

COMPARISON OF INSULATION TESTING IN LABORATORY USING SOLID-STATE-BASED TESLA HIGH-FREQUENCY VOLTAGE GENERATION

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ABSTRACT. *Tesla transformers are parts or devices that generate a voltage from a high-frequency, damped oscillating wave that uses resonance to move energy from the primary to the secondary. The working principle of the Tesla transformer utilizes the principle of electromagnetic induction resonance from a series of capacitors and inductors that resonate at high frequencies. Tesla transformers can be used in insulation testing. Insulators play an essential role in the operation of the electrical system, so their performance needs to be considered. Testing the insulator using a Tesla transformer has the advantage that it is cheap and does not require a large area. Insulator testing is done by varying the distance, type of electrode and frequency of the test voltage. Testing the insulator is due to the distribution of the electric field at the electrodes, which will affect the breakdown voltage. The test results of the Tesla transformer have a better comparison value when compared to the test transformer. This test module is expected to help find out whether the Tesla transformer circuit based on solid-state components can be used as an alternative to high-voltage testing by comparing the test transformer test.*

Keywords: Frequency, High voltage generation, Insulator, Insulator testing, Solid-state, Tesla transformer, Test transformer

1. Introduction. High voltages have a good sine shape and a reasonably smooth high voltage boost setting. Mathematically, the peak voltage value should not vary more than $\pm 5\%$ of the practical stress value multiplied by 2 [1]. A Tesla transformer is an electrical instrument that can provide high potentials between a few hundred kilovolts and several megavolts. A damped oscillating wave with a typical frequency of 50 to 400 kHz results in the voltage. The damped high-frequency oscillations of Tesla transformers are similar to typical transient disturbances found in power systems (e.g., caused by switching operations or by arcing to ground). Several studies on Tesla's high voltage have been carried out. One concentrates on designing and constructing a modern Tesla transformer called a dual-resonant solid-state Tesla transformer with higher efficiency than conventional ones. Tesla transformer was first build for performance in electrical health tests for post-type suspensions and insulators. From the test results, the developed Tesla transformer can perform electrical health tests on suspensions and post-type insulators efficiently [2]. The high voltage generated from Tesla transformers is often applied to testing insulation and

materials, pulse generation high voltage, and is used for research on lightning discharges [3].

Several studies on the generation of high-voltage Tesla have been carried out. A Tesla coil based on a double-tuned resonant transformer was examined and created in a study published by the *International Journal of Advanced Research in Electrical Electronics and Instrumentation Engineering (IJAREEIE)* [4]. The results were obtained from component specifications used to generate high-voltage Tesla. In another reference, research is also found that discusses the analysis of a Tesla transformer based on Dual Resonant Solid State [5]. The researcher compares the Tesla transformer and the test transformer from the two papers. Another reference from the *International Symposium on Electrical Insulating Materials (ISEIM)* 2017 conference proceedings from Pongsathit et al. explains the implementation of a solid-state-based Tesla transformer in flashover testing of suspension isolators and post-type isolators [6]. The controller system for the Tesla transformer uses a simple control system that can change the input voltage source [7]. Another study from Plangklang et al. explained the output voltage waveform tested on the line post insulator [8]. The five papers show the use of the Tesla transformer as an alternative to insulator testing without using laboratory equipment.

Insulation is essential in electrical engineering operations, especially in high-voltage operations. The function of the insulator is essential to separate two or more high-voltage electrical conductors so that there is no electric jump. Insulators can perform their functions with good electrical, mechanical, thermal, and chemical properties [9]. Therefore, the insulators' performance in the operation of high-voltage systems needs to be considered. High-frequency high voltage is used in motor/generator testing. The breakdown voltage is the voltage when an insulator can no longer deal with the voltage stress between separate electrodes that have a potential difference [10].

2. Basic Theory. This section will describe the theoretical underpinnings of the construction of Tesla transformers and the insulation testing process using Tesla transformers and test transformers.

2.1. Definition of Tesla transformer. Tesla transformers are electrical devices capable of developing high potentials from a few hundred kilovolts to several megavolts. The resulting voltage is a damped oscillating wave with a typical frequency of 50 to 400 kHz. Resonance is used in Tesla transformers to move energy from the primary to the secondary. The input voltage on the primary is a low voltage at the working frequency, while the output voltage is a high voltage at a high frequency. High-frequency high-voltage is helpful for many purposes. Tesla transformers have a resonant air core and are used to produce high alternating voltages with low current and high frequency. The transformer increases the voltage by two principal steps: the first step-up the conventional iron core, and the second by increasing the voltage in the resonant air core to hundreds of kilovolts. The damped high-frequency oscillations of a Tesla transformer are similar to typical transient disturbances found in power systems (e.g., caused by switching operations or by the arc to ground) [11].

2.2. Definition of solid-state Tesla coil (SSTC). The resonance circuit of the solid-state Tesla coil is modeled as a driven RLC circuit. The characterized RLC circuit and three parameters must be identified. Inductance can be easily found by calculation or measurement, and capacitance can be determined from the resonant frequency. Resistance is a characteristic of the load, but it can undergo an impedance transformation if it is parallel to the capacitor, as is often the case. In practice, the system can be built without

knowing the exact value of these five resistances, and then it can be adjusted to provide the appropriate output power [12].

2.3. Definition of Tesla coil design. The classic Tesla coil contains two stages of voltage increase. The first is a conventional iron core transformer which increases the available line voltage to a voltage in the 12 to 50 kV, 60 Hz range. The second is a resonant air core transformer (the Tesla coil itself) with an up voltage of 200 kV to 1 MV. High voltage output at some frequencies higher than 60 Hz, perhaps 500 kHz for small units and 80 kHz (or less) for substantial units [13].

2.4. Definition of full bridge inverter. A full bridge inverter is a primary circuit for converting DC to AC. One type of full bridge inverter, the TC4422, is a single channel non-inverting gate driver with a peak output current of 10 A. 10 A is the limiting factor in how fast the IGBT gate capacitance can be charged and discharged. The propagation delay for the TC4422 is typically 42 ns when driving a 10,000 pF load. It can operate up to 20 V, which is ideal for powering a complete MOSFET switch with minimal resistance [14].

2.5. Definition of electrical breakdown. Electrical breakdown is a process that occurs when an insulating material that is unable to conduct electricity is given a high enough voltage, suddenly becoming an electrical conductor, and an electric current flows through it. All insulating materials will be damaged when the electric field caused by the applied voltage exceeds the dielectric strength of the insulating material. The breakdown is a local process, and in an insulating medium subjected to a high voltage difference starting at any point inside the insulator, the electric field first exceeds the local dielectric strength of the material. Damage usually starts at protruding points, sharp points and edges because the electric field at the conductor's surface is highest in homogeneous insulator parts such as air or oil adjacent to the conductor.

2.6. Definition of insulation materials and their failure mechanism. The insulator is a device that functions as insulation and mechanical holder of equipment or conductors subjected to a potential difference. If the insulator fails to use as a separator between the line or the line with grounding, the energy distribution will fail or be not optimal. The influence of the surrounding air and pollutants attached to the surface causes the surface of the insulator to be conductive. Several things need to be considered when determining an insulator to be made and how it works in an electric power system. Namely, the material's properties contain the essential ingredients to make the insulator ability in lousy weather, conditions when it is contaminated, and consideration of production costs.

The mechanism of failure of solid insulation can be caused by intrinsic failure due to the influence of temperature and type of material. Streamer failure in solid insulation is caused by an avalanche or cumulative movement of the ionization. Electromechanical failure in solid insulation is caused by the difference in polarity between the electrodes flanking the solid. Thermal failure in solid insulation is a failure that occurs if the speed of heat generation at a point in the material exceeds the rate of heat dissipation, and a hole or cavity causes erosion failure in the middle of the electrode or dielectric used [15].

The failure mechanism in the liquid insulation has the characteristics of the liquid insulation that will change if there is an impurity. The failure of liquid insulation will increase, and the failure process will occur quickly. Factors that affect insulation failure include the presence of solid particles, water vapor and gas bubbles [16].

The mechanism of gas failure is characterized by a failure process in the gas characterized by a sudden spark. This spark can occur because of the release that occurs in

the gas. The gas failure mechanism is called a spark, transitioning from non-sustainable discharges to various sustainable discharges up to breakdown voltage [17].

2.7. Definition of insulation test. Insulation testing refers to calculating the resistance between an electrical cable's conducting and non-conducting sections, usually in the Megaohm range or more significant. Over time, the insulation of conductors that are not properly maintained will degrade, exposing personnel and equipment to hazardous leakage currents. Depending on the magnitude of the flows involved, this can be life-threatening to factory employees or lead to severe downtime [18].

3. Method and Testing Equipment. In this journal, we show the components used in the manufacture of Tesla transformers, how the tests were carried out and the equipment and materials we used in our research.

3.1. Tesla transformer test circuit. The Tesla Coil High Generation is based on solid-state components with an output voltage of 150 kV with a ratio of 8 primary windings and 2320 secondary windings, and an output frequency of 22 kHz. In this research, experimental methods were used in the form of tool design, tool making and measurement of each component. In designing the tool, first, use calculations and simulations using PSIM and Proteus software to determine the working function of the tool system is correct. Then the design of the shape of the Tesla transformer will be carried out to determine the location of each component. The part for the semiconductor is mounted with an insulated-gate bipolar transistor (IGBT). A miniature circuit breaker (MCB) is installed for the safety of the equipment. Figure 1 shows the scheme of the Tesla transformer.

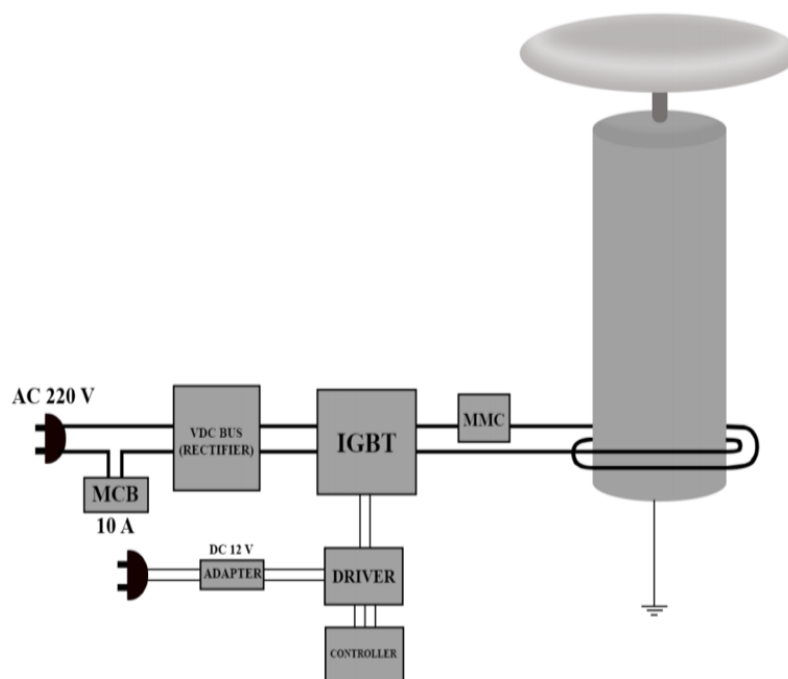


FIGURE 1. Tesla high generating work scheme based on solid-state components

The first component is the primary coil of this Tesla transformer using a flat-spiral winding type which is made by winding a copper wire (conductor) resembling a mosquito coil with up to 8 turns. The copper wire used is a pipe diameter of 8 mm. Based on the measurements that have been made, the inductance value of the primary coil is $23.8 \mu\text{H}$. Figure 2(a) shows the primary coil used in the Tesla coil.

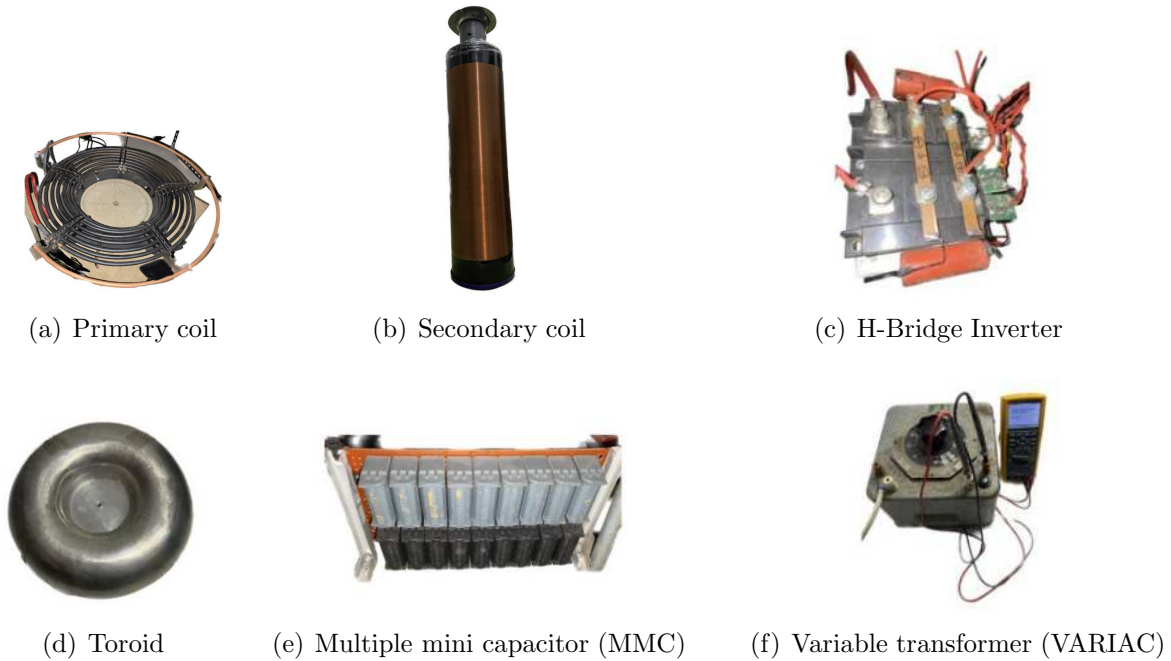


FIGURE 2. Component of Tesla transformer

The second component is the secondary coil of this Tesla transformer. In designing a Tesla transformer, it is necessary to know the capacitance on the secondary side of the transformer. Capacitance consists of load capacitance and stray capacitance. The secondary coil is the output that will be generated from the Tesla transformer [19]. The secondary coil of this Tesla transformer uses a 0.25 mm diameter wire wrapped around a 5-inch diameter PVC pipe. The wire is wrapped until it reaches a height of ± 58 cm. Figure 2(b) shows the secondary coil used in the Tesla transformer. Based on the measurements that have been made, the value of the secondary coil inductance is 93.47 mH. The secondary coil we employ has 2320 turns in total. To find the secondary coil value, use Equation (1) and Equation (2).

The third component is H-Bridge Inverter. A half-bridge inverter is a circuit that converts DC voltage into AC voltage. Tesla transformer was designed using 2 IGBT components and two electrolytic capacitors [20]. The output of the H-Bridge converter is connected to the primary coil. Figure 2(c) shows the IGBT module used.

The fourth component is the toroid. The toroid is the top load in the form of a capacitor for the secondary circuit. Each part of the toroid will form a capacitance. Toroid will form a frequency according to the resonance of the secondary coil [21]. The toroid used in this Tesla transformer is made of aluminum in the form of a ring without cavities. The dimensions of the toroid used are 45 cm \times 15 cm. Based on the measurements, the capacitance value of the toroid used is 42.3 pF. Figure 2(d) shows an image of the toroid used.

The fifth component is the multiple mini capacitor (MMC). The choice of capacitor affects both the primary resonant frequency and the maximum pulsed power available to the Tesla coil. The ideal option for multiple mini capacitor (MMC) is Polypro-foil capacitors, Piles, shielded by polyester wrap and epoxy end seals since they have modest dielectric losses and may be used continuously at high AC voltages [22]. Multiple mini capacitors act as primary capacitors connected in series with the primary coil of the Tesla transformer. Multiple mini capacitors are assembled using BM MKPH capacitors. Figure 2(e) shows an image of the MMC used.

The sixth component is the variable transformer (VARIAC). The variable transformer is one autotransformer whose tap point can be shifted. VARIAC in this test is used to adjust the input voltage of the Tesla transformer. The VARIAC output voltage can be measured using a multimeter. Figure 2(f) shows an image of the VARIAC used.

The last component is a solid-state Tesla transformers controller. The controller circuit uses IC NE555, which is used as a timer with monostable circuit operation and a pulse generator with stable circuit operation capable of delaying accurate time delays or oscillations. The circuit can be triggered and reset on the dropped waveform, and the output structure can be sourced or sunk up to 200 mA.

$$G = \frac{H}{N} \quad (1)$$

$$Ls = \frac{r^2 \cdot N^2}{2540(9r + 10h)} \quad (2)$$

3.2. Tesla transformer simulation using PSIM. The simulation of the Tesla coil system based on solid-state components is carried out using PSIM software. Assuming the IGBT input voltage is the same as the output voltage of the source, which is 220 V. Figure 3 shows a series of Tesla coil simulations based on solid-state. The output of the Tesla transformer secondary coil is shown in Figure 4. The output voltage of the Tesla transformer is 150 kV. Figure 4 shows the result of the output waveform of the Tesla transformer at no-load conditions.

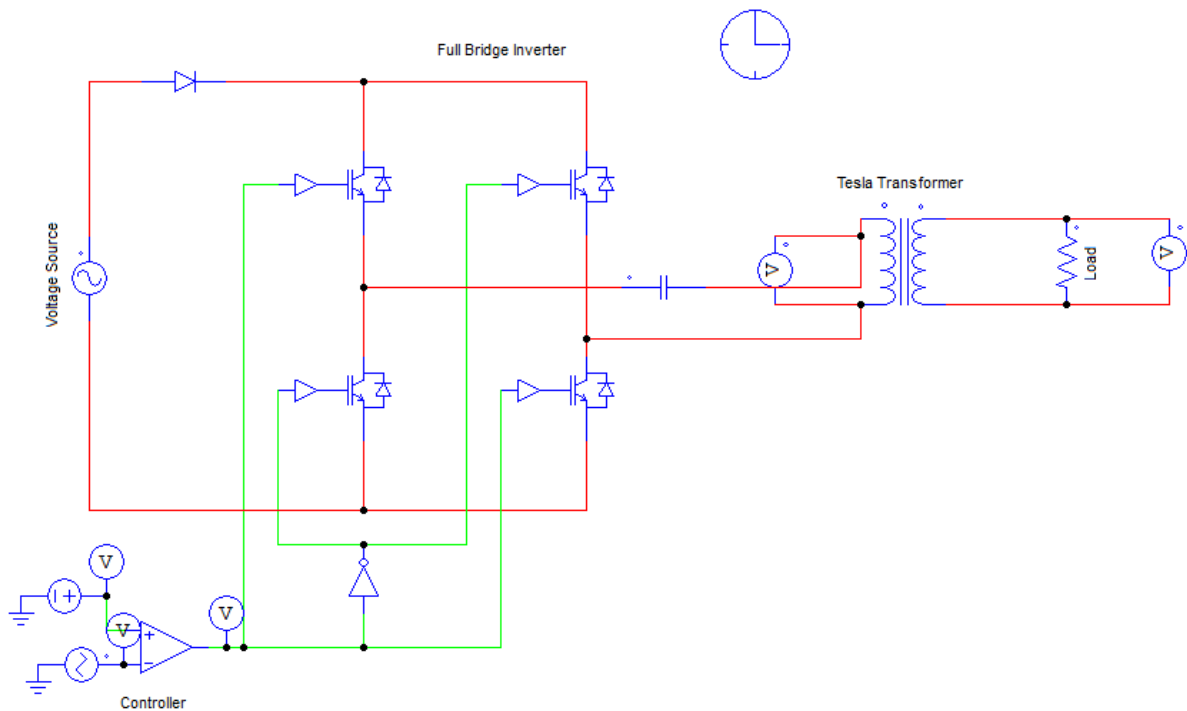


FIGURE 3. Solid-state Tesla coil circuit schematic on PSIM software

3.3. Testing equipment and materials. This section describes the testing equipment and materials used in this study. The testing equipment is an electrode. The electrode serves to drain the high voltage the Tesla transformer generates to the tested insulator. The electrodes are attached to the test medium and placed to flank the insulator under the test. Electrodes can be installed by rotating the replaced electrode and replacing it

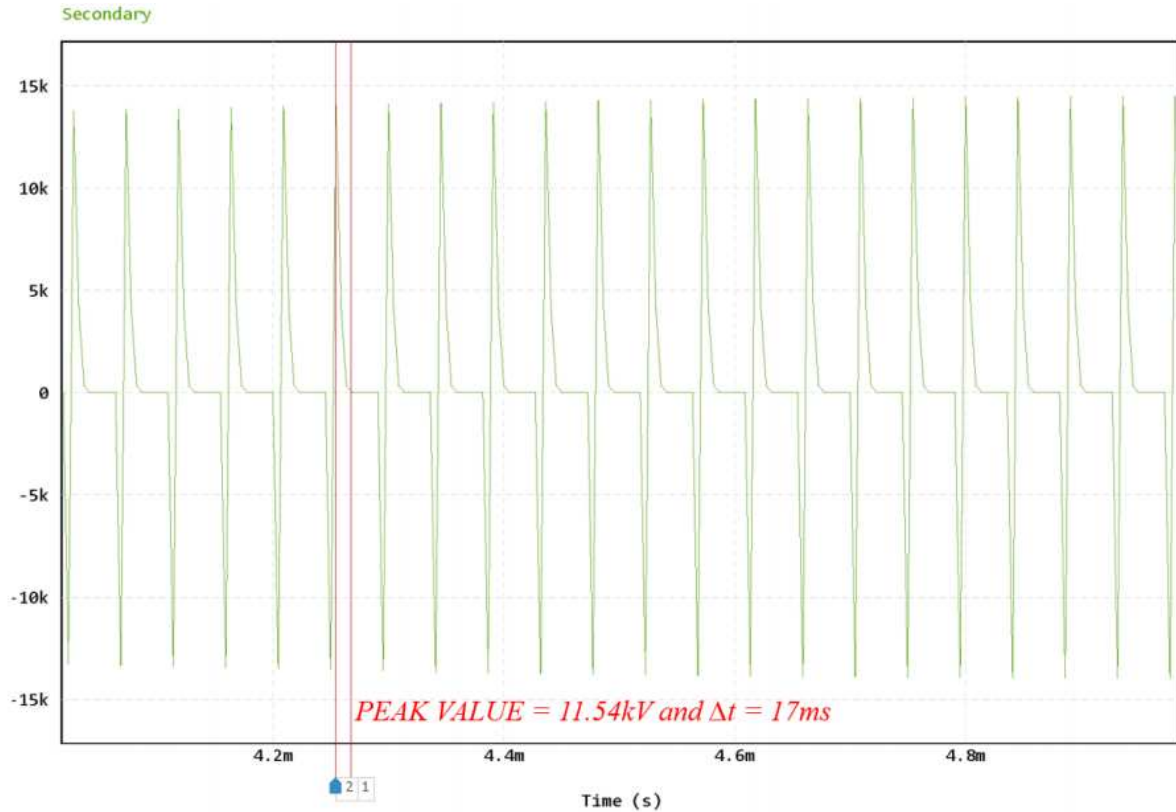


FIGURE 4. Secondary output wave from a Tesla transformer



(a) Pointed electrode

(b) Spherical electrode

(c) Flat electrode

FIGURE 5. Testing electrode

with the desired electrode. The electrodes used in this test are spherical, pointed and flat [23]. Figure 5 shows the type of electrode used in this research.

Next, we will discuss the test material in this research. The first material is a solid insulator. The solid insulator tested in this research is a ceramic insulator. The ceramic insulator used is a tile measuring 30 cm × 30 cm. This research uses ceramic insulation with a ceramic thickness of 0.7 cm. Ceramic insulator material is placed on the test medium at a distance of 0.7 cm and 1.4 cm.

The second material is gas insulator. The gas insulator tested in this research project is free to air. The test is carried out by providing a distance to the electrodes installed on the test medium. The electrode distances applied were 0.7 cm and 1.4 cm.

The last is liquid insulator. The liquid insulator tested in this research is transformer oil. The tested transformer oil is placed in a media chamber with dimensions of 15 cm × 15 cm. The volume of the tested transformer oil is ±120 ml.

3.4. Testing circuit of test transformer with AC high voltage source. The setup of the AC high-voltage generation circuit can be seen in Figure 6. The insulator test



FIGURE 6. Test setup using test transformers

TABLE 1. AC high voltage generating specifications

Equipment	Specification
Max output voltage	100 kV rms
Max output power	10 kVA
Control box	OT 276 and DM 1551
Parallel (wave tail) resistor (RE)	Max. DC and impulse voltage 140 kV, 2.4 k Ω
Measuring capacitor	Max. AC voltage 100 kV, capacitance 100 pF
Earth switch	—

using an AC high-voltage source was carried out to compare the test results using a Tesla transformer. The variation of the insulating material and the type of electrode used in this test is the same, using flat, mushroom and pointed electrodes. The electrode distance used in this test is 0.7 cm and 1.4 cm. Specifications of AC high voltage generation can be seen in Table 1.

4. Analysis of Results and Discussion. In this section, data from the results of tests that have been carried out in this research will be given.

4.1. Measurement of Tesla transformer based on solid-state components. This Tesla coil supply comes from a single-phase 220 V plan power source rectified using a diode bridge and will be input to the half-bridge inverter using the IGBT module. Figure 7 shows the Tesla transformer made in this research. The trigger of the IGBT module will be regulated using a Tesla coil driver, which is supplied with a 12 V DC voltage from the adapter. The control board can be used to set the interrupter for this driver. The control board controls the gain and frequency of the Tesla coil output. The IGBT module is connected to the primary capacitor and the primary winding. The primary winding will induce the secondary winding, which has been connected to the toroid. The end of this toroid will be connected using a high-voltage cable to conduct the resulting lightning to the insulator under test.

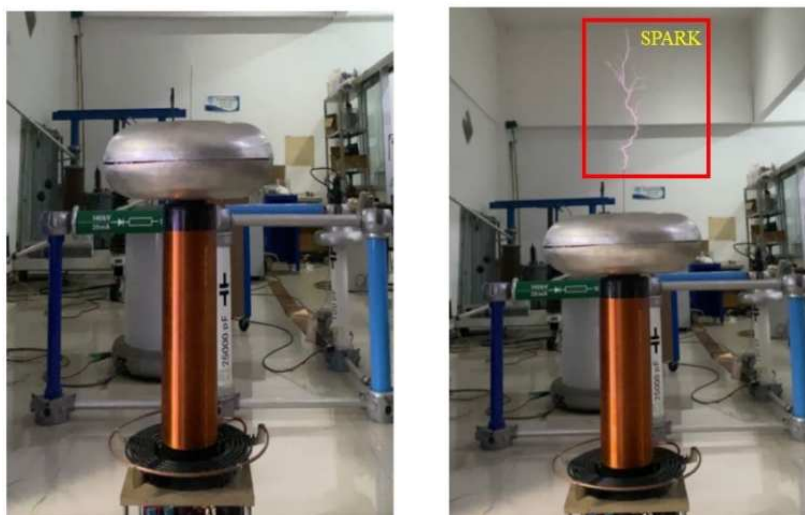
4.2. Spark output test. The spark output test aims to determine the assembled tool functions as planned. This test is carried out simultaneously with the source current test and is only done visually, namely, making sure the spark has come out of the breakout point, as shown in Figure 8.



FIGURE 7. Tesla transformers

TABLE 2. Tesla transformers specifications

Type	Value
Max output voltage	150 kV
Max output frequency	22 kHz
Comparison of winding transformer	8:2250
Maximum power	1760 kW



(a) Frequency 0%

(b) Frequency 50%

FIGURE 8. Spark output test

4.3. Comparison of gas insulator tests on Tesla transformers and AC high voltage generation. In this research, testing was carried out by comparing the electrode type and the electrode's distance. The comparisons shown in Tables 3 and 4 are the ratio of breakdown voltage to frequency. Table 3 and Table 4 show that the breakdown voltage

TABLE 3. Testing a Tesla transformer using a gas insulator

Electrode type	Electrode distance (cm)	Frequency (kHz)	% gain	Breakdown voltage (kV)	
				Experiment	Simulation
Flat electrode	0.7	4.4	19	2.1375	1.51
	0.7	8.8	19	2.1375	2.05
	0.7	13.2	18	2.025	2.46
	1.4	4.4	25	2.8125	1.52
	1.4	8.8	23	2.5875	1.89
	1.4	13.2	23	2.5875	2.44
Spherical electrode	0.7	4.4	18	2.025	1.54
	0.7	8.8	18	2.025	2.05
	0.7	13.2	17	1.9125	2.39
	1.4	4.4	20	2.25	1.52
	1.4	8.8	19	2.1375	2.05
	1.4	13.2	19	2.1375	2.46
Pointed electrode	0.7	4.4	15	1.6875	1.52
	0.7	8.8	15	1.6875	2.12
	0.7	13.2	15	1.6875	2.42
	1.4	4.4	18	2.025	1.54
	1.4	8.8	17	1.9125	2.06
	1.4	13.2	18	2.025	2.46

TABLE 4. Testing a test transformer using a gas insulator

Electrode type	Frequency (Hz)	Electrode distance (cm)	Breakdown voltage (kV)
Spherical electrode	50	0.7	12.96
		1.4	21.57
Pointed electrode	50	0.7	11.73
		1.4	18.91
Flat electrode	50	0.7	14.8
		1.4	23.69

sequence from the largest to the smallest is the flat electrode, spherical electrode and pointed electrode. The results of the breakdown voltage of the electrode are due to the influence of the surface area. The sharper the electrode surface used, the faster partial discharge will occur. Partial discharge can occur more quickly due to the buildup of an electric field, especially at the pointed electrode. Partial discharge occurs due to the uniform distribution of the electric field on the flat electrode, so a higher breakdown voltage is needed to test the insulator. From the table, it can be seen that there is a significant difference between the breakdown voltages produced from these two tests. This partial discharge can occur due to the significant frequency difference between the two tests. The frequency used in the test transformer is 50 Hz, which is very far from that of the Tesla transformer, which reaches 4.4 kHz.

4.4. Comparison of solid insulator tests on Tesla transformers and AC high voltage generation. The comparison of the breakdown voltage of the solid insulator to the type of electrode is carried out by comparing the data obtained from tests carried out at the same electrode distance. A comparison of breakdown voltage for this type

TABLE 5. Testing a Tesla transformer using a solid insulator

Electrode type	Electrode distance (cm)	Frequency (kHz)	% gain	Breakdown voltage (kV)	
				Experiment	Simulation
Flat electrode	0.7	4.4	25	2.8125	1.52
	0.7	8.8	24	2.7	2.17
	0.7	13.2	23	2.5875	2.44
	1.4	4.4	35	3.9375	1.52
	1.4	8.8	35	3.9375	2.15
	1.4	13.2	32	3.6	2.32
Spherical electrode	0.7	4.4	19	2.1375	1.51
	0.7	8.8	18	2.025	2.05
	0.7	13.2	16	1.8	2.39
	1.4	4.4	28	3.15	1.54
	1.4	8.8	27	3.0375	2.11
	1.4	13.2	27	3.0375	2.34
Pointed electrode	0.7	4.4	17	1.9125	1.14
	0.7	8.8	16	1.8	2.08
	0.7	13.2	16	1.8	2.39
	1.4	4.4	25	2.8125	1.52
	1.4	8.8	24	2.7	2.17
	1.4	13.2	23	2.5875	2.44

TABLE 6. Testing a test transformer using a solid insulator

Electrode type	Frequency (Hz)	Electrode distance (cm)	Breakdown voltage (kV)
Spherical electrode	50	0.7	15.33
		1.4	21.36
Pointed electrode	50	0.7	17.71
		1.4	25.10
Flat electrode	50	0.7	18.31
		1.4	26.99

of electrode is shown in Table 5 and Table 6. Based on Table 5 and Table 6, it can be analyzed the order of breakdown voltages from the largest to the smallest is flat electrodes, spherical electrodes and pointed electrodes. The results of the breakdown voltage of the electrode are due to the influence of the surface area. The sharper the electrode surface used, the faster partial discharge will occur. Partial discharge can occur more quickly due to the buildup of an electric field, especially at the pointed electrode. This partial discharge occurs due to the uniform electric field distribution on the flat electrode, so a higher breakdown voltage is needed to test the insulator. It is clear from Table 5 and Table 6 that the breakdown voltages generated by these two tests varied significantly from one another. This partial discharge can occur due to the significant frequency difference between the two tests. The frequency used in the test transformer is 50 Hz, which is very far from that of the Tesla transformer, which reaches 4.4 kHz.

In the solid insulator test and gas insulator, an input voltage of 20 V is used. The maximum output voltage of the Tesla transformer can be calculated by Equation (3). V_s is defined as the input voltage of the VARIAC, N_s is defined as the secondary coil and N_p is defined as the primary coil. The breakdown voltage data can be calculated by

knowing the percentage of the applied gain. The breakdown voltage can be calculated using Equation (4).

$$V_{\max} = \frac{2 \times V_s \times N_s}{N_p} \quad (3)$$

$$V_b = \%gain \times V_{\max} \quad (4)$$

4.5. Liquid insulator testing using a solid-state-based Tesla transformer. The liquid insulator test is carried out by providing the same input voltage of 20 V. When testing a liquid insulator using a spherical electrode, breakdown occurs not at the electrode but in the insulated part of the test electrode rod. The phenomenon of this breakdown event is presented in Figure 9. This phenomenon can occur due to an insulator (transformer oil) that can withstand the voltage applied to the insulator test so that the breakdown occurs at the top of the rod of the test medium, which has lower insulation resistance. The magnitude of the frequency, which reaches units of kHz, is one of the reasons why a spark can occur in the rod of the test medium, which will affect the capacitance value between the two rods of the test medium. This phenomenon is also influenced by the position of the electrode rods that are too close so that it can spur breakdown not occur in the isolated part of the test electrode.



FIGURE 9. Spark phenomenon on the test media

5. Conclusion. In this journal, we defined the research conducted. It can be concluded that the Tesla Coil High Voltage Generation based on solid-state components can function as previously planned, generating high voltages using solid-state components. A trend compares the breakdown voltage value of gas insulator and solid insulator testing using test transformers and Tesla generators with the three types of frequency variants. The average comparison values of the three frequencies from the smallest to the largest are 4.4 kHz, 8.8 kHz, and 13.2 kHz. In this research, a comparison between PSIM simulations was carried out on Tesla transformer and testing using a Tesla transformer. The research shows that the Tesla transformer simulation and experiment are better than testing using a test transformer. In the research, the frequency value of the Tesla transformer affects the breakdown voltage. A comparison of solid insulator tests also shows the same trend. The significant difference in the comparison value occurs due to the difference in the applied frequency. The greater the frequency applied, the greater the value of the comparison.

However, based on the comparison between the insulator test using a Tesla high-voltage generator and the test transformer, it can be seen that the trend is identical in the two

tests. The effect of increasing the electrode distance, and the type of electrode used, showed the same direction in both tests, both in gas and solid insulator tests. It can be concluded that testing using a Tesla high voltage generator can be an alternative in conducting insulator testing, where the average comparison value of test results using a Tesla generator and a test transformer is 1:8. For the future it will be compared with other insulation materials that are often used in high voltage equipment and testing such as insulating oil, air insulation, and some solid insulation.

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