Lecture # 9

Generation of High Voltage AC

High Voltage Alternating Current (HVAC) plays a vital role in electrical power engineering. The most important application is the transmission line that carries electrical energy from generating stations to the load centers. Transmission of electrical energy at high voltages has numerous advantages; reducing the size of conductors, voltage drops and power loss. However, the use of higher voltages complicates the electric field condition due to which the insulators can be abnormally stressed. This necessitates proper selection and testing of insulation to establish the insulation level for best performance.

Step-up Transformers

The most common method of producing high voltage AC in the laboratories for testing purposes is by using single-phase step-up transformers. According to the theory, the secondary voltage can be considerably increased by increasing the number of turns of secondary winding with respect to the primary winding. If the voltage applied to the primary winding of N number of turns is V and if the voltage V_0 is developed across the secondary winding with N_0 number of turns, then: $\frac{V_0}{V} = \frac{N_0}{N}$

Or $$V_0 = V\left(\frac{N_0}{N}\right) \qquad 1$$

Thus it can be noted from Eq (1) that voltage at the secondary of transformer can be considerably increased by increasing the voltage transformation ratio: $\left(\frac{N_0}{N}\right)$, accomplished by increasing the number of turns of the secondary winding. However, the increase is often limited by the size of the overall transformer unit and the amount of insulation. For ensuring adequate clearance between the high voltages of the secondary winding, both the size of the steel tank enclosure and oil volume becomes excessively large. Transportation of such large units, especially for outdoor testing will become difficult and their cost of maintenance of is usually high. Therefore, single-phase, transformer units are seldom designed for testing voltages beyond 500 kV. Small units up to 100 kV are more popular in high voltage testing laboratories. A typical testing transformer has rating between 1 to 2kVA, unless used for testing insulation under contaminated conditions, in which case the current and kVA ratings are relatively higher.

Cascade Transformers

To obtain higher voltages for testing purpose, identical units of transformers are usually cascaded (output of preceding unit is input to the following unit). This has an advantage of using identical, smaller transformer units, which can at times be dismantled for convenience and the arrangement can be made available for field testing due to easier transportation. Moreover, much higher voltages can be obtained by cascading appropriate number of similar transformer units. This also occupies less space as compared to a single testing transformer unit of the same rating. To understand the procedure of cascading, consider an example of cascading three similar transformers, the schematic arrangement of which is shown in Figure (1). Suppose that each transformer is rated at 200V / 200kV and preferably the same kVA rating.

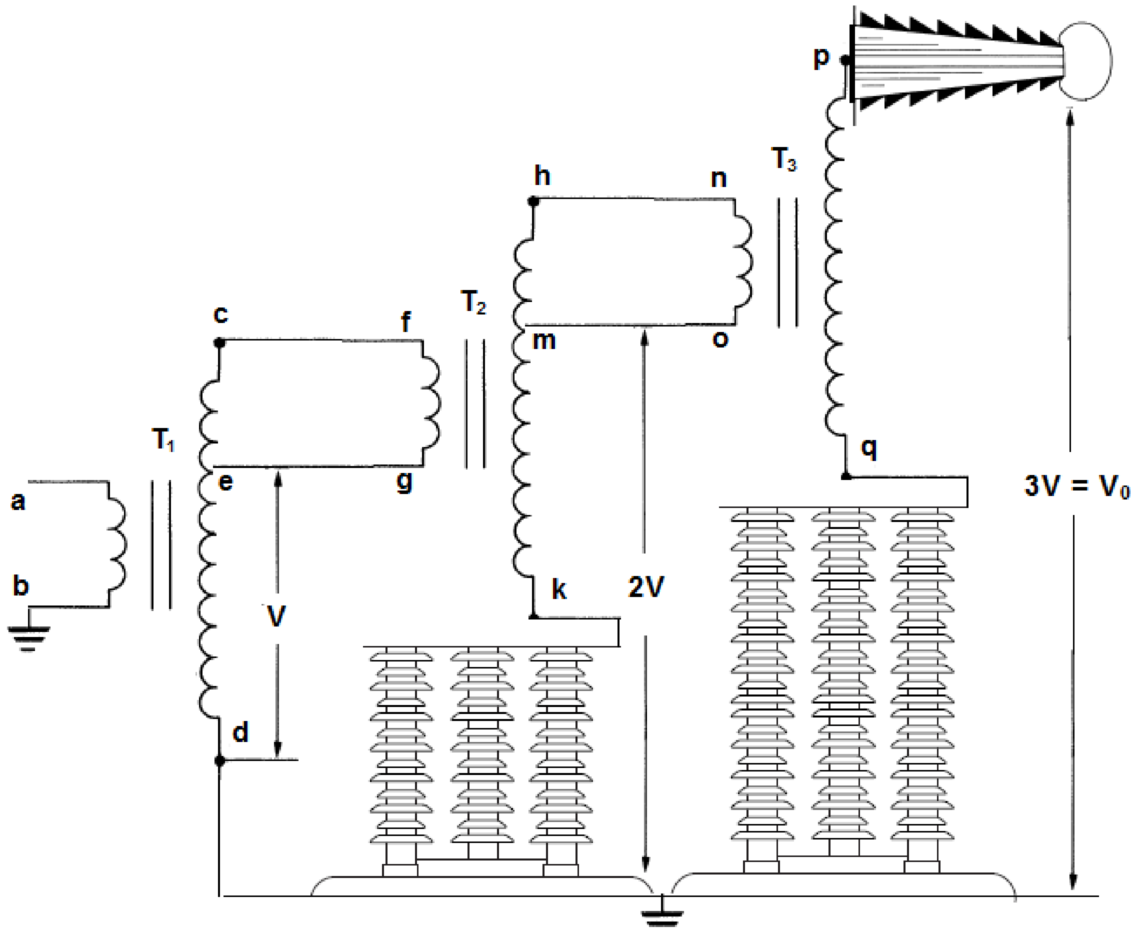

Figure 1: Cascade arrangement of three Transformers

Referring to Figure (1), the primary voltage of transformer T_1 is V_{ab} = 200 volts, which produces a voltage V_{cd} = 200 kV at the secondary. In order to apply a rated voltage of 200 volts across the primary winding of transformer T_2, a tap-point *e* on the secondary winding of T_1 must be chosen such that the voltage between terminal *c* and this tap-point is 200 volts. Thus by choosing the tap-point at a potential of V_e = 199.8 kV, a potential difference of 200 volts results between terminal *c* and tap point *e*. That is:

$$V_{ce} = V_c - V_e = 200000 - 200 = 199800 = 199.8 \text{ kV}$$

The voltage applied across the primary winding of transformer T_2 is thus derived from the secondary winding (output winding) of T_1, such that $V_{fg} = V_{ce}$. It must be noted that the enclosure tank of transformer T_2 must be isolated from the ground by a column of insulation since the transformer T_2 is live-tank at potential of 199.8 kV. Thus the potential at terminal k is 199.8 kV. Since the secondary winding of the transformer T_2 is rated for potential difference of 200 kV when 200 volts exists across its primary winding, the potential of terminal h must therefore be 399.8 kV, that is:

$$V_h = V_{hk} + V_h = 199.8 + 200 = 399.8\,\text{kV}$$

The input voltage to be applied to the primary winding of the third transformer T_3 is derived from the output winding (secondary winding) of T_2 in a similar manner as that from transformer T_1. Thus appropriately choosing a tap-point on the secondary winding of T_2 will result in a potential difference of 200 volts between terminal h and tap-point m. A tap-point is selected so as to produce a potential of 399.6 kV at point m, therefore resulting is a potential difference of 200 volts between terminal h and m, that is:

$$V_{hm} = V_h - V_m = 399.8 - 399.6 = 200 \text{ volts}$$

This voltage of V_{hm} = 200 volts is fed across the input winding (primary winding) of transformer T_3, so that the voltage applied across the primary winding of the third transformer T_3 is V_{no} = V_{hm} = 200 volts. This will produce a potential difference of 200 kV across the secondary winding of T_3. The enclosure tank of transformer T_3 is maintained at a potential of 399.6 kV, is live-tank, and must therefore be isolated from the ground by appropriate insulating column. Since the tank of T_3 is at a potential of 399.6 kV, the terminal p of transformer T_3 secondary is at a potential of 599.6 kV in order to result in a potential difference of 200 kV across the secondary winding of T_3, that is;

$$V_p = V_{pq} + V_q = 399.6 + 200 = 599.6\,\text{kV}$$

With slight adjustments from the input voltage regulator at the primary of transformer T_1, a potential difference of 600 kV can be produced between the terminal p of transformer T_3 and the ground. Thus the output voltage of the cascaded system of three transformers, in this example will produce 600 kV, which is equal to three-times the secondary voltage of a single transformer. In general the output voltage V_0 from a cascaded system of transformers is:

$$V_0 = nV \qquad 2$$

Where V is the secondary voltage of a single transformer and n are the number of transformers connected in cascade.

It must be remembered that in order to maintain the tank of the next transformer in cascade connection at the potential of the tap-point of preceding transformer, the tap-point of the preceding transformer must be electrically connected to the enclosure tank of the next transformer. For example, the tap-point e of secondary winding of transformer T_1 is electrically connected to the end of that primary winding of T_2, which is electrically connected to the tank, making the tank of T_2 at a potential of V_e = 199.8 kV. Similar procedure is adopted for the tap-point of secondary winding of T_2 and the transformer T_3.

High voltage step-up transformers are widely used in laboratories and field for testing of insulation. However, harmonics present in supply voltage and in the no-load magnetizing currents can excite natural oscillations at various frequencies, which can lead to distortion and severe overvoltages in the secondary side of transformers, which may result in explosion. This may happen when test object that have appreciable capacitance, such as cables. The capacitive reactance of the cable, connecting leads and insulator bushing may become equal to the inductive reactance of the testing transformer's windings (including stray inductance) at any harmonic frequency thus producing resonance. This result in very high voltages impressed on the test object and across the transformer winding which can cause explosions and related accidents. Cables are therefore seldom tested with transformers.

Example: Estimate the capacitance of the test object that may produce accidental resonance at third harmonic present in the supply frequency in a 1.5kVA, 220V/100kV testing transformer with inductances of the primary and secondary winding are in the same ratio as the voltage transformation ratio. Assume that the inductance of the primary winding is 0.02H.

Solution:

Given that: L_1 = 0.02H. From the given voltage rating, the voltage transformation ratio is: 100000/220 = 454.5. Thus the inductance of the secondary winding is:

$$L_2 = 454.5 \times 0.02 = 9.09\,\text{H}$$

Considering power supply frequency of 50Hz,. the third harmonic component will have a frequency of 3 x 50 = 150Hz. Therefore using:

$$f_r = \frac{1}{2\pi\sqrt{C(L_1 + L_2)}}$$

Or

$$C = \frac{1}{4\pi^2(150)^2(0.02+9.09)} = \mathbf{0.12\mu F}$$

HV Resonance Test set (Tesla Coil)

The property of resonance is fundamental to the operation of all Tesla coil, named after Nickola Tesla. A Tesla coil is composed of specially designed air-core step-up transformer. It has a primary winding, with relatively few turns, and a secondary winding with hundreds, or even thousands, of turns. With air core, the windings are "loosely coupled" and therefore typically only 10-20% of the primary winding total magnetic field links with the secondary winding.

The basic circuit of a Tesla coil is shown in the circuit of Figure (2). Referring to Figure (2), a Tesla coil essentially consists of two parallel resonant LC circuits, the primary circuit and the secondary circuit and a spark gap. The secondary capacitor C_2 is typically composed of the stray capacitance and capacitance of the cable under test or it may be a capacitor itself. The primary winding inductance L_1 and primary and capacitance C_1 combine to form a one resonant circuit, which will tend to oscillate at a specific frequency (called the natural resonance frequency), uniquely determined by the values of L_1 and C_1. In a similar fashion, the secondary winding's inductance L_2, combined with the self-capacitance of the secondary and the self-capacitance of the terminal connected to the top of the secondary (total capacitance C_2), form another resonant circuit. The secondary terminal is connected to a HV electrode. The HV electrode is a metal sphere or a toroidal electrode.

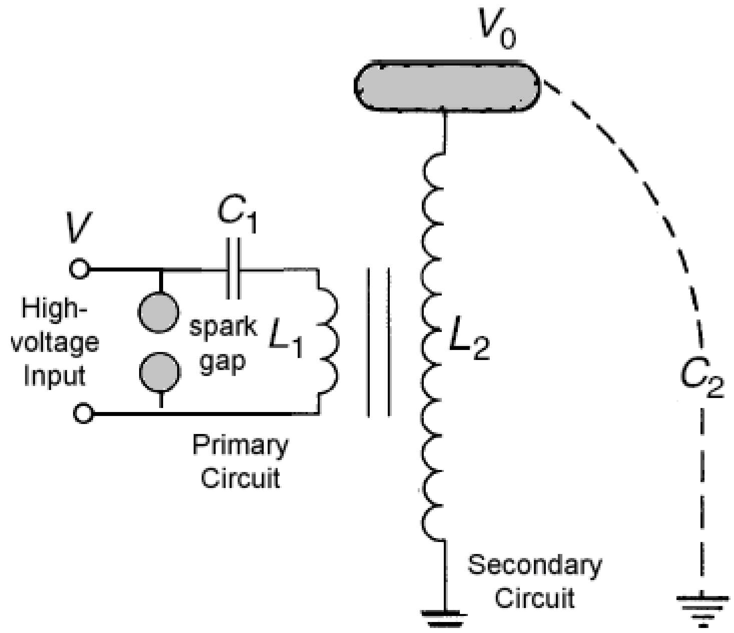

Figure 2: Schematic of a Tesla Coil

Principle of Working

The primary capacitor C_1 charges up from the high voltage DC source or in some circuits from power frequency AC source. The spark gap is remotely adjusted to breakdown, which places short-circuit and closes the loop around C_1 and L_1 forming a resonant circuit. This causes high current with pronounced frequency range between few kHz to few MHz to flow in the primary LC circuit. The windings are tuned to a frequency somewhere between 10 and 100 kHz by means of the selecting capacitors C_1 and C_2. At design resonance frequency, the voltage across primary winding becomes very high. The loosely-coupled secondary LC circuit causes the oscillatory energy in the primary to gradually get transferred to the secondary. The primary voltage rating is usually about 10 kV and the secondary may be rated to as high as 500 to 1000 kV. Usually, the windings resistance is very small and contributes only to damp out the oscillations. The entire operation of the Tesla coil depends on the correct timing of operation of the spark gap. The secret behind a good Tesla coil is making both to resonate at the same frequency, allowing them to interact with each other.

There is a common misconception that a Tesla coil operates like a regular voltage transformer. This is not the case. While it is true that the ratio between the primary and secondary turns is related to the step-up voltage like a regular transformer, it is actually the ratios of inductances that cause the voltage step-up. Since the secondary inductor has a much higher inductance than the primary inductor, the voltage step-up from the primary circuit to the secondary circuit can be considerable. Resonance sets have self-protection; that is voltage collapse automatically when resonance is lost. The two important advantages of resonance sets over conventional step-up testing transformers are:

1. Unlike most transformers, output voltage is a function of the relative ratio of inductances or capacitances between the primary and secondary.
2. Extremely high voltages can be easily generated.