DESIGN AND CONSTRUCTION HIGH VOLTAGE, HIGH FREQUENCY TRANSFORMER RATED 500 kV 250 kHz

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Abstract

This paper presents design and constructions high voltage, high frequency transformer or Tesla transformer. The Tesla transformer is design at 500 kV rating voltage and 250 kHz resonant frequency. By coupling air axle and have the air are the electric insulator between primary coil and secondary coil, Which primary coil test at 60 degree, Group part spark gap is will the Electrostatic gap. This paper propose and consider high voltage, high frequency transformer at 500 kV and 250 kHz rated. For use a transformer aforementioned is the equipment for test flash over phenomena of porcelain insulator and electric insulation

Key words: high frequency transformer, Tesla transformer, spark gap, insulator

1. Introduction

To create and Testing tesla transformer 120 kV 120 kHz for testing the suitable corner. The testing result that the suitable corner is 60 degree. According to the project, it is the idea and reason to create tesla transformer corner at 60 degree but have to change to 500 kV 250 kHz to make sure that the corner of 60 degree is the suitable for create testla transformer. This is using for testing flash of insulator. For the device of tesla transformer it has to improve to be high efficiency. Also the safety in using the result analysis by using the circuit model of testla transformer by using FEMLEB, MATLAB program and then create the tesla transformer.

2. Terms of Design

2.1 Voltage specified

Normally the high voltage and frequency tesla transformer will use for testing every insulators in the manufacturing for checking the base standard that any insulator is damage in Porcelain or not by doing flash on insulator to the standard setting. Maximum voltage transformer, high voltage high frequency it should has maximum voltage at 500 kVpeak because this size of voltage can test every type of insulator. But for this research has objective for electric insulator of Porcelain insulation which has spark gap on the surface 50 Hz at 200 kV or can be calculated around 280 kV. So that there are specific voltages at 500 kV for easily finding the other device to consist such as Neon transformer to be a source of power so that it is no need to using the high electric.

2.2 Frequency Specify

High frequency that makes the problem to the power distribution system it is around 80 kHz. Operation caused by a damped frequency during switching or arcing ground in the electric system. According to the study information there is flash on the surface in the frequency of 100 kHz – 250 kHz. There is not much difference so that ANSI C 29.1-1976 standard has specify the frequency of high power distribute. For testing porcelain insulator which is not less than 100 kHz, to choose the frequency of high voltage high frequency that has design, it should select the frequency at 250 kHz. The first concerning in design is the size of Capacitors in high voltage C_2 that how value it is. Cause of voltage force and frequency of output will be change when the size of Load C_2 has change. High voltage, high frequency of Transformer that has to design in this way, the objective is to test the porcelain insulator that has flash on the surface so it has specific the voltage and frequency as following. High voltage 500 kVrms frequency 250 kHz voltage input 0-15 kVrms

2.3 Frequency Specify

From the theory, there are find the frequency and voltage which has happen it is relate to the power capacity and induce of coil. The high power capacity of the high voltage, high frequency transformer circuit consist of the power capacity of insulator in the length of 10-15 pF Stray Capacitance of high voltage coil around 10 pF Sphere Gap is around 5-10 pF the power capacity of electric field stress around 5-20 pF. To calculate the summary of the power capacity it would has C_2 around 90 pF from voltage and frequency that specific. And the high voltage power capacity could calculate for finding dimension of component structure

. **3. Components Design**

3.1 High voltage coil design

If circuit in the turning condition, it would be L_1C_1 or L_2C_2 it would has induce of high voltage coil from equation

$$f_2 = \frac{1}{2\pi\sqrt{L_2C_2}}$$

From the equation, it would calculate the high voltage induce is

$$L_2 = \frac{1}{4\pi^2 f_2^{\,2} C_2}$$

To bind the high voltage coil, induce it can be mistake; to make sure that the frequency would be on specific, it should select the first frequency is 250 kHz. If binding coil and induce too much, the frequency will decrease. If binding coil and induce is less, it would not have the problem but it would have the high frequency. And when instant f_2 at 250 kHz and the load summary of C_2 equal to 90 pF, it will get

$$L_2 = \frac{1}{4\pi^2 \times (250\text{kHz})^2 \times (90\text{pF})}$$

$$\cong 4.5 \text{ mH}$$

High voltage and high frequency which has created has an air axis so it should have insulation. This research will use the PVC tube for binding the coil in the high voltage because insulation has the qualification of insulator, it's not absorb humidity, Mechanical strength, fit, not expensive and can produce in the country. To select the tube, it should choose the suitable size which the diameter will be specify the height of binding coil because it would help in the dimension of a good coupling as the table 1.

Table 1. Showing the tube size and suitable height in binding high voltage coil

Size Tube diameter (inch)	height / diameter	Length to bind the coil (inch)
3	6.0:1	18.0
4	5.0:1	20.0
5	4.5:1	22.5
6	4.0:1	24.0
7	3.5:1	24.5
More than 8	3.0:1	24.0

Induce of high voltage L2 is one thing for design the high voltage coil by finding the size of coil which would binding high voltage coil. This is specifying by the density of current by calculate from the short circuit current of high voltage, high frequency transformer. When using for the testing of flash on the insulator surface which is seem high voltage circuit. So the current flow in the high voltage coil will limit by impedance of coil, it could calculate the current circuit as follow:

$$I_{SC} = \frac{Vrms}{Z} = \frac{Vrms}{2\pi f_2 L_2}$$

$$\frac{500\times10^3}{2\pi\times250\times10^3\times4.5\times10^{-3}}$$

$$= 70.73 \text{ A.}$$

But cause short circuit current which is pulse which is not continuous in the frequency of voltage that input to the transformer (50Hz). Pulse which happens will wide around half period of frequency 250 kHz (4.00 μs). After half period, current that flow through high voltage would equal to zero until there are created high voltage again. If pulse is happen every time that increase of voltage input until frequency of pulse 100 Hz (10ms). Current effectiveness that flow through the high voltage coil would calculate as following:

$$I_{eff} = I_{sc} \times \sqrt{\frac{\text{ช่วงเวลาที่มีกระแส1คาบ}}{\text{ช่วงเวลา1คาบ}}}$$

$$= 70.73 \times \sqrt{\frac{4\,\mu S}{10mS}}$$

$$= 1.4146\ A$$

The current density that flow through coil that up to the current effectiveness, increase temperature and acceptable. In generally, copper will equal to 2.5 A/mm^2 cross section of copper will find from

$$A_{eff} = \frac{I_{eff}}{J}$$

When J = Current density, A/mm^2
I_{eff} = Current effectiveness, A
A_{eff} = cross section , mm^2

$$A_{eff} = \frac{1.4146A}{2.5 \, A/_{mm^2}}$$

$$= 0.56584\ mm^2$$

When calculate the skin effect that has the depth of skin effect which could calculate from

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}}$$

When δ = Depth of skin effect
σ = Conductivity ,mho/cm
f = Frequency ,Hz
μ = Permeability

In case of copper $\sigma = 5.8 \times 10^9$ mho/cm

$$\delta_{CU} = \frac{6.62}{\sqrt{f}} \text{ cm}$$

And needed frequency is 250 kHz it would be

$$\delta_{CU} = \frac{6.62}{\sqrt{250 \times 10^3}}$$

$$= 0.01324 \text{ cm}$$

If using the round wire to bind the high voltage. Current will flow through only the radius surface r_1 as showing on figure 1. To calculate the radius r_1 as follow:

$$\left(\pi r_1^{\,2} - \pi r_2^{\,2}\right) = A_{eff}$$

$$\left(\pi r_1^{\,2} - \pi\left(r_1 - \delta\right)^2\right) = 5.6584 \times 10^{-3}$$

$$r_1 = \frac{5.6584 \times 10^{-3}}{2\pi \times 0.01324} + \frac{0.01324}{2}$$

$$= 0.0746 \text{ cm.}$$

From radius 1 to calculate for 50 % safety

$$r_1 = 0.0746 + (0.0746 \times 0.5)$$

$$= 0.1119 \text{cm}$$

It could be find the diameter of coil (d) as follow:

$$d_1 = 2 \times r_1 = 2 \times (0.1119) = 0.2238 \text{ cm}$$

According from the information copper wire that produce and distribute has the similar size and can use for binding high voltage coil. It would induce similarly at the size of mediator 2.33 mm or 13 SWG. The qualification of copper coil number 13 SWG, it has resistant 0.424 Ω/100m at temperature 25 °C.

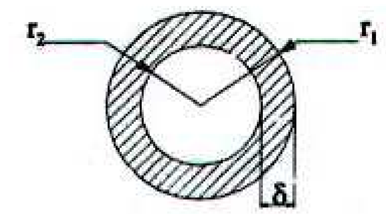


Figure 1. Show the area that current flow because of conductivity of copper coil.

To bind high voltage, it will binding as table 1 which is using the tube diameter 6 inch. So when compare it would have the height at 24 inch. It would bind coil without insulation between rounds which would calculate for finding the length of coil from the equation.

$$L = \frac{(NR)^2}{9R + 10H}$$

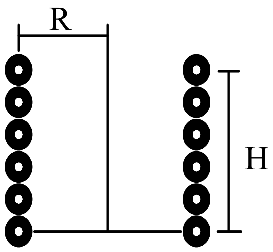


Figure 2. Show the dimension in binding high voltage

When L = Induce , μH
R = Radius of axis to center of coil, inch.
N = round binding
H = height of binding, inch.

To calculate for finding the round binding of high voltage this is from equation

$$N = \sqrt{\frac{L(9R + 10H)}{R^2}}$$

$$= \sqrt{\frac{4.5 \times 10^{-3}((9 \times 3) + (10 \times 24))}{3^2}}$$

$$= \quad 365 \text{ รอบ}$$

When it is create, it could calculate induce of the secondary coil (Ls) it has 4.1 mH. This would less than the model that has design before but it would not any disadvantage but it could be advantage because it will make more frequency in high voltage and it will have stor electric capacity that can find from the equation

$$C_S = 0.29H + 0.41R + 1.94\sqrt{\frac{R^3}{H}}$$

When C_S = Electric capacity , pF
R = Radius of axis to center of coil, inch
H = Height of round binding, inch

Substitute

$$C_S = (0.29 \times 24) + (0.41 \times 3) + 1.94\sqrt{\frac{3^3}{24}}$$
$$= 10.24 \text{ pF}$$

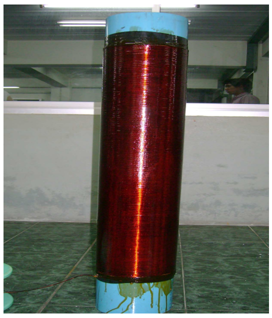


Figure 3. High voltage binding with 6 inch. PVC tube

3.2 To select transformer that distribute low voltage

To select transformer that distribute low voltage is important because it would specify the capacity of low voltage capacitor. This project has select transformer that using for Neon sign transformer, there are specific as follow:

Primary : 230 V 2.0 A
Secondary : 15 kV30 mA;450VA 50Hz

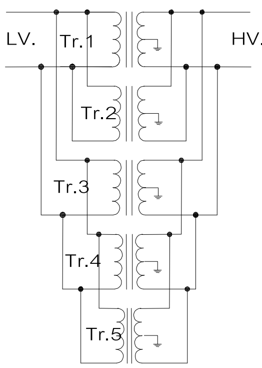


Figure 4. Circuit of 5 transformers parallel

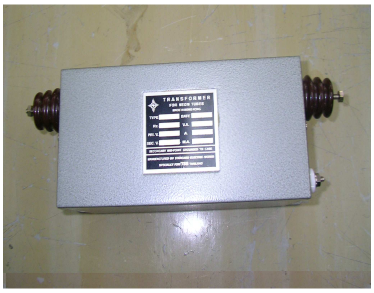


Figure 5. Transformer that distribute low voltage

By using 5 transformers to parallel this would get more the current of the secondary coil. The reason that is why has to bring the transformer to parallel, there would tell in the next topic. After that find impedance of transformer in the secondary coil.

$$Z = \frac{Vrms}{Isc}$$

$$= \frac{15000\ Vrms}{150\ mA} = 100k\Omega$$

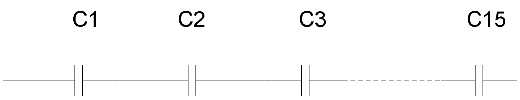
3.3 Design of capacitor of low voltage

To design the capacitor of low voltage, it could find by taking impedance of transformer that has calculated to find the maximum capacity of the capacitor is

$$C_{1max} = \frac{1}{2\pi fZ}$$

$$= \frac{1}{2\pi\times 50\times 100000} = 31.83\ \ nF$$

$$Cn = 22.5\ \ kVp$$



$$Cn = 22.5\ \ kVp$$

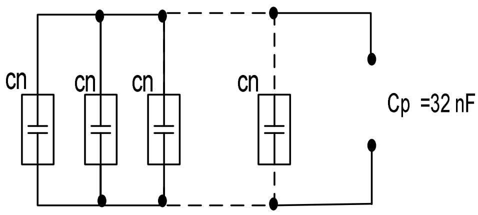


Figure 6. Internal circuit of capacitor of low voltage

For this project, there are select to use the capacity of Polypropylene, capacity 15 nF +/- 5% 1500 V. By taking 15 serials to connecting and take the resistance size 10 MΩ to connecting the serial.Using 32 capacity to endurable the voltage around 22.5 kVpeak, it would get capacity at 32 nF which can be real measure at 31.8 nF according to figure 3.6 from the topic number 3.3. The reason that brings 5 transformers to parallel is for getting the capacitor of low voltage to increase so that it could be distribute the voltage and frequency will according the condition that has design. It would help to get the correctly frequency and distribute the voltage in the condition.

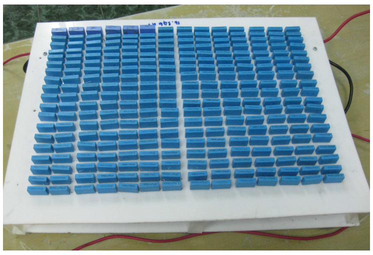


Figure 7.Capacitor of the low voltage

3.4 Design of a low voltage coil

To create the low voltage coil, it will bring copper tube size 3/8 inch that the copper is thick 0.03 inch. Binding in whorl style, lift up the angle to the ground in 60 degree, length between the first low voltage coils and high voltage coil is 4 inch. DI is equal to 14 inch, W equal to 0.5 inch, S equal to 1 inch and binding 10 rounds. Induce could be found from the equation.

$$L = \frac{(NA)^2}{30A - 11DI}$$

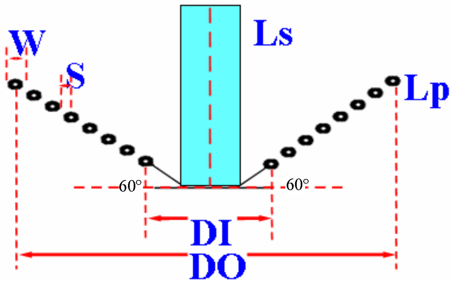


Figure 8.Dimension of binding the low voltage

$$A = \frac{DI + N(W+S)}{2}$$

When

$$A = \frac{14 + 10(0.375 + 1)}{2} = 7.375$$

Substitute

$$L_p = \frac{(10 \times 7.375)^2}{(30 \times 7.375) - (11 \times 14)}$$
$$= 80.8782 \quad \mu F$$

Figure 9. Showing binding low voltage

To select the size of copper tube, we need to concern about the thickness that can be used or not by finding the thickness (δ) in inch.

$$\delta_{CU} = \frac{2.602}{\sqrt{f}}$$

Frequency substitute at 250 kHz it will get

$$\delta_{CU} = \frac{2.602}{\sqrt{250 \times 10^3}}$$
$$= 0.005204 \quad \text{นิ้ว}$$

When comparing with the thickness of copper tube that binding 0.028 inches. It would see that the calculated is less than. It is shows that copper tube can use for binding.

3.5 Design of Spark Gap

Design of Spark Gap, it will use spark gap according the theory of Richard that called this spark gap “Richard Quick Spark Gap”. By using the copper tube to connect with 11 serials. The number of gap, it would up to the size of distributor of low voltage which can be seen from table 1. This project will use copper tube size ¾ inches, length 3.5 inch and each gap will distance 0.75 mm. All the gaps, there are totally 10 gaps by calculate the electric field stress approximately between electros that will have arc around 20 kV/cm. The gap could be finding.

$$\text{Gap} = 10\text{g} = \frac{15kV}{20kV/cm}$$
$$10\text{g} = 0.75 \text{ cm}$$
$$\text{g} = \frac{0.75cm}{10}$$
$$\text{g} = 0.075 \text{ cm}$$

Gap can be adjust to narrow than this but it should not too far from the calculation because of the file stress of electric will not enough to breakdown the process which would make gap not function.

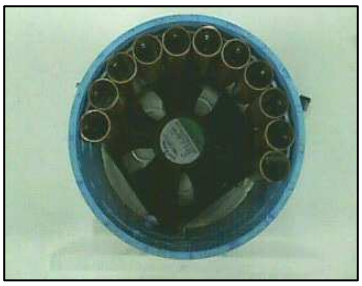


Figure 10. Spark Gap Components

In each arc of gap, it would more heat so it is necessary to cooling by installing ventilator that would transferring ion heat that occur from arc. This would make arc to switch off faster.

Figure 11. Ventilators for spark gap

3.6 Circle to protect the power distributor of transformer

When connect the transformer for transformer to breakdown though the air. Sometimes it would be some part of voltage try to breakdown into low voltage. The coil that connect to the power distribute transformer, if there are high voltage get into the transformer. It would effect to the transformer to damage. So it has to use the circle to protect the low voltage that will make high voltage breakdown into the circle which has been connected with the ground. The current and voltage will not damage to the transformer by using the copper tube size ¼ inches to hold over the low voltage coil at the last round position as figure 12.

Figure 12. Circle of Protection Installation

3.7 safety gap

Safety gap benefit is to protect the damage that would occur to the transformer which is cause from too much voltage that from the breakdown into the low voltage coil feed back to the transformer. When it is too much voltage in each pole, the gap will breakdown and ventilates the current into the ground as the figure 13.

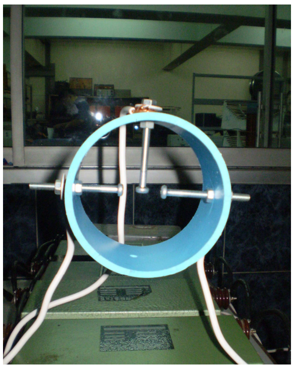


Figure 13. safety gap

3.8 Toroid

When need to use the high voltage transformer and high frequency to show the thunderbolt. We have to use toroid connect to high voltage for tuning. Because toroid is seem like the capacitor which can find the capacity from the equation 2.3 and all details with the qualification in the topic 2.4.4. This project will use the toroid which is capacity size of 20 pF. By create from stainless diameter size 3 inches as figure 14.

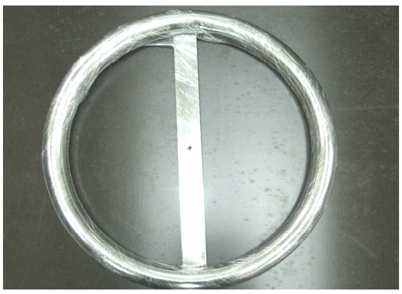


Figure 14. Showing Feature of Toroid

3.9 Framework

When there are finish design and create the components, it would combine together on framework. That it would be 2 base layers. First layer, it will consist of low voltage capacitor. Second layer is consist of low voltage coil, high voltage coil and circle protection of power distribution transformer. By install the wheeled vehicle for the convenient to move.

Figure 15. Framework

4. Test and evaluation

4.1 Duplication of electric field distribution of high frequency high voltage transformer with the FEMLAB program.To duplication of electric field distribution of high frequency high voltage transformer with the finite element by using FEMLAB program. By specific the electric voltage at the low voltage coil which has electric voltage at 15 kV and high voltage coil which has electric voltage at 500 kV and permeability (ε_r) of PVC tube equal to 3.5. To duplicate of electric filed compare with the angle at the low voltage coil and high voltage coil at 60 degree, the result of duplication of electric show as the following figure.

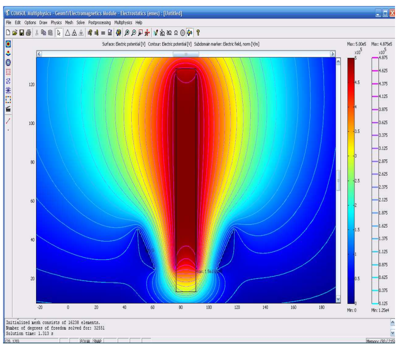


Figure 16. The result of duplication of electric field at the60 degree angle of low voltage coil from the ground which has a maximum electric filed equal to 231.795 kv/cm. at high voltage coil.

4.2 The calculation to find the electric field between low voltage coil (Lp) and high voltage coil (Ls)

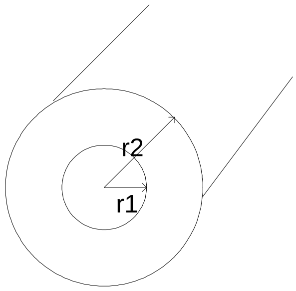


Figure 17. Double Coaxial Cylinder

That r_1 is radius of coil (Ls)

r_2 is radius of coil (Lp)

U voltage

Equation $$E_{max} = \frac{U}{r_1 \ln(r_2/r_1)}$$

angle 60 degree (Lp coil no.5)

r_1 = 7.73 cm

r_2 = 24.73 cm

U = 500 kV, so that

$$E_{max} = \frac{500 \times 10^3}{7.73 lh\left(\frac{24.73}{7.73}\right)}$$

= 55.621 kV/cm.

4.3 The Measurement of frequency of high frequency, high voltage transformer.

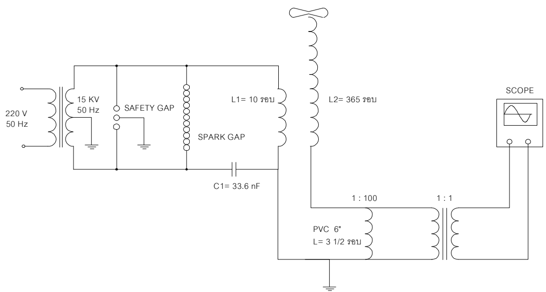


Figure 18. Circuits that used to test the high voltage and high frequency transformers

To measure the waveform of output of high voltage transformer and high frequency by connecting as figure 18. It use the Isolation Transformer to be the waveform frequency measurement together with Oscilloscope. When loading the insulator, the low voltage capacitor C1 = 31.83 nF and amount of low voltage coil equal to 5 rounds. From Oscillogram, it could find the frequency as figure 19 and then compare to the calculation result from the related equation.

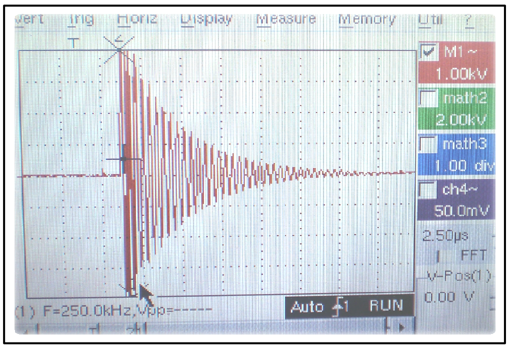


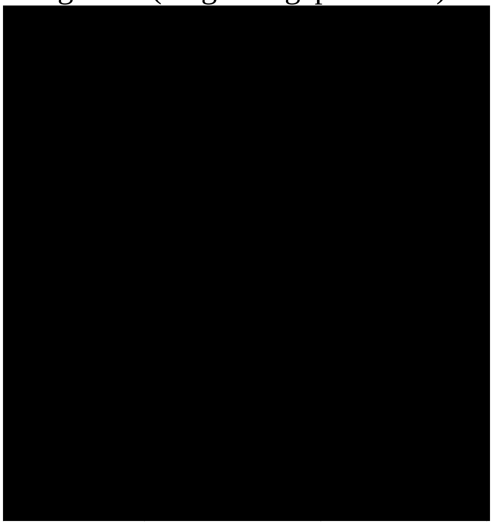
Figure19.Circuit measurement of waveform Oscillogram, delay Oscillation of high voltage output of high voltage and high frequency of transformer 250 kHz.

Waveforms that get from the measure of Oscillogram as figure 19, it has frequency at 250 kHz which is equal frequency with the design. That means electric capacitor of loading high voltage is equal to the design which is 90 pF. And this waveform, it will be perfect waveform sign.

4.4 The Result of voltage output distribution

This testing has the objective to study about the result of position that has suitable tune point. To get the maximum voltage output and the length of spark gap that effect to the output voltage of high voltage, high frequency transformer.

Table 2. Output voltage of high voltage, high frequency transformer, when it is change in the round of low voltage coil (length of gap 0.4 mm)



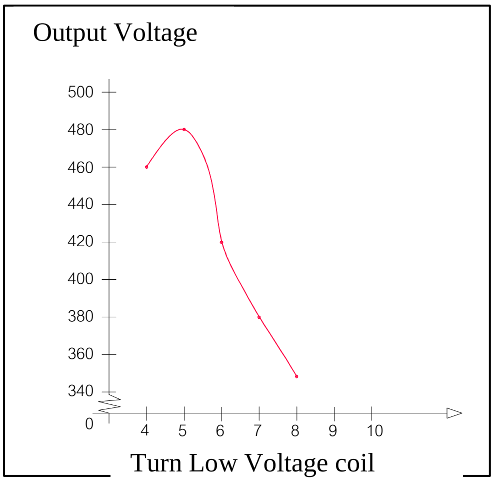


Figure 20. Graph show the relationship between the output voltage and number of low voltage coil

Table 3. The Output Voltage with number of difference gap (low voltage coil at the round 5).

Gap (round)	Input Voltage (V)	Output Voltage (kV)
6	220	360
7	220	375
8	220	400
9	220	420
10	220	480

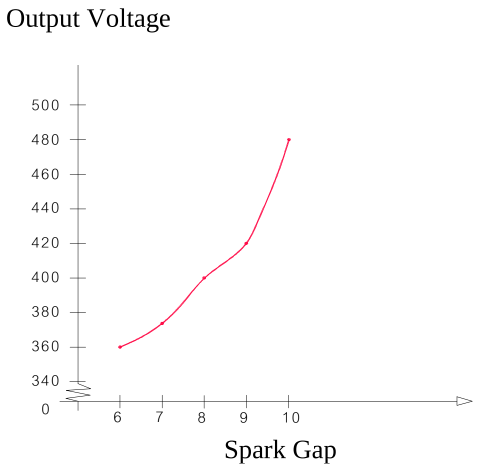


Figure 21. Graph show the relationship between the input voltage and number of gap(low voltage coil at the round 5).

4.5 Result of Insulator Testing

To bring high voltage, high frequency transformer that has created for testing the good insulator, it would flash on the surface of insulator as figure 22.

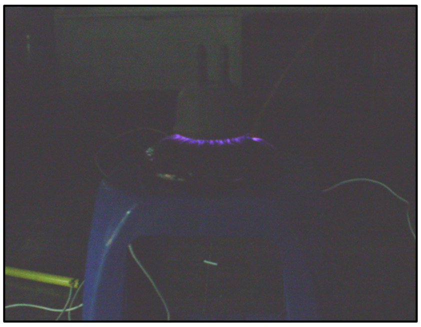


Figure 22. Test the flash on the surface of good insulator.

5. Testing Result

Result from the measure of high voltage output distribution; it can give the high voltage at 480 kV_{rms} by input low voltage around 15 kV and frequency at 250 kHz which is higher than calculation. Output high voltage is specific with the input high voltage. It would get the maximum specific load at the tune position. This is according to the condition $L_1C_1 = L_2C_2$. Induce of high voltage coil will constant, when load C_2. It has to change L_1C_1 according to Resonance equation. The suitable way is change the low induce by tap the round of low voltage coil again. From the testing result, output voltage will increase or decrease, it is up to the following factors.

- Binding the low voltage coil, if increase the binding of low voltage coil. The output will increase to the maximum point that will suitable tune. And it will reduce, if adjust the binding coil increasing.
- The length of gap, output voltage will increase according to length of gap. But the length of gap should not far from the maximum design. Because there are the voltage turn back to the distribution source of low voltage.
- The amount of Electrode pole of spark gap, output voltage will reduce if electrode has few amounts than design.

6. References

[1]Somruay Sangsa-ard, HighVoltage Engineering.Edition2 Chulalongkorn University, 2528

[2] IEC Publication No.60-2 “High Voltage test techniqued Part 2: Measuring Systems.”,1994

[3] IEC Publication No.156 “Method for the determination of the electric strength of insulating Oil.”., 1994

[4] Supawud Nedphograw, High Voltage Engineering. Edition1-2 Rajamangala University of Technology Phra Nakhon (RMUTP.),2550-2551

[5] ANSI C 29.1-1976 (Test methods for electrical power insulators)

7. Biographies (Optional)

Supawud Nedphograw received his B.Eng. and M.Eng.degrees in Electrical Engineering from RMUT-T,King Mongkut’s Institute of Technology Ladkrabang (KMITL.) In November 2006 he worked as lecturer and Head ,Department of Electrical Power Engineering in RMUT-P Bangkok Thailand