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Modeling and Simulation of Multi-State Impulse Voltage Generator 22 kV 32 J

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Abstract

This article proposed the multi-layer pulse pressure generator includes a charge compression resistor with a value of 6K, a forward wave resistor of 270, and a backward wave resistor of 10 has a spark plug, using a spherical head nut with a diameter of 0.5 centimeters and a gap of 0.3 centimeters. Through experiments, a suspended insulator head was used as the experimental load. When the experiment starts, it can be concluded that the 22kV multi-layer pulse generator can generate pulse voltage. However, the standard 1.2/50 μ s waveform is not available. From the charging waveform to the discharge time is 187.7 ns. When the peak value is reached, the tail wave will quickly decrease to the minimum value. The maximum value is 80 ns. The amplitude 54 V rated voltage 37.6 kV, minimum voltage 20 kV, test output voltage 20-37.6. kV can be seen that when the peak value is reached, the waveform fluctuates up and down to 0, indicating that the actual test results are passed. The oscilloscope has a larger oscillator because in actual testing, compared to analog oscilloscopes

Keywords: Impulse Pressure, Spark Gap, charge, discharge

1. Introduction

The increasing complexity and expansion of electrical power systems have amplified the necessity for advanced high-voltage testing techniques to ensure the reliability and safety of electrical infrastructure. Multi-stage impulse voltage generators are critical tools in this context, designed to simulate the high-voltage transients that can occur due to lightning strikes, switching operations, and other transient phenomena. These generators are essential for evaluating the dielectric strength and insulation performance of various high-voltage components such as transformers, insulators, cables, and circuit breakers [1-2]. The ability to accurately replicate high-voltage impulse waveforms allows engineers and researchers to predict the behavior of electrical equipment under extreme conditions, thereby preventing failures and enhancing the overall robustness of power systems. Multi-stage impulse voltage generators function by charging a series of capacitors to a high voltage and then discharging them in a controlled sequence through spark gaps. This process generates precise and repeatable voltage impulses necessary for rigorous testing [3].

Research into the optimization and development of these generators is of paramount importance. Advances in design, such as improved configurations of capacitors and spark gaps, have led to generators that are more efficient, reliable, and capable of producing higher voltages. Additionally, the integration of sophisticated simulation tools like MATLAB and the Electromagnetic Transients Program (EMTP) has enabled more accurate modeling of generator performance, facilitating better design and troubleshooting [4]. Moreover, recent innovations have focused on making these generators more compact and portable, enhancing their practicality for on-site testing in various industrial settings. The development of new materials and components has also contributed to increased operational efficiency and reduced costs. These advancements not only improve the testing capabilities but also support the continuous improvement of electrical safety standards and the resilience of electrical grids [5].

Therefore, this paper presents the impulse voltage according to the requirements of a 22 kV 32 J impulse voltage generator. It will help to further develop the design and construction of higher-level impulse voltage generators. In order to develop studies, research and develop insulators in the future. Impulse voltage is a voltage whose waveform mimics that of the transient surge voltage associated with lightning phenomena is called lightning impulse voltage waveform. It also occurs from causes in the distribution system, namely due to the operation of switches or circuit breakers. When a fault occurs in the system it is called switching impulse voltage which is the purpose of generating the impulse voltage. In order to research or test various equipment before using it to see if it can withstand these overpressures or not.

2. Objectives

2.1 To study and understand the working principle of an impulse voltage generator of 22 kV 32 J.

2.2 To study the various components and functions of each type of equipment of an impulse voltage generator, size 22 kV 32 J.

2.3 To study and test the design and construction of an impulse voltage generator of 22 kV 32 J to obtain an impulse voltage waveform according to the specified standards.

3. Generation of impulse voltage

Impulse voltage is a voltage whose waveform imitates the transient overvoltage caused by external events related to lightning phenomena. It is called a lightning impulse voltage waveform. It may occur from reasons within the distribution system itself, namely due to the operation of switches or circuit breakers when a fault occurs in the system, called switching impulse voltage.

3.1 Calculation of impulse voltage circuits

The impulse voltage waveform characteristics, which vary in time terms, are expressed by the peak value and the wave-front time T_1 (T_{cr}). The wave tail time T_2 depends on the circuit element values that can be analyzed and calculated.

1. Variation of the impulse voltage in time terms from the basic circuit creates the circuit impulse voltage B. In Figure 3, when the capacitor C_s is charged with charging voltage U_o and a spark gap SG occurs, C_s is connected to the waveform adjustment circuit. The analysis may use the Laplace transform to write the voltage-generating circuit as shown in Figure 1.

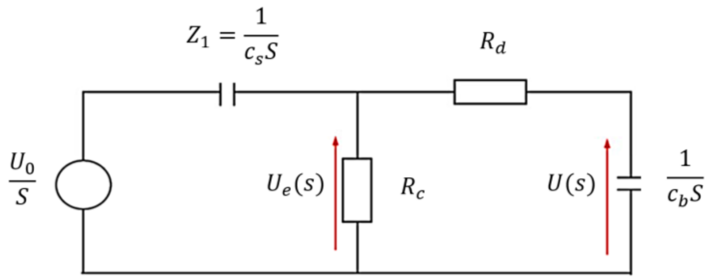


Figure 1 Laplace transform of a basic impulse circuit[x]

From the circuit in Figure 1, the voltage across R_e can be written as

$$U_s(S) = \frac{U_o}{S}\frac{Z_2}{(Z_1 + Z_2)}$$

When $$Z_1 = C_s S$$

$$Z_2 = \frac{R_e[R_d + \frac{1}{C_b S}]}{R_e + R_d + \frac{1}{C_b + S}}$$

$$U_e(S) = \frac{U_0(R_d R_e C_s C_b S + R_e C_s)}{R_d C_b S + R_e C_b S + R_e C_s S + R_d R_e C_s C_b S^2} \quad (1)$$

The output voltage at the load can be calculated from $U_e(S)$ according to the impedance ratio.

$$U(S) = \frac{U_e(S)\frac{1}{C_b S}}{R_d + \frac{1}{C_b S}} = \frac{U_e(S)}{R_d C_b S + 1}$$

$$U(S) = \frac{U_0 R_e C_s}{R_d R_e C_s C_b S^2 + (R_d C_b + R_e C_s + R_e C_b)S + 1}$$

$$U(S)=\frac{U_0}{R_dC_b}\frac{1}{S^2+\frac{(R_dC_b+R_eC_s+R_eC_b)S}{R_dR_eC_sC_b}+\frac{1}{R_dR_eC_sC_b}}$$

Equation 1 can be combined

$$U(S)=\frac{U_0}{K}\frac{1}{S^2+aS+b}=\frac{U_0}{K}\frac{1}{(\alpha_2+\alpha_1)}\left[\frac{1}{S-\alpha_1}-\frac{1}{S-\alpha_2}\right] \tag{2}$$

When $$a=\frac{(R_dC_b+R_eC_s+R_eC_b)S}{R_dR_eC_sC_b}$$

$$b=\frac{1}{R_dR_eC_sC_b}$$

$$K=\mathrm{R}_d\mathrm{C}_b$$

α_1, α_2 are the square roots of the equation $S^2 + aS + b = 0$

Where $$\propto_1,\propto_2=\frac{a\pm\sqrt{a^2-4b}}{2}$$

Therefore, the impulse voltage value can be written in terms of time as

$$U(t)=\frac{U_0}{K}\frac{1}{(\alpha_1-\alpha_2)}\left[\exp(-\alpha_1 t)-\exp(-\alpha_2 t)\right] \tag{3}$$

Standard impulse voltage waveform defined with wave-front and wave-back times T_1 and T_2 respectively. It is related to the time constants $1/\alpha_1$ and $1/\alpha_2$ depending on the ratio T_1/T_2. which represents the characteristics of the waveform. The values k_1 and k_2 are constants depending on the waveform as shown in Table 1.

T_1 and T_2 values may be obtained from the following relationship:

$$T_1=\frac{k_2}{\alpha_2},\frac{k_1}{\alpha_1}$$

Table 1 K_1 and K_2 factor for standard waveforms

T_1T_2	**K_1**	**K_2**	**$1/\alpha$ (μs)**	**$1/\alpha$ (μs)**
1.2/5	1.44	1.49	3.47	0.805
1.2/50	0.73	2.96	68.5	0.405
1.2/200	0.70	3.15	286	0.381
250/2500	0.87	2.41	2875	104.0

2. Calculation of circuit element values

When knowing what impulse voltage waveform to create, given the values T_1 and T_2, we normally start from the load capacitance value C_b. Select the impulse capacitor C_s following

C_b, that is C_s stores enough energy to supply the load. Therefore, once the values of C_b and C_s are known, the remaining components that need to be calculated are the resistances R_b and R_e, which can be found from the relationship of the time constants $1/\alpha_1$, $1/\alpha_2$, which is circuit equation B.

$$R_d = \frac{1}{2C_b}\left[\left(\frac{1}{\alpha_1}+\frac{1}{\alpha_2}\right)-\sqrt{\left(\frac{1}{\alpha_1}+\frac{1}{\alpha_2}\right)^2-4\frac{(C_s+C_b)}{\alpha_1\alpha_2 C_s}}\right] \quad (4)$$

$$R_e = \frac{1}{2(C_{s+}C_b)}\left[\left(\frac{1}{\alpha_1}+\frac{1}{\alpha_2}\right)-\sqrt{\left(\frac{1}{\alpha_1}+\frac{1}{\alpha_2}\right)^2-4\frac{(C_s+C_b)}{\alpha_1\alpha_2 C_s}}\right] \quad (5)$$

3. Circuit efficiency

When referring to the efficiency of a circuit or impulse voltage generator, it refers to the ratio of the peak voltage generated to the charging voltage. Normally it will always have a value less than 1 for both circuit A and circuit B.

$$\eta = U_m / U_o < 1 \quad (6)$$

When U_m is the peak value of the impulse voltage u(t)

U_o is the charging pressure of C_s

In the case of a lightning impulse voltage (1.2/50 μs), the efficiency of the impulse circuit, which depends on the value of C_b to C_s, is shown in Figure 2.

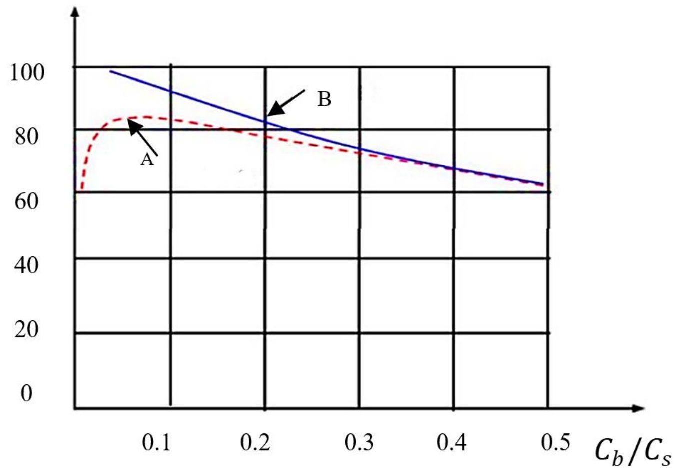


Figure 2 Compares the efficiency of the impulse voltage-generating circuit[xx].

The peak impulse voltage value is calculated from the impulse voltage equation:

$$\frac{du(t)}{dt} = 0$$

$$-\alpha_1 e^{-\alpha_1 t_m} + \alpha_2 e^{-\alpha_2 t_m} = 0$$

where t_m is the time during which the voltage reaches the peak value U_m is obtained.

$$t_m = \frac{1}{(\alpha_1 + \alpha_2)} \ln \frac{\alpha_1}{\alpha_2} \tag{7}$$

$$U_m = \frac{U_0}{K} \frac{1}{(\alpha_1 + \alpha_2)} - e^{\alpha_1 t_m} - e^{\alpha_2 t_m} \tag{8}$$

Calculating the time values of T_1 and T_2 waveforms

In the case where the values of various components of the impulse circuit are known if it is necessary to know the wave- front time, the approximate value can be calculated from the values k_1 and k_2 as follows:

Table 2. Impulse voltage generating circuit component values

Impulse circuit elements	Circuit A	Circuit B
T_1	$k_2 \frac{R_d R_e}{(R_d + R_e)} \frac{C_b C_s}{(C_b + C_s)}$	$k_2 R_d \frac{C_b C_s}{(C_b + C_s)}$
T_2	$k_1 (R_d + R_e)(C_b + C_s)$	$k_1 R_d (C_b + C_s)$
η	$\frac{R_d R_e}{(R_d + R_e)(C_b + C_s)}$	$\frac{C_s}{(C_s + C_b)}$

3.2 Generation of switching impulse voltage

Generating a switching impulse voltage generally uses the aforementioned lightning waveform impulse voltage generator circuit. Just adjust the values of the circuit components Rd and Re to get the waveform as specified. Factor values K_1 and K_2 can also be calculated from Table 2. An example impulse voltage generator is shown in Figure 3, which can generate 1.2/50 µs lightning impulse voltage and 250/2500 µs switching waveform impulse.

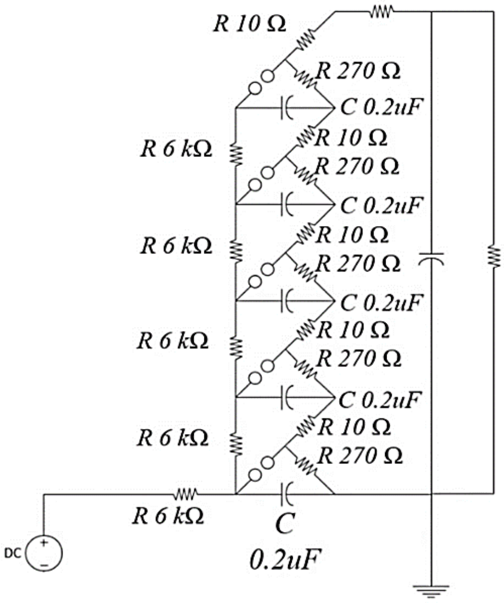


Figure 3 The 22 kV 5-step impulse voltage generator can generate both lightning waveforms and switching waveforms[x].

3.3 Generation of steep front impulse voltage

The purpose of generating a steep wave-front impulse voltage is to test the durability of high-voltage insulators used in air-strung distribution systems. There is a chance of being exposed to a lightning surge with a slope of S = du/dt of 200 kV/µs or more, causing the type B insulator to penetrate, as discussed in section 1.5.3. Modern standards for insulators require tests for their durability against steep wave front impulse voltages, flashover, or penetration conditions in insulators.

1. Requirements of steep wave front impulse voltage

The wave-front impulse voltages required for testing insulators according to currently referenced standards are IEC 1211-1994, AS-29470-1989, and CAN/CASC411.1- M89-1989. Different requirements can be summarized as two important parameters that determine the steep wave-front impulse voltage:

- Impulse voltage wave-front slope (S)
- Impulse voltage size as compared to the values in Table 3

Table 3 compares steep wave-front impulse voltage specifications[x]

Standard	**Requirements**	
	Specified voltage	**Slope S**
IEC 1211-1994	2-3 times (p.u) of critical impulse flashover value U_b50% of standard waveform 1.2/50 µs higher polarity	Not specified
AS 2947-1989	Not specified	2500 kV/μs or wave-front cutoff time < 0.4 µs
CAN/CSA-C411.1-M 198989	Not specified	> 2500 kV/µs

4. Methodology

Calculating the values of capacitors, resistors, and spark gaps within a circuit. The impulse voltage generator to be designed has the following requirements:

- Used to generate standard 1.2/50 s impulse voltage waveforms.
- The specified voltage is 22 kV, both positive and negative.
- Use 25 1 µF 2 kV capacitors as impulse capacitors to store energy.

4.1 Voltage value of the impulse voltage generator

In the design, we will use a charging voltage per layer of 4.4 kV. This impulse voltage generator has 5 levels, giving a total charging voltage of 22 kV. The energy of this impulse voltage generator is 32 J, which is calculated using the following values:

$$U_o = 5\,U'_o$$
$$= 5 \times 4.4 \text{ kV}$$

Total charging voltage $U_o = 22$ kV

where the total electrical capacity $C_s = (C'_s/5)$

$$= 0.04\ \mu\text{F}$$

Therefore, an impulse voltage generator will have a rated power

$$W = C_S U_0^2 / 2 \quad (3.0)$$
$$= 0.04 \times 10^{-6} \times (40 \times 10^3)^2 / 2$$
$$W = 32 \text{ J}$$

4.2 Calculating the value of the wavefront adjustment resistor (R_d)

The resistance of the wave-front adjusting resistors is 9.3184 Ω ohms each, which can be found from the equation in Table 2.1 using a 0.2 µF 10 kV capacitor. There are 5 levels of impulse voltage generators which can be described:

$$C_s = (C'_s/5)$$
$$= 0.2\ \mu F/5$$
$$= 0.04\ \mu F$$

The surface area of the spark gap: $4\pi r_2 = 4\pi 0.52$

Semi-spherical spark gap: $\pi = 22/7$

$\pi/2 = 11/7$

The surface area of the spark gap: $A = 11/7 \text{ cm}^2$

Distance between spark gap: $d = 0.001 \text{ m}^2$

$$C_b = \varepsilon_{max} \times \frac{A}{d}$$
$$= 708.32 \times 10^{-12}$$
$$= 0.00000001112$$
$$C_b = 11.12 \text{ nF}$$

From the factor value table for the standard waveform of Circuit B, the values K_1 and K_2 are constants depending on the waveform:

$$K_1 = 0.73$$
$$K_2 = 2.96$$
$$T_1 = 1.2\ \mu s$$
$$T_2 = 50\ \mu s$$

Wavefront adjustment resistance (R_d) from the equation of circuit B, standard waveform size 1.2/50 µs.

$$T_1 = k_2 R_d \frac{C_S C_b}{C_S + C_b}$$

$$1.2 \times 10^{-6} = 2.96 \times R_d \frac{0.04 \times 10^{-6} \times 11.12}{0.04 \times 10^{-6} + 11.12}$$

$$R_d = \frac{1.2 \times 10^{-6}}{2.96} \frac{0.04 \times 10^{-6} + 11.12}{0.04 \times 10^{-6} \times 11.12}$$

$$R_d = 46.592$$

$$R'_d = \frac{46.592}{5}$$

$$R'_d = 9.3184\ \Omega$$

4.3 Calculating the value of the wavefront adjustment resistor (R_e)

The resistance of the adjustable resistor at the end of the wave (R_e) is equal to 267.97 Ω, which can be found in the equation in Table 1

$$T_2 = k_1 R_e (C_s + C_b)$$
$$50 \times 10^{-6} = 0.73Re\,(0.04 \times 10^{-6} + 11.12 \times 10^{-9})$$
$$R_e = 1339.85$$
$$R'_e = \frac{1339.85}{5}$$
$$R'_e = 267.97\ \Omega$$

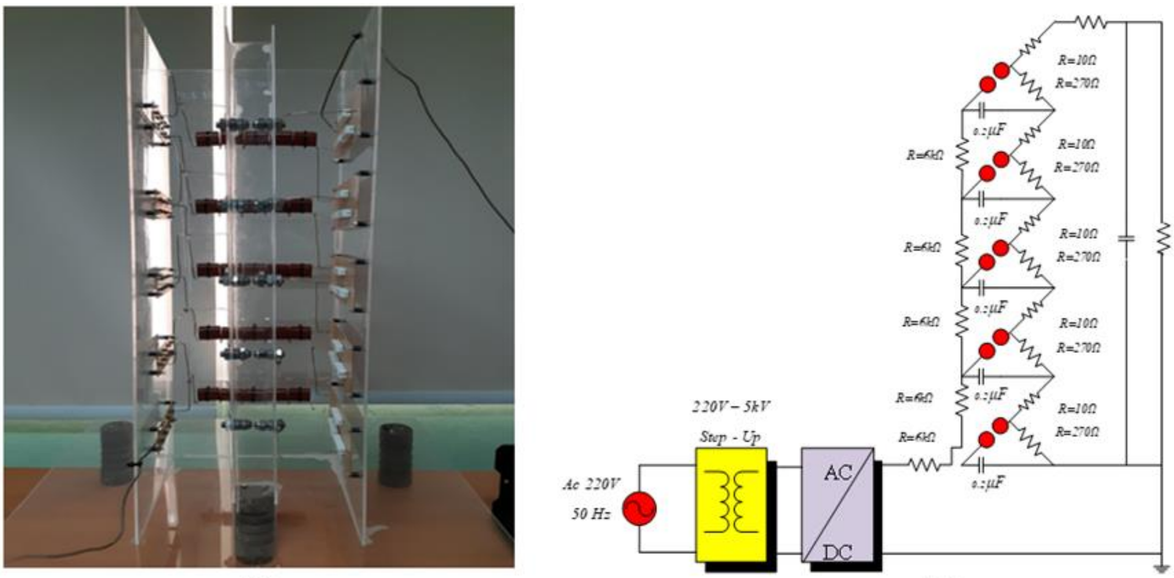
4.4 Diode calculation in Bridge Rectifier circuit

The diode used in the Bridge Rectifier circuit must be able to reduce the voltage supplied by the transformer. Diode number 1N4007 was chosen. It can withstand a voltage of 1 kV. Connected in series to withstand a V_{rms} voltage of the transformer 3 times. Therefore, 24 diodes must be used in series on each side, both positive and negative, for a total of 64 diodes.

$$V_{rms} = 5000\ V$$
$$V_{peak} = \sqrt{2} \times 5000$$
$$V_{peak} = 7071.068\ V$$

The voltage that the diode must withstand is 3 times that of the transformer.

$$\text{Pressure 3 times} = 7071.068 \times 3$$
$$= 21213.204\ V$$



(a) (b)

Figure 4 Multilayer impulse voltage generator 22 kV
(a): Implementation of Multilayer impulse voltage generator 22 kV
(b): Diagram of Multilayer impulse voltage generator 22 kV

5. Results and Discussion

5.1 Multilayer impulse voltage generator 22 kV

The impulse voltage generator used for project experiments creates an impulse voltage waveform that mimics the lightning waveform as shown in Figure 4. The impulse pressure generator was tested to produce a standard waveform of 1.2/50 µs with air as the intermediate load. The experiment of this impulse pressure generator must be done in a laboratory and must have safety equipment and an advisor to supervise while experimenting. The experiment is divided into 2 separate experiments, simulating the operating cycle with a computer program and an experiment by measuring the energy obtained from the experiment and using the results of both types to compare the operating system further.

5.2 Experimenting with the PSIM program on a computer

The circuit can be simulated in a PSIM computer as shown in Figure 5. and has parameter values as shown in Table 4.

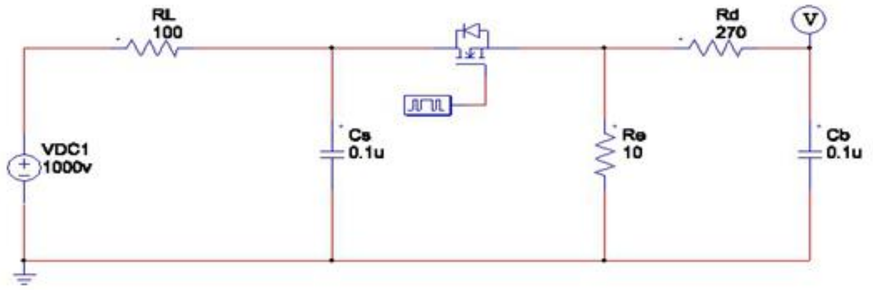


Figure 5 Simulates the test circuit through the PSIM program

Table 4 Parameter values

Period	V_{DC}	R_L	R_e	R_d	C_s	C_b
Wave front time T1 (µs)	1000V	100Ω	270Ω	10Ω	0.1uF	0.1uF
Wave tail time T2 (µs)	1000V	100Ω	10Ω	270Ω	0.1uF	0.1uF

From Figure 6, simulate the control system through a computer program to find the wave-front cutoff value according to the IEC 60060-1 standard of an impulse voltage of 1.2/50µs. The wave-front simulation results of the PSIM program yielded a value of 1.19µs, which slightly deviates from the standard value due to the error of the device but is within acceptable limits. It is shown that the parameters designed in the system can be used as a reference in the construction of an impulse voltage generator.

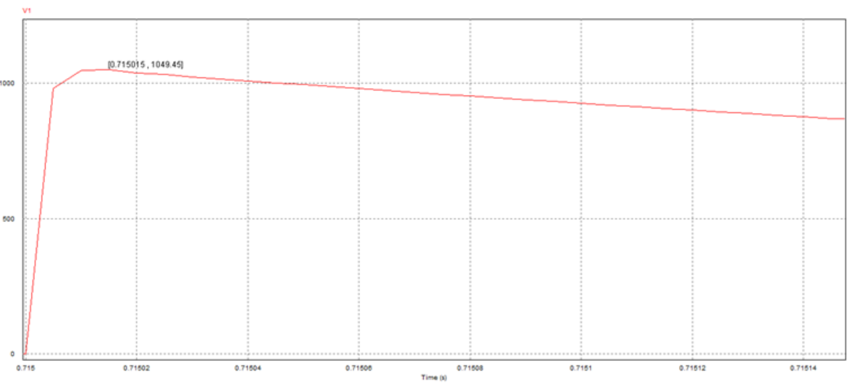


Figure 6 Results from impulse voltage testing through the PSIM program that cuts the wave-front

From Figure 7, it is a mathematical simulation to find the cut-off value according to IEC 60060-1 standard of an impulse voltage of 1.2/50µs. The wave-tail simulation results of the PSIM program yielded a value of 50.2µs, which slightly deviates from the standard value due to the error of the device but is within acceptable limits. It is shown that the parameters designed in the system can be used as a reference in the construction of an impulse voltage generator.

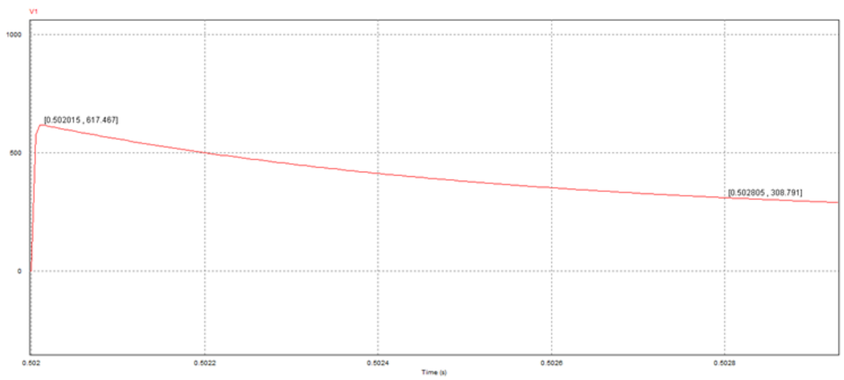


Figure 7. Results from the impulse voltage testing through the PSIM program that cuts the wave-tail

From the computer circuit test results, the values obtained from the measurement results with the program can be used to calculate the maximum voltage while the system is operating for use in comparison with the IEC standard values.

$$\Delta t = 0.7150\ \mu s$$

and

$$T_1 = \Delta t \text{ X } 1.67$$

$$T_1 = 1.19\ \mu s$$

Finding the value of T2 at a pressure value of 50% of the maximum pressure, therefore:

$$0.5U_o = \frac{617.467}{2}$$

$$= 308.7 \text{ V}$$

From the impulse voltage waveform graph (wave tail) in Figure 7:

$$T_2 = 50.2\ \mu s$$

5.3 Breakdown experiment on insulators

The insulators used in the test are hanging-type insulators. Breakdown experiment on insulators that will be used as output experiments with air as the intermediate load.

Figure 8 Flashover experiment of insulator

Flashing on the surface of the porcelain insulator when an electric current passes through the heat from the electric current will stimulate the electrical conductor strip. This enlargement creates a large conductor on the insulator, causing a voltage drop called Flasher or Flashover as shown in Figure 8.

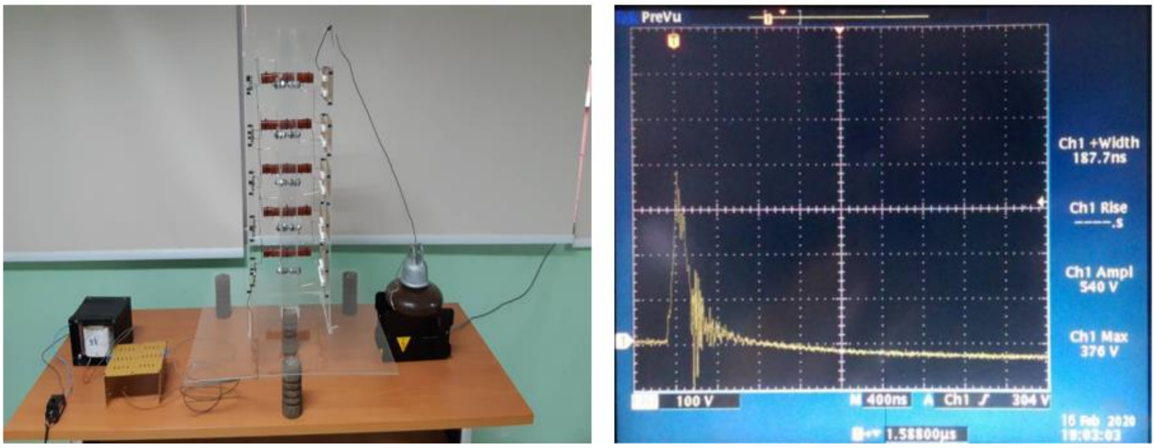


Figure 9 The overall image of the experiment with Flashover on the insulator and the display graph

The measured values from the operation of the system by experimenting with creating an impulse pressure on the surface of the insulator will have the measured values as follows:

Time value to start charging – discharging	187.7 ns
The time taken to peak was	80 ns
Amplitude value	54 V
Maximum voltage value	37.6 kV

From Figure 9, the waveform obtained from the wave-front from the charge to the discharge of the wave, it can be seen that the Peak value has a ripple of force up and down until it is 0. It shows that the results measured in the Oscilloscope test have more oscillations than in the actual test in the device that was calculated. Setting the parameters in the system will have a hidden inductance value, causing the image to be tested and measured before reaching a stable state. It is also within the values that can be used for testing with real working equipment. The values have been set as shown in Table 5.

Table 5 Experimental values

Type of insulator used for testing	**Suspended insulator**
Gap distance (cm)	0.3 Cm
Minimum charging pressure (kV)	20 kV
Maximum charging pressure (kV)	37.6 kV
Time T_1/T_2 (µs)	80/280.7 µs

6. Conclusion

This experiment uses hanging-type insulators as the load in the experiment, and when the machine is turned on, it can be concluded that the 22 kV multilayer impulse voltage generator can actually generate impulse voltage, but is still unable to make the undulation curve to the standard 1.2/50 µs. The obtained waveform has a charge-to-discharge wavefront with a time of 187.7 ns, a peak time of 80 ns, an amplitude of 54 V, a peak voltage of 37.6 kV, and a minimum voltage of 20. kV. It can be seen that the undulation graph when reaching the Peak value has a ripple of force up and down until it is 0. It shows that the results from the actual test using the Oscilloscope have more oscillations because the actual test is not the same as the test using the PSIM program because the parameters in the system have hidden inductance values. Therefore, the image that was tested and measured for noise before entering a stable state.

7. Acknowledgments

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