

## Chapter II

## THEORY OF TESTING TRANSFORMER



## 2.1 General Fundamental Principle

When an electric circuit is supplied with a voltage, that circuit must take sufficient current from the source to build up a counter electromotive force equal and opposite to the voltage applied. The primary of a transformer is a circuit wound on an iron core. The resistance of the winding is purposely made low. Thus the counter electromotive is made up essentially of a voltage produced by the action of the flux on the primary turns. The instantaneous value of this counter electromotive force is

$$e_1 = -N_1 \frac{d\phi}{dt} 10^{-8} \text{ volts} \dots\dots\dots(1)$$

where  $N_1$  is the number of turns on the primary winding and  $\phi$  is the instantaneous value of the flux in the core. Assuming the primary resistance to be zero, the applied voltage  $v_1$  (instantaneous value) is equal and opposite to  $e_1$ , or

$$v_1 = N_1 \frac{d\phi}{dt} 10^{-8}$$

If the applied voltage is sinusoidal, that is

$$v_1 = v_{1 \max} \sin 2\pi ft$$

then  $\phi = \phi_{\max} \sin 2\pi ft$  and

$$e_1 = -N_1 \phi_{\max} \cos 2\pi ft \times 2\pi f \times 10^{-8} \dots\dots\dots(2)$$

To obtain the root mean square values, divide the maximum value of equation (2) by  $\sqrt{2}$ . Then

$$E_1 = \frac{2\pi}{\sqrt{2}} f N_1 \phi_{\max} 10^{-8} \dots \dots \dots (3)$$

The cosine term has no significance except to derive instantaneous values. From equation (3) the expression for root mean square values becomes

$$E_1 = 4.44 f N_1 \phi_{\max} 10^{-8} \dots \dots \dots (4)$$

If a secondary winding having  $N_2$  turns is now placed on the core as shown in Fig. 2.1 a voltage will be produced in it by the flux  $\phi$ .

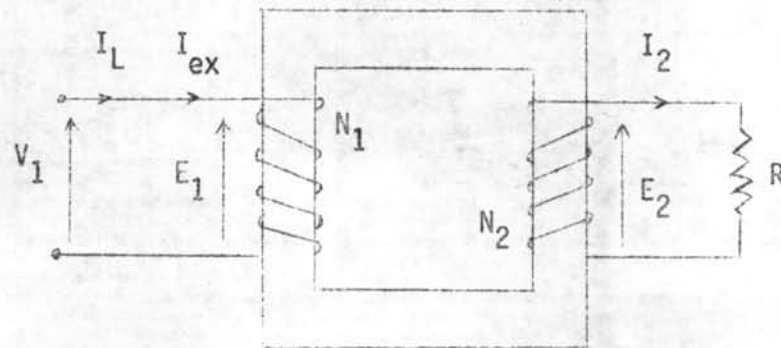


Fig. 2.1 Typical core and primary, secondary winding

The magnitude of this voltage  $E_2$  is directly proportional to the number of turns  $N_2$ .

From equation (3) the expression for root mean square values becomes

$$\frac{E_1}{E_2} = \frac{N_1}{N_2} \dots \dots \dots (5)$$

If a secondary winding having  $N_2$  turns is now placed on the core as shown in Fig. 2.1

Let it be assumed that all flux  $\phi$  links both windings  $N_1$  and  $N_2$ . Then if a resistance is connected to the secondary, a current  $I_2$  will flow from it in time phase with  $E_2$ . This current will tend to produce a flux  $\phi_2$ . However, the primary must keep the total flux constant at a

value  $\phi$  in the direction shown. This is accomplished by the primary only through its production of another flux,  $-\phi_2$ . To produce  $-\phi_2$ , the primary must carry another current in the direction of  $-\phi_2$ . The magnetomotive force of the primary  $N_1 I_L$  necessary to counteract the magnetoforce  $N_2 I_2$  requires a load component of current  $I_L$  such that

$$I_L = I_2 \cdot \frac{N_2}{N_1} \dots\dots\dots(6)$$

Thus the ratio of primary load current to secondary current can be expressed as

$$\frac{I_L}{I_2} = \frac{N_2}{N_1} \dots\dots\dots(7)$$

The total current  $I_1$  in the primary, when  $N_2$  is supplying the above load, is the vector sum of  $I_L$  and  $I_{ex}$ .

## 2.2 Rating or Power Output of Testing Transformer.

The testing transformer should be rated higher than the charging rate of the test sample and is given by

$$P = 2 \pi f C_t U^2 \times 10^{-9} \dots\dots\dots(8)$$

$P$  = power output, in KVA

$f$  = frequency, in cps

$C_t$  = load capacitance, in pF

$U$  = test voltage at the transformer terminal, in kv rms.

The self capacitance of the testing transformer as well as the stray capacitance of the various shielded high voltage terminals and

connections must be considered in order to determine the capacitive load. This is especially important for very high voltage where the shields are necessarily very large. For instance, the capacitance (in pF) of a sphere to earth is larger than sphere radius (in cm.)

Capacitance of test-samples:

Strings and Pin-type insulators	several pF
Bushings	100 to 400 pF
Current transformer	200 to 600 pF
Power transformer up to 1000 KVA	1000 pF
Power transformer over 1000 KVA	1000 to 8000 pF
Power Cables	150 to 300 pF/m

### 2.3 Equivalent Circuit of Transformer Winding.

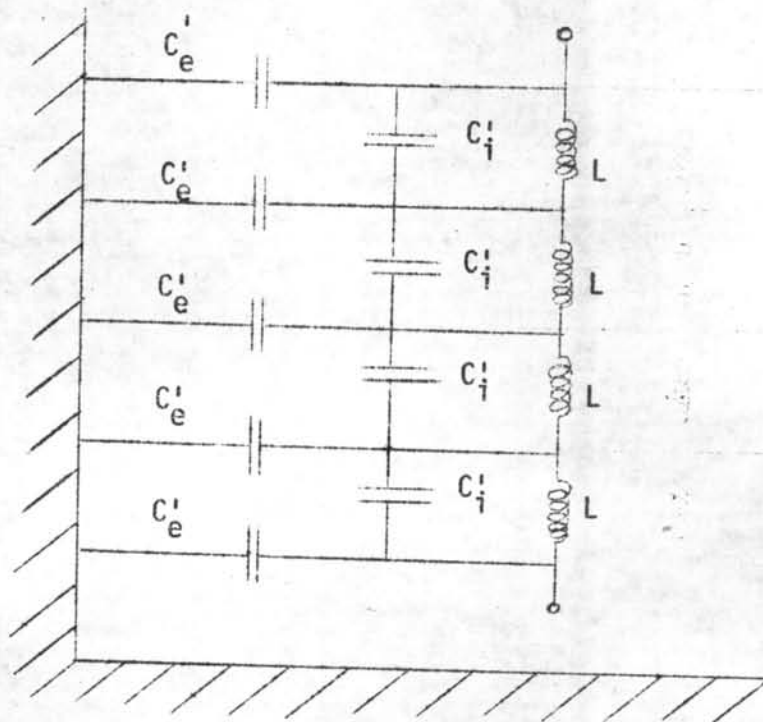


Fig. 2.2 Equivalent circuit of Transformer Winding



$$C'_e = \text{capacitance to ground (tank, core)}$$

$$C'_i = \text{capacitance between coils.}$$

Fig. 2.2 Equivalent circuit of transformer winding.

The behaviour of a transformer to steep-fronted surges is largely determined by the capacitances in and between successive high voltage coils, and of these coils to earth (i.e. to the low voltage winding, the core, and the tank wall). To a rapidly-changing voltage a capacitor offers a low impedance thus the electric field, as represented by its equivalent capacitances, becomes a predominant factor in determining the voltage distribution when the voltage has a high time rate of change.

Fig. 2.2 gives the equivalent circuit of transformer with its associated inter-coil capacitances  $C'_i$  and coil-to-earth capacitances  $C'_e$ . The relationship between the voltage  $U_m$  (m-th term) of a lattice capacitor network and the voltage  $U_0$  at the input is :

$$U_m = U_0 \cosh m\gamma - I_0 Z \sinh m\gamma \quad \dots\dots(9)$$

$$I_m = I_0 \cosh m\gamma - \frac{U_0}{Z} \sinh m\gamma \quad \dots\dots(10)$$

where

$U_m, I_m$	=	voltage, current at the m-th term
$U_0, I_0$	=	voltage, current at the input terminals
$m$	=	number of quadripole
$\gamma$	=	propagation coefficient
$Z$	=	surge impedance

If the ladder consists of n-quadripoles then voltage and current at the last term are

$$U_n = U_0 \cosh n\delta - I_0 Z \sinh n\delta \dots (11)$$

$$I_n = I_0 \cosh n\delta - \frac{U_0}{Z} \sinh n\delta \dots (12)$$

where

$$\cosh \delta = 1 + \frac{C'_e}{2C'_i} \dots \dots \dots (13)$$

If the output terminal of the winding is isolated from earth, then the current there is  $I_n = 0$

From eq. (12) follows:

$$I_0 \cdot Z = U_0 \frac{\sinh n\delta}{\cosh n\delta}$$

with this from eq. (9)

$$U_m = U_0 \cosh m\delta - \frac{U_0 \sinh n\delta}{\cosh n\delta} \sinh m\delta$$

$$\frac{U_m}{U_0} = \frac{\cosh m\delta \cosh n\delta - \sinh n\delta \sinh m\delta}{\cosh n\delta}$$

$$\frac{U_m}{U_0} = \frac{\cosh (n-m)\delta}{\cosh n\delta} \dots \dots \dots (14)$$

This is the voltage at coil m out of a total of n coils.

If the output terminal of the winding is short circuit, then the voltage there is  $U_n = 0$

From eq. (11) follows :

$$I_0 \cdot Z = U_0 \frac{\cosh n\delta}{\sinh n\delta}$$

with this from eq. (9)

$$U_m = U_0 \cosh m\delta - U_0 \frac{\cosh n\delta}{\sinh n\delta} \sinh m\delta$$

$$\frac{U_m}{U_0} = \frac{\cosh m\delta \sinh n\delta - \cosh n\delta \sinh m\delta}{\sinh n\delta}$$

$$\frac{U_m}{U_0} = \frac{\sinh (n-m)\delta}{\sinh n\delta} \dots\dots\dots(15)$$

m = number of coil

n = total number of coils

For most transformer designs,  $C'_i > C'_e$ . The ratio  $C'_e/2C'_i$  is therefore smaller than 1. The expansion in series of  $\cosh \delta$  may therefore be interrupted after the second term.

$$\cosh \delta = 1 + \frac{C'_e}{2C'_i} = 1 + \frac{\delta^2}{2}$$

$$\delta = \sqrt{\frac{C'_e}{C'_i}} \dots\dots\dots(16)$$

and

$$n\delta = n \sqrt{\frac{C'_e}{C'_i}} = \sqrt{\frac{C_e}{C_i}} \dots\dots\dots(17)$$

$C_e$  = Total capacitance to earth

$C_i$  = resulting capacitance between first and last coil of winding.

From eq. (16), (17) it follows that greater  $C'_e$  means greater  $\delta$  which means great voltage drops across the first coils of a high voltage winding.

#### 2.4 Effect of Overvoltages

A source of unwanted overvoltages in alternating current testing circuits are overvoltages due to a transient earth fault (breakdown). An alternating current testing circuit consists of mainly of a high voltage testing transformer, the conductors, which connect the transformer to the test sample, and the sample itself. A breakdown somewhere in the test circuit and not necessarily at the test sample means the discharge

of the stray capacities of transformer, leads and test sample. After the earth fault has disappeared these stray capacities will be recharged through the transformer inductance. This forms a more or less damped R-L-C- circuit. The result is a transient overvoltage at the transformer terminals and the test sample. The first and highest peak value of this oscillation is

$$\hat{U}_1 = u_0 \left[ 1 + \exp \left( -\frac{\pi}{2} \cdot \frac{R}{\sqrt{\frac{L}{C}}} \right) \right]$$

This overvoltages may cause a breakdown of the test sample besides being dangerous to the test transformer. Attention must be kept on such breakdowns which actually occur at a value much higher than according to the excitation.

Overvoltages in low voltage winding caused by breakdown in the testing circuit and transmitted by the interwinding capacity may be dangerous for the low voltage feeder circuit. Protection by increasing the capacitance to ground of the feeding circuit or by grounded shield between low and high voltage winding.

## 2.5 Reactive Power Compensation

Testing transformer operate mainly with a capacitive load. Thus, the necessary transformer supply given by a voltage regulating transformer or a motor generator set can be reduced by the use of compensating reactors, in testing circuit. It should be emphasized that the testing transformer must be able to supply the highest value of the load current for which it has been designed at all intermediate voltages, up to the rated voltages.



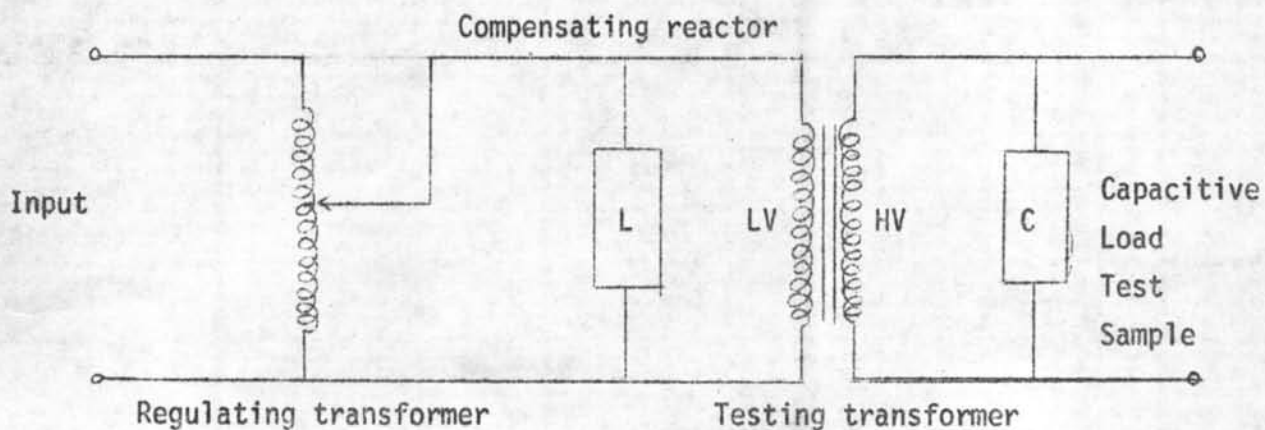


Fig. 2.3 Arrangement of Compensating reactor in Testing circuit

When a testing transformer is on open circuit, the secondary high voltage side may have sufficient capacitance to cause a displacement current  $I_c$  to circulate, the counterpart of which has to be supplied to the primary together with the magnetizing current  $I_m$ . It is quite possible for its displacement current  $I_c$  to exceed the magnetizing current  $I_m$ , so that the no-load exciting current  $I_o$  appears to be in leading capacitance current

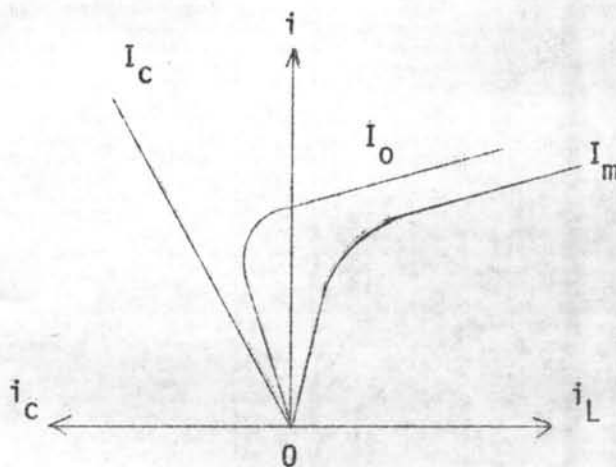


Fig. 2.4 compensation of exciting current

The design of the compensating reactors depends upon the available supply power, the power of the testing transformer, the different change-over possibilities and finally upon the operation range given by the test object within the voltage-power characteristic.