Resonant Transformers: The fig.1 (b) shows the equivalent circuit of a high voltage testing transformer (shown in fig.1 (a)) which consists of the leakage reactance, the shunt capacitance across the output terminal due to the bushing of the high voltage terminal and also that of the test object. It may be seen that it is possible to have series resonance at power frequency $\omega$ if \((L_1 + L_2) = 1/\omega C\). With this condition, the current in the test object is very large and is limited only by the resistance of the circuit.

From the fig.1 (a) and 1(b) we have
- T – Testing transformer
- L – Choke
- C – Capacitance of H.V. terminal and test object
- \(L_0\) – Magnetizing Inductance
- \(L_1, L_2\) – Leakage inductances of the transformer
- \(r_1, r_2\) – Resistances of the transformer windings
- \(R_0\) – Resistance due to core loss

The waveform of the voltage across the test object will be purely sinusoidal and its magnitude is given by

$$V_C = \frac{-jV_XC}{\frac{R}{\omega} + j(X_L - X_C)} = \frac{V}{R} \frac{X_C}{\omega CR}$$

Where R is the total series resistance of the circuit. The quality factor Q of the circuit is given by \(X_C/R = 1/\omega CR\) which gives the magnitude of the voltage multiplication across the test object under resonance conditions. Therefore the input voltage required for excitation is reduced by a factor \(1/Q\) and the output kVA required is also reduced by a factor \(1/Q\). The secondary power factor of the circuit is unity.

The resonant testing method for generating high a.c. voltage is basically used for testing purposes which require both high voltage as well as high current such as cable testing, dielectric loss measurements, partial discharge measurements etc. In this method a transformer with 50 to 100 kV voltage rating and a relatively large current rating is connected together with an additional choke if necessary. The test condition is set such that \(\omega(L_e + L) = 1/\omega C\) where \(L_e\) is the total equivalent leakage inductance of the transformer including its regulating transformer. The main advantages of generating high a.c. voltage using resonance are as follows:

a) It gives an output of pure sine wave.

b) Power requirement is very less (only 5 to 10 % of total kVA required.)
c) There is no high power arcing and heavy current surges occur if the test object fails as resonance is lost at the failure of the test object.
d) Cascading is possible for very high voltages.
e) The test arrangement is quite simple and compact.
f) There is no repeated flashover in case of partial failure of the test object and insulation recovery.

The disadvantage of this method is that additional variable chokes which are capable of withstanding the full test voltage and full current rating are required. There following are three types of circuits used for generating high voltage a.c. at power frequency using resonance principle:

i. Series resonance circuit.
ii. Parallel resonance circuit.

Single unit resonant test systems are built for output voltages upto 500 kV, while cascaded units for outputs upto 3000 kV are available.

**Series Resonance Circuit:** The equivalent circuit of a single stage test transformer alongwith its capacitive load is shown in fig.2 (a) where \( L_1 \) represents the inductance of voltage regulator and transformer primary, \( L_2 \) represents inductance of transformer secondary, \( L \) is the exciting inductance of transformer and \( C \) is capacitance of the load. Normally \( L >> L_1 \) and \( L >> L_2 \), hence its shunting effect can be neglected.

![Fig. 2(a) Equivalent circuit of single stage test series resonant transformer](image)

Therefore the inductances \( L_1 \) and \( L_2 \) get connected in series with the load capacitance \( C \) forming a series LC circuit. In general the load capacitance is variable but while generating high voltage using resonance the load capacitance remains fixed. Hence we introduce a variable reactor in the transformer primary so that it becomes possible to have resonance at power frequency by making the inductive reactance become equal to capacitive reactance. At resonance the current in the circuit is only limited by the value of resistance circuit (which in general for resonant test transformer is very small). The fig.2 (b) shows a series resonant test transformer circuit.

![Fig. 2(b) Series Resonant Test Transformer Circuit](image)
The development of series resonance circuit for testing purpose has been widely welcomed as it helped in overcoming resonance problem faced in testing transformer while testing short length of cables. It consists of a continuously variable reactor connected in the low voltage winding of the step up transformer whose secondary is rated for the full test voltage. For certain setting of reactor, the inductive reactance of the circuit becomes equal to the capacitive reactance at power frequency which will result in resonance. Thus the reactive power requirement of the supply becomes zero and it has to supply only the losses of the circuit. However, the transformer has to carry the full load current on H.V. side which is a disadvantage of this method. The inductors are designed for high Q factor. The feed transformer therefore only supplies the losses of the circuit.

However now a new technique is being used to generate high voltage using series resonance in which a split iron core is used in the construction of H.V. continuous variable reactor which results in omission of testing step up transformer as shown in fig. 2(c)

**Fig. 2(c) Series Resonant circuit with variable H.V. reactors having split iron core**

The inductance of these inductors can be varied over a wide range depending upon the capacitance of the load to produce resonance. The following are the advantages of a series resonant circuit:

- **i)** The power requirement of the feed circuit is very small.
- **ii)** It suppresses harmonics and interference to a large extent.
- **iii)** In case of flashover/breakdown of test specimen during testing on H.V. side, the resonant circuit is detuned and the test voltage collapses immediately. The short circuit current is limited by the reactance of the variable reactor.
- **iv)** In this case no compensating reactor’s are required which results in a lower overall weight.
- **v)** In case of testing of SF₆ switchgear there is no special protection required against transients as there are no multiple breakdowns in high transients.
- **vi)** Any number of units can be connected in series without any impedance problem which is very severely associated with cascaded test transformer.

**Parallel Resonant Circuit:** The fig. 3 shows a schematic of a typical parallel resonance circuit. In this the variable reactor is incorporated into the high voltage transformer by introducing a variable air gap in the core of the transformer. In this circuit the variation in load capacitance and losses cause variation in input current only whereas the output
voltage remains practically constant. In case of single stage design, the parallel resonant method offers optimum testing performance.

![Fig. 3 Parallel Resonance Circuit](image)

Series – Parallel Resonant Circuit: The fig. 5 shows testing circuit which utilizes the advantages of both series resonant circuit and parallel resonance circuit.

![Fig. 5 Series Parallel Resonance High Voltage System](image)

The following points need to be kept in mind while considering a series-parallel resonant circuit:

- The output voltage is achieved by auto transformer action and parallel compensation is achieved by the connection of the reactor.
- For a certain gap opening uncontrolled overvoltage of test sample results in case of parallel connected test system and if test set is allowed to operate for a long time resulting in heating and damage to the reactor.
- Experimentally it has been observed that complete balance of ampere turns takes place when the system operates under parallel resonance conditions. However under all other settings of variable reactor, an unbalance in AT forces large leakage flux into the surrounding metallic tank causing large circulating currents resulting in hot spots which adversely affects dielectric strength of oil in the tank.
- So instead of using only series resonant or only parallel resonant circuit, it is recommended to use a series – parallel resonant mode for testing purposes. For a single stage system upto 300 kV, series resonance method is strongly recommended and beyond that parallel resonance method.

**Generation of High Frequency A.C. High Voltages:** A high frequency high a.c. voltage is not only required for d.c. power supplies but also for testing electrical apparatus for
switching surges. This requires high voltage high frequency transformer. The advantages of these high frequency transformers are:

(i) The high frequency resonant transformers do not use iron core which results in saving in cost and size.

(ii) These transformers give pure sine wave output.

(iii) The voltage build up is slow over a few cycles and hence there is no damage due to switching surges.

(iv) The voltage distribution is uniform across the winding coils due to subdivision of coil stack into a number of units.

The most commonly used high frequency resonant transformer is Tesla coil which is a doubly tuned resonant circuit whose equivalent circuit is shown in fig.6

![Fig. 6 Equivalent Circuit of Tesla Coil](image)

The primary voltage rating is 10 kV and the secondary maybe related to as high as 500 to 1000 kV. The primary is fed from a d.c. or a.c. supply through the capacitor $C_1$. A spark gap $SG$ connected across the primary winding is triggered at the desired voltage $V_1$ which induces a high self – excitation in the secondary. The primary and secondary windings (having inductance $L_1$ and $L_2$) are wound on an insulated former having air core immersed in oil. The windings are tuned to a frequency of 10 to 100 kHz by means of the capacitors $C_1$ and $C_2$.

The output voltage $V_2$ is a function of the parameters $L_1$, $L_2$, $C_1$, $C_2$ and mutual inductance $M$. Usually the winding resistance being small contributes only for damping oscillations. The output voltage is given by

$$V_2 = V_1 \sqrt{\frac{C_1}{C_2}}$$

Where $\eta = \text{efficiency of transformer}$. If the coupling $K = M/L_1L_2$ is large then for large values of winding resistances the output voltage waveform may become a unidirectional impulse instead of a sinusoidal waveform.

**Advantages of high voltage high frequency transformer:** The following are the advantages of a high voltage high frequency transformer:

(i) There is saving in cost and size due to the absence of iron core.

(ii) The output wave obtained is purely sinusoidal.

(iii) There is no damage due to switching surges as voltage build up is slow over few cycles.