CHAPTER I

GENERAL THEORIES

1-1 Introduction

Tesla Transformer is very cheap, has a simple lay-out in construction and the service reliability is so very good over many years. It has low voltage side on the primary circuit and the high voltage side on the secondary circuit. Both primary and secondary coils are called Tesla coil and have a very low mutual inductance i.e. M is much less than unity. It is an air-core transformer and has the same natural frequency on both sides. The energy changes from one circuit to the other circuit with the beat frequency.

This Chapter presents the general theories that will be used for the foundation of the design and construction of the Tesla Transformer. Chapter II presents step by step in design, lay-out, construction and design data. The experiments and characteristic curves of the Tesla Transformer will be found in Chapter III.

1-2 Definition Terms[1]

For further clear understanding the following definition of terms relating to this thesis should be included.

Coefficient of Coupling (K) is the ratio of the mutual inductance actually present to the maximum possible value that can occur and is written as

$$K = \frac{M}{\sqrt{L_1 L_2}}$$

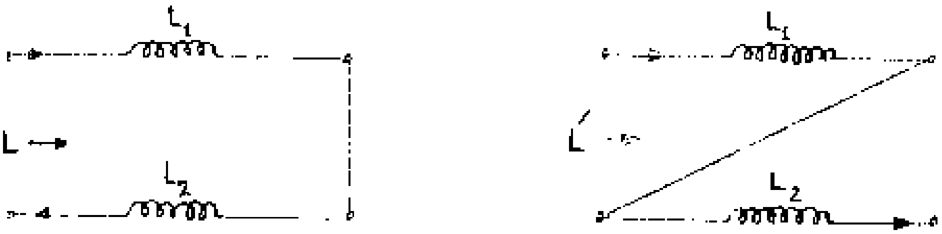
The maximum value of mutual inductance that can exist between two coils of inductance L_1 and L_2 is $\sqrt{L_1 L_2}$ which occurs when all the flux of one coil links with all the turns of the other. In this case it is said to be coupled perfectly and $K = 1$. If only half of the lines set up in the first circuit link the turns of the second circuit, the coupling is only 50 percent. For an air-core transformer, the closely coupled coils have a value of K of 0.5 or greater, and 0.01 or less are said to be loosely coupled.

Mutual inductance (M). When two windings are placed so that a change of current in one will cause its changing magnetic field to cut the turns of the other, an induced emf will be set up in the second coil. These two circuits are then said to possess "Mutual inductance".

The fairly close approximation for mutual inductance can be calculated from Appendix B (3)

For measurement, M can be measured by arranging the circuits as shown in Fig.1-1.

For circuit (a) $L = L_1 + L_2 + 2M$ and for circuit



(a) (b)

Fig. 1-1 Method of measuring Mutual inductance.

(b) $L' = L_1 + L_2 - 2M$.

By subtraction, $L - L' = 4M$ or $M = \frac{L - L'}{4}$ where L and L' are the measured self-inductance.

Resistivity (ρ). The resistivity of a material is the reciprocal of its conductivity. For copper at 20°C., $\rho = 1.724 \times 10^{-6}$ ohm - cm.

Temperature coefficient (α_{20}) gives the ratio of the change in resistivity due to a change in temperature of one degree centigrade relative to resistivity at 20°C. For copper $\alpha_{20} = 0.00393$ ohm/°C.

Conductivity (λ). The conductivity of a material is the direct current conductance between the opposite, parallel faces of a portion of the material having unit length and unit cross section.

Absolute permeability (μ). The ratio of the magnetic flux density in a medium or material to the magnetising force. Absolute permeability can be expressed as $\mu =$

$\mu_0 \mu_r$. For free space $\mu = 1$.

Relative permeability (μ_r). The ratio of the magnetic flux density in a medium or material to that produced in free space by the same magnetising force. For copper and other non-magnetic materials $\mu_r = 1$.

Conduction. Conduction is the name given to the movement of electrons, or ions, or both, giving rise to the phenomena termed by "electric current".

Dissipation factor (D) is the ratio of the energy dissipated to the energy stored in the dielectric per cycle or is the tangent of the loss angle. It is expressed as $D = \tan \delta$

Dielectric constant (ε). The dielectric constant or permittivity of an insulating material is the ratio of the capacitance of an electrode system using the material as a dielectric to its capacitance with a vacuum dielectric. It is defined as $\varepsilon = \varepsilon_0 \varepsilon_r$.

Phase difference or Loss angle (δ) is the difference between the theoretical 90 electrical degrees phase advance of the current through a perfect capacitor and the actual angle of phase advance, θ of the current through the dielectric material.

Loss Factor is the product of the dielectric constant and the dissipation. It is defined $\varepsilon \tan \delta$

Power loss is the loss in the dielectric depending on the material, the applied frequency, and the temperature.

Conductor. A body or substance which offers a low resistance to the passage of an electric current.

Insulating Material. Material which offers relatively high resistance to the passage of an electric current.

Insulation Resistance (Insulance). The resistance under prescribed conditions between two conductors or systems of conductors normally separated by an insulating material.

Impulse Voltage is an unidirectional voltage which, without appreciable oscillations, rises rapidly to a maximum value and falls more or less rapidly to zero.

50 percent breakdown voltage is the breakdown voltage between two sphere-gaps occurring 5 times in 10 discharging of capacitor.

1-3 Theory of a Tesla Transformer

There are two kinds of high-frequency, high voltage tests carried out which are as follow :-

a) Tests with apparatus which produces undamped high frequency oscillations.

b) Tests with apparatus producing damped high frequency oscillations.

In case (a) it can not expect to be occurred in the power systems, but they are very useful for insulation testing purposes, especially for insulation to be used in communication or radio work.

In case (b) they are obtained by the use of a Tesla coil together with a circuit containing a quenched spark-gap.

The author's work is dealt with the case (b) which is a damped high frequency oscillations.

1-3a Tesla coil. The circuit of a Tesla coil consists of two air-core coils placed concentrically as shown in Fig.1-2[5]. The high voltage secondary coil has a large

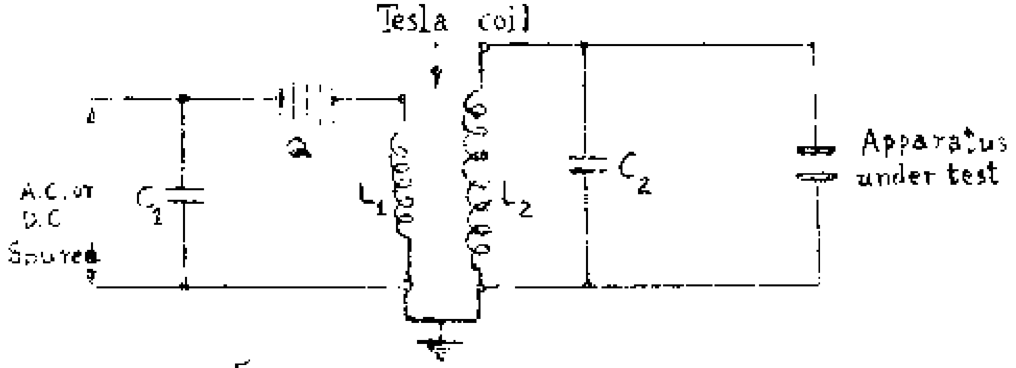


Fig.1-2[5] Circuit for connection of Tesla Transformer.

number of turns, wound on a frame of insulating material (porcelain core). The insulation between turns is Araldite. The primary winding has only a few turns, wound on an insulating frame made of wood. The supplyis a.c. or d.c. source. C_1 and C_2 are two capacitors connected in the primary and secondary circuits respectively, of the Tesla Transformer. C_1 is an oil or air capacitor. C_2 is usually made up of the internal (stray) capacitance of the secondary winding of the Tesla coil, a sphere-gaps for voltage measurement purposes, and the capacitance of the apparatus under test. The capacitance of the apparatus under test is usually small in comparison with the other two. Q is the quenched air gap which sparks over when C_1 charged from an a.c. or d.c. source reaches a given potential, which depends upon the setting of the quenched air gap. When C_1 reaches this voltage the quenched gap breaks down. The primary circuit, then closed, and C_1 discharged, forms an oscillatory circuit which is a train of damped oscillations of high frequency.

For 50 cycle supply or in $\frac{1}{50}$ sec in one voltage cycle, there will take place twice of charged and discharged of capacitor C_1. Thus there will be 100 of these trains of damped oscillations per second.

The oscillation frequency is high but usually about 100 Kcs. Its value depends upon the inductance and capacitance of the oscillatory circuit.

The oscillation frequency is given approximately by

$$f = \frac{1}{2\pi\sqrt{L_1C_1}}$$

where L_1 is the inductance of the primary circuit.

Oscillations are induced in the secondary circuit of the Tesla Transformer by oscillatory current in the primary, and these will be of the same frequency as those in the primary circuit. Then, the primary circuit will supply energy to the secondary circuit L_2C_2 to which the primary coil L_1 is coupled so that the primary voltage falls and the secondary voltage rises.

When the secondary inductance, L_2 and capacitance, C_2 are adjusted so that the two circuits are in tune i.e. if $L_1C_1 = L_2C_2$ the series of trains of damped oscillations are applied to the apparatus under test.

1-3b Voltage wave forms characteristics. When the primary circuit supplies energy to the secondary circuit so that the primary voltage falls and the secondary voltage rises, the energy is transferred from L_2C_2 to L_1C_1. The process is repeated giving damped wave trains. Because of the finite circuit losses in both primary and secondary circuits the voltage wave shapes can be obtained as shown in Fig.1-3[18]

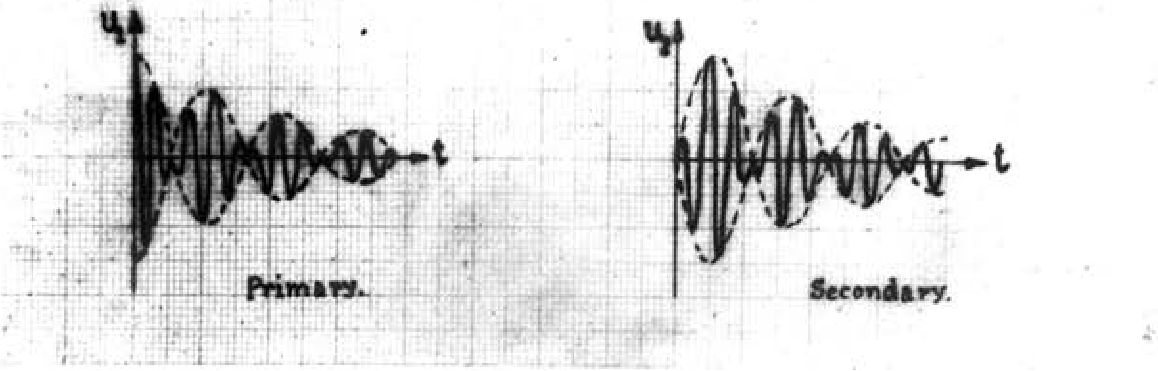


Fig.1-3[18] Voltage wave shapes in a Tesla Transformer with no interruption to primary circuit oscillations.

If the arc in the gap, Q is often interrupted with an air-blast after the first quarter of the beat-frequency wave so that the energy remains in the secondary circuit, the Fig.1-4[18] can be obtained.

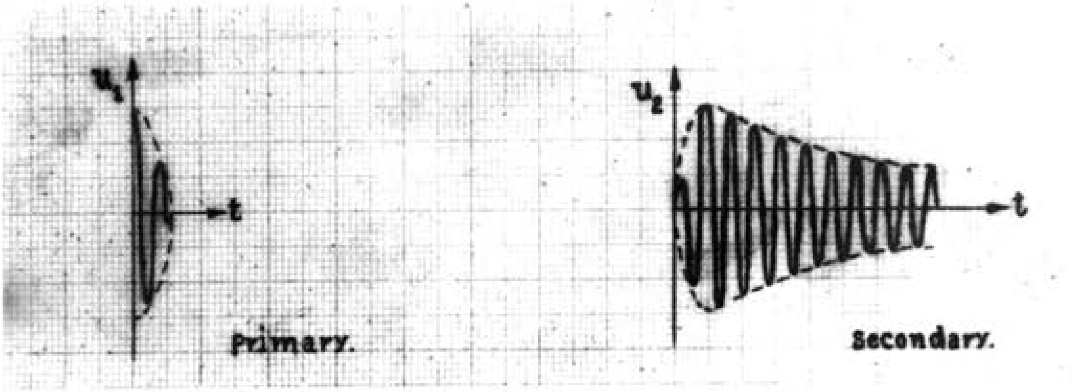


Fig.1-4[18] Voltage wave shapes in a Tesla Transformer with primary circuit oscillations interrupted by air blast.

The Cathode-ray oscillograph can be used to obtain these wave forms and a sphere-gaps for voltage measurement.

1-3c Oscillation frequencies and Mutual inductance between two windings. Let M be the mutual inductance between the two windings and $w = 2\pi f$

For the primary circuit in Fig.1-2

$$I_1 \left(jwL_1 - \frac{1}{wC_1}\right) - jwMI_2 = 0$$

For the secondary circuit in Fig.1-2

$$I_2\ (jwL - \frac{j}{wC_2}) - jwMI_1 = 0$$

Then, $$\frac{I_1}{I_2} = \frac{jwM}{jwL_1 - \frac{j}{wC_1}} = \frac{jwL_2 - \frac{j}{wC_2}}{jwM}$$

Hence, $$w^2M^2 - w^2L_1L_2 - \frac{1}{w^2C_1C_2} + \frac{L_2}{C_1} + \frac{L_1}{C_2} = 0$$

$$w^2\ (M^2 - L_1L_2) + \frac{L_2}{C_1} + \frac{L_1}{C_2} - \frac{1}{w^2C_1C_2} = 0$$

Let $K^2 = \frac{M^2}{L_1L_2}$ where K is the coefficient of coupling

or $K = \frac{M}{\sqrt{L_1L_2}}$

Then $$w^2(K^2L_1L_2 - L_1L_2) + \frac{L_2}{C_1} + \frac{L_1}{C_2} - \frac{1}{w^2C_1C_2} = 0$$

$$w^2(1-K^2) - \frac{1}{L_1C_1} - \frac{1}{L_2C_2} + \frac{1}{w^2L_1L_2C_1C_2} = 0$$

Since $L_1C_1 = L_2C_2$ when two circuits are tuned

Thus $$\left\{w(1-K) - \frac{1}{wL_1C_1}\right\}\left\{w(1+K) - \frac{1}{wL_1C_1}\right\} = 0$$

$$w^2 = \frac{1}{L_1C_1(1-K)}$$

$$\therefore\ f_1 = \frac{1}{2\pi\sqrt{L_1C_1(1-K)}}$$

where f_1 is one value of the frequency

and $$w^2 = \frac{1}{L_1C_1(1+K)}$$

$$= \frac{1}{L_2C_2\ (1+K)}$$

$$\therefore f_2 = \frac{1}{2\pi\sqrt{L_2C_2(1+K)}}$$

where f_2 is another value of the frequency

Now, K is usually small compared with L_1C_1 and L_2C_2, so the frequency is

$$f = \frac{1}{2\pi\sqrt{L_1\,C_1}} = \frac{1}{2\pi\sqrt{L_2C_2}}$$

In this case, neglecting the resistances of the two circuits and L_1, L_2 being the inductances of the primary and secondary circuits respectively.

The effect of variation in mutual inductance, M is a great importance in Tesla Transformer, becuase it effects the output voltage wave-forms. Goodlet[19] points out that, the closer the coupling, the lower is the oscillation frequency as compared with the beat frequency; and for tight coupling, i.e. high M, the output voltage will tend to be impulsive (as in Fig.1-3 and Fig.1-4). For loose coupling, i.e. low M, will tend to give an undamped secondary wave train as shown in Fig.1-5[19].

1-4 Properties of Conductor

In design, there are many factors that should be considered e.g. the properties of the conductor, properties of the insulating materials, etc. These two factors are of great importance. Otherwise, if the materials used

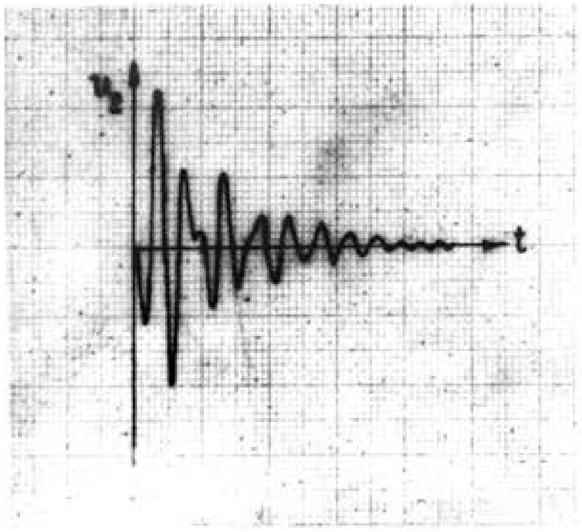


Fig.1-5[19] Tesla Transformer secondary voltage wave form with low M (discussed by Goodlet[19])

are not good, the results of the design are also not good.

1-4a <u>Variation of Resistance of electrical conductors.</u>

No material is a perfect conductor at ordinary temperature. The resistance of conductors made from a given homogeneous materials is found to depend upon the length, cross-section, and temperature. The D.C. or Ohmic resistance can be expressed[14] as

$$R = \rho \frac{\ell}{A} \text{ ohm}$$

where ρ = specific resistance or resistivity of the material in ohm-cm.

ℓ = length of conductor in cm.

A = cross-section area in cm^2.

This expression is true when the current is uniformly distributed over the cross-section of the conductor and flows in paths parallel to the boundary walls.

1-4b Temperature effects. The resistivity of most pure metal rises with temperature then, the resistance at any temperature is given[14] by

$$R_T = R_{20}\left[1 + \alpha_{20}(T - 20)\right] \quad \text{ohm/}_{\text{cm}}$$

where R_{20} = resistance in ohms at 20°C.
T = temperature in °C
α_{20} = temperature coefficient of resistivity per °C at 20°C.

For the problem of coil design,to find the correct size of wire, it is necessary to consider the effect of coil temperature. The coil temperature will increase under operating conditions. Since this increase of temperature will result an increase of resistance. For this reason, it is necessary to allow a margin over the available winding space after the copper wire is putting.

1-4c Frequency effects. The resistance of a given conductor is affected by the frequency of the current carried by it. For example,in an isolated wire of circular cross section, the inductance of the central parts of the conductor is greater than that of the outside skin because of the additional flux linkages due to the internal magnetic flux lines. The impedance of the central parts is consequently greater, and the current flows mainly at and near the surface of the conductor where the impedance is least. The useful cross-section of the conductor is less than the actual area, and the effective resistance is consequently higher. This is called the 'Skin Effect . At power frequencies and for small conductors the effect is negligible. In case of large conductors it is necessary to investigate the skin effect.

By subdividing the conductor into a number of smaller conductors, separated by some distance from each other, or by the use of a hollow conductor, or a flat conductor, as a bar or ribbon, the effect is reduced.

1-4d Skin depth or Depth of penetration[15] (S), is that distance below the surface of a conductor where the current density flows uniformly and has diminished to $\frac{1}{e}$ or 36 percent of its value at the surface. The thickness of the conductor is assumed to be several (about three) times the skin depth. The depth of penetration can be expressed[15] by

$$S = 5{,}033 \sqrt{\frac{\rho}{\mu f}} \text{ cm}$$

where ρ is in ohm-cm.

f is in cps.

or $$S = \frac{6.62}{\sqrt{f}} \text{ cm, for copper at } 20^{\circ}\text{C}$$

The skin effect and skin depth of the conductor can be shown in Fig.1-6.

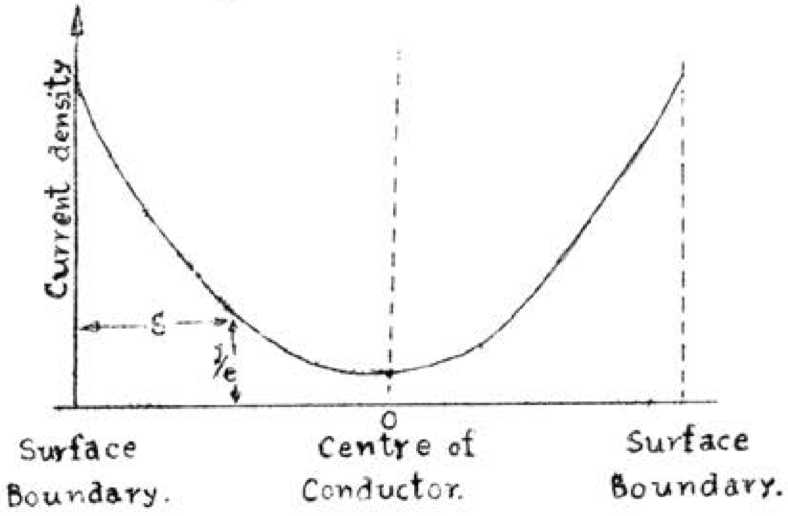


Fig.1-6 Distribution of current density in the solid round wire conductor.

It is interesting to calculate the depth of penetration of alternating current, for different frequencies, in different materials, to indicate what thickness of conductor may be employed (usually the depth of penetration must be less than one half of the thickness of conductor). The skin depth can also be used to calculate the effective or a-c resistance of the conductors and is given[15] by

For round wire conductor,

$$R_{ac} = \frac{83.2\sqrt{f}}{d} \times 10^{-9} \text{ ohms}/_{\text{cm}}.$$

where d is diameter in cm.

f is frequency in cps.

1-4c High frequency resistance calculation method.

Another method of measurement of the high frequency resistance is by the oscillograph.[21] Consider the R-L-C circuit in Fig.1-7.

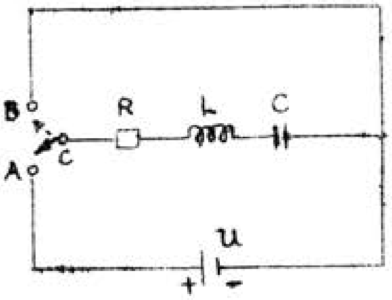


Fig.1-7 R-L-C circuit in series.

When switch at A, $Ri + L\frac{di}{dt} + \int_0^t \frac{i}{C}\,dt = U$

At B, $$Ri + L\frac{di}{dt} + \int_0^t \frac{i}{C}\,dt = 0$$

or $$L\frac{d^2i}{dt^2} + R\frac{di}{dt} + \frac{i}{C} = 0$$

$$\frac{d^2i}{dt^2} + \frac{R}{L}\frac{di}{dt} + \frac{i}{LC} = 0$$

Let $\sigma = \frac{R}{2L}$ and $w_o = \frac{1}{\sqrt{LC}}$

Then $$\frac{d^2i}{dt^2} + 2\sigma\frac{di}{dt} + w_o^2 i = 0$$

Therefore the solution is in the form, $i = Ae^{pt}$

Substitute in the above equation,

$$Ap^2e^{pt} + 2\sigma Ape^{pt} + w_o^2Ae^{pt} = 0$$

$$Ae^{pt}(p^2 + 2\sigma p + w_o^2) = 0$$

$$p^2 + 2\sigma p + w_o^2 = 0$$

Then $p_1 = -\sigma + \sqrt{\sigma^2 - w_o^2}$

$$p_2 = -\sigma - \sqrt{\sigma^2 - w_o^2}$$

If $w_o^2 > \sigma^2$, then $p_1 = -\sigma + j\sqrt{w_o^2 - \sigma^2}$

$$= -\sigma + jw$$

$$p_2 = -\sigma - j\sqrt{w_o^2 - \sigma^2}$$

$$= -\sigma - jw$$

where $w = \sqrt{w_o^2 - \sigma^2}$

$\therefore\ i(t) = A_1 e^{p_1 t} + A_2 e^{p_2 t}$

when $t = o_+$, $i(t) \approx o$

$\therefore\ A_1 = -A_2 = I_o$

Then $i(t) = I_o (e^{p_1 t} - e^{p_2 t})$

At $t = o_+$, $Ri \approx o$, $U_C \approx o$ and $\frac{L di(t)}{dt} = U$

Then $U = \frac{L di(t)}{dt} = LI_o (p_1 e^{p_1 t} - p_2 e^{p_2 t})$

$$= LI_o (p_1 - p_2)$$

or $I_o = \frac{U}{L(p_1 - p_2)}$

$$= \frac{U}{L\ 2jw}$$

Hence, $i(t) = \frac{U}{2jwL} \left[e^{p_1 t} - e^{p_2 t} \right]$

Then $i(t) = \frac{U}{2jwL} \left[e^{(-\sigma + jw)t} - e^{(-\sigma - jw)t} \right]$

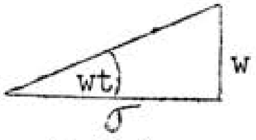
$$i(t) = \frac{U}{wL} e^{-\sigma t} \frac{e^{jwt} - e^{-jwt}}{2j}$$

$$= I_o e^{-\sigma t} \text{ Sin } wt$$

For maximum current $\frac{di(t)}{dt} = o$

$$0 = I_o e^{-\sigma t} w \text{ Cos } wt - e^{-\sigma t} \text{ Sin } wt$$

or $\tan(wt) = \frac{\text{Sin } wt}{\text{Cos } wt} = \frac{w}{\sigma}$



$$\therefore wt_{(max.)} = wt + nT = wt + n(2\pi)$$

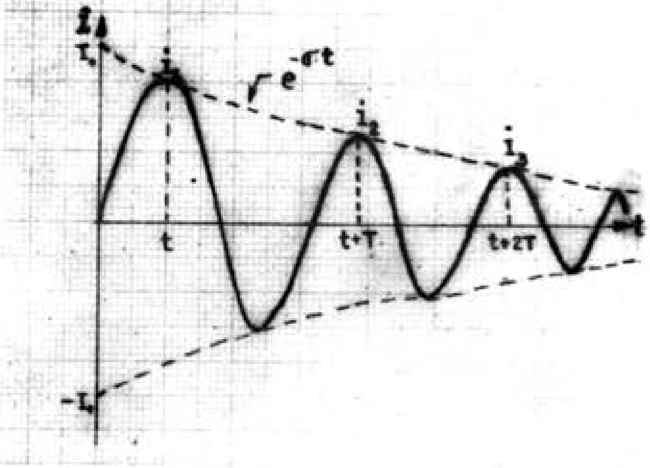


Fig.1-8 Double energy transient.

Therefore,

$$i_1 = I_o e^{-\sigma t} \text{ Sin } wt$$

$$i_2 = I_o e^{-\sigma(t+T)} \text{ Sin } w(t+T) = I_o e^{-\sigma(t+T)} \text{ Sin } w(t+2\pi)$$

$$= I_o e^{-\sigma t} e^{-\sigma T} \text{ Sin } wt = i_1 e^{-\sigma T}$$

Then, $\frac{i_1}{i_2} = \frac{i_t}{i_{t+T}} = e^{\sigma T}$

Similary, $i_3 = I_o e^{-\sigma(t+2T)} \text{ Sin } w(t+2T)$

$$i_3 = i_1 e^{-2\sigma T}$$

$$\text{or} \quad \frac{i_1}{i_3} = e^{2\sigma T}$$

$$\text{and} \quad \frac{i_1}{i_4} = e^{3\sigma T}$$

$$\text{Hence} \quad \sigma = \frac{R}{2L} = \frac{1}{T} \ln \frac{i_t}{i_{t+T}}$$

$$\text{or} \quad R = \frac{2L}{T} \ln \frac{i_t}{i_{t+T}} \quad \text{ohms}$$

In selection the suitable size of the conductor, the skin depth should be checked and less than one half of the thickness of the conductor.

1-5 Electric field

When two charged bodies or two conductors separated in vacuum (or for all general purposes in air) and are maintained at a potential difference, an electrified state is discoverable in the surrounding space, especially that between the charged bodies or the conductors. This electrical state is called the Electric field and the intensity or strength of the electric field is expressed in volts per millimeter, or volts per centimeter, or volts per mil (1 mil = 1/1,000 inch). For uniform fields at power frequencies the electric strength or breakdown of air at normal temperature (20°C) and sea level (760 mm.

of mercury) is 30 kilovolts per centimeter.[16] The breakdown voltage is approximately proportional to pressure and inversely proportional to absolute temperature.

The gradient at the surfaces of conductors depends on their shape and position relative to one another, being decided mainly by the curvature of the surface; it can be calculated for many geometrical shapes, e.g. spheres, flat plates, wires and concentric cylinders. In the case of the Tesla coils design, it is assumed to be concentric cylindrical condenser.

Concentric cylindrical condenser.[6] Consider the Fig.1-9

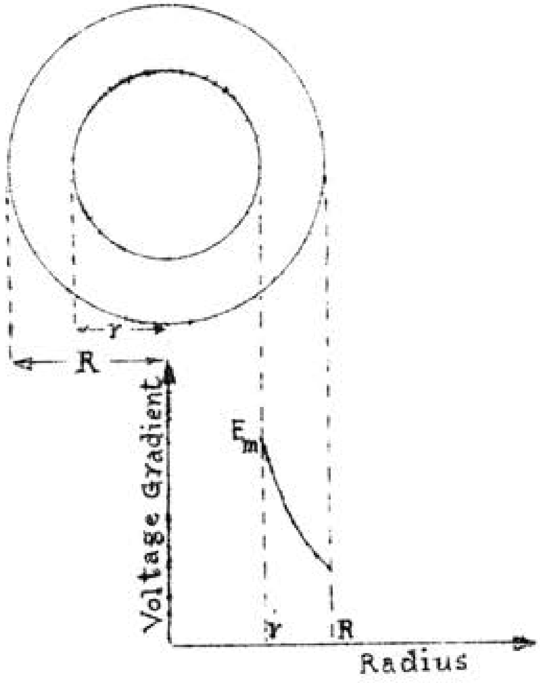


Fig.1-9 Voltage gradient distribution in Concentric cylindrical condenser.

Let Q is the charge per metric length of condenser

$\frac{Q}{\varepsilon_o \varepsilon_r}$ lines is the electric force emerging radially from the inner cylinder to the outer

$E_x = \frac{Q}{\varepsilon_o \varepsilon_r 2\pi x}$ is the electric field intensity at radius x

Then, the potential difference between the two condensers is $U = \int_r^R E_x dx = \frac{Q}{\varepsilon_o \varepsilon_r 2\pi x} \ln\frac{R}{r}$ volts

The maximum gradient occurs at the radius, r of the inner condenser.

Then,

$$E_m = \frac{Q}{2\pi \varepsilon_o \varepsilon_r r}$$

$$= \frac{U}{r \ln\frac{R}{r}} \text{ volts/m.}$$

The maximum potential difference between the condensers occurs when,

$$\frac{d}{dr}\left(E_m r \ln\frac{R}{r}\right) = 0$$

$$\frac{d}{dr}\left[r(\ln R - \ln r) \right] = 0$$

$$\ln R - \ln r - r\frac{1}{r} = 0$$

$$\ln\frac{R}{r} = 1$$

$$\frac{R}{r} = e = 2.718$$

$$\therefore R = 2.718\, r$$

This is one value of the radius, R of the outer cylindrical condenser at a given value of inner cylindrical condenser of radius, r and at a given maximum voltage difference between the two cylindrical condensers. This value of R is used for a rough approximation for calculation of radius of the outer coil of a Tesla Transformer.

1-6 Insulating or Dielectric Materials

The behaviour of insulating materials at high frequencies is very different from that at ordinary commercial frequencies. This is largely due to the very much greater dielectric power loss, within the material at the high frequency. The heat produced by this power loss tends to produce breakdown of the insulation at voltages which are smaller than those at which breakdown occurs when the frequency is low. Therefore, it is necessary to consider the electrical and physical properties of insulating or dielectric materials being used.

1-6a Ideal Insulating Material. Insulating materials have a great variety of constituents; they may be organic, inorganic, mineral, natural or artificial. An ideal insulating material would have the following properties:

a) high dielectric strength, particularly at high temperatures;

b) good heat conductivity;

c) permanence, particularly at high temperatures;

d) good mechanical properties, such as ease of working and application, resistance to failure by vibration;

e) no attraction for moisture.

The cost of the insulating materials may be a significant proportion of the total. The selection of material is particularly exacting, and it may sometimes be found that an expensive material has economic advantage over a cheaper one in higher electric and mechanical strength, superior resistance to "tracking", higher thermal conductivity, or shorter processing times. The behaviour of the material must be closely predictable, because breakdowns can be very costly.

1-6b Types of Insulating Materials. There are three types of Insulating Materials, namely

a) Gases.

b) Liquids.

c) Solids.

1-6c Dielectric Breakdown. A practical dielectric will break down (i.e. fail to insulate) when the electric field stress or voltage gradient exceeds the value that the material will withstand. It is expressed in Volts per centimeter or per millimeter. Its value differs for different materials.

Gases - with gases dielectrics (e.g. air, hydrogen), ions are always present on account of light, heat, sparking etc. These are set in motion making additional ionisation, which may be cumulative, causing glow discharge, sparking or arcing unless the field strength is below a critical value. A field strength of the order of 3 mega-volts per metre is a limiting value for gases at normal-temperature-pressure. The dielectric strength increases with the gas pressure.

Liquids - When very pure, liquids may behave like gases. Usually, however, impurities are present.

Solids - Solid dielectrics are rarely homogeneous, and are often hygroscopic. Breakdown depends on many factors, especially thermal ones, and is a function of the time of application of the potential difference.

1-6d Conduction and Absorption. Solids dielectrics in particular, and to some degree liquids also, show conduction and absorption effects. Conduction appears to be mainly ionic in nature. Absorption is an apparent storing of charge within the dielectric.

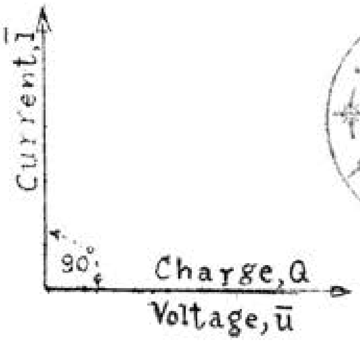
1-6e Power Factor (Cos θ). Where a capacitor is subjected to an alternating potential difference, losses additional to those of conduction occur due to absorption, the effect being sometimes called Dielectric hysteresis. Due to these losses, the current in a capacitor will not be in leading phase-quadrature with the voltage. The phase angle is less than 90° by the angle δ, the loss angle. With a reasonably good condenser the current is given by

$I = wCU$, and the loss is $P^{7} = UI \cos\theta = UI \sin\delta$

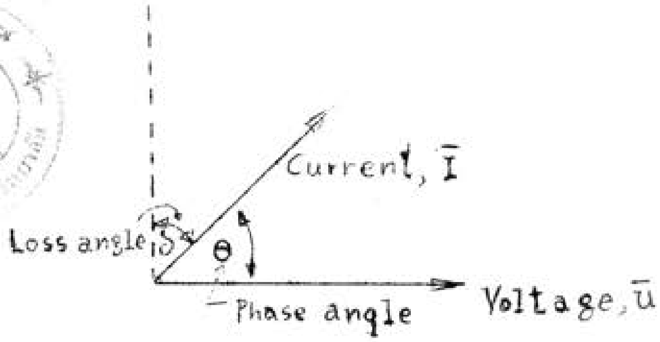
$$= wCU^2 \sin\delta$$

$$= wCU^2 \tan\delta \text{ watts,}$$

when δ is so small. This phenomena can be represented by the Fig.1-10 and Fig.1-11 respectively.



Fig^{7}.1-10 Vector Diagram of Pure capacitor.



Fig^{7}.1-11 Vector Diagram of Imperfect capacitor.

1-7 Properties of Insulating Materials

The properties of insulating materials may be classified as:

1-7a Physical Properties.

Specific Gravity is of importance in the cases of vanishes, oils and other liquids. The density of solid insulations varies widely, e.g. from 0.6 for certain papers to 3 for mica.

Moisture Absorption usually causes serious depreciation of electrical properties, particularly in oils and fibrous material. Swelling, corrosion and other effects often result from absorption of moisture. Under severe conditions of humidity, moisture sometimes causes serious deterioration.

Thermal Effects is very often seriously influence the choice and application of insulating materials, the principal features being: melting-point(e.g. of waxes); softening or plastic yield temperature; ageing due to heat, and the maximum temperature which a material will withstand without serious deterioration of essential properties; flash point (of liquids); ignitability; resistance to electric arcs; liability to carbonise; specific heat; thermal coefficient of expansion and freezing point.

1-7b Electrical Properties. The essential electrical property of a dielectric is that it shall insulate, not allow the passage of an excessive current when electric stress is applied. There are other electrical properties concerning with the dielectric; they are, resistivity, dielectric strength, permittivity, and power factor.

Resistivity determines the passage of current to flow through the body of the insulator. It depends upon the amount of moisture present either within a material or as a film on the surface.

Dielectric Strength (or Electric Strength) is the property of an insulating material which enables it to withstand electric stress without injury.

The dielectric strength of most materials falls with increase of temperature.

Surface Breakdown and Flash-over. When a high voltage stress is applied to conductors separated only by air where they are close together, and the stress is increased, break-down of the intermediate air will take place when a certain stress is attained, being accompanied by the passage of a spark from one conductor to the other. This may also be followed by a continuous arc. The voltage at which this takes place is usually termed the spark-over or flash-over value.

In the majority of electrical devices, especially terminal boards and parts of switchgear, live parts are separated by solid insulation and air surrounding it, so that it is possible for failure to occur along the surface of the material named, surface flash-over.

Permittivity. The capacitance of a system consisting of two or more conductors at different potential separated by a dielectric medium is determined by the geometry of the conductors and the intervening dielectric. property of the dielectric known as Permittivity. The definition of permittivity is previously defined.

Power Factor and Dielectric Losses. This term has already explained in the last section.

Power factor varies sometimes with frequency, also with temperature, values of tan δ usually increasing with rise of temperature, particularly when moisture is content, in which case the permittivity also rises with temperature, so that total dielectric losses increase as the temperature rises.

1-8 Araldite Epoxy Resins[3]

The insulating material used for high voltage coil in the construction of Tesla Transformer presented in this thesis is of the liquid type. Upon consideration on various properties of insulating materials and the appropriate type available in the market, the epoxy resins (or trade name, Araldite epoxy resins) type is the best suitable insulating material.

Epoxy resins have a widespread interested in many fields of application on account of their versatility and high performance. They are of particular interest to the electrical industry because in addition to their excellent mechanical properties, they have good electrical characteristics which make them particularly suitable for wire enamels and insulating vanished, for glass fibre laminates, and as casting resins for electrical components.

It will dry at room temperature or slightly elevated temperatures. The main feature of castings is their high strength and toughness, low water vapour transmission and absorption characteristics and a low coefficient of linear expansion. Other uses for the resins are as metal to metal adhesives and as stabilisers for P.V.C. wire and other chlorinated compounds.

1-8a Properties of Araldite epoxy resins. The features of "Araldite" epoxy resins which make them suitable for applications in the electrical industry are:-

1) Hardening is by a polyaddition reaction with no volatile matter given off during the curing process.
2) Excellent dielectric strength (about 400-500 volts/mil), volume and surface resistivity (about $3.8 \times 10^{14} - 6 \times 10^{16}$ ohm-cm at 20°C), and resistance to tracking.
3) Good adhesion to metals, porcelain, copper and other materials.
4) Excellent resistance to water and chemicals.
5) Good heat resistance and dimensional stability.
6) High mechanical strength and durability.
7) Ease of casting to good dimensional tolerances.

1-8b Casting and Curing Process[4]. Araldite casting resins are amber-coloured, low-molecular products, supplied either as liquids or heat fusible solids. The casting compound is prepared by mixing the resins with the recommended hardener, mixing by weight. The curing or demoulding time may be carried out either at room temperature or in a few minutes at an elevated temperature.

1-8c Instruction for using of epoxy casting resins, system Araldite D (CY230) with Hardener HY 956. The mixing and casting process of Araldite epoxy resins can be made following these steps:

1) Clean receptacles, tools, moulds and/or surfaces throughly.

   Moulds: Apply a thin and even coat of oil to the parting surfaces of the mould. This will serve as a release agent.

   Surface to be bonded. Degrease with acetone. Ensure complete absence of moisture before applying the resin.

2) Prepare the necessary volume of resin in a suitable receptacle (tin or beaker). Specific gravity of Araldite D is 1.2 gm per cubic centimeter.
3) Add colour if necessary and mix slowly.
4) Add hardener HY 956 the mixing ratio by weight is:

Araldite D (CY 230)	100 parts
Hardener HY 956	18±2 parts

5) Mix resin slowly (avoid bubles) with a metal or wooden spatula. Preheat resin during mixing period up to about 40°C.

   Curing takes place as soon as the hardener is added (poly-addition reaction, exothermic).

<u>Pot life</u> (period during which the mixture remains castable after the hardener has been added) is at $40^{o}C$ about 1/2 hour.

6) <u>Cast resin</u>
7) Clean tools with soaps or acetone or throw them away.
8) <u>Remove</u> mould after about 5 hours of curing time.

1-9 Sphere-Gaps

The sphere-gaps is used for voltage measurement. It is compos-ed of two metallic spheres, separated by an air gap. The potential difference between the spheres is raised until a spark passes between them. The value of the potential difference required for spark-over depends upon the dielectric strength of air, the size of the spheres, their distance apart and upon a number of other factors.

There are twelve sizes of spheres being used to cover a range of voltage from 2 to 2,500 Kv, namely, of diameters 2, 5, 6.25, 10, 12.5, 15, 25, 50, 75, 100, 150 and 200 cm. The sphere-gaps being used for voltage measurement of the Tesla Transformer is 25 cm. diameter, in which its characteristic curve of breakdown voltages and gap distances can be found in Appendix A.

1-9a <u>Precautions in Measurement of High Voltages</u>. The following precautions should be considered during the high voltage measurement with the sphere-gaps:

1) metallic spheres should be cleaned, smooth, free from grease films, dust or deposited moisture. Always keep the gap as free as possible from floating dust particles. These are to avoid effect of uncontrolled irradiation of the gap;
2) spacing does not exceed the radius of the spheres, to prevent the corona prior to spark-over;
3) one sphere may be earthed or both may be insulated.

1-9b <u>Effect of Relative Air Density and Humidity</u>. The spark-over voltage of the needle points for a spark-gap is dependent of humidity because the corona will form at the points when the variation of the humidity of the atmosphere takes place. While, the spark-over caused by the two sphere-gaps does not occur but depends upon the air density.

The effect of increase in air density is to raise the spark-over value, the breakdown voltage increasing with increase in atmospheric pressure and with decreasing temperature. The breakdown voltage of a sphere-gaps is approximately proportional to the changes in relative air density due to changes in barometric pressure and/or temperature.

The relative air density (d) (based upon the density at $20^\circ C$, 760 mm. pressure) is given[8] by

$$d = \frac{p}{760} \quad \frac{273 + 20}{273 + t} = 0.386 \left(\frac{p}{273 + t}\right)$$

where p = barometric pressure in mm. of mercury

t = temperature in degrees C

The breakdown voltage under atmospheric conditions other than normal can therefore be obtained by multiplying the relative air density for those conditions by the breakdown voltage for the particular gap at N.T.P. (see Appendix A), when d is greater than 0.95 but not more than 1.05.

Therefore, $U = dU_n \qquad 0.95 < d < 1.05$

where U = breakdown voltages at any air density

U_n = breakdown voltages at N.T.P.

At frequency above 10 Kcs. the dielectric strength of air decreases slightly. Owing to the low velocity of positive ions, they are not swept to the electrodes during one half cycle, so that they remain to distort the field on the next half cycle. If the gap is illuminated with ultraviolet light, a decrease of 17 to 20 per-cent in breakdown voltage is obtained.

1-10 Corona Effect

Corona is the glow or brush discharge around conductors occurring when air stressed beyond the ionisation point without spark-over developing (corona occurs prior to dielectric breakdown).

It causes a certain amount of energy loss with alternating current particularly on high voltage transmission line; it produces radio interference; it may commence surface deterioration and breakdown on solid insulation surfaces; and it produces chemical effects. Corona is normally prevented by operation at reduced voltages or by the use of suitable corona shields.

1-11 Effects of Harmonic Distortion

Circuits containing non-linear circuit parameters will normally carry non-sinusoidal currents, even when a sinusoidal e.m.f. is applied. The wave shape of an alternating voltage or current can be obtained with the aid of an oscillograph, a cathode-ray oscillograph employing a linear sweep being most commonly used.

Any periodic wave-form may be represented by a summation of sine waves comprising (i) a fundamental wave having a frequency equal to the frequency of recurrence of the complex wave; and (ii) a series of harmonic waves of frequencies 2, 3, 4, - - n times that of the fundamental and can be written as

$$\begin{aligned} y = f(wt) &= A_o + a_1\mathrm{Cos}(wt) + a_2\mathrm{Cos}(2wt) + .. + a_n\mathrm{Cos}(nwt) \\ &\quad + b_1\mathrm{Sin}(wt) + b_2\mathrm{Sin}(2wt) + .. + b_n\mathrm{Sin}(nwt) + \ldots \end{aligned}$$

$$= A_o + A_1 \text{Sin}(wt + \alpha_1) + A_2 \text{Sin}(2wt + \alpha_2) + \ldots\ldots\ldots \ldots\ldots + A_n \text{Sin}(nwt + \alpha_n) + \ldots\ldots\ldots\ldots$$

where $A_1 = \sqrt{a_1^2 + b_1^2}$

and $A_n = \sqrt{a_n^2 + b_n^2}$ ...... etc. are the amplitudes of various components, $\alpha_n = \tan^{-1}\left(\frac{a_n}{b_n}\right)$ and A_o = constant

Harmonic contents. Practical wave-forms may be very complex, but there is generally some recognisable degree of symmetry. This may help in choosing the starting for the series (i.e. the arbitrary point $\theta = 0, 2\pi, 4\pi, --$) and in predicting the harmonic content. The types of wave-form of harmonic content are generally shown as in Fig.1-12.

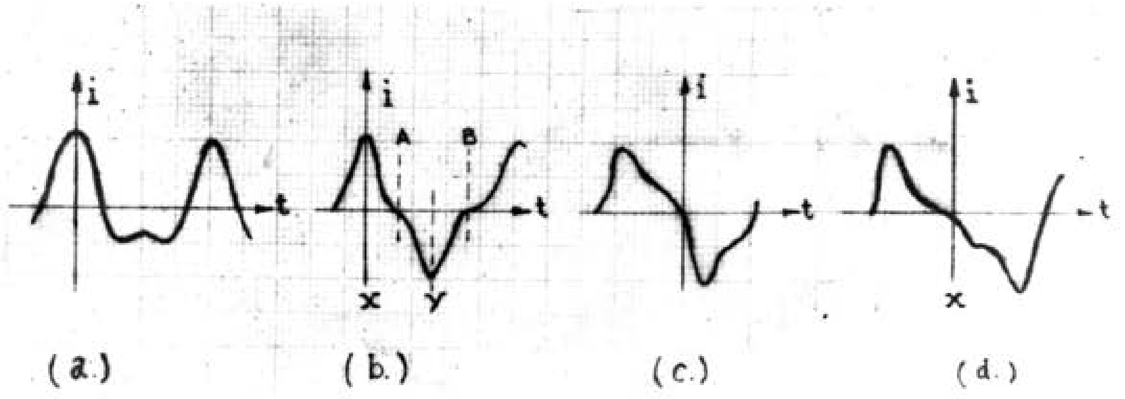


Fig.1-12 Types of Wave-form of Harmonic contents.

In (a), the curve has equal positive and negative areas and hence no constant term and can be expressed as

$$I = i_1 \text{Cos}\,\theta + i_2 \text{Cos}\,2\theta + i_3 \text{Cos}\,3\theta + \ldots\ldots$$

In (b), it can be expressed as a sine series about axes A or B or a cosine series about axes x or y.

In (c), it is very commonly found in a-c circuits not containing rectifiers. The second half-wave repeats the first half-wave, but negative in the same time-sequence. It contains only odd-order harmonic i.e. its expression is of the form:

$$I = a_1 \mathrm{Cos}\ \theta + a_3 \mathrm{Cos}\ 3\theta + a_5 \mathrm{Cos}\ 5\theta + \ldots\ldots$$
$$+ b_1 \mathrm{Sin}\ \theta + b_3 \mathrm{Sin}\ 3\theta + b_5 \mathrm{Sin}\ 5\theta + \ldots\ldots$$

In (d), the second half-wave repeats the first half-wave, but negative and in reversed time-sequence. The curve contains only sine terms about axis x and can be expressed as

$$I = i_1 \mathrm{Sin}\ \theta + i_2 \mathrm{Sin}\ 2\theta + i_3 \mathrm{Sin}\ 3\theta + \ldots\ldots$$