement, we connect three 3.3 nF capacitors in series, resulting in a total voltage rating of 120 kV. We repeat this arrangement 18 times in parallel to achieve the desired capacitance of 19.8 nF at the required voltage.

Two critical properties of diodes play a crucial role in selecting the appropriate diode for use in a Symmetrical Cockcroft Walton Generator:

1. *Peak Inverse Voltage (PIV):*
    - PIV, also known as reverse breakdown voltage, represents the maximum reverse voltage that a diode or PN-junction can withstand in a non-conducting state (reverse bias) before breakdown occurs.
    - Ensuring that the diode's PIV rating exceeds the maximum reverse voltage encountered is essential for safe operation during reverse bias conditions.
2. *Reverse Recovery Time ($T_{rr}$ ):*
    - refers to the duration it takes for a diode to transition from its conducting state (ON) to its blocking state (OFF) when switching from forward bias to reverse bias.
    - During this time, stored charge within the diode is discharged, allowing it to effectively block reverse current.
    - Proper management of $T_{rr}$ ensures smooth transitions and prevents voltage spikes.

We currently have HVRW-4 HV Diodes with a peak inverse voltage (PIV) rating of 4 kV, a current capacity of 1 A, and a reverse recovery time ($T_{rr}$) of 150 ns. However, our requirement is for HV Diodes with a PIV of 90 kV. To achieve this, we connect the HVRW-4 diodes in series to ensure smooth operation. Specifically, we connect 36 diodes in series within each stage.

## Calculation of SCW multiplier Output Voltage at loaded condition

$$V_i = 45kV - 0 - 45kV$$

$$N = 15$$

$$f = 10kHz$$

$$C = 20nF$$

$$I = 100mA$$

$$V_L = 2NV_i - \frac{I}{fC}\left(\frac{N^3}{6} + \frac{N^2}{4} + \frac{N}{3}\right) \pm \frac{NI}{2fC}$$

$$V_L = (2 \times 15 \times 45) - (\frac{0.1}{10^4 \times 20 \times 10^{-9}})(623.75) \pm \frac{15 \times 0.1}{2 \times 10^4 \times 20 \times 10^{-9}}$$

$V_L = (1350kV) - (311.875kV) \pm (3.75kV)$

$V_L = (1350kV) - (311.875kV) \pm (3.75kV)$

$V_L = (1.038MV) \pm (3.75kV)$

$No\ Load\ Voltage = 1.350MV$

$Load\ Voltage = 1.038MV$

$Regulation = 311.875kV$

$Ripple\ = 3.75kV$

$\%\ Voltage\ Regulation = 23.10\%$

$\%\ Ripple$=0.277%

## Applications of Cockcroft-Walton Circuits

1. ***High-Voltage Power Supplies:***
   - The symmetrical Cockcroft-Walton circuit is commonly employed to generate high DC voltages efficiently.
   - It is used in X-ray machines, electron microscopes, and other medical and scientific equipment that require high-voltage power supplies.
2. ***Particle Accelerators:***
   - Particle accelerators, such as cyclotrons and linear accelerators, accelerate charged particles (e.g., protons, electrons) to high energies.
   - Its simplicity and scalability make it suitable for use in particle accelerators.
3. ***Nuclear Physics Experiments:***
   - In nuclear physics research, experiments often require high voltages to accelerate particles or create electric fields.
   - The Cockcroft-Walton circuit can supply the needed voltages for ionization chambers, detectors, and other equipment.
4. ***Electrostatic Precipitators:***
   - Electrostatic precipitators are used to remove particulate matter (dust, smoke, etc.) from industrial exhaust gases.
   - The high-voltage output of the Cockcroft-Walton circuit charges the plates in these precipitators, attracting and collecting particles.
5. ***Photomultiplier Tubes (PMTs):***
   - PMTs are sensitive light detectors used in applications like scintillation detectors, fluorescence measurements, and night vision devices.
   - The Cockcroft-Walton circuit provides the necessary high voltage to accelerate photoelectrons within PMTs.
6. ***Ion Implantation in Semiconductor Manufacturing:***
   - Ion implantation is a key process in semiconductor manufacturing.
   - The Cockcroft-Walton circuit can generate the high voltages needed to accelerate ions into the semiconductor substrate.

## Simulation of 15 stage symmetrical Cockcroft Walton

We have simulated the SCWM circuit in LTSpice and use ideal diodes and capacitors, replacing the transformer with two independent voltage sources. Additionally, we assume default values for the diode's Peak Inverse Voltage (PIV) and Reverse Recovery Time ($T_{rr}$), which are infinite and 0 seconds, respectively. The simulation duration is 200 milliseconds to ensure steady state condition is achieved. Data recording begins at 199 milliseconds to minimise LT Spice raw file size, with a time step of 10 nanoseconds to get smooth waveform. Smaller the time step, more will be simulation run time.

SCWM have two AC column and one DC Column.

**At No Load:**

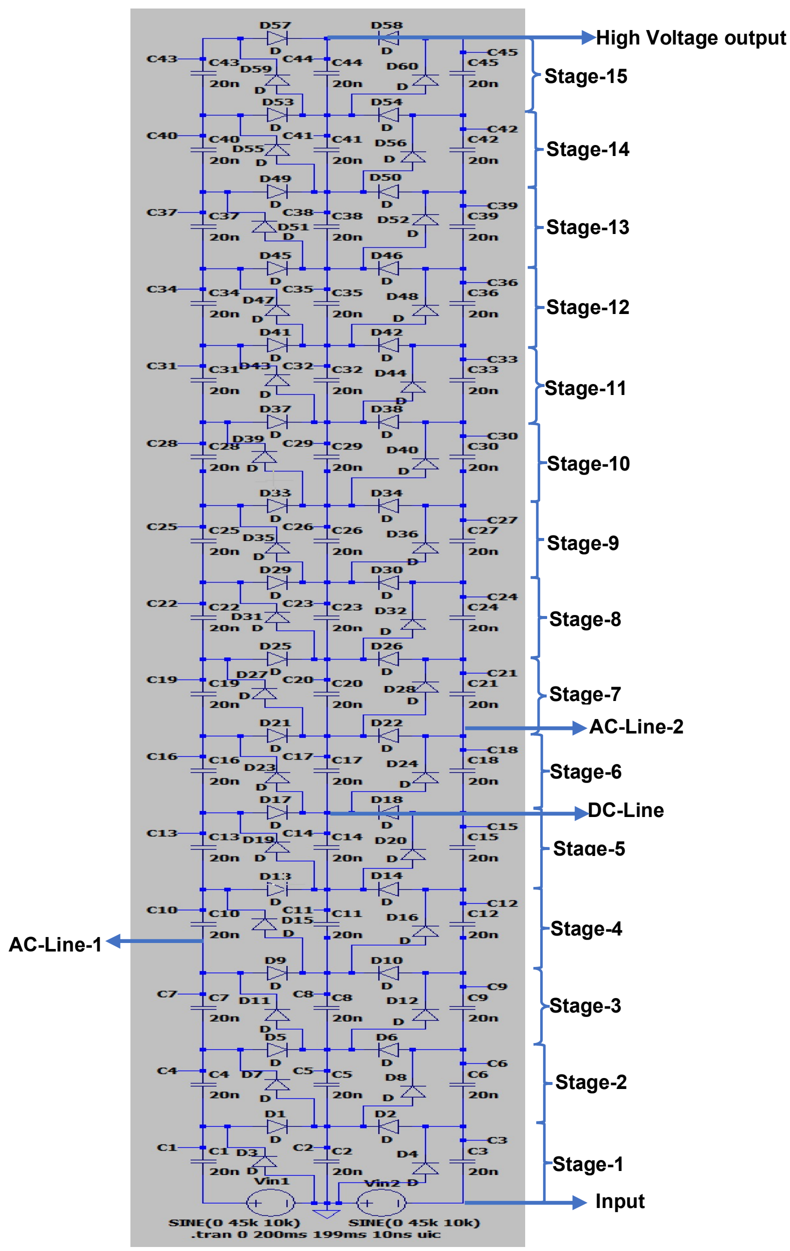



Figure- 5: Simulation at No Load Condition



Stage-

### *Voltage Level(At No load):*

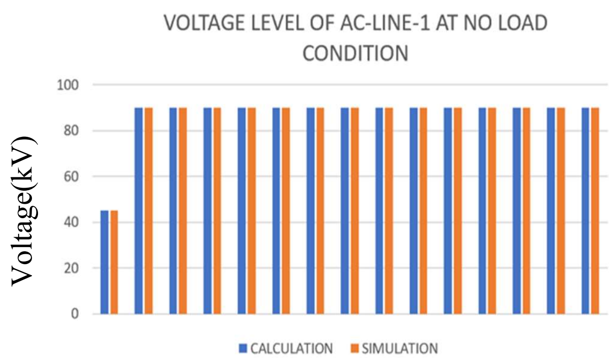
| STAGE | AC-1(kV) | DC(kV) | AC-2(kV) | Voltage Built up w.r.t Ground(kV) |
|---|---|---|---|---|
| 1 | 44.99 | 89.99 | 44.99 | 89.99 |
| 2 | 89.99 | 89.99 | 89.99 | 179.99 |
| 3 | 89.99 | 89.99 | 89.99 | 269.99 |
| 4 | 89.99 | 89.99 | 89.99 | 359.99 |
| 5 | 89.99 | 89.99 | 89.99 | 449.99 |
| 6 | 89.99 | 89.99 | 89.99 | 539.99 |
| 7 | 89.99 | 89.99 | 89.99 | 629.98 |
| 8 | 89.99 | 89.99 | 89.99 | 719.98 |
| 9 | 89.99 | 89.99 | 89.99 | 809.98 |
| 10 | 89.99 | 89.99 | 89.99 | 899.97 |
| 11 | 89.99 | 89.99 | 89.99 | 989.97 |
| 12 | 89.99 | 89.99 | 89.99 | 1079.99 |
| 13 | 89.99 | 89.99 | 89.99 | 1169.995 |
| 14 | 89.99 | 89.99 | 89.99 | 1259.94 |
| 15 | 89.99 | 89.99 | 89.99 | 1349.93 |

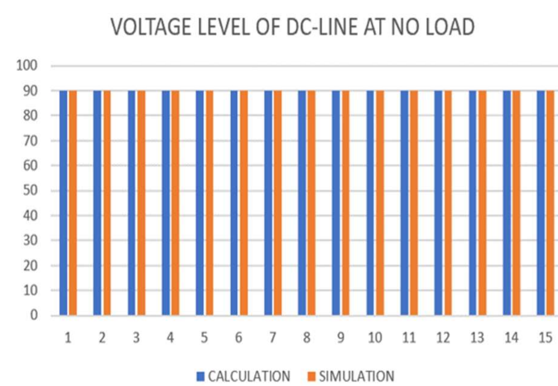
### *Input Voltage Level:*

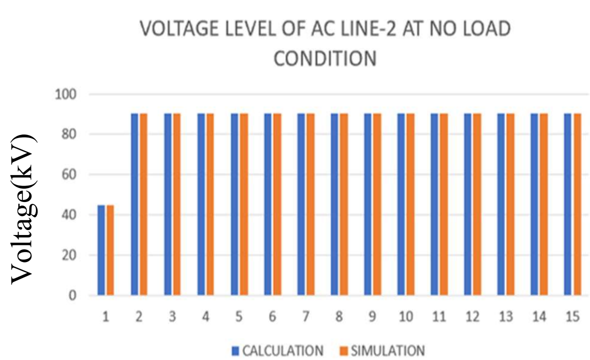
INPUT VOLTAGE

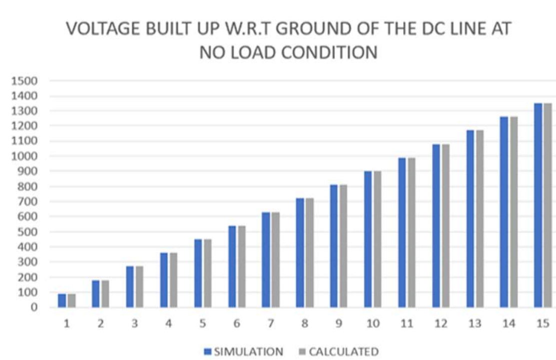
| Vin (kV)(1) | Vin (kV)(2) |
|---|---|
| 44.99 | 44.99 |

## <u>GRAPHICAL REPRASENTATION OF VOLTAGE LEVEL AT NO LOAD</u>



# Waveform of Voltage at Different stages and input Voltage

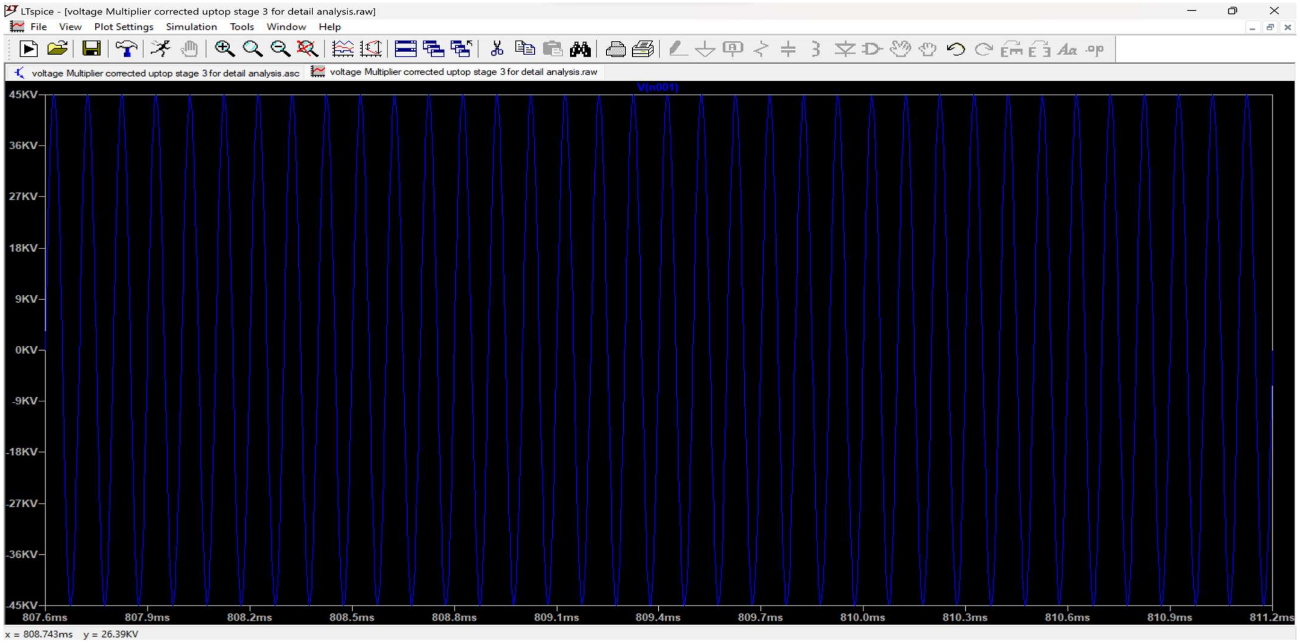



*Figure-6: Input Voltage at ACLine-1(45kV)*

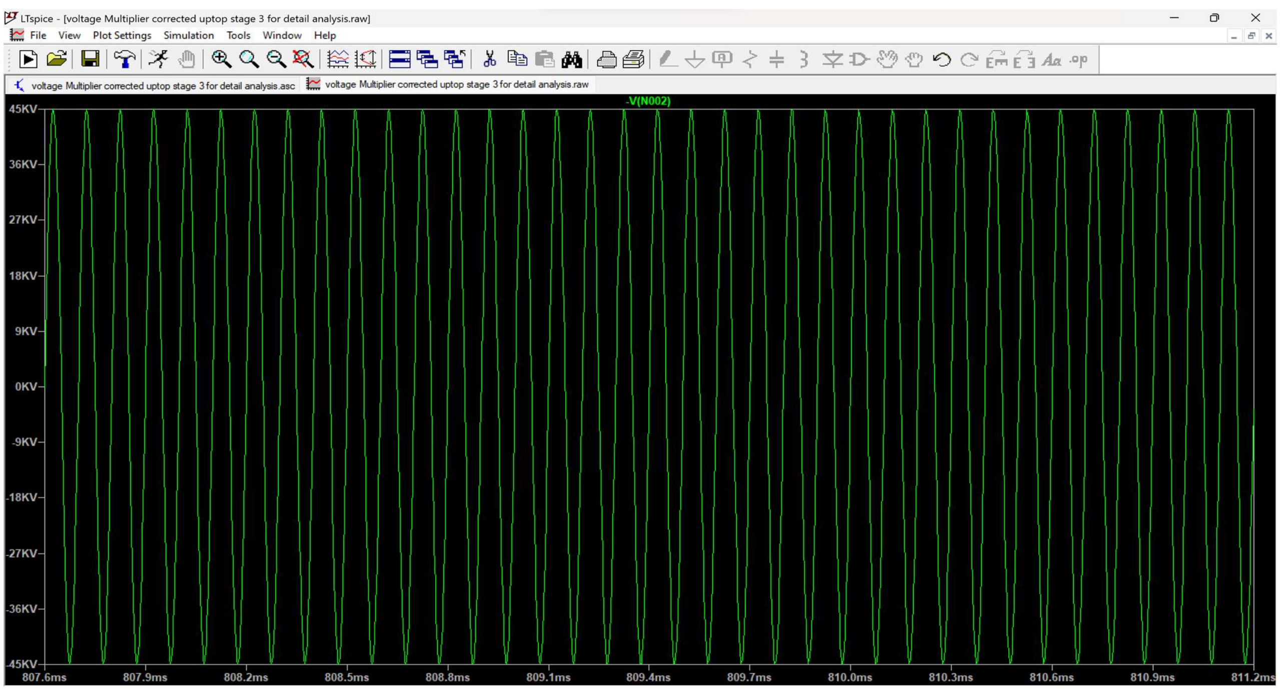



*Figure-7: Input Voltage at ACLine-2(45kV)*

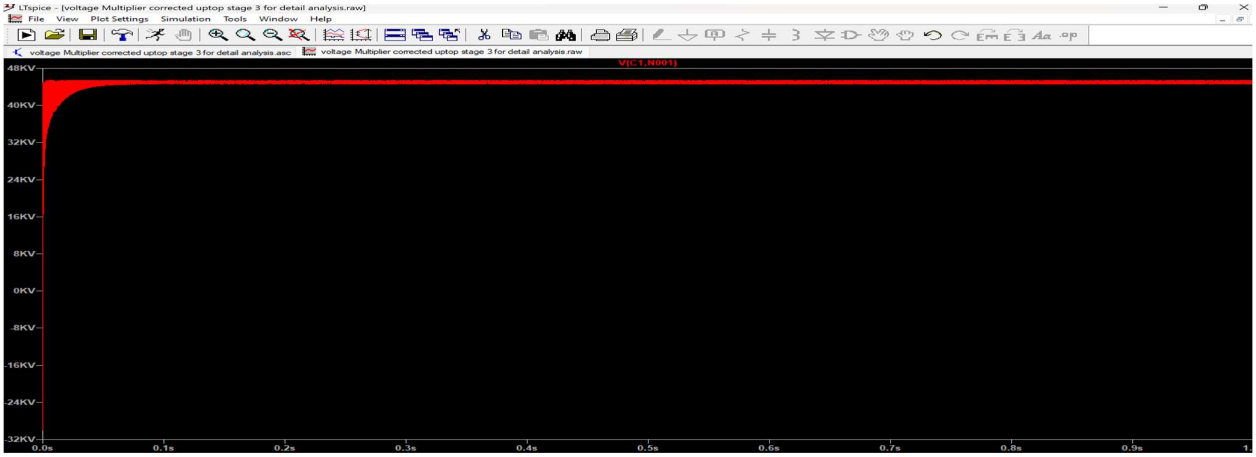



*Figure-8: Voltage across Stage-1 Capacitor of ACLine-1*

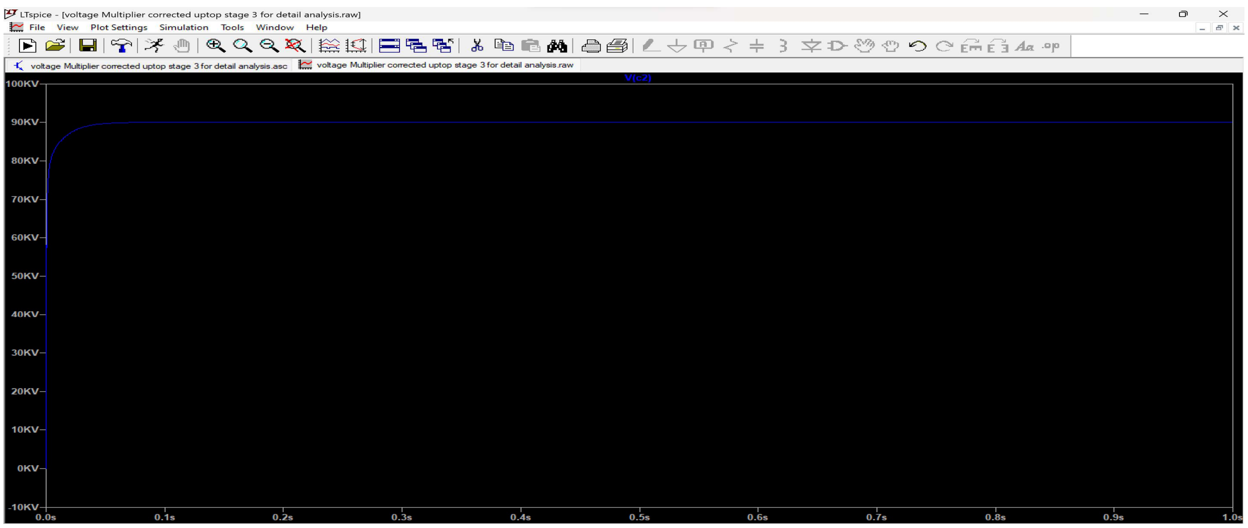



*Figure-9: Voltage across Stage-1 Capacitor of DC Line*

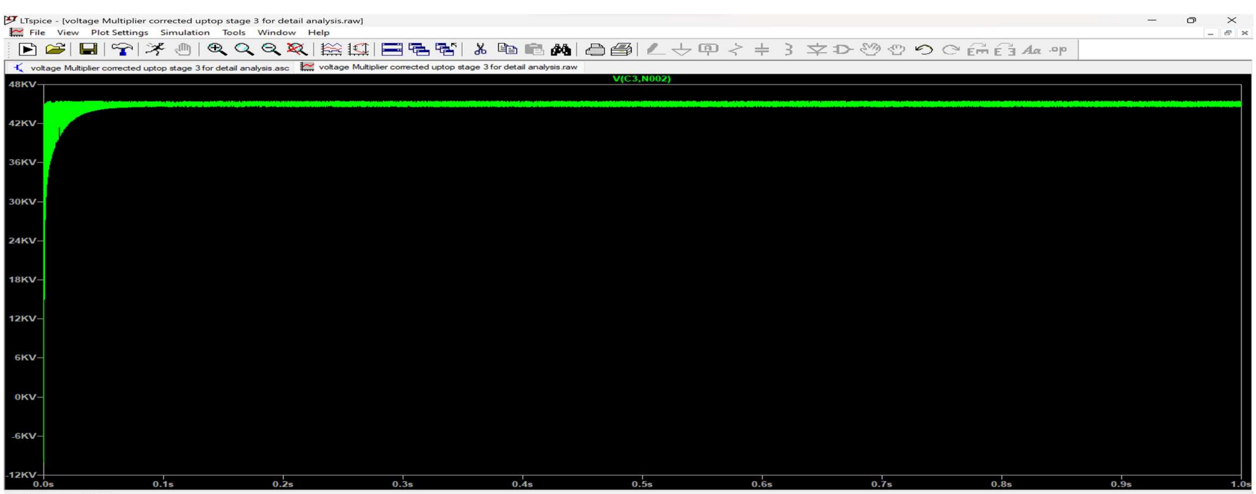



*Figure-10: Voltage across Stage-1 Capacitor of ACLine-2*


*Figure-11: Voltage across Stage-2 Capacitor of ACLine-1*

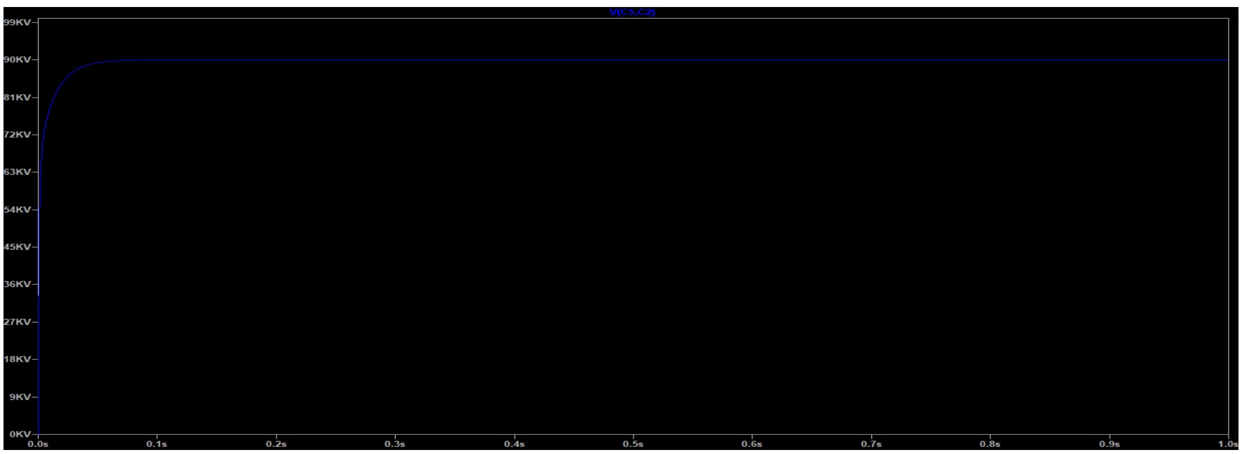



*Figure-12: Voltage across Stage-2Capacitor of DC Line*

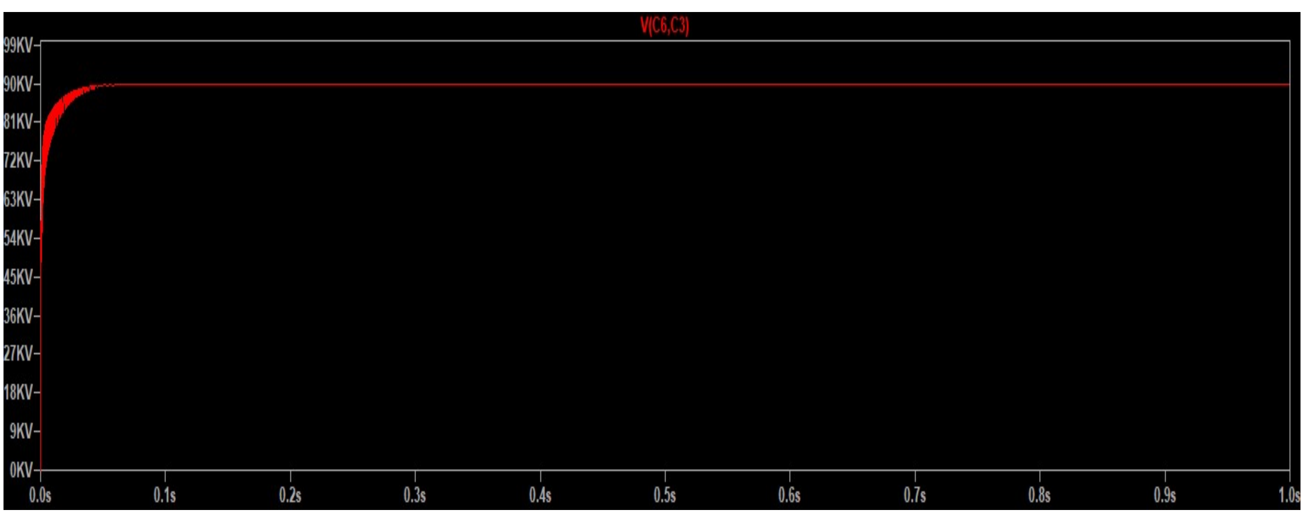



*Figure-13: Voltage across Stage-2 Capacitor of ACLine-2*

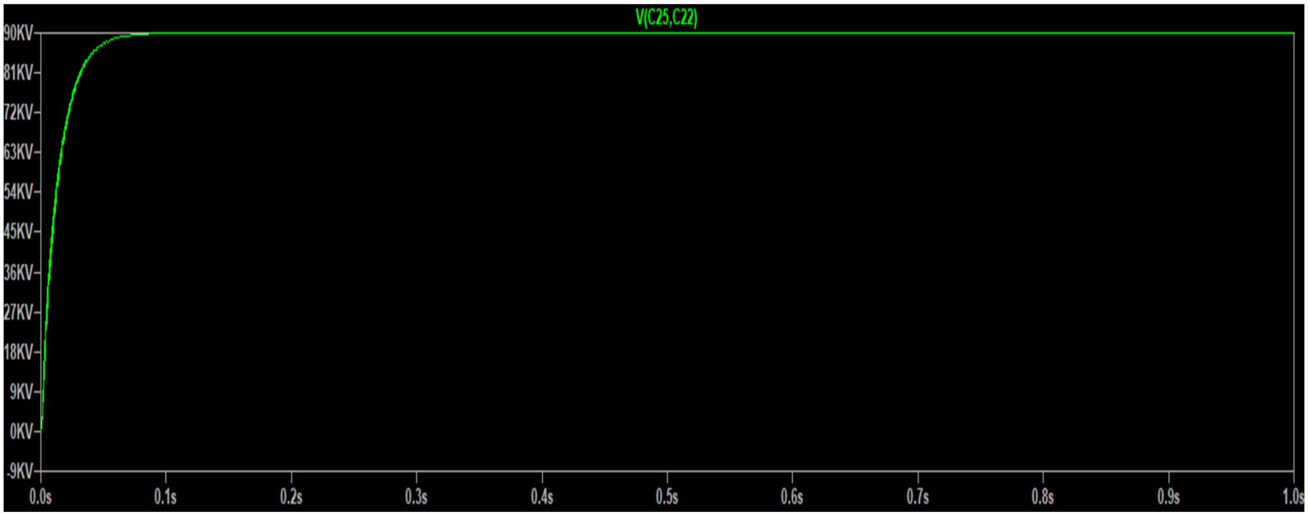



***Figure-14: Voltage across stage -9 Capacitor of ACLine-1***

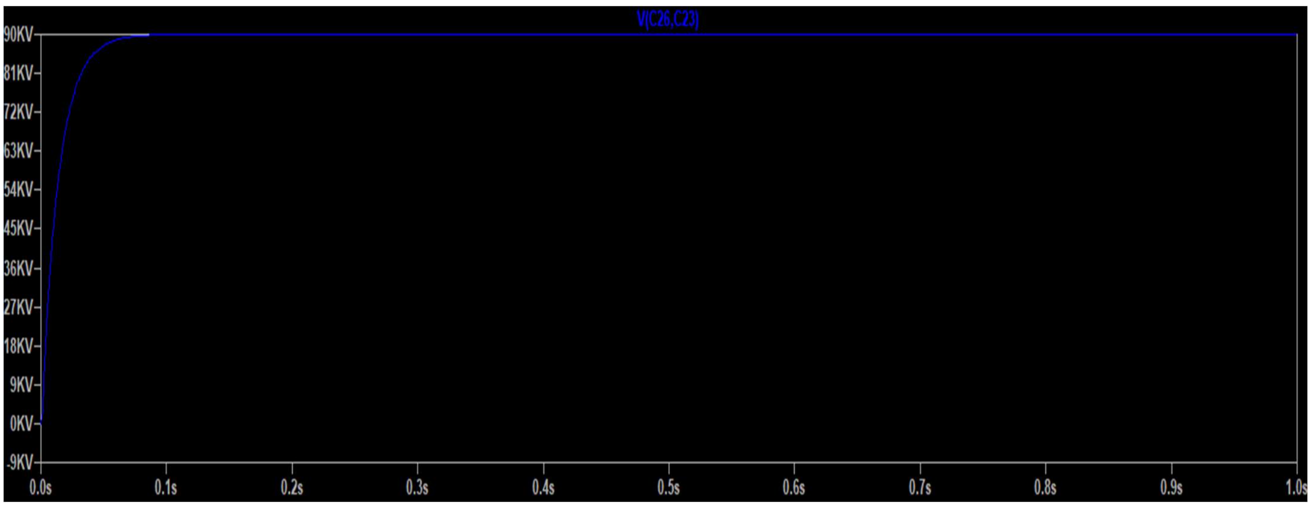



***Figure-15: Voltage across Stage-9 of DC Line***

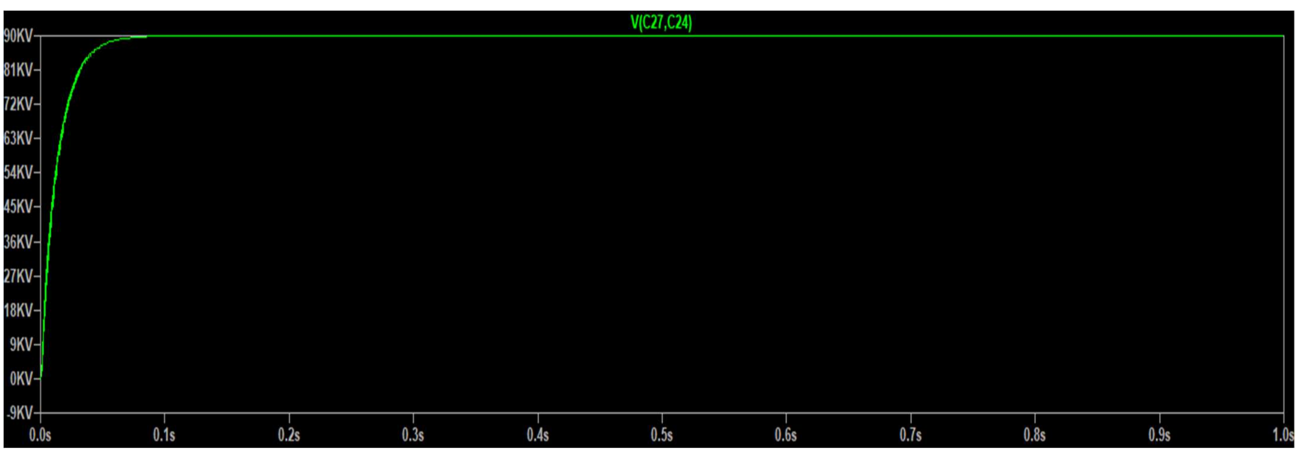



***Figure-16: Voltage across Stage-9 Capacitor of AC Line-2***

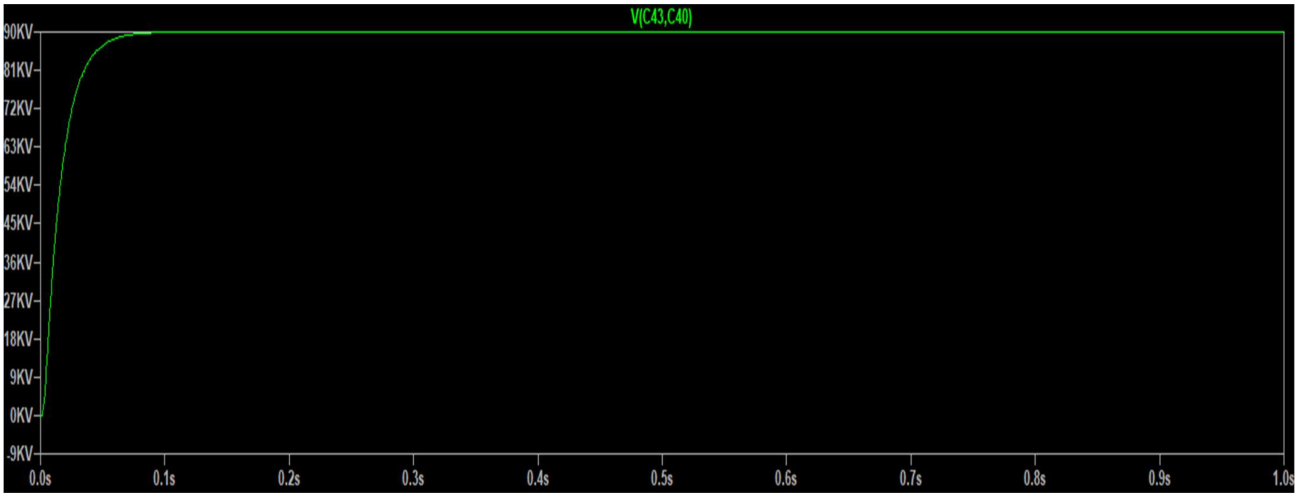



***Figure-17: Voltage across Stage-15 Capacitor of ACLine-1***

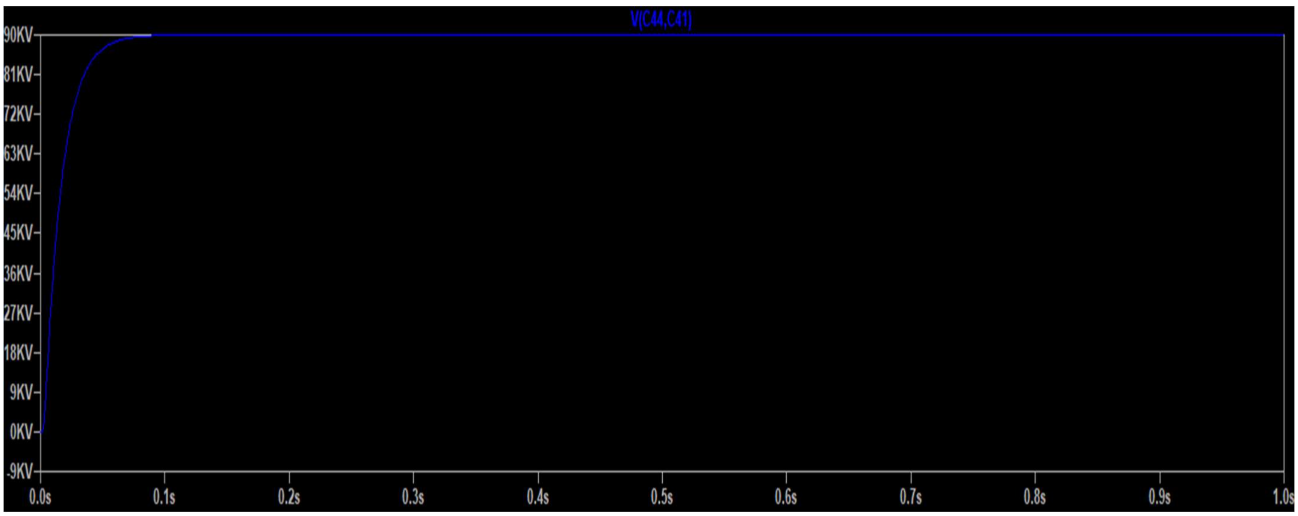



***Figure-18: Voltage across Stage-15 Capacitor of DC Line***

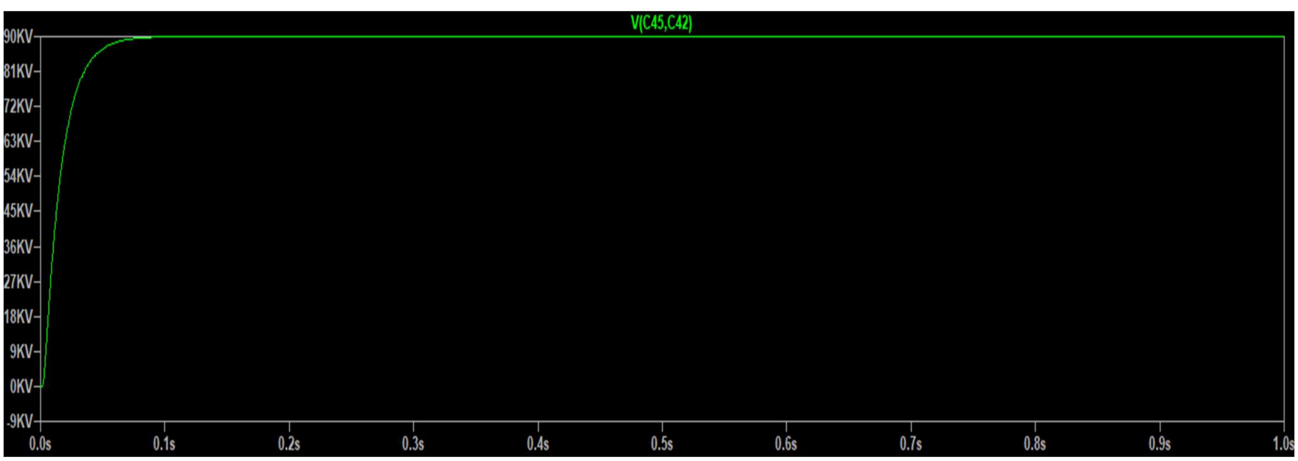



***Figure-19: Voltage across Stage-15 Capacitor of ACLine-2***

### *Stage Capacitor Current at No Load:*

| STAGE | AC-LINE-1 | | DC-LINE | | AC-Line-2 | |
|---|---|---|---|---|---|---|
| | MAX(A) | RMS(A) | MAX(A) | RMS(A) | MAX(A) | RMS(A) |
| 1 | 0.0239258 | 0.000122939 | 0.0296224 | 8.24E-06 | 0.0228068 | 0.000122784 |
| 2 | 0.0232747 | 0.000118087 | 0.0297852 | 8.53E-06 | 0.0228678 | 0.000117933 |
| 3 | 0.0238851 | 0.000111926 | 0.0292358 | 8.37E-06 | 0.0227458 | 0.000111772 |
| 4 | 0.0257568 | 0.000104936 | 0.0302734 | 8.64E-06 | 0.0224609 | 0.00010478 |
| 5 | 0.0249430 | 9.73E-05 | 0.0301107 | 8.56E-06 | 0.0233154 | 9.72E-05 |
| 6 | 0.0225016 | 8.91E-05 | 0.0313721 | 8.49E-06 | 0.0223796 | 8.91E-05 |
| 7 | 0.0233968 | 8.07E-05 | 0.0280151 | 9.64E-06 | 0.0222982 | 8.06E-05 |
| 8 | 0.0190430 | 7.19E-05 | 0.0280762 | 1.04E-05 | 0.0220947 | 7.19E-05 |
| 9 | 0.0209147 | 6.29E-05 | 0.024821 | 9.16E-06 | 0.0224202 | 6.29E-05 |
| 10 | 0.0187174 | 5.38E-05 | 0.0256348 | 8.86E-06 | 0.0202637 | 5.38E-05 |
| 11 | 0.0165202 | 4.48E-05 | 0.0258789 | 8.96E-06 | 0.0187174 | 4.44E-05 |
| 12 | 0.0156250 | 3.57E-05 | 0.0256755 | 1.06E-05 | 0.0166423 | 3.52E-05 |
| 13 | 0.0142415 | 2.62E-05 | 0.0209351 | 8.08E-06 | 0.0159912 | 2.63E-05 |
| 14 | 0.0141602 | 1.65E-05 | 0.0142415 | 6.14E-06 | 0.00960286 | 1.70E-05 |
| 15 | 0.0068766 | 7.29E-06 | 0.00683594 | 4.84E-06 | 0.00793457 | 7.59E-06 |

### *Input Current*

INPUT CURRENT AT NO LOAD

| Iin(1) | Iin(2) |
|---|---|
| 13.1866mA | 12.8952mA |
| 76.107µA | 76.389µA |

## *Diode Voltage and Current :*

| Stage | Diode no. | Current | | Voltage(Max)(V)(N-P) |
|---|---|---|---|---|
| | | Max(A) | RMS(A) | |
| 1 | 1 | 0.000262217 | 4.11E-06 | 89999.4 |
| | 2 | 0.000264632 | 4.11E-06 | 89999.4 |
| | 3 | 0.000203351 | 3.17E-06 | 89999.4 |
| | 4 | 0.00020182 | 3.17E-06 | 89999.4 |
| 2 | 5 | 0.000305113 | 4.77E-06 | 89999.4 |
| | 6 | 0.000306252 | 4.76E-06 | 89999.4 |
| | 7 | 0.000278911 | 4.35E-06 | 89999.4 |
| | 8 | 0.000277921 | 4.35E-06 | 89999.4 |
| 3 | 9 | 0.000336334 | 5.26E-06 | 89999.4 |
| | 10 | 0.000334327 | 5.25E-06 | 89999.4 |
| | 11 | 0.000313646 | 4.93E-06 | 89999.4 |
| | 12 | 0.00031514 | 4.94E-06 | 89999.4 |
| 4 | 13 | 0.000360458 | 5.64E-06 | 89999.3 |
| | 14 | 0.000358526 | 5.63E-06 | 89999.3 |
| | 15 | 0.000341915 | 5.38E-06 | 89999.4 |
| | 16 | 0.000344183 | 5.39E-06 | 89999.4 |
| 5 | 17 | 0.000378202 | 5.94E-06 | 89999.4 |
| | 18 | 0.000379254 | 5.92E-06 | 89999.4 |
| | 19 | 0.000366746 | 5.74E-06 | 89999.4 |
| | 20 | 0.000365049 | 5.75E-06 | 89999.4 |
| 6 | 21 | 0.000395995 | 6.15E-06 | 89999.3 |
| | 22 | 0.000392912 | 6.14E-06 | 89999.3 |
| | 23 | 0.000383975 | 6.00E-06 | 89999.3 |
| | 24 | 0.000386109 | 6.01E-06 | 89999.3 |
| 7 | 25 | 0.000408518 | 6.32E-06 | 89999.4 |
| | 26 | 0.000401494 | 6.31E-06 | 89999.4 |
| | 27 | 0.000378202 | 5.94E-06 | 89999.4 |
| | 28 | 0.000401791 | 6.22E-06 | 89999.4 |
| 8 | 29 | 0.000415525 | 6.43E-06 | 89999.4 |
| | 30 | 0.000412308 | 6.42E-06 | 89999.4 |
| | 31 | 0.000406981 | 6.35E-06 | 89999.4 |
| | 32 | 0.000411796 | 6.37E-06 | 89999.4 |
| 9 | 33 | 0.000419593 | 6.51E-06 | 89999.4 |
| | 34 | 0.000422102 | 6.50E-06 | 89999.4 |
| | 35 | 0.000418047 | 6.46E-06 | 89999.4 |
| | 36 | 0.000418309 | 6.47E-06 | 89999.4 |
| 10 | 37 | 0.000423404 | 6.56E-06 | 89999.4 |
| | 38 | 0.000428111 | 6.55E-06 | 89999.4 |
| | 39 | 0.000425846 | 6.53E-06 | 89999.4 |
| | 40 | 0.00042154 | 6.54E-06 | 89999.4 |
| 11 | 41 | 0.000428212 | 6.59E-06 | 89999.4 |
| | 42 | 0.000431802 | 6.58E-06 | 89999.4 |
| | 43 | 0.000430876 | 6.57E-06 | 89999.3 |
| | 44 | 0.000426303 | 6.58E-06 | 89999.4 |
| 12 | 45 | 0.000430724 | 6.60E-06 | 89999.4 |
| | 46 | 0.0004334 | 6.59826E-06 | 89999.4 |
| | 47 | 0.000433345 | 6.58E-06 | 89999.3 |
| | 48 | 0.000429536 | 6.60E-06 | 89999.3 |
| 13 | 49 | 0.000432179 | 6.60E-06 | 89999.3 |
| | 50 | 0.000434144 | 6.59E-06 | 89999.4 |
| | 51 | 0.000434885 | 6.59E-06 | 89999.4 |
| | 52 | 0.000431652 | 6.61E-06 | 89999.4 |
| 14 | 53 | 0.000433621 | 6.61E-06 | 89999.4 |
| | 54 | 0.000435196 | 6.60E-06 | 89999.4 |
| | 55 | 0.000434876 | 6.58E-06 | 89999.4 |
| | 56 | 0.000431896 | 6.60E-06 | 89999.4 |
| 15 | 57 | 0.000219 | 6.61E-06 | 89999.4 |
| | 58 | 0.000219056 | 6.61E-06 | 89998.4 |
| | 59 | 0.0004255 | 6.44E-06 | 89999.4 |
| | 60 | 0.000422838 | 6.45E-06 | 89999.4 |

## *Waveform of Diode Voltages and Current at each stage*

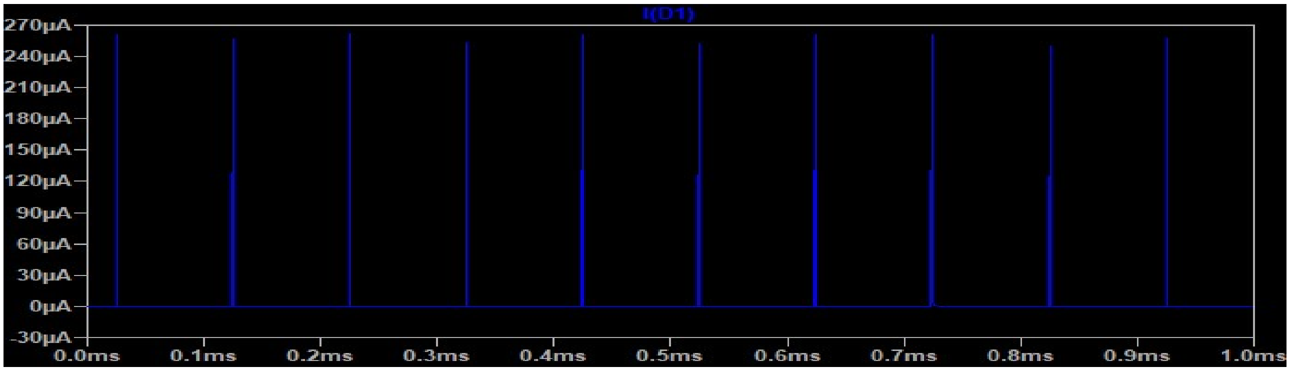



***Figure-20: Current through $D_1$ (Stage-1)***

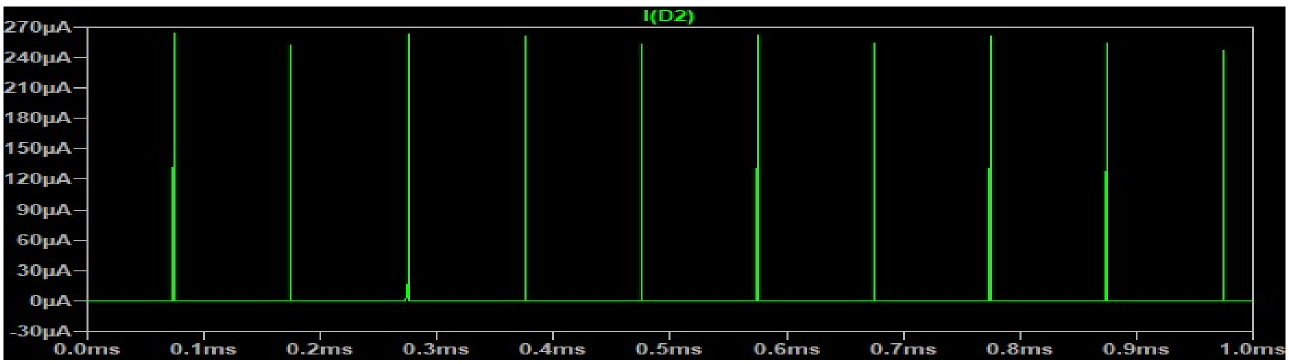



***Figure-21: Current through $D_2$ (Stage-1)***

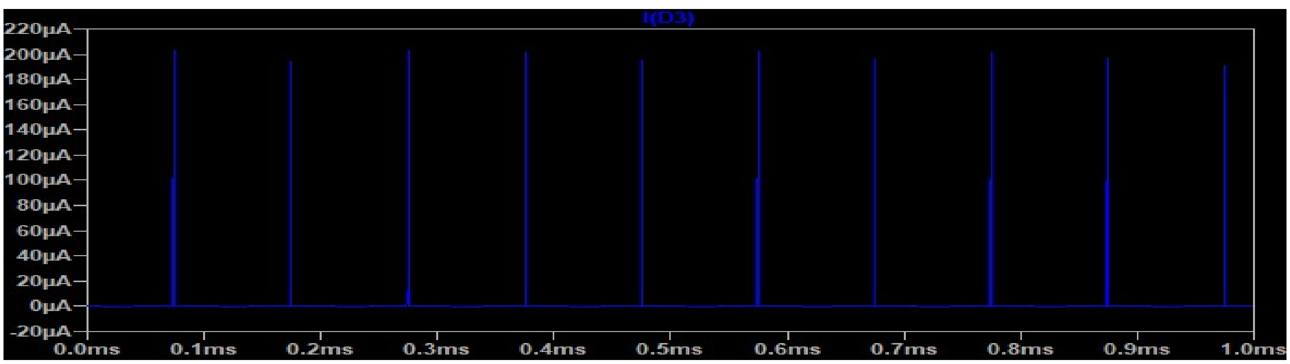



***Figure-22: Current through $D_3$ (Stage-1)***

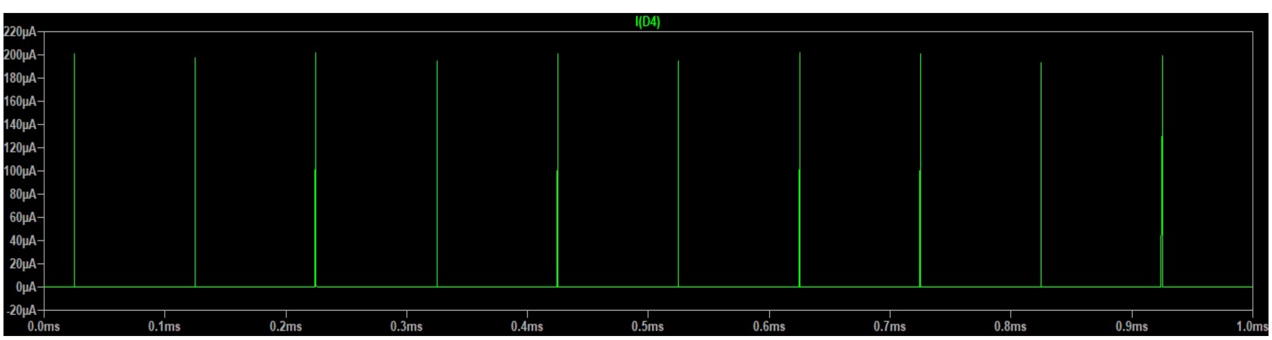



***Figure-23: Current through $D_4$ (Stage-1)***

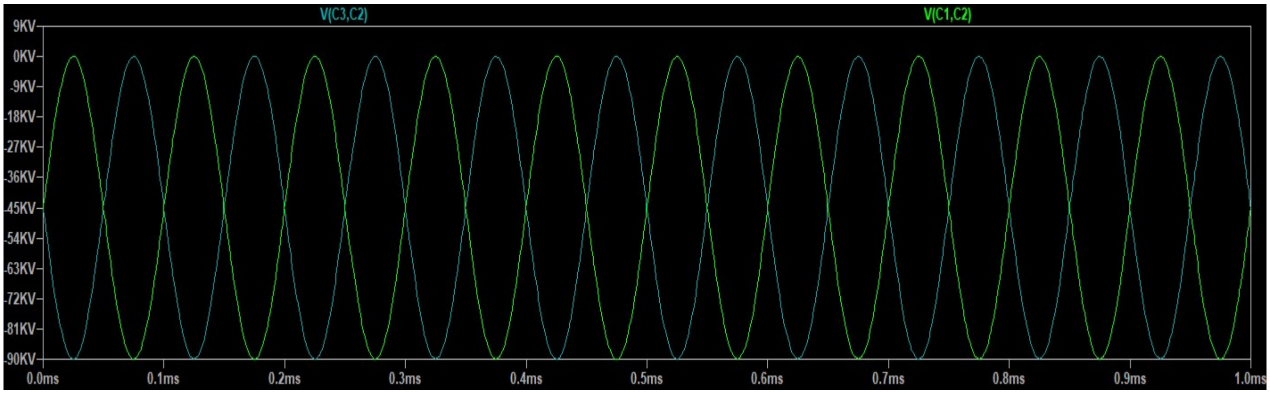



*Figure-24: Voltage across $D_1$ and $D_2$ (Stage-1)*

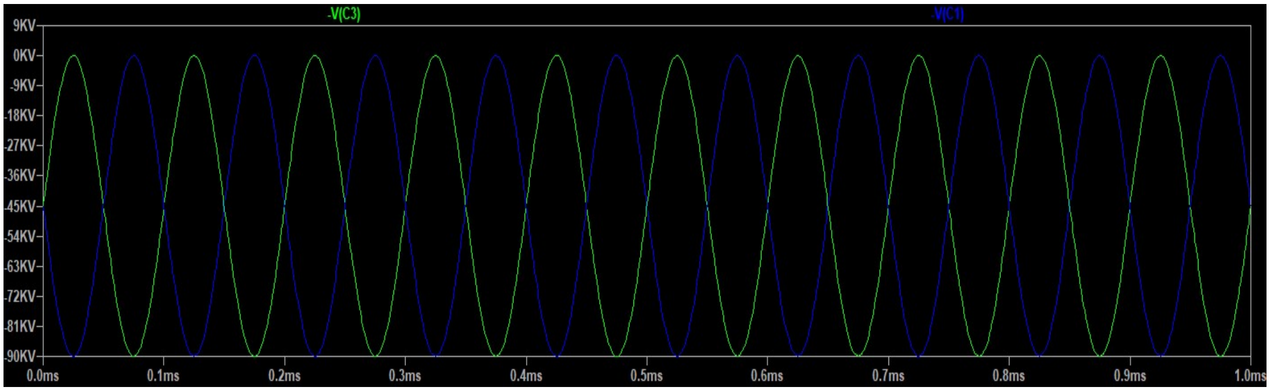



*Figure-25: Voltage across $D_3$ and $D_4$ (Stage-1)*

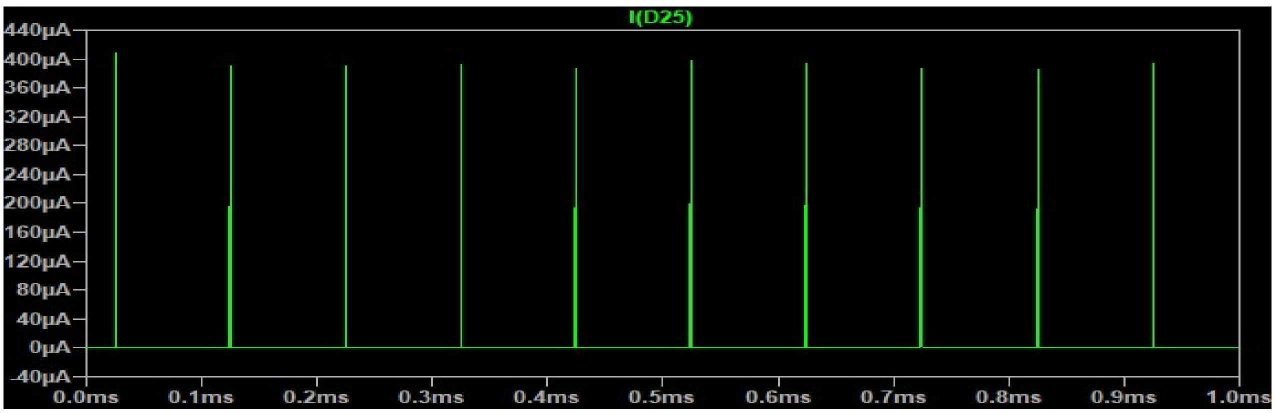



*Figure-26: Current through $D_{25}$ (Stage-7)*

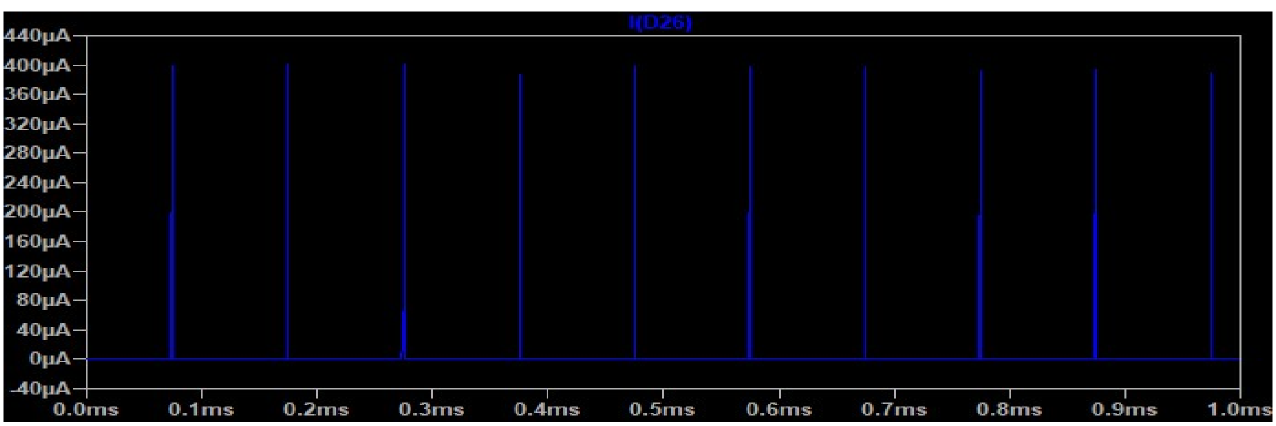



*Figure-27: Current through $D_{26}$ (Stage-7)*

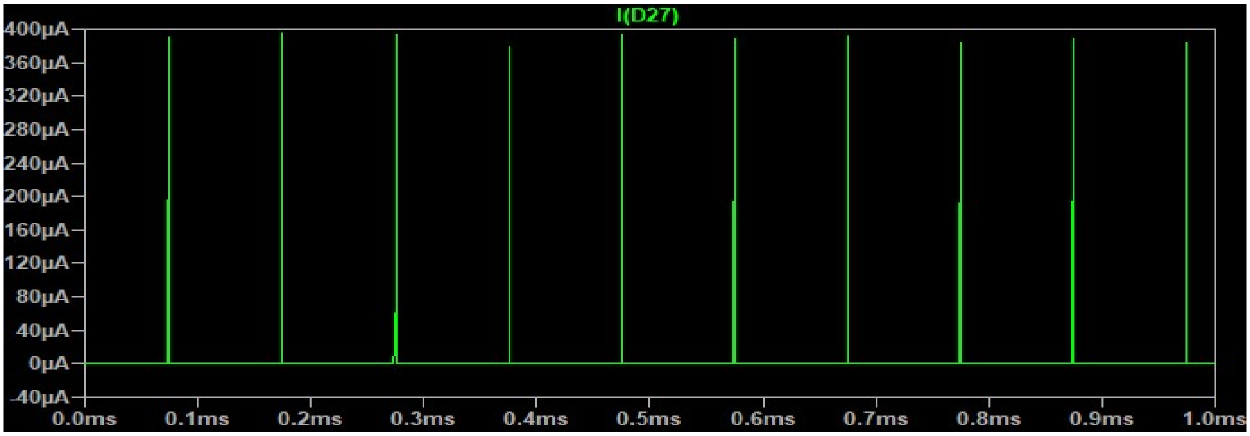



*Figure-28: Current through $D_{27}$ (Stage-7)*

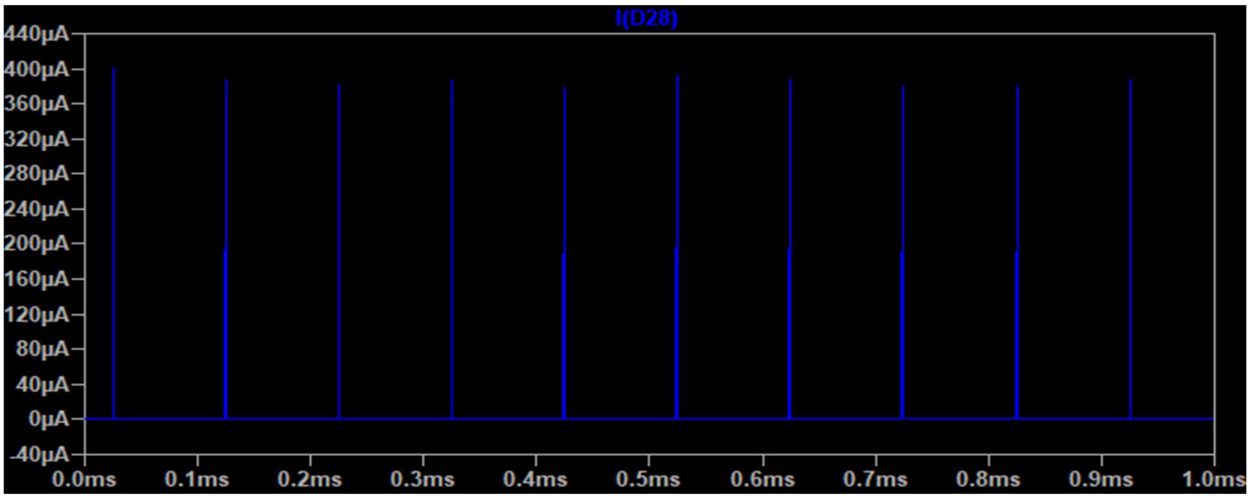



*Figure-29: Current through $D_{28}$ (Stage-7)*

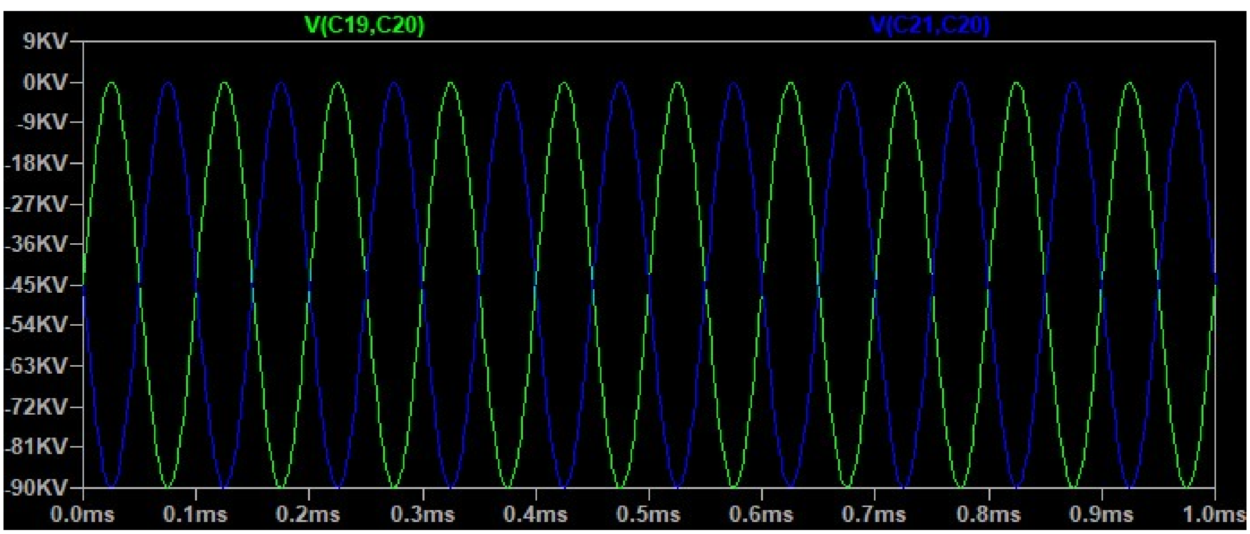



*Figure-30: Voltage across $D_{25}$ and $D_{26}$ (Stage-7)*

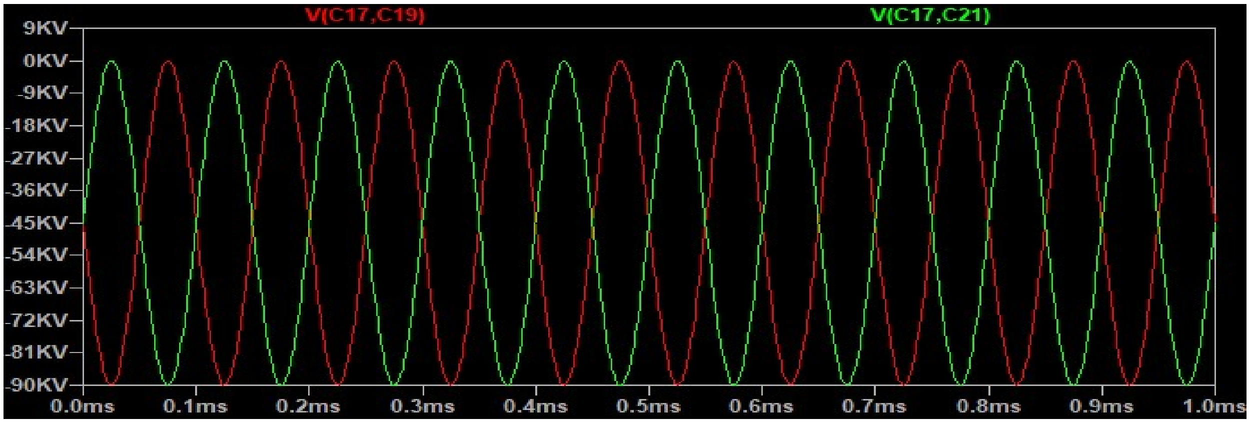



***Figure-31: Voltage across $D_{27}$ and $D_{28}$ (Stage-7)***

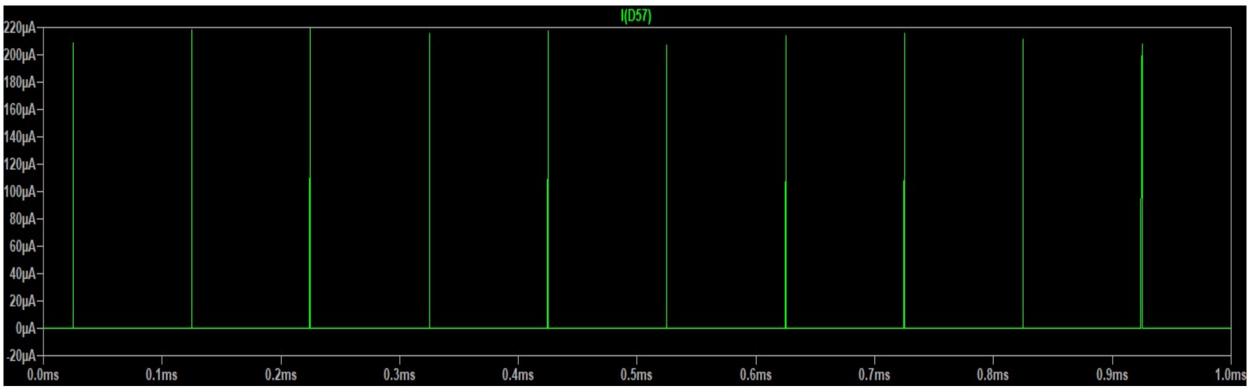



***Figure-32: Current through $D_{57}$ (Stage-15)***

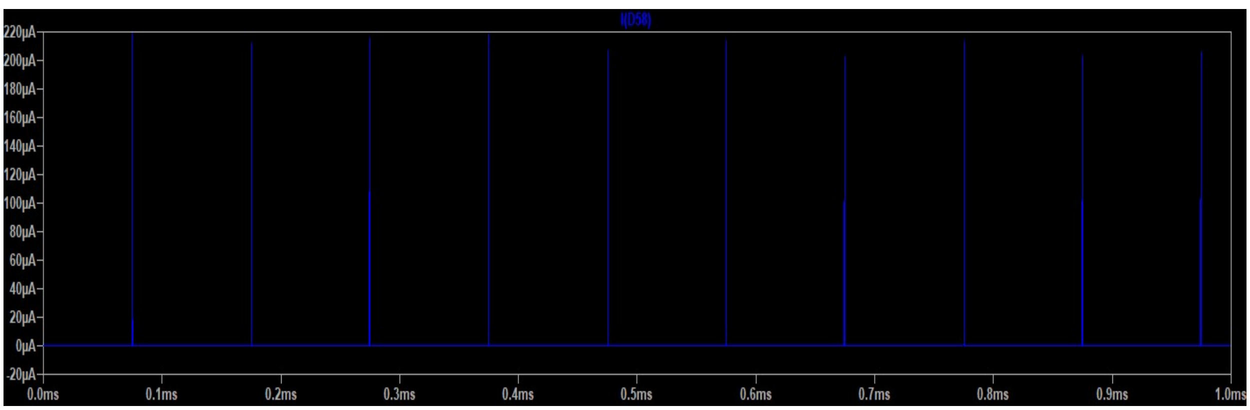


***Figure-33: Current through $D_{58}$ (Stage-15)***

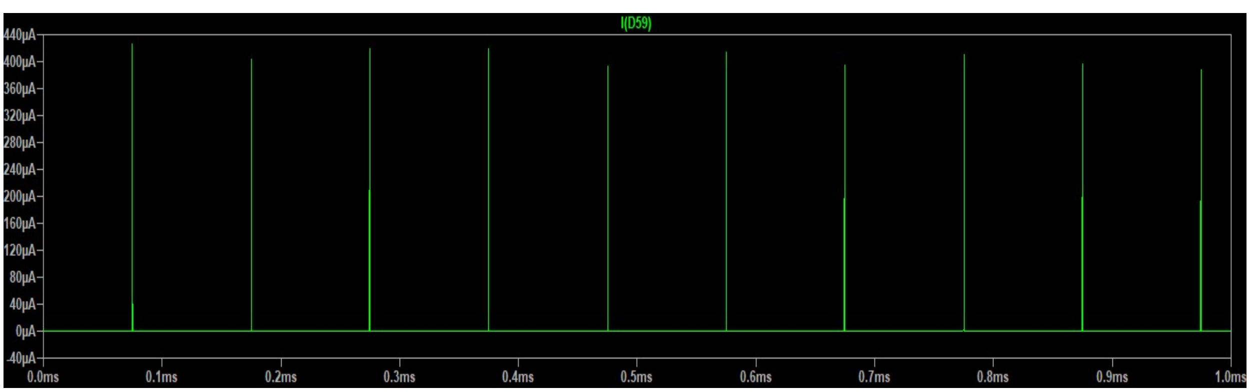



***Figure-34: Current through $D_{59}$ (Stage-15)***

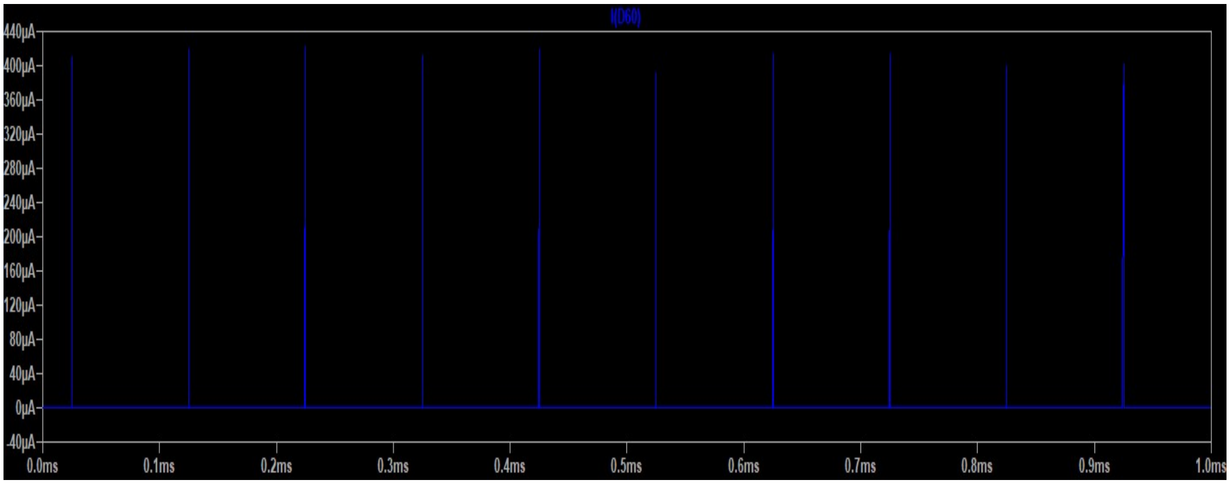



***Figure-35: Current through $D_{60}$ (Stage-15)***

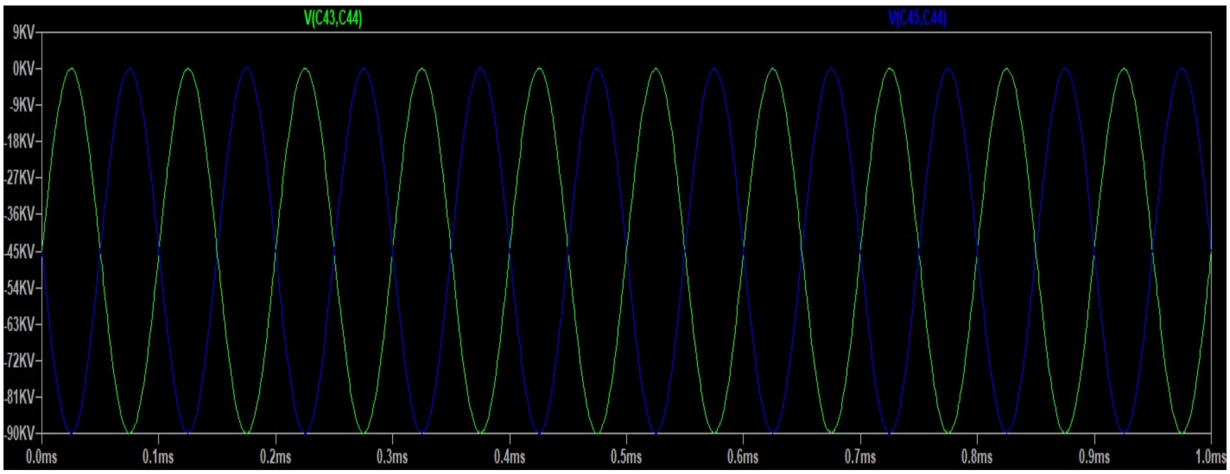



***Figure-36: Voltage across $D_{57}$ and $D_{58}$ (Stage-15)***

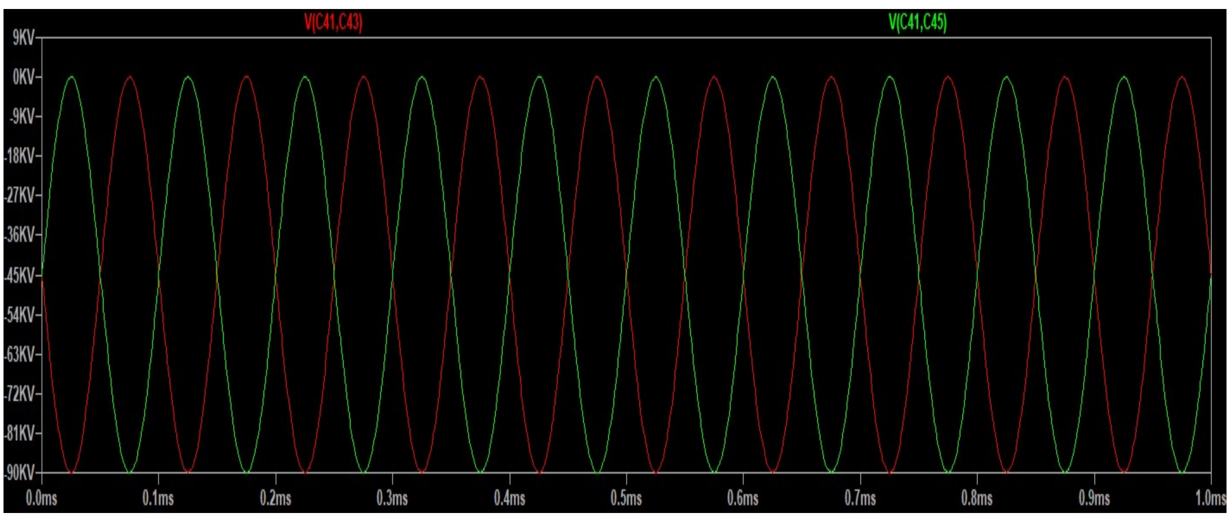



***Figure-37: Voltage across $D_{59}$ and $D_{60}$ (Stage-15)***

### *At 100kW beam load (10MΩ Load):*

Given that we require a **current of 100 mA** and the output DC voltage at the 15th stage is approximately **1 MV**, the **load resistance would be 10 MΩ.**

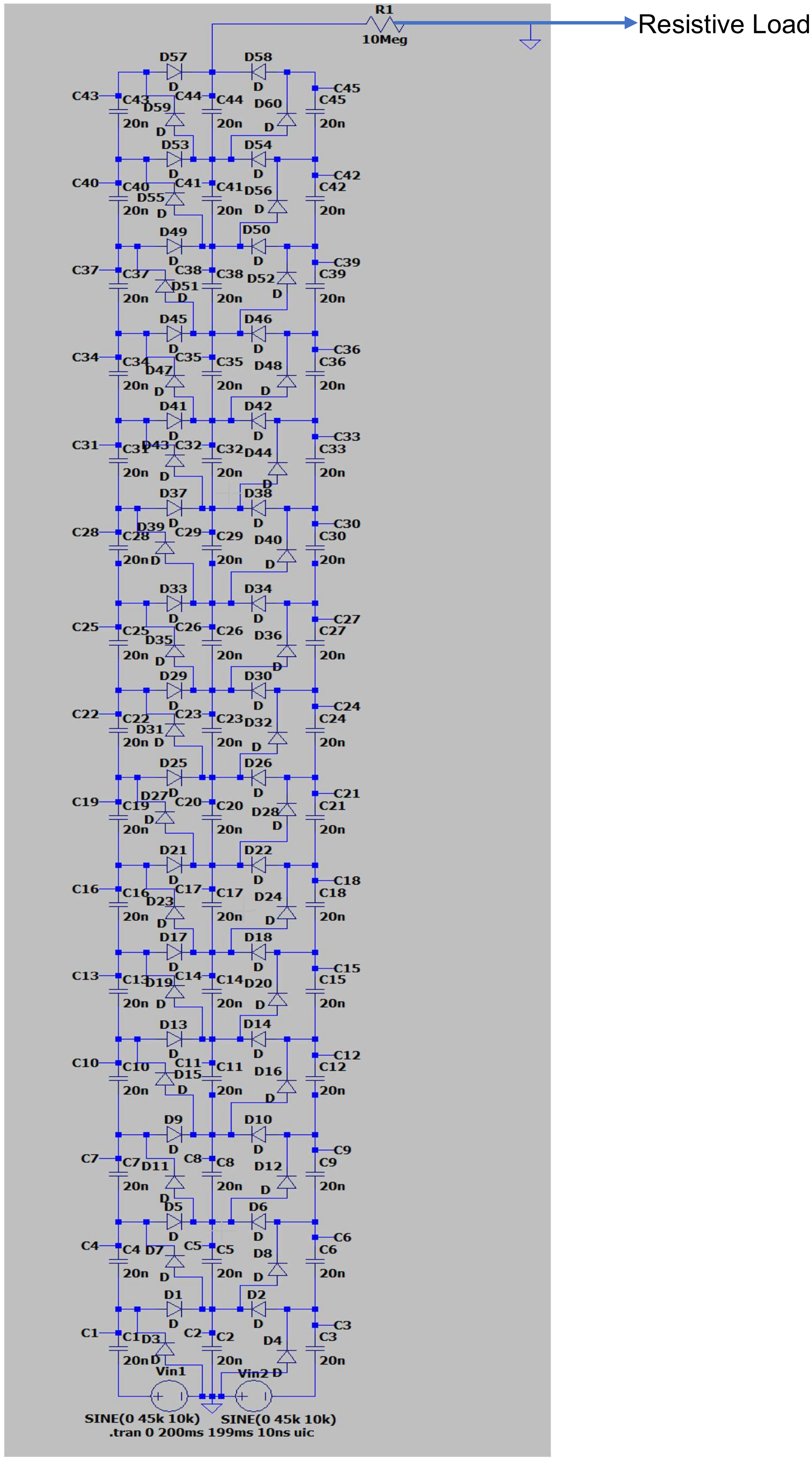
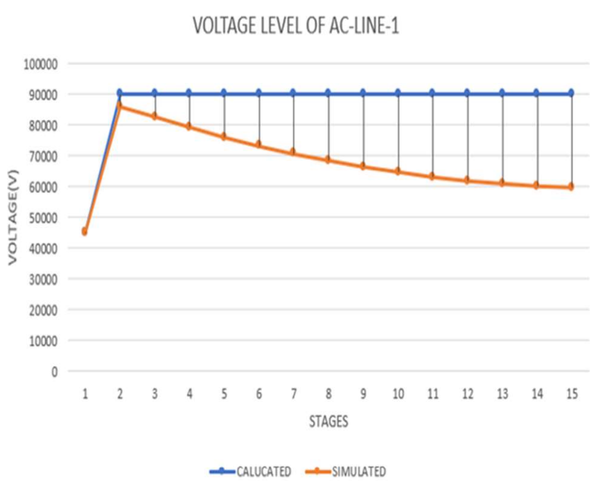


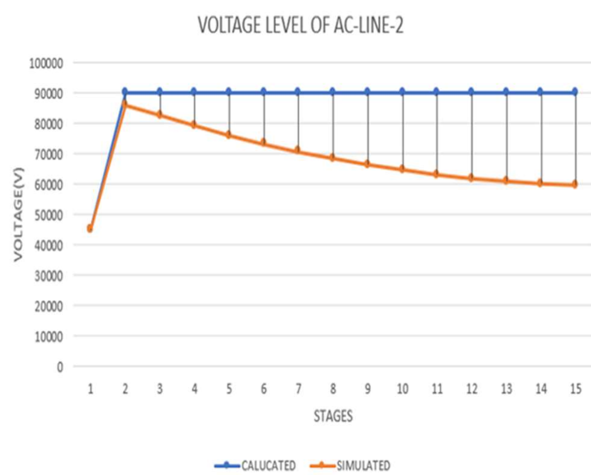

***Figure-38: Simulation at Loaded Condition***

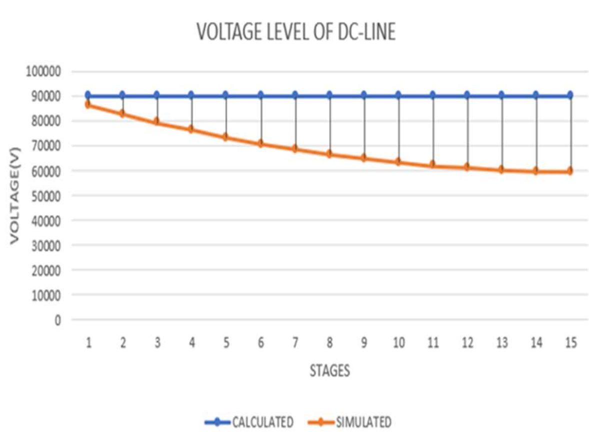
## *Voltage Level (At Loaded Condition):*

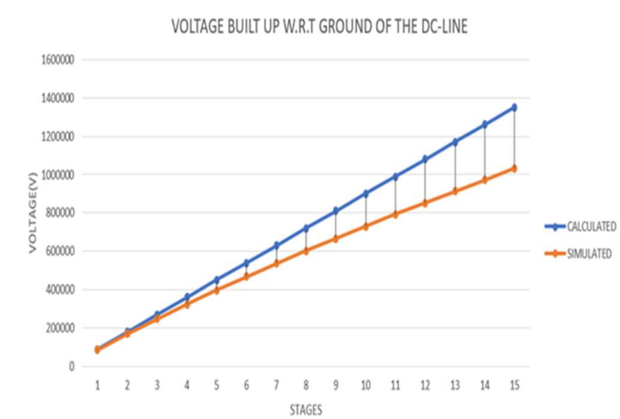
| Stage | AC-Line(1) | DC-Line | AC-Line(2) | Voltage Built up w.r.t Ground (V) |
|---|---|---|---|---|
| 1 | 44999.3 | 86132.1 | 44999.3 | 86132.1 |
| 2 | 86132.1 | 82529.3 | 86132.1 | 168656 |
| 3 | 82529.5 | 79187.5 | 82529.4 | 247835 |
| 4 | 79187.6 | 76106.5 | 79187.6 | 323930 |
| 5 | 76106.6 | 73286.8 | 76106.6 | 397202 |
| 6 | 73286.9 | 70727.8 | 73286.9 | 467912 |
| 7 | 70728 | 68429.7 | 70727.9 | 536320 |
| 8 | 68429.7 | 66392.8 | 68429.9 | 602689 |
| 9 | 66392.9 | 64617.1 | 66392.9 | 667278 |
| 10 | 64617.1 | 63102.5 | 64617.4 | 730350 |
| 11 | 63102.7 | 61849 | 63102.7 | 792165 |
| 12 | 61849.3 | 60856.5 | 61848.9 | 852984 |
| 13 | 60856.8 | 60125.5 | 60856.6 | 913069 |
| 14 | 60125.8 | 59655.6 | 60125.5 | 972680 |
| 15 | 59655.6 | 59447.6 | 59655.8 | 1.03E+06 |

## <u>Graphical Representation of voltage level at each Stage</u>

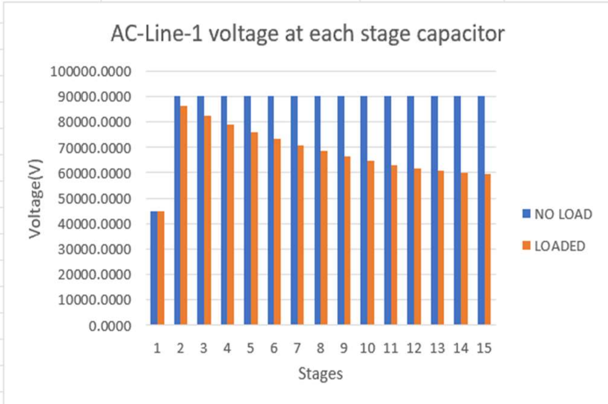


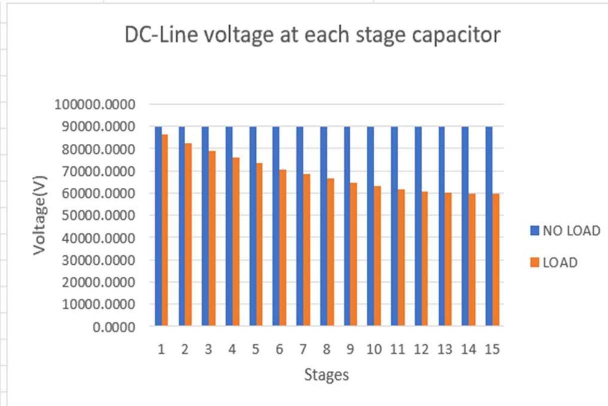



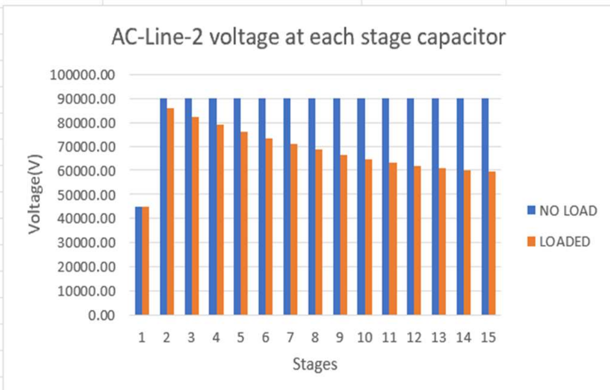



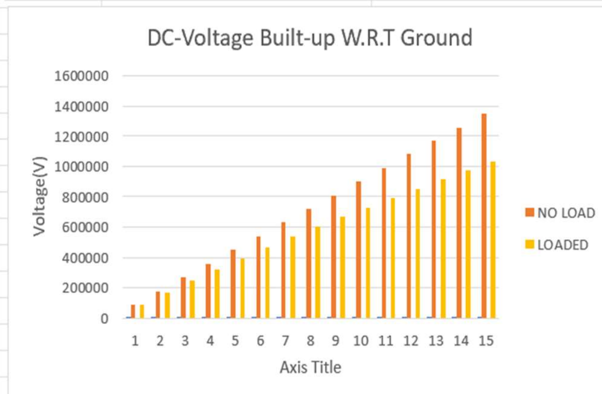



## Graphical Comparison of voltages at each stage capacitor at No load and Loaded condition




***Input Voltage Level:***

| Vin (V) -1 | Vin (V) -2 |
|---|---|
| 45000.00 | 45000.00 |

## <u>Waveform of voltage and current across the load of 10MΩ</u>

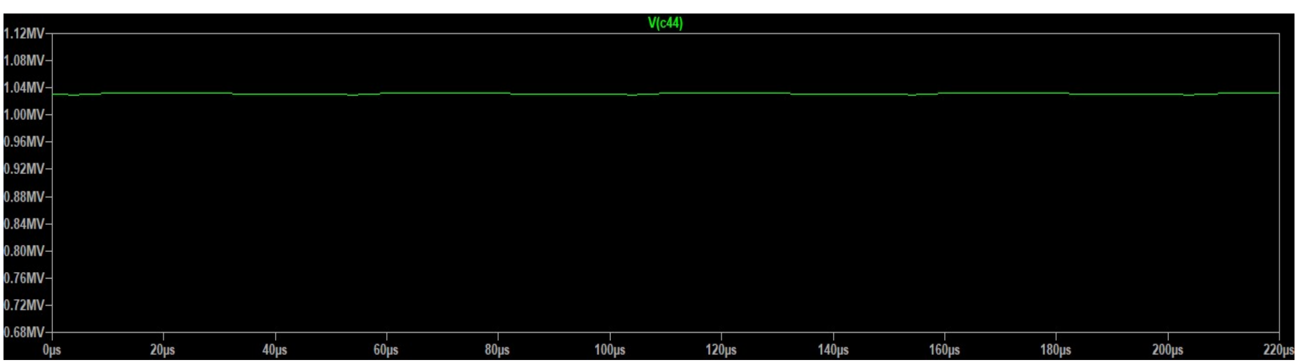



***Figure39: Voltage across the load of 10MΩ*** **(1.0313MV)**

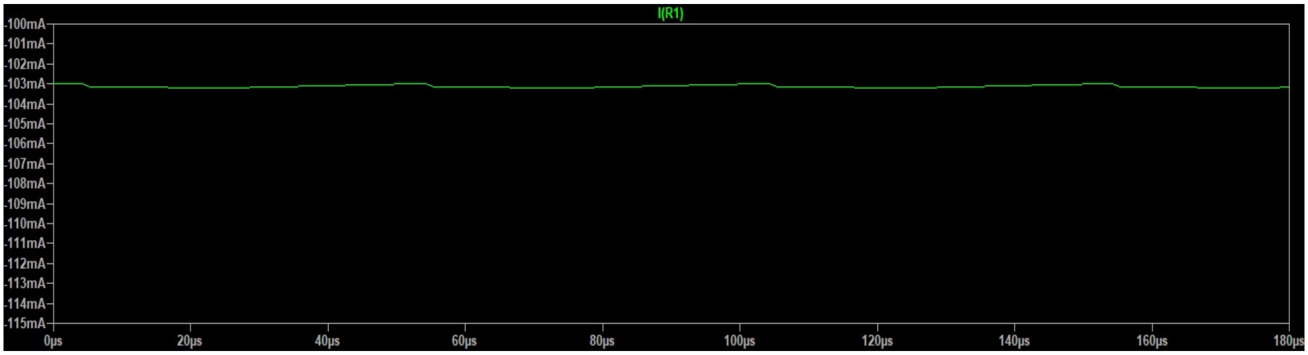



***Figure-40: Current through the load of 10MΩ* (-103.13mA)**

## <u>Waveform of Voltage across Capacitors at Different Stages</u>

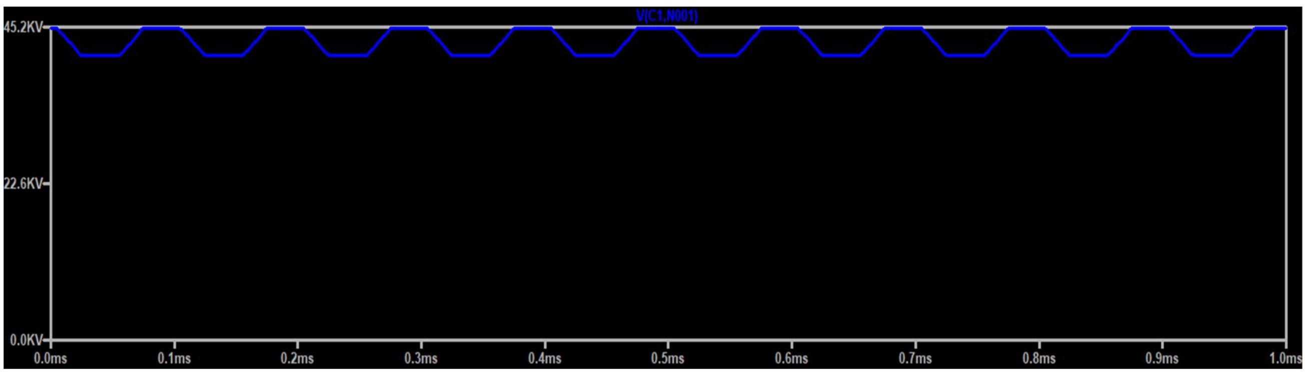



***Figure- 41: Voltage across Stage-1 Capacitor of AC-Line-1***

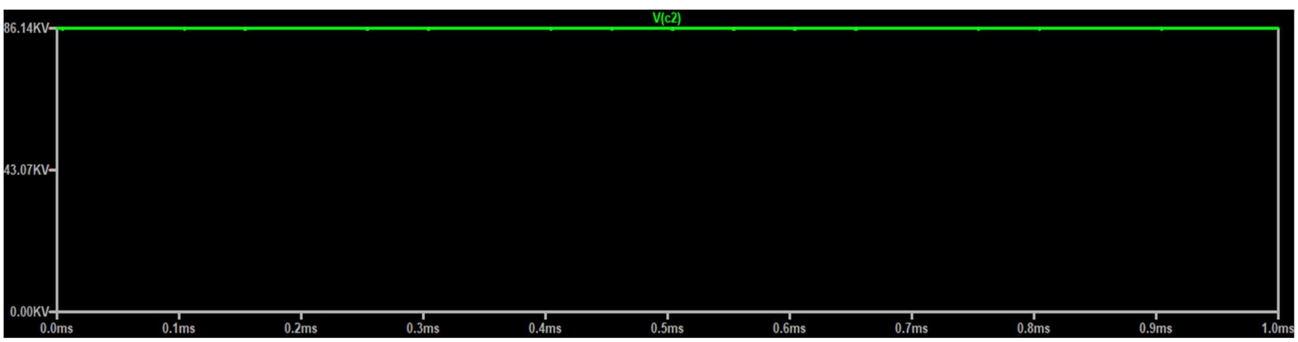



***Figure-42: Voltage across Stage-1 Capacitor of DC-Line***

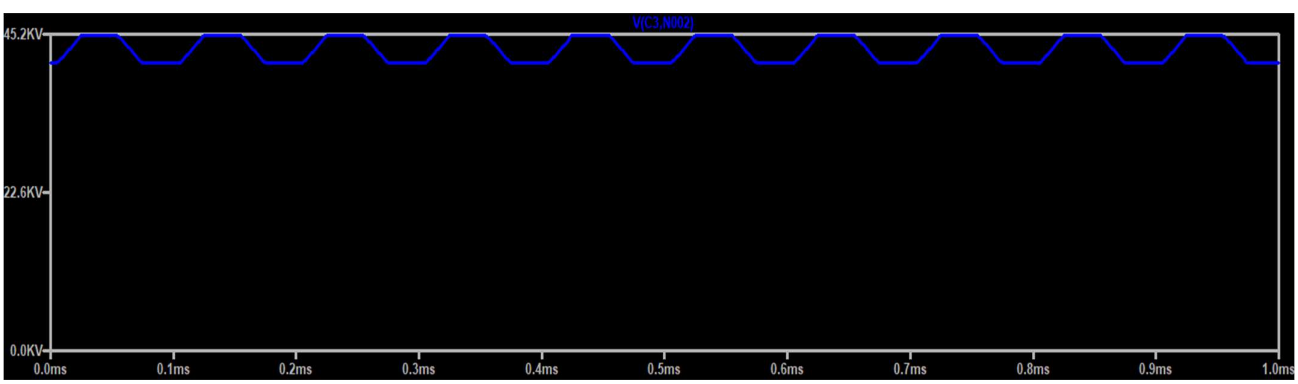



***Figure-43: Voltage across Stage-1 Capacitor of AC-LINE-2***

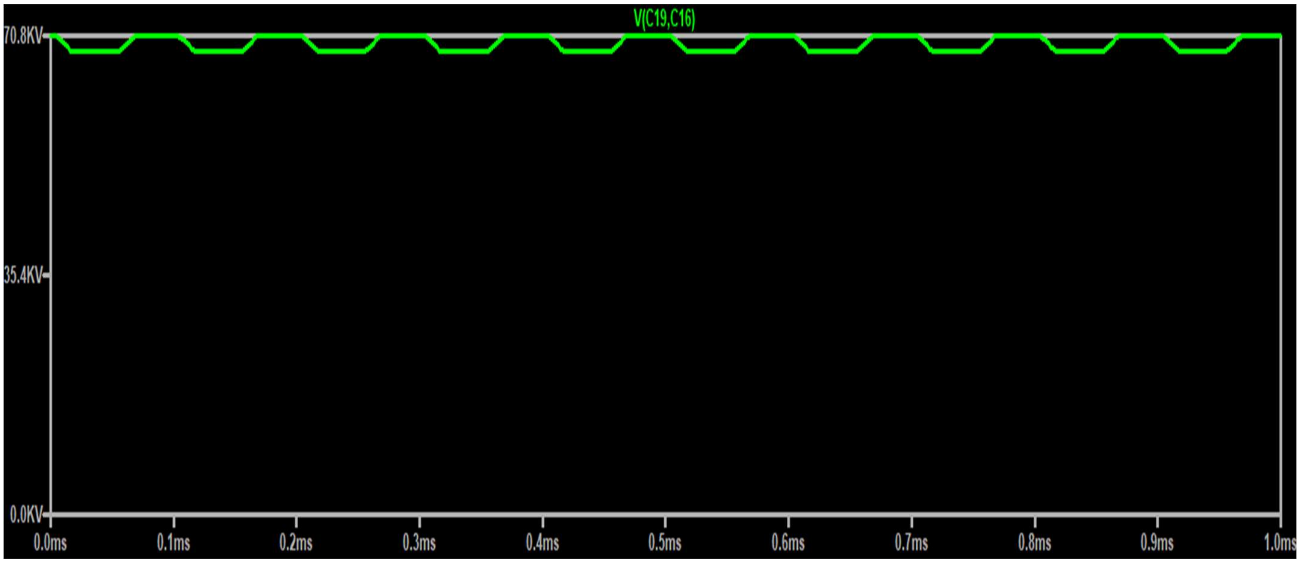



***Figure-44: Voltage across Stage-7 Capacitor of AC-LINE-1***

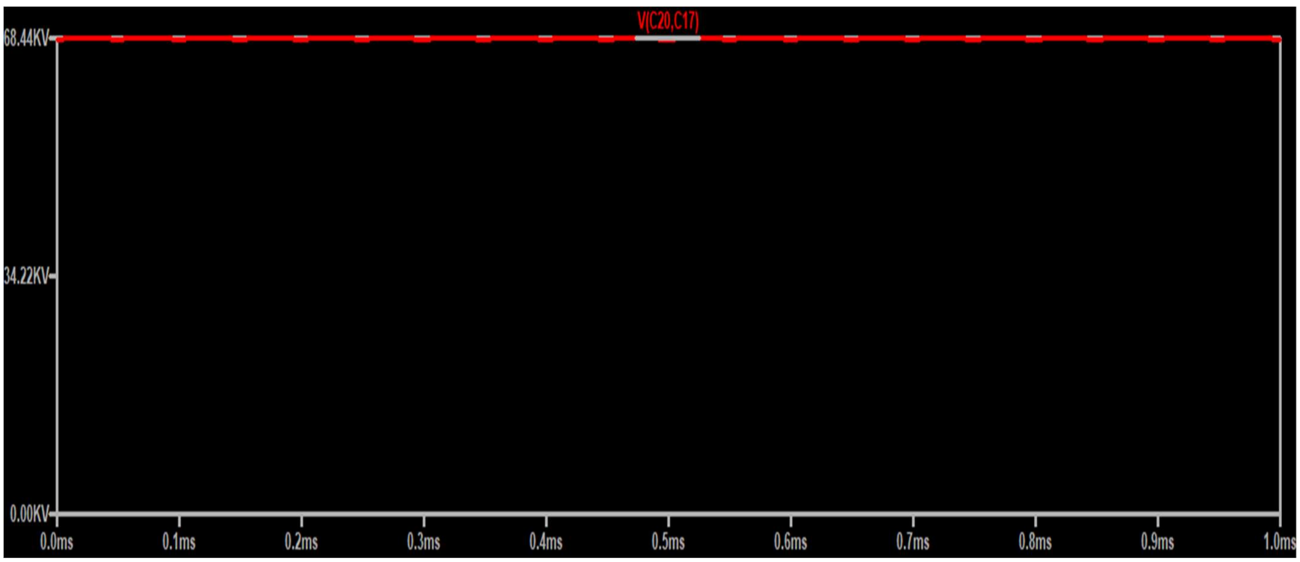



***Figure-45: Voltage across Stage-7 Capacitor of DC-Line***

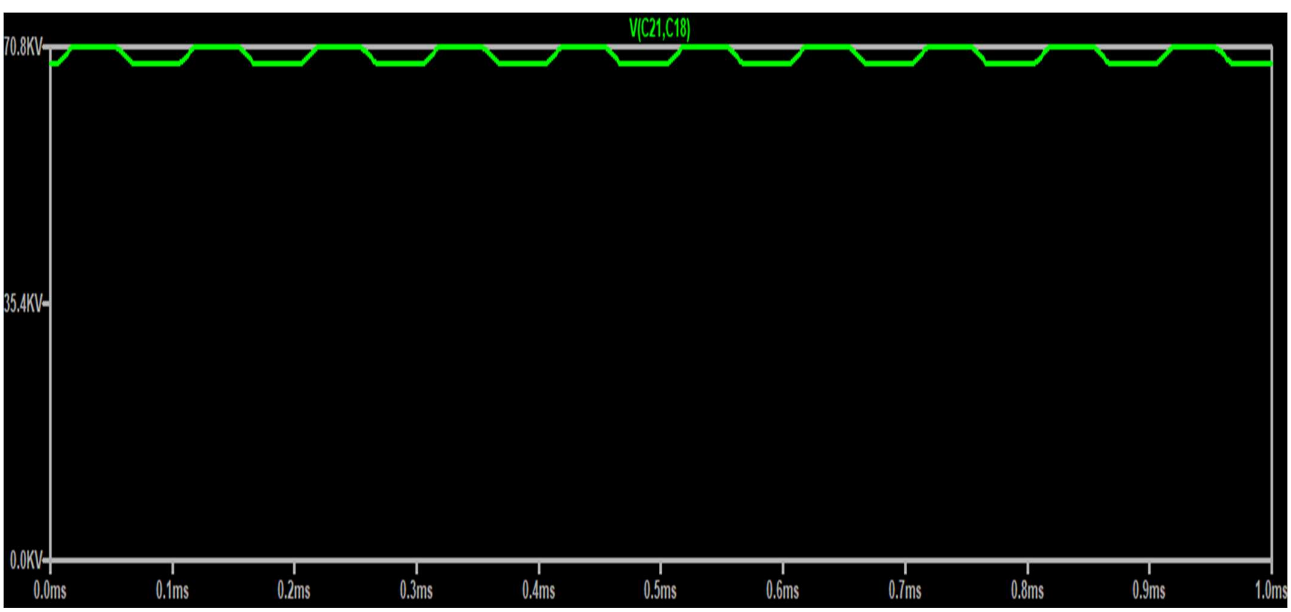



***Figure-46: Voltage across Stage-7 Capacitor of AC-LINE-2***

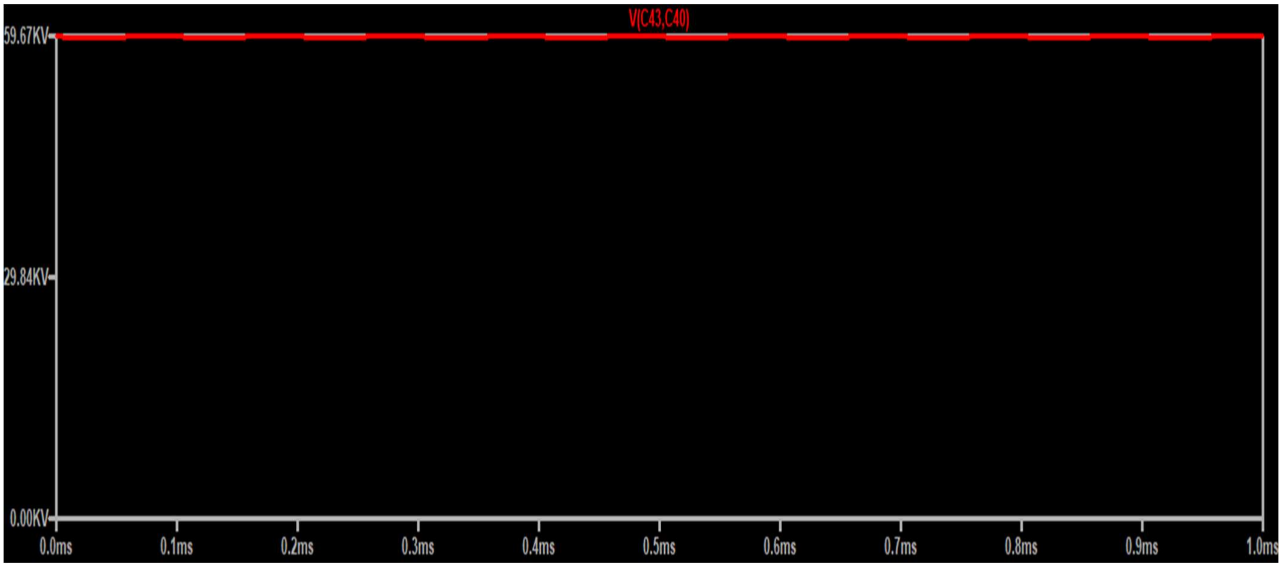



***Figure-47: Voltage across Stage-15 Capacitor of AC-LINE-1***

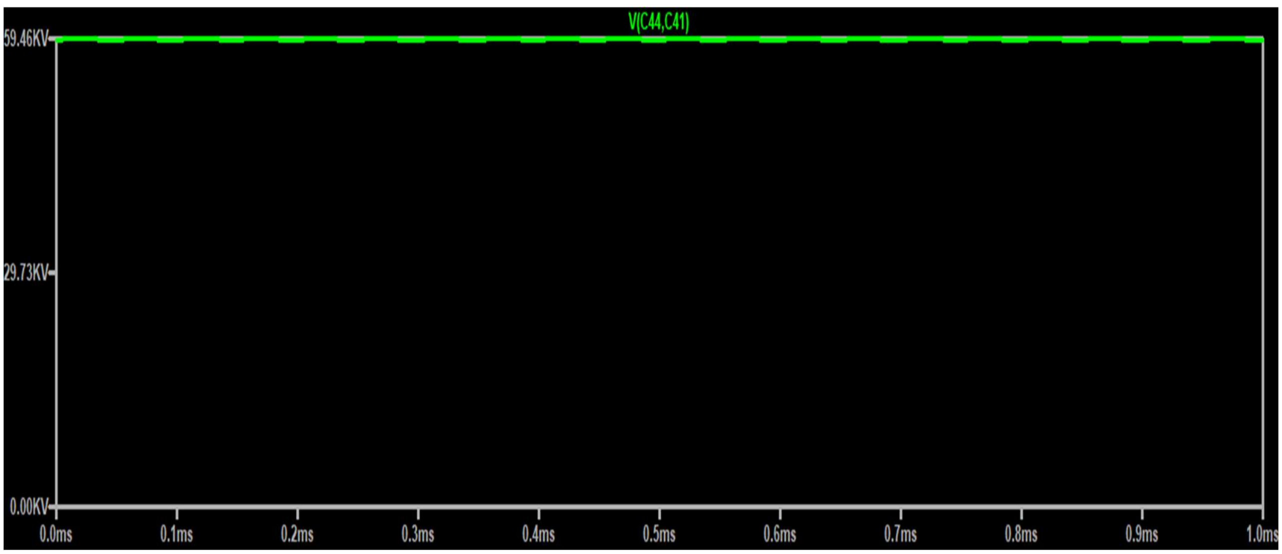



***Figure-48: Voltage across Stage-15 Capacitor of DC-Line***

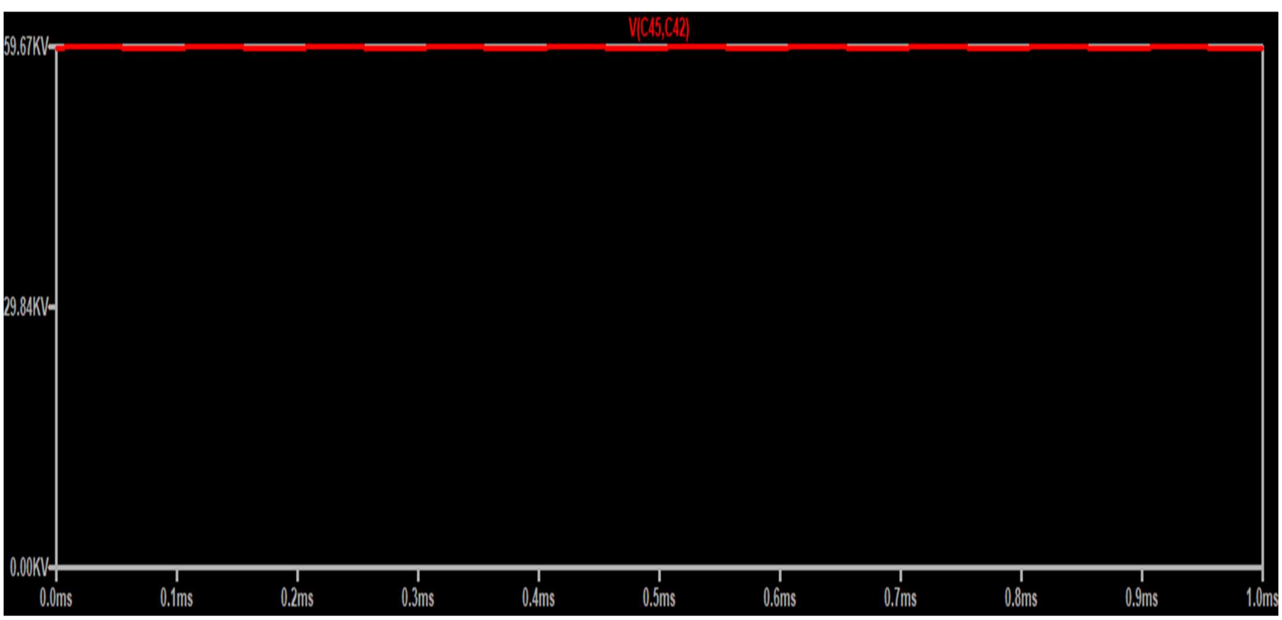
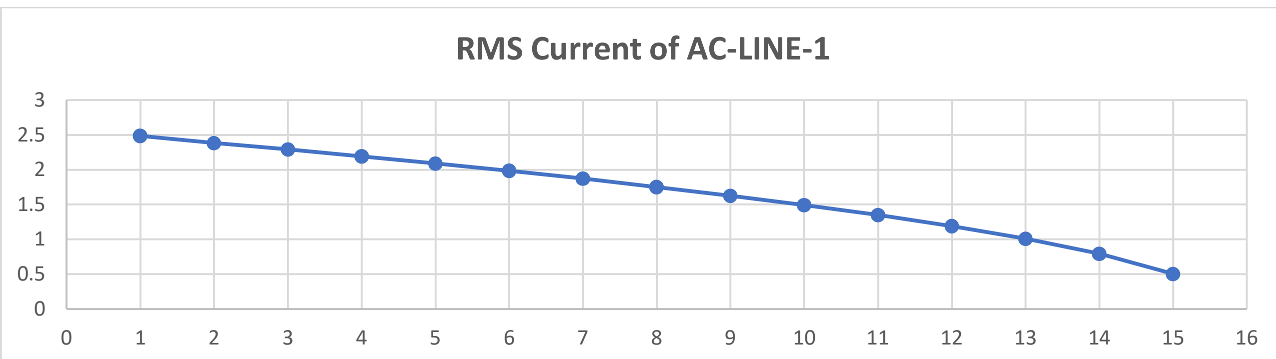


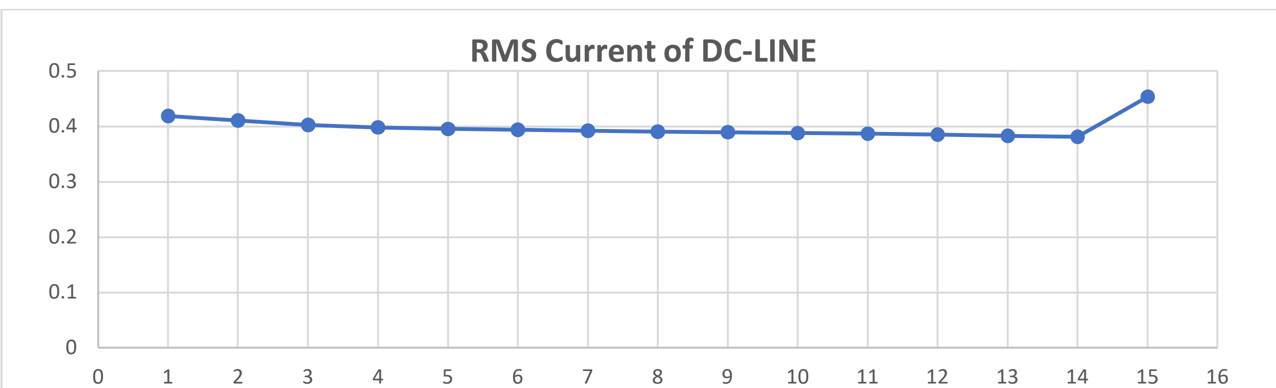

***Figure-49: Voltage across Stage-15 Capacitor of AC-LINE-2***

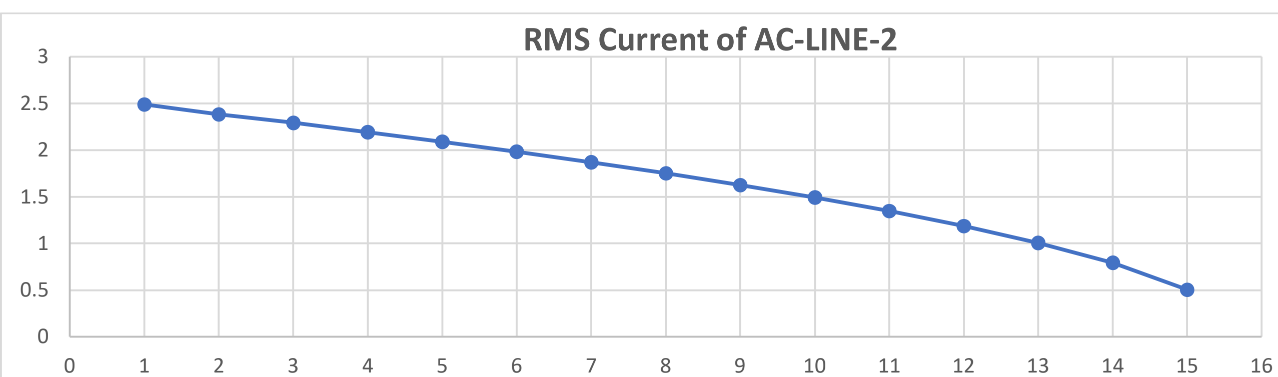
### *Current at Loaded Condition:*

| STAGE | AC-LINE-1 | | DC-LINE | | AC-Line-2 | |
|---|---|---|---|---|---|---|
| | MAX(A) | RMS(A) | MAX(A) | RMS(A) | MAX(A) | RMS(A) |
| 1 | 8.01483 | 2.48879 | 2.68187 | 0.418967 | 8.13692 | 2.48882 |
| 2 | 5.60418 | 2.38394 | 2.96291 | 0.410671 | 5.65007 | 2.38398 |
| 3 | 5.05425 | 2.29201 | 2.90442 | 0.402595 | 5.06416 | 2.292 |
| 4 | 4.92799 | 2.19366 | 2.94189 | 0.398353 | 4.78046 | 2.19367 |
| 5 | 4.92799 | 2.09104 | 2.92624 | 0.395684 | 4.6485 | 2.091 |
| 6 | 4.92799 | 1.98375 | 2.85928 | 0.393912 | 4.56003 | 1.98377 |
| 7 | 4.92799 | 1.8713 | 2.71713 | 0.392156 | 4.39388 | 1.87125 |
| 8 | 4.92799 | 1.7528 | 2.61609 | 0.390744 | 4.27173 | 1.75286 |
| 9 | 4.92799 | 1.62742 | 2.78619 | 0.389389 | 4.21823 | 1.62731 |
| 10 | 4.92799 | 1.49336 | 2.63209 | 0.38806 | 4.07482 | 1.49327 |
| 11 | 4.92799 | 1.34833 | 2.65079 | 0.386591 | 4.02237 | 1.34844 |
| 12 | 4.92799 | 1.18903 | 2.61609 | 0.38491 | 3.87235 | 1.18904 |
| 13 | 4.92799 | 1.00875 | 2.61609 | 0.383137 | 3.80198 | 1.00888 |
| 14 | 4.92799 | 0.794229 | 2.61609 | 0.381217 | 3.6944 | 0.794221 |
| 15 | 4.92799 | 0.504244 | 3.99759 | 0.4536 | 3.6944 | 0.504278 |

## <u>Graphical Representation of Current level at each Stage</u>



### *Input Voltage Level:*

| Iin(1)(RMS) | Iin(2)(RMS) |
|---|---|
| 2.4888A | 2.4888A |

## <u>Waveform of Current through Capacitors at Different Stages</u>

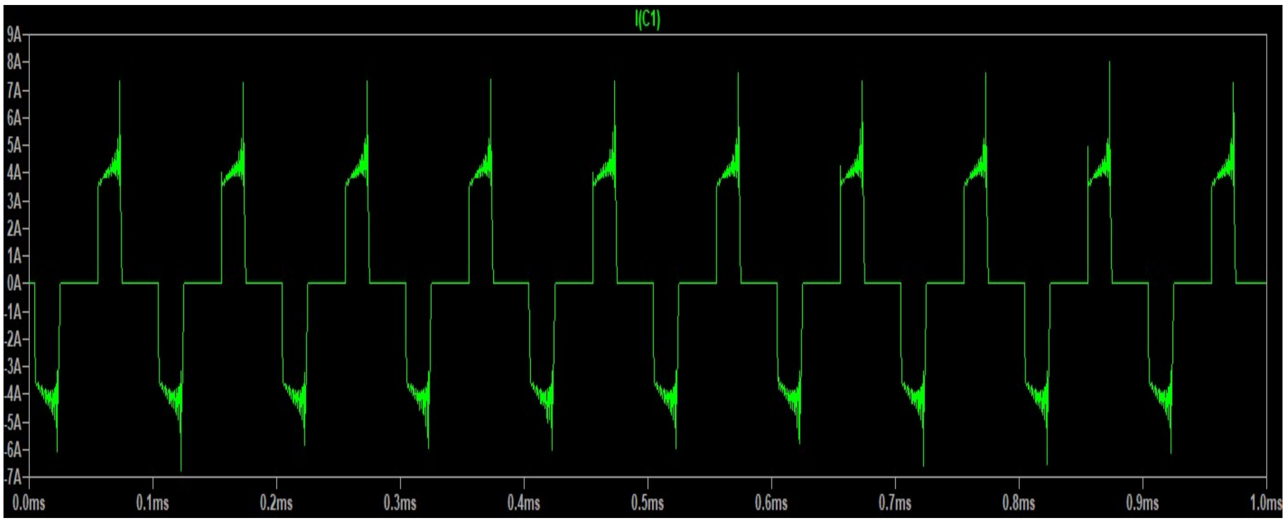



***Figure-50: Current through Stage-1 Capacitor of AC-LINE-1***

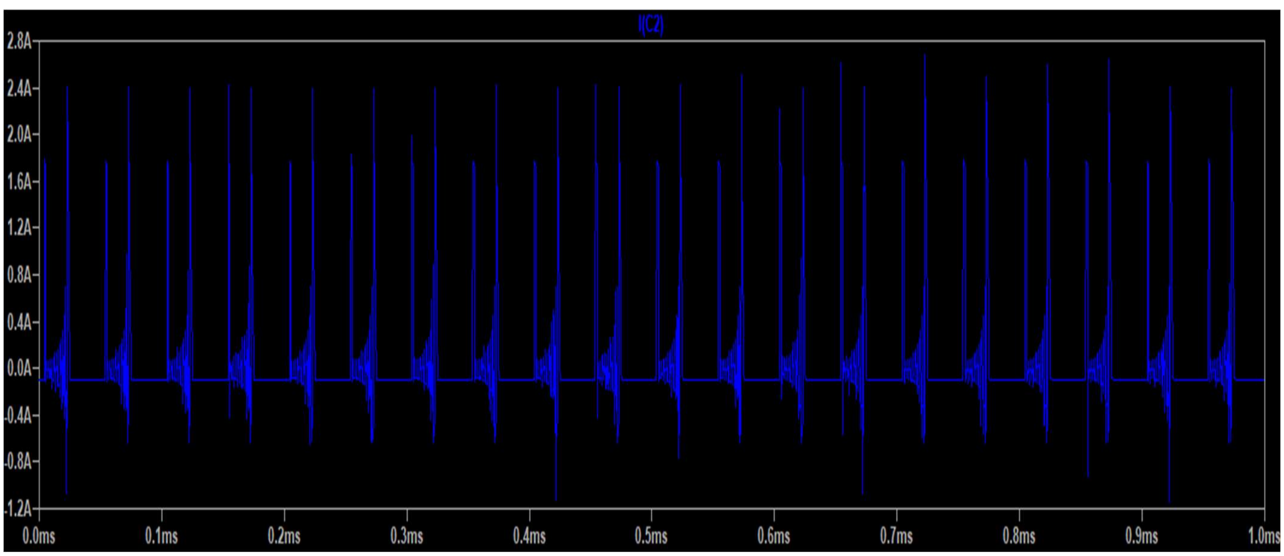



***Figure-51: Current through Stage-1 Capacitor of DC-LINE***

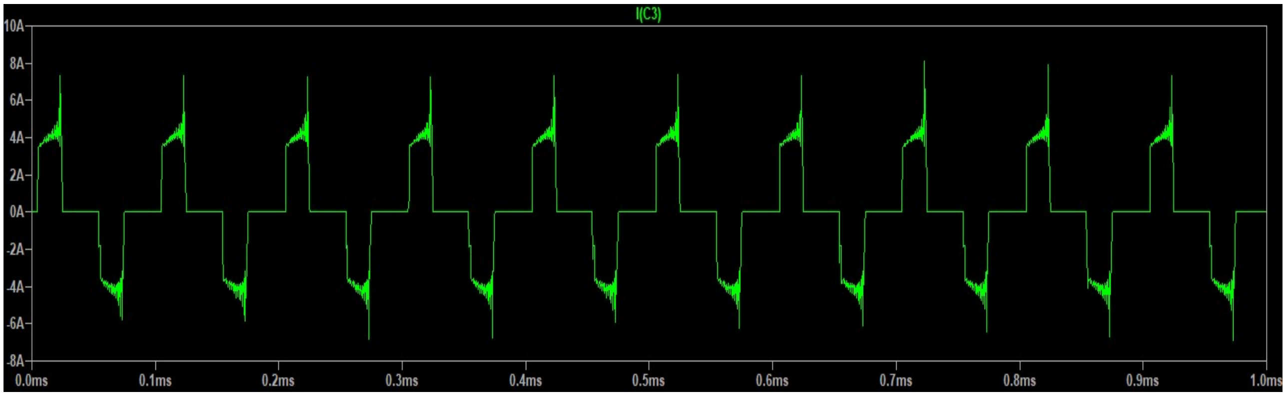



***Figure-52: Current through Stage-1Capacitor of AC-LINE-2***

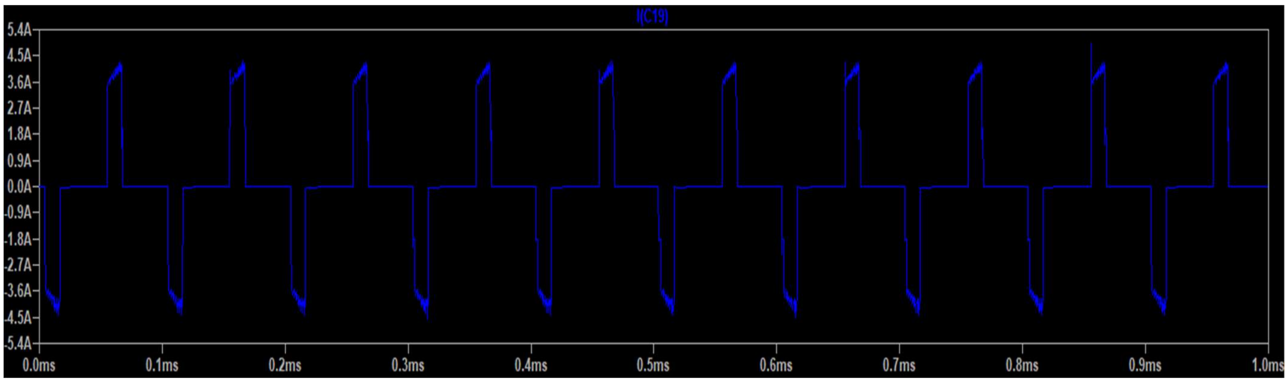



***Figure-53: Current through Stage-7 Capacitor of AC-LINE-1***

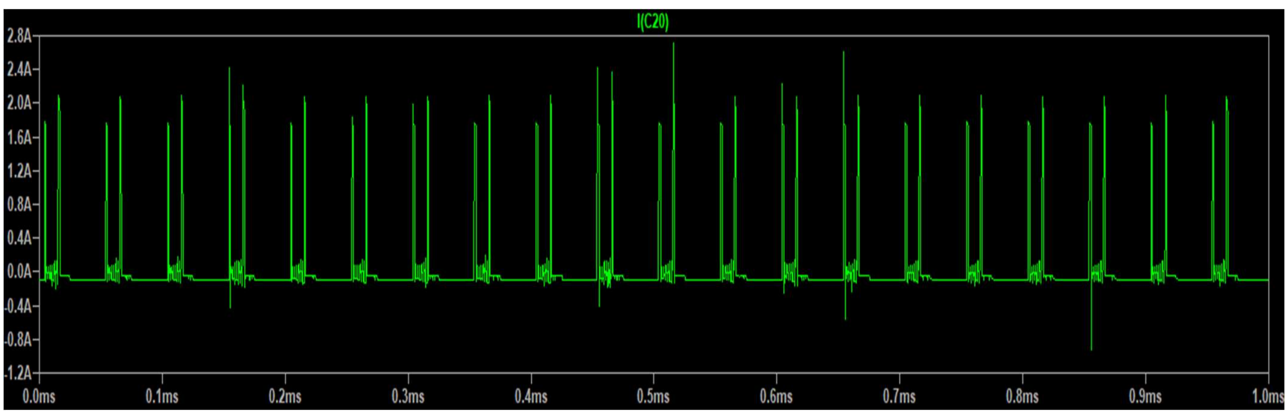



***Figure-54: Current through Stage-7 Capacitor of DC-LINE***

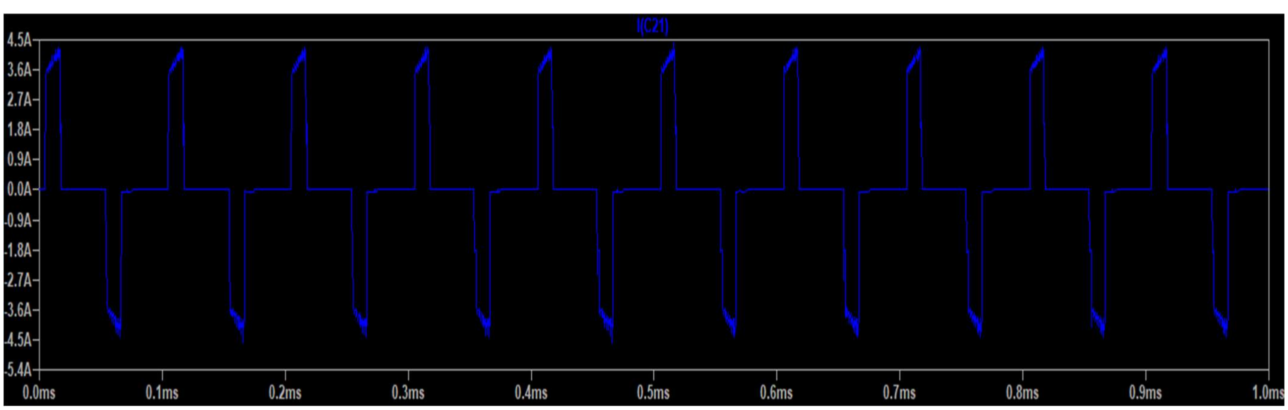



***Figure-55: Current through Stage-7 Capacitor of AC-LINE-2***

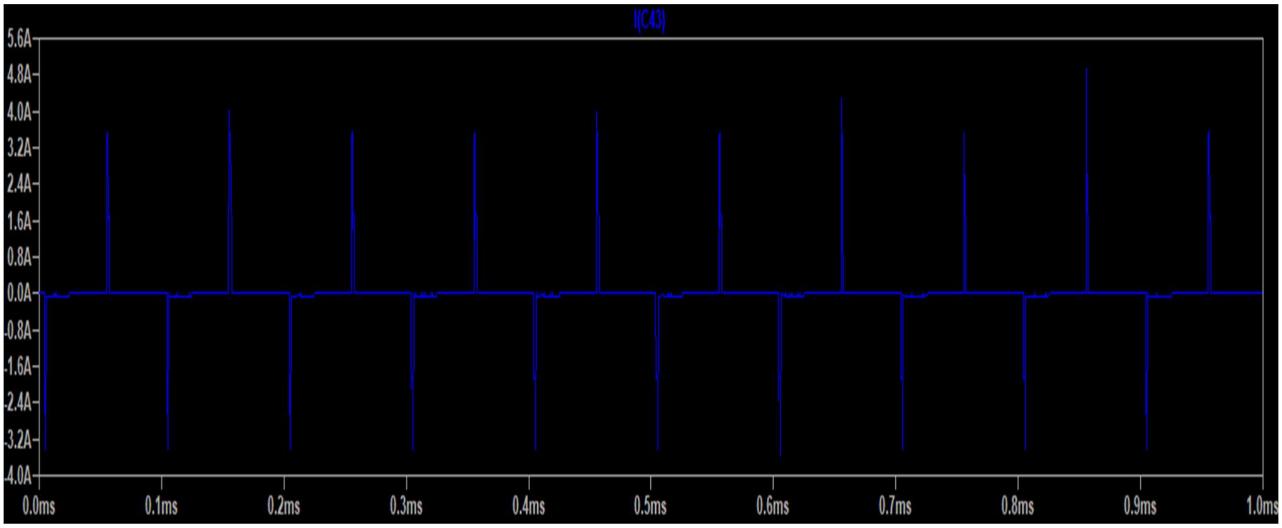



*Figure-56: Current through Stage-15 Capacitor of AC-LINE-1*

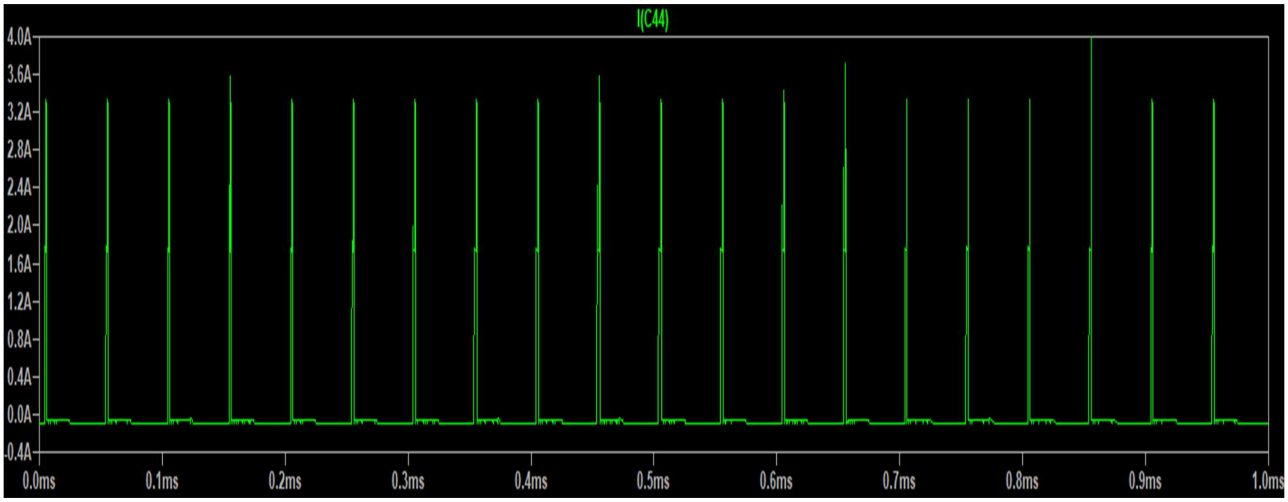



*Figure-57: Current through Stage-15 Capacitor of DC-LINE*

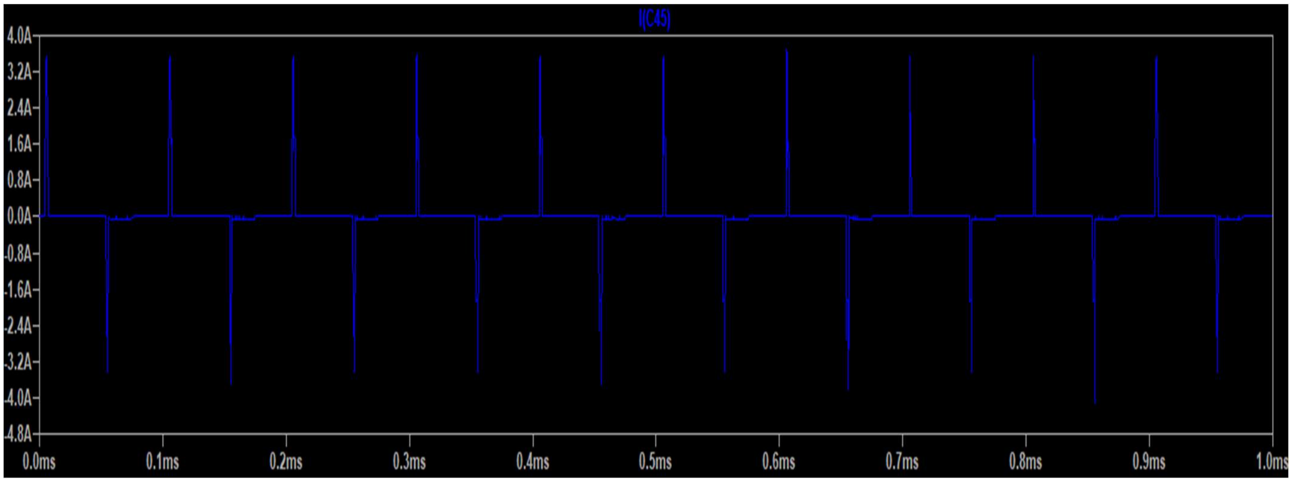



*Figure-58: Current through Stage-15 Capacitor of AC-LINE-2*

## *Diode Voltage and Current :*

| Stage | Diode no. | Current Max(A) | Current RMS(A) | Voltage(Max)(V)(N-P) |
|---|---|---|---|---|
| 1 | 1 | 6.60633 | 0.412409 | 86132.8 |
| | 2 | 6.71585 | 0.412334 | 86132.9 |
| | 3 | 6.11594 | 0.411358 | 86132.8 |
| | 4 | 6.32217 | 0.411283 | 86132.8 |
| 2 | 5 | 5.54549 | 0.461769 | 82530.2 |
| | 6 | 5.50354 | 0.46182 | 82530.1 |
| | 7 | 4.58003 | 0.328082 | 82529.9 |
| | 8 | 4.54312 | 0.328321 | 82529.9 |
| 3 | 9 | 5.1542 | 0.464303 | 79188.3 |
| | 10 | 5.18829 | 0.464334 | 79188.3 |
| | 11 | 4.42213 | 0.358727 | 79188.1 |
| | 12 | 4.45655 | 0.358583 | 79188.1 |
| 4 | 13 | 4.97443 | 0.463673 | 76107.3 |
| | 14 | 4.85893 | 0.463806 | 76107.3 |
| | 15 | 4.39195 | 0.364323 | 76107.1 |
| | 16 | 4.3776 | 0.364432 | 76107.2 |
| 5 | 17 | 4.80374 | 0.462671 | 73287.5 |
| | 18 | 4.63712 | 0.462489 | 73287.7 |
| | 19 | 4.29568 | 0.36605 | 73287.3 |
| | 20 | 4.32871 | 0.365792 | 73287.2 |
| 6 | 21 | 4.52862 | 0.460584 | 70728.6 |
| | 22 | 4.54799 | 0.460748 | 70728.6 |
| | 23 | 4.23955 | 0.36626 | 70728.3 |
| | 24 | 4.25908 | 0.366345 | 70728.3 |
| 7 | 25 | 4.51689 | 0.458584 | 68430.4 |
| | 26 | 4.54897 | 0.458421 | 68430.5 |
| | 27 | 4.80374 | 0.462671 | 68430.4 |
| | 28 | 4.1878 | 0.365006 | 68430.3 |
| 8 | 29 | 4.34879 | 0.455275 | 66393.6 |
| | 30 | 4.3589 | 0.455657 | 66393.6 |
| | 31 | 4.13114 | 0.363599 | 66393.4 |
| | 32 | 4.13119 | 0.363879 | 66393.4 |
| 9 | 33 | 4.32479 | 0.452618 | 64617.8 |
| | 34 | 4.33292 | 0.452533 | 64618 |
| | 35 | 4.06817 | 0.361425 | 79188.1 |
| | 36 | 4.07043 | 0.361093 | 79188.1 |
| 10 | 37 | 4.06558 | 0.448781 | 63103.4 |
| | 38 | 4.18242 | 0.448567 | 63103.3 |
| | 39 | 4.00174 | 0.35893 | 63102.8 |
| | 40 | 4.00279 | 0.358492 | 63102.9 |
| 11 | 41 | 4.06287 | 0.444477 | 61849.9 |
| | 42 | 4.10722 | 0.444587 | 61849.6 |
| | 43 | 3.92802 | 0.355079 | 61849.6 |
| | 44 | 3.92441 | 0.355526 | 61849.6 |
| 12 | 45 | 3.86844 | 0.439846 | 60857.4 |
| | 46 | 3.99212 | 0.439741 | 60857.3 |
| | 47 | 3.84605 | 0.351601 | 60857.2 |
| | 48 | 3.8448 | 0.351586 | 60857.1 |
| 13 | 49 | 3.873693 | 0.434502 | 60126.4 |
| | 50 | 82872 | 0.434668 | 60126.2 |
| | 51 | 3.75637 | 0.347078 | 60126.1 |
| | 52 | 3.75341 | 0.347409 | 60126.1 |
| 14 | 53 | 3.79342 | 0.428748 | 59656.4 |
| | 54 | 3.74103 | 0.4287 | 59656.4 |
| | 55 | 3.65604 | 0.342542 | 59655.6 |
| | 56 | 3.657 | 0.342597 | 59656.3 |
| 15 | 57 | 3.54351 | 0.328793 | 59448.4 |
| | 58 | 4.10073 | 0.32906 | 59448.3 |
| | 59 | 4.92799 | 0.382305 | 59447.8 |
| | 60 | 3.6944 | 0.38212 | 59447.8 |

# Waveform of Diode Voltages and Current at each stage

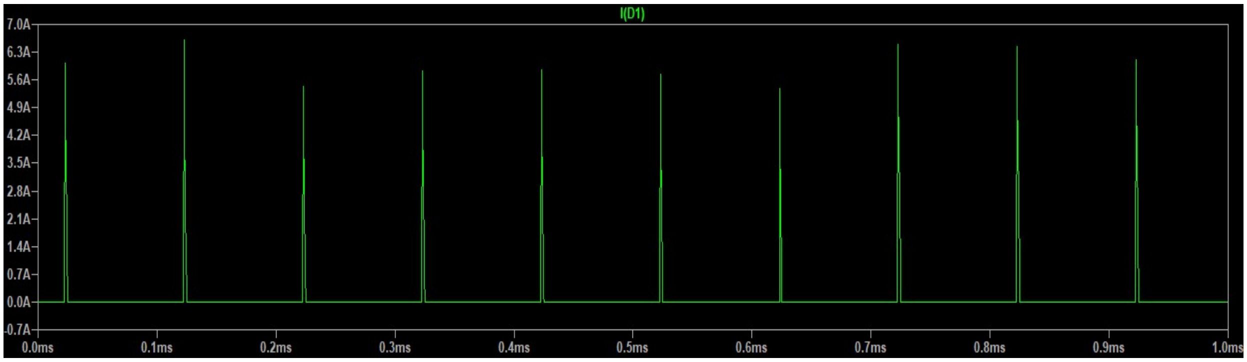



***Figure-59: Current through $D_1$ (Stage-1)***

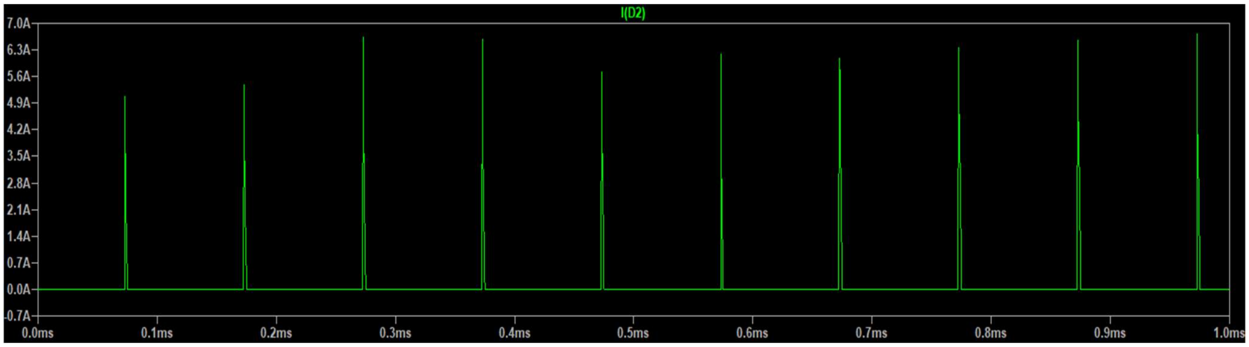



***Figure-60: Current through $D_2$ (Stage-1)***

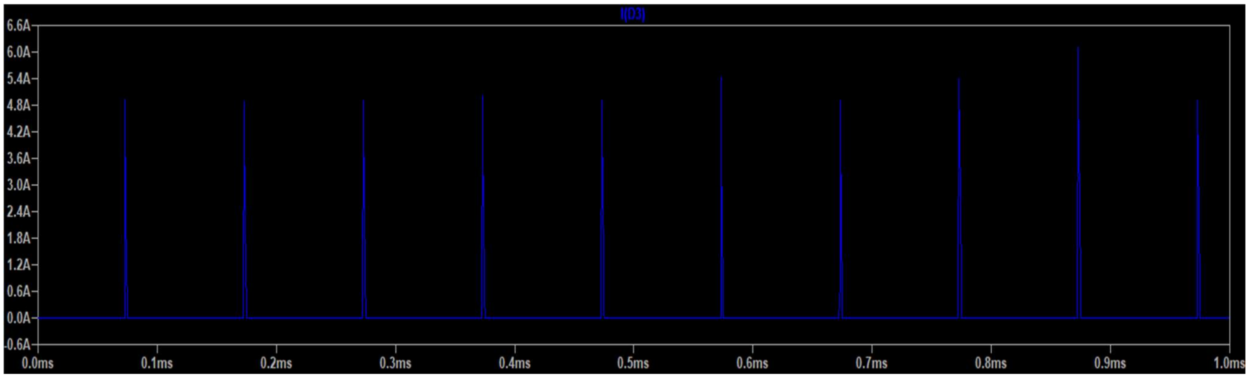



***Figure-61: Current through $D_3$ (Stage-1)***

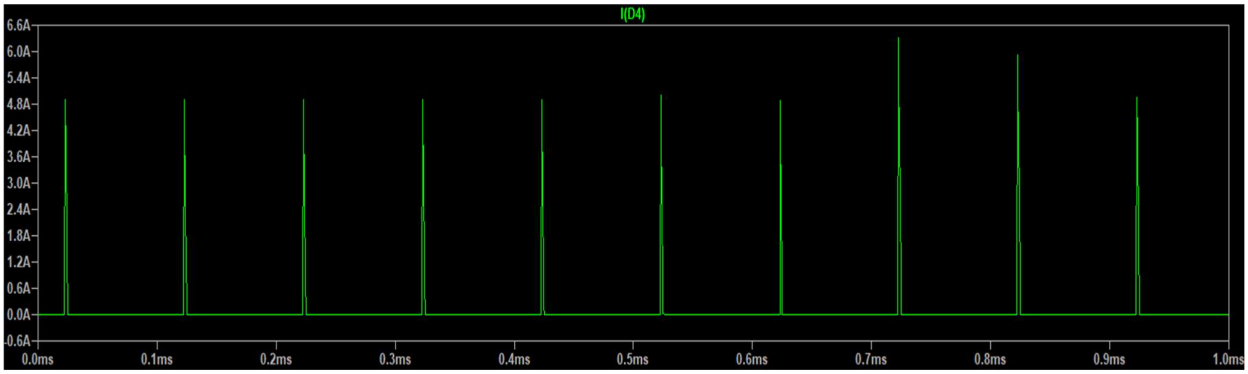



***Figure-62: Current through $D_4$ (Stage-1)***

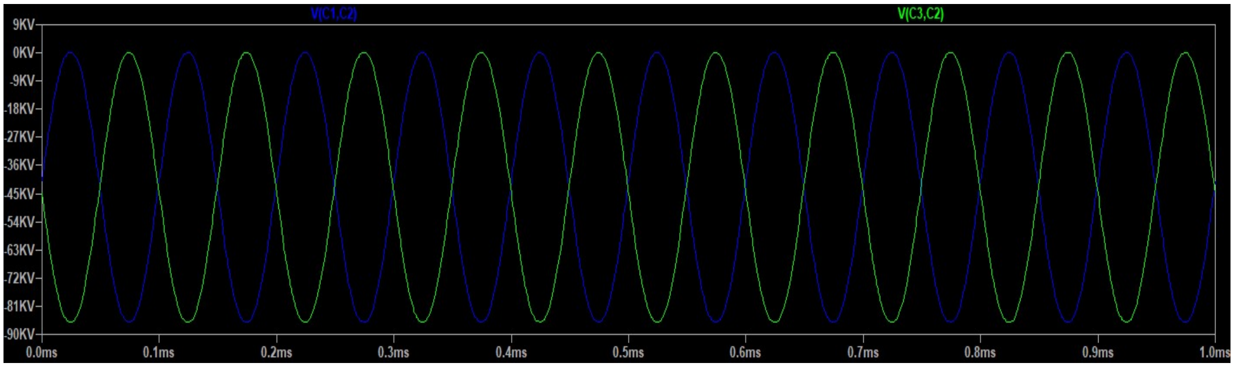



***Figure-63: Voltage across $D_1$ and $D_2$ (Stage-1)***

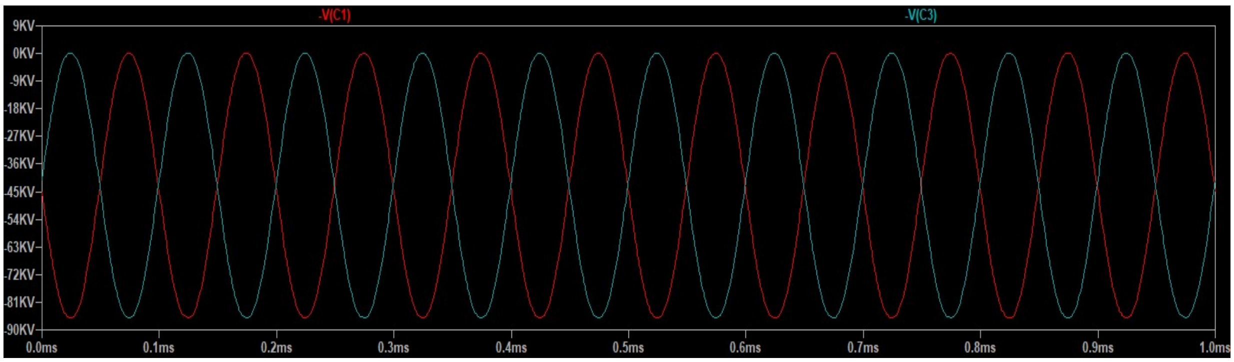



***Figure-64: Voltage across $D_3$ and $D_4$ (Stage-1)***

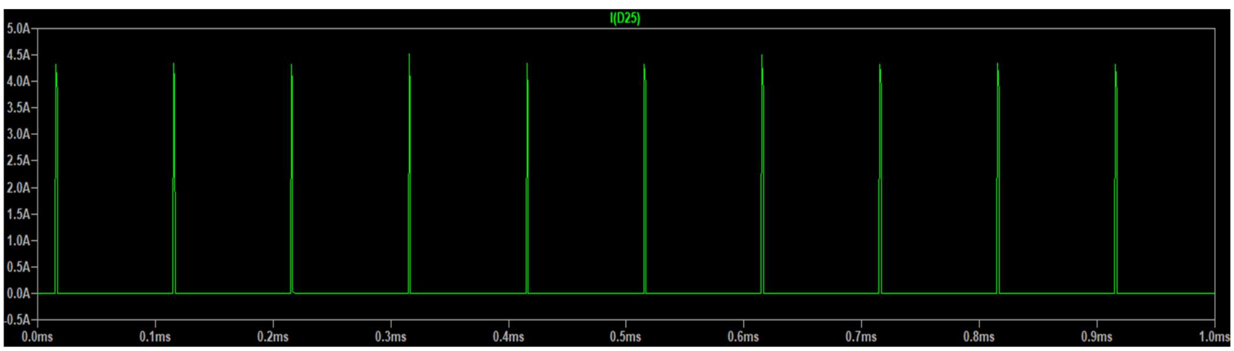



***Figure-65: Current through $D_{25}$ (Stage-7)***

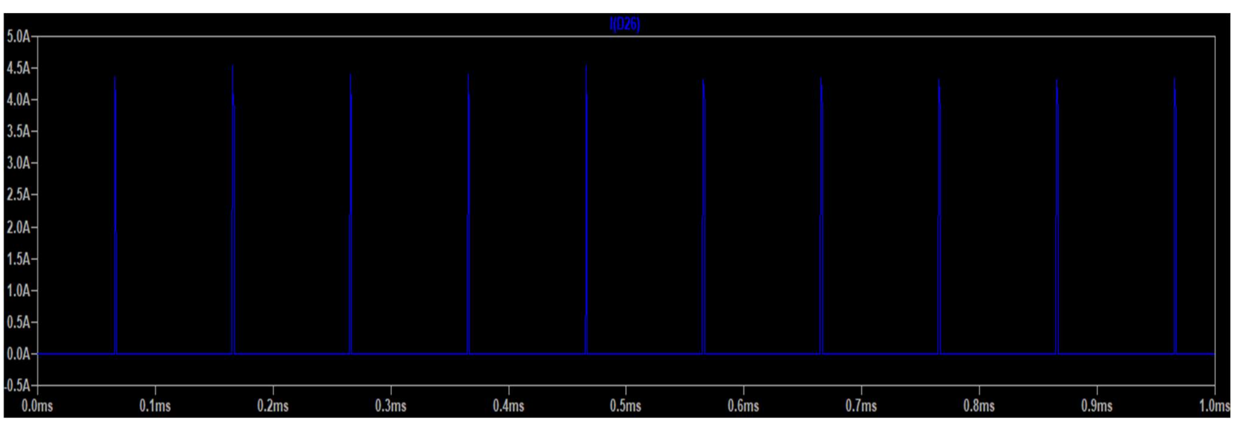



***Figure-66: Current through $D_{26}$ (Stage-7)***

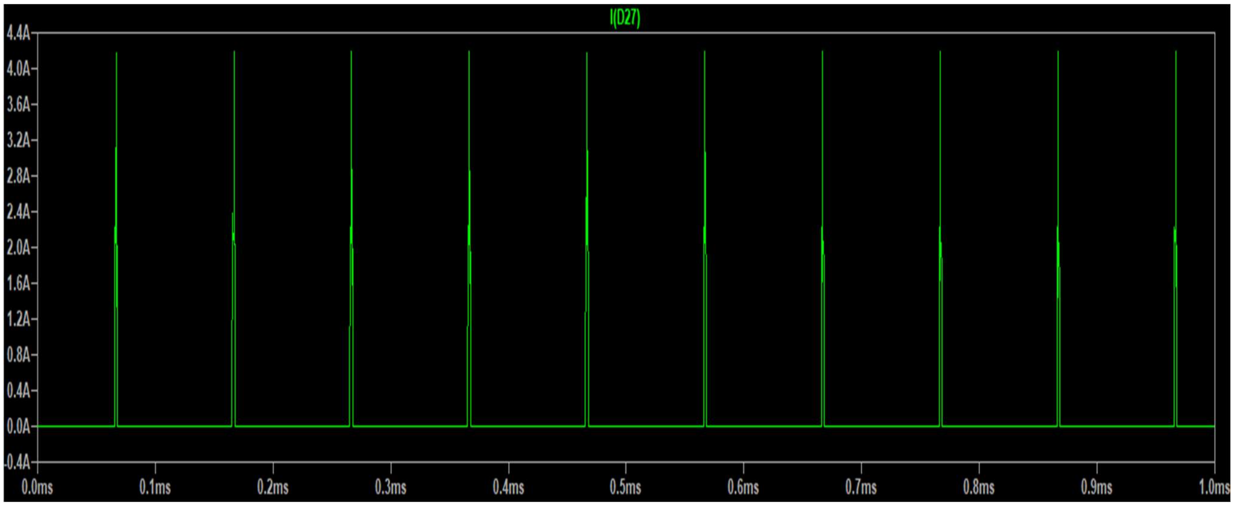



***Figure-67: Current through $D_{27}$ (Stage-7)***

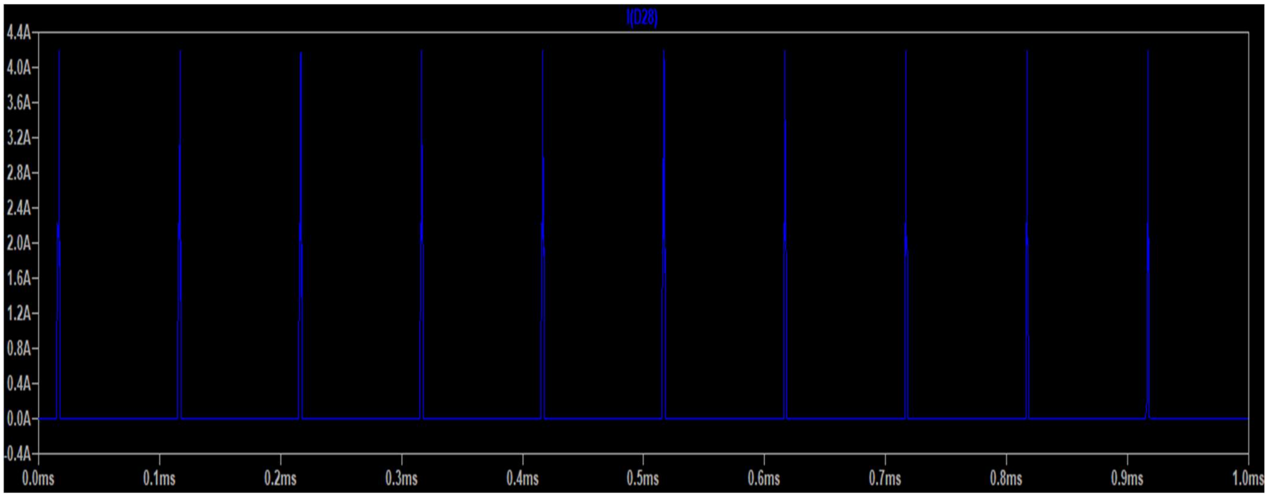



***Figure-68: Current through $D_{28}$ (Stage-7)***

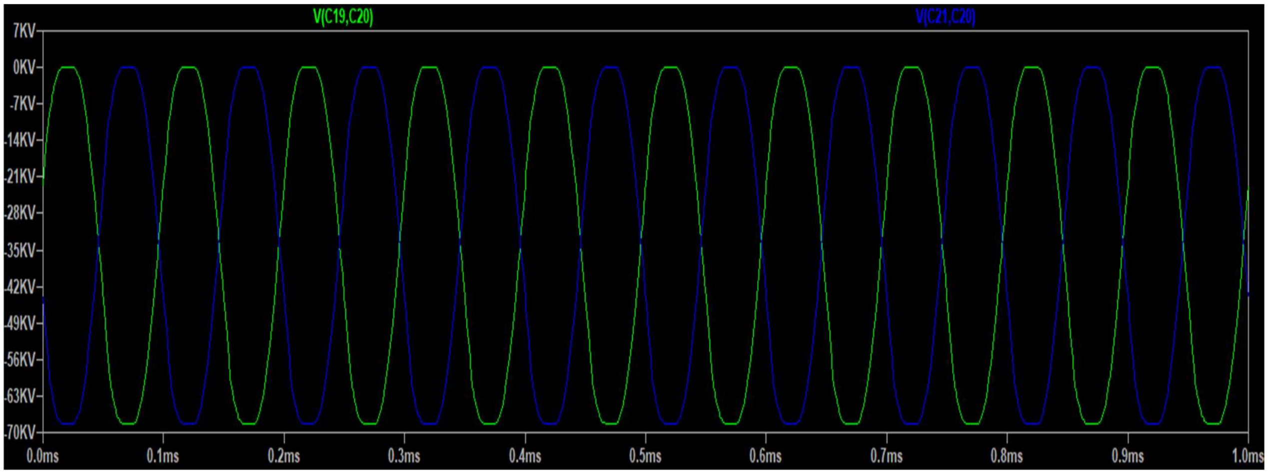



***Figure-69: Voltage across $D_{25}$ and $D_{26}$ (Stage-7)***

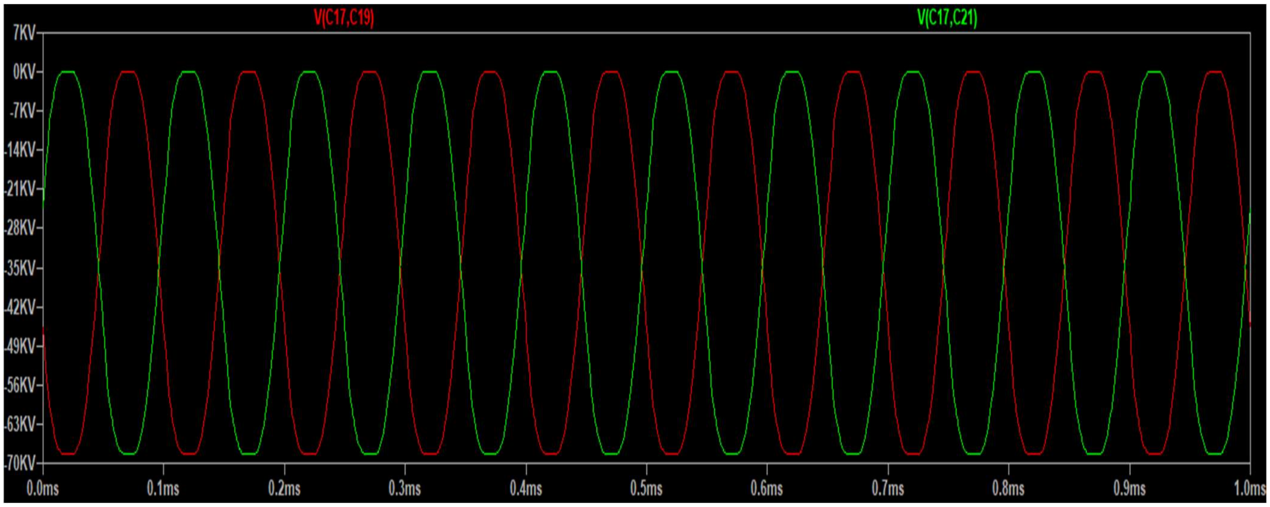



*Figure-70: Voltage across $D_{27}$ and $D_{28}$ (Stage-7)*

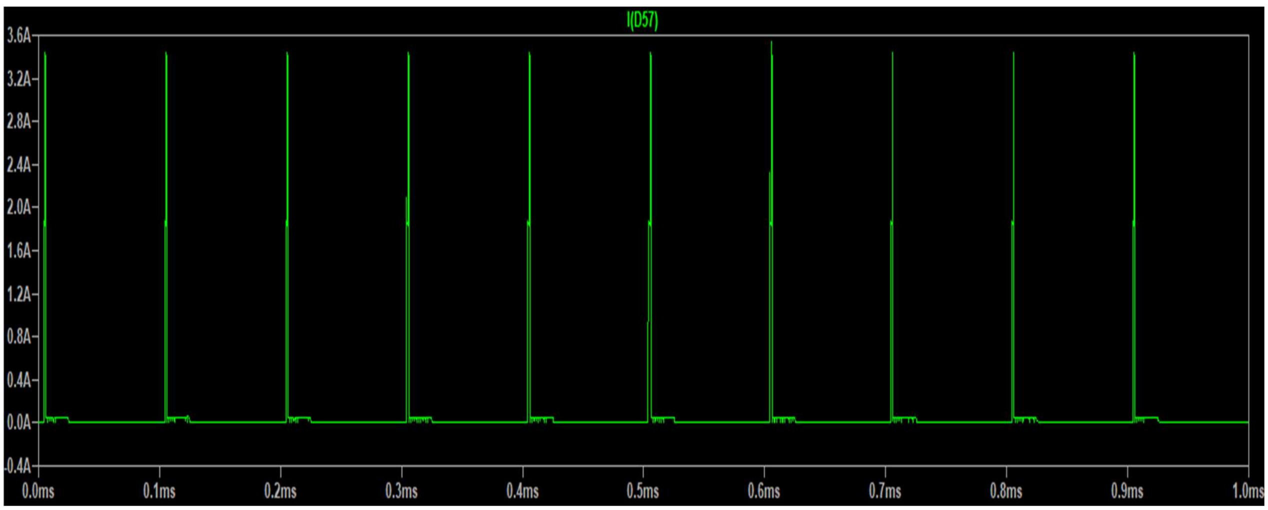



*Figure-71: Current through $D_{57}$ (Stage-15)*

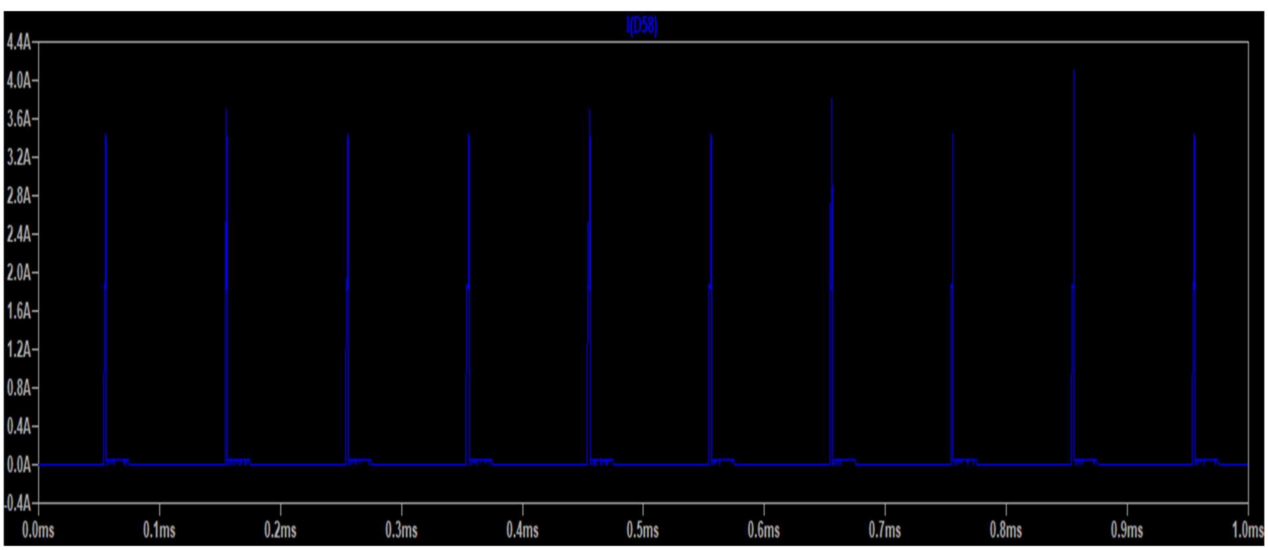



*Figure-72: Current through $D_{58}$ (Stage-15)*

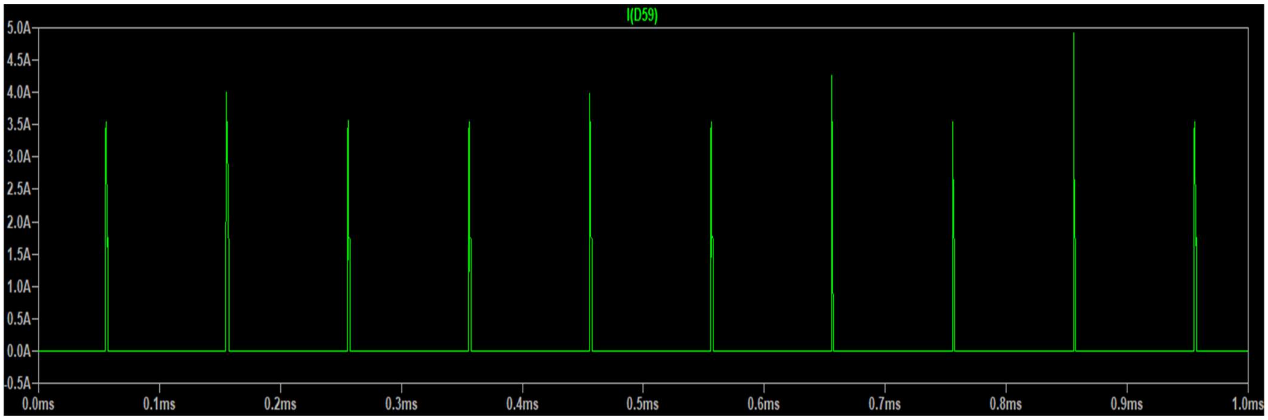



***Figure-71: Current through $D_{59}$ (Stage-15)***

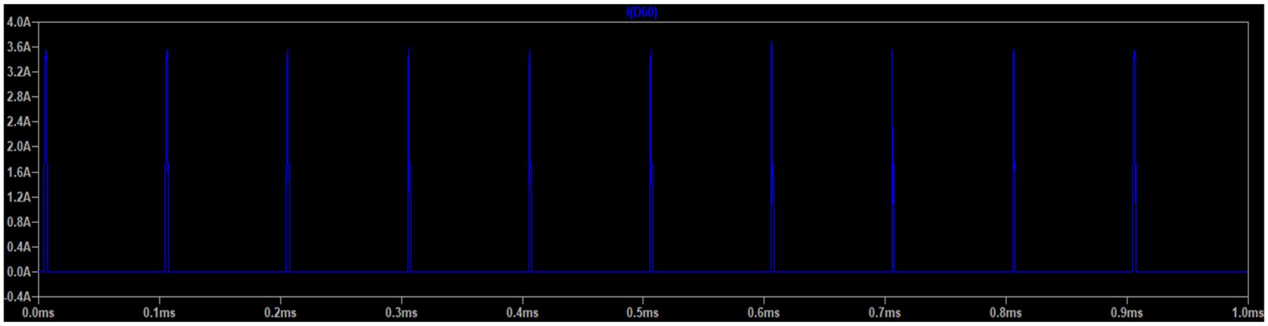



***Figure-72: Current through $D_{60}$ (Stage-15)***

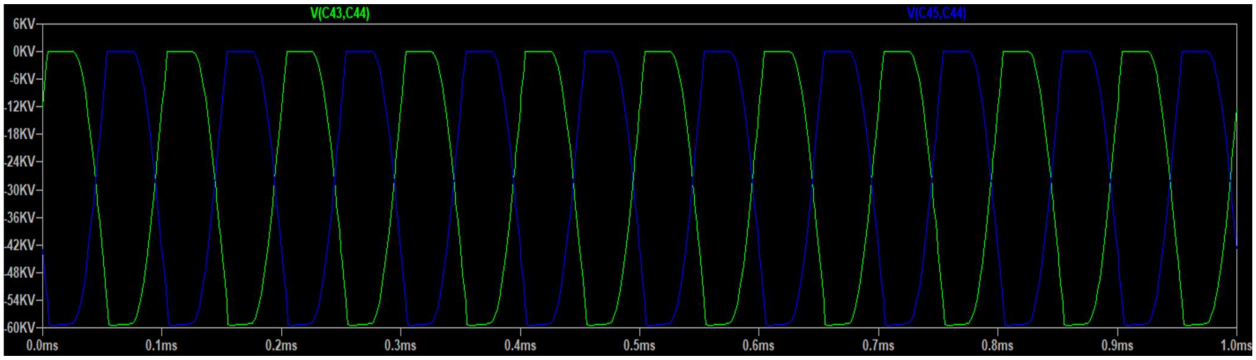



***Figure-73: Voltage across $D_{57}$ and $D_{58}$ (Stage-15)***

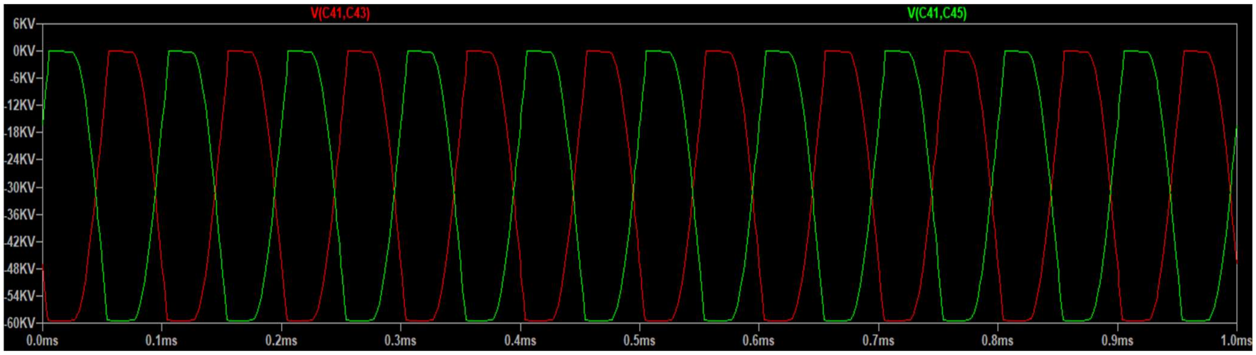



***Figure-74: Voltage across $D_{59}$ and $D_{60}$ (Stage-15)***

## Power Dissipation calculation in stage capacitance:

$P = I_{rms}^2 \times R_C$

$Consider, Dissipattion\ factor(tan\delta) = 0.02$

$$tan\delta = \frac{R_c}{X_c}$$

$f = 10KHz$

$C = 20nF$

$R_c = 0.02 \times X_c$

$$R_C = \frac{0.02}{2\pi fc} = \frac{0.02}{2 * \pi * 10^4 * 20 * 10^{-9}} = 15.915\Omega$$

$Total\ Power\ Dissipation = \ 1528.733692\ watts$

| Rc | Stage | AC-line-1 | | DC-line | | AC-line-2 | |
|---|---|---|---|---|---|---|---|
| | | Irms | Power Dissipation | Irms | Power Dissipation | Irms | Power Dissipation |
| 15.915 | 1 | 2.48879 | 98.57871419 | 0.418967 | 2.793613219 | 2.48882 | 98.58109075 |
| 15.915 | 2 | 2.38394 | 90.44764933 | 0.410671 | 2.684075417 | 2.38398 | 90.45068459 |
| 15.915 | 3 | 2.29201 | 83.60642611 | 0.402595 | 2.579546712 | 2.292 | 83.60569656 |
| 15.915 | 4 | 2.19366 | 76.58527487 | 0.398353 | 2.525473567 | 2.19367 | 76.58597312 |
| 15.915 | 5 | 2.09104 | 69.5875144 | 0.395684 | 2.49174515 | 2.091 | 69.58485212 |
| 15.915 | 6 | 1.98375 | 62.62972755 | 0.393912 | 2.469477453 | 1.98377 | 62.63099042 |
| 15.915 | 7 | 1.8713 | 55.73056913 | 0.392156 | 2.447509415 | 1.87125 | 55.72759099 |
| 15.915 | 8 | 1.7528 | 48.89577927 | 0.390744 | 2.429916102 | 1.75286 | 48.89912683 |
| 15.915 | 9 | 1.62742 | 42.15081155 | 0.389389 | 2.413092671 | 1.62731 | 42.14511366 |
| 15.915 | 10 | 1.49336 | 35.49242489 | 0.38806 | 2.39664882 | 1.49327 | 35.48814699 |
| 15.915 | 11 | 1.34833 | 28.93337115 | 0.386591 | 2.378538149 | 1.34844 | 28.93809225 |
| 15.915 | 12 | 1.18903 | 22.50050511 | 0.38491 | 2.357898094 | 1.18904 | 22.50088358 |
| 15.915 | 13 | 1.00875 | 16.19473099 | 0.383137 | 2.336225886 | 1.00888 | 16.19890537 |
| 15.915 | 14 | 0.794229 | 10.0391773 | 0.381217 | 2.312869673 | 0.794221 | 10.03897505 |
| 15.915 | 15 | 0.504244 | 4.046579914 | 0.4536 | 3.274558358 | 0.504278 | 4.047125635 |
| | | | 745.4192558 | | 37.89118869 | | 745.4232479 |

## *Simulation Conclusion:*

Here, I have simulated a 15-stage symmetrical Cockcroft-Walton circuit under no-load and loaded conditions. In this simulation, I considered ideal capacitors and diodes. The simulation ran for 200 ms , with data recording starting at 199ms and a time step of 10 ns.

Here are the key observations from the simulation:

1. **Voltage Levels (At No load Condition):**
   - AC-Line-1 , DC-Line , AC-Line-2 voltage in the 1st stage: 45 kV(Approx) for 45kV-0-45kV. 10kHz input.
   - From $2^{nd}$ to the $15^{th}$ stage, all capacitors have a voltage around 90 kV.
   - However, the voltage with respect to ground on the DC line keeps increasing and reaches approximately 1350 kV which matches with the calculation.
2. **Current Behaviour(At No load Condition):**
   - Since there is no load connected, the current through the capacitors remains very low.
   - The ideal diodes have nearly zero forward voltage, and also a gradual decrease in RMS current through the diodes with each stage.
3. **Loaded Condition:**
   - For the loaded condition, we consider 10 MΩ resistances to achieve a current of 100 mA.
   - In the simulation, I observed a DC-line voltage of 1.03 MV with respect to ground, which closely matches with the calculated value of 1.038 MV.
   - The RMS Current through the capacitor decreases with each stage. But at the DC-Line there is a Sudden Peak of RMS current at the $15^{th}$ stage
   - The diode current is approximately constant.

4. **Voltage Drop and Power Dissipation:**
   - The regular decrease in the DC-line voltage is due to the $(I_{rms}X_c)$ drop of the capacitors.
   - The power dissipation of the capacitors is calculated using the formula $(I_{rms}^2 * R_c)$considering a dissipation factor of 0.02. This yields an effective resistance $R_c$ of 15.915Ω .
   - Overall, power dissipation decreases on both the AC-Lines over stages and the DC-line power dissipation remains nearly constant. Maximum power loss at first stage capacitor. Total power loss in stage capacitance is 1.5kW.

## Simulation of Heat Run Testing circuit of Single Capacitor Module (20nF,10Khz)

Here we are simulating the heat run test circuit, which we perform under resonance conditions. Initially, for simplicity we replace the step-down transformer with an independent source of 100V at 10 kHz in the simulation . We use a 12.66 mH inductor to ensure that the circuit operates at resonance. Next, we simulate the original circuit by using a transformer with a turn ratio of 22 and replaced the inverter with an independent source of 10 kV at 10 kHz.

However, we observe that the input voltage and current are not perfectly in phase. In resonance conditions, they should ideally be in phase. To achieve this, we need to adjust the value of the inductor. The optimal value for the inductor is approximately 12.489 mH.

### *Calculations:*

$We\ know\ at\ resonances,$

$$\omega^2 = \frac{1}{LC}$$

$$L = \frac{1}{\omega^2 C}$$

$$L = \frac{1}{20 * 10^{-9}(2 * \pi * 10^4)^2} = 12.66mH$$

$$\boldsymbol{L = 12.66\ mH}$$

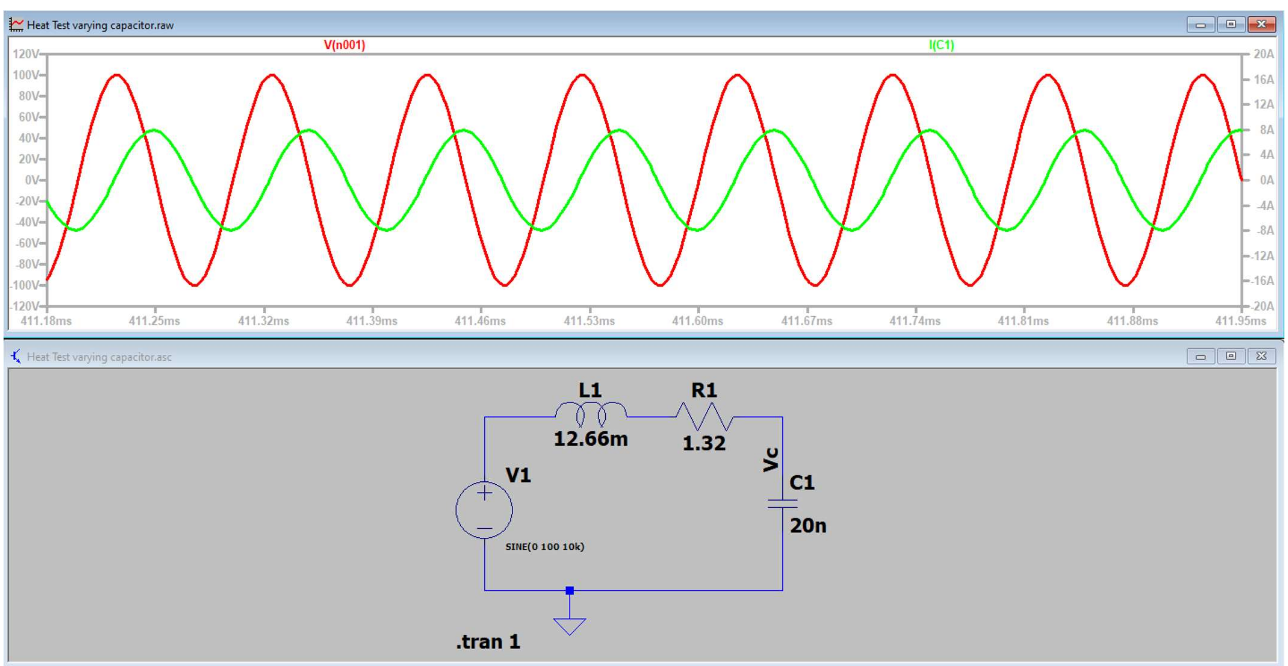



*Figure-75: Heat run test circuit using calculated inductance(12.66mH)*

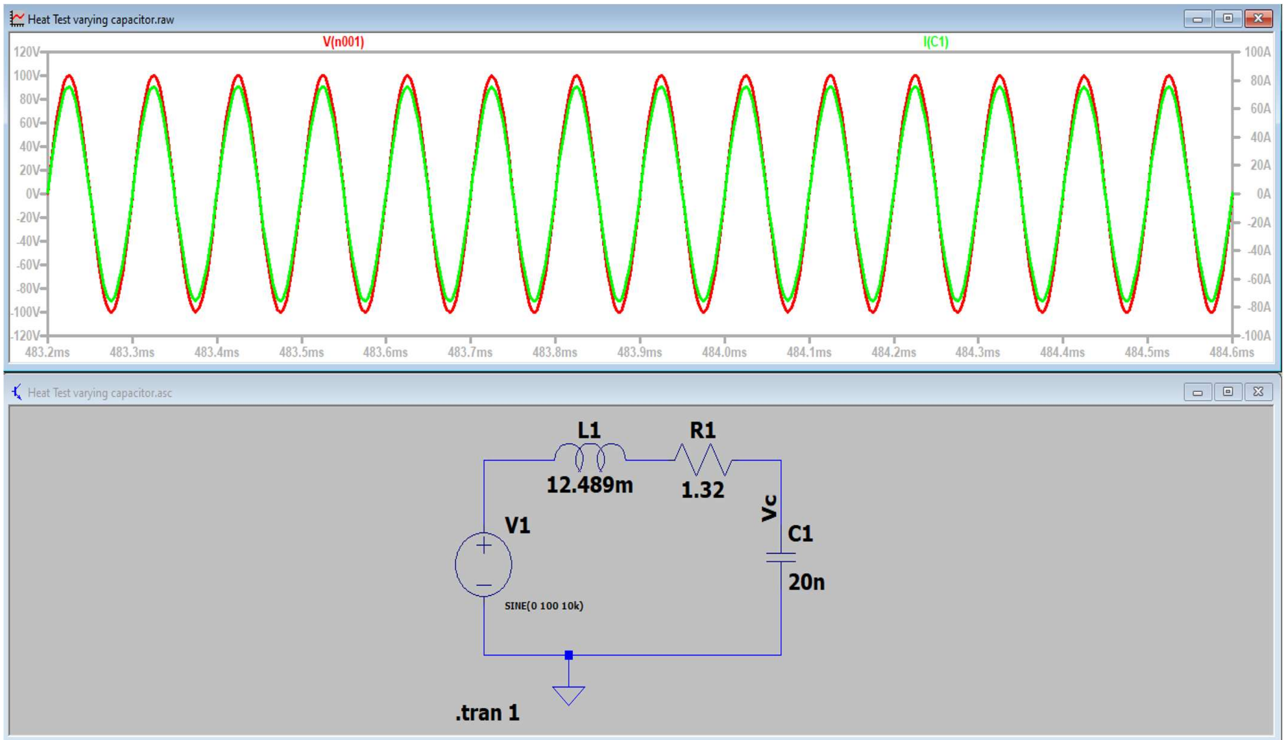



*Figure-76: Heat run test using tuned inductance value(12.489mH)*

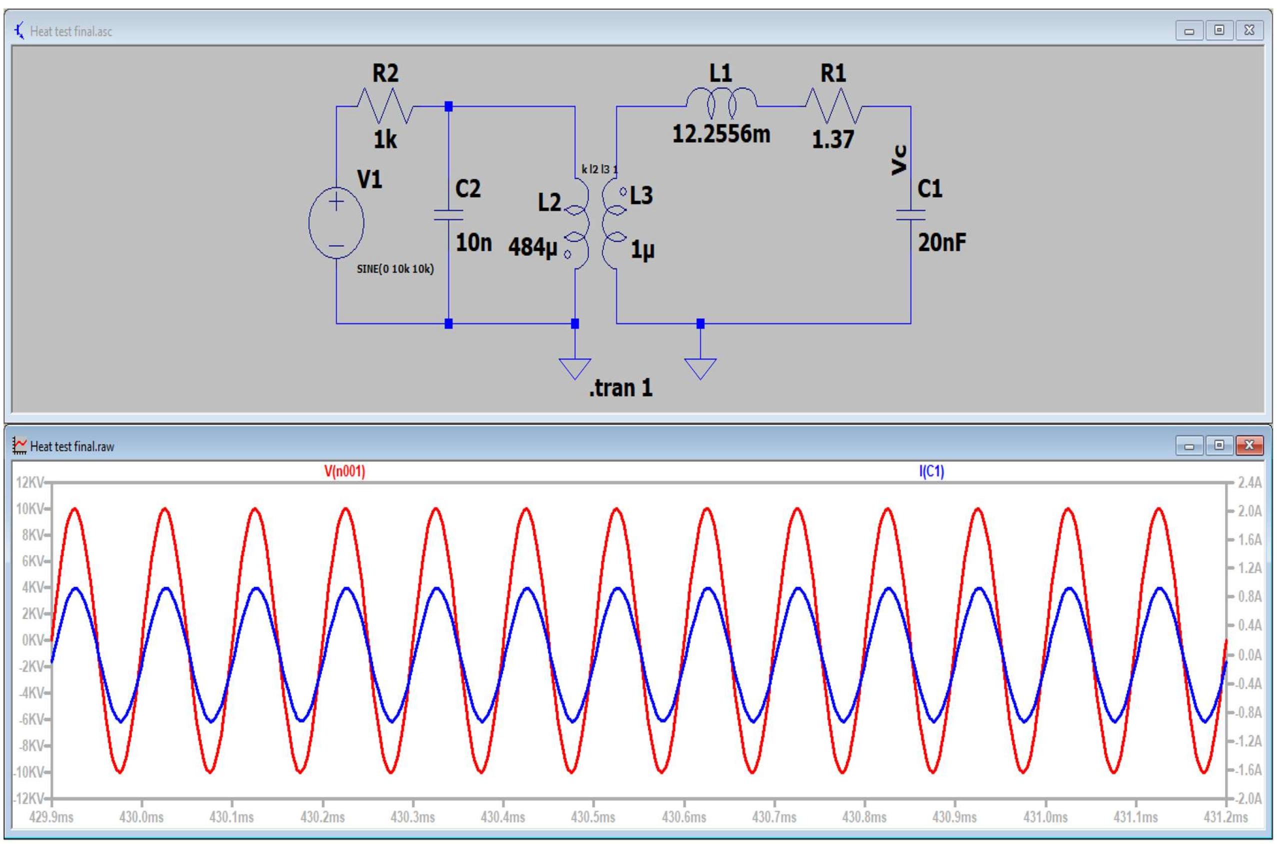



*Figure-77: Original Heat run test circuit*

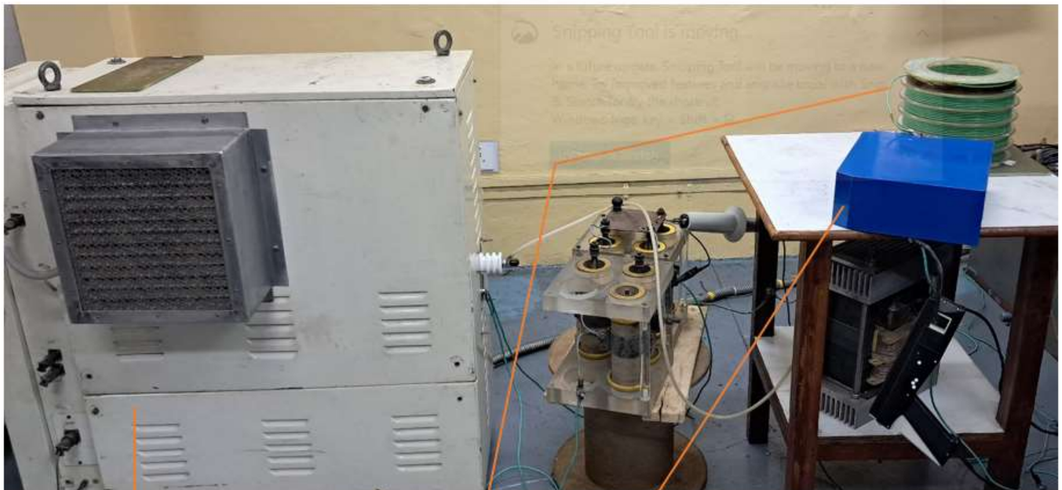
## Inspection and testing of SCWM stage Capacitor

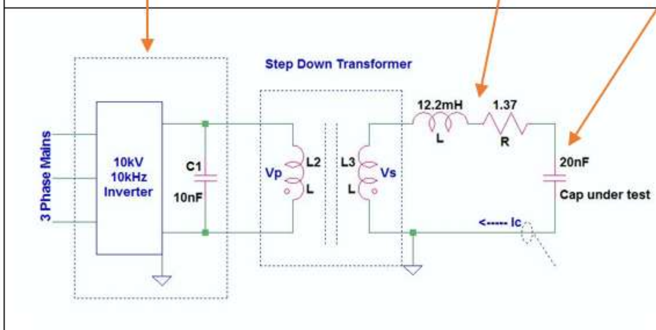
| Technical Specification for High Voltage Capacitor | | |
|---|---|---|
| S No. | Parameter | Value |
| 1. | Capacitance | 20nF |
| 2. | Cap. Value measuring frequency | 1 kHz |
| 3. | Tolerance | ±15% |
| 4. | Rated voltage | 120kV$_{DC}$ (42 kVrms) |
| 5. | Test Voltage | 150kV DC 1 minute |
| 6. | Current Rating | 3Arms@10kHz |
| 7. | Dielectric | Solid Dielectric(Ceramic-BaTiO3 or equivalent) |
| 8. | Dissipation factor | ≤ 0.001 at 1kHz |
| 9. | Operating conditions | (i) Continous working in 5%$SF_6$ +95%$N_2$ at 6kg/cm$^2$ external bar Pressure<br>(ii) 30mbar vacuum for 4 hours |
| 10. | Dimension | Overall Dimension: 342 ± 0.2mm (L), 262 ± 0.5mm (W) & 112mm ± 0.5mm(H) |
| 11. | Termination | Threaded Inserts |

**A)LCR measurement:** LCR values of capacitor has been measured to be C 19.45nF & D = 0.00088 @ 1kHz.

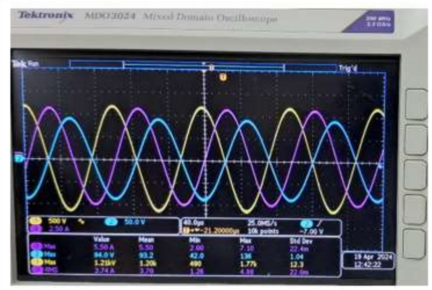
| LCR measurements | | | | |
|---|---|---|---|---|
| Before RMS current test | | | After RMS current test | |
| V=1V | | | | |
| f, kHz | Cp, nF | D | Cp | D |
| 1 | 19.45 | 0.00088 | 19.4 | 0.0006 |
| 10 | 19.35 | 0.00011 | 19.39 | 0.0004 |
| 20 | 19.43 | 0.00071 | 19.4 | 0.0009 |
| 50 | 19.26 | 0.00099 | 19.39 | 0.0015 |
| 100 | 19.44 | 0.0012 | 19.4 | 0.0025 |
| 200 | 1.51 | 0.0022 | 19.46 | 0.0046 |
| 300 | 19.6 | 0.0028 | 19.56 | 0.0068 |
| 500 | 20 | 0.0041 | 19.87 | 0.011 |
| 1000 | 22 | 0.0064 | 21.5 | 0.023 |
| V=5V | | | | |
| f, kHz | Cp | D | Cp | D |
| 1 | 19.44 | 0.0008 | 19.42 | 0.00064 |
| 10 | 19.43 | 0.0004 | 19.4 | 0.00056 |
| 20 | 19.45 | 0.00064 | 19.41 | 0.00063 |

**B) RMS current testing**: Capacitor has been successfully tested at continuous 3.5Arms, 10kHz current using test inverter under series resonance method. The temperature rise on capacitor with 6 hours continuous testing was 0.5°C. Circuit diagram and test set-up and waveform are shown below:






Schematic Circuit of RMS Current Test Setup



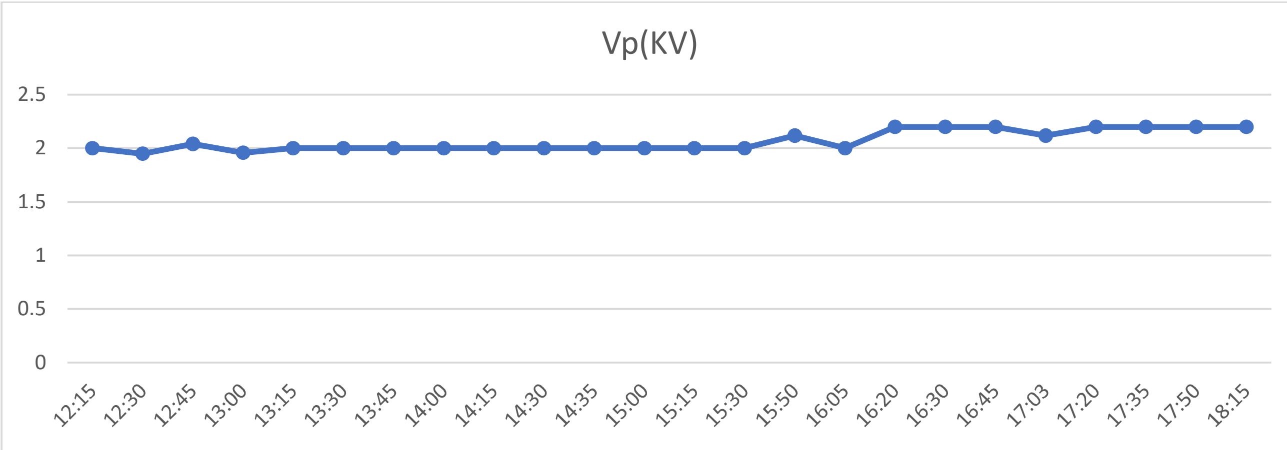

Yellow Color: Vp, Blue Color: Vs

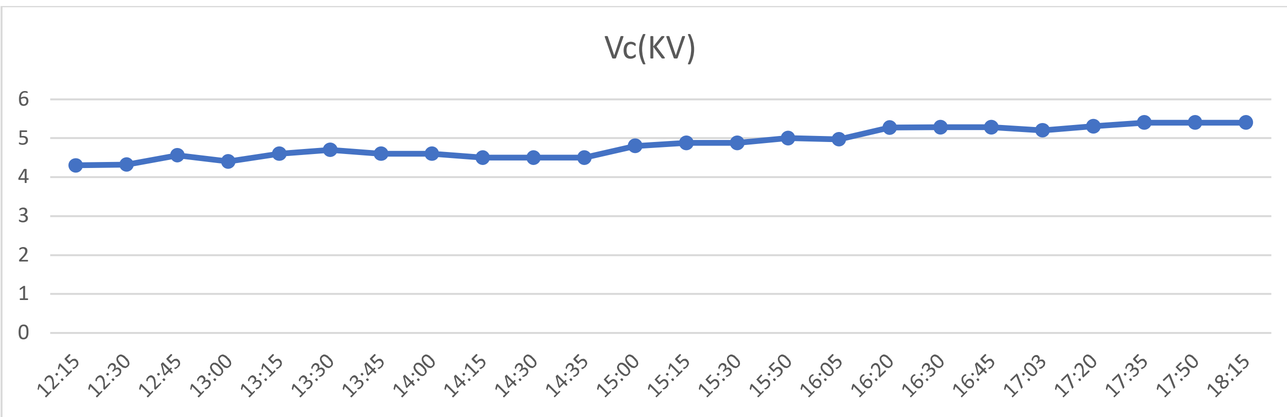
Pink Color: Ic (Capacitor Current)

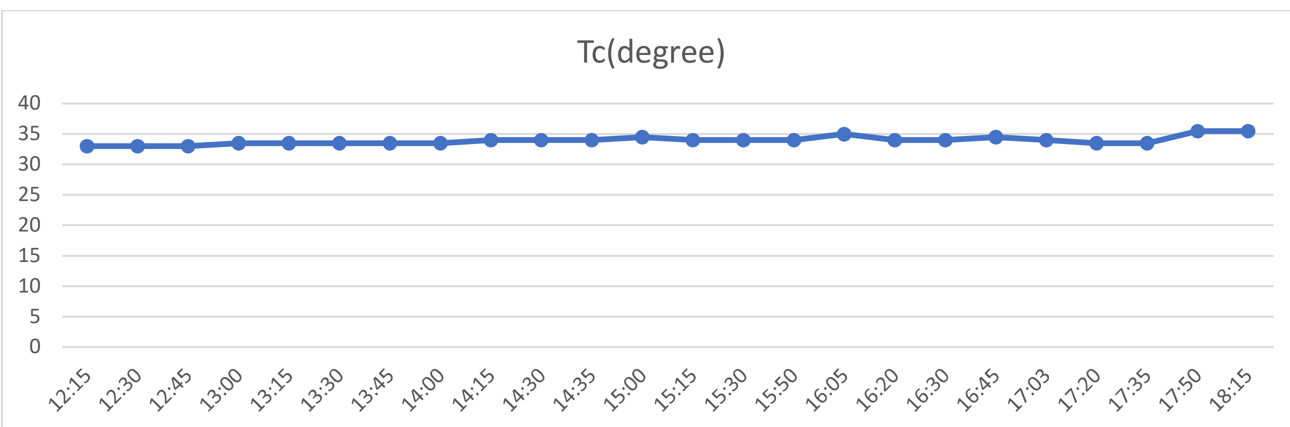
**<u>Original Data of Heat run test of Single Capacitor Module</u>**

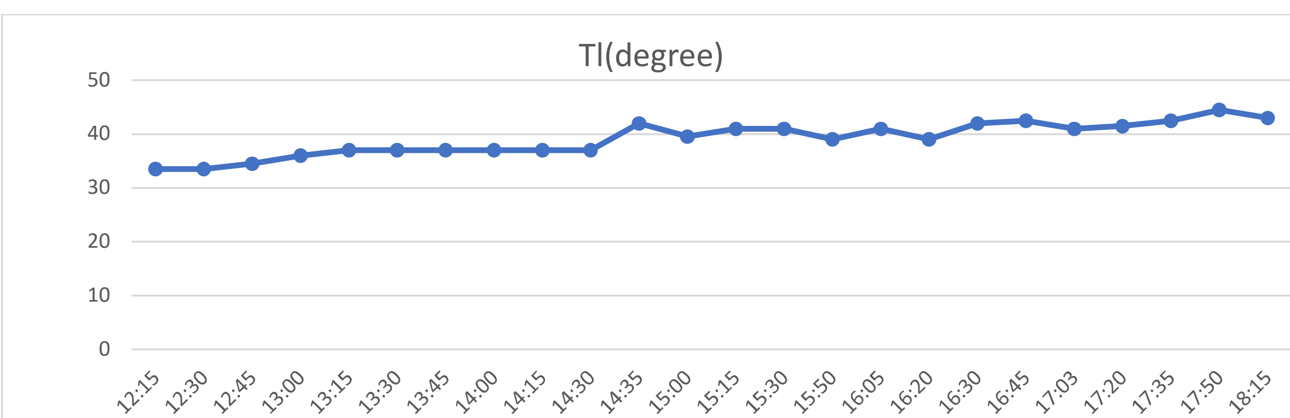
| Sl.No. | Time | Vp(kV) | Vc(kV) | Ic(Peak)(A) | Ic(RMS)(A) | Tc(degree) | Tl(degree) |
|---|---|---|---|---|---|---|---|
| 1 | 12:15 | 2 | 4.3 | 5.4 | 3.72 | 33 | 33.5 |
| 2 | 12:30 | 1.95 | 4.32 | 5.4 | 3.77 | 33 | 33.5 |
| 3 | 12:45 | 2.04 | 4.56 | 5.7 | 3.97 | 33 | 34.5 |
| 4 | 13:00 | 1.96 | 4.4 | 5.6 | 3.82 | 33.5 | 36 |
| 5 | 13:15 | 2 | 4.6 | 5.8 | 4.02 | 33.5 | 37 |
| 6 | 13:30 | 2 | 4.7 | 5.8 | 4.02 | 33.5 | 37 |
| 7 | 13:45 | 2 | 4.6 | 5.8 | 4.02 | 33.5 | 37 |
| 8 | 14:00 | 2 | 4.6 | 5.8 | 4.6 | 33.5 | 37 |
| 9 | 14:15 | 2 | 4.5 | 5.7 | 3.93 | 34 | 37 |
| 10 | 14:30 | 2 | 4.5 | 5.7 | 3.95 | 34 | 37 |
| 11 | 14:35 | 2 | 4.5 | 5.82 | 4.01 | 34 | 42 |
| 12 | 15:00 | 2 | 4.8 | 6 | 4 | 34.5 | 39.5 |
| 13 | 15:15 | 2 | 4.88 | 6.1 | 4.14 | 34 | 41 |
| 14 | 15:30 | 2 | 4.88 | 6.1 | 4.12 | 34 | 41 |
| 15 | 15:50 | 2.12 | 5 | 6.34 | 4.37 | 34 | 39 |
| 16 | 16:05 | 2 | 4.97 | 6.23 | 4.3 | 35 | 41 |
| 17 | 16:20 | 2.2 | 5.27 | 6.6 | 4.5 | 34 | 39 |
| 18 | 16:30 | 2.2 | 5.28 | 6.7 | 4.61 | 34 | 42 |
| 19 | 16:45 | 2.2 | 5.28 | 6.7 | 4.64 | 34.5 | 42.5 |
| 20 | 17:03 | 2.12 | 5.2 | 6.5 | 4.53 | 34 | 41 |
| 21 | 17:20 | 2.2 | 5.3 | 6.8 | 4.6 | 33.5 | 41.5 |
| 22 | 17:35 | 2.2 | 5.4 | 6.9 | 4.7 | 33.5 | 42.5 |
| 23 | 17:50 | 2.2 | 5.4 | 6.9 | 4.7 | 35.5 | 44.5 |
| 24 | 18:15 | 2.2 | 5.4 | 6.9 | 4.7 | 35.5 | 43 |

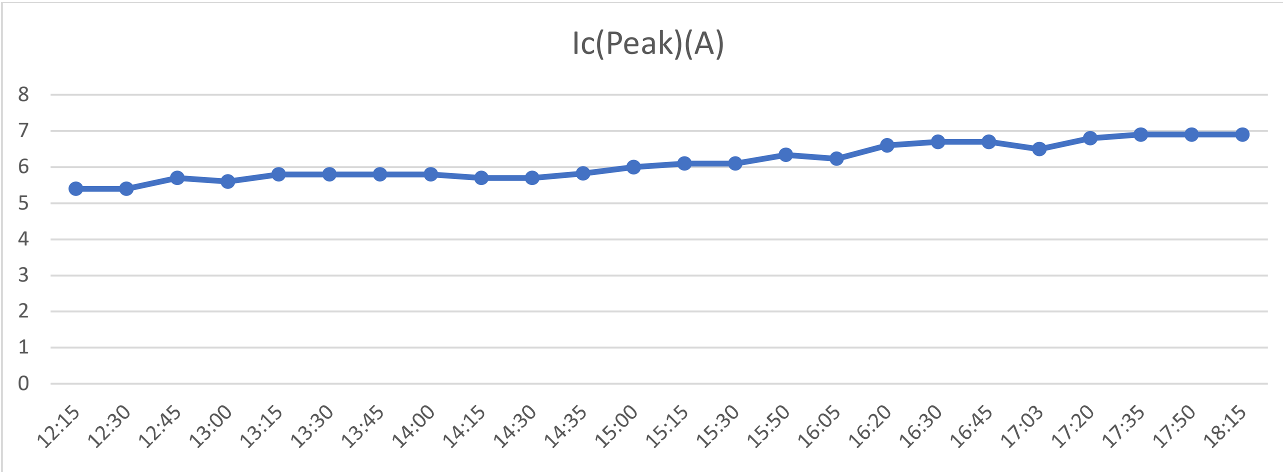
## Graphical Representation of the change of parameter W.R.T time

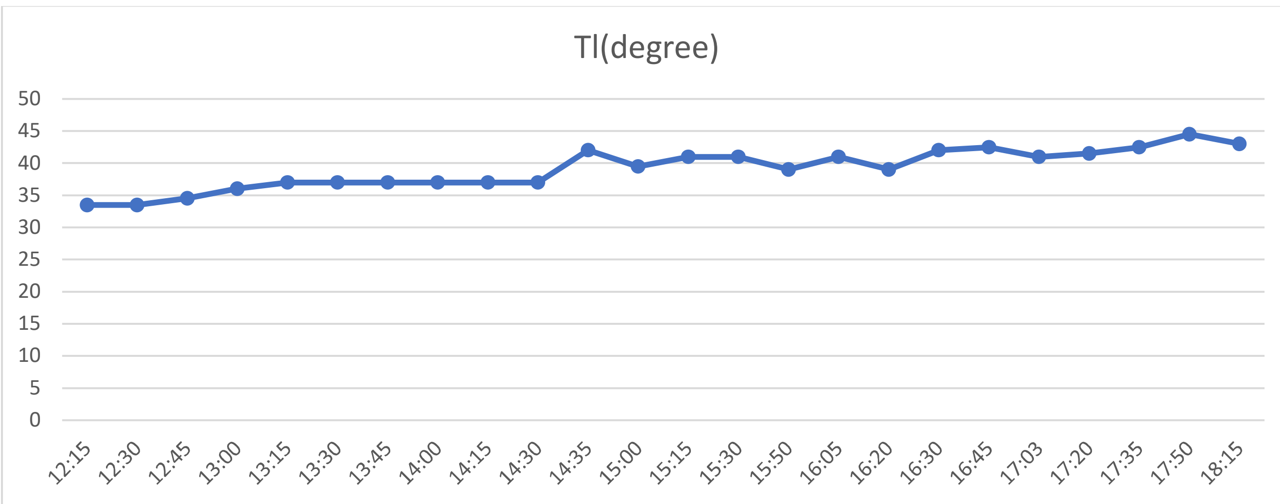



Ic(Peak)(A)
8
7
6
5
4
3
2
1
0
12:15
12:30
12:45
13:00
13:15
13:30
13:45
14:00
14:15
14:30
14:35
15:00
15:15
15:30
15:50
16:05
16:20
16:30
16:45
17:03
17:20
17:35
17:50
18:15


Tl(degree)
50
45
40
35
30
25
20
15
10
5
0
12:15
12:30
12:45
13:00
13:15
13:30
13:45
14:00
14:15
14:30
14:35
15:00
15:15
15:30
15:50
16:05
16:20
16:30
16:45
17:03
17:20
17:35
17:50
18:15

# HV testing and LCR Testing of 3.3nF ,40kV, tan δ=0.002 at 1KHz

## A) HV TESTING

High-voltage (HV) testing assesses the performance and safety of electrical components, such as capacitors, under elevated voltage conditions. It helps verify their insulation integrity and suitability for specific applications.

## SET-UP INSTRUCTIONS

- See Instruction Manual for Clearance from HV Circuit and HV module required for Safety and for use of barriers.
- Connect the GROUND terminal of the HV module to a known earth ground.
- Connect the HV output cable to the HV output connector located on the HV module. The exposed shield connection on the HV output cable is at guard potential and must not be grounded.
- The EXTERNAL INTERLOCK plug must be wired to an external interlock switch or shorted with a jumper.
- With MAIN BREAKER off, plug INPUT cord into control panel receptacle and into grounded outlet
- Identify the HV terminal and the ground terminal of the specimen to be tested. Connect the ground terminal to the GROUND post of the HV module. Attach the spring Clip of the HV cable to the HV terminal of the specimen.
- The specimen under test may retain a lethal electrical charge even when the test set is turned off. The Specimen must be discharged with a properly grounded grounding stick.

## B) LCR TESTING

LCR meter is an essential electronic instrument that measures the inductance (L), capacitance (C), and resistance (R) of electronic components. These parameters are crucial for the design and testing of electronic circuits, as they determine the performance and behaviour of these circuits.

## Working Principle of LCR meters

LCR meters work on the principle of impedance measurement. Impedance is the opposition to the flow of alternating current (AC) in a circuit, and it comprises of resistance, inductance, and capacitance. The LCR meter applies an AC voltage or current to the component under test and measures the resulting voltage or current. By analysing the phase difference and amplitude ratio between the input and output signals, the LCR meter can calculate the component's impedance and extract its L, C, and R values.

## Precaution:

Before testing a specimen like capacitor, we should discharge the capacitor by shorting their terminals.

## *Dimensional Check and Torque Test :*

| SL.NO. | Diameter(Max) | Diameter(Terminal) | Height(with T) | Height(W/O T) | Torque(N/m) |
|---|---|---|---|---|---|
| 1 | 55.87 | 15.2 | 33.13 | 26.8 | 1.5 |
| | 55.79 | 15.18 | 33.09 | 26.34 | 1.5 |
| | 55.75 | 15.1 | 33.1 | 26.48 | 1.5 |
| | | | | | |
| 2 | 55.74 | 15.16 | 32.98 | 26.86 | 1.5 |
| | 55.79 | 15.21 | 33.08 | 26.65 | 1.5 |
| | 55.72 | 15.18 | 33.02 | 26.62 | 1.5 |
| | | | | | |
| 3 | 55.77 | 15.1 | 32.96 | 26.32 | 1.5 |
| | 55.82 | 15.12 | 33.02 | 26.59 | 1.5 |
| | 55.85 | 15.14 | 33.04 | 27.16 | 1.5 |
| | | | | | |
| 4 | 55.73 | 15.13 | 32.97 | 26.42 | 1.5 |
| | 55.75 | 15.08 | 33.06 | 26.94 | 1.5 |
| | 55.79 | 15.11 | 32.96 | 27.01 | 1.5 |
| | | | | | |
| 5 | 55.72 | 15.11 | 32.95 | 26.5 | 1.5 |
| | 55.84 | 15.1 | 33.01 | 27.26 | 1.5 |
| | 55.93 | 15.05 | 32.98 | 26.98 | 1.5 |

## *HV Testing :*

| Sl.No. | Voltage(kV) | Current(µA) | Time(minute) |
|---|---|---|---|
| 1 | 10.2 | 0.0-0.0 | 1 |
| | 20.3 | 0.0-0.0 | 1 |
| | 30.3 | 0.0-0.0 | 1 |
| | 40 | 0.0-0.0 | 1 |
| | | | |
| 2 | 10.2 | 0.0-0.0 | 1 |
| | 20.2 | 0.0-0.0 | 1 |
| | 30.8 | 0.0-0.0 | 1 |
| | 40.2 | 0.0-0.0 | 1 |
| | | | |
| 3 | 10.2 | 0.0-0.0 | 1 |
| | 20.3 | 0.0-0.0 | 1 |
| | 30 | 0.0-0.0 | 1 |
| | 40 | 0.0-0.0 | 1 |
| | | | |
| 4 | 10.2 | 0.0-0.0 | 1 |
| | 20 | 0.0-0.0 | 1 |
| | 30.4 | 0.0-0.0 | 1 |
| | 40.4 | 0.0-0.0 | 1 |
| | | | |
| 5 | 10.4 | 0.0-0.0 | 1 |
| | 20 | 0.0-0.0 | 1 |
| | 30.1 | 0.0-0.0 | 1 |
| | 40.2 | 0.0-0.0 | 1 |

## *LCR Testing:*

| Sl.NO | Frequency | Before HV testing | | | | | After HV Testing | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | AC-1v | | Ac-5v | | | AC-1v | | Ac-5v | |
| | | Cp(nf) | D | Cp(nf) | D | | Cp(nf) | D | Cp(nf) | D |
| 1 | 1kHz | 3.29 | 0.000 | 3.33 | 0.000 | | 3.33 | 0.0007 | 3.32 | 0.0009 |
| | 10KHz | 3.31 | 0.003 | 3.33 | 0.003 | | 3.33 | 0.0037 | 3.32 | 0.0034 |
| | 20KHz | 3.30 | 0.003 | 3.33 | 0.005 | | 3.32 | 0.0058 | 3.31 | 0.0056 |
| | 50KHz | 3.30 | 0.010 | 3.32 | 0.011 | | 3.31 | 0.0113 | 3.31 | 0.0108 |
| | 100KHz | 3.29 | 0.018 | 3.30 | 0.018 | | 3.30 | 0.0183 | 3.29 | 0.0181 |
| | | | | | | | | | | |
| 2 | 1kHz | 3.31 | 0.000 | 3.33 | 0.000 | | 3.32 | 0.00064 | 3.34 | 0.0009 |
| | 10KHz | 3.30 | 0.002 | 3.32 | 0.003 | | 3.33 | 0.0034 | 3.34 | 0.0035 |
| | 20KHz | 3.30 | 0.004 | 3.32 | 0.005 | | 3.33 | 0.0056 | 3.34 | 0.0012 |
| | 50KHz | 3.29 | 0.009 | 3.31 | 0.010 | | 3.32 | 0.0107 | 3.33 | 0.0109 |
| | 100KHz | 3.31 | 0.02 | 3.30 | 0.017 | | 3.31 | 0.0179 | 3.31 | 0.0180 |
| | | | | | | | | | | |
| 3 | 1kHz | 3.34 | 0.000 | 3.34 | 0.000 | | 3.34 | 0.00056 | 3.35 | 0.00077 |
| | 10KHz | 3.33 | 0.002 | 3.34 | 0.003 | | 3.34 | 0.00300 | 3.35 | 0.0032 |
| | 20KHz | 3.33 | 0.004 | 3.33 | 0.004 | | 3.34 | 0.005 | 3.35 | 0.0054 |
| | 50KHz | 3.32 | 0.009 | 3.33 | 0.009 | | 3.33 | 0.0098 | 3.34 | 0.0104 |
| | 100KHz | 3.31 | 0.017 | 3.32 | 0.01 | | 3.32 | 0.0163 | 3.33 | 0.0172 |
| | | | | | | | | | | |
| 4 | 1kHz | 3.25 | 0.000 | 3.26 | 0.001 | | 3.25 | 0.0013 | 3.25 | 0.0010 |
| | 10KHz | 3.24 | 0.004 | 3.25 | 0.004 | | 3.25 | 0.0044 | 3.24 | 0.0043 |
| | 20KHz | 3.24 | 0.006 | 3.25 | 0.007 | | 3.24 | 0.0072 | 3.241 | 0.0069 |
| | 50KHz | 3.23 | 0.012 | 3.23 | 0.013 | | 3.23 | 0.0136 | 3.23 | 0.0127 |
| | 100KHz | 3.22 | 0.018 | 3.22 | 0.021 | | 3.21 | 0.021 | 3.216 | 0.0205 |
| | | | | | | | | | | |
| 5 | 1kHz | 3.32 | 0.000 | 3.34 | 0.000 | | 3.33 | 0.0007 | 3.34 | 0.00077 |
| | 10KHz | 3.32 | 0.002 | 3.34 | 0.003 | | 3.33 | 0.0031 | 3.34 | 0.0033 |
| | 20KHz | 3.32 | 0.004 | 3.33 | 0.005 | | 3.33 | 0.0054 | 3.34 | 0.0054 |
| | 50KHz | 3.31 | 0.009 | 3.32 | 0.010 | | 3.32 | 0.0104 | 3.33 | 0.0104 |
| | 100KHz | 3.3 | 0.016 | 3.31 | 0.016 | | 3.31 | 0.0176 | 3.32 | 0.0172 |

***HV testing of Ceramic Capacitor in Dielectric fluid (Test voltage=1.5 * rated voltage,1minute duration, standard IEC60384-1;2008):***

| Sl.No. | Voltage(kV) | Current(μA) | Time(minute) |
|---|---|---|---|
| 1 | 10 | 0.0-0.0 | 1 |
| | 20 | 0.0-0.0 | 1 |
| | 30.1 | 0.0-0.0 | 1 |
| | 40.1 | 0.0-0.0 | 1 |
| | 50.1 | 0.0-0.0 | 1 |
| | 60.3 | 0.0-0.0 | 1 |
| 2 | 10 | 0.0-0.0 | 1 |
| | 20 | 0.0-0.0 | 1 |
| | 30.2 | 0.0-0.0 | 1 |
| | 40.4 | 0.0-0.0 | 1 |
| | 45 | 0.0-0.0 | 1 |
| | 50.5 | 0.1-0.0 | 1 |
| | 55.4 | 0.0-0.0 | 1 |
| | 60.1 | 0.0-0.0 | 1 |

## *LCR Testing After HV testing of Ceramic Capacitor in the Dielectric fluid:*

| Sl.NO | Frequency | AC-1v | | Ac-5v | |
|---|---|---|---|---|---|
| | | Cp(nf) | D | Cp(nf) | D |
| 1 | 1kHz | 3.3065 | 0.0006 | 3.280 | 0.0007 |
| | 10KHz | 3.3039 | 0.0032 | 3.290 | 0.00285 |
| | 20KHz | 3.304 | 0.005 | 3.291 | 0.00478 |
| | 50KHz | 3.297 | 0.0099 | 3.286 | 0.00925 |
| | 100KHz | 3.286 | 0.016 | 3.277 | 0.01559 |
| | | | | | |
| 2 | 1kHz | 3.3079 | 0.0007 | 3.318 | 0.001 |
| | 10KHz | 3.308 | 0.0027 | 3.316 | 0.003 |
| | 20KHz | 3.305 | 0.0049 | 3.3141 | 0.0051 |
| | 50KHz | 3.298 | 0.0094 | 3.3074 | 0.010 |
| | 100KHz | 3.288 | 0.016 | 3.2974 | 0.0164 |

# CONCLUSION

During my two-month summer training at the EBC, APPD, BARC, I acquired a comprehensive understanding of the fundamental principles and practical applications of HV multiplier circuit for DC Electron Beam Accelerator.

I gained proficiency in simulating circuits using LT Spice and developed a thorough knowledge of the symmetrical Cockcroft-Walton Voltage Multiplier Circuit, including its operating principles and various configurations. Additionally, I learned about the connection and rating of capacitors and diodes used in multiplier circuits. Through simulations, I analysed the performance of the circuit under both no-load and loaded conditions, and interpreted the results through graphical representations.

Furthermore, I successfully simulated the heat run test circuit of the single capacitor module (20nF, 10kHz) and performed HV and LCR tests on a new specimen (3.3nF, 40kV, D=0.002 at 1KHz). This training experience has equipped me with valuable knowledge and skills in the field of high voltage engineering.